

Australian Standard™

Semiconductor converters

Part 1.2: General requirements and line commutated converters—Application guide



This Australian Standard was prepared by Committee EL-027, Power Electronics. It was approved on behalf of the Council of Standards Australia on 4 June 2002 and published on 4 July 2002.

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Australian Electrical and Electronic Manufacturers Association
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STANDARDS AUSTRALIA

RECONFIRMATION

OF

AS 60146.1.2—2002

Semiconductor converters

Part 1.2: General requirements and line commutated converters—Application guide

RECONFIRMATION NOTICE

Technical Committee EL-027 has reviewed the content of this publication and in accordance with Standards Australia procedures for reconfirmation, it has been determined that the publication is still valid and does not require change.

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NOTES

Australian Standard™

Semiconductor converters

Part 1.2: General requirements and line commutated converters—Application guide

Originated as part of AS 1995.1—1977.
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PREFACE

This Standard was prepared by the Standards Australia Committee EL-027, Power Electronics to partially supersede AS 1955.1—1977, *Semiconductor converters*, Part 1: *General* six months after publication.

The objective of this Standard is to provide designers, manufacturers and users with information on extending the requirements of AS 60146.1.1 to special cases and types of line commutated converters.

This Standard is the second of a three part Standard; the parts of which are as follows:

AS 60146	Semiconductor converters
AS 60146.1.1	Part 1.1: General requirements and line commutated converters—Specifications of basic requirements
AS 60146.1.2	Part 1.2: General requirements and line commutated converters—Application guide (this Standard)
AS 60146.1.3	Part 1.3: General requirements and line commutated converters—Transformers and reactors

This Standard is technically identical with, and has been reproduced from, IEC 60146-1-2:1991, *Semiconductor converters—General requirements and line commutated converters*, Part 1-2: *Application guide*. Minor editorial changes have been made to the text such as the use of the word ‘converter’ throughout the document (to standardize spelling across this series of Standards).

A reference to an International Standard identified in the Bibliography by strikethrough (~~example~~) is replaced by a reference to the Australian or Australian/New Zealand Standard(s) listed immediately thereafter and identified by shading (**example**). Where the struck-through referenced document and the referenced Australian or Australian/New Zealand Standard are identical, this is indicated in parenthesis after the title of the latter.

In January 1997, the IEC commenced numbering its Standards from 60000 by adding 60000 to the number of each existing Standard. This coordinates IEC numbering with ISO numbering. During the transition period an IEC Standard might be identified by its new number or its old number (for example, IEC 60050 or IEC 50).

As this Standard is reproduced from an International Standard, the following applies:

- (a) Its number does not appear on each page of text and its identity is shown only on the cover and title page.
- (b) In the source text ‘this International Standard’ should read ‘this Australian Standard’.
- (c) A full point should be substituted for a comma when referring to a decimal marker.

The term ‘informative’ has been used in this Standard to define the application of the annex to which it applies. An ‘informative’ annex is only for information and guidance.

CONTENTS

Clause		<i>Page</i>
	Section 1 - General	
1.1	Scope	1
1.2	Application of semiconductor power converters.....	1
1.2.1	Conversion equipment.....	1
1.2.2	Supply source conditioning (active and reactive power).....	2
1.3	Equipment specification data	2
1.3.1	Main items of the specification.....	2
1.3.2	Additional information.....	2
1.3.3	Unusual service conditions	3
1.4	Converter transformers and reactors.....	3
1.5	Calculation factors	3
1.5.1	Voltage ratios	3
1.5.2	Line side transformer current factor	4
1.5.3	Valve-side transformer current factor.....	4
1.5.4	Voltage regulation	4
1.5.5	Magnetic circuit	7
1.5.6	Power loss factor.....	7
1.6	Parallel and series connections.....	7
1.6.1	Parallel or series connection of valve devices.....	7
1.6.2	Parallel or series connection of assemblies and equipment units.....	7
1.7	Power factor	8
1.7.1	General	8
1.7.2	Symbols used in the determination of displacement factor	9
1.7.3	Circle diagram for the approximation of the displacement factor $\cos \varphi_{1N}$ and of the reactive power Q_{1LN} for rectifier and inverter operation.....	10
1.7.4	Calculation of the displacement factor $\cos \varphi_1$	10
1.7.5	Conversion factor	12
1.8	Direct voltage regulation	13
1.8.1	Inherent direct voltage regulation	13
1.8.2	Direct voltage regulation due to a.c. system impedance.....	15
1.8.3	Information to be exchanged between supplier and purchaser about direct voltage regulation of the converter	18
1.9	Voltage limits for reliable commutation in inverter mode.....	18
1.10	A.C. voltage waveform	19

Section 2 - Definitions

2.1	Definitions related to converter faults.....	21
2.1.1	Conduction through (shoot through) (IEV 551-05-58, modified).....	21
2.1.2	Firing failure (IEV 551-05-57, modified)	21
2.1.3	Breakthrough (IEV 551-05-53, modified).....	21
2.1.4	Breakdown (IEV 551-05-59, modified)	21
2.1.5	False firing (IEV 551-05-56, modified)	21
2.1.6	Commutation failure (IEV 551-05-52, modified)	21
2.2	Definitions related to converter generated transients.....	21
2.2.1	D.C. side transients	21
2.2.2	Commutation transients on the line (repetitive transients).....	21

Section 3 - Application information

3.1	Practical calculation of the operating parameters	23
3.1.1	Assumptions.....	23
3.1.2	Preliminary calculations.....	23
3.1.3	Calculation of the operating conditions	24
3.2	Supply system voltage change due to converter loads	26
3.2.1	Fundamental voltage change.....	26
3.2.2	Minimum R_{SC} requirements for voltage change	27
3.2.3	Converter transformer ratio.....	27
3.2.4	Transformer rating	28
3.3	Compensation of converter reactive power consumption	29
3.3.1	Average reactive power consumption	29
3.3.2	Required compensation of the average reactive power	29
3.3.3	Voltage fluctuations with fixed reactive power compensation	30
3.4	Direct voltage harmonic content.....	30
3.5	Supply voltage distortion.....	31
3.5.1	Commutation notches.....	31
3.5.2	Operation of several converters on the same supply line	33
3.6	Quantities on the line side.....	34
3.6.1	R.M.S. value of the line current	34
3.6.2	Harmonics on the line side, approximate method for 6-pulse converters ...	35
3.6.3	Minimum R_{SC} requirements for harmonic distortion	36
3.6.4	Calculation of the harmonic current spectrum	37
3.6.5	Estimated phase shift of the harmonic currents.....	39
3.6.6	Addition of harmonic currents	39
3.6.7	Peak and average harmonic spectrum	39
3.6.8	Transformer phase shift.....	39
3.6.9	Sequential gating, two 6-pulse converters	40

