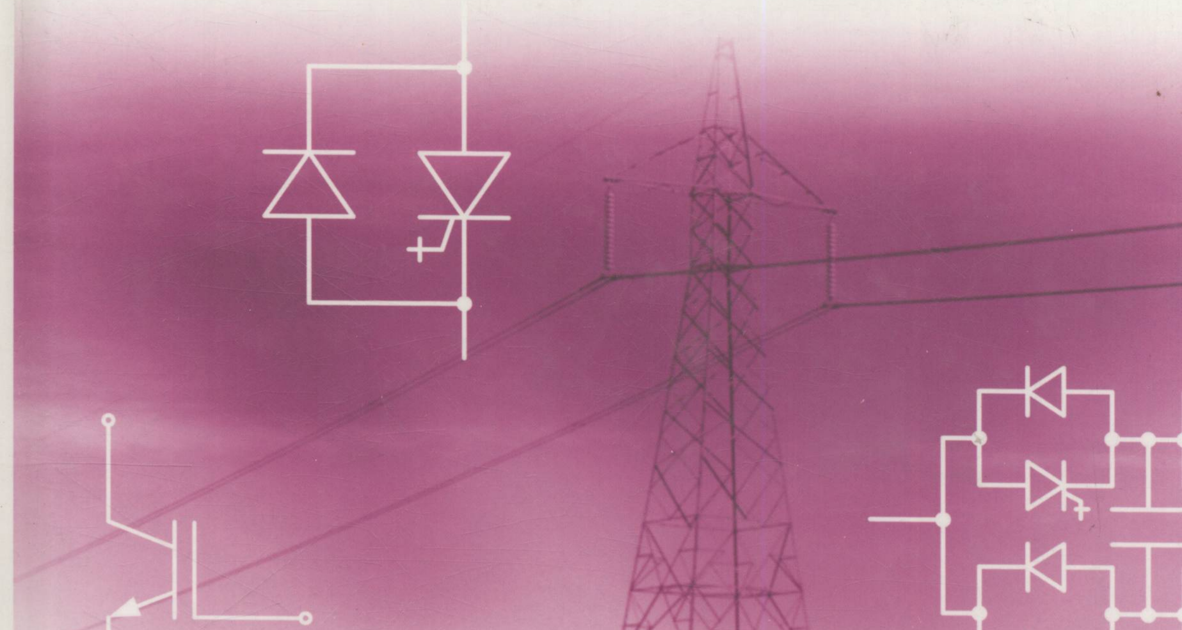
Flexible Power Transmission

The HVDC Options



J. Arrillaga Y. H. Liu N. R. Watson

WILEY

Flexible Power Transmission

The HVDC Options

J. Arrillaga
University of Canterbury, New Zealand

Y.H. Liu
Inner Mongolia University, China

N.R. Watson
University of Canterbury, New Zealand

BICENTENNIAL 1807 WILEY 2007 BICENTENNIAL

John Wiley & Sons, Ltd

Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk
Visit our Home Page on www.wiley.com

Other Wiley Editorial Offices

John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 42 McDougall Street, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 6045 Freemont Blvd, Mississauga, ONT, Canada L5R 4J3

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Anniversary Logo Design: Richard J. Pacifico

Library of Congress Cataloging in Publication Data

Arrillaga, J.
Flexible power transmission—the HVDC options / J. Arrillaga, Y.H. Liu, N.R. Watson.
p. cm.
ISBN 978-0-470-05688-2 (cloth)
1. Electric power transmission. 2. Electric power distribution. I. Liu, Y. H.
II. Watson, N. R. III. Title.
TK3111.A76 2007
621.319′12—dc22

2007019888

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 978-0-470-05688-2 (HB)

Typeset in 10/12pt Times by Integra Software Services Pvt. Ltd, Pondicherry, India
Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire
This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

Flexible Power Transmission

The HVDC Options

Preface

The structure and characteristics of HVDC (High-Voltage Direct Current) converters have remained practically unaltered for the first 40 years of commercial operation. Restricted by the switching characteristics, first of the mercury arc valve and later of the silicon-controlled rectifier, this technology requires substantial extra support at the link terminals to ensure stable operation.

More recently the development of power semiconductors with improved characteristics has provided the basis for a flexible AC transmission system (FACTS) technology. This technology covers a variety of power electronics controllers created to enhance the performance of the traditional grid. The individual members of the FACTS family are designed to solve a specific problem, e.g. active or reactive power flow control, short-circuit current limitation, etc. So it is the complete family that provides transmission flexibility, rather than the individual controllers.

