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IEEE Guide for Planning DC Links Terminating at AC Locations Having Low Short-Circuit Capacities

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Abstract: Guidance on the planning and design of dc links terminating at ac system locations having low short-circuit capacities relative to the dc power infeed is provided in this guide. This guide is limited to the aspects of interactions between ac and dc systems that result from the fact that the ac system is “weak” compared to the power of the dc link (i.e., ac system appears as a high impedance at the ac/dc interface bus). This guide contains two parts: Part I, AC/DC Interaction Phenomena, classifies the strength of the ac/dc system, provides information about interactions between ac and dc systems, and gives guidance on design and performance; and Part II, Planning Guidelines, considers the impact of ac/dc system interactions and their mitigation on economics and overall system performance and discusses the studies that need to be performed.

Keywords: ac/dc interaction, fault recovery, frequency instability, harmonic transfer, instability, low short-circuit ratio (SCR), power, resonance, subsynchronous torsional interaction, temporary overvoltage (TOV), voltage instability

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Introduction

(This introduction is not part of IEEE Std 1204-1997, IEEE Guide for Planning DC Links Terminating at AC Locations Having Low Short-Circuit Capacities—Part I: AC/DC Interaction Phenomena; Part II: Planning Guidelines.)

The purpose of this document is to give guidance on the planning and design of dc links terminating at ac system locations having low short-circuit capacities relative to the dc power infeed. This guide is limited to the aspects of interactions between ac and dc systems that result from the fact that the ac system is “weak” compared to the power of the dc link (i.e., ac system appears as a high impedance at the ac/dc interface bus). Some more general aspects of the design and planning of high-voltage dc transmission schemes are described only when this adds to the understanding of the interaction phenomena and for the sake of completeness of the guide.

The content of this guide is put into practical perspective through reference to experience from existing systems. It explains how special ac/dc interaction problems, in a low or very low short-circuit ratio situation, were considered during system planning; what specific solutions were applied; and the subsequent operating experience.

This guide contains two parts:

- Part I, AC/DC Interaction Phenomena, classifies the strength of the ac/dc system, provides information about interactions between ac and dc systems, and provides guidance on design and performance.
- Part II, Planning Guidelines, considers the impact of ac/dc system interactions and their mitigation on economics and overall system performance and discusses the studies that need to be performed.

Part I is separated into the following clauses:

- Clause 1 contains general introductory and useful reference information.
- Clauses 2 and 3 discuss the strength of the ac/dc systems and their effects on voltage stability and power transfer limits.
- Clause 4 discusses HVDC controls and protection because they play an important role in most interaction phenomena.
- Clause 5 provides information about resonances, instabilities, and harmonic transfers.
- Clause 6 examines subsynchronous torsional interactions between dc convertors and nearby turbine generators.
- Clause 7 discusses the various types of ac system stabilities (i.e., transient, steady-state, low-frequency, and power-frequency stabilities).
- Clause 8 explains temporary overvoltages.
- Clause 9 examines rotational inertia of an ac system, which is an important aspect of the performance of an ac/dc link.
- Clause 10 describes the recovery of dc systems from ac and dc system faults.
- Annex A gives a brief description of the dc conversion process (i.e., basic rectifier and inverter operation).
- Annex B provides a bibliography pertaining to Part I. While it is not essential reference material for Part I of this guide, and while no claim is made that it is an exhaustive list, it is a useful resource of background information.

Part II is separated into the following clauses:

- Clause 1 contains general introductory and useful reference information.
- Clause 2 contains references.
- Clause 3 sets the stage for planning and design by identifying performance criteria and explains how these criteria can be defined and evaluated. This clause provides the basis for considering interaction and for evaluating the effectiveness of adopted strategies.

- Clause 4 discusses various aspects of system performance, in the context of low and very low short-circuit ratios, for the incorporation of the criteria developed in Clause 3. Alternative solutions to accommodate ac/dc interaction problems are presented.
- Clause 5 deals with aspects of economics and reliability.
- Clause 6 provides guidance on appropriate planning studies, once a dc link has been selected, with particular reference to low and very low SCR applications. After a review of appropriate study methods, both analog and digital, the stages of planning and design are suggested, and guidance is offered on which aspects to include.
- Clause 7 summarizes examples from the literature, in the context of planning studies for low SCR dc projects.
- Clause 8 describes selected projects that are in service with low and very low short-circuit ratios.
- Annex A provides a bibliography pertaining to Part II. While it is not essential reference material for Part II of this guide, and while no claim is made that it is an exhaustive list, it is a useful resource of background information.

This guide is the result of the work of the Joint Task Force (JTF) of the CIGRÉ Working Group 14.07—AC/DC System Interactions, and IEEE Working Group 15.05.05—Interaction with Low SCR AC Systems, which was set up in 1986 following the agreement between D. D. Wilson, Chairman of the IEEE Transmission and Distribution Committee, and T. E. Calverley, Chairman of the CIGRÉ Study Committee 14—DC Links.

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Contents

Part I: AC/DC Interaction Phenomena

1.	Overview.....	1
1.1	Scope.....	1
1.2	Purpose.....	1
1.3	General.....	1
1.4	References.....	3
1.5	Definitions.....	3
1.6	Acronyms and abbreviations.....	4
2.	AC/DC system strength	5
2.1	Introduction.....	5
2.2	High-impedance systems	5
2.3	Inadequate and zero mechanical inertia.....	21
2.4	Numerical examples of CSCRs and TOV_{fc} values.....	23
2.5	Calculation of CSCRs	24
2.6	Numerical examples of power reduction due to ac system impedance increase and ac voltage reduction	27
2.7	AC/DC system strength—summary tables	28
3.	DC power transfer limits.....	28
3.1	Description of phenomena	28
3.2	Power limits of an inverter.....	32
3.3	Power limits of a dc link	36
3.4	Principal parameters.....	40
3.5	Trends and sensitivities of system parameters.....	40
3.6	Possible improvements	41
3.7	Influence of dc controls	43
3.8	Methods of study.....	43
3.9	Discussion of power curves	44
4.	Control and protection for dc transmission.....	46
4.1	Introduction.....	46
4.2	Hierarchical division of the dc control system	46
4.3	Types of interaction between controls and the ac system.....	49
4.4	Current control	51
4.5	Power control	56
4.6	Reduction of the direct current at low voltage.....	56
4.7	AC system instabilities	57
4.8	Influence on the control of resonances in the ac network.....	58
4.9	Summary of convertor control instability phenomena.....	58
4.10	System parameters of principal interest to the controls.....	59
4.11	AC voltage variations	59
4.12	AC network frequency and stabilization control	62
4.13	Control and protection considerations for back-to-back schemes	67
4.14	Control and protection considerations for multiterminal schemes	68
4.15	Higher-level controller characteristics for dc schemes in operation.....	68

4.16 Protection	72
5. Resonances, instabilities, and harmonic transfer	73
5.1 Introduction.....	73
5.2 Basic concepts.....	73
5.3 Harmonic resonance-related instabilities and solutions.....	75
5.4 Factors influencing harmonic problems.....	79
5.5 Trends and sensitivities of system parameters.....	79
5.6 Methods of study.....	79
5.7 Different types of schemes and harmonic problems.....	80
5.8 Comments	81
6. Subsynchronous torsional interactions between dc convertors and nearby turbine-generators	81
6.1 Introduction and summary	81
6.2 Description of the phenomenon	82
6.3 Principal parameters.....	82
6.4 Trends and sensitivities of system parameters.....	84
6.5 Influence of dc controls	85
6.6 Methods of study.....	87
7. Transient, steady-state, low-frequency, and power-frequency stabilities.....	89
7.1 Introduction.....	89
7.2 Descriptions of stability types.....	89
7.3 Main parameters and effects	90
7.4 Trends and sensitivities of system parameters.....	91
7.5 AC and dc parallel operation	92
7.6 Influence of dc control.....	92
7.7 Methods and tools for study.....	93
7.8 Different types of schemes.....	94
8. Temporary overvoltages (TOVs).....	95
8.1 Description of phenomena	95
8.2 Main parameters affecting the phenomena	97
8.3 Trends and sensitivities of the system parameters.....	97
8.4 Influence of dc control.....	98
8.5 Methods and tools for study.....	98
8.6 Measures for the limitation of TOVs	101
8.7 Different types of schemes.....	103
9. Zero- and low-inertia systems.....	104
9.1 Introduction.....	104
9.2 Zero-inertia systems—Island of Gotland.....	105
9.3 Low-inertia system—Island of Corsica	107
10. Recovery of dc systems from ac and dc system faults.....	109
10.1 Introduction.....	109
10.2 Parametric behavior of the phenomena.....	110
10.3 Different types of schemes.....	115

10.4 System experience and examples.....	117
10.5 Methods and tools for studies	121
Annex A (informative) The dc conversion process	123
Annex B (informative) Bibliography.....	135

Part II: Planning Guidelines

1. Overview.....	141
1.1 Scope.....	141
1.2 Purpose.....	141
1.3 General.....	141
2. References.....	142
3. Performance criteria and evaluation	142
3.1 General considerations.....	142
3.2 Power transfer limits and SCR.....	143
3.3 Recovery from ac and dc faults	145
3.4 Reactive compensation	145
3.5 Temporary overvoltages (TOVs).....	146
3.6 Operation under low ac voltage conditions	146
3.7 Power transfer during ac and dc faults.....	147
3.8 Operation with and without ground return.....	148
3.9 DC line re-energization.....	148
3.10 Overload considerations.....	148
3.11 Operation without communication	149
3.12 Commutation failures.....	149
3.13 Voltage changes during reactive switching	149
3.14 Availability (adequacy and security)	150
3.15 Economic and reliability criteria for comparison of different solutions to interaction problems.....	150
3.16 Multiterminal considerations	150
4. Planning considerations	151
4.1 General aspects	151
4.2 Power transfer limits	152
4.3 Electromechanical stability.....	157
4.4 Planning considerations of HVDC controls.....	159
4.5 Planning of ac/dc performance enhancement	163
4.6 Consideration of existing dc schemes in the same system	164
5. System economics and reliability	164
5.1 General considerations.....	164
5.2 Aspects of alternative solutions to solve ac/dc interaction problems	165
5.3 Reliability and economic aspects of different dc system configurations.....	167
5.4 Study methods, sources of data, and assumptions	168
6. Planning and initial design studies.....	170

6.1	Introduction.....	170
6.2	Planning studies	170
6.3	Initial design studies	173
6.4	Required system data	179
7.	Examples of system studies	181
7.1	Introduction.....	181
7.2	Itaipu transmission system.....	181
7.3	Chateauguay.....	182
7.4	Highgate.....	182
7.5	Gotland.....	183
7.6	Virginia Smith (formerly Sidney).....	183
7.7	MTDC system studies.....	183
7.8	Reliability studies.....	184
7.9	Additional references	184
8.	Examples of existing low and very low SCR systems.....	184
8.1	Introduction.....	184
8.2	Miles City converter station.....	186
8.3	Virginia Smith (formerly Sidney)	188
8.4	Highgate.....	190
8.5	Chateauguay.....	191
8.6	Blackwater	191
8.7	Cross Channel	192
8.8	Vindhyachal	193
8.9	Gotland.....	194
8.10	Comerford.....	195
8.11	Nelson River	196
8.12	Itaipu	197
8.13	McNeill	198
	Annex A (informative) Bibliography.....	201

IEEE Guide for Planning DC Links Terminating at AC Locations Having Low Short-Circuit Capacities

Part I: AC/DC Interaction Phenomena

1. Overview

1.1 Scope

Part I of the guide discusses the effects of various aspects of the ac/dc interactions on the design and performance of dc schemes where the ac system appears as a high impedance at the ac/dc interface bus; i.e., low and very low short-circuit (short-circuit ratio [SCR]) conditions. AC systems having zero or inadequate mechanical rotational inertia, such as island schemes with no or with limited local generation, are also considered. Environmental, siting, and construction issues are not addressed. General issues, such as steady-state reactive compensation and ac and dc filter requirements, are not in the scope of this guide, but would be included in a complete study for a particular dc scheme design. In order to assist those not familiar with dc transmission and convertors, a brief description of basic rectifier and inverter operation is given in Annex A of Part I.

Part II of this guide, which is bound together with Part I, considers how the ac/dc interaction phenomena described in Part I should be taken into account in the planning and the preliminary design of ac/dc systems having low or very low SCR values.

1.2 Purpose

The purpose of Part I of this guide is to address factors required to be considered in the design of dc transmission schemes in the context of system interactions resulting from dc links terminating at ac system locations having low short-circuit capacities relative to dc power infeed and for cases where the inertia of the ac system is too low for satisfactory operation. The following ac/dc interactions are considered: power, voltage, and frequency instabilities; harmonic resonance-related instabilities; subsynchronous torsional interactions; temporary overvoltages; and recoveries from ac and dc faults.

1.3 General

The introduction of thyristor valves based on large-size thyristors, over the last twenty years, has contributed to the improvement of overall high-voltage, direct-current (HVDC) economy and reliability, making the application of HVDC transmission more widespread.

From earliest commercial applications of HVDC, planners found, in a number of schemes, that the ac system at the point of the proposed dc power infeed was “weak”—that is, its impedance relative to the dc power was high, and in some cases, the inertia of the ac system was low.

One of the important criteria in the design of dc links is the value of the permissible temporary overvoltage (TOV) at ac terminals of the convertor stations. In early schemes, the problem of too-high TOV was solved by the addition of synchronous compensators in the inverter stations; i.e., by the reduction of the ac system impedance as seen by the HVDC convertor. The application of metal-oxide (MO) arrestors has been made in some recent schemes to control TOV without the need for synchronous compensators. However, for a given dc power, this resulted in the need to accept an ac system having higher impedance compared to previous schemes, and several aspects of interactions between ac and dc systems became more evident.

The “weaker the ac system”—that is, the lower the ratio of the ac system short-circuit capacity to dc link power—the greater will be the ac/dc interactions. The ac/dc system strength, from the impedance point of view, is defined in this guide. Based on that definition and on typical inverter characteristics (such as the value of the convertor transformer reactance) the following SCR values can be used to classify an ac/dc system:

- a) A high SCR ac/dc system is categorized by an SCR value greater than 3.
- b) A low SCR ac/dc system is categorized by an SCR value between 2 and 3.
- c) A very low SCR ac/dc system is categorized by an SCR value lower than 2.

It should be emphasized that a scheme may be operating with high SCR for most of the time, but that it may appear as a low or very low SCR scheme during an emergency; that is, at ac system outage conditions. In such cases, the scheme must be designed to operate for those conditions, unless dc power reduction is acceptable.

Operation with very low SCR systems is possible only if very fast and continuous control of ac voltage is exercised, because the inverter operation is in the “unstable” region of the ac voltage/dc power characteristic. In modern ac system terms, this mode of operation is similar to an ac system whose voltage stability is maintained by a fast static var compensator (SVC). In such dc links presently in service, the required fast voltage control is executed by the HVDC convertor itself.

From the above, it can be seen that problems associated with very low SCR ac systems can be resolved either by strengthening the system with the addition of synchronous compensators or by stabilizing the ac system voltage with very fast control. On the other hand, synchronous compensators must be used to strengthen the system whenever there is a requirement to increase the inertia of the ac system. The system inertia constant referred to dc power, H_{DC} , should, for example, be greater than 2 s in order to maintain frequency deviation under fault conditions at less than 5%.

In addition to the system strength classification mentioned above, Part I of this guide defines and discusses a number of ac/dc interaction phenomena and proposes methods of preventing associated potential problems.

Good preliminary judgement on the impact of most interactions on the design and performance of a dc transmission scheme can be based on the SCR and inertia values quoted above, and on the discussions given in this document. However, this guide stresses the need to carry out adequate studies at all stages of planning and design.

HVDC controls play an important role in most interaction phenomena, and for that reason a detailed description of controls is included in this guide.

AC/DC system interactions are concerned with voltage stability (voltage collapse phenomena), overvoltages, resonances, and recovery from disturbances. Examples of their influence on the station design are the following:

- Voltage stability conditions will determine the type of voltage control and the type of reactive power supply. The voltage stability–voltage collapse interaction is similar to such phenomena in a purely ac system.

