Chapter 1
Introduction

In this Chapter, the objectives, characteristics and instructions of how to use this book will be explained. The mathematical notation used in this book will also be summarized.

1 Control of electrical power system

1.1 Importance of interdisciplinary integration aimed at power system reform

In Japan, the reformation of the power system began with the Great East Japan Earthquake in March 2011, and the full-scale introduction of renewable energy, such as solar, wind and geothermal power took place after the full liberalization of the electricity retail market in April 2016. Furthermore, in October 2020, Japan pledged to achieve carbon neutrality by 2050 as a matter of national policy. Thus, improvements to the existing energy supply system and maximization of the use of renewable energy are strongly required. To achieve such an ambitious goal, technologies related to energy generation, as well as digital technologies, such as telecommunications, must be fully utilized to create a smart grid that improves the operation of power systems and to control supply and demand of renewable energy, where power supply fluctuates with weather.

A power system is a large-scale system that consists of the interaction of events and phenomena on a wide range of spatio-temporal scales. Specifically, the operation of actual power systems is influenced not only by the properties of electromechanical devices and facilities, such as generators and transmission lines, but also by natural phenomena, such as weather condition and natural disasters, and human-related activities, such as electricity demand by the consumers, and commercial activities of power generation, transmission and distribution companies.

Therefore, the reformation of current power systems should be supported by the expertise of various academic fields in addition to energy-related fields. For instance, notions of economics are essential for designing a fair market system capable of adding value to the planned and observed values of energy supply and demand, and at the same time avoiding monopoly formation. In addition, to manage the uncertainties of renewable energy generation, it is imperative to develop methods to plan supply and demand and to forecast power generation from these resources. For this purpose, notions of mathematical optimization and statistics are fundamental. Finally, expertise in feedback control methods is essential for improving system stability against disturbances such as load fluctuations and ground faults.

In summary, the design and operation of power systems require expertise of various research fields. This academic diversity will lead to challenging yet attractive research and development topics.

1.2 Objective of this book

Control systems engineering is an interdisciplinary field that covers many areas of science, such as control theory, information theory, data science, systems engineering and mathematical optimization, and it is expected to contribute to the research and development of power systems. However, since power systems are complex systems composed by a wide range of devices and phenomena, it is often very challenging for beginners to get an overview of the whole system. This difficulty hinders the contribution of experts in other areas in research and development of power systems. This book attempts to tackle this problem by providing an introduction and an overview of power systems.

By explaining modeling, numerical simulation, control system design and mathematical analysis for power systems will be explained from a viewpoint of network system analysis and control, this book aims to make students and researchers in the field of system control to be able to:

- understand the structure of power systems and mathematical foundation in the language of control systems engineering, and
- build a numerical simulation environment for analysis and control of power systems on their own.

For this purpose, the structure and characteristics of power systems will be explained by using fundamental concepts of control systems engineering, such as state-space representation, equilibrium point, stability and feedback control. In addition, the numerical simulation enviornment will be conducted based on the foundations of object-oriented programming, describing the entire complex power system as classes and methods and providing code examples for easier understanding.

1.3 Characteristics of this book

Review English in this section There are many good books, both in Japanese and other languages, on electrical power systems. Characteristics of this book compared to these books are as follows:

- one can follow this book without a background in electromagnetism, and
- the structure and characteristics of power systems as a network system are clearly described.

For example, a standard book on electrical power system engineering assumes that one has knowledge on three-phase electric power and electromagnetic induction, and focuses on the explanation of electromagnetic phenomena inside of each generator and so on. Meanwhile, as far as the authors are aware, there are few if any books that clearly explain the dynamic characteristics and structures of the whole system when multiple generators are connected via a power grid from the viewpoint of control systems engineering. In addition, while a model in which multiple generators are connected in a power grid is used to analyze power transmission distribution, known as power flow calculation, in system stability discussions, different models are often introduced depending on the topic of discussions (e.g., single machine infinite bus system models, models consisting of only one generator). This makes it difficult for novice learners who are unfamiliar with electrical power system engineering to see the link between explained topics and gain a comprehensive view of the entire power system. Considering these situations, this book presents essential basics for students, researchers, and technologists in the field of system control to “understand” the structure and characteristics of power systems “based on system theory.”

As discussed above, various academic knowledge is required to design and operate power systems. With the help of the information in this book, we hope that challenging and attractive research and development targets will be used as one of the benchmark models in the field of system control.

2 How to use this book

2.1 Overall structure

Review English in this section This book introduces mathematical models of electrical power systems in Chapter 2, then explains the steps for numerical simulation of the electrical power system model in Chapter 3. This is followed by discussions of the stability of the electrical power system model in Chapter 4 and control methods to improve the system stability in Chapter 5. Finally, in Chapter 6, we present the results of numerical simulations using a large-scale electrical power system model.

This book assumes that readers will follow from Chapter 2 to Chapter 6 in that order. However, readers who aim to perform numerical simulations on their own can skip Sections with "‡" in the title. These Sections primarily describe development topics that are useful in understanding the mathematical structure of the electrical power system model. Since this book focuses on explanations of the basics of electrical power system analysis, topics related to new energy, such as solar power, wind power, and batteries are not presented. Please refer to [**?**] for these topics.

2.2 Published numerical simulation codes and supplementary material

Review English in this section The numerical simulations described in this document were created with a Matlab program called GUILDA (Grid & Utility Infrastructure Linkage Dynamics Analyzer), which is being developed mainly by the authors. and can be freely extended by users. The programs used for the numerical simulations in this book are also available. For details, please refer to the web page of this book by Corona Inc. for more details. Color versions of the figures in this book are also provided. Translated with www.DeepL.com/Translator (free version)

2.3 Mathematical notations

Real numbers and complex numbers are expressed as $\mathbb{R}$ and $\mathbb{C}$, respectively. Real vectors with n dimensions are expressed as $\mathbb{R}^n$, while real matrices with dimensions $n \times m$ are expressed as $\mathbb{R}^{n\times m}$. The same style of notation is used for complex vectors and matrices. In addition, the imaginary unit is expressed as $\boldsymbol{j}$, and bold font is used for complex scalars, vectors and matrices.

