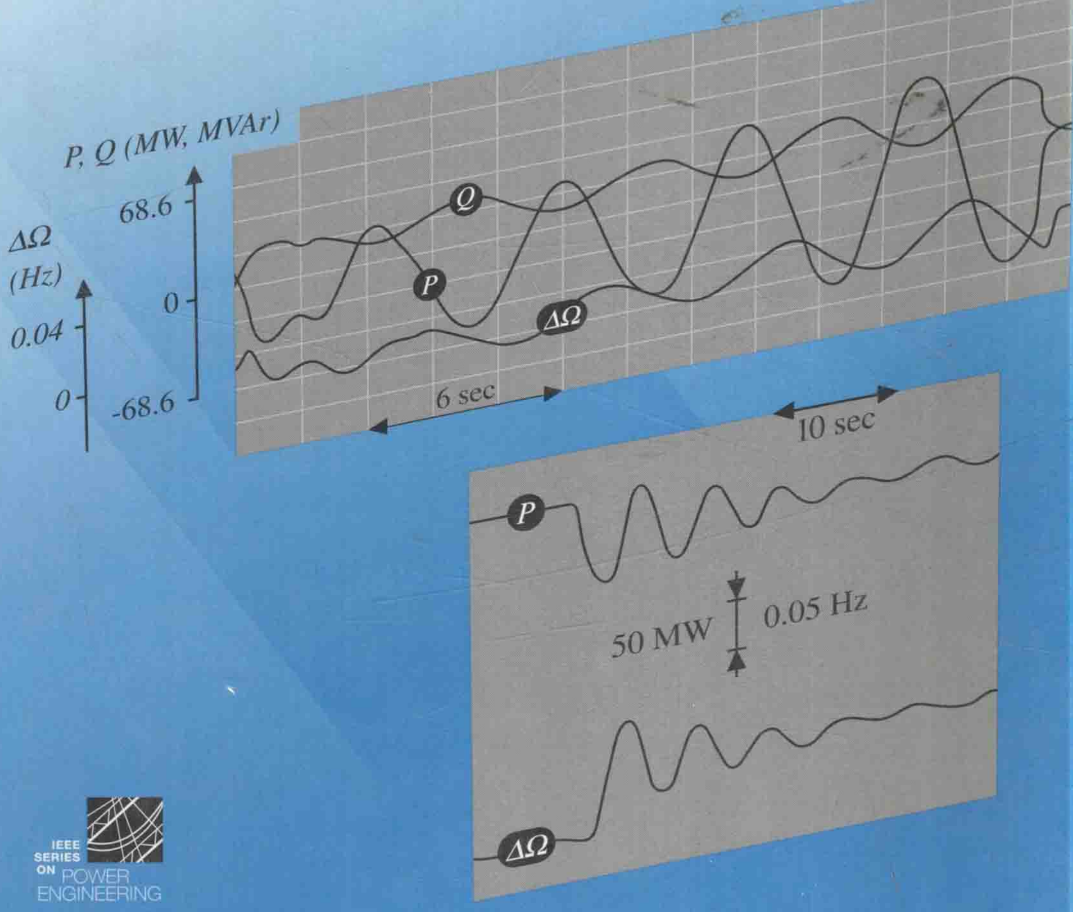
ELECTRIC POWER SYSTEMS

ANALYSIS AND CONTROL

Fabio Saccomanno



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FOREWORD

It gives me great pleasure to write the Foreword for this book because it covers a subject very dear to me and is written by someone whose work I have followed with interest for many years.

Research and development in electric power systems analysis and control has been an area of significant activity for decades. However, because of the increasing complexity of present-day power systems, this activity has increased in recent years and continues to do so because of the great economic significance of this field in the evolving scenario of a restructured electric power industry. I cannot think of a more qualified person than Professor Fabio Saccomanno to write on this subject. He has worked at the leading edge of developments in power system analysis and control for more than three decades. In addition to his extensive industrial and academic experience, he has made significant contributions to this area through his participation in the activities of international technical organizations, such as CIGRE, IEEE, IFAC, and PSCC.

This book covers a wide range of topics related to the design, operation, and control of power systems that are usually treated separately. Various issues are treated in depth with analytical rigor and practical insight. The subject matter is presented in a very interesting and unique perspective. It combines, in a structured way, control theory, characteristics and modeling of individual elements, and analysis of different aspects of power system performance.

