CABLE SYSTEM TRANSIENTS

Theory, Modeling and Simulation

AKIHIRO AMETANI
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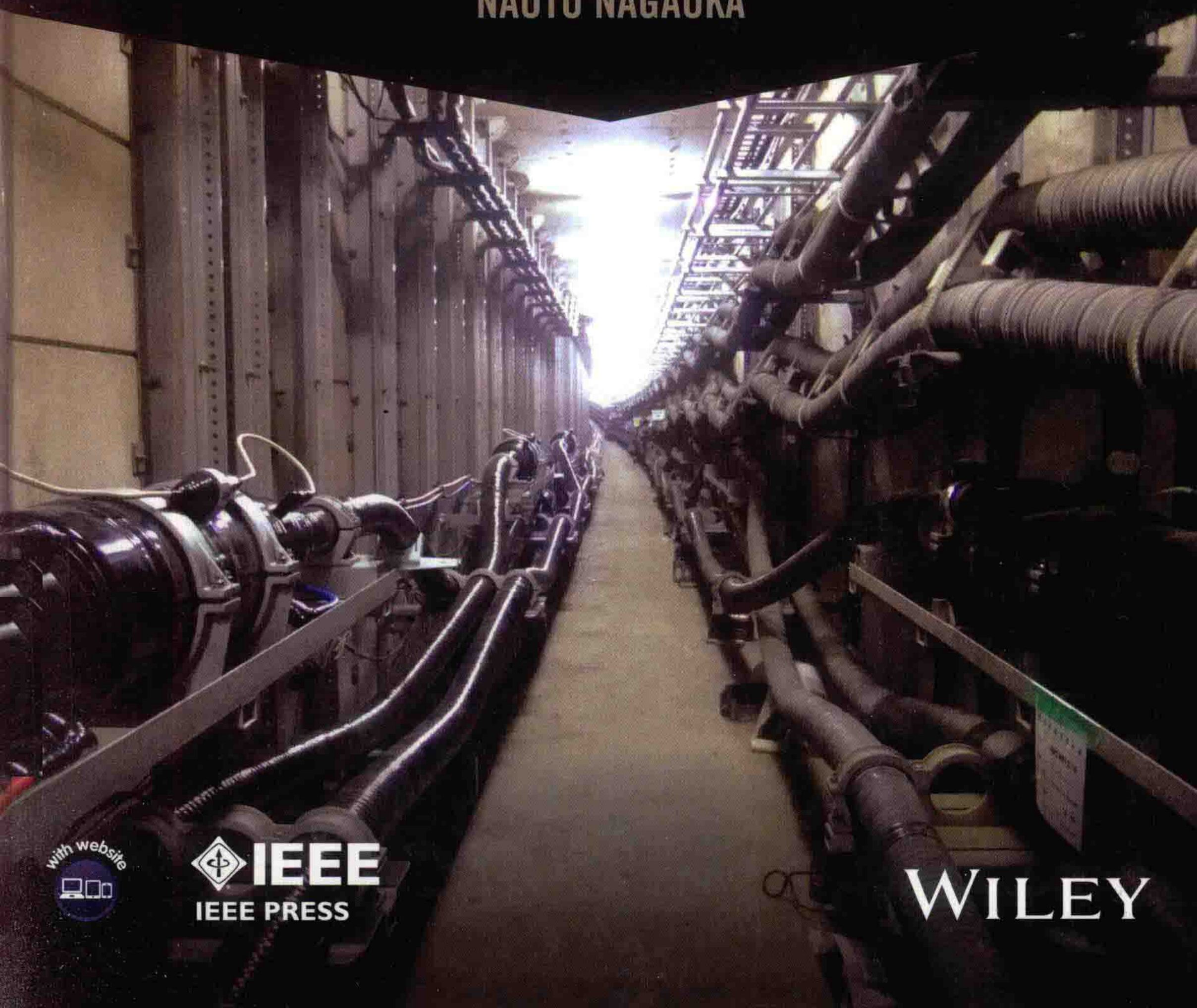

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Akihiro Ametani received his PhD degree from the University of Manchester (UMIST), Manchester, UK, in 1973. He was with UMIST from 1971 to 1974, and with Bonneville Power Administration for the summers from 1976 to 1981, and developed the electromagnetic 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.

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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 $c_0 \fallingdotseq 300\ \mathrm{m/\mu s}$ (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
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Contents

1

Various Cables Used in Practice

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1.1 Introduction

Transmission system operators (TSOs) throughout the world have been seeing growing numbers of transmission line projects in recent years for different reasons including the increase of cross-border trade, renewable energy sources, smart grid projects, the replacement of aging facilities, and in some countries due to growing demand.

Until recently, TSOs have responded to these necessary transmission upgrades mostly by the introduction of overhead lines (OHLs). HVAC underground cable systems have been used, but their applications have been mainly limited to densely populated areas. As such, HVAC underground cable systems are limited both in length and number to date.

