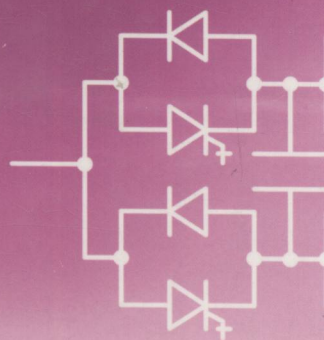
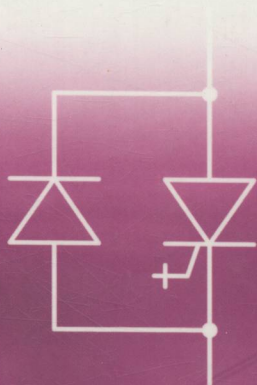


Flexible Power Transmission

The HVDC Options



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

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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.

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Contents

Preface	xi
1 Introduction	1
1.1 The Conventional Power Grid	1
1.1.1 Power Transfer Mechanism	1
1.2 Towards a More Flexible Power Grid	5
1.2.1 Power Electronics Control	5
1.3 HVDC Transmission	8
1.3.1 Thyristor-Based CSC Transmission	10
1.3.2 VSC Transmission Based on the Integrated Gate Bipolar Transistor (IGBT)	11
1.3.3 Multi-terminal HVDC	12
1.3.4 The Flexibility Concept Applied to HVDC	13
1.4 Relative Power Carrying Capability of AC and DC Transmission Lines	13
1.5 The Impact of Distributed Generation	16
1.6 The Effect of Electricity Deregulation	16
1.7 Discussion	18
References	19
2 Semiconductor Power Devices	21
2.1 Introduction	21
2.2 Semiconductor Principles	21
2.3 Power Semiconductor Elements	22
2.3.1 The pn Rectifier	22
2.3.2 The Transistor	25
2.3.3 Metal-Oxide-Semiconductor Field-Effect Transistor	25
2.4 Dynamic Stresses on Power Switches	27
2.4.1 Rate of Change of Voltage (dv/dt)	27
2.4.2 Rate of Change of Current (di/dt)	28
2.4.3 Balancing Problems in Series Chains	28

2.5	Other Switching Issues	29
2.5.1	Switching Frequency	29
2.5.2	Switching Losses	29
2.5.3	Soft Switching	29
2.5.4	Use of Snubbers	30
2.6	Thyristor-Type Power Switches	31
2.6.1	The Thyristor	31
2.6.2	Gate Turn-Off Thyristor	36
2.6.3	Insulated Gate-Commutated Thyristor	41
2.6.4	MOS Turn-Off Thyristor	42
2.6.5	MOS Controlled Thyristor	44
2.6.6	Emitter Turn-Off Thyristor	45
2.7	Insulated Gate Bipolar Transistor	47
2.7.1	IGBT (Series) Chains	49
2.8	Diodes	51
2.9	Prognostic Assessment	53
2.9.1	Ratings and Applicability	53
2.9.2	Relative Losses	55
	References	56
3	Line-Commutated HVDC Conversion	57
3.1	Introduction	57
3.2	Three-Phase AC-DC Conversion	57
3.2.1	Basic CSC Operating Principles	58
3.2.2	Effect of Delaying the Firing Instant	58
3.3	The Commutation Process	62
3.3.1	Analysis of the Commutation Circuit	62
3.4	Rectifier Operation	64
3.5	Inverter Operation	67
3.6	Power Factor and Reactive Power	69
3.7	Characteristic Harmonics	71
3.7.1	DC Side Harmonics	72
3.7.2	AC Side Harmonics	73
3.8	Multi-Pulse Conversion	74
3.8.1	Transformer Phase Shifting	74
3.8.2	DC Ripple Reinjection	77
3.9	Uncharacteristic Harmonics and Interharmonics	81
3.9.1	Imperfect AC Source	83
3.9.2	DC Modulation	87
3.9.3	Control System Imperfections	88
3.9.4	Firing Asymmetry	88
3.9.5	Magnification of Low-Order Harmonics	89
3.10	Harmonic Reduction by Filters	90
3.10.1	AC Side Filters	90
3.10.2	DC Side Filters	92