	<i>Page</i>
3.7 Power factor compensation and harmonic distortion.....	40
3.7.1 Resonant frequency.....	40
3.7.2 Directly connected capacitor bank	40
3.7.3 Estimation of the resonant frequency.....	41
3.7.4 Detuning reactor	42
3.7.5 Ripple control frequencies (Carrier frequencies)	43
3.8 Other considerations.....	43
3.8.1 Random control angle.....	43
3.8.2 Sub-harmonic instability	44
3.8.3 Harmonic filters	44
3.8.4 Approximate capacitance of cables.....	44
3.9 Calculation of d.c. short-circuit current of converters.....	44
3.10 Guide-lines for the selection of the immunity class.....	45
3.10.1 Converter immunity class	45
3.10.2 Selection of the immunity class.....	45

Section 4 - Test requirements

4.1 Guidance on power loss evaluation by short-circuit test	49
4.1.1 Single-phase connections.....	49
4.1.2 Polyphase double-way connections	49
4.1.3 Polyphase single-way connections	49
4.2 Procedure for evaluation of power losses by short-circuit method	49
4.3 Test methods.....	50
4.3.1 Method A1.....	50
4.3.2 Method B.....	51
4.3.3 Method C.....	51
4.3.4 Method D.....	51
4.3.5 Method E.....	53
4.3.6 Method A2.....	54

Section 5 - Performance requirements

5.1 Presentation of rated peak load current values	55
5.2 Definitions and letter symbols related to virtual junction temperature	56
5.2.1 Letter symbols.....	56
5.2.2 Thermal resistance R_{th}	57
5.2.3 Transient thermal impedance Z_{th}	57
5.2.4 Virtual junction temperature Θ_j	57

	<i>Page</i>
5.3 Determination of peak load capability through calculation of the virtual junction temperature	57
5.3.1 Approximation of the shape of power pulses applied to the semiconductor device	58
5.3.2 The superposition method for calculation of temperature	59
5.3.3 Calculation of the virtual junction temperature for continuous load.....	59
5.3.4 Calculation of the virtual junction temperature for cyclic loads	61
5.3.5 Calculation of virtual junction temperature for a few typical applications ...	62
5.4 Circuit operating conditions affecting the voltage applied across converter elements.....	62
 Section 6 - Converter operation	
6.1 Stabilization	64
6.2 Static properties.....	64
6.3 Dynamic properties of the control system.....	64
6.4 Mode of operation of single and double converters	64
6.4.1 Single converter connection.....	64
6.4.2 Double converter connections and limits for rectifier and inverter operation	66
6.5 Transition current.....	67
6.6 Suppression of direct current circulation in double converter connections	68
6.6.1 Limitation of delay angles	68
6.6.2 Controlled circulating current.....	68
6.6.3 Blocking of trigger pulses	68
6.7 Principle of operation for reversible converters for control of d.c. motors	69
6.7.1 Motor field reversal.....	69
6.7.2 Motor armature reversal by reversing switch.....	69
6.7.3 Double converter connection to motor armature.....	69
 Section 7 - Converter faults	
7.1 General.....	71
7.2 Fault finding.....	71
 Annex	
A Bibliography.....	72

Figures

1	Circle diagram for approximation of the displacement factor	10
2	Displacement factor as a function of d_{xN} for $p = 6$	11
3	Displacement factor as a function of d_{xN} for $p = 12$	11
4	d_{LN} as a function of d_{xN} for $p = 6$ and $p = 12$	17
5	AC voltage waveform	20
6	Voltages at converter faults	22
7	Harmonic current spectrum on the a.c. side for $p = 6$	38
8	Influence of capacitor rating and a.c. motor loads on the resonant frequency and amplification factor	41
9	Example of power distribution	47
10	Test method A1	50
11	Test method D	52
12	Single peak load	55
13	Repetitive peak loads	56
14	Approximation of the shape of power pulses	59
15	Calculation of the virtual junction temperature for continuous load	60
16	Calculation of the virtual junction temperature for cyclic loads	61
17	Circuit operating conditions affecting the voltage applied across converter elements	63
18	Direct voltage waveform for various delay angles	65
19	Direct voltage for various loads and delay angles	66
20	Direct voltage limits in inverter operation	67
21	Direct voltage at values below the transition current	68
22	Operating sequences of converters serving a reversible d.c. motor	70

Tables

1	Connections and calculation factors.....	5
2	Per unit value of I_L^* as a function of delay angle (α) and overlap angle (u).....	35
3	Minimum R_{SC} requirement for low voltage systems	37
4	Transformer phase shift and harmonic orders	39
5	Approximate kVar/km of cables	44
6	Short-circuit values of converter currents	45
7	Calculated values for the example in figure 9	48
8	Virtual junction temperature	62

STANDARDS AUSTRALIA

Australian Standard**Semiconductor converters****Part 1.2: General requirements and line commutated converters—Application guide**

Section 1 - General**1.1 Scope**

This report gives guidance on variations to the specifications in IEC 146-1-1 to enable the specification to be extended in a controlled form for special cases. Background information is also given on technical points which should facilitate the use of IEC 146-1-1.

This report primarily covers line commutated converters and is not in itself a specification, except as regards certain auxiliary components, in so far as existing standards may not provide the necessary data.

1.2 Application of semiconductor power converters

Semiconductor power converters are used in most industries for the conversion of electrical power and also to facilitate the conversion of thermal or mechanical energy into electrical power and vice versa.

Examples:

1.2.1 Conversion equipment

- a) d.c. load, stabilized/adjustable voltage/current control;
- b) a.c. power controllers (a.c. or d.c. output);
- c) a.c. variable frequency: line-commutated converters;
 slip energy recovery;
 machine-commutated converters;
 self-commutated converters: voltage source;
 current source;
- d) adjustable speed drives (covered by specific IEC standards);
- e) chemical processes (electrolysis, electroplating, electrophoresis);
- f) computer power supplies;
- g) traction substations, railways, tramways, mines, electric vehicles;
- h) telephone power supplies;
- i) electromagnets, field supplies;
- j) radio transmitter d.c. supplies;
- k) plasma torches;
- l) arc furnace d.c. power supplies;
- m) solar energy conversion;
- etc.