- The level of TOV will influence station design, including thyristor valve and surge arrester ratings. The lower the value of SCR, the higher the potential value of TOV.
- Shunt capacitors are used in converter stations for ac filters and for var supply. The larger the ratio of shunt capacitor Mvar to ac system short-circuit MVA, the lower will be the resonant frequency.

Commutation failures and recovery from ac and dc faults represent an important aspect of dc operation. However, it should be noted that modern controls have a dominating influence on the recovery from faults and are less affected by ac system impedance compared to controls used in earlier schemes.

1.4 References

This standard shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply:

IEC 60919-1 (1988-12), Performance of high-voltage d.c. (HVDC) systems—Part 1: Steady-state conditions.¹

IEC 60919-2 (1990-10), Performance of high-voltage d.c. (HVDC) systems—Part 2: Faults and switching. (Equivalent to IEEE P1030.2/D4, Dec. 1990.)²

IEC 60919-3...³, Performance of high-voltage d.c. (HVDC) systems—Part 3: Dynamic conditions.

1.5 Definitions

1.5.1 critical short-circuit ratio (CSCR): The SCR corresponding to the operation at maximum available power (MAP); for typical inverter design, CSCR = 2.

NOTE— The following operational characteristics are associated with CSCR:

- CSCR represents the borderline between “stable” and “unstable” operating regions. For SCR values lower than CSCR, the operation is in the “unstable” region of the ac voltage/dc power characteristic.
- If the operation is at unity power factor for systems at CSCR (i.e., the operation is at MAP), then the fundamental component of the temporary overvoltage (TOV_{f_c}) at full load rejection would be near to $\sqrt{2}$.
- A resonance near the second harmonic will occur for systems operating at CSCR.

1.5.2 effective dc inertia constant (H_{dc}): The rotational ac system inertia constant H converted to the base of dc power.

1.5.3 high-impedance ac system: An ac/dc system having low or very low SCR. (In this guide, rated values are assumed to be equal to nominal.)

1.5.4 inadequate inertia systems: An ac system having limited local generation, and therefore rotational inertia, so that the required voltage and frequency cannot be adequately maintained during transient ac or dc faults.

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³This IEC standard was not published at the time this publication went to press. Publication is expected in Spring 1998. For information about obtaining a draft, contact the IEC.

1.5.5 maximum available power (MAP): The maximum power that can be obtained by increasing dc current while not controlling the ac voltage.

1.5.6 operation with minimum constant γ : Operation of an inverter at minimum commutation margin angle γ in order to ensure transmission at the maximum dc voltage (possible only at powers below MAP; i.e., in the “stable” region of the ac voltage/dc power characteristic).

1.5.7 operation with variable γ : Margin angle γ is varied around an average value in order to stabilize the ac voltage. This can be achieved either by direct control of the ac voltage or by indirectly controlling the dc voltage. Another way of stabilizing the receiving system ac voltage is to arrange for the inverter, and not the rectifier, to be the current-controlling station. These modes of control are normally used for operation beyond MAP; that is, in the “unstable” region of the ac voltage/dc power characteristic.

1.5.8 short-circuit ratio (SCR): The ratio of the ac system three-phase short-circuit MVA (expressing the ac system impedance) to dc power.

1.5.9 weak ac system: *See: high-impedance ac system.*

1.5.10 zero inertia system: An isolated ac system having no local generation.

1.6 Acronyms and abbreviations

ac	alternating current
AVR	automatic voltage regulator
C	capacitor
CCA	current control amplifier
CESCR	critical effective short-circuit ratio
CQESCR	critical Q (reactive) effective short-circuit ratio
CSCR	critical short-circuit ratio
dc	direct current
emf	electromotive force
EMTP	electromagnetic transients program
EPRI	Electric Power Research Institute
ESCR	effective short-circuit ratio
FSPC	frequency-sensitive power controller
GTO	gate turn-off thyristor
LVCL	low-voltage current limit
MAP	maximum available power
MO	metal-oxide
MPC	maximum power curve
MTDC	multi-terminal direct current
OLTC	on load tap-changes
OSCR	operating short-circuit ratio
PMC	pole master control
QESCR	Q (reactive) effective short-circuit ratio
RAS	remedial action scheme
SC	synchronous compensator
SCR	short-circuit ratio
SR	saturated reactor
SSDC	supplementary subsynchronous damping control
SSO	subsynchronous oscillation
SVC	static var compensator
TCR	thyristor-controlled reactor

TCU	thyristor control unit
TOV	temporary overvoltage
TSC	thyristor-switched capacitor
UIF	unit interactional factor
VCO	voltage-controlled oscillator
VDCOL	voltage-dependent current order limit
VSF	voltage stability factor

2. AC/DC system strength

2.1 Introduction

Alternating-current system disturbances can affect the operation of any convertor, but mal-operation of a small convertor should have negligible effect on the ac system. However, it is not uncommon for a dc link to supply a large proportion of the ac system load so that the loss of its real power and the associated reactive power changes can have a profound effect on the system.

The interaction between ac and dc systems becomes more pronounced as the impedance of the ac system, as seen from the convertor ac terminals, is increased for a particular dc power. It follows that even a relatively small dc link connected to a point of the ac system having high impedance (low short-circuit capacity) may have considerable effect on the local ac network, even if the latter may be part of a large ac system.

It is important that an adequate system electromotive force (emf) is available not only for normal operation, but also following a system fault. The rotational mechanical inertia of the ac system transiently provides the energy to maintain the system emf despite a temporary reduction in the supply of dc power through the inverter. The ac system generators and their turbines are the main source of the ac system rotational inertia.

If a system receives all or most of its power from a dc link, the inertia of the receiving system may be inadequate, so that upon the interruption of the dc infeed, due to any cause, the system emf and frequency may decrease to unacceptably low values. In such cases synchronous compensators are used to act as “transient generators” to maintain the system emf and frequency.

An ac system can be defined as “weak” from two aspects:

- a) Alternating-current system impedance may be high relative to dc power at the point of connection.
- b) Alternating-current system mechanical inertia may be inadequate relative to the dc power infeed.

2.2 High-impedance systems

2.2.1 Short-circuit ratios (SCRs)

2.2.1.1 Calculating SCRs

The calculation of SCRs is discussed in 2.2.5, which shows that it is really per unit (pu) admittance. However, for most practical cases this is not very different from that of pure inductance, and the SCR is then often obtained from the following equation:

$$\text{SCR} = \frac{S}{P_{d1}} \quad (1)$$

where S is the ac system three-phase symmetrical short-circuit level in megavolt-amperes (MVA) at the converter terminal ac bus with 1.0 pu ac terminal voltage, and P_{d1} is the rated (considered in this guide to be equal to the nominal) dc terminal power in megawatts (MW).

When considering the effects of short-circuit currents on equipment, only the maximum value needs to be calculated. In contrast, it is the minimum value of S at which the rated power P_{d1} will be transmitted that must be used when examining limiting operating conditions.

2.2.1.2 Effective short-circuit ratio (ESCR)

Shunt capacitors including ac filters connected at the ac terminal of a dc link can significantly increase the effective ac system impedance. To allow for this, the effective short-circuit ratio (ESCR) is defined as follows:

$$\text{ESCR} = \frac{S - Q_c}{P_{d1}} \quad (2)$$

where Q_c is the value of three-phase fundamental Mvar in per unit of P_{d1} at per unit ac voltage of shunt capacitors connected to the converter ac bars (ac filters and plain shunt banks).

2.2.1.3 Operating short-circuit ratio (OSCR)

The ratio S/P_{d1} will vary in practice due to changes in ac system configuration and due to different levels of dc power being transmitted. Therefore, it should be remembered that it is the operating short-circuit ratio (OSCR) that is important, and that refers to actual power and corresponding actual S . Normally, the OSCR will be higher than the minimum specified SCR of the scheme, particularly at transmission below rated power. However, the lowest value of OSCR may not necessarily coincide with rated power. For example, operation at a lower power level may coincide with a system arrangement having higher impedance value than the one specified for the rated value. It should be borne in mind that, at very low currents, satisfactory operation may be achieved only at a value of OSCR that has a higher value than the minimum SCR specified for operation at normal dc currents.

2.2.1.4 Effect of converter reactive power consumption and QESCR

SCRs are sometimes used as a measure of expected performance of ac/dc systems, but as discussed later, this can give only an approximate indication, and comparisons between systems made by referring only to their respective short-circuit ratios can be misleading.

One of the major reasons for different performance of dc systems having the same SCR or ESCR is the converter reactive consumption, which may differ considerably between the schemes under consideration. The reactive consumption of the converter (Q_d) (see Annex A of Part I) can vary greatly depending on the operating α or γ and on the value of the commutating reactance (usually the converter transformer leakage reactance). The value of Q_d can have a significant effect on performance, in particular on power transfer limits and on temporary overvoltages. If the system short-circuit MVA and Q_c are referred to the sum of P_d and Q_d rather than to P_d , a better, but still approximate indication of performance can be obtained as can be seen from examples given in 2.4.

The Q effective short-circuit ratio (QESCR) is defined as follows:

$$\text{QESCR} = \frac{S - Q_c}{P_d - Q_d} \quad (3)$$

2.2.1.5 Synchronous compensators (SCs) and static var compensators (SVCs)

Synchronous compensators (SCs) contribute directly to the reduction of the ac system impedance, and they are included in the calculation of short-circuit ratios. SCs have been used to strengthen the ac system at the terminals of an inverter, this being a more economic solution compared to, for example, addition of a transmission line.

Operation of a dc link terminating at a point of high ac system impedance (i.e., of low short-circuit capacity) can be enhanced by fast control of ac voltage. This can be done by using the convertors themselves to control the voltage or by employing a separate thyristor-controlled reactor (TCR) or a saturated reactor (SR) at the ac terminals of the inverter. Fast control of the ac voltage does, in effect, “strengthen” the ac system.

If the ac system has a very high impedance, relative to the power being transmitted (a very low SCR system; see 2.2.4.3), satisfactory operation can be achieved in two ways:

- a) By strengthening the ac system by, for example, addition of a synchronous compensator—and in so doing, transforming the system to a low SCR system (see 2.2.4.2)
- b) By applying very fast ac voltage control (see 2.2.7)

It is possible to express, approximately, the strengthening of the ac system by fast voltage control in terms of a reduction of the ac system impedance (see 2.2.7.1). However, it is recommended to ignore this effect when calculating the short-circuit ratios. The ac voltage control and the dc power controls must be coordinated for each scheme; also, the convertor or TCR or SR are designed, due to economic considerations, to execute the voltage control within a predetermined ac voltage range. Later in this document it is emphasized that short-circuit ratios describe the system only approximately and that operation with very low SCR assumes fast voltage control.

A static var compensator (SVC) normally consists of an element (TCR, SR) that provides continuously variable vars and one or more of the following elements:

- Fixed shunt filters, capacitors, or reactors
- Thyristor switched shunt capacitors
- Mechanically switched shunt capacitors
- Thyristor switched shunt reactors
- Mechanically switched shunt reactors

TCR and SR are excluded, as already stated, from the definition of short-circuit ratios, as their effects depend on their designed range, speed of response, and coordination with other controls. The other elements, fixed or mechanically switched, would have to be included for calculating ESCR, because their presence adds directly to the ac system impedance.

Shunt reactors are usually disconnected for normal operating conditions, but would have to be considered if normally connected.

2.2.2 Power-current characteristics

2.2.2.1 Maximum power curve (MPC)

For a given ac system impedance and other parameters of the ac/dc system shown in Figure 2-1, there will be a unique P_d/I_d characteristic, shown in Figure 2-2, provided the starting conditions are defined. Additionally, it is assumed that I_d changes almost instantaneously in response to the change of α of the rectifier; for example, due to a change in current order. All other quantities—ac system emf, γ (minimum) of the inverter, tap-changers, automatic voltage regulation (AVR), and the value of shunt capacitors and reactors—are assumed not to have changed. When considering the inverter power capability, it is also assumed that the rectifier provides no

limitation to the supply of dc current at rated dc voltage. Each subsequent point is calculated by steady-state equations. These “quasi-steady-state” characteristics give a good indication of dynamic performance.

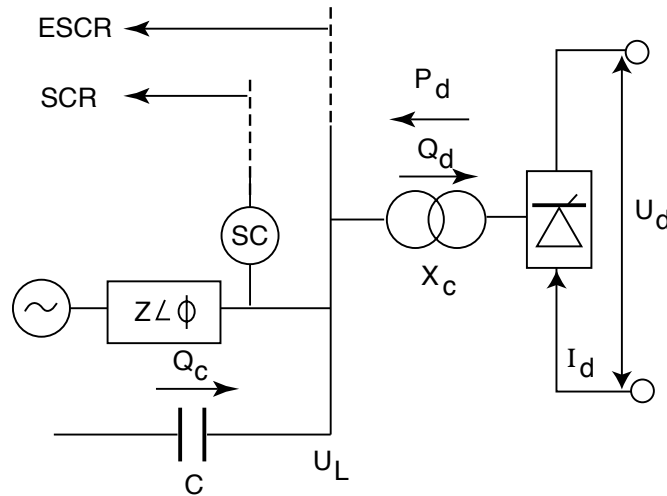


Figure 2-1—Simplified representation of a dc link feeding an ac system with shunt capacitors (Cs) and synchronous compensators (SCs) (if any) at converter station busbars

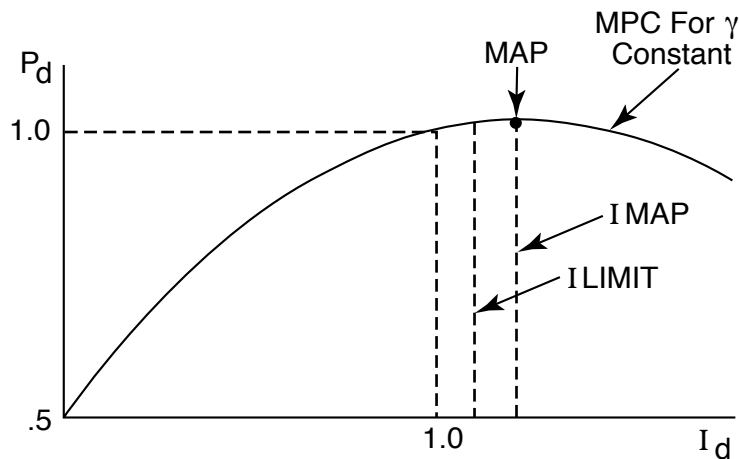


Figure 2-2—DC power—dc current curve for γ minimum

The starting conditions are defined to be as follows:

$$P_d = 1.0 \text{ pu}, U_d = 1.0 \text{ pu}, U_L = 1.0 \text{ pu}, \text{ and } I_d = 1.0 \text{ pu}.$$

(P_d = dc power; U_L = ac terminal—i.e., converter transformer line-side voltage; U_d = dc voltage of the inverter; and I_d = dc current.)

If the inverter is operated throughout at minimum constant γ , the resulting characteristics will represent maximum obtainable power for the system parameters being considered. This curve is termed the maximum power curve (MPC). Any power can be obtained below MPC by increasing α and γ , but power higher than

MPC can be obtained only if one or more system parameters are changed—e.g., by reduced system impedance, increased system emf, larger capacitor banks, etc.

A similar MPC curve can be obtained for the rectifier at minimum constant α .

2.2.2.2 Maximum available power (MAP)

An MPC exhibits a maximum value, termed maximum available power (MAP) as can be seen in Figure 2-2. The increase of the current beyond MAP reduces the dc voltage to a greater extent than the corresponding dc current increase. This could be counteracted by changing the ac system conditions—e.g., by controlling the ac terminal voltage. It should be noted that dP_d/dI_d is positive for operation at dc currents smaller than I_{MAP} , the current corresponding to MAP; dP_d/dI_d is negative at dc currents larger than I_{MAP} .

2.2.3 Critical short-circuit ratios (CSCRs)

Maximum power curves are plotted in Figure 2-3 for an inverter connected to ac systems having four different strengths. It can be seen that the rated (nominal) operating point A is located at different parts of MPC for different values of SCR.