The new power semiconductors have also, in the past decade, changed the attitude towards HVDC transmission, and a variety of converter configurations have been developed to take advantage of the higher controllability and switching frequencies of the new devices.

Although the main market for HVDC is still thyristor based, a transistor-based technology has recently been developed, and is already being used throughout the world. The new HVDC technology can provide most of the enhancements of the individual FACTS controllers, i.e. permit large stable power transfers, deliver or absorb the required reactive power to maintain the specified voltages at the interconnected buses, contain fast emergency controls to avoid large fault current levels, be designed (if required) to control sub-synchronous resonances, etc. Moreover, the DC link is the only practical way of connecting asynchronous systems and systems of different frequencies. For a given HVDC configuration, all these tasks can be achieved purely by control action.

Therefore, a modern HVDC interconnection is potentially the most flexible power transmission system. However, the provision of greater HVDC transmission flexibility comes at a price, in terms of either reduced efficiency or increased structural complexity. Thus, when considering a new scheme, it is important to decide on the degree of flexibility required for the particular application (i.e. taking into account power ratings, transmission distances, extent of ancillary services expected, etc.).

A critical review of the HVDC options already available and under consideration constitutes the purpose of this book, which therefore complements recent titles describing the FACTS technology to help power system engineers to make informed decisions on the planning, design and operation of future power transmission systems. It is also a useful reference text for students taking advanced courses in power transmission.

The first five chapters describe the principles and components of existing converter technology. Chapters 6 and 7 discuss alternative proposals for self-commutating conversion and Chapters 8, 9, 10 and 11 the application of the various converter configurations to HVDC transmission.

The authors would like to acknowledge the main sources of information that have made the book possible and in particular the material reproduced, with permission, from CIGRE Study Committee B4 and ABB industry documents.

At the personal level they wish to acknowledge the services of Greta Arrillaga (who half a century ago also typed the first book on the subject of HVDC by Adamson and Hingorani!), the advice received from Alan Wood and Nick Murray of Canterbury University, Dennis Woodford of Electranix and Gunnar Asplund of ABB.

They also wish to thank The University of Canterbury and The University of Inner Mongolia for providing the facilities for their work.

Contents

1

Introduction

1.1 The Conventional Power Grid

The power sources in conventional power systems must operate at exactly the same frequency and in perfect synchronism. Each generator controls the magnitude of its terminal voltage by the excitation current and the phase angle of this voltage by means of the mechanical torque developed by the turbine. The generators are designed to produce relatively low voltages, and thus the generated power undergoes a number of voltage transformations, from low to high voltage (for efficient power transmission) and from high to medium and low voltage (for economic and safe power distribution). These changes are implemented by power transformers.

Within a national grid, the use of a fully interconnected primary transmission system, to which the new power stations are connected, has traditionally been the generally accepted philosophy behind the development of an efficient power system.

The expansion of the primary transmission system was normally continued until the rated switchgear fault level was exceeded. Beyond that point a new primary transmission system, of higher voltage and fault levels, was created, while the previous one continued expanding into several separate (secondary) systems. Each of these secondary transmission systems in turn supplied a number of distribution (normally radial) feeders. So the conventional power grid has traditionally been grouped into three separate parts, i.e. generation, transmission and distribution, all of them inflexibly tied by the synchronous constraints.

1.1.1 Power Transfer Mechanism

Transformers, generators and transmission lines are predominantly inductive, and most loads have an inductive component as well. The presence of inductance delays the current response of these components to the voltage variation across them, and this effect causes phase shifts between the voltage and current waveforms which affect the efficiency of the power transmission process.

Flexible Power Transmission: The HVDC Options J. Arrillaga, Y.H. Liu and N.R. Watson

The instantaneous power (p) associated with a power system component is the product of the instantaneous values of the voltage (v) and current (i) at its terminals ($p = vi$). The integration of the instantaneous power variation over a complete cycle divided by the period of repetition, i.e.

$$(1/T)\int_{t}^{t+T} pdt$$

provides the average or ***active power***. If both the voltage and current vary sinusoidally at the same frequency, in terms of rms (root mean square) voltage (V) and current (I) quantities, the active power is expressed as

$$P = VI\cos(\phi) \tag{1.1}$$

where ϕ is the phase angle between the voltage and the current fundamental frequency waves.

As the rms values are always positive, the product VI (referred to as volt-ampere or apparent power), gives no indication of the active power sign. It is the sign of cos (ϕ) (the ***power factor***) that determines whether the circuit component is generating or absorbing power.