1.2.2 Supply source conditioning (active and reactive power)

- a) HV or MV systems (transport and distribution, in-plant P.F. correction);
- b) LV systems (energy saving);
- c) Isolated or standby generating plant;
- d) D.C. or a.c. supply particularly from solar, wind or chemical energy.

NOTE - Some of the applications listed above are the subject of particular IEC Publications now existing or in preparation.

1.3 Equipment specification data

1.3.1 Main items of the specification

See 3.11.4 of IEC 146-1-1: Rating plate.

1.3.2 Additional information

In addition to the essential data such as should appear on the rating plate as specified in IEC 146-1-1, the following list may prevent other important information being omitted from the specification, concerning the purchaser's requirements or the supplier's product.

1.3.2.1 Supply source

- a) Voltage and frequency (if applicable); Range of rated values, unbalance, short time outage;
- b) Short-circuit power (or description of cables, lines and transformers): minimum, statistical average, maximum values;
- c) Other existing loads (motors, capacitors, furnaces, etc.);
- d) Limits of disturbances (prevailing or permitted);
- e) Type of earthing.

1.3.2.2 Output specification

- a) Output voltage and frequency (if applicable);
- b) Required range of variation (continuous or stepwise);
- c) Voltage and/or current reversing capability (quadrant(s) of operation);
- d) Limits of permitted voltage/current/frequency variation;
- e) Character of load;
- f) Type of earthing.

1.3.2.3 Environment specification

- a) Temperate, tropical, arctic climates;
- b) Temperature, humidity, dust content (unless IEC 664, degree 1, is applicable);
- c) Unusual service conditions;
- d) Outdoor/indoor installation;
- e) Protection class (according to IEC standards);
- f) Compliance with specific standards (IEC or others, including safety standards).

1.3.2.4 Electrical service conditions

- a) Supply bus category:
- converter dedicated system (converters only);
 - general purpose system (includes a.c. motor loads);
 - high quality system (supplying loads with low immunity level such as computers, medical instrumentation etc.);
- b) Immunity class of the equipment: a different immunity class may be selected for one or more parameters.

1.3.3 Unusual service conditions

1.3.3.1 Abnormal temperature conditions

The preferred values of specified ambient temperature conditions are given in IEC 146-1-1, 2.2.2 to 2.2.2.1.

For cases where special conditions have to be considered the following is applicable:

- a) different cooling medium temperatures may be specified for the assemblies and for the converter transformer. The values of cooling medium temperatures relating to the transformers are given in IEC 146-1-3 and those relating to assemblies are given in IEC 146-1-1;
- b) the maximum and the minimum ambient temperatures or the cooling medium temperature may be specified by the purchaser or by the supplier.

1.3.3.2 Dust and solid particle content

For particular applications the degree of pollution may be specified separately, according to IEC 664 or other relevant IEC Publications, for example specifying pollution classes other than degree 1 as specified in IEC 664.

1.4 Converter transformers and reactors

See IEC 146-1-3.

1.5 Calculation factors

See table 1. For letter symbols and definitions refer to 1.4, 1.5 of IEC 146-1-1 and 1.7.2, 1.8.1.4 of this report.

1.5.1 Voltage ratios

Table 1 gives the ratios:

column 10

column 11

$$\frac{U_{di}}{U_{v0}}$$

$$\frac{U_{iM}}{U_{di}}$$

where:

U_{di}	ideal no-load direct voltage;
U_{v0}	transformer valve winding voltage;
U_{iM}	ideal crest no-load voltage, appearing between the end terminals of an arm neglecting internal and external voltage drops in valves, at no load. The ratio remains the same at light load current close to the transition current.

NOTE - For connections Nos. 5, 11 and other connections employing interphase transformers, the ratio U_{iM}/U_{di} increases at no-load.

1.5.2 Line side transformer current factor

The quotient of the r.m.s. value I'_L of the current on the line side and the direct current I_d is indicated in table 1, column 8, on the assumption of smooth direct current, rectangular waveshape of the alternating currents and on the following voltage ratio for single or double-way connections:

$$\frac{\text{phase-to-phase voltage on line side}}{\text{voltage between two commutating phases on valve side}} = \frac{U_L}{U_{v0}} = 1$$

For different values of the voltage ratio, the line side current is approximately:

$$I_L = I'_L \times \frac{U_{v0}}{U_L}$$

NOTE - For connections 14 and 15, the line side current factor depends on the delay angle α as follows:

$$0 < \alpha < \frac{\pi}{3}; \quad \frac{I'_L}{I_d} = \sqrt{\frac{2}{3}} \approx 0,816$$

$$\frac{\pi}{3} < \alpha < \pi; \quad \frac{I'_L}{I_d} = \sqrt{\frac{\pi - \alpha}{\pi}}$$

1.5.3 Valve-side transformer current factor

The quotient of the r.m.s. value I_v of the valve-side current in each terminal of the transformer and the direct current I_d is indicated in table 1, column 9.

NOTE - For connections 14 and 15, the valve-side current factor depends on the delay angle α as follows:

$$0 < \alpha < \frac{\pi}{3}; \quad \frac{I_v}{I_d} = \sqrt{\frac{2}{3}} \approx 0,816$$

$$\frac{\pi}{3} < \alpha < \pi; \quad \frac{I_v}{I_d} = \sqrt{\frac{\pi - \alpha}{\pi}}$$

1.5.4 Voltage regulation

Table 1, column 12, gives the ratio:

$$\frac{d_{xtN}}{e_{xN}}$$

between the direct voltage regulation d_{xtN} at rated load due to the transformer commutating reactance, expressed as per unit of U_{di} and the inductive component e_{xN} of the transformer impedance voltage at rated line current I_{1LN} for the whole equipment, expressed as per unit of the rated alternating voltage U_{LN} the secondaries being short-circuited according to column 17.

The inductive direct voltage regulation d_{xtN} can be calculated from the knowledge of e_{xN} of a three-phase transformer only for connections with a commutating number $q = 3$.