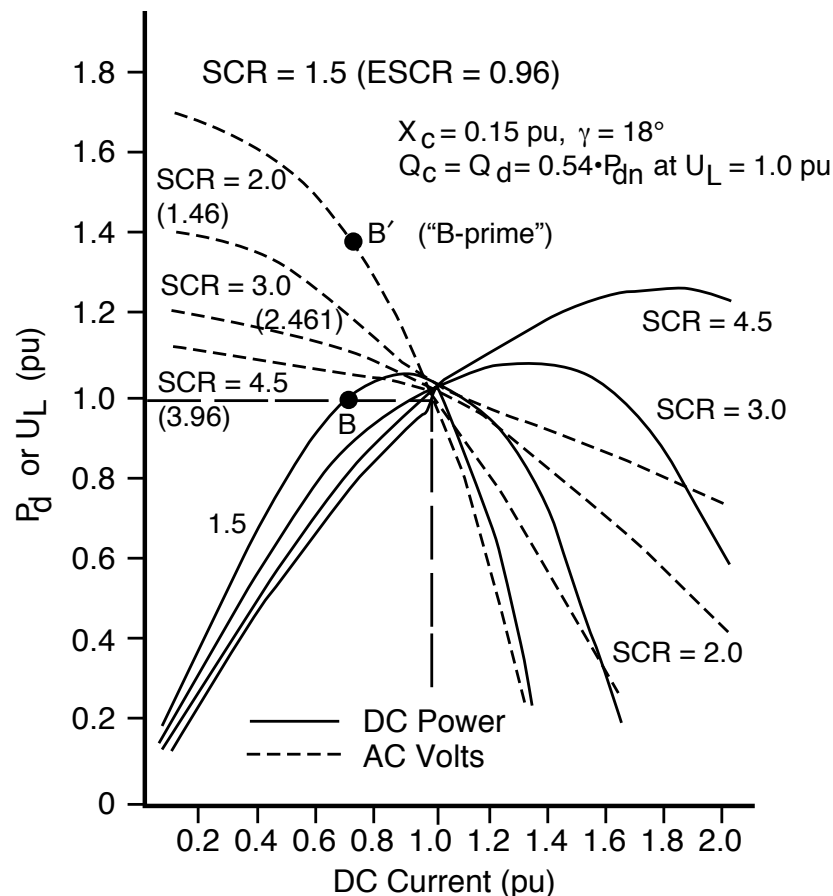


Figure 2-3—Variation of inverter ac terminal voltage

For SCR = 4.5, the operating point A is well below MAP and the one per unit current is considerably smaller than $I_{\text{MAP}} = 1.8$ pu. For SCR = 3, A is nearer to MAP and I_{MAP} is 1.4 pu. In both of these cases, dP_d/dI_d is positive.

For $SCR = 1.5$, the operating point A is “beyond” MAP, corresponding to $I_{MAP} = 0.8$ pu of rated dc current, I_{dN} . The value of dP_d/dI_d is negative. It may appear that there is another possible operating point for $SCR = 1.5$ at the left of MAP, point B. However, inspection of Figure 2-3 will indicate that the voltage corresponding to point B for $SCR = 1.5$ is too high to be utilized, as indicated by point B.

When the rated values of P_d , I_d , U_d , and U_L (all at 1.0 pu) correspond to the maximum point of P_d/I_d curve for operation with minimum γ , then the corresponding SCRs are termed critical ratios (critical SCR [CSCR], critical effective SCR [CESCR], and critical Q effective SCR [CQESCR]).

In this example, $CSCR = 2$, and the operating point A coincides with the MAP of the curve for $SCR = 2$. However, as discussed in 2.4, the value of CSCR depends on the inverter reactive consumption; i.e., on the values of the commutating reactance X_c and on the commutation margin γ .

For calculation of critical short-circuit ratios, see 2.5.

It is clear that the critical short-circuit ratios represent a borderline, when operating at γ constant, as the ratio dP_d/dI_d changes its sign. This is further discussed in Clause 3.

2.2.4 Short-circuit ratios as indication of ac/dc system strength

Three typical cases can be distinguished by considering the transient conditions that would temporarily reduce the ac terminal voltage and/or increase the system impedance; e.g., due to the loss of an ac line. In such a case, the power for a given current would be reduced; i.e., the temporary system condition would result in a new power curve that has a lower maximum value.

2.2.4.1 High SCR system

Figure 2-4 shows an inverter connected to a system by two parallel ac lines. It is assumed that the original SCR of 4.5 is temporarily reduced to an SCR of 3 if one of the two lines has tripped.

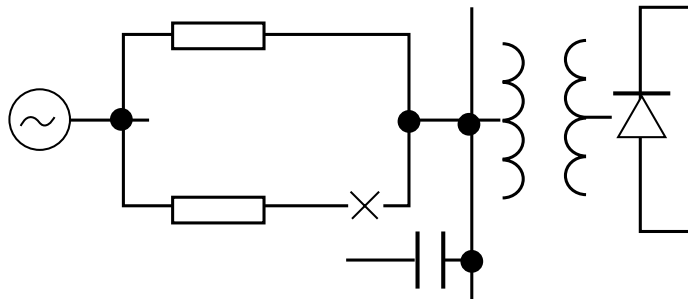


Figure 2-4—An inverter connected to a system by two parallel ac lines

In this case, power can be maintained at one per unit value despite the reduction of MAP, as shown in Figure 2-5 by increasing dc current at the new operating point, B. Operation throughout is at dc currents having a lower value than the current corresponding to MAP ($I_d < I_{MAP}$). The assumed system disturbances have resulted in a reduction of MPC, but the new maximum, MAP-2, is still higher than the rated power. All operating conditions are at γ minimum constant and correspond to $SCR > CSCR$.

(It should be noted that a sufficiently severe system disturbance could always cause an excursion beyond MAP, but such rare events are not considered as part of the definition of system strength.)

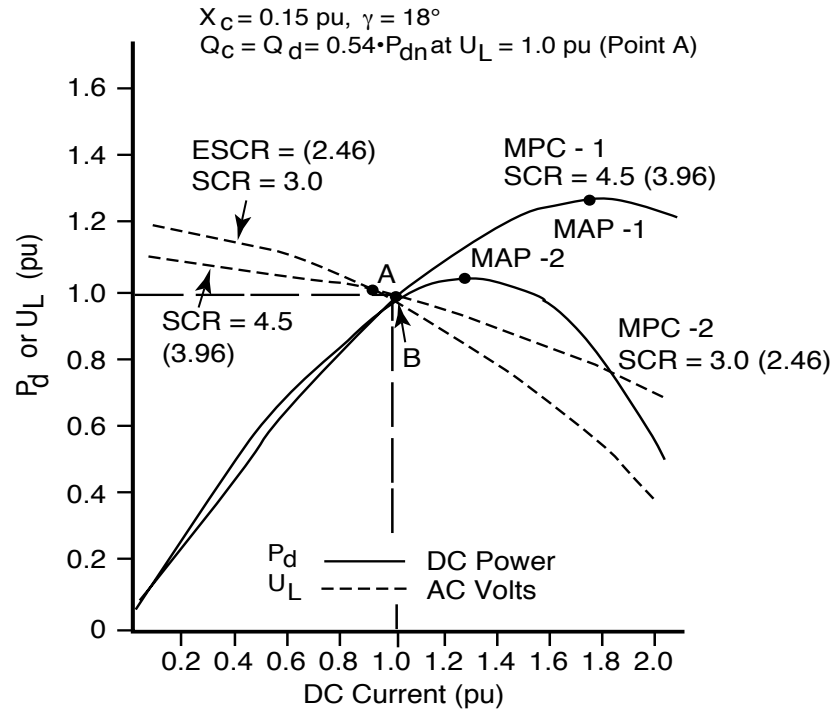


Figure 2-5—AC/DC system—high SCR, sudden change of SCR from 4.5 to 3.0

2.2.4.2 Low SCR system

The normal operation is at $I_d < I_{MAP}$ but a system disturbance could reduce MAP below the rated power and operation would continue at a reduced power in current control at I_d , which may be greater than I_{MAP} , or in power control at a reduced power order. Normal operating conditions are at $SCR > CSCR$ for operation at minimum γ , but temporary operation may be at $SCR < CSCR$ at a power level lower than rated.

Power curves for this case are shown in Figure 2-6a. It has been assumed that an SCR of three reduces to a value of two, as a consequence of the tripping of one line (Figure 2-4). The power at MAP-2 of the reduced MPC-2 is lower than the rated power at A. Any increase of current beyond 1.0 would be counter-productive, as the power would further reduce. It should be noted that the system impedance for curves $SCR = 2$ of Figures 2-3 and 2-6a are identical, but MAP-2 of Figure 2-6a has a lower value than MAP for $SCR = 2$ of Figure 2-3. The reason for this is that the initial ac terminal voltage, U_L , for all values of SCRs of Figure 2-3 was adjusted at one per unit. In the case of Figure 2-6a, U_L was adjusted to one per unit for initial conditions at $SCR = 3$. After the line tripping ac terminal voltage was decreased, due to an increase of the system impedance, to a value of 0.93 pu of U_{LN} and power decreased to 0.92 pu of P_{dN} at 1.0 pu of I_d . These values represent the initial conditions for MPC-2.

2.2.4.3 Very low SCR system

Normal operation is at a direct current equal to or larger than the current corresponding to MAP ($I_d > I_{MAP}$). Normal operating conditions are at $SCR \leq CSCR$ as indicated by point A on a curve for $SCR = 1.5$ in Figure 2.3. In such cases, a stable condition in power control is achieved by operation with variable γ . The variable γ is normally kept at a value higher than the minimum, so that the inverter itself can control the voltage. An alternative way of operating at $SCR < CSCR$ can be achieved by the use of very fast static var compensators to control the ac voltage, and hence the dc voltage.

The operation with very low SCR systems is discussed in Clauses 3 and 4.

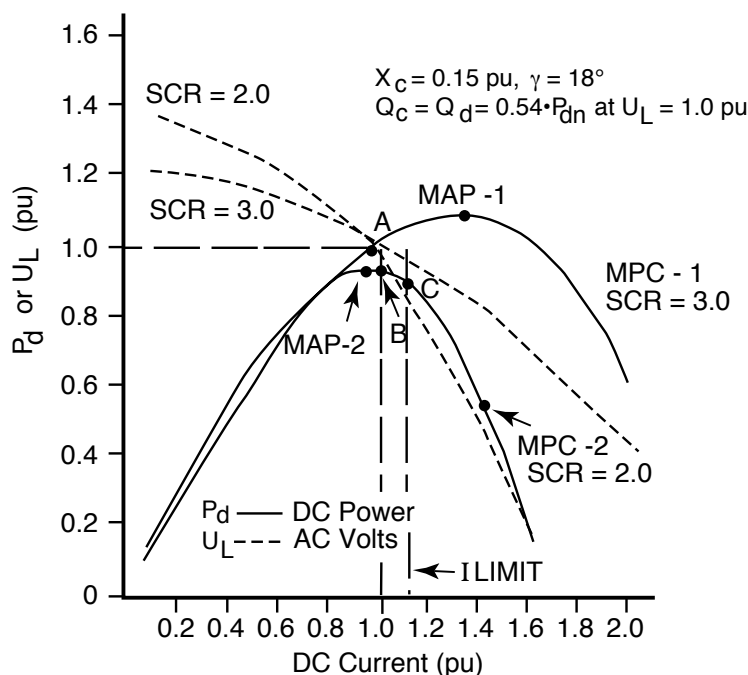


Figure 2-6a—AC/DC system—low SCR power and ac voltage curves, sudden change of SCR from 3.0 to 2.0

2.2.4.4 Typical values of SCR

In the initial stages of planning, the utility may know only the short-circuit MVA of the system and the required dc MW. The following are very approximate indications of the ac/dc system strength in terms of SCR.

For a high SCR system (approximately $SCR > 3.0$) as defined in 2.2.4.1, dc could normally be introduced without the need for any special steps. However, as can be seen from the ac voltage curves of Figure 2-3, the TOV—the value of U_L at load rejection ($I_d = 0$)—is becoming relatively high as SCR reduces and approaches the value of three, and ac voltage control has been used for some schemes having SCR in that region (Cross Channel, Chateauguay).

The application of HVDC with a low SCR system as defined in 2.2.4.2 (approximately $3 > SCR > 2$) may need some additional control features (see Clauses 3 and 4). In addition, consideration should be given to ac voltage control and to the possibility of second/third harmonic resonance. These considerations may result in the need for some additional steps to be taken.

If SCR is lower than two, the system may prove to be a very low SCR system as defined in 2.2.4.3, and the use of “variable γ control strategy” (see Clauses 3 and 4) may prove to be essential. Operation at constant γ could be possible, provided very fast ac voltage control is used. Special steps would be needed to control ac overvoltages and low-order harmonics.

When comparing the performance of a dc link based on the values of SCR, it should be appreciated that the value of CSCR, unlike SCR, depends on the value of Q_d , which in turn depends on the commutating reactance, X_c , and the value of γ . Two inverters rated for the same nominal power, but having different nominal Q_d , will have the same SCR, but the values of CSCRs will be different. It can be seen in 2.4 that, for some typical examples, CSCR may vary by more than 30%. In the examples considered in previous subclauses, $X_c = 15\%$ and $\gamma = 18^\circ$ have been assumed, which may be considered to be in the middle of the range of practical values.

One system may have requirements that necessitate deeper study than another system. System damping, which in the simple model is represented by the impedance angle, may differ greatly between two systems having the same value of SCR. This can be important for some interaction phenomena. All meaningful studies should use the available system data in sufficient detail to match the requirements of a particular study. However, it should be noted that the trends in converter control design are making stability and recovery from faults less influenced by system damping. Hence, in the future, the damping will principally affect the steady-state harmonics and overvoltages due to major disturbances, such as total load rejection.

2.2.4.5 The nature of ac system disturbance

The definitions of the system strength given in 2.2.4 depend also on the operating conditions of a given system. For example, the disturbance described in 2.2.4.2 may be considered, by some utilities, to be an exceptional event, and more “normal,” relatively frequent disturbances may not result in the reduction of maximum available power (MAP-2) below the rated power.

The utilities usually specify the disturbance for which the power should be maintained at the rated value in terms of the ac terminal voltage reduction, without specifying any associated change of the system impedance; i.e., as if the terminal voltage was reduced only by ac system emf reduction.

The effect on dc power will be different for the same amount of ac terminal voltage reduction, depending on whether the ac system impedance has changed or not.

In Figure 2-6b, MPC-1 and MPC-2 are the same as in Figure 2-6a: MPC-2 resulted from the ac system impedance increase by one-third, from SCR = 3 to SCR = 2; this resulted in an ac terminal voltage drop from 1.0 pu (point A) to 0.93 pu (point B) at I_d = one per unit; the power has reduced from one per unit to 0.92 pu, which is very close to the value of MAP-2.

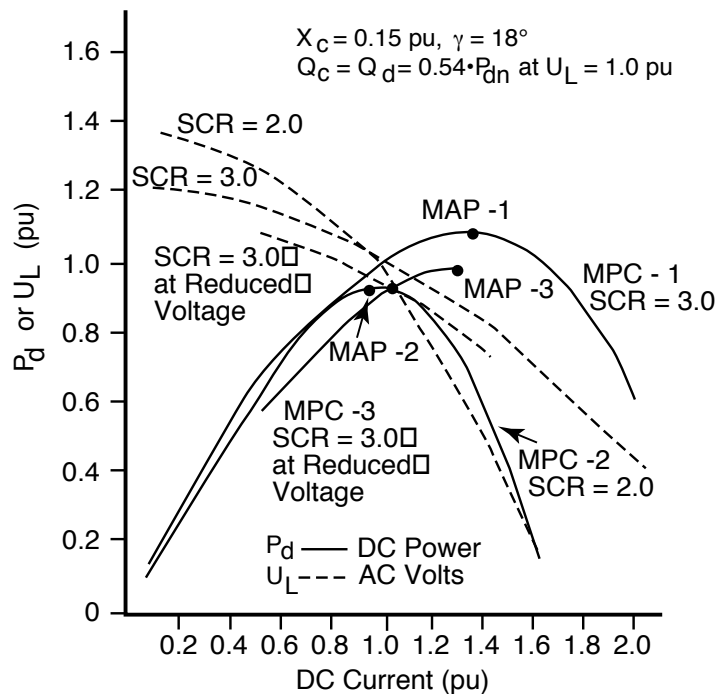


Figure 2-6b—AC/DC system—low SCR, sudden ac voltage reduction without SCR change (MAP-3)

MPC-3 was obtained by assuming that ac terminal voltage has reduced to 0.93 pu without a change of the system impedance. Direct-current power has reduced initially to a similar value as for MPC-2, but because MAP-3 has a greater value than MAP-2, the power can be increased to 0.98 pu (MAP-3) by increasing dc current to 1.25 pu.