A vector in which all elements are one is expressed as $\mathbb{1}$. A diagonal matrix that has real scalar, $c_1, \ldots, c_n$, as diagonal elements is expressed as $(c_i)_{i\in\{1,\ldots,n\}}$. When it is clear from the context, subscripts are omitted and the diagonal matrix is simply expressed as $\mathsf{diag}(c_i)$. The same applies to complex numbers. In addition, the inverse matrix of a nonsingular complex matrix $\boldsymbol{Z}$ is expressed as $\boldsymbol{Z}^{-1}$.

The transposed matrix of real matrix A is expressed as A^T. The real and imaginary parts of a complex matrix $\boldsymbol{Z}$ are expressed as $\mathsf{Re}[\boldsymbol{Z}]$ and $\mathrm{i}[\boldsymbol{Z}]$, respectively. In other words, for an arbitrary complex matrix $\boldsymbol{Z}$:

$$\boldsymbol{Z} = \mathsf{Re}\,[\boldsymbol{Z}] + \boldsymbol{j}\mathrm{i}\,[\boldsymbol{Z}]$$

In addition, the conjugate of a complex matrix $\boldsymbol{Z}$ is expressed as $\overline{\boldsymbol{Z}}$, and the conjugate of its transpose is expressed as $\boldsymbol{Z}^*$. In other words:

$$\overline{\boldsymbol{Z}} = \mathsf{Re}\,[\boldsymbol{Z}] - \boldsymbol{j}\mathrm{i}\,[\boldsymbol{Z}]\,, \qquad \boldsymbol{Z}^* = (\mathsf{Re}\,[\boldsymbol{Z}])^\mathsf{T} - \boldsymbol{j}\,(\mathrm{i}\,[\boldsymbol{Z}])^\mathsf{T}$$

The absolute value of a complex scalar $\boldsymbol{z}$ is expressed as $|\boldsymbol{z}|$, while its argument is expressed as $\angle\boldsymbol{z}$. In other words, $\boldsymbol{z} = |\boldsymbol{z}|e^{\boldsymbol{j}\angle\boldsymbol{z}}$.

When complex symmetric matrix $\boldsymbol{Z} = \boldsymbol{Z}^*$ is positive definite, it is written as $\boldsymbol{Z} > 0$. When $\boldsymbol{Z}$ is positive semi-definite, it is written as $\boldsymbol{Z} \geq 0$. Similarly, negative definite and negative semi-definite are expressed with inequality signs of the opposite direction.

COFFEE BREAK

Singularity of matrix: A square matrix $\boldsymbol{A}$ is said to be **regular**(nonsingular) if it has an inverse $\boldsymbol{A}^{-1}$ such that:

$$\boldsymbol{A}\boldsymbol{A}^{-1} = I$$

The above condition is true if and only if the determinant of $\boldsymbol{A}$ is non-zero.

Positive and negative definiteness of matrices: For a given complex vector $\boldsymbol{x}$, a square matrix $\boldsymbol{A}$ is said to be **positive semi-definite** if the following relationship is true:

$$\boldsymbol{x}^*\boldsymbol{A}\boldsymbol{x} \geq 0$$

Additionally, $\boldsymbol{A}$ is **positive definite** if $\boldsymbol{x} \neq 0$ and:

$$\boldsymbol{x}^*\boldsymbol{A}\boldsymbol{x} > 0$$

The definition of semi-negative and negative definiteness are similar, with the only difference being the sign of the inequality. A necessary and sufficient condition for a complex symmetric matrix $\boldsymbol{A}$ to be positive semi-definite is that all its eigenvalues are non-negative. Similarly, a necessary and sufficient condition for $\boldsymbol{A}$ to be positive definite is that all its eigenvalues are strictly positive.

The null space of real matrix $A \in \mathbb{R}^{n\times m}$, $\mathsf{ker}\, A$, is defined as:

$$\mathsf{ker}\, A := \{x \in \mathbb{R}^m : Ax = 0\}$$

where the symbol ":=" means that the term on the right side of the symbol defines the term on its left side. The null space of a complex matrix $\boldsymbol{Z} \in \mathbb{C}^{n\times m}$ is similarly defined as:

$$\mathsf{ker}\, \boldsymbol{Z} := \{\boldsymbol{x} \in \mathbb{C}^m : \boldsymbol{Z}\boldsymbol{x} = 0\}$$

Moreover, given a set of real vectors $v_1, \ldots, v_m \in \mathbb{R}^n$, the linear space formed by all the vectors that can be written as linear combination of vectors $v_1, \ldots, v_m$ is defined as:

$$\mathsf{span}\{v_1, \ldots, v_m\} := \{c_1 v_1 + \cdots + c_m v_m : (c_1, \ldots, c_m) \in \mathbb{R} \times \cdots \times \mathbb{R}\}$$

Finally, the Euclidean norm of a real vector $x \in \mathbb{R}^n$ is represented by $\|x\|$. In other words:

$$\|x\| := \sqrt{|x_1|^2 + \cdots + |x_n|^2}$$

where the x_i is thee ith element of x.

Please note that, in this book, standard symbols in control systems and electrical power system engineering might overlap. For example, in control systems engineering, "G" is often used to represent a system, whereas in electrical power system engineering, it is commonly used to express conductance. Unless there is a concern about misunderstanding of the context, overlaps between these symbols will not be discussed.