Table 1 – Connections and calculation factors

Con- nec- tion No.	Transformer connection		Valve connection	p	q	$\frac{e_{qs}}{q}$ 1)	Line side current factor 2)	Valve side current factor 3)	$\frac{U_{d1}}{U_{v0}}$	$\frac{U_{d2}}{U_{v0}}$	$\frac{d_{v11}}{e_{v11}}$	Terminals to be short-circuited at transformer loss test			Total losses in windings in converter operation	Terminals to be short-cir- culed for e_{v11}
	Line side	Valve side										A	B	C		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Single converter, single-way connections																
1				2	2	2	0,5	$0,707 \left(\frac{1}{\sqrt{2}} \right)$	$0,45 \left(\frac{\sqrt{2}}{n} \right)$	$3,14 \left(\frac{1}{n} \right)$	$0,707 \left(\frac{1}{\sqrt{2}} \right)$	0-1	0-2		$0,5(P_A + P_B)$	1-2
2				3	3	3	$0,471 \left(\frac{1}{\sqrt{3}} \right)$	$0,577 \left(\frac{1}{\sqrt{3}} \right)$	$0,675 \left(\frac{3}{n\sqrt{2}} \right)$	$2,09 \left(\frac{2n}{3} \right)$	$0,886 \left(\frac{\sqrt{3}}{2} \right)$	1-2-3			$P_A + I_{v2}/3$	1-2-3
3				6	6	6	$0,816 \left(\frac{\sqrt{2}}{\sqrt{3}} \right)$	$0,408 \left(\frac{1}{\sqrt{6}} \right)$	$1,35 \left(\frac{3\sqrt{2}}{n} \right)$	$2,09 \left(\frac{2n}{3} \right)$	$1,5 \text{ to } 0,5$	1-3-5	2-4-6		$0,75(P_A + P_B)$	Average of 1-3-5 and 2-4-6
4				6	6	6	$0,816 \left(\frac{\sqrt{2}}{\sqrt{3}} \right)$	$0,408 \left(\frac{1}{\sqrt{6}} \right)$	$1,35 \left(\frac{3\sqrt{2}}{n} \right)$	$2,09 \left(\frac{2n}{3} \right)$	$1,5 \text{ to } 0,5$	1-2 3-4 5-6	2-3 4-5 6-1	Average of 1-3-5 and 2-4-6	$(P_A + 2P_B + 3P_C)/6$	Average of 1-3-5 and 2-4-6
5				6	3	3/2	$0,408 \left(\frac{1}{\sqrt{6}} \right)$	$0,289 \left(\frac{1}{2\sqrt{3}} \right)$	$0,675 \left(\frac{3}{n\sqrt{2}} \right)$	$2,42 \left(\frac{4n}{3\sqrt{3}} \right)$	0,5	1-3-5	2-4-6		$0,5(P_A + P_B)$	Average of 1-3-5 and 2-4-6
6				6	2	2/3	$0,272 \left(\frac{1}{3\sqrt{3}} \right)$	$0,236 \left(\frac{1}{3\sqrt{2}} \right)$	$0,45 \left(\frac{\sqrt{2}}{n} \right)$	$3,14 \left(\frac{1}{n} \right)$	$0,75 \text{ to } 0,5$	1-3-5 I-II-III	2-4-6 I-II-III		$1,125(P_A + P_B)/2$	1-4 2-5 3-6
Single converter, uniform double-way connection																
7				2	2	8	1	1	$0,9 \left(\frac{2\sqrt{2}}{n} \right)$	$1,57 \left(\frac{n}{2} \right)$	$0,707 \left(\frac{1}{\sqrt{2}} \right)$	1-2			P_A	1-2
8				6	3	6	$0,816 \left(\frac{\sqrt{2}}{\sqrt{3}} \right)$	$0,816 \left(\frac{1}{\sqrt{3}} \right)$	$1,35 \left(\frac{3\sqrt{2}}{n} \right)$	$1,05 \left(\frac{n}{3} \right)$	0,5	1-2-3			P_A	1-2-3
9				12	3	3	$0,789 \left(\frac{1+\sqrt{3}}{2\sqrt{3}} \right)$	$0,408 \left(\frac{1}{\sqrt{6}} \right)$	$1,35 \left(\frac{3\sqrt{2}}{n} \right)$	$1,05 \left(\frac{n}{3} \right)$	0,26	1-3-5	2-4-6	1-3-5 2-4-6	$0,035(P_A + P_B) + 0,93 P_C$	Average of 1-3-5 and 2-4-6
NOTES 1 Refer to 146-1-2, 1.7.2 and 1.8.1.4. 2 Refer to transformer primary. 3 Refer to transformer secondary.																
															r_2 = resistance of one cell winding	

Table 1 – Connections and calculation factors (continued)

Con- nection No.	Transformer connection		Valve connection	p	q	$\frac{6qs}{g}$ 1)	Line side current factor 2)	Valve side current factor 3)	$\frac{U_{L1}}{U_{L0}}$	$\frac{U_{M1}}{U_{M0}}$	$\frac{d_{v1n}}{e_{v1n}}$	Terminals to be short-circuited at transformer loss test			Total losses in windings in converter operation	Terminals to be short-cir- cued for e_{v1n}
	Line side	Valve side										A	B	C		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
10	Same as 9, but with two different transformers		Same as 9	12	3	3	$\frac{0,789}{\left(\frac{1+\sqrt{3}}{2\sqrt{3}}\right)}$	$\frac{0,408}{\left(\frac{1}{\sqrt{6}}\right)}$	$\frac{1,35}{\left(\frac{3\sqrt{2}}{n}\right)}$	$\frac{1,05}{\left(\frac{n}{3}\right)}$	0,52			1-3-5 2-4-6	1,07 P_C	1-3-5 2-4-6
11				12	3	3	$\frac{0,789}{\left(\frac{1+\sqrt{3}}{2\sqrt{3}}\right)}$	$\frac{0,408}{\left(\frac{1}{\sqrt{6}}\right)}$	$\frac{1,35}{\left(\frac{3\sqrt{2}}{n}\right)}$	$\frac{1,05}{\left(\frac{n}{3}\right)}$	0,26	Average of 1-3-5 and 2-4-6	2-3 4-5 6-1	1-2 3-4 5-6	$1,34 P_A - 0,08 P_B$ $- 0,27 P_C$	Average of 1-3-5 and 2-4-6
12				12	3	12	$\frac{1,577}{\left(\frac{1+\sqrt{3}}{\sqrt{3}}\right)}$	$\frac{0,816}{\left(\frac{1}{\sqrt{3}}\right)}$	$\frac{2,7}{\left(\frac{6\sqrt{2}}{n}\right)}$	$\frac{0,524}{\left(\frac{n}{6}\right)}$	0,26	1-3-5	2-4-6	1-3-5 2-4-6	$0,035(P_A + P_B)$ $+ 0,93 P_C$	Average of 1-3-5 and 2-4-6
13	Same as 12 but with two separate transformers		Same as 12	12	3	12	$\frac{1,577}{\left(\frac{1+\sqrt{3}}{\sqrt{3}}\right)}$	$\frac{0,816}{\left(\frac{1}{\sqrt{3}}\right)}$	$\frac{2,7}{\left(\frac{6\sqrt{2}}{n}\right)}$	$\frac{0,524}{\left(\frac{n}{6}\right)}$	0,52			1-3-5 2-4-6	1,07 P_C	1-3-5 2-4-6
Single converter, non-uniform double-way connections																
14				2	2	-	$\sqrt{\frac{n-\alpha}{n}}$	$\sqrt{\frac{n-\alpha}{n}}$	$\frac{0,9}{\left(\frac{2\sqrt{2}}{n}\right)}$	$\frac{1,57}{\left(\frac{n}{2}\right)}$	$\frac{0,707}{\left(\frac{1}{\sqrt{2}}\right)}$	1-2			P_A	1-2
15				6	3	-	See 1.5.2	See 1.5.3	$\frac{1,35}{\left(\frac{3\sqrt{2}}{n}\right)}$	$\frac{1,05}{\left(\frac{n}{3}\right)}$	0,5	1-2-3			P_A	1-2-3
Double converter connections																
16				See connection No. 5												
17				See connection No. 5												
18				See connection No. 8												
19				See connection No. 8												