This tendency has been changing over the past 10 years as the service experience of HVAC, especially EHV AC, cable systems has become satisfactory [1]. The applications of HVAC cable systems are proposed more often in order to protect the landscape and also public health (e.g., EMF). Hence, HVAC cable systems recently planned or installed are longer than those installed previously.

For example, in Denmark, after receiving public and political pressures to underground its OHLs, Danish TSO, Energinet.dk, published a report on the future expansion and undergrounding of its transmission grid on the 3rd of April 2008 [2]. The report proposed and compared five principles (A–E in Figure 1.1). From the five principles, the Danish government has selected Principle C, as shown in Figure 1.2, in which all new 400 kV lines will basically be undergrounded.

A similar tendency can be observed on HVDC, especially EHV DC, submarine cable systems. The NorNed cable, which connects Norway and the Netherlands, and the BritNed cable, which connects the Netherlands and the UK, are symbolic examples of such a trend. These cable lines, mainly for cross-border trades, have a total length of 580 and 260 km, respectively.

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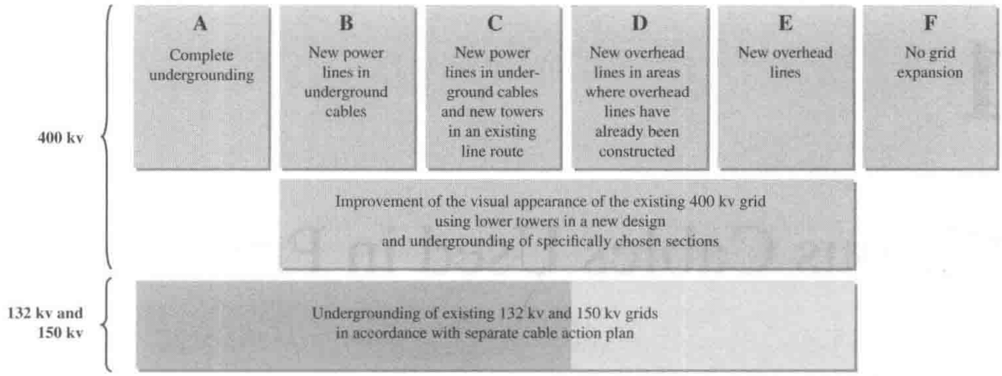

Figure 1.1 Five principles for the future grid expansion (from [2])

The scale of these projects is beyond the level many people expected at the beginning of this century.

As these cable projects increase, there is an increased need to study cable system transients. In particular, the introduction of long cable systems may cause peculiar phenomena, such as resonance overvoltages, which require careful attention. Severe temporary overvoltages in the power system with long cable systems which can be caused in specific network conditions or configurations have been reported [3–9].

Cable modeling for studies on cable system transients, as discussed in Chapter 4, requires the understanding of cable systems. This chapter first discusses the cable itself and then introduces the laying configuration and the sheath bonding, that is, the cable as the cable system. Various cables used in practice are explained in the following two sections – land cables in Section 1.2 and submarine cables in Section 1.3. Section 1.4 discusses the laying configuration including the sheath bonding. The main focus of this chapter is on how these physical characteristics of cable systems affect their electrical characteristics.

Land cables in Section 1.2 cover three major cable types, that is, XLPE (cross-linked polyethylene, PE) cables, SCOF/SCFF (self-contained oil-filled/self-contained fluid-filled) cables and HPOF/HPFF (high-pressure oil-filled/high-pressure fluid-filled) cables. The term “fluid-filled” is used to include both oil-filled cables and gas-filled cables, but most fluid-filled cables are oil-filled cables in actual installations. Even though XLPE cables are increasingly selected for new cable lines in many countries, SCOF cables and HPOF cables are still a popular choice in some countries. HPOF cables are selected, in particular, for the replacement of old HPOF cables since it is often possible to continue using their steel pipes even after the cable replacement.

The laying configuration and the sheath bonding affect cable system transients as the cable itself does. They need to be modeled correctly in order to obtain accurate impedance/admittance of the cable system or reasonable simulation results. Section 1.4 discusses different laying conditions and sheath bonding methods together with their impact on the cable system transients.