This means that the power immediately available following the disturbances will differ by 6.5% for the two cases.

Relevant quantities for these two cases are tabulated in 2.6.

2.2.4.6 Temporary overvoltages (TOVs)

When considering power transfer limits, MAP represents a clear change in the P_d/I_d characteristic. Moreover, for operation at currents higher than I_{MAP} , the control strategy based on constant γ operation cannot be used in power control mode.

When considering the values of TOVs, there is no such definite “break point.” In addition, depending on the location of the convertor station and on the utility practice, the acceptable value of TOV may vary from scheme to scheme.

Also, in highly meshed systems having generators that are electrically close to the convertor station, the effective short-circuit impedance corresponding to the SCR value calculated by subtransient reactances will apply only to the first fundamental cycle, and the subsequent TOV would be higher as transient reactances rather than subtransient values influence the voltages.

The fundamental components of TOV (TOV_{fc}) calculated from Equation (27) in 8.5 have the following approximate values:

- a) High SCR systems ($SCR > 3$): TOV_{fc} lower than 1.25 pu
- b) Low SCR systems ($3 > SCR > 2$): TOV_{fc} higher than 1.25 but lower than 1.4 pu
- c) Very low SCR systems ($SCR < 2$): TOV_{fc} higher than 1.4 pu

[These are theoretical values, ignoring saturation of transformers; TOV_{fc} values will be lower in reality due to this (refer to 8.1).] However, the TOV peak values that include harmonic components may not be reduced by saturation of convertor transformers.

It should be pointed out that operation with low SCR systems does not seem to cause particular difficulties from the point of view of transfer of power. Occasional temporary power reduction (see 2.2.4, 3.2.2, and 3.6.2) can be contained. However, the corresponding TOV is not always acceptable.

In Figure 2-7, P_d/I_d curve MPC-2 was plotted using data of the Cross Channel scheme. It can be seen that for $SCR = 3$ (ACV-2) this would have resulted in TOV_{fc} of just over 1.3 pu, which was not acceptable to the utility. Static var compensators were included in the installation to limit TOV_{fc} to 1.16 pu. SCR equal to three is the minimum specified value; the operation is normally at an SCR value higher than three.

It is interesting to compare MPC for the uncompensated Cross Channel scheme with the MPC for the “average” scheme data used in Figures 2-6a and 2-6b for the same $SCR = 3$. For the “average” system, TOV_{fc} is just over 1.2 pu, compared to the uncompensated Cross Channel scheme of just over 1.3 pu. This is due to the difference in the value of the commutating reactance and consequent higher var consumption. The difference in MAP values should also be noted.

MCP-1 $X_C = 0.15$ pu, $\gamma = 18^\circ$, $Q_d = Q_c = 0.54 \cdot P_{dn}$ at $U_L = 1.0$ pu
MCP-2 $X_C = 0.23$ pu, $\gamma = 15^\circ$, $Q_d = 0.6 P_{dn}$, $Q_c = 0.52 \cdot P_{dn}$ at $U_L = 1.0$ pu

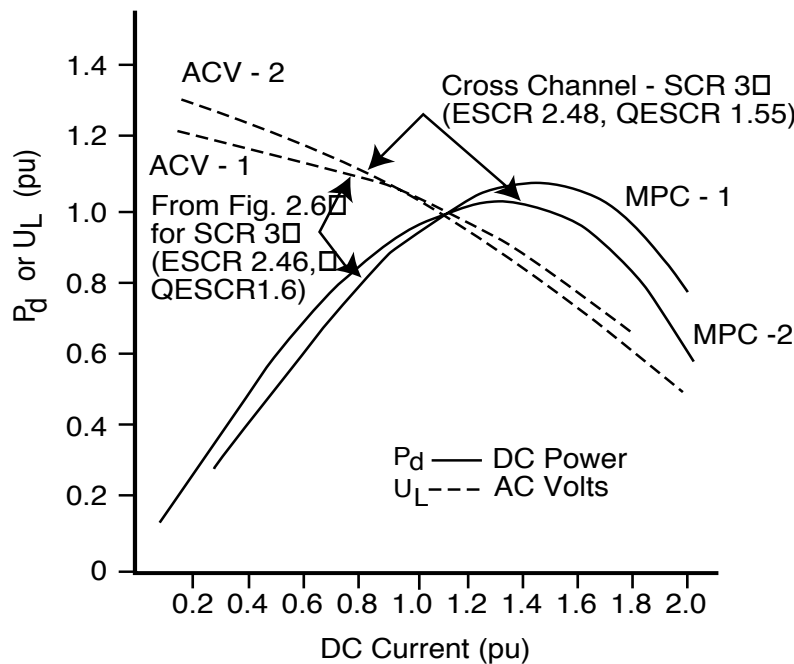


Figure 2-7—Power and ac voltage curves for SCR = 3 for two different converter characteristics

2.2.5 Calculation of SCRs

2.2.5.1 General

In many preliminary calculations it is convenient and customary to use a simplified representation of the ac system, as discussed in 2.2.5.2. To determine the system impedance and SCRs, digital short-circuit programs from different origins can give different results for SCR for the same system, while giving the correct results for the normal purpose of these programs, which are usually used for studying ac systems alone. For example, a program may not represent the transmission lines' shunt capacitance, which would give unrealistically low system impedance, Z_s , and in consequence, a too-high SCR. Some interaction phenomena are significantly influenced by the system resistive component (system damping), which is primarily provided by loads, but may not be represented in some short-circuit programs.

2.2.5.2 Simplified representation of the ac/dc system

Referring to Figure 2-1, it is assumed that the ac system can be represented by a Thevenin equivalent emf at fundamental frequency, behind an impedance Z (or admittance $Y = 1/Z$).

SCR is defined as the value of Y at fundamental frequency, on a base of rated power (MW) of the converter and rated ac system voltage, that is consistent with SCR defined in 2.2.1. Synchronous compensators, existing or supplied as part of the converter station, are deemed to be connected as required for the operation considered; i.e., they form part of the SCR calculation.

ESCR is defined as $(Y + Y_c)$ on the same base as for SCR, where Y_c is the admittance of all shunt filters and capacitor banks on the busbar that are connected for the operation under consideration. This definition is consistent with the definition in 2.2.1.

The following notes may be useful for defining a suitable system representation:

- a) Representation of the ac system by an admittance defined by SCR is assumed to be relevant only to transients (e.g., ac faults) of a few hundred milliseconds. (For more detailed study of some particular characteristics, a more detailed representation may be required.)
- b) As a consequence of a), the calculation of Y at fundamental frequency shall assume that synchronous machine field controls, transformer tap positions, and capacitor switching controls have no appreciable effect during the transient.
- c) The reactance value of a synchronous machine is not constant, but effectively depends on the part of the transient being studied and the method of supplying the field. The apparent value varies between subtransient and transient reactances (but not synchronous reactance). The effect of any errors in assumptions about this will normally be reduced by fixed ac system line and transformer reactances, hence calculation based on subtransient reactances (as commonly used in short-circuit level calculation) will generally be sufficiently accurate. However, in this simple representation it would be safer to use the transient reactance for synchronous compensators connected in the station and for any nearby synchronous machines.
- d) The system damping is important for most phenomena, and therefore the impedance values corresponding to SCR and ESCR (and QESCR) should be expressed in polar form as magnitude and angle. Thus, for example, for a system with $SCR = 3 \angle -80^\circ$ the addition of 0.6 pu of capacitors plus filters gives ESCR of about $2.4 \angle -8^\circ$. (Please note that because SCR and ESCR are defined as admittances [see 2.2.5.2], the angle should be negative as indicated.)
- e) SCR (ESCR) values calculated at the ac terminals of the convertors may not be directly applicable in special cases, such as where the convertor transformers have tertiaries connected to a synchronous compensator or compensators. In this case, the physical position of the tertiary usually is between line and valve windings such that there is a finite reactance between the filter bus and the tertiary terminals.
- f) If the ac filters are connected to the tertiary winding of the convertor transformer, and if this winding has a reactance value of almost zero (the tertiary is placed physically between line and valve windings), then the tertiary becomes the commutating bus. This means that the equivalent ac system impedance is increased by the reactance of the line winding. Short-circuit ratios must be calculated as if the line winding reactance forms part of the ac system.
- g) Any capacitor banks associated with static var compensators (SVCs) should be lumped with other capacitors on the busbar. If switched capacitor banks are used, then the maximum value of capacitors that may be connected during the operation to give lowest value of ESCR (or OESCR) for a particular system configuration should be used. The representation of continuously responding SVCs requires careful consideration, as discussed in 2.2.1.5.
- h) Short-circuit ratios defined in this subclause are not applicable for studies involving mechanical shaft resonances of machines; such studies should use relevant system representation. The same applies in general to all studies of slow phenomena associated with machines; e.g., inter-machine and inter-system swinging, field controls, and governors.
- i) For some other studies (e.g., overvoltages and recovery from faults), it is important to represent the convertor transformer saturation properties and nearby loads accurately. This may also apply to other large transformers close to the convertor stations.

Although SCR (ESCR) calculated as above would give a numerical definition of the ac system admittance (and impedance) represented by the Thevenin equivalent circuit, when comparing the results all relevant convertor quantities must also be stated: commutating reactance X_c , delay angle α or commutation margin (γ), and the control strategy. As discussed in 2.2.1.4, QESCR takes most of these into account.

It was noted in 2.2.5.1 that different computer programs may give different values of system impedance, which may lead to small errors. The more direct method to obtain an equivalent system impedance value is to make all system emfs zero, inject a current at the terminal of the convertor, and measure the resulting voltage. This is, in effect, what a network reduction program does. It should always be remembered that it is necessary to obtain the value of the system impedance as accurately as possible; the short-circuit MVA has no direct relevance in the study of dc operation, although it is a convenient quantity to use in discussion.

2.2.5.3 Load representation

It was pointed out in 2.2.5.1 that load representation is important. For example, induction motors add to the emf of the system, but they do collapse at low ac voltage. A large number of induction motors in the vicinity of the inverter may have considerable effect on the performance. It is recommended that users of both in-house and externally sourced computer programs scrutinize how loads are represented in assessing the validity of SCR calculations. Loads should be represented using the best knowledge available. In the absence of load data, it is suggested that load characteristics should be estimated rather than completely omitted. The ac/dc system behavior is influenced by load characteristics, and the omission of load representation may give misleading and possibly overly pessimistic results. For example, loads may contribute substantial damping to transient disturbances, and possibly be the source of additional short-circuit MVA.

2.2.6 Application of synchronous compensators

Synchronous compensators have been used to strengthen the ac system at the inverter end in a number of dc schemes. The cost and maintenance requirements of synchronous compensators may restrict their application to special situations.

In addition to the reduction of the system impedance, both at fundamental and harmonic frequencies, the synchronous compensators have the following beneficial characteristics:

- a) They can supply both positive and negative continuously variable reactive power, which in most cases eliminates the need for frequent shunt capacitor switching.
- b) They tend to increase the natural resonant frequency between the filters and the ac system.
- c) They are able to provide an increase of reactive power on reduction of ac busbar voltage, in contrast with var reduction when supplied by shunt capacitors.

The application of synchronous compensators at schemes like Nelson River (Manitoba, Canada) and Itaipu (Brazil) has changed the system from being a very low SCR system to a low SCR system as defined in 2.2.4.

A requirement for dimensioning the synchronous compensator in these schemes was the need to limit the fundamental component of the temporary overvoltages to values lower than 1.4 pu. From the second table in 2.4, it can be seen that the operation at the CSCR corresponds to TOV_{fc} of 1.4 pu (see also 3.1). It should be noted that the reduction of the system impedance, by addition of synchronous compensators, to reduce TOV has at the same time resulted in bringing the operating point, and therefore the operating direct current, to a smaller value than I_{MAP} .

2.2.7 Control of ac voltage by variable static equipment

The consequence of ac/dc interaction, when the ac system impedance is high, is evidenced by large ac voltage variations. Very fast and continuous ac voltage control would effectively strengthen the system.

The application of MO gapless surge arresters has contributed to the possibility of limiting TOV to required values without the need to use SCs.

2.2.7.1 The application of TCR and SR static var compensators

A fast TCR or SR static var compensator can be used to keep the terminal ac voltage constant within the required range. The compensator var absorption must be continuously variable within its prescribed range.

In practice, the size (var range) of the TCR or SR has to be limited on economic grounds. These compensators lose control at very low ac voltage and may have limited overload range. The operating range is usually increased by the use of thyristor-switched capacitors (TSCs) and/or mechanically switched capacitors to keep the TCR or SR within its designed range.

Usually, a voltage/current or voltage/var characteristic of the TCR or SR is designed with a slope to suit the ac system, usually 3–5% on the SVC rating. The equivalent system impedance is determined by the addition of this slope reactance in parallel with the ac system impedance. However, as discussed in 2.2.1.5, the effect of a TCR or SR is not included in the definition of SCR but has to be considered for each separate scheme.

2.2.7.2 The application of the inverter with variable γ

The reactive power consumption of the inverter can be varied by operation with different values of the commutation margin angle γ (see Annex A of Part I).

Highgate and Virginia Smith (Sidney) convertors in the United States and McNeill in Alberta, Canada, are examples of schemes that are designed to operate with very low SCR systems, and TOV is controlled by a combination of MO arresters, convertor control action, and subsequent mechanical switching of capacitors/filters. In the case of the McNeill station, the effective system impedance is increased by the line winding of the convertor transformer [see 2.2.5.2, item c).]

If γ is varied in response to ac voltage variation, the inverter can be designed to act as a TCR in a limited range of conditions. As the dc transmission voltage depends on the value of γ , during steady-state conditions the convertor transformer tap-changer and mechanically or thyristor switched capacitors are used to keep γ near its nominal value. These matters are further discussed in Clauses 3 and 4.

2.2.8 Multiconvertor systems

General guidelines have to be considered with caution while studying a system, because a particular system has to be studied in detail commensurate with its complexity.

Practical experience with, and the background investigations of, multiconvertor systems are not as widespread as that for more conventional two-terminal schemes. For this reason, the comments in this subclause are kept in very general terms.

2.2.8.1 Multi-infeed systems

Multi-infeed inverters connected to the same busbar or being electrically close can be divided into two categories:

- a) All inverters are controlled by one master controller, which shares the duty evenly among the separate inverters. In this case, the ac system impedance should be referred to the total dc power. The short-circuit ratios should be calculated as if this were one large inverter. However, it should be noted that even when only one master controller is used, the recovery of individual inverters can be staggered with the effect being as if each inverter is recovering against a stronger system.
- b) Two (or more) inverters are operated separately. As an example, suppose inverter A is at constant power, and inverter B is at constant power but with power modulation. In most respects, the various phenomena would be as if the system consisted of one large inverter. However, the demand for power increase from the inverter B will respond as if short-circuit ratios are referred only to its own power, but Q_c in the formula must include all capacitors used with both inverters.

2.2.8.2 Rectifier–inverter system

There are regions where convertors of two or more different dc schemes of comparable ratings are located electrically close to each other. If one convertor is operating as an inverter while a neighboring convertor acts as a rectifier, it can be viewed that the power infeed from the inverter of one dc scheme is totally or partially taken away by the rectifier of another dc scheme, as shown in Figure 2-8. The situation is not dissimilar from multi-infeed systems (2.2.8.1). To the first approximation, the reactive power consumption of the rectifier and the inverter are similar. Therefore, for most phenomena, the SCRs should be calculated by reference to the total power P of rectifier plus inverter.

