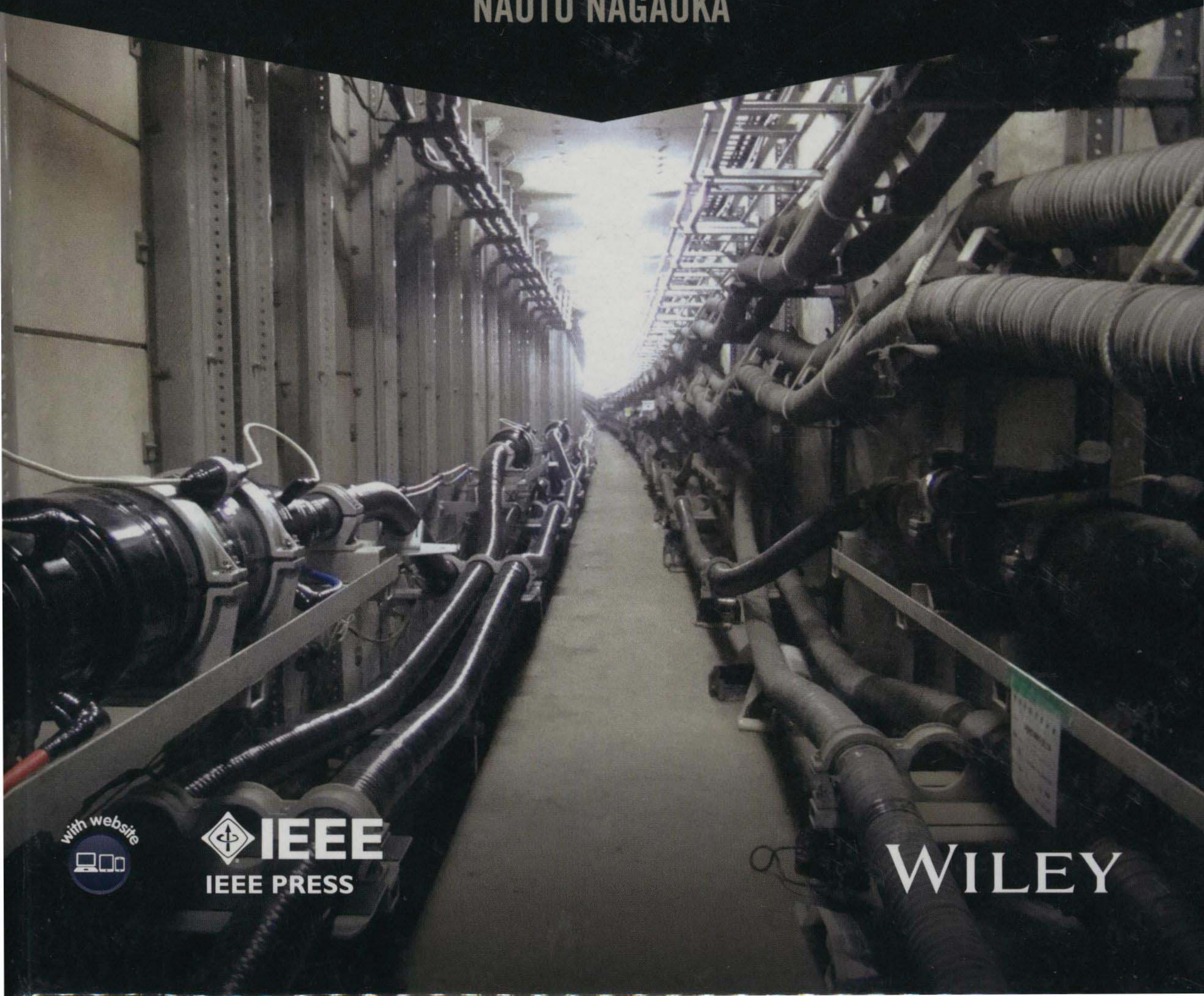
CABLE SYSTEM TRANSIENTS

Theory, Modeling and Simulation

AKIHIRO AMETANI
TERUO OHNO
NAOTO NAGAOKA



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Akihiro Ametani
Emeritus Professor, Doshisha University, Japan

Teruo Ohno
Manager, Tokyo Electric Power Company, Japan

Naoto Nagaoka
Professor, Doshisha University, Japan

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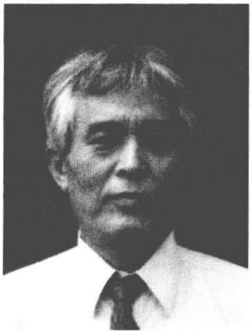
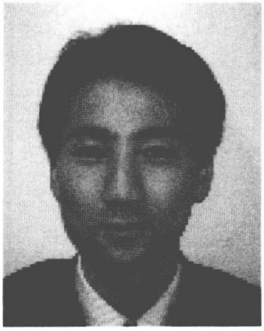
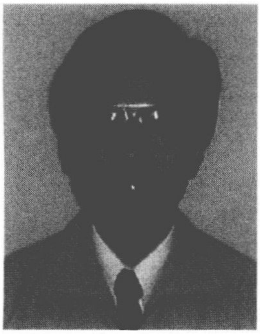
About the Authors



Akihiro Ametani received his PhD degree from the University of Manchester (UMIST), Manchester, UK, in 1973. He was with UMIST from 1971 to 1974, and with Bonneville Power Administration for the summers from 1976 to 1981, and developed the electromagnetic transients program. Since 1985, he has been a Professor at Doshisha University, Kyoto, Japan. In 1988, he was a Visiting Professor at the Catholic University of Leuven, Belgium. From April 1996 to March 1998, he was the Director of the Science and Engineering Institute, Doshisha University, and the Dean of the Library and Computer/Information Center from April 1998 to March 2001. He was the Chairperson of the Doshisha Council. He is a Chartered Engineer in the UK, a distinguished member of the International Council on Large Electric Systems, and a Life Fellow of the Institute of Electrical and Electronic Engineers. He was awarded D. Sc. from the University of Manchester in 2010.