NOTES

1 Refer to 146-1-2, 1.7.2 and 1.8.1.4.

2 Refer to transformer primary.

3 Refer to transformer secondary.

4 $n \leq 4$; $0,707(1/\sqrt{2})$; $0,24$; $0,354(1/2\sqrt{2})$; $\cos \mu = 1 - X_s \cdot (1/\sqrt{2}) \cdot U_{L0}$

NOTES

- 1 Refer to 146-1-2, 1.7.2 and 1.8.1.4.
- 2 Refer to transformer primary.
- 3 Refer to transformer secondary.
- 4 $n < u$: $0,707(1/\sqrt{2})$; $n > u$: $0,354(1/2\sqrt{2})$; $\cos \alpha = 1 - X_s \times I_s / \sqrt{2} \times U_{L0}$

For all other connections with a three-phase transformer, the ratio between d_{xN} and e_{xN} depends on the proportions of primary and secondary reactances in the transformer.

NOTES

- 1 It is assumed that the angle of overlap u is less than $2\pi/p$, p being the pulse number. See 3.1.3.
- 2 For connection numbers 9, 12 and 13 the figures in column 12 assume that e_{xN} is defined for the line current of the whole equipment. If each transformer is tested separately with its rated line current ($0,816 I_{dN}$ and $1,632 I_{dN}$ respectively), the value of column 12 should read 0,5.

1.5.5 Magnetic circuit

The magnetic circuits corresponding to the connections supplied with three-phase currents in table 1 are assumed to have three legs.

1.5.6 Power loss factor

Table 1, column 16, gives the relationship between power losses in converter operation and in the short-circuit test at rated line current I_{LN} for the whole equipment and according to columns 13, 14 and 15.

The validity of this factor is restricted according to 4.1 of IEC 146-1-3.

1.6 Parallel and series connections

1.6.1 Parallel or series connection of valve devices

When diodes or thyristors are connected in series or parallel, precautions should be taken to ensure that all devices operate within rated values for voltage and current.

1.6.1.1 Current balancing of parallel connected valve devices

Unequal current distribution may be caused by differences in forward voltage or on-state voltage drop and by differences in thyristor turn-on time and delay angles. Differences in the impedances of the parallel arms are also of considerable influence.

If factory matching of forward or on-state characteristics and turn-on time properties of the valve devices is used for current balancing, this should be stated by the equipment supplier.

1.6.1.2 Voltage division for series connected valve devices

Unequal voltage distribution may be caused by differences in reverse and off-state characteristics, differences in the turn-on instant for thyristors and differences in recovery charge.

1.6.2 Parallel or series connection of assemblies and equipment units

1.6.2.1 Parallel connection

a) *Units not provided with means for voltage adjustment*

In the case of equipment units designed for parallel connection, none of the parallel connected units should exceed its rating when operating at total rated output.

If the equipment is required to operate in parallel with other sources having dissimilar characteristics, the requirements for load-sharing should be specified separately.

b) *Units provided with means for output voltage adjustment*

For such equipment, when required to operate in parallel the requirements for load sharing should be specified separately.

1.6.2.2 Series connection

When assemblies or equipment units are designed for series connection, precaution should be taken to ensure that each unit operates within its limits of rated voltages, even if the a.c. side is disconnected and the d.c. side is still connected to an active load.

In the case of series connection, the voltage to ground may be considerably higher than the voltage between the terminals. In this case, the insulation should be designed and tested accordingly.

1.7 Power factor

1.7.1 General

For converters with a pulse number of 6 or more, the total power factor is of limited interest. The value which is useful for normal purposes is the displacement factor $\cos \phi_1$ of the fundamental wave.

The displacement factor $\cos \phi_1$ is referred to the line side of the converter transformer.

For this reason, if a guarantee is required, it should, unless otherwise specified, refer to the displacement factor calculated under the assumption of both symmetrical and sinusoidal voltage.

The displacement factor for three-phase uniform thyristor connections should be determined by calculation from the measured reactances in accordance with 1.7.4.

For single-phase equipment exceeding 300 kW rated output, for equipment with non-uniform three-phase connections and for converters with sequence control, the method of determining the displacement factor is to be specified separately.

When a converter is operating in the rectifier mode, it is consuming active and reactive power from the a.c. system.

When a converter is operating in the inverter mode, it is delivering active power into the a.c. system but still consuming reactive power from it.