If the common ac system voltage suddenly reduces with or without ac system impedance increase, the rectifier will consume more reactive power and both dc currents will increase to maintain dc power which would further increase reactive power consumption.

For the remote inverter, regarding any effects due to its ac system changes or power changes, its short-circuit ratio should be referred only to its own power.

2.2.8.3 Multiterminal schemes

Each inverter SCR should be calculated with reference only to its own power for all phenomena, except when considering recovery from faults. The dc peak current due to faults and commutation failures will depend on the combined rating of the rectifiers. This fact will lead to a risk of consequential commutation failures, because the recovery will be carried out at this higher dc overcurrent compared to what would be expected based on the inverter rating.

2.2.8.4 Two independent dc schemes operating in the same ac system

Two independent convertors may be connected to two different parts of the same ac system. To make two inverters independent of each other, the ac impedance between them should have a high value. If two inverters are interconnected by a high-impedance ac line, they will be more independent of each other than if they are further away from each other geographically but connected by strong ac lines. A low-impedance ac interconnection may lead to more interactions between the two inverters than if they were interconnected by a “weak” ac link. An ac system fault anywhere on the “strong” ac system will affect, more or less similarly, the inverters connected to it and will approach conditions described in 2.2.8.1.

2.2.9 DC link in parallel with an ac line

The effect of an arrangement such as is illustrated in Figure 2-9 is not immediately obvious, and it is advisable to carry out studies with full representation rather than rely on SCRs. The following comments may serve as general guidelines.

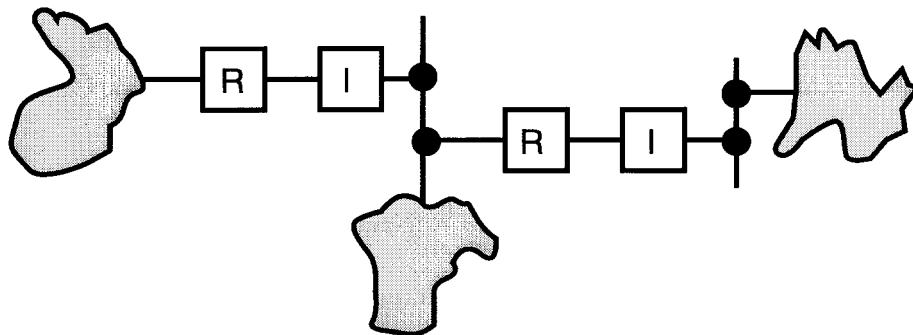


Figure 2-8—A rectifier and inverter connected at the same location

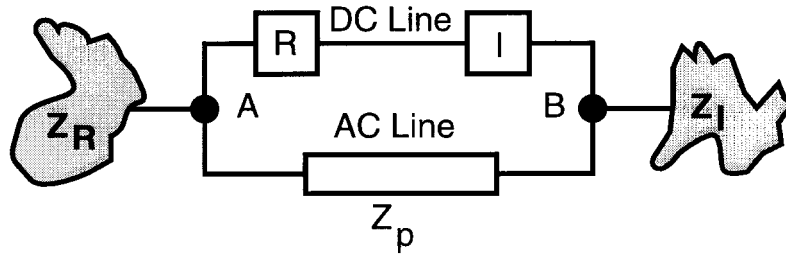


Figure 2-9—Ac and dc operating in parallel

2.2.9.1 Power transfer limits

In Clause 3 it is stated that values of MAP can be calculated for point-to-point schemes initially for the receiving terminal under the assumption that the sending terminal will not impose a limitation, particularly as the rectifier station can be designed, if that is desirable, not to impose a power limitation. However, for the system shown in Figure 2-9, the following cases will indicate the position:

- High SCR rectifier-end ac system (low Z_R) and high-impedance parallel ac path (high Z_p).
In this case, the rectifier loading will have negligible effect on the ac voltage at A, and the rectifier will not impose a limitation as for normal point-to-point transmission. Furthermore, the inverter-end ac system will benefit from the ac parallel line, and the impedance to calculate the SCR at B would be equal to Z_I in parallel with $Z_p + Z_R$.
- Low and very low SCR ac system at rectifier end (high Z_R) and low impedance parallel path (low Z_p).
In this case, the rectifier loading will influence the voltage at A, and due to the low Z_p , the voltage at B will be affected by both inverter and rectifier loading. Thus, the two convertors will behave in a manner approaching the case of being connected to the same ac busbars. The use of SCR is not recommended in this case and full representation is preferred.
- Low and very low SCR ac system at rectifier end (high Z_R) and high impedance parallel ac path (high Z_p).
In this case, the rectifier loading may be limited by the low SCR sending-end system. The high Z_p will tend to decouple the two ac systems, but again, the use of SCR is not recommended and full representation is preferred.
- For the fourth combination of high SCR rectifier end system (low Z_R) and low impedance parallel ac path (low Z_p), the inverter end system is unlikely to have low or very low SCR.

2.2.9.2 Temporary overvoltages

Direct-current load rejection affects both the rectifier and the inverter, and therefore similar arguments apply as in 2.2.9.1.

2.2.9.3 Recovery from faults

The inverter recovers against a system impedance, and therefore it will always benefit from a reduced impedance.

2.2.9.4 Resonances

This case is similar to 2.2.9.3.

2.2.10 General comments

It has been pointed out that the use of SCRs for estimating scheme performance should be made with caution. This is true in particular if the system departs from the standard point-to-point scheme. The more complex the scheme, the greater the need for full representation of the system.

When studying or designing a scheme, the ac system representation has to be as accurate and comprehensive as required by a particular study. It must be stressed that it is often required to assume the possibility of a particular ac/dc interaction in order to set up the simulator correctly or use a digital program. For example, in a number of schemes no studies were carried out during planning or design stages that would have looked for second harmonic or subsynchronous interactions and instabilities or resonances, and yet these effects were experienced in service. One purpose of this guide is to draw attention to possible ac/dc interactions so that correct studies can be carried out at appropriate times.

The effects of dc operation and mal-operation at fundamental frequency with a balanced ac system can be simulated accurately using load flow, transient stability, and other digital programs. The operating conditions with distorted and/or unbalanced ac systems are studied by the use of dc simulators and electromagnetic transients program (EMTP)-type programs.

2.3 Inadequate and zero mechanical inertia

2.3.1 Inertia constants

Turbine generators in an ac system represent a large rotating mass. Their inertia ensures that an ac system does not collapse due to system faults. During a fault, a balance of power between load consumption and generation is not maintained. The mechanical inertia of a turbine generator set ensures that its speed, and therefore the frequency of the system (except for some oscillation), has not changed substantially.

A typical steam turbine generator set may have an inertia constant H of 5 s based on the generator MVA rating. Assume that a generator operates at 0.9 power factor, so that the inertia constant H_p based on its MW rating is

$$H_p = \frac{5}{0.9} = 5.55 \text{ s}$$

Assuming that 2/3 of the power of an ac system is supplied by dc, then the inertia of the system referred to dc power would correspond to

$$H_{dc} = \frac{5.55}{2} = 2.77 \text{ s, based on dc infeed}$$

As is shown in the next subclause, an H_{dc} of 2.77 is usually adequate for satisfactory operation. It follows that the dc infeed must represent a very large proportion of the system power supply, before steps need to be taken to increase the inertia by addition of a synchronous compensator.

2.3.2 Infeed into a system without any generation

2.3.2.1 Calculation of frequency change

If all the power is brought into a system by dc (i.e., if there is no local generator), then that system will have no mechanical inertia (apart from the inertia of motor loads, which can initially be neglected). The inverters presently used in dc are line-commutated; i.e., they rely for their operation on the ac system providing adequate

sinusoidal voltage to achieve the commutation process. Therefore, a dc inverter supplying an “island system” must be provided with a synchronous compensator having inertia adequate to maintain the frequency and voltage at an acceptable level during system faults.

The relationship between change of machine frequency (df), mechanical power input (P_m), and electrical power output (P_e) for small changes of frequency can be represented by

$$df = \frac{(P_m - P_e) \times f_o \times dt}{2H} \quad (4)$$

Where f_o is the system nominal frequency and H is the conventional inertia constant of the machine expressed in MW·s/MVA of machine capacity, and P_m and P_e are in per unit of machine MVA rating.

If the inertia constant is converted to the base of dc power, it gives an effective inertia constant, H_{dc} .

$$H_{dc} = H \cdot \frac{\text{MVA rating of the machine}}{\text{MW rating of the dc system}} \quad (5)$$

giving from Equation (4)

$$df = \frac{p \times dt \times f_o}{2H_{dc}} \quad (6)$$

Where p is the per unit machine accelerating power ($P_m - P_e$) to the base of rated dc power.

It can therefore be seen that H_{dc} gives a measure of the inertial weakness of the system by relating the change of machine speed to the temporary energy imbalance ($p \cdot dt$) imposed by any given disturbance.

Temporary reduction of the power infeed by dc may be caused by the following typical events:

- a) A commutation failure lasting some 100 ms
- b) A fault in the sending ac system or in the receiving system that may last up to some eight cycles, depending on the backup breaker setting
- c) A dc line fault, which may be cleared by dc controls in 100–200 ms

From Equation (6)

$$H_{dc} = \frac{p \times dt \times f_o}{2df} \quad (7)$$

For a loss of power for, say, 200 ms, to allow for the breaker clearance time and for the fact that the dc power would not instantly recover to its rated level, it can be calculated from Equation (7) that H_{dc} to limit the frequency reduction to be, for example, 5%, will be equal to 2 s. It should be stressed that these values give only an approximate indication of the requirements.

Zero-inertia systems are further discussed in Clause 9.

2.3.2.2 Forced commutation

Feeding into a system without any generation of its own and without synchronous compensators is not possible with conventional, line-commutated inverters, but “forced commutation” is required and convertor circuits have been proposed. However, such schemes have not as yet been considered for actual projects.

2.3.2.3 Gate turn-off thyristors (GTOs)

Inverters using gate turn-off thyristors (GTOs), or similar devices, supplying power into a “dead load” have been used in industrial applications. However, so far, the application of these devices to dc transmission has not proved economical, but the promise is there.

2.4 Numerical examples of CSCRs and TOV_{fc} values

CSCRs and the fundamental component of the temporary overvoltage for an assumed impedance angle of $\phi = 80^\circ$ have been calculated for six cases of inverter operation with different equipment characteristics. For cases A, B, C, and D, it is assumed that $Q_c = Q_d$. For cases E and F, shunt capacitors are sized to provide some net vars to the ac system at the rated condition.

Case	Commutating reactance X_c %	Commutation margin γ (minimum)	Q_d	Q_c
A	12%	18°	0.5 P	0.5 P
B	15%	18°	0.54 P	0.54 P
C	20%	18°	0.6 P	0.6 P
D	20%	20°	0.63 P	0.63 P
E	12.6%	17°	0.5 P	0.875 P
F	20%	18°	0.6 P	0.875 P

Case	CSCR		CESCR*		CQESCR [†]	$\text{TOV}_{\text{fc}}^{\ddagger}$
A	1.87	-80°	1.37	-76.4°	0.91	1.43
B	2.01	-80°	1.47	-76.4°	0.95	1.42
C	2.2	-80°	1.6	-76.3°	1.0	1.40
D	2.25	-80°	1.62	-76.1°	0.99	1.41
E	2.24	-80°	1.37	-73.7°	0.91	1.39
F	2.47	-80°	1.60	-74.5°	1.0	1.39

NOTE—For these examples, commutating reactance = convertor transformer leakage reactance.

* Calculated by the equations in 2.5.

† Calculated from CESCR by adding the corresponding value of Q_c in pu of P_d .

‡ Calculated by Equation (27), which gives a theoretical value, as it does not include the transformer saturation effect.

The maximum difference between the cases are as follows (see also Figure 2-10):

CSCR	CESCR	CQESCR	TOV
32.0%	17%	10%	1.8%

It is clear that the value of MAP depends on the system impedance, shunt capacitor Mvar Q_c , and the reactive consumption of the inverter Q_d . For this reason, the variation in CSCR is the largest. CESCR takes into account the influence of Q_c and the difference in CESCRs is greatly reduced. CQSCR takes into account the value of both Q_c and Q_d . If QESCR is between 0.9 and 1.0, the operation is at or near MAP.

It is also interesting to note that the value calculated for TOV for all cases is around 1.4 pu. It can be shown that if the operation at MAP (i.e., at CSCR) is at unity power factor, then TOV_{fc} (for complete load rejection) is $k \cdot 2^{1/2}$ of the terminal ac voltage at MAP. The factor k has a value close to unity for typical ac system data (see also 3.1).

Even if the normal operation is at a γ larger than minimum, CSCR should be calculated for γ minimum, as that would represent the maximum obtainable power (MPC). However, TOV should be calculated using the normal (operating) γ , as the rated Q_d (not the one corresponding to minimum γ) will be rejected by the convertor in case of a fault.

CSCR, CESC, and CQESCR are plotted on Figure 2-10 against the commutating reactance X_c for values of $\gamma = 15^\circ$ and 20° , $\Phi = 70^\circ$ and 90° and for $Q_c/Q_d = 1.0$ and 1.5 .

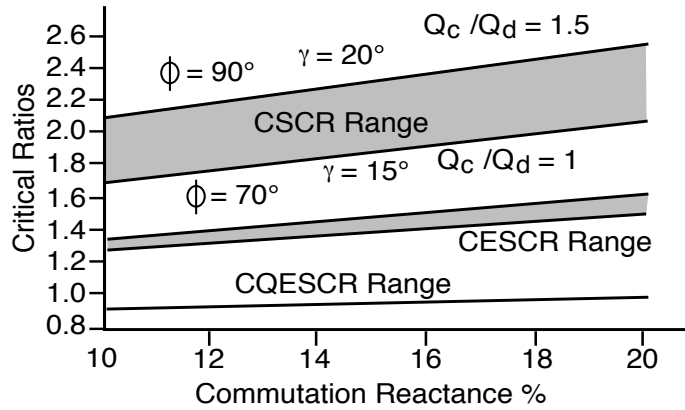


Figure 2-10—Sensitivity of CSCRs

2.5 Calculation of CSCRs

If the starting conditions ($P_d = 1.0$, $U_L = 1.0$, $I_d = 1.0$) coincide with the MAP of MPC (e.g., Figure 2-3 for $SCR = 2$), the corresponding SCR is termed “critical.”

For a simplified system representation (Figure 2-1), the critical ac system impedance can be calculated from the following equation:

$$CESCR = \frac{1}{U_L^2} \left[\sin \phi P_d \tan(\gamma + u) - Q_d + \sqrt{\left[\frac{P_d}{\cos(\gamma + u)} \right]^2 - \cos^2 \phi (P_d \tan(\gamma + u) - Q_d)^2} \right] \quad (8)$$

It should be noted that shunt capacitors must be assumed to be connected.

The value of CESC is little affected by the system damping in the range of 70° – 90° , and if system damping is neglected ($\phi = 90^\circ$ approximately), a good approximation is obtained by the following:

$$CESCR = \frac{1}{U_L^2} [-Q_d + P_d \cotan 1/2(90^\circ - \gamma - u)] \quad (9)$$

U_L is convertor bus ac voltage per unit,

Q_d is reactive power consumed by the inverter (per unit) [calculated from Equation (A.7), (A.11), or (A.13) in Annex A of Part I],

- P_d is active power supplied by the inverter to the ac system (per unit),
- γ is extinction angle of the inverter,
- u is overlap angle of the inverter [calculated from Equation (A.9) in Annex A of Part I],
- ϕ is angle of ac system impedance.

CSCR can be calculated by adding Q_c to Equation (9).

CESCR can also be calculated by considering the effect on the ac voltage of small var changes at the converter ac busbars. The magnitude of this effect can be judged by the voltage stability factor.

