BRITISH STANDARD

BS EN 61642:1998
IEC 61642:1997

Industrial a.c. networks affected by harmonics — Application of filters and shunt capacitors

The European Standard EN 61642:1997 has the status of a British Standard

ICS 31.060.99; 31.160

National foreword

This British Standard is the English language version of EN 61642:1997. It is identical with IEC 61642:1997.

The UK participation in its preparation was entrusted to Technical Committee PEL/33 Power capacitors, which has the responsibility to:

— aid enquirers to understand the text;

— present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep the UK interests informed;

— monitor related international and European developments and promulgate them in the UK.

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Cross-references

Attention is drawn to the fact that CEN and CENELEC Standards normally include an annex which lists normative references to international publications with their corresponding European publications. The British Standards which implement these international or European publications may be found in the BSI Standards Catalogue under the section entitled "International Standards Correspondence Index", or by using the "Find" facility of the BSI Standards Electronic Catalogue.

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Summary of pages

This document comprises a front cover, an inside front cover, pages i and ii, the EN title page, pages 2 to 28 and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

This British Standard, having been prepared under the direction of the Electrotechnical Sector Board, was published under the authority of the Standards Board and comes into effect on 15 January 1998

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Contents

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EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 61642

October 1997

ICS 31.060.99; 31.160

Descriptors: Capacitors, shunts, power capacities, alternating current, electric filters, definitions, generalities

English version

Industrial a.c. networks affected by harmonics Application of filters and shunt capacitors

(IEC 61642:1997)

Réseaux industriels à courant alternatif affectés par les harmoniques — Emploi de filtres et de condensateurs shunt
(CEI 61642:1997)

Von Overschwingungen beeinflußte industrielle Wechselstromnetze Anwendung von Filtern und Parallelkondensatoren
(IEC 61642:1997)

This European Standard was approved by CENELEC on 1997-10-01. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the Central Secretariat has the same status as the official versions.

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CENELEC

European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

Central Secretariat: rue de Stassart 35, B-1050 Brussels

Ref. No. EN 61642:1997 E

Foreword

The text of document 33/255/FDIS, future edition 1 of IEC 61642, prepared by IEC TC 33, Power capacitors, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 61642 on 1997-10-01.

The following dates were fixed:

— latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement (dop) 1998-07-01

— latest date by which the national standards conflicting with the EN have to be withdrawn (dow) 1998-07-01

Annexes designated "normative" are part of the body of the standard. Annexes designated "informative" are given for information only. In this standard, Annex ZA is normative and Annex A is informative. Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 61642:1997 was approved by CENELEC as a European Standard without any modification.

In the official version, for Annex A, Bibliography, the following notes have to be added for the standards indicated:

IEC 60110, NOTE Harmonized as HD 207 S1:1977 (not modified).

IEC 60143, NOTE Harmonized in the EN 60143 series.

IEC 60358, NOTE Harmonized as HD 597 S1:1992 (not modified).

IEC 60252, NOTE Harmonized as EN 60252:1994 (modified).

IEC 61048, NOTE Harmonized, together with its corrigendum 1992, as EN 61048:1993 (modified).

IEC 61049, NOTE Harmonized, together with its corrigendum 1992, as EN 61049:1993 (modified).

IEC 60056, NOTE Harmonized, together with its amendments 1:1992 and 2:1995, as HD 348 S6:1995.

IEC 60255-6, NOTE Harmonized as EN 60255-6:1994 (modified).

IEC 60265-1, NOTE Harmonized, together with its amendments 1:1984 and 2:1994, as HD 355.1 S3:1995 (not modified).

IEC 60265-2, NOTE Harmonized, together with its corrigendum 1990, as EN 60265-2:1993 (not modified).

IEC 60269, NOTE Harmonized in the EN 60269 series and in the HD 630 series.

IEC 60282, NOTE Harmonized as EN 60282-1:1996 (not modified) and as HD 636 S1:1996 (not modified).

IEC 60289, NOTE Harmonized as EN 60289:1994 (modified).

IEC 60831-1, NOTE Harmonized as EN 60831-1:1996 (not modified).

IEC 60871-1, NOTE Harmonized as HD 525.1 S1:1989 (not modified).

IEC 60871-2, NOTE Harmonized as HD 525.2 S1:1989 (not modified).

IEC 60931-1, NOTE Harmonized as EN 60931-1:1996 (not modified).

IEC 61000-2-2, NOTE Harmonized as ENV 61000-2-2:1993 (modified).

Contents

1 General

1.1 Scope and object

This International Standard gives guidance for the use of passive a.c. harmonic filters and shunt capacitors for the limitation of harmonics and power factor correction intended to be used in industrial applications, at low and high voltages. The measures proposed in this standard are applicable to harmonic orders greater than 1 and up to and including 25.

The following capacitors are excluded from this standard:

— capacitors for inductive heat generating plants, operating at frequencies between 40 Hz and 24 000 Hz (see IEC 60110 [1][1]);

— series capacitors for power systems (see IEC 60143 [2]);

— coupling capacitors and capacitor dividers (see IEC 60358 [3]);

— power electronic capacitors (see IEC 61071 [4]);

— AC motor capacitors (see IEC 60252 [5]);

— capacitors for use in tubular fluorescent and other discharge lamp circuits (see IEC 61048 [6] and IEC 61049 [7]);

— capacitors for the suppression of radio interference;

— capacitors intended to be used in various types of electric equipment and thus considered as components;

— capacitors intended for use with d.c. voltage superimposed on a.c. voltage;

— capacitors intended for use with arc furnaces.