In Figure 1.1, using the voltage as the phase angle reference and resolving the current into in-phase (I_p) and quadrature (I_q) components, the product of V and I_p is clearly the active power, while the product of V and the quadrature component I_q, i.e.

$$Q = VI\sin(\phi) \tag{1.2}$$

is referred to as ***reactive power***.

Reactive power is needed to establish the magnetic and electrostatic fields; it is temporarily stored and then released (i.e. it consists of positive and negative regions within the cycle). In fact the energy associated with the reactive power oscillates between the element and the rest of the circuit (at the rate of two reversals per period). Although the reactive power has a zero average value, it still represents real reciprocating energy that must be present by virtue of the inductance or capacitance of the network.

When ϕ, the phase angle difference in Equation (1.2), is between 0 and π, $\sin(\phi)$ is positive and the circuit element is said to be a consumer of Q; similarly, when ϕ is between π and 2π, $\sin(\phi)$ is negative and the element is said to be a generator of Q. The convention

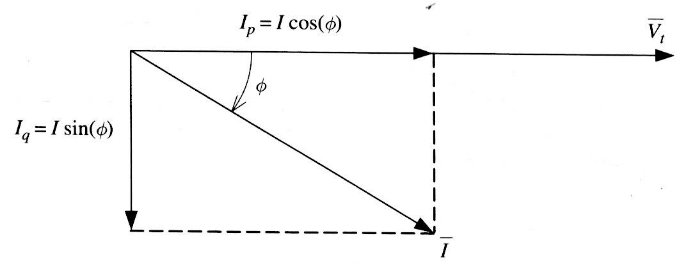


Figure 1.1 In-phase and quadrature current components

used is that when Q is positive the current lags the voltage and when Q is negative the current leads the voltage

Squaring the expressions of P and Q in Equations (1.1) and (1.2) and adding them gives

$$(VI\cos(\phi))^2 + (VI\sin(\phi))^2 = (VI)^2 \tag{1.3}$$

and

$$VI = \sqrt{P^2 + Q^2} \tag{1.4}$$

Equations (1.3) and (1.4) can be represented in a four-quadrant complex diagram, as shown in Figure 1.2, with the axes labelled $\pm P$ and $\pm jQ$.

Power transfer between active sources

Figure 1.3 shows a purely inductive line interconnecting two ideal voltage sources V_1 and V_2 (which can be either generators or nodes of a synchronous system). The phasor diagram in Figure 1.4 represents the operating condition when the voltage at terminal 1 leads that of terminal 2 by an angle δ (referred to as the power angle) and the current at terminal 2 lags its voltage by an angle ϕ (referred to as the power factor angle). Using the voltage of terminal 2 as a phase reference, the following expressions are derived from this diagram:

