

The background of the cover is a photograph showing the silhouettes of three workers on a high-voltage power line tower. The workers are positioned at different levels of the tower, with one at the top and two lower down. The sky is a gradient of purple and pink, suggesting a sunset or sunrise. The power lines stretch across the frame from the bottom left towards the top right.

YOSHIHIDE HASE

HANDBOOK OF
**POWER SYSTEMS
ENGINEERING**

WITH POWER ELECTRONICS APPLICATIONS

Second Edition

 **WILEY**

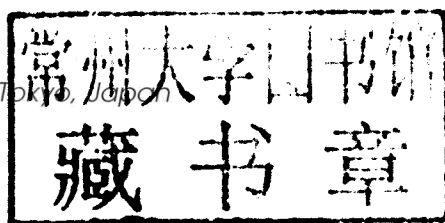


Handbook of Power Systems Engineering with Power Electronics Applications

Second Edition

Yoshihide Hase

Power System Engineering Consultant, Tokyo, Japan



 **WILEY**

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Handbook of Power Systems Engineering with Power Electronics Applications

To Keiko for her endurance and stimulation

Preface

This book is a revision of 'Handbook of Power System Engineering' originally published in 2007. Further to various additional revisions on previous chapters 1–24, new chapters 25–28 for power electronics applications have been prepared. The preface for the original version is first quoted.

This book deals with the art and science of power systems engineering for those engineers who work in electricity-related industries such as power utilities, manufacturing enterprises, engineering companies, or for students of electrical engineering in universities and colleges. Each engineer's relationship with power system engineering is extremely varied, depending on the types of companies they work for and their positions. We expect readers to study the characteristics of power systems theoretically as a multi-dimensional concept by means of this book, regardless of readers' business roles or specialties.

We have endeavoured to deal with the following three points as major features of the book:

First, as listed in the Contents, the book covers the theories of several subsystems, such as generating plants, transmission lines and substations, total network control, equipment-based local control, protection, and so on, as well as phenomena ranging from power (fundamental) frequency to lightning and switching surges, as the integrally unified art and science of power systems. Any equipment in a power system network plays its role by closely linking with all other equipment, and any theory, technology or phenomenon of one network is only a viewpoint of the profound dynamic behaviour of the network. This is the reason why we have covered different categories of theories combined in a single hierarchy in this book.

Secondly, readers can learn about the essential dynamics of power systems mostly through mathematical approaches. We explain our approach by starting from physically understandable equations and then move on to the final solutions that illustrate actual phenomena, and never skip explanations or adopt half-measures in the derivations.

Another point here is the difference in meaning between 'pure mathematically solvable' and 'engineering analytically solvable'. For example, a person (even if expert in transient analysis) cannot derive transient voltage and current solutions of a simple circuit with only a few *LCR* constants connected in series or parallel because the equational process is too complicated, except in special cases. Therefore only solutions of special cases are demonstrated in books on transient analysis. However, engineers often have to find solutions of such circuits by manual calculation. As they usually know the actual values of *LCR* constants in such cases, they can derive 'exact solutions' by theoretically justified approximation. Also, an appropriate approximation is an important technique to find the correct solution. Readers will also find such approximation techniques in this book.

Thirdly, the book deals with scientific theories of power system networks that will essentially never change. We intentionally excluded descriptions of advanced technologies, expecting such technologies to continue to advance year by year.

In recent years, analytical computation or simulation of the behaviour of large power system or complicated circuits has been executed by the application of powerful computers with outstanding software. However, it is quite easy to mishandle the analysis or the results because of the number of so many influential parameters. In this book, most of the theoretical explanation is based on typical simple circuits with one or two generators and one or two transmission lines. Precise understanding

of the phenomena in such simple systems must always be the basis of understanding actual large systems and the incidents that may occur on them. This is the reason why power system behaviour is studied using small models.

The new chapters 25–28 are arranged for power electronic applications but from four different viewpoints. These are: the theory of induction generators/motors (chapter 25), fundamental characteristics of various power electronic devices (chapter 26), power electronic circuits and control theories (chapter 27) and finally various applications of power electronics focusing on power system engineering and some industrial load applications (chapter 28). The author intended to describe these four different layered subjects all together in this book, because, the author believes, most of existing books for power electronics applications usually discusses only two or three subjects, omitting the other closely related ones. In particular, chapter 25 for induction machines may be helpful for readers who are already familiar with power electronic applications.

Yoshihide Hase
Kawasaki-city, Japan
15 August, 2012

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This book contains the various experiences and knowledge of many people. I am deeply indebted to these people, although I can only humbly acknowledge them in a general way.

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About the author

Yoshihide Hase was born in Gifu Prefecture, Japan, in 1937. After graduating in electrical engineering from Kyoto University, he joined the Toshiba Corporation in 1960 and took charge of various power system projects, both at home and abroad, including the engineering of generating station equipment, substation equipment, as well as power system control and protection, until 1996. During that time, he held the positions of general manager, senior executive of technology for the energy systems sector, and chief fellow. In 1996, he joined Showa Electric Wire & Cable Company as the senior managing director and representative director and served on the board for eight years. He was a lecturer at Kokushikan University for five years since 2004. He was the vice president of the IEEJ (1995–96) and has been bestowed as a honorary member. He was also the representative officer of the Japanese National Committee of CIGRE (1987–1996) and has been bestowed as a distinguished member of CIGRE.