The voltage stability factor (VSF) is defined as the incremental ac voltage variation, dU_L , due to a small reactive power (dQ) injected into the commutation busbar for a given power level, i.e.,

$$\text{VSF} = \frac{dU_L}{dQ} \quad (10)$$

This index can be used for calculating the critical ratios for large systems using digital computer programs. VSF is a more general factor than CSCR and CESCR, and is also used in the study of ac systems. VSF also permits an approximate evaluation of the system dynamic behavior under small perturbations from a voltage oscillation point of view. VSF is plotted against ESCR in Figure 2-11. This figure assumes operation in the constant γ mode. A positive VSF indicates that the dc would operate, in constant γ mode, at currents smaller than I_{MAP} . A negative VSF indicates that the system would operate, in constant γ mode, at a dc current greater than I_{MAP} . The transition point of VSF as dc current changes gives the same criterion as the MAP concept and Equation (1) applies identically to both. It should be noted that a negative VSF indicates that the constant power control mode with constant γ would be unstable. However, in constant current control with constant γ , VSF has a positive value.

CSCRs can be calculated with adequate accuracy for planning considerations using the following simple equations derived from Equation (3):

$$\text{CESCR} = \text{CQESCR}(1 + Q_d) \quad (11)$$

and

$$\text{CSCR} = \text{CQESCR}((1 + Q_d) + Q_c) \quad (12)$$

where

Q_d and Q_c are in per unit of P_d .

From Figure 2-12, approximate values of CQESCR and Q_d can be obtained, and Q_c can be selected according to the desired reactive compensation.

Example 1, for average value of the commutating reactance $X_c = 15\%$: From Figure 2-12, CQESCR = 0.95; for $\gamma = 15^\circ$, $Q_d = 0.54$; and for $Q_c = Q_d$, the following value for CSCR is obtained from Equation (3):

$$\text{CSCR} = 0.95 * (1 + 0.54) + 0.54 = 2.0$$

Using the correct Equation (1) for $X_c = 15\%$, $\gamma = 18^\circ$, $Q_c = Q_d$, $\Phi = 80^\circ$, CSCR = 2.0.

Using the correct Equation (1) for $X_c = 15\%$, $\gamma = 20^\circ$, $Q_c = Q_d$, $\Phi = 70^\circ$, CSCR = 2.04.

Using Equation (12) and Figure 2-12, we also get CSCR = 2.04.

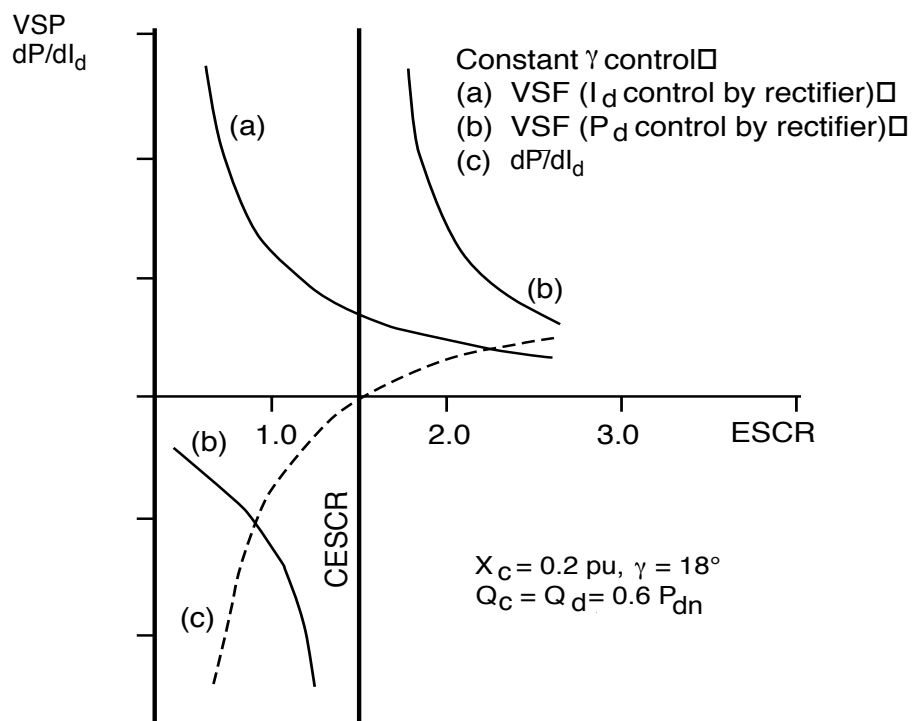


Figure 2-11—VSF and dP/dI_d as a function of the ESCR at nominal operating conditions and unity power factor

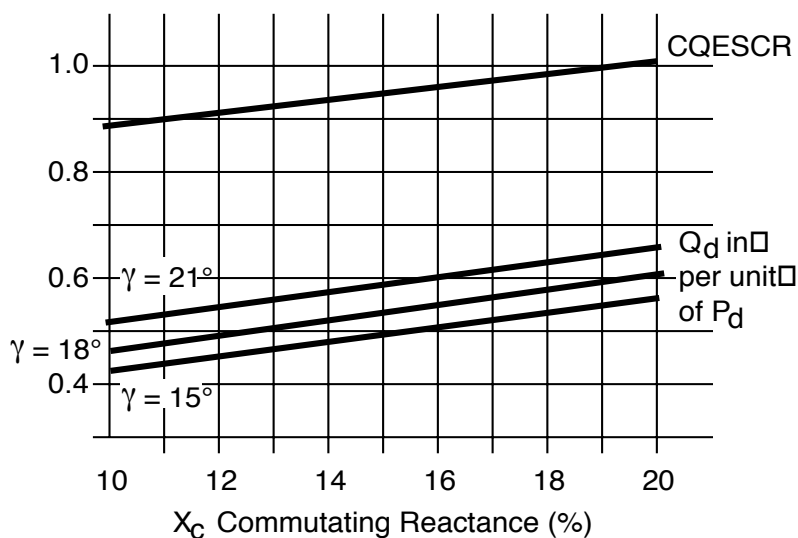


Figure 2-12—CQESCR and Q_d as a function of X_c

Example 2, for $X_c = 20\%$: From Figure 2-12, CQSCR = 1.0; and for $\gamma = 20^\circ$, $Q_d = 0.64$, for $Q_c = 1.5Q_d$:

$$\text{CSCR} = 1.0 * (1 + 0.64) + 0.96 = 2.6$$

Using the correct formula for $X_c = 20\%$, $\gamma = 20^\circ$, $\Phi = 70^\circ$, $Q_c = 1.5Q_d$, CSCR = 2.56.

Using the correct formula for $X_c = 20\%$, $\gamma = 15^\circ$, $\Phi = 70^\circ$, $Q_c = 1.5Q_d$, CSCR = 2.4.

Using Equation (12) and Figure 2-12, we also get CSCR = 2.04.

2.6 Numerical examples of power reduction due to ac system impedance increase and ac voltage reduction

As discussed in 2.2.4.5, power reduction due to a reduction of the terminal voltage is greater if the system impedance is increased at the same time.

Consider the case represented in Figure 2.6a and Figure 2-6b.

Initial conditions at SCR = 3.

System emf	I_d	U_L	U_d	P_d	γ	SCR
0.998	1.0	1.0	1.0	1.0	18°	3

a) Condition after the line trip, increases Z_s by 1/3.

0.998	1.0	0.93	0.92	0.92	18°	2
0.998	1.1	0.84	0.81	0.90	18°	2
0.998	0.96	0.97	0.96	0.93 (MAP)	18°	2

b) Condition after system emf reduces to give $U_L = 0.93$ at SCR = 3.

0.947	1.0	0.93	0.92	0.92	18°	3
0.947	1.1	0.89	0.87	0.96	18°	3
0.947	1.25	0.82	0.78	0.98(MAP)	18°	3

It can be seen that conditions immediately after system change and before dc current changes (i.e., at $I_d = 1.0$) are identical for the two cases, but in case a), I_{MAP} is at 0.96 pu, and in case b), it is at 1.25 pu of I_d . Operation at a current limit of, say 1.1 pu, would result in a power of 0.9 in case a) and 0.96 in case b).

A demand to maintain rated power (without, say, capacitor switching) at a specified minimum SCR for a sudden system change may not justify the increase in the extra cost of the converter equipment and the extra cost of losses. This is especially true if the particular system change is an uncommon event.

2.7 AC/DC system strength—summary tables

2.7.1 Power transfer and TOV

	MAP ⁽²⁾	TOV _{fc} (theoretical)
High SCR systems SCR > 3, ESCR > 2.5	$P_{\text{MAP}} > 1.1$	$1.25 < \text{TOV}_{\text{fc}}$
Low SCR systems $3 > \text{SCR} > 2$, $2.5 > \text{ESCR} > 1.5$	$P_{\text{MAP}} > 1.1$	$1.25 < \text{TOV}_{\text{fc}} < 1.4$
Very low SCR systems $2 > \text{SCR}$, $1.5 > \text{ESCR}$	(3)	$\text{TOV}_{\text{fc}} > 1.4$

2.7.2 CSCRs

CSCR = 2

CESCR = 1.47

CQESCR = 0.95

NOTES to 2.7.1 and 2.7.2:

1—The figures in 2.7.1 and 2.7.2 are based on assumed typical values of X_c (15%), $\gamma_{\min}$ (18°), and $Q_d = Q_c = 0.54 \cdot P_{dN}$.

If X_c and $\gamma_{\min}$ have higher values resulting in larger Q_d , then the theoretical division between high and low SCR systems would be at an SCR value higher than 3, and the division between low SCR and very low SCR systems would be at an SCR value higher than 2.

Similarly, values of ESCR, CSCR, or CESCR would have correspondingly higher values.

CQESCR would still have a value near unity; see Figure 2-10.

2— P_{MAP} represents the maximum power immediately available starting from nominal (rated) conditions (P_d , U_L , and I_d are all at one per unit, and $\gamma_{\min} = \text{const}$), without the use of fast ac voltage control.

3—The additional power available immediately, starting from nominal rated conditions, depends on the equipment design; i.e., the value of γ , or on the available range of TCR and SR.

2.7.3 Inadequate inertia systems

To avoid frequency reduction by more than 5% (i.e., 2.5 Hz for 50 Hz systems or 3 Hz for 60 Hz systems) due to a system fault, the effective dc inertia constant, H_{DC} , should be greater than 2 s.

3. DC power transfer limits

3.1 Description of phenomena

Considering the fundamental components of ac currents and voltages, a power system may exhibit two major types of instabilities:

- a) Phase angle instability and
- b) Voltage instability

The first of these is characterized by the fact that, after a disturbance, a generator or a group of generators loses synchronism with the rest of the system and line trips are executed by out-of-step relays or some other protection. The reason for the system to separate could either be that no new operating point exists (steady-state instability), or that the system cannot settle down to the new equilibrium point due to the kinetic energy injected into the rotors of the generators as a consequence of the fault (transient instability). The system could also become unstable due to inadequate damping. The time scale for this instability is typically in the region of a few to ten seconds. These matters are discussed further in Clause 7.

The voltage instability is characterized by the fact that the voltage at a certain bus or in a certain region of the network progressively decreases. (Usually it collapses, and this type of instability is often called voltage collapse.) The generator pole angles do not necessarily change significantly. (This is at least true during the initial stages of the breakdown. The voltage instability may cause protection to act, which could cause the system to become phase-angle unstable). The time scale for this instability may vary substantially, depending on different characteristics of the system. If tap-changers are involved, the process can extend over several minutes. The instability could develop much faster if, for example, tripping of a line or of a shunt capacitor bank results in sudden lack of voltage support, or some fast controllable devices play decisive roles in the dynamics of the system.

Extensive work is going on at present concerning the voltage collapse phenomenon as a consequence of a number of large breakdowns and disturbances that occurred in recent years and are believed to have been caused by voltage instabilities. No generally accepted method of analysis or description of the phenomenon exists for a generic system, but some general characteristics could be described by the following simple model.

Consider a load supplied by a strong network via a transmission line, as in Figure 3-1. For a given load, there exist in steady state two possible modes of operation: one with “high” voltage and “low” current, and one with “low” voltage and “high” current. Normally, the first of these two solutions is the desired one, since it gives lower losses and exhibits other properties that are attractive. If the voltage at the sending end is kept constant, curves as shown in Figure 3-2a are obtained for different power factors of the load. From these curves the following important observations can be made:

- There is a maximum possible load that can be supplied at a given power factor.
- For a given load smaller than the maximum, two different operating points exist corresponding to different voltage levels.

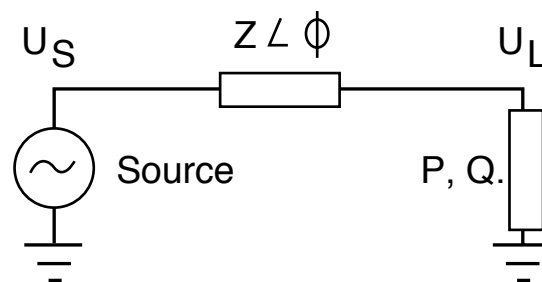


Figure 3-1 — Simplified ac system representation

Furthermore, a simple analysis shows that

- For operating points on the upper branch of the curve, $dU/dQ > 0$; and on the lower branch, $dU/dQ < 0$.
- If U_s is the voltage at the sending end it can be shown that $dU/dU_s > 0$ for points on the upper branch, whereas $dU/dU_s < 0$ on the lower branch.

The last two observations, together with the standard ways of controlling voltage in ac systems, lead to the fact that points on the upper branch are called stable and those on the lower branch are called unstable. The point corresponding to the maximum load is mathematically called a static bifurcation point. If a power larger than this maximum is demanded by a load device, the system cannot converge to any of the solutions that are given in Figure 3-2a. To predict the behavior of the system for such a case, the dynamic properties of the system are needed, such as load characteristics, tap-changer control, and generator/motor dynamics.

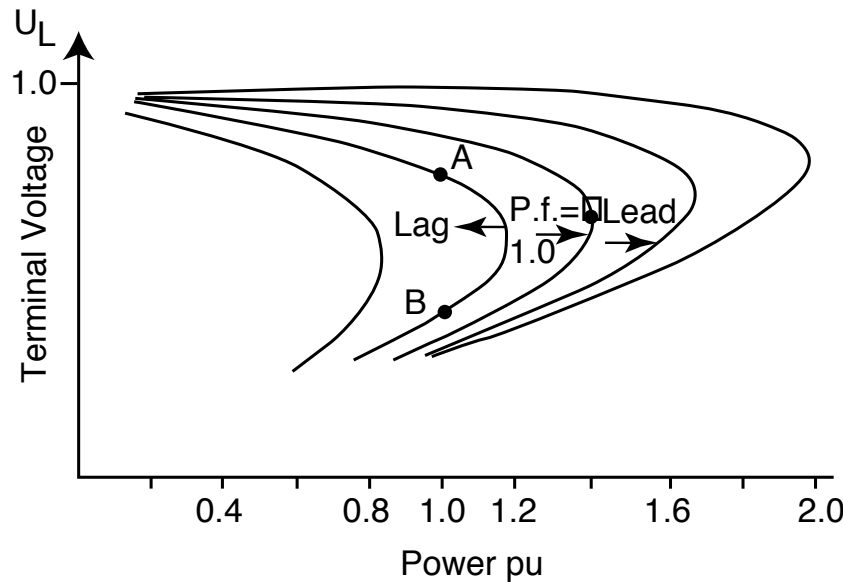


Figure 3-2a—Terminal voltage versus power for different load power factors

Consider the curve for unity power factor of Figure 3-2b for the case in which the small resistance of the ac line is neglected. It can be shown that for such a case, the terminal voltage, U_L , corresponding to the MAP, is related to the sending end voltage by the following equation:

$$U_L = \frac{U_s}{\sqrt{2}} \quad (13)$$

In the curves in Clause 2, dc power and ac terminal voltages are plotted as a function of dc current. From these curves it is seen that the ac terminal voltage is a monotonic decreasing function of dc current, and consequently there is a unique relationship between the dc current and the ac terminal voltage. Therefore, it is possible to plot the dc power as a function of the ac terminal voltage. Furthermore, if in such a plot the ac terminal voltage is on the y-axis and the dc power on the x-axis, the well-known ac voltage/power curve used in ac system analysis is obtained. Some of the curves shown as dc power versus dc current will be discussed below as ac voltage versus dc power.