While the book naturally covers topics presented in many other books on the subject, it includes many important original contributions based on pioneering work by the author, in particular, in analysis and control of electromechanical oscillations, nonlinear stability analysis, dynamic modeling and experimental identification, reactive compensation, emergency control, and generation scheduling. The comprehensive and rigorous coverage of all aspects of the subject was accompanied by the search for simplification and practical applications using intuition and common sense. The original Italian edition of this book was published in 1992 by UTET, Turin (Italy). It is not surprising that the original edition received the Galileo Ferraris Award from the Associazione Elettrotecnica ed Elettronica Italiana (AEI) in 1994. I am pleased to have been involved in editing the English translation of the original publication, along with Professor Stefano Massucco, Dr. Lei Wang, and Mr. G. K. Morison.

This book will be an invaluable source of reference for teachers and students of power engineering courses as well as practicing engineers in an area of major significance to the electric power industry.

DR. PRABHA KUNDUR
President & CEO
Powertech Labs, Inc.

Surrey, British Columbia, Canada
December, 2002

PREFACE

Some years ago, before I started to write this book, I already had an idea about how to structure the Preface. It was to be organized essentially as a "Preface-diary," to assist and encourage me in my work by recording the difficulties encountered along the way, the choices made and the subsequent changes, which often required rearranging the entire order of the subjects and rewriting complete parts of the book.

Now that the book is written, such a Preface would make no sense, not even to me. With the work finished, a strange feeling is aroused in me, a mixture of pride and perplexity, mainly when thinking about the courage and the tenacity I have had.

Drawing from the results of a long personal experience–technical, scientific, and teaching–which has been intensively matured in industrial and academic fields, I have tried to put together whatever I thought was necessary to achieve an up-to-date, organized, and coherent treatise; quite a challenging project which I have been thinking about for a long time.

The typical topics of electric power area (and related areas such as hydro and thermal power plants) are discussed here according to a "system approach" in order to allow, according to the most recent theories and methods, a global and right vision of the different problems involved. Special attention is dedicated to operational scheduling, control, and modelling of phenomena (essential, by the way, for simulations), and to the interpretation of the phenomena themselves, to make them more understandable to the reader and to ensure a sufficient mastery of the problems.

On the whole, the aim of this book is to be critical and constructive, not only for the ability to "do" but, before that, for "knowledge." It expresses the constant desire to clarify concepts and justify simplifications, so to maintain the *human being* at the core of problems. Therefore, this book is intended as a basic and up-to-date text, both for students and for anyone concerned, working in universities, industries or consulting. I hope that the presence of commonly separated topics will offer, for the homogenity of the treatment, interesting comparisons, useful correlations, and a deeper and wider knowledge for specialists in different branches.

I cited at the beginning, pride and perplexity; it seems to me that what has been said could justify such feelings, at least for the variety of contents and ambitious intention. The attempt of assembling (consistently) so many topics may appear successful, but such an effort has required, apart from a sort of cultural "challenge," a continuous and tiring research of the most effective way of presentation, to avoid lack of uniformity in style and emphasis; it is difficult for me to evaluate the result.

I am also aware of having, perhaps, "invaded" too many fields, with the risk of appearing sometimes superficial to specialists, but I hope they can forgive me by considering this invasion an obliged (and possibly discreet) choice and by still appreciating the outcome of the work and the intention that has driven me.

Just before closing, I wish to thank everybody who contributed to my preparation, and the ones who shared, in different ways, more or less directly, the discomforts originating from my work.

FABIO SACCOMANNO

Genoa, Italy
December, 2002

ACKNOWLEDGMENTS

Professor Stefano Massucco played an important role in the preparation of the English version of this book. He has also been precious for constant assistance in the project and a spirit of deep participation which has characterized his contribution. Dr. Prabha Kundur reviewed and edited the English translation, and provided valuable comments and helpful suggestions. He was ably assisted by Dr. Lei Wang and Mr. G. K. Morison in this effort. The large and tiring work of editing the equations has been carried out with competence and great care by Mr. Paolo Scalera.

F.S.

