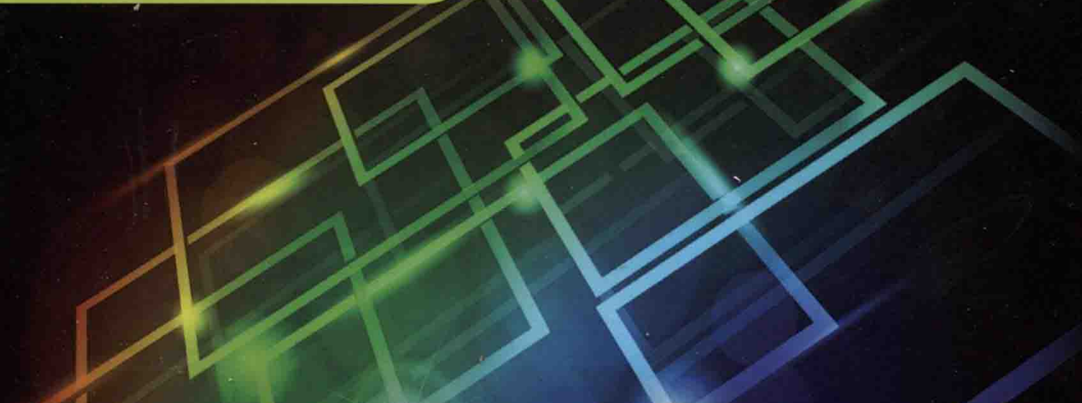
# Control and Dynamics in Power Systems and Microgrids

Lingling Fan



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# Preface

The main part of the book was written in Spring 2016 when the author taught Power Systems II, a graduate course at University of South Florida, Tampa Florida. The course was designed to focus on control and dynamics of power systems. Bergen and Vittal's book, *Power System Analysis*, was adopted as the textbook. Dynamics and control, especially in the area of power systems applications where rotating magnetic fields are involved, is a formidable subject to students. Hence, a set of class notes was developed in that semester to offer a tutorial approach of learning. Many examples and codes were developed to facilitate understanding and hands-on training. A highlight of this textbook is its many tutorial examples.

The first version of Bergen and Vittal's book was written in 1981 by Professor Bergen. Thirty-six years have passed since then. This classic textbook has been highly recognized and helped to educate a generation of power systems engineers. Professor Bergen passed away in July 2014. As a power systems engineer, this author would like to contribute to the field by reinterpreting the classics of power system control and dynamics. This textbook is also a tribute to Professor Bergen.

There will be several things different from the classic textbook.

The generator model derivation is very sophisticated in Bergen and Vittal (2009). In Bergen and Vittal (2009), Park's transformation was employed to derive generator models. The alternative of Park's transformation is space vector and complex vector transformation, a concept used much more often in machines and power electronics after the 1980s. The space vector concept makes Park's transformation straightforward. In this textbook, the author will explain synchronous generator dynamics, the most formidable dynamics in power systems, using space vector concepts.

In the 1980s, power electronics and microgrids were yet to be developed. This field is well developed in the 21st century. Many techniques used in power systems for power sharing, e.g., droop control, can also be found in power electronic converter coordination. This part is now related and put into the textbook to help readers understand converter control and coordination. This is another highlight of the textbook.

Advanced controls such as networked control (consensus control) were developed after 2000. Many classic engineering implementations follow the advanced control framework. It is appealing to find them and interpret the intuitive engineering design with concepts and ideas from networked control. In this textbook, inter-area oscillations are explained using consensus control.

Professor Bergen's book has steady-state analysis and dynamics all together. This textbook focuses on dynamics and control only. This author would also like to have a better flow to focus on power system control. Starting from the beginning, the ordinary differential equation, the building block of dynamics and control, is explained using examples. Dynamic simulation and linear system analysis are conducted for the examples. With the fundamental concept of dynamics built, readers can then pursue the learning tasks related to power system control and dynamic stability with ease.

The flow of the text is to treat frequency or voltage control as control problems. For control problems, first we discuss the plant model and its related steady-state and dynamic responses. The plant model should be identified with the inputs and outputs specified. In the frequency control case, it is obvious that the output of the plant model should be frequency. The inputs are from a generator's mechanical system inputs. After setting up the plant model, we then think about how to design feedback controls to realize control objectives. After the control design is conducted, we then employ dynamic simulation to verify controller performance.

The author is grateful to have the opportunity to write and publish this book through the CRC press. The author would like to acknowledge the University of South Florida Electrical Engineering Department for providing a great environment for conducting research and teaching. The author wishes to acknowledge her family for their encouragement.