The ac system impedance for Figure 3-2b was chosen to be equivalent to the system impedance of the inverter operation curve for SCR = 2 (ESCR = 1.46) of Figure 2-3. The ac voltage/power curve corresponding to Figure 2-3 for SCR = 2 is almost identical to that of Figure 3-2b. The reason for this is that in Figure 2-3, the power factor at $P_{dN} = 1.0$ pu is unity.

AC voltage and power from Figure 3-3 for SCR = 4.5 and from Figure 3-4 for SCR = 3 are plotted in Figure 3-2c. The main difference between the curves of Figure 3-2c and Figure 3-2a is that the former are calculated to give one per unit ac voltage at one per unit dc power, and those of the latter are calculated to

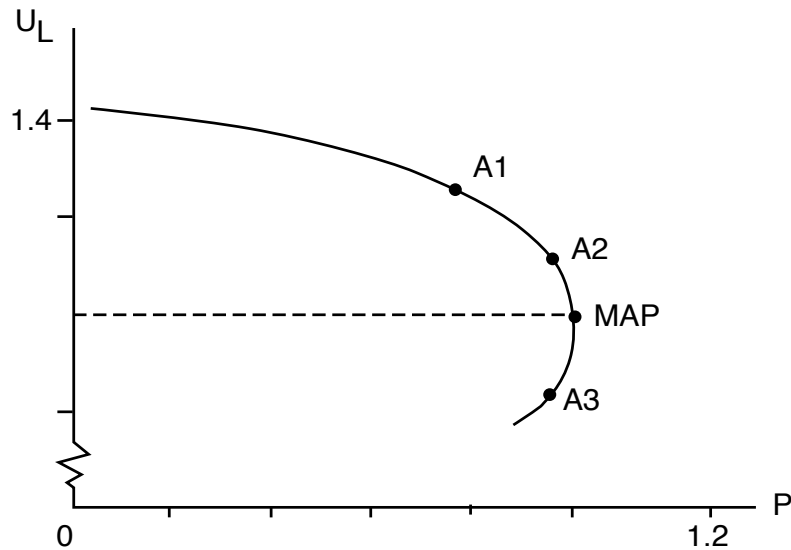


Figure 3-2b—AC voltage/power curve (unity load power factor)

give one per unit ac voltage at zero power; also, there are differences in system impedances in the former curves. However, curves corresponding to the operation of a dc converter are the same as those of an ac load having the same P and Q characteristics.

The third curve in Figure 3-2c corresponds to the curve for $SCR = 2$ of Figure 3-4. This curve is obtained by tripping one of the two parallel ac lines to which the inverter was connected (Figure 2-4) when operating at the point A of the curve for $SCR = 3$, as discussed in 2.2.4.2 and 3.2.2. It can be seen that the maximum power (MAP) of the curve, corresponding to the new condition, is lower than the power before the disturbance at point A. The attempt of the converter load to draw an increasing current, in order to maintain the original power, would result in voltage collapse, as already discussed.

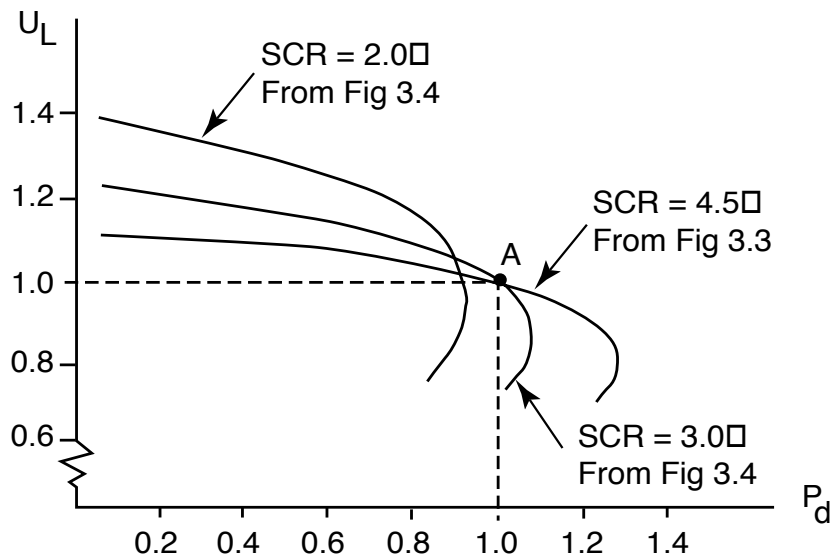


Figure 3-2c—AC voltage—dc power curves

An important factor, which differs in the dc case as compared with the pure ac configuration, is the controllability of the dc converter. As will be shown in this clause, unlike the general ac case, the converters can be controlled in such a way that voltage instability does not occur and that, moreover, the dc controls can further enhance the performance of the ac system. For these reasons, it is convenient to plot power against dc current, the controlled quantity, rather than against the voltage, but the phenomena are considered the same.

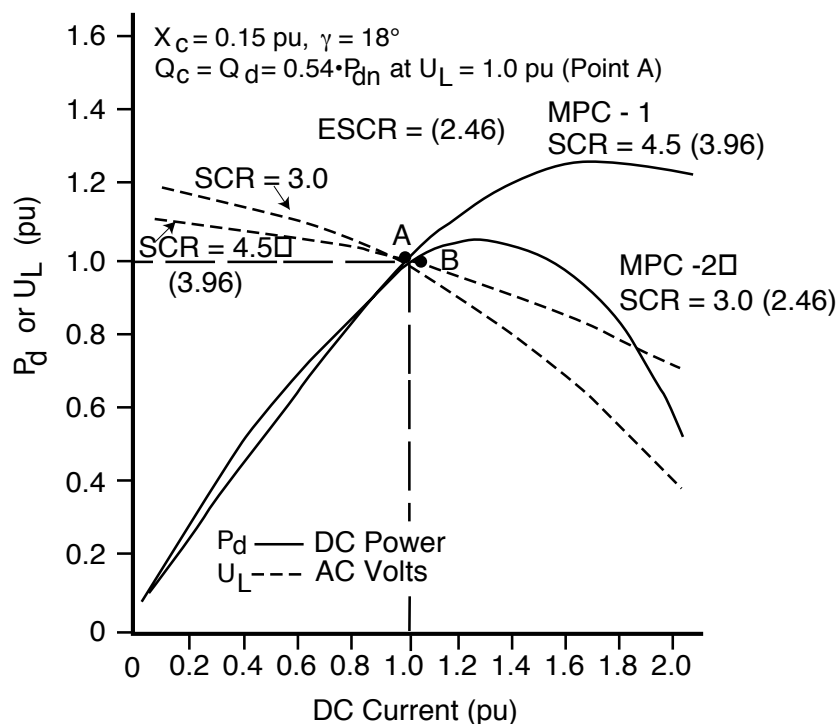


Figure 3-3—AC/DC system—high SCR, sudden change of SCR from 4.5 to 3.0

3.2 Power limits of an inverter

3.2.1 Power limits of an inverter connected to a high SCR ac system—with γ constant

The operating point of an inverter connected to an ac system having a high SCR, will be well below MAP; in Figure 3-3 an SCR = 4.5 has been assumed. In such cases, it is most economic to design the system so that the operating point is on the MPC for γ minimum. The operation at MPC is achieved while operating the inverter at a constant commutation margin having minimum γ value of, say, 15° (50 Hz), 18° (60 Hz). The dc voltage is maintained close to its rated value by the inverter transformer tap-changer

Operation at MPC (minimum γ) gives minimum cost due to the following factors:

- Minimum reactive power consumption
- Minimum ratings of valves, transformers, and shunt capacitors
- Minimum generation of harmonic currents
- Minimum losses

MPC can be suddenly reduced by a combination of the increase of the ac system impedance and of the reduction of terminal ac bus voltage, possibly due to a line trip in the ac system. Such a reduction of MPC is shown in Figure 3-3.

The pre-disturbance operation is with a system having $SCR = 4.5$. The operating point A corresponds to P_d , U_L , U_d , and I_d having the rated values of 1.0 pu. The commutating reactance is 15%, the inverter reactive consumption $Q_{dN} = 0.54 \cdot P_{dN}$. The nominal rating of shunt capacitors (including filters), Q_{cN} , is fixed and, at $U_L = 1$ pu, is equal to Q_{dN} . Operation is at minimum constant γ .

If, following an ac line trip, as discussed in 2.2.4.1, while operating at point A, the system impedance is increased by one-third corresponding to the sudden reduction of SCR from 4.5 to 3, the operation will be according to MPC-2 of Figure 3-3.

MPC-2 is also a quasi-steady-state curve, but for the new ac system conditions.

Assuming constant- γ control at the inverter, a decrease in the inverter ac voltage causes an immediate decrease in dc voltage. Assuming for the present that the HVDC master control at the rectifier is for constant power (which is not always the case), then it will increase dc current to maintain power at the set value, unless the current-limit setting in the rectifier is reached. It is still assumed that AVRs, circuit breakers controlling shunt capacitors, etc., and on load tap-changes (OLTCs) have not operated, as they are slow compared to dc current controls. MAP-2 in this case is higher than the rated power P_{dN} and the power has been maintained at its predisturbance level, at the new operating point B.

For details of numerical values see 3.9.

3.2.2 Power limits of an inverter connected to a low SCR ac system with γ constant

There are a number of schemes in service with SCR having an approximate value of three or lower, but higher than SCR equal to two, with normal operating point at MPC with constant γ at rated currents smaller than I_{MAP} (see 3.6.2). However, the operation is sufficiently near MAP-1 that a sudden, but relatively moderate, change in the ac system voltage may result in a MAP-2 being lower than the rated power. This event is illustrated in Figure 3-4. A similar event, as shown in Figure 3-3, has been assumed, except that the system impedance prior to the line trip corresponds to $SCR = 3$, and after the line trip to $SCR = 2$. The required power cannot be maintained, but the current limit imposed by the rectifier prevents the collapse of the system, despite the demand for higher power from the master controller.

The operating point B on MPC-2 will be in the region where dP_d/dI_d is negative and stable operation would not be achieved in power control mode, but stable operation continues in constant current control mode.

If the dc system is used to control ac frequency or to provide system damping, operation in the constant-current mode would not be acceptable except for a very brief period of time; e.g., while the fault is being cleared. Also, for these changes in ac system conditions, the power level may drop quickly to a lower value (determined by current limit) and also jump back to the original value if ac system conditions are suddenly restored. For possible steps to be taken to enhance performance in such cases, see 3.6.

For details of numerical values, see 3.9.

3.2.3 Power limit of an inverter connected to a very low SCR ac system with variable γ control

The operation at currents higher than I_{MAP} corresponds to operation at a point on the lower branch of a curve shown in Figure 3-2, which in ac transmission is considered the unstable part of the characteristics. In principle, it can be argued that it is the nature of the load that determines the stability. Assume that the load in Figure 3-1 is a static impedance load. If the impedance of the ac supply line is high, and if the inductive component of the load is high, the maximum power in Figure 3-2 would be relatively low and the operating point may be at the lower “unstable” part of the curve. An inverter connected to a high-impedance ac line operating at constant γ in the region where dP_d/dI_d is negative will be unstable if its controls demand an increasing current to keep the power constant. But if the controls are arranged to keep the current constant, stability can be achieved. However, any variation of ac voltage would directly cause variation of power that would not be acceptable for most applications.

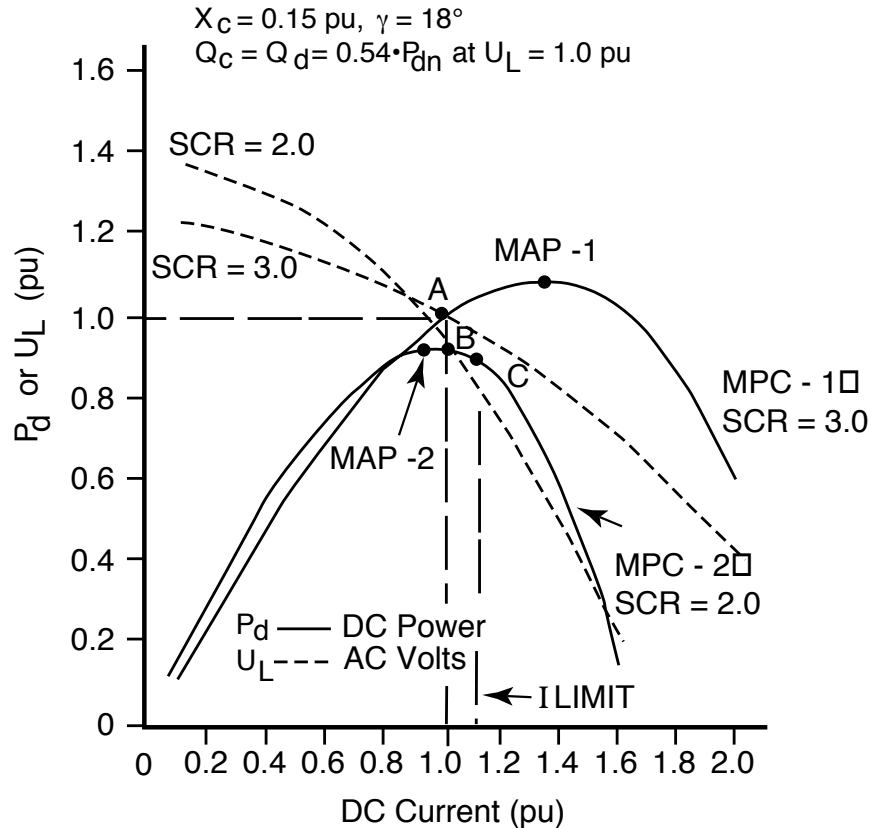


Figure 3-4—AC/DC system—low SCR power and ac voltage curves, sudden change of SCR from 3.0 to 2.0

An alternative control strategy, used in a number of schemes, is to control the dc voltage through inverter action by varying γ . The rectifier performs the same duty as in the previous case of controlling the dc current in order to achieve the desired power. An increase of γ increases var consumption and a decrease of γ reduces the var consumption. Therefore, in order to be able to increase ac voltage, as well as to reduce it, the inverter must be normally operating at a higher γ than the minimum.

Consider the four power curves in Figure 3-5. Normal operation is at point A with $\gamma = 25^\circ$, curve MPC-1. Commutating reactance X_C is 15%, as in the previous cases. The value of shunt capacitors is made equal to Q_d at $\gamma = 25^\circ$ at $U_L = 1.0 \text{ pu}$. It should be noted that normal operation at currents smaller than 1.0 are not practical due to the high voltage as explained in 2.2.3 and by Figure 2-3. For example, MAP-1 occurs at $I_{MAP} = 0.75 \text{ pu}$, $U_L = 1.4 \text{ pu}$, and $U_d = 1.5 \text{ pu}$. Therefore, for normal operation with ac systems having very low SCR at dc currents higher than I_{MAP} , the power transfer limit is lower than the power corresponding to MAP. In the example in Figure 3-5, the maximum transmittable power, before ac system conditions are changed, is obtained by reducing γ to its minimum value. In this example, at the minimum $\gamma = 18^\circ$, the point B is reached on MPC-2, which represents the maximum power that can be achieved from normal operating conditions by increasing current. The straight line O-A-B is the line of constant dc voltage. It should be noted that control of dc voltage, for operation with ac systems having very low SCRs, is not necessarily the only control strategy for operation at $I_d > I_{MAP}$. Controlling other quantities, such as ac voltage, reactive components of the inverter current, etc., could also be considered.