CONTENTS

CHAPTER 1

INTRODUCTION TO THE PROBLEMS OF ANALYSIS AND CONTROL OF ELECTRIC POWER SYSTEMS

1.1. PRELIMINARIES

1.1.1 Electric power can be easily and efficiently *transported* to locations far from production centers and *converted* into desired forms (e.g., mechanical, thermal, light, or chemical).

Therefore, electric power can satisfy the requirements of a variety of users (e.g., factories, houses, offices, public lighting, traction, agriculture), widely spread around the intended territory.

On the other hand, it is generally convenient to concentrate electric power generation into a few appropriately sized generating plants. Moreover, generating plants must be located according to both technical and economic considerations. For example, the availability of water is obviously of primary concern to hydroelectric power plants as well as the availability of fuels and cooling water to thermoelectric power plants. General requirements — about primary energy sources to be used, area development planning, and other constraints, e.g., of ecological type — must also be considered.

Consequently, the network for electric power transportation must present a branched configuration, and it can be required to cover large distances between generation and end-users. Moreover, the possible unavailability of some generating units or interconnection lines could force electric power flows to be routed through longer paths, possibly causing current overloads on interconnection lines.

These considerations make it preferable to have a network configuration sufficiently meshed to allow greater flexibility in system operation (as an adequate rerouting when encountering partial outages) thus avoiding excessive current flows in each line and limiting voltage dips and power losses to acceptable levels.

1.1.2 As it is widely known, electric power is produced, almost entirely, by means of synchronous three-phase generators (i.e., alternators) driven by steam or water turbines. Power is transported through a three-phase alternating current (ac) system operated by transformers at different voltage levels.

More precisely:

- Transportation that involves larger amounts of power and/or longer distances is carried out by the "transmission" system, which consists of a meshed network and operates at a very high voltage level (relative to generator and end-user voltages). This system ensures that at the same transmitted powers the corresponding currents are reduced, thereby reducing voltage dips and power losses[1].
- Power transportation is accomplished through the "distribution" system, which also includes small networks of radial configuration and voltages stepped down to end-user levels.

The use of ac, when compared with direct current (dc), offers several advantages, including:

- transformers that permit high-voltage transmission and drastically reduces losses;
- ac electrical machines that do not require rotating commutators;
- interruption of ac currents that can be accomplished in an easier way.

Moreover, the three-phase system is preferable when compared with the single-phase system because of its superior operating characteristics (rotating field) and possible savings of conductive materials at the same power and voltage levels.

For an ac three-phase system, reactive power flows become particularly important. Consequently, it is also important that transmission and distribution networks be equipped with devices to generate or absorb (predominantly) reactive power. These devices enable networks to adequately equalize the reactive power absorbed or generated by lines, transformers, and loads to a larger degree than synchronous machines are able.

These devices can be static (e.g., inductive reactors, capacitors, static compensators) or rotating (synchronous compensators, which can be viewed as

[1] Moreover, an improvement in stability can be obtained, at the same transmitted powers, due to reduced angular shifts between synchronous machine emfs, resulting in a smoother synchronism between machines.

synchronous generators without their turbines or as synchronous motors without mechanical loads).

Furthermore, interconnection between different systems — each taking advantage of coordinated operation — is another important factor. The electrical network of the resulting system can become very extensive, possibly covering an entire continent.

1.1.3 The basic elements of a power system are shown in Figure 1.1. Each of the elements is equipped with devices for maneuvering, measurement, protection, and control.

The nominal frequency value is typically 50 Hz (in Europe) or 60 Hz (in the United States); the maximum nominal voltage ranges 20–25 kV (line-to-line voltage) at synchronous machine terminals; other voltage levels present much larger values (up to 1000 kV) for transmission networks, then decrease for distribution networks as depicted in Figure 1.1.

Generation is predominantly accomplished by thermal power plants equipped with steam turbines using "traditional" fuel (coal, oil, gas, etc.) or nuclear fuel, and/or hydroelectric plants (with reservoir or basin, or fluent-water type). Generation also can be accomplished by thermal plants with gas turbines or diesel engines, geothermal power plants (equipped with steam turbines), and other sources (e.g., wind, solar, tidal, chemical plants, etc.) whose actual capabilities are still under study or experimentation.