3.11	Frequency Cross-Modulation Across the LCC	93
3.12	Summary	94
	References	94
4	Self-Commutating Conversion	97
4.1	Introduction	97
4.2	Voltage Source Conversion	97
4.2.1	VSC Operating Principles	97
4.2.2	Converter Components	102
4.2.3	The Three-Phase VSC	105
4.3	Comparison of LCC and VSC	114
4.4	Current Source Conversion	114
4.4.1	Analysis of the CSC Waveforms	116
4.5	The Reinjection Concept with Self-Commutation	116
4.5.1	Application to VSC	116
4.5.2	Application to CSC	121
4.6	Discussion	124
	References	125
5	Pulse Width Modulation	127
5.1	Introduction	127
5.2	PWM Operating Principles	127
5.3	Selective Harmonic Cancellation	128
5.4	Sinusoidal (Carrier-Based) PWM	131
5.5	PWM Carrier-Based Implementation	133
5.5.1	Naturally Sampled PWM	134
5.5.2	Uniformly Sampled	136
5.6	Modulation in Multi-Bridge Converters	137
5.7	Summary	138
	References	140
6	Multi-Level Conversion	141
6.1	Introduction	141
6.2	Diode Clamping	142
6.2.1	Three-Level Neutral Point Clamped VSC	142
6.2.2	Five-Level Diode-Clamped VSC	145
6.2.3	Diode Clamping Generalisation	149
6.3	Flying Capacitor Configuration	154
6.3.1	Three-Level Flying Capacitor	154
6.3.2	Multi-Level Flying Capacitor	155
6.4	Cascaded H-Bridge Configuration	158
6.5	Combined PWM/Multi-Level Conversion	161
6.6	Relative Merits of the Multi-Level Alternatives	164
6.6.1	A Cost Comparison of Alternative Configurations for Use in HVDC	165
	References	167

7 Multi-Level DC Reinjection	169
7.1 Introduction	169
7.2 Soft Switching in Multi-Level Reinjection Converters	170
7.3 Clamp-Controlled MLVR	170
7.3.1 Firing Coordination	174
7.3.2 Analysis of the Voltage Waveforms	174
7.3.3 Analysis of the Output Current	178
7.3.4 Capacitor Voltage Balancing	179
7.3.5 Dynamic Performance	185
7.4 Transformer-Coupled MLVR	187
7.5 Cascaded H-Bridge MLVR	193
7.5.1 Basic Structure and Waveforms	193
7.5.2 Switching Pattern of the Reinjection Bridges	196
7.5.3 Design of the Cascaded H-Bridge Chain	197
7.5.4 Capacitors' Balancing	199
7.5.5 STATCOM Application	204
7.6 Summary of Main Characteristics of MLVR Alternatives	209
7.7 Multi-Level Current Reinjection (MLCR)	210
7.7.1 Structure and Operating Principles	210
7.7.2 Self-Commutating Thyristor Conversion	213
7.7.3 EMTDC Verification	216
7.8 MLCR-CSC Versus MLVR-VSC	221
References	222
 8 Line-Commutated CSC Transmission	 225
8.1 Introduction	225
8.2 The Line-Commutated HVDC Converter	226
8.3 HVDC Converter Disturbances	232
8.4 Structure of the HVDC Link	233
8.5 DC System Configurations	239
8.6 DC System Control and Operation	242
8.6.1 General Philosophy	242
8.6.2 Different Control Levels	243
8.6.3 Overall Control Coordination	243
8.6.4 Pole Controls	245
8.6.5 Converter Unit Controls	253
8.7 AC-DC System Interaction	257
8.7.1 Voltage Interaction	257
8.7.2 Dynamic Voltage Regulation	258
8.7.3 Dynamic Stabilisation of AC Systems	259
8.7.4 Controlled Damping of DC-Interconnected Systems	260
8.7.5 Damping of Sub-Synchronous Resonances	260
8.7.6 Active and Reactive Power Coordination	261
8.7.7 Transient Stabilisation of AC Systems	261
8.8 AC-DC-AC Frequency Interactions	262
8.8.1 Harmonic Cross-Modulation Across the DC Link	262
8.8.2 Complementary and Composite Resonances	265

8.9	DC Link Response to External Disturbances	266
8.9.1	Response to AC System Faults	266
8.9.2	Response to DC Line Faults	267
8.10	Reliability of LCC Transmission	267
8.11	Concluding Statements	273
	References	273
9	Developments in Line-Commutated HVDC Schemes	275
9.1	Introduction	275
9.2	Capacitor Commutated Conversion	276
9.2.1	Basic CCC Operation	277
9.2.2	Simulated Performance	277
9.3	Continuously Tuned AC Filters	280
9.4	Active DC Side Filters	281
9.5	STATCOM-Aided DC Transmission	282
9.6	AC Transmission Lines Converted for Use with HVDC	286
9.6.1	Modulated (Tripole) DC Transmission	287
9.7	HVDC Transmission at Voltages above 600 kV	288
9.8	Concluding Statements	289
	References	289
10	VSC Transmission	291
10.1	Introduction	291
10.2	Power Transfer Characteristics	292
10.2.1	Current Relationships	294
10.3	Structure of the VSC Link	296
10.3.1	VSC-HVDC Cable Technology	297
10.4	VSC DC System Control	299
10.4.1	General Philosophy	299
10.4.2	Different Control Levels	302
10.4.3	DC Link Control Coordination	303
10.4.4	Control Capability of VSC Transmission	304
10.4.5	Assistance During Grid Restoration	305
10.5	HVDC Light Technology	306
10.5.1	Two-Level PWM Schemes	308
10.5.2	Three-Level PWM Schemes	312
10.5.3	HVDC Light Performance	314
10.6	Other VSC Projects	321
10.7	Potential for Multi-Terminal Sub-Transmission Systems	323
10.8	Discussion	324
	References	326
11	Multi-Level VSC and CSC Transmission	327
11.1	Introduction	327
11.2	Multi-Level VSC Transmission	328
11.2.1	Power Flow Considerations	328
11.2.2	DC Link Control Characteristics	331