The book was developed from the author's class notes of Power Systems II for Spring 2016. Minyue Ma, a Ph.D. student, was the teaching assistant for that course and helped work out examples and homework problems for the class. A few students in the class, e.g., Abdullah Alassaf, highly complimented the class notes, which encouraged the author to contact the CRC press for publication. Yin Li, a Ph.D. student, built the MATLAB®/Simulink models used in Chapter 6 Frequency and voltage control in microgrids. Yangkun Xu, another Ph.D. student drew many figures for Chapter 3 and Chapter 5. Graduate students at the USF Power Systems Smart Grid Lab reviewed the book during the holiday season in December 2016. The author wishes to acknowledge Minyue Ma and Yin Li as reviewers. The author also wishes to acknowledge Yi Yang from Eaton Cooperation as a reviewer.

# Contents

# Chapter 1

# Introduction

## 1.1 Why a new textbook?

A traditional power system dynamics and control book covers synchronous generator models (steady-state and dynamics), generator voltage control, power system frequency control, and power system transient stability. A typical textbook is Bergen and Vittal's book *Power Systems Analysis* (Chapters 6, 7, 8, 11, and 14). With today's smart grid industry, the following aspects need to be added in teaching and in textbooks.

1. How to carry out demonstration for power system dynamics and control.

To address this task, dynamic simulation of ordinary differential equation-based models and further programming implementation in software environment such as MATLAB® or Python should be covered. This part is usually not found in a traditional textbook. Rather, students have to go to another course or read another book on computing to learn how to conduct validation and demonstration. In this text, tutorial examples on programming and dynamic simulation will be provided and students can quickly manage to conduct validation through coding or MATLAB/Simulink.

2. How to carry out control design.

Classic control methods such as the root locus method are repeatedly used in Bergen and Vittal (2009). In the 1980s, MATLAB and its control toolbox were not yet popular. Therefore, Bergen and Vittal (2009) did not present examples related to MATLAB codes. This textbook will provide MATLAB examples for control design problems.

3. How to better explain rotating machines.

Generator model derivation is the most sophisticated part in Bergen and Vittal (2009). In Bergen and Vittal (2009), Park's transformation was employed to derive generator models. The alternative to Park's transformation is space vector and complex vector transformation, a concept used much more often in machines and power electronics after the 1980s. The space vector concept makes Park's transformation straightforward. In this textbook, the author will explain synchronous generator dynamics, the most formidable dynamics in power systems, using the space vector concept.

4. How are microgrids controlled?

In the traditional power system dynamics and control books, the focus is on synchronous generators. With the current industry where renewable energy, power electronics converters and microgrids arise, the related system-level dynamics and control should be covered. For example, when frequency control is discussed, it is very natural to extend the applications from large-scale power systems to microgrids where droop control is also used. Coverage on microgrid control is a highlight of this textbook.

In short, the aim of this textbook is to provide more insights using programming examples, state-of-the-art control design tools, and advanced control concepts to explain traditional power system dynamics and control. In addition, microgrid control will be covered as extended applications.

While reading this textbook, readers will get the chance of training in programming and control design. They will gain knowledge on dynamics and control in both synchronous generator-based power systems and power electronic converter enabled microgrids.

## 1.2 Structure of this book

The book is organized in eight chapters. The book has two main parts: control (frequency and voltage control) and dynamics (large-signal stability and small-signal stability). Before control problems are introduced, the validation tool: dynamic simulation, is examined in Chapter 2. Along with dynamic simulation, linear system analysis tools such as Bode plots, are also introduced.

There are four chapters related to control: Chapters 3-6. Frequency control and power sharing of synchronous generators are examined in Chapter 3. Electromechanical dynamics of a synchronous generator is considered while electromagnetic dynamics are not considered in Chapter 3. This treatment makes analysis concise with only critical dynamics included. After frequency control, voltage control is to be examined. To better explain voltage control, a detailed examination of a synchronous generator's model with electromagnetic dynamics is required. Therefore, Chapter 4 focuses on the derivation of synchronous generator models using the space vector concept. Both steady-state and dynamic models are presented in Chapter 4. Chapter 5 presents voltage control of synchronous generator.

Chapter 6 covers converter control and power sharing among converters in a microgrid. The materials presented in Chapter 6 have never been found in any textbook on power system control and dynamics. Chapter 6 first presents a single voltage source converter's control. Depending on its operation mode, a converter can either work in PQ control mode for grid-connected operation or in VF control mode for autonomous operation. With the fundamental control covered, droop control for power sharing among converters is then presented. This chapter gives many examples on control design and simulation-based validation.

Part II of the book focuses on dynamics. Two chapters are included. Chapter 7 focuses on large-signal stability. An example is transient stability of a synchronous generator. Chapter 8 focuses on small-signal stability. Three engineering problems are used as examples in this chapter: small-signal model derivation of a single-machine infinite-bus (SMIB) system for stability analysis, inter-area oscillation explanation using networked control theory, and torsional interactions in a synchronous generator. For each problem, linear system models are derived and linear system analyses are conducted.

This book provides many examples and tutorials to facilitate learning. Through the study of this book, readers can master the skill of linear system analysis and simulation-based validation. What's more, this book builds a bridge between traditional synchronous generator-based large-scale power system control and converter-based microgrid control.