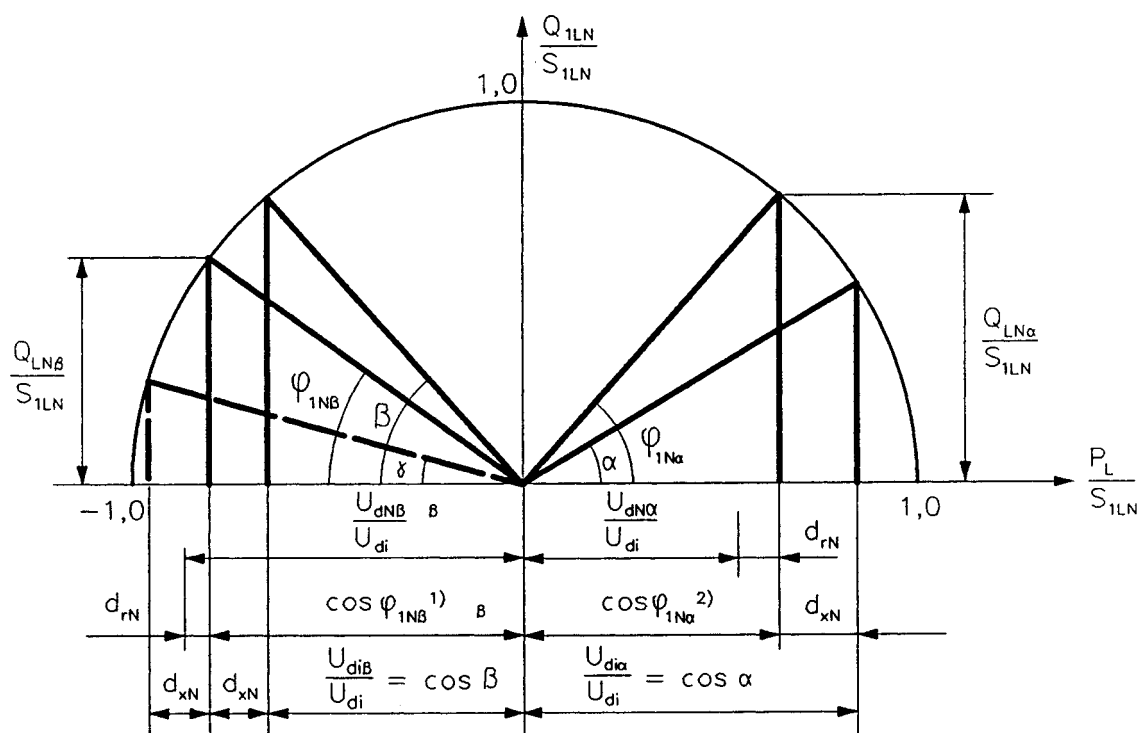
NOTE - For many applications, i.e. small PWM (Pulse width modulated) drives with small or no d.c. reactor, the ripple influences very much the total power factor.

1.7.2 Symbols used in the determination of displacement factor

$\cos \varphi_{1N}$	displacement factor at rated direct current for zero delay angle
$\cos \varphi_{1\alpha N}$	displacement factor at rated direct current, for delay angle α
d_{rN}	$= d_{rtN} + d_{rbN}$, total resistive direct voltage regulation at rated load in per unit of U_{di}
d_{xN}	$= d_{xtN} + d_{xbN}$, total inductive direct voltage regulation at rated load in per unit of U_{di}
d_{rbN}, d_{xbN}	resistive (resp. inductive), direct voltage regulation due to other parts of the converter, for example anode reactors, line side reactors and transformers etc., if any, at rated current, in per unit of U_{di}
d_{rtN}, d_{xtN}	resistive (resp. inductive), direct voltage regulation due to the converter transformer at rated direct current, in per unit of U_{di}
d_{LN}	additional direct voltage regulation due to a.c. system impedance, expressed in per unit of U_{di} , at rated direct current I_{dN} , when the r.m.s. voltage on line side terminals is kept constant.
E_{dN}	d.c. motor counter e.m.f. at rated shaft speed and rated flux
f_{1N}	rated line frequency
I_{dN}	rated direct current
p	pulse number
P_{LN}	$= U_{dN} \times I_{dN} + P_{rN}$, active power on line side at rated load
P_{rN}	power losses in circuit resistance at rated load
Q_{1LN}	reactive power on line side at rated load, related to I_{1LN}
R_a	motor armature circuit resistance
R_C	system resistance of the supply source
R_{SC}	short-circuit ratio
S_{1LN}	$= U_{di} \times I_{dN} = U_{LN} \times I_{1LN} \times \sqrt{3}$ = apparent power on line side at rated load, based on the fundamental wave I_{1LN} of the line current
S_C	short-circuit power of the supply source
S_{tN}	transformer rated apparent power
u	overlap angle
U_{di}	ideal no-load direct voltage
U_{dN}	rated direct voltage
U_{drN}	resistive direct voltage regulation, at rated load
U_{dpN}	ideal internal direct voltage at rated load including the total resistive direct voltage regulation
X_c	system reactance of the supply source
α	angle of delay of phase control in rectifier operation
β	angle of advance of phase control in inverter operation
γ	extinction angle of commutation for inverter operation
φ_{1N}	displacement angle (of fundamental wave) of the line current at rated direct current (neglecting the transformer magnetizing current)
α	suffix for rectifier operation with the delay angle α
β	suffix for inverter operation with the angle of advance β

1.7.3 Circle diagram for the approximation of the displacement factor $\cos \varphi_{1N}$ and of the reactive power Q_{1LN} for rectifier and inverter operation

The approximate displacement factor $\cos \varphi_{1N}$ and the approximate reactive power Q_{1LN} for a converter may be estimated by use of the circle diagram given in figure 1.



$$1) \quad \cos \varphi_{1N\beta} = \frac{U_{dpN\beta}}{U_{di}} = \frac{P_{1N\beta}}{S_{1LN}}$$

$$2) \quad \cos \varphi_{1N\alpha} = \frac{U_{dpN\alpha}}{U_{di}} = \frac{P_{1N\alpha}}{S_{1LN}}$$

Figure 1 - Circle diagram for approximation of the displacement factor

1.7.4 Calculation of the displacement factor $\cos \varphi_1$

1.7.4.1 Displacement factor, at rated direct current, for zero delay angle $\cos \varphi_{1N}$

This is obtained, for the appropriate value of a.c. system reactance, from figures 2 and 3, respectively. If not otherwise stated, it is assumed that the r.m.s. value of the line side terminal voltage is kept constant.

Figure 2 is used for 6-pulse connections.

Figure 3 is used for 12-pulse connections.

The values of α_p indicated in figure 3 are those of the inherent delay angle which occurs in a 12-pulse connection in certain operating regions, even where no phase control is applied. For phase controlled converters, they represent the minimum delay angles that can exist under the indicated conditions.

