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electrical power system essentials

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Electrical Power System Essentials

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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 supports it, enhances it and as such is an integral part of the book.

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 like '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, 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 principals 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, and underground cables 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.

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 Hz 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. FACTS-devices (Flexible AC Transmission Systems) 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 centre, 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 SCADA (Supervisory Control and Data Acquisition) 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 centre 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, like the loadflow or power flow, and the optimal powerflow. The loadflow 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 loadflow, a decoupled loadflow and the DC loadflow 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 chapter, 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 with 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, are given. After that, a more general description of the transformer by means of magnetically coupled coils is derived. In the next step the non-ideal 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 which 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. The helpful comments and support of Prof. Wil Kling, Prof. Braham Ferreira, Prof. Johan Smit, Dr Bob Paap and Dr Henk Polinder, all of the Electrical Power Engineering Department of the Delft University of Technology, are greatly acknowledged.

The companion website for the book is http://www.wiley.com/go/powersystem

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1

Introduction to Power System Analysis

1.1 INTRODUCTION

As electricity comes out of the 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 35 minutes' interruption to their supply in the year 2006 [7] out of a total of 8760 hours, resulting in an availability of 99.99334 %!

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's discover what lies beyond the AC outlet and enter the challenging world of power system analysis . . .

Electrical Power System Essentials Pieter Schavemaker and Lou van der Sluis

Figure 1.1 The Earth's city lights, indicating the most urbanized areas. Reproduced by permission of NASA, taken from The Visible Earth.

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 Hz 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 Hz or 60 Hz).
  This is the time scale on which this text 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, e.g. when connecting or disconnecting loads or switching off faulty sections, or into

the effect of atmospheric disturbances, such as lightning strokes, and the accompanying over-voltages and over-currents 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 wave length [km]
v the speed of light $\approx$ 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 (Maxwell's laws)). 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 any more. The distributed nature of the transmission line has to be taken into account and we have to calculate with travelling 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 [13,27]:

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

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

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]

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

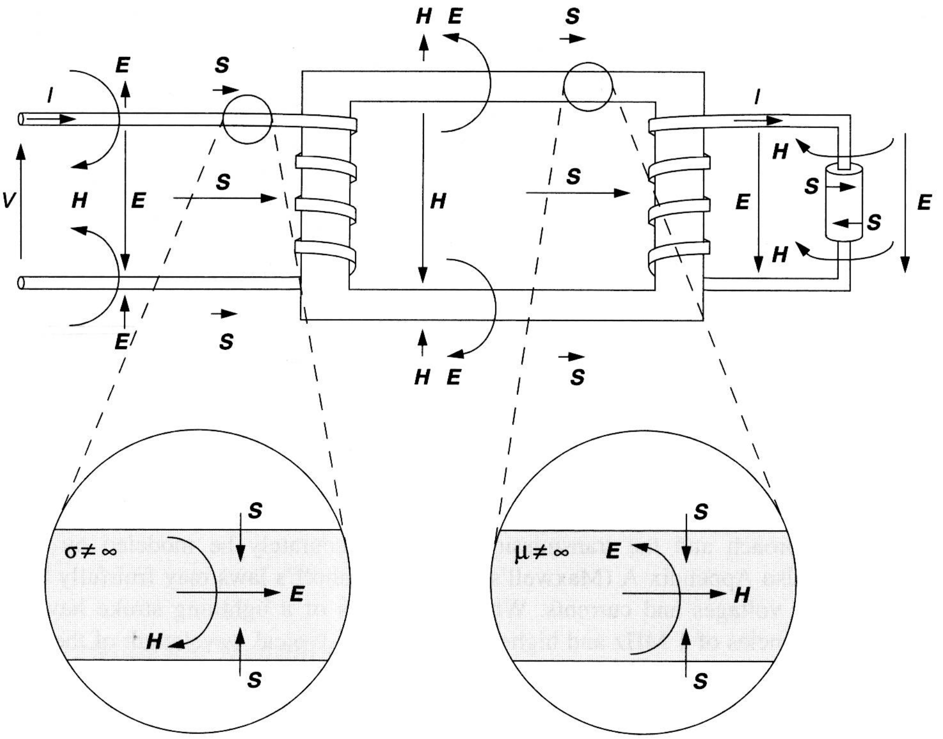

Figure 1.2 Transmission line – transformer – transmission line – load: the energy is stored in the electromagnetic field.

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

This leads to small Poynting vectors pointing towards 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 Hz 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 Nicolas 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