Teruo Ohno received his BS degree from the University of Tokyo, Tokyo, Japan in Electrical Engineering in 1996, his MS degree from the Massachusetts Institute of Technology, Cambridge, USA in Electrical Engineering in 2005, and his PhD degree from Aalborg University, Aalborg, Denmark in Energy Technology in 2012. Since 1996 he has been with the Tokyo Electric Power Company, Inc., where he is currently involved in power system studies, in particular, on cable systems, generation interconnections, and protection relays. He was a secretary of Cigré WG C4.502, which focused on technical performance issues related to the application of long HVAC cables. He is a member of the Institute of Electrical and Electronics Engineers and the Institute of Electrical Engineers of Japan.



Naoto Nagaoka received his BS, MS, and PhD degrees from Doshisha University, Kyoto, Japan, in 1980, 1982, and 1993, respectively. In 1985, he joined Doshisha University, where since 1999 he has been a Professor. From April 2008 to March 2010, he was the Dean of the Student Admission Center, Doshisha University. From April 2010 to March 2012, he was the Director of both the Liaison Office and the Center of Intellectual Properties, Doshisha University. He is a member of the Institution of Engineering and Technology and the Institute of Electrical Engineers of Japan.

Preface

Power transmission by cable is widely used in densely populated areas. Recently off-shore windfarms have become quite common, especially in Europe, and a number of off-shore windfarms are under construction and planned. Thus, a number of submarine cables have been installed and constructed. Submarine cables are also commonly used to connect an island to a mainland. Further, in Denmark all the overhead lines above 100 kV are replaced by underground cables. Thus, transients in cable systems become a very important subject, especially in long and complex cable systems.

The most significant difference of a cable from an overhead line is that a single-phase cable is composed of multi-conductors, that is, a core and a metallic sheath (shield), while a single overhead line is a single conductor. Thus, a three-phase cable (single-core coaxial cable) becomes a six conductor system. When the three-phase cable is enclosed in a conducting pipe, it becomes a seven conductor system. Therefore, an analysis of cable voltages and currents necessitates a theory of multi-conductors.

Another significant difference is that a cable is, in most cases, buried underground. This results in the propagation velocity of the earth-return mode along the cable being far smaller than that of an overhead line, which is nearly the velocity of light in free space. Also, the propagation velocity between a core and a metallic sheath (called "coaxial mode") is determined by the relative permittivity ε_i of an insulator between the core and the sheath, which ranges from two to four, that is coaxial mode velocity $c_c = c_0/\sqrt{\varepsilon_i}$, where $c_0 \fallingdotseq 300\ \mathrm{m}/\mu\mathrm{s}$ (velocity of light).

There are various types and kinds of cables: (1) a power transmission cable, a communication cable and a control/single cable; (2) a directly buried or tunnel installed underground cable, a submarine cable and an overhead cable such as a gas-insulated bus; (3) a single-core coaxial (SC) cable, a multi-core cable, and a pipe-enclosed type (PT) cable; (4) circular or cylindrical, and flat-shaped cables; (5) normal-bonded and cross-bonded cables. This makes an analysis of cable voltages and currents far more complicated than that of an overhead line. As a matter of fact, the overhead line is categorized as just one of the cables, that is, a cable composed only of a core.

This book deals with transients in a power system cable. In Chapter 1, various cables manufactured and used in practice are described.

Chapter 2 explains the impedance and admittance formulas of typical cables, that is, an SC cable and a PT cable. Exact but complicated formulas for numerical calculations are described. Also simple but approximate formulas for a hand calculation are explained so readers understand the physical meaning of the formulas.

In Chapter 3, theories of wave propagation in various cables are described. Section 3.1 explains a basic theory to handle a multi-conductor system called "modal theory". Then, wave propagation characteristics, which are the basis of a transient analysis, are investigated for an SC cable, a PT cable and a cross-bonded cable.

Chapter 4 discusses cable modeling for transient simulations by using well-known EMTP (electromagnetic transients program). A method of calculating the sequence impedances of a cable system is explained by using a lumped PI-circuit model. As the most conventional modeling method for a transient analysis, Dommel's distributed line model is explained first. Then, Semlyen's and Marti's frequency-dependent line models are described. Also, frequency-dependent line models using vector fitting are explained.

In Chapter 5, transients in a single-phase cable are investigated based on experimental results and EMTP simulation results. Then, analytical calculations are carried out based on the theory explained in Chapter 3 so as to be able to understand the surge phenomena in a cable physically and theoretically.

Chapter 6 deals with field test results on various three-phase cables. A comparison with simulation results is carried out. Surge characteristics and the effect of various parameters are investigated based on the field test and simulations results. Also, EMTP simulation results by frequency-independent and -dependent line (cable) models prepared in the EMTP are discussed.

Chapter 7 explains abnormal transients in high voltage large cable systems where reactive power compensation is inherent. Because of a large capacitance due to a long cable and a large inductance of a shunt reactor, series and parallel resonance appears in the large cable systems. Also, system islanding, slow-front overvoltages, leading current interruption, zero missing phenomenon and cable discharge become significant problems. EMTP simulations are carried out, and the characteristics of the above mentioned transients are investigated based on the simulation result.

Chapter 8 describes transients in distributed generation systems where various cables are involved. Modeling of various components in a windfarm and a solar plant by the EMTP are explained. Handling EMTP simulations of transients in the windfarm and in the solar plant is explained, and the EMTP input data are described in detail.

Akihiro Ametani
March 2015

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