$$I_2 X\cos(\phi) = V_1\sin(\delta) \tag{1.5}$$

$$I_2 X\sin(\phi) = V_1\cos(\delta) - V_2 \tag{1.6}$$

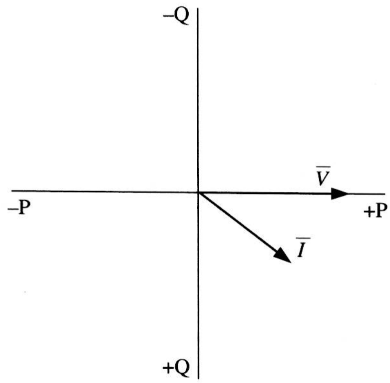


Figure 1.2 Four-quadrant diagram with the voltage as reference

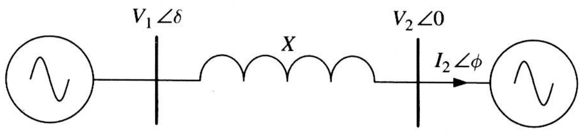


Figure 1.3 Interconnection between two synchronous systems

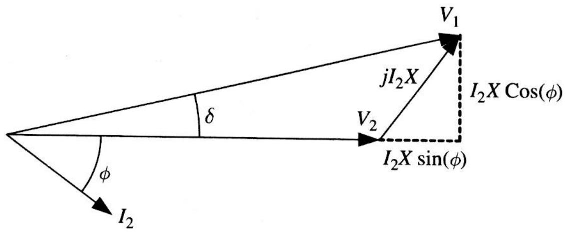


Figure 1.4 Phasor diagram for the interconnection of Figure 1.3

From Equations (1.5) and (1.6) the active and reactive power transfers become

$$P = V_2 I_2 \cos(\phi) = \frac{V_1 V_2 \sin(\delta)}{X} \tag{1.7}$$

$$Q = V_2 I_2 \sin(\phi) = \frac{V_2 (V_1 \sin(\delta) - V_2)}{X} \tag{1.8}$$

Thus to control the P and/or Q transfers it is necessary to vary one or more of the four variables V_1, V_2, δ and X in Equations (1.7) and (1.8). As indicated earlier, the generated voltage phase and magnitude values can be controlled by the turbine governor and generator excitation respectively. However, from the power transmission viewpoint, the generator controls are slow and inefficient: the slow control imposes a power transmission restriction on the steady-state operating point, as the power angle δ in Equation (1.7) has to be kept low in order to preserve transmission stability following large disturbances; also the relatively large requirement of reactive power (Equation (1.8)) will overload unnecessarily the generation and transmission systems.

Power transfer to a consumer load

Consumer loads are connected to radial feeders, normally at the end of the power distribution network. Low power factor loads have a detrimental effect on the load voltage and, therefore, on the power transfer capability. This effect is illustrated with reference to Figure 1.5 on the assumption that the feeder and the primary system behind it are represented by a voltage source (V_s) in series with a total system reactance (X_s). To maintain the active power constant when the power factor reduces (i.e. angle ϕ increases) requires an increase in the load current, i.e. $I'_L > I_L$; this increase causes a higher voltage drop in the system reactance which, in turn, reduces the load voltage (V_L).

Thus to maintain the required power level, either the source voltage must increase or some means of voltage support must be provided locally. For instance, the latter can be achieved by connecting a capacitance in parallel with the load. This will add a quadrature component to the load current and will reduce the overall current in the feeder; this solution is referred to as ***power factor correction***. However, the use of local compensation by means of passive components, although efficient, is neither fast nor continuous and increases the likelihood of low-order harmonic resonance with the system impedance.

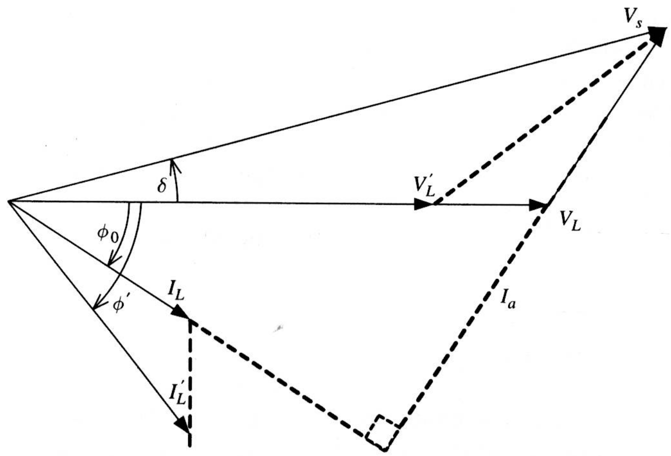


Figure 1.5 Effect of the load power factor on the load voltage

1.2 Towards a More Flexible Power Grid

A variety of technical, economical and environmental reasons affecting the generation, transmission and utilisation of power are forcing a rethink on the conventional power system development philosophy. The dilemma is that, on the one hand, there is growing opposition to the acceptance of new transmission lines and ever increasing primary transmission voltages. On the other hand, there is the realisation that power system interconnections bring undisputable benefits, such as economies of scale, wider choices of generating plant, reductions in reserve capacity, diversity in demand, supply reliability, pooling opportunities, etc.

Clearly an important factor in the solution is the possibility of increasing the power carrying capability of the transmission lines. In this respect conventional AC transmission is severely restricted by the need to keep the two systems interconnected by the line in synchronism following disturbances (i.e. when the phase difference between the terminal voltages increases rapidly), a condition referred to as transient stability. Therefore increases in the steady-state power carrying capability are linked to improvements in the transient stability levels, which in turn require faster controllability. Controllability and flexibility are used in power transmission as synonymous terms; in other words, greater flexibility implies greater and faster controllability. The latter has been made possible by the development of power semiconductors (discussed in Chapter 2) and their application to the control of power apparatus and systems, commonly referred to as power electronics.

1.2.1 Power Electronics Control

The advent of power electronics technology has been the catalyst for the provision of greater grid flexibility. A power electronics controller can be broadly described as a matrix of static switches connecting a number of input nodes to a number (not necessarily the same) of output nodes and the power flow may be in either direction. The circuits behind these nodes may be either DC or AC and predominantly inductive or capacitive.