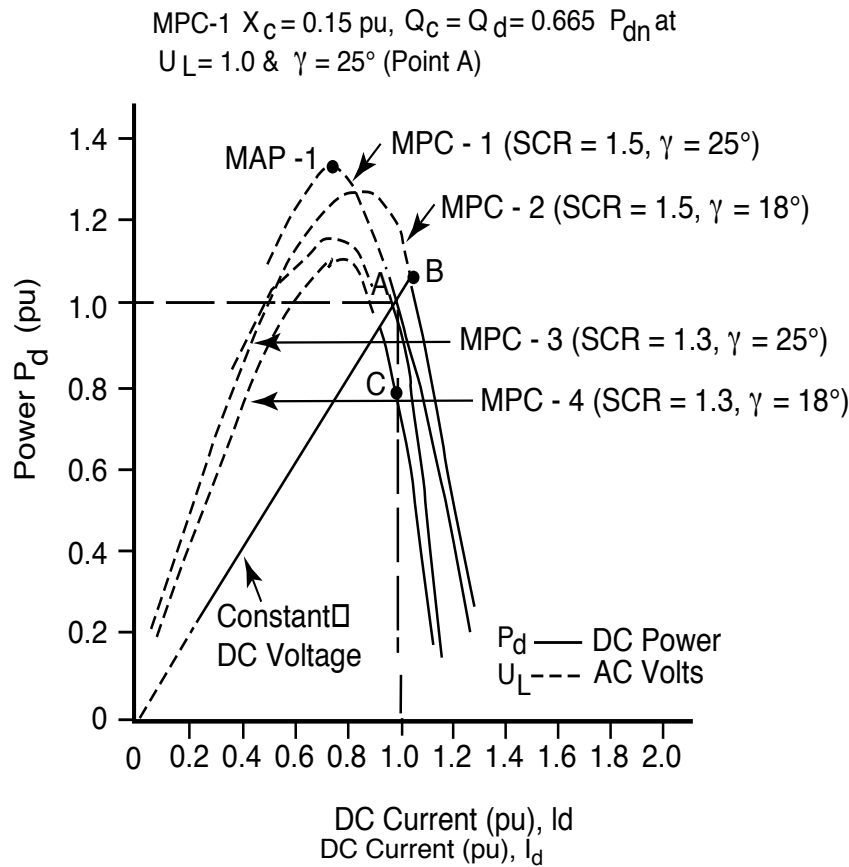


Figure 3-5—AC/DC system—very low SCR, sudden change of SCR from 1.5 to 1.3

Curve MPC-3 is obtained by assuming that an ac line has tripped, causing an increase in the system impedance by 13%. At $I_d = 1.0$, before a change of γ value, this would result in reductions of U_L to 0.81 pu, U_d to 0.8 pu, and P_d to 0.8 pu, point C on MPC-3. However, γ would instantly respond by reducing its value. In this example, this would result in restoring the power to 1 pu, with $U_L = 0.95$, $\gamma_d = 1.0$, and $I_d = 1.0$, at minimum $\gamma = 18^\circ$; i.e., point A on MPC-4.

The variable γ is maintained at its normal value, in the example considered at 25° by the inverter tap-changer and by shunt capacitor switching. For example, if the condition of MPC-4 persisted, additional shunt capacitors would be switched in order to increase the ac voltage and allow γ to return to a value near 25° . It must be stressed that, as in the previous cases, the controls must be stable during the period before capacitor switching in, for operation at γ minimum in the current control mode (at $dP_d/dQ < 0$).

The cost of the inverter designed for continuous operation at larger values of γ will be higher compared to the inverter designed for operation at minimum γ for the following reasons:

- Reactive power consumption will be greater.
- Valves, transformers, and shunt capacitors will have higher ratings.
- Generation of ac and dc harmonics will be higher.
- Convertor terminal losses will be higher.

The benefit of operating with variable γ is the ability to operate stably in the power control mode, for the design range of ac system variations, at dc currents larger than I_{MAP} , with ac systems having very low SCRs.

A further benefit is that, due to normal operation at γ larger than minimum, the probability of commutation failures would be reduced.

For details of numerical values, see 3.9.

3.2.4 Results from a transient stability program

As discussed in the previous subclauses, to determine the power limits of an inverter (or of a rectifier) “quasi-steady-state” power curves are used; i.e., each subsequent point is calculated by steady-state equations. These calculations are conveniently done by hand or, as in most cases of curves in this guide, by digital load-flow programs having adequate dc link representation. The statement that these quasi-steady-state curves give a good indication of dynamic performances was verified by using a transient stability program. The conditions of an inverter having data as used in the case of the power curve in Figure 3-4 for $\text{SCR} = 3$ has been used. The SCR of the rectifier was set to a very high value in order not to represent a limitation to the inverter performance. Results are shown in Figure 3-6. It should be noted that the particular controls used with this program allowed normal γ to reduce from 18° to an absolute minimum of 15° . Temporary reduction of γ allows a higher (short time) overload or maintenance of required power for a slightly greater voltage depression, at a risk of higher commutation failure probability. The power order was increased by 10% at time = 0.04 s. The current limit was set to a value of just over 1.3 pu in order to show the power increase to MAP and its subsequent reduction, despite the current increase. Soon after 0.1 s the current is reduced in response to ac voltage reduction, and so reduces the inverter var consumption. This is one of the methods used in practice to avoid ac voltage collapse. The analysis of the values of I_d , U_d , P_d , and γ indicates that these quantities are consistent with values achieved for Figure 3-4 for $\text{SCR} = 3$.

3.3 Power limits of a dc link

3.3.1 Introduction

In the preceding subclauses, the limits that an inverter may impose on the value of power transmitted were considered under the assumption that the rectifier operation will not be responsible for a lower limit. However, the rectifier is subject to the same limitations as the inverter; at increasing dc current the voltage will be reducing and the amount of control in hand depends on the value of α in normal operation. In this subclause, an example is given that takes into account both ends of the dc link. It has been assumed that the scheme is bidirectional and that the two ac systems have different values of SCRs. Either end may function as an inverter, but with differing operating strategies. Normal operation at $\gamma = 19^\circ$ (with absolute limit at $\gamma = 15^\circ$) was assumed for the ac system having a low SCR value (system X) and a variable γ strategy was assumed to control dc voltage for the other end, which has a very low SCR value (system Y). The effect of a 5% ac voltage reduction on power transfer was calculated.

3.3.2 Example data

	System X	System Y
ESCR	2.75	1.0
X_c	15%	14%

(ϕ was assumed to be 90° , as the resistive component has only a small effect on power calculation.)

Table 3-1 gives initial conditions. Power is assumed positive for the system X to system Y direction and it is assumed negative (marked with a minus sign), for the opposite direction.

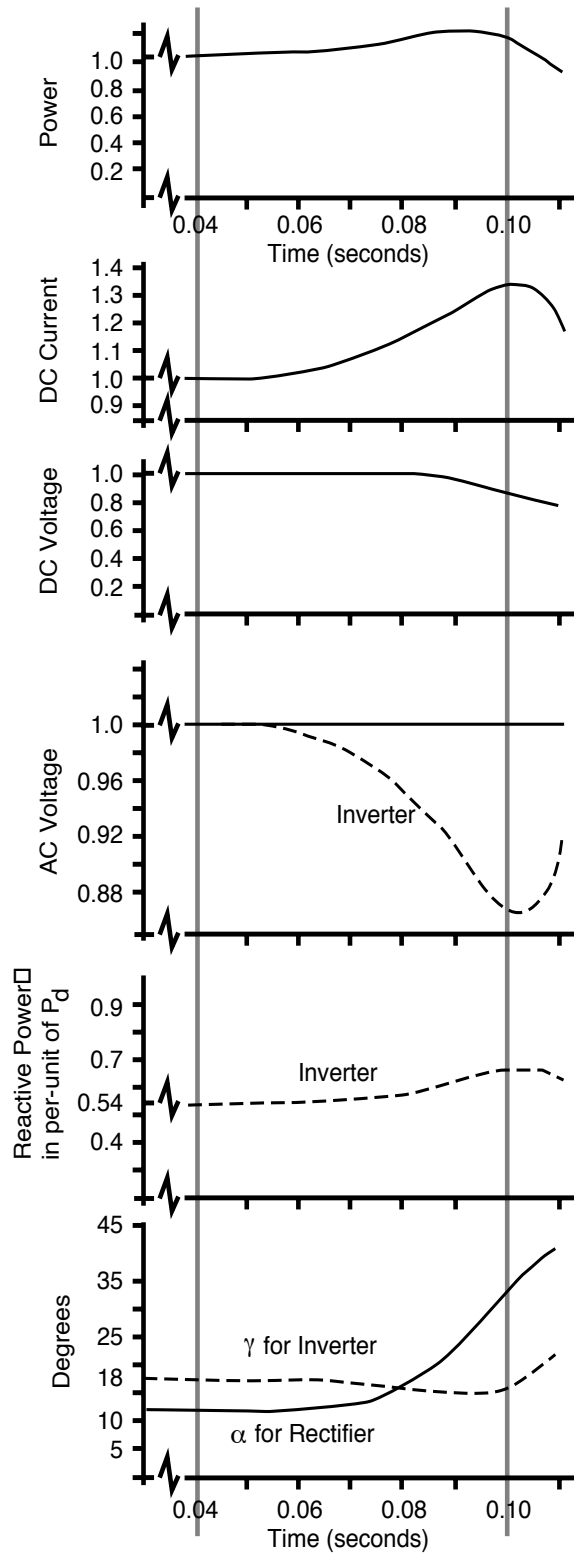


Figure 3-6—Results of transient stability program for a 10% increase of power order, applies at 0.04 s, $X = 0.15\%$, $Q_c = Q_d = 0.54P_d$, $\gamma = 18^\circ$ at $U_L = 1.0$

Table 3-1—Initial conditions

DC system data					System emf	
Case	U_{dc} pu	I_d pu	α (rectifier)	γ (inverter)	X	Y
A	1	1	12°	25°	1.047	1.169
*B	−1	1	12°	19°	1.047	1.101

*Power from Y to X.

3.3.3 Application of the disturbance

Voltage changes are specified as “changes of 5% of the nominal bus voltage.” It is therefore assumed here that the observed voltage change at the disturbed busbar is 5%, whatever the prime cause (e.g., a remote fault or loss of a line with negligible change in the value of the system impedance).

Table 3-2 summarizes the cases studied.

Table 3-2—Summary of cases studied

Case ref.	Power flow	System voltage depressed 5% at
A ₁	X–Y	X
A ₂	X–Y	Y
B ₁	Y–X	X
B ₂	Y–X	Y

3.3.4 Calculated solutions

Table 3-3 gives the calculated solutions. These are for the conditions after the convertor controls have settled (i.e., after about 100 ms) but before tap-changers or capacitors have switched. The “remote busbar” is the convertor busbar not subjected to the initial voltage depression.

Table 3-3—Calculated solutions after voltage depression

Case	Power pu	AC voltage on the remote busbar	U_{dc} pu	I_d pu	α (rectifier)	γ (inverter)
A ₁	0.970	0.990	0.970	1	3°	26.7°
A ₂	1	1	1	1	12°	18.4°
*B ₁	0.969	0.969	−0.962	1.039	10.5°	15°
*B ₂	0.972	0.997	−0.972	1	3°	21.9°

*Power from Y to X.

3.3.5 Comments on individual cases

For cases A₁ and B₂, the rectifier α reaches its minimum of 3° and the inverter takes over control of current (and power) by increasing its γ , which increases its reactive power consumption—hence reducing its ac busbar voltage.

For case B₁, a combination of the reduction of γ to 15° and the increase of dc current to 1.039 pu successfully restores power to 1.0 pu.

Power is reduced by up to 3% for cases A₁ and B₂; otherwise, power control is maintained (except for a brief dip until the master control takes effect). This is because the master power control output (current order) reaches the sliding current limit (refer to 3.6.2.1), which, for a power order of 1 pu, limits dc current to 1.05 pu if the rectifier is still in control or to 1 pu if the inverter is in control.

The ac voltage on the “remote” busbar is only slightly depressed in all cases, with a maximum of 3.1% (case B₁).

The results in Table 3-3 are to some extent a compromise, because they depend on the values used for the current limits (1.05 and 1.0 as described above). For example, an increase in current limit by .05 pu for case A₁ would cause the power to be maintained at 1 pu (instead of 0.97 pu) but with a larger reduction of remote ac voltage—by 3.2% instead of 1%. In other cases, an increase in current limit would actually reduce power, with a further voltage depression, and would therefore be pointless.

In practice, the capacitor switching and tap-changer control would restore the desired conditions.

3.3.6 Rectifier connected to a very low SCR ac system

The main consideration in this guide is given to the conditions at the inverter of a dc link terminating at locations having low short-circuit capacity. However, particular attention must be given to the case in which the rectifier ac/dc system has a very low SCR.

In ac/dc systems having a very low SCR, it is essential to have fast control of the voltage. If the dc link itself is used to provide this fast control, the inverter is the voltage-controlling convertor. One common method is to control for constant dc voltage, which indirectly exerts a control on the ac voltage. In back-to-back systems, if the ac voltage at either end rises to a predetermined value, an ac voltage loop takes over to control ac voltage directly, operating through the inverter control system.

If there is a dc line between the rectifier and the inverter and the rectifier ac/dc system has a high SCR value and the inverter has a low or very low SCR value, the system will operate well, as the inverter controls dc and ac voltages local to the very low ac/dc system. However, if the rectifier ac/dc system has a very low SCR value, the inverter will not be very effective in quickly controlling the dc voltage at the rectifier end, and therefore its ac voltage (due to the inductance and the capacitance of the dc line), even if the telecommunication were to be very fast. There are examples of back-to-back schemes where both ac systems have low or very low SCRs. On the other hand, it is difficult to visualize a practical case where power would be supplied from a very low SCR ac/dc system over a transmission line. However, the application of a fast compensator at the rectifier ac system would enable operation even in such a case. Of course, there is always the option of strengthening the ac system (2.2.6).

Using only the inverter to provide fast voltage control in back-to-back schemes where both ac/dc systems have very low SCR values may have some limitations. If both ac systems exhibit frequent and fast ac voltage variations, inverter voltage control, coupled with automatic capacitor and inductor switching at the two ac bus-bars, may not always provide acceptable performance. In such cases, consideration should be given to improving the conditions of one of the two ac systems. This can be done by providing fast ac voltage control by an independent compensator (2.2.7.1) or by strengthening one of the ac systems (2.2.6).

3.4 Principal parameters

For ac/dc systems having low and very low SCRs, the ac voltage stability at the terminals of the convertor station has to be fully analyzed and studied. Such a phenomenon can be responsible for the ac voltage excursions during steady-state as well as dynamic operation of the dc scheme. Fault recovery performance, temporary overvoltages, and overall ac/dc system transients and dynamic stabilities are also closely tied to the ac voltage stability phenomenon.

The solution(s) adopted to alleviate such a problem stem from the following parameters, which directly influence the severity of such a phenomenon:

- a) AC system impedance (fundamental frequency)
- b) Rated dc power
- c) Rated reactive power (which depends on commutating reactance and on α and γ)
- d) Range of acceptable ac voltage regulation
- e) Level of var compensation
- f) DC control strategy

For a given system impedance and other system parameters shown in Figure 2-1, there will be a unique P_d/I_d characteristic for operation at γ minimum (constant), which will represent the maximum power curve.

3.5 Trends and sensitivities of system parameters

3.5.1 AC system impedance

The closer that the system impedance approaches that corresponding to the CSCR, the greater the probability that the operation may take place at currents larger than the I_{MAP} .

The curves of constant MAP have been drawn in Figure 3-7 [see B11⁴] for different values of system admittances and for three different values of ac terminal voltage. For a system impedance having the angle $\phi = 90^\circ$, ESCR has the numerical value of the susceptance B, and for a system impedance having the angle $\phi = 0^\circ$, ESCR has the numerical value of the conductance G. It can be seen that the value of MAP, and therefore of CSCR, does not vary much for system impedance angles in the practical range of, say, $\phi = 70^\circ$ to $\phi = 85^\circ$, which means that the simpler Equation (9) given in 2.5 can be normally used.

The variation of the terminal ac voltage was achieved by varying the emf behind the ac system impedance without varying the value of impedance, in order to indicate the effect of ac voltage on MAP. In practice, a disturbance, such as an ac line trip, would result in a change of both impedance and terminal voltage values.

3.5.2 Convertor reactive power consumption

It was shown in Clause 2 that QESCR gives a better indication of ac/dc system operation, because it takes into account the convertor reactive power consumption (Q_d). The values of CSCR and CESCR will be higher for higher values of Q_d . This means that the higher the Q_d , the lower the value of MAP, and hence of power transfer for the same values of SCR and ESCR. A value of QESCR equal to about 0.95 indicates that the operation is near MAP (see 2.4).

⁴The numbers in brackets correspond to those of the bibliography in Annex B of Part I.