The *transmission* system includes an extensive, relatively meshed network. A single generic line can, for example, carry hundreds or even thousands of megawatts (possibly in both directions, according to its operating conditions),

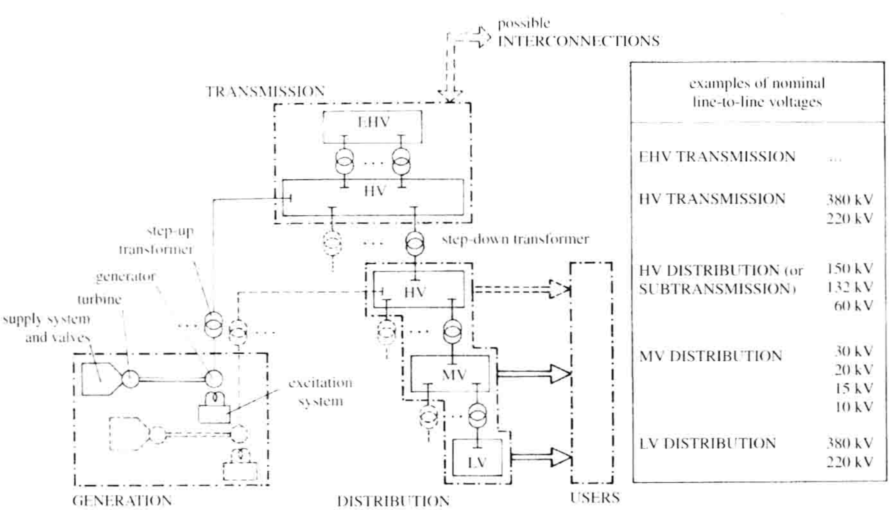

Figure 1.1. Basic elements of an electric power system (EHV, HV, MV, LV mean, respectively, extra-high, high, medium, and low voltage).

covering a more or less great distance, e.g., from 10 km to 1500 km and over. The long lines might present large values of shunt capacitance and series inductance, which can be, at least partially, compensated by adding respectively shunt (inductive) reactors and series capacitors.

The task of each generic *distribution* network at high voltage (HV), often called a "subtransmission" network, is to carry power toward a single load area, more or less geographically extended according to its user density (e.g., a whole region or a large urban and/or industrial area). The power transmitted by each line may range from a few megawatts to tens of megawatts.

Electric power is then carried to each user by means of medium voltage (MV) distribution networks, each line capable of carrying, for example, about one megawatt of power, and by low voltage (LV) distribution networks. To reduce the total amount of reactive power absorbed, the addition of shunt capacitors might be helpful ("power factor correction").

Reactor and *capacitor* types can be fixed or adjustable (through the use of switching devices); the adjustment increases the networks' operation flexibility and may be realized before ("no-load") or even during operation ("under-load", or "on-load").

To further improve system behavior, *controlled compensators* (*synchronous* and/or *static* ones) may be added in a shunt configuration at proper busbars of HV (transmission and subtransmission) networks. *Tap-changing transformers*, which are controllable under load, are also adopted, mostly at the HV to MV transformation, sometimes between HV transformations. While at the MV/LV transformation, the use of tap-changing transformers, set up at no load, can be sufficient.

Moreover, some transmission lines are equipped with series *"regulating" transformers*, by which a range of voltage variations (both in magnitude and phase)—particularly useful to control line power flows—can be achieved.

More recently, the so-called FACTS (Flexible AC Transmission Systems) have also emerged; these equipments recall and integrate the above-cited functions, providing controlled injections of active and reactive powers, through the use of high-performance electronic devices.

The possibility of adopting *direct current links*, by using controlled converters (i.e., rectifiers and inverters) at line terminals, also must be discussed. This is particularly helpful with very long distances and/or with cable connections (e.g., sea-crossing connections); that is, when the ac option would prevent voltage variations within given ranges at the different locations or the synchronism between connected networks.

Finally, the *interconnections* between very large systems (e.g., neighboring countries) are generally developed between their transmission networks. Similar situations involving a smaller amount of power can occur, even at the distribution level, in the case of "self-generating users" (e.g., traction systems, large chemical or steel processing plants, etc.), which include not only loads in the strict sense but also generators and networks.