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Introduction

'Utilization of fire', 'agricultural cultivation' and 'written communication': these three items are sometimes quoted as the greatest accomplishments of humankind. As a fourth item, '**social structures based on an electrical infrastructure**', which was created by humans mostly within the twentieth century, may be added.

Within the last hundred years, we have passed through the era of 'electricity as a convenient tool' to the point where electricity has become an inevitable part of our infrastructure as a means of energy acquisition, transport and utilization as well as in communication media. Today, without electricity we cannot carry out any of our living activities such as 'making fire', 'getting food and water', 'manufacturing tools', 'moving', 'communicating with others', and so on. Humans in most parts of the world have thus become very dependent on electricity. Of course, such an important electrical infrastructure means our modern power system network.

A power system network can be likened to the human body. A trial comparison between the two may be useful for a better understanding of the essential characteristics of the power system.

First, the human body is composed of a great many subsystems (individual organs, bones, muscles, etc.), and all are composed in turn of an enormous number of minute cells. A power system network of a large arbitrary region is composed of a single unified system. Within this region, electricity is made available in any town, public utility, house and room by means of metal wires as a totally integrated huge network.

Generating plants, substations and transmission lines; generators, transformers, switchgear and other high-voltage equipment; several types of control equipment, protection equipment and auxiliary equipment; control and communication facilities in a dispatching or control centre; and the various kinds of load facilities – all these are also composed of a very large number of small parts or members. Individual parts play their important roles by linking with the rest of the network system. Human operators at any part of the network can be added as important members of the power system. We might say that a power system network is the **largest and greatest artificial system** ever produced by people in the modern era.

Secondly, the human body maintains life by getting energy from the external environment, and by processing and utilizing this energy. New cellular tissue is consequently created and old tissue is discarded. In such a procedure, the human body continues to grow and change.

A power system can be compared in the same way. A prerequisite condition of a power system network is that it is operated continuously as a single unified system, always adding new parts and discarding old ones. Since long-distance power transmission was first established about a hundred years ago, power systems have been operating and continuing to grow and change in this way, and, apart from the failure of localized parts, have never stopped. Further, no new power system isolated from the existing system in the same region has ever been constructed. A power system is the **ultimate inheritance succeeded by every generation** of humankind.

Thirdly, humans experience hunger in just a few hours after their last meal; their energy storage capacity is negligible in comparison with their lifetimes. In a power system such as a pumped-storage hydro-station, for example, the capacity of any kind of battery storage system is a very small

part of the total capacity. The power generation balance has to be maintained every second to correspond to fluctuations or sudden changes in total load consumption. In other words, '**simultaneity and equality of energy generation and energy consumption**' is a vital characteristic of power system as well as of human body.

Fourthly, humans can continue to live even if parts of the body or organs are removed. At the other extreme, a minute disorder in cellular tissue may be life-threatening. Such opposites can be seen in power systems.

A power system will have been planned and constructed, and be operated, to maintain reasonable redundancy as an essential characteristic. Thus the system may continue to operate successfully in most cases even if a large part of it is suddenly cut off. On the contrary, the rare failure of one tiny part, for example a protective relay (or just one of its components), may trigger a kind of domino effect leading to a **black-out**.

Disruption of large part of power system network by '**domino-effect**' means big power failure leaded by abrupt segmentation of power system network, which may be probably caused by cascade trips of generators caused by total imbalance of power generation and consumption which leads to 'abnormal power frequency exceeding over or under frequency capability limits (OF/UF) of individual generators', 'cascade trips of generators caused by power stability limits, Q-V stability limits or by any other operational capability limits', 'cascade trips of trunk-lines/stations equipment caused by abnormal current flow exceeding individual current capacity limits (OC), or by over or under voltage limits (OV/UV)', 'succeeding cascade trips after fault tripping failure due to a breaker set back or caused by mal-operation of a protective relay' and so on, and may be perhaps caused as of 'these composite phenomena'. These nature of power systems is the outcome that **all the equipment and parts of the power system, regardless of their size, are closely linked and coordinated. The opposites of toughnees with well redundancy and delicacy** are the essential nature of power systems.

Fifthly, as with the human body, a power system cannot tolerate maltreatment, serious system disability or damage, which may cause **chronic power cuts**, and moreover would probably causes extremely fatal social damages. Recovery of a damaged power system is not easy. It takes a very long time and is expensive, or may actually be impossible. Power systems can be kept sound only by the endeavours of dedicated engineers and other professional people.

Sixthly, and finally, almost as elaborate as the human body, all the parts of power system networks today (including all kinds of loads) are **masterpieces of the latest technology**, based on a century of accumulated knowledge, something which all electrical engineers can share proudly together with mechanical and material engineers. Also all these things **have to be succeeded to our next generations** as the indispensable social structures.

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