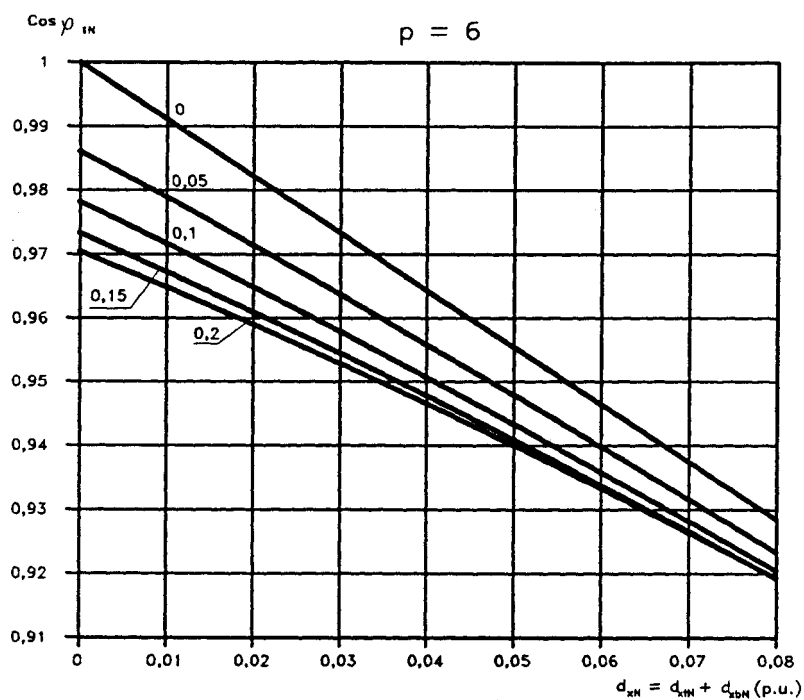


Figure 2 - Displacement factor as a function of d_{xN} for $p = 6$

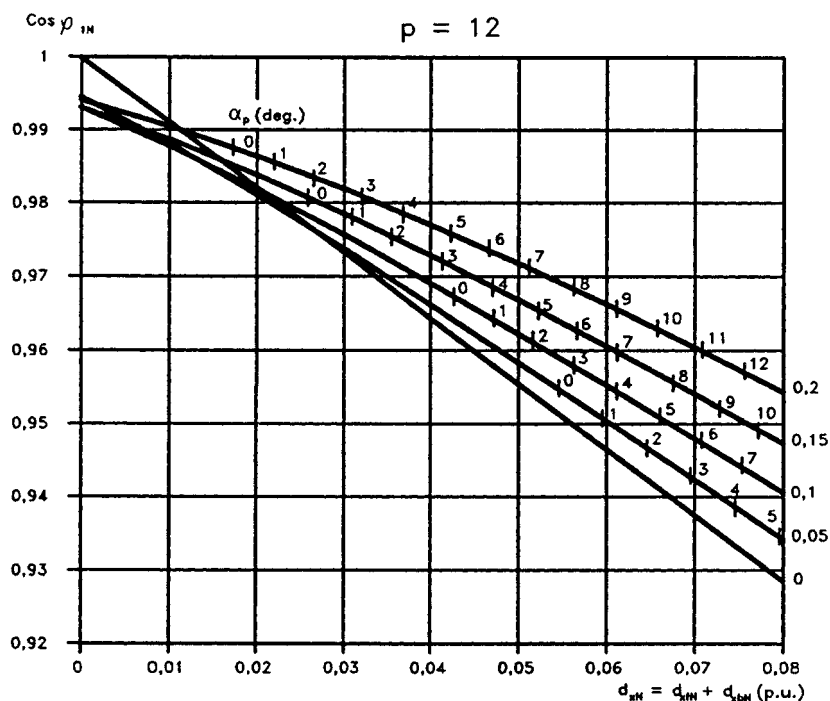


Figure 3 - Displacement factor as a function of d_{xN} for $p = 12$

NOTE - The parameter for figures 2 and 3 is:

$$\frac{1}{R_{sc}} = \frac{S_{1LN}}{S_c} = \frac{U_{di} \times I_{dN}}{S_c}$$

1.7.4.2 Displacement factor $\cos \varphi_{1\alpha N}$, at rated direct current, for delay angle α

If there is phase control with delay angle α , the corresponding value $\cos \varphi_{1\alpha N}$ may be calculated from the following formula, which is sufficiently accurate for practical purposes:

$$\cos \varphi_{1\alpha N} = \cos \alpha - (1 - \cos \varphi_{1N})$$

For the inverter range, the displacement factor may be obtained from the following formula:

$$\cos \varphi_{1\beta N} = \cos \beta + (1 - \cos \varphi_{1N})$$

For an inverter, the abscissa in figures 2 and 3 represents the inductive direct voltage increase at rated load in per unit of U_{di} .

For non-uniform connections, the following formula is applicable:

$$\cos \varphi_{1\alpha N} = \cos \left(\frac{\alpha}{2} \right) - \frac{1 - \cos \varphi_{1N}}{\cos \left(\frac{\alpha}{2} \right)}$$

For asymmetrical control, with delay angles α_1 and α_2 , respectively, the following formula is applicable:

$$\cos \varphi_{1\alpha N} = \cos \left(\frac{\alpha_1 + \alpha_2}{2} \right) - \frac{1 - \cos \varphi_{1N}}{\cos \left(\frac{\alpha_1 + \alpha_2}{2} \right)}$$

1.7.4.3 Displacement factor at loads other than rated load, $\cos \varphi_{1\alpha}$

When using the curves of figures 2 and 3 for other loads than the rated load, the actual values of I_d , d_{xt} , d_{xb} should be used to obtain the $\cos \varphi_1$ for the actual direct current I_d .

That is, the value:

$$d_{xt} + d_{xb} = (d_{xtN} + d_{xbN}) \times \frac{I_d}{I_{dN}}$$

should be used to obtain $\cos \varphi_1$ from figures 2 and 3 respectively. Then:

$$\cos \varphi_{1\alpha} = \cos \alpha - (1 - \cos \varphi_1)$$

1.7.5 Conversion factor

For converters with a pulse number of 6 or more, the conversion factor and the power efficiency are almost equal (see IEC 146-1-1, 1.5.24).

The conversion factor should be given in addition to the power efficiency, especially for low power converters, for converters with pulse number of 6 or less if specified by the purchaser and in cases of applications where the power of the a.c. components of currents and voltages in the d.c. circuit is considered not to contribute to the useful power.

The conversion factor should always be determined by the input/output method for specified load conditions.

1.8 Direct voltage regulation

The voltage regulation of a single converter connected to a system that does not include power factor correction capacitors is mainly due to:

- resistive voltage regulation, i.e. the voltage regulation consequential of power dissipation within the converter;
- inductive voltage regulation due to commutation. Commutation distorts the voltage waveform at the terminals of semiconductor assemblies and change d.c. voltage that is basically made up of samples of the a.c. voltages;
- voltage regulation due to the impedance of the line and non-sinusoidal input currents of the converter that also distort the voltage waveform at converter terminals.