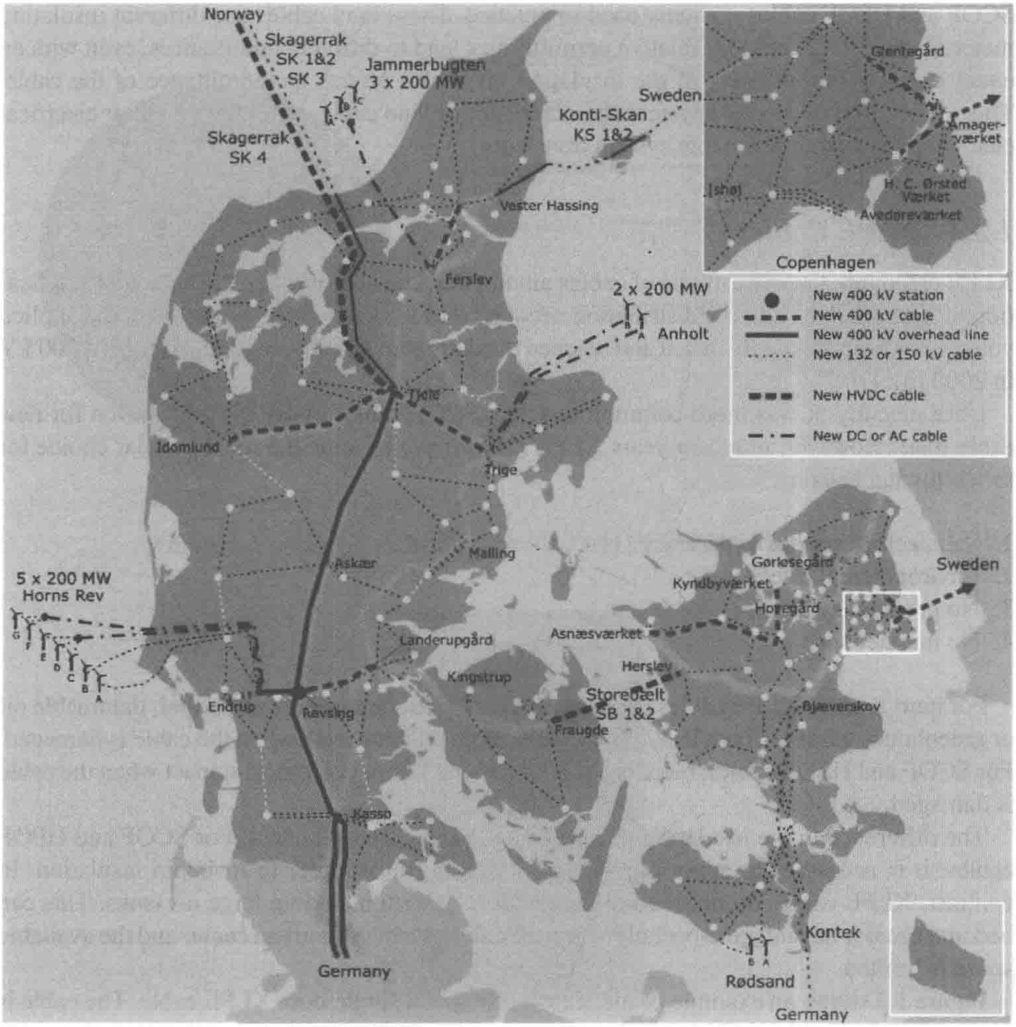

Figure 1.2 Grid expansion plan based on Principle C (from [2])

1.2 Land Cables

1.2.1 Introduction

One obvious difference of a cable from an OHL is that the outer surface of the cable is insulated from the core conductor. This leads to the relatively large admittance of cables compared with OHLs.

The difference in the admittance can be observed not only between cables and OHLs but also between different types of cables. This section explains three types of land cables – XLPE, SCOF and HPOF cables – widely used in practice. These land cables use different insulating materials, and their different relative permittivities lead to different admittances, even with an equal length. The thickness of the insulation layer also affects the admittance of the cable. This section also discusses physical characteristics of land cables together with their electrical characteristics that affect cable system transients.

1.2.2 XLPE Cables

XLPE cables are the newest type of cables among the three major types. The practical application of XLPE cables into the distribution network started in the 1960s. Since then, the applied voltage has been gradually raised and reached the current maximum nominal voltage of 500 kV in 2000 [3], [10].

Until recently, it was more common to select SCOF cables or HPOF cables even for new cable lines. However, in recent years XLPE cables have become the most popular choice for the following reasons:

1. Satisfactory service experience [1]
2. Environmental effect
3. No pressure system
4. No maintenance

For item 2, since XLPE cables use cross-linked PE as the insulating material, flammable oil or greenhouse gases will not leak into the soil or atmosphere even when the cable is damaged. For SCOF and HPOF cables, there is a risk of causing fire or ecological impact when the cable is damaged.

The difference in the insulating material also leads to items 3 and 4. For SCOF and HPOF cables, it is necessary to apply pressure to insulating oil in order to maintain insulation. In contrast, XLPE cables do not require the pressure system including large oil tanks. This can become a major advantage especially when the cable is laid in an urban center and the available space is limited.

Figure 1.3 shows an example of the cross-section of a single-core XLPE cable. The cable is composed of the following layers:

1. Core conductor
2. Inner semiconducting layer
3. Insulation layer
4. Outer semiconducting layer
5. Metallic sheath
6. Outer cover

This configuration of layers is basically identical for single-core XLPE cables with recent technology, regardless of the cross-section size and the adopted material for each layer. The following describes each layer from inside to outside.

1.2.2.1 Core Conductor

The core conductor carries load currents of the cable and is made of copper or aluminum. The copper or aluminum wire is wound to form a stranded conductor as shown in Figure 1.4. Even