11.2.3	Test System and Simulation Results	332
11.2.4	Provision of Independent Reactive Power Control	337
11.3	Multi-Level CSC Transmission	341
11.3.1	Dynamic Model	343
11.3.2	Control Structure	344
11.3.3	Simulated Performance under Normal Operating Conditions	345
11.3.4	Simulated Performance Following Disturbances	348
11.3.5	Reactive Power Control in Multi-Level CSC Transmission	352
11.4	Summary	356
	References	357
	Index	359

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.

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.

$$(1/T) \int_t^{t+T} p dt$$

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

$$P = VI \cos(\phi) \quad (1.1)$$

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 $\cos(\phi)$ (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.

$$Q = VI \sin(\phi) \quad (1.2)$$

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

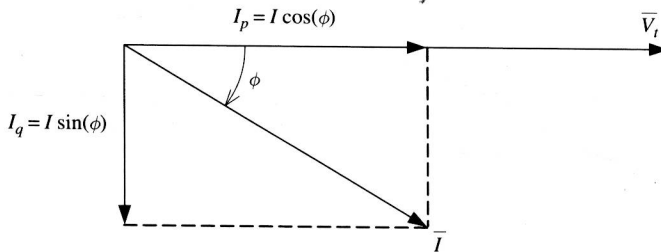


Figure 1.1 In-phase and quadrature current components

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

$$(VI \cos(\phi))^2 + (VI \sin(\phi))^2 = (VI)^2 \quad (1.3)$$

and

$$VI = \sqrt{P^2 + Q^2} \quad (1.4)$$

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:

$$I_2 X \cos(\phi) = V_1 \sin(\delta) \quad (1.5)$$

$$I_2 X \sin(\phi) = V_1 \cos(\delta) - V_2 \quad (1.6)$$

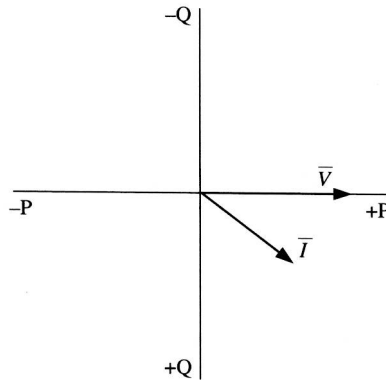


Figure 1.2 Four-quadrant diagram with the voltage as reference

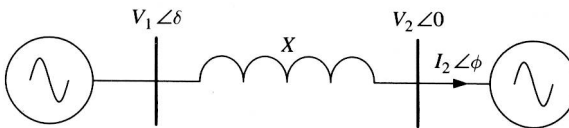


Figure 1.3 Interconnection between two synchronous systems

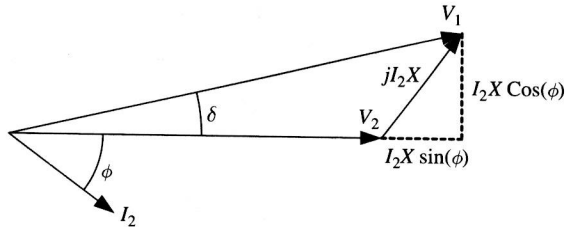


Figure 1.4 Phasor diagram for the interconnection of Figure 1.3

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

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

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

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.

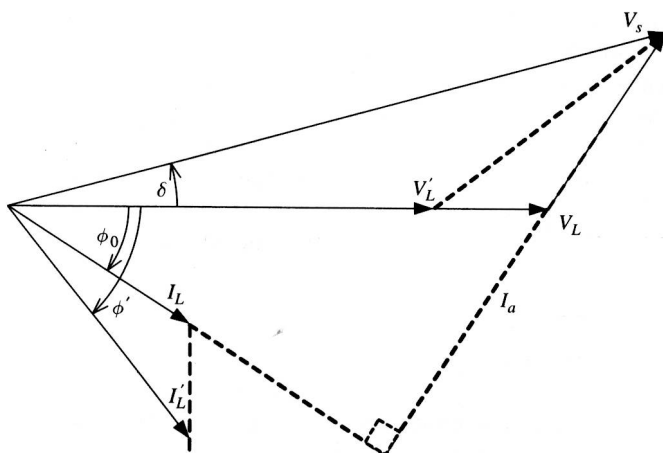


Figure 1.5 Effect of the load power factor on the load voltage

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.