The ideal no-load direct voltage U_{di} could then be referred to the voltage of the infinite bus, i.e. voltage regulation should include the effect of all impedances existing between such infinite power source and the a.c. terminals of the converter.

However this report assumes the r.m.s. line voltage to be constant at the a.c. terminals of the converter, not at infinite power source.

Thus the ideal no-load direct voltage U_{di} should be referred to converter terminal voltage and the voltage regulation results from two contributions:

- the inherent direct voltage regulation, i.e. the voltage regulation of the converter itself (see 1.8.1 and IEC 146-1-1, 1.5.28.1);
- the additional direct voltage regulation due to the influence of a.c. system impedance on the waveform of converter terminal voltage (see 1.8.2).

When power factor correction capacitors are included in the system the frequency behaviour influences the voltage waveform and the voltage regulation.

1.8.1 Inherent direct voltage regulation

The inherent voltage regulation is given by the sum of the direct voltage regulation produced by the transformer and other parts of the converter equipment, such as reactors, etc., plus the change with current of on-state voltage for thyristors and forward voltage for diodes.

It is assumed that the alternating voltage at the line side terminals of the converter is constant.

The voltage regulation should refer to the principal tap of the transformer. When a thyristor converter operates in the inverter range, the voltage regulation is adding to and gives an increase of the direct voltage.

The inherent voltage regulation should be calculated from the reactances and power losses of the components of the equipment. The voltage regulation may be determined by direct measurement in an input/output load test on the equipment if so preferred by the supplier.

For single-phase equipment, for equipment with non-uniform thyristor connections and for converters with sequence control, the method of determining the inherent voltage regulation will be specified.

1.8.1.1 Resistive direct voltage regulation due to main and interphase transformer

This regulation is given by the formula:

$$U_{\text{drtN}} = \frac{\text{losses in transformer windings at rated current}}{I_{\text{dN}}}$$

1.8.1.2 Resistive direct voltage regulation due to other components

Examples of such components are series-smoothing reactors, line side reactors, transductors, current balancing means, diodes, thyristors etc.

This regulation is calculated from the formula:

$$U_{\text{drbN}} = \frac{\text{losses in the components at rated current}}{I_{\text{dN}}}$$

1.8.1.3 Inductive direct voltage regulation due to the converter transformer

For all connections, the inductive voltage regulation can be calculated from the transformer commutating reactance test (see IEC 146-1-3) using the formula:

$$U_{\text{dxtN}} = d_{\text{xtn}} \times U_{\text{di}}$$

NOTE - The formula is not valid for multiple commutation. For connections listed in table 1, the voltage regulation can also be calculated from the factor: $d_{\text{xtn}}/e_{\text{xN}}$ given in table 1 and e_{xN} (see 1.5.4). In such case:

$$U_{\text{dxtN}} = \left(\frac{d_{\text{xtn}}}{e_{\text{xN}}} \right) \times e_{\text{xN}} \times U_{\text{di}}$$

1.8.1.4 Inductive direct voltage regulation due to other components

For example line side reactors, current balancing reactors, etc.

The following symbols are used in the calculation formulae:

d_{xbLN}	inductive direct voltage regulation at I_{dN} due to line side reactors in per unit of U_{di}
d_{xbvN}	inductive direct voltage regulation at I_{dN} due to valve side reactors in per unit of U_{di}
U_{dxbLN}	inductive direct voltage regulation, corresponding to d_{xbLN}
U_{dxbvN}	inductive direct voltage regulation, corresponding to d_{xbvN}
X_{bL}	reactance per phase on line side of reactor, transformer etc.
X_{bv}	reactance per phase on valve side of reactor, transformer etc.
I_{bN}	r.m.s. current in reactor, corresponding to I_{dN} , calculated on the basis of rectangular current waveform
I_{dN}	rated direct current
U_{bN}	rated phase-to-phase voltage at the line side terminals of the reactor etc.
g	number of commutating groups between which I_{dN} is divided
p	pulse number

- q commutation number
 s number of commutating groups in series
 δ number of commutating groups commutating simultaneously per reactor

a) For reactors, transformers etc., on the line side:

For three-phase systems:

$$d_{xbLN} = \frac{\sqrt{3} \times I_{bN} \times X_{bL}}{U_{bN}} \sin\left(\frac{\pi}{p}\right) \quad \text{and} \quad U_{dxbLN} = \frac{\sqrt{3} \times I_{bN} \times U_{di} \times X_{bL}}{U_{bN}} \sin\left(\frac{\pi}{p}\right)$$

For single-phase systems:

$$d_{xbLN} = \frac{1}{\sqrt{2}} \times \frac{I_{bN} \times X_{bL}}{U_{bN}} \quad \text{and} \quad U_{dxbLN} = \frac{1}{\sqrt{2}} \times \frac{I_{bN} \times X_{bL} \times U_{di}}{U_{bN}}$$

b) For valve side reactors:

$$d_{xbvN} = \frac{\sigma \times q \times s}{2 \times \pi \times g} \times \frac{I_{bN} \times X_{bv}}{U_{di}} \quad \text{and} \quad U_{dxbvN} = \frac{\sigma \times q \times s}{2 \times \pi \times g} \times I_{bN} \times X_{bv}$$

The inductive direct voltage regulation due to other components is:

$$U_{dxbN} = U_{dxbLN} + U_{dxbvN}$$

1.8.1.5 Inherent direct voltage regulation of the converter

The direct voltage regulation at rated direct current due to main and interphase transformers (if any), is given by:

$$U_{dtN} = U_{drtN} + U_{dxtN}$$

The direct voltage regulation at rated direct current due to other components of the converter, is given by:

$$U_{dbN} = U_{drbN} + U_{dxbN}$$

The inherent direct voltage regulation at rated direct current, is given by:

$$U_{dtN} + U_{dbN} = U_{drtN} + U_{dxtN} + U_{drbN} + U_{dxbN}$$

1.8.2 Direct voltage regulation due to a.c. system impedance

1.8.2.1 Influence of a.c. system impedance on dc. voltage regulation of the converter

Even if the converter terminal voltage r.m.s. value is maintained constant, the a.c. system impedance causes an additional voltage regulation to appear on the d.c. terminals of the converter.

This is a consequence of changes in waveform of converter terminal voltages, due to non-sinusoidal currents drawn by the converter, that influence the voltage regulation.

This influence depends on the pulse number and the ratio (R_{SC}) of the system short-circuit power to the fundamental apparent power of the converter.