The object of this standard is to identify problems and give recommendations for general applications of capacitors and a.c. harmonic filters in a.c. power systems affected by the presence of harmonic voltages and currents.

1.2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All normative documents are subjected to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60050(131):1978, *International Electrotechnical Vocabulary (IEV) — Chapter 131: Electric and magnetic circuits.*

IEC 60050(161):1990, *International Electrotechnical Vocabulary (IEV) — Chapter 161: Electromagnetic compatibility.*

1.3 Definitions

For the purpose of this International Standard, the following definitions apply.

1.3.1
harmonic

the component of the Fourier-series decomposition of a voltage or current periodic wave
[IEV 161-02-18 modified]

1.3.2
harmonic order, *h*

the ratio of the frequency of a harmonic (f_h) to the fundamental (rated) network frequency (f_1)
[IEV 161-02-19 modified]

[1] Figures in square brackets refer to the bibliography given in Annex A.

1.3.3
characteristic harmonics

those harmonics produced by static converters in the course of theoretically ideal operation. The characteristic-harmonic order of static a.c./d.c. converters is given by $h = mp \pm 1$, where p is the pulse number of the converter and m is any integer. For example, the six-pulse converter circuit has characteristic harmonics with order numbers h = 5, 7, 11, 13, 17, 19 ....

1.3.4
non-characteristic harmonics

those harmonics which are produced as a result of imbalance in the a.c. power system or asymmetrical delay of firing angle of the converter. They are also produced by other non-linear, time-varying devices, for example frequency changers, fluorescent lamps, arc furnaces, electric welding machines, etc.

1.3.5
power factor

the ratio of the active power to the apparent power [IEV 131-03-20]

1.3.6
displacement factor

the ratio of the active power of the fundamental wave to the apparent power of the fundamental wave [IEV 131-03-21 modified]

1.3.7
distortion factor

the ratio of the root-mean-square value of the harmonic content to the root-mean-square value of the fundamental quantity, expressed as a percentage of the fundamental [IEV 131-03-04 modified]

$$DF = \frac{(\text{Sum of the squares of r.m.s values of the harmonics})^{1/2}}{\text{r.m.s value of the fundamental}} \; 100\ \%$$

1.3.8
filter

an equipment generally constituted of reactors, capacitors and resistors if required, tuned to present a known impedance over a given frequency range

1.3.9
tuning frequency

the frequency for which the filter impedance, calculated from the rated values, has a minimum or maximum value

1.3.10
tuned filter

a filter with a tuning frequency which differs by no more than 10 % from the frequency which is to be filtered

1.3.11
detuned filter

a filter with a tuning frequency more than 10 % below the lowest harmonic frequency with considerable current/voltage amplitude

1.3.12
damped filter

a filter with low, predominantly resistive, impedance over a wide band of frequencies

1.3.13
ripple control installation

an installation to inject audio-frequency signals into the high voltage (HV) network in order to control receivers on the low voltage (LV) network

1.3.14
reference voltage

the voltage to which the impedance calculations are referred

1.4 General considerations

1.4.1 AC harmonics

Harmonic currents in power networks are produced, in general, when the loads are non-linear or time-varying. One of the main sources of harmonics in industrial networks are static converters.

There are two groups of converter a.c. current harmonics: characteristic and non-characteristic. The characteristic harmonics correlate strongly with the converter circuit and have a constant frequency spectrum. Their magnitude is approximately in inverse proportion to the harmonic number.

The main sources of non-characteristic harmonics are frequency changers, although small amounts of non-characteristic harmonics can result from system imbalances (voltage and impedance) and imbalance in the converter firing angle.

The rectifiers for d.c. drives produce mostly characteristic harmonics.

The effect of non-linear and time-varying loads can be amplified under certain conditions of the electrical supply-network, for example by resonances. Depending on the network conditions and on the amplification effect of the resonances, the supply voltage can be distorted even in electrical installations where non-linear and time-varying loads are absent or represent a small part of the total utility power.

Harmonics increase the losses in power networks and may affect the correct operation of various equipments, in particular electronic circuits.

To keep the harmonic disturbances to an acceptable level, local requirements and national and international standards may specify limits for the harmonic distortion. For the reduction of harmonic distortion, filters can be used.

1.4.2 Reactive power

In general, the reactive power flowing in networks is caused by inductive loads and static converters.

In a network the power factor is determined by the most economical use of the distribution system or is imposed by the utility. Penalties may be imposed through the tariff structure for poor power factor. It is therefore advisable to compensate the inductive reactive power by fitting suitable compensating equipments.

For power factor correction shunt capacitors are normally used. If there are harmonics in the network, unwanted overvoltages and/or overcurrents can appear. In addition, ripple control installations may be disturbed. In these cases, filters can be used in place of shunt capacitors alone.

2 Resonance problems and solutions

2.1 Introduction

In electrical networks, different components are connected together, for example generators, power lines, cables, transformers, capacitors and loads.

The impedance at any point of the network is dependent on the frequency, on the components and on the configuration.

The series connection of an inductance and a capacitance will result in a very low impedance in a certain frequency range, close to the resonance frequency. This effect is called series resonance.

The parallel connection of an inductance and a capacitance will result in a very high impedance in a certain frequency range, close to the resonance frequency. This effect is called parallel resonance.

Series resonance and parallel resonance may occur in the same network over a wide range of frequencies.

If harmonic voltage- or current-sources excite such resonance circuits, an amplification of voltages and currents may occur which can disturb, overload or even destroy network components.

An example of a simplified network and its one-line diagram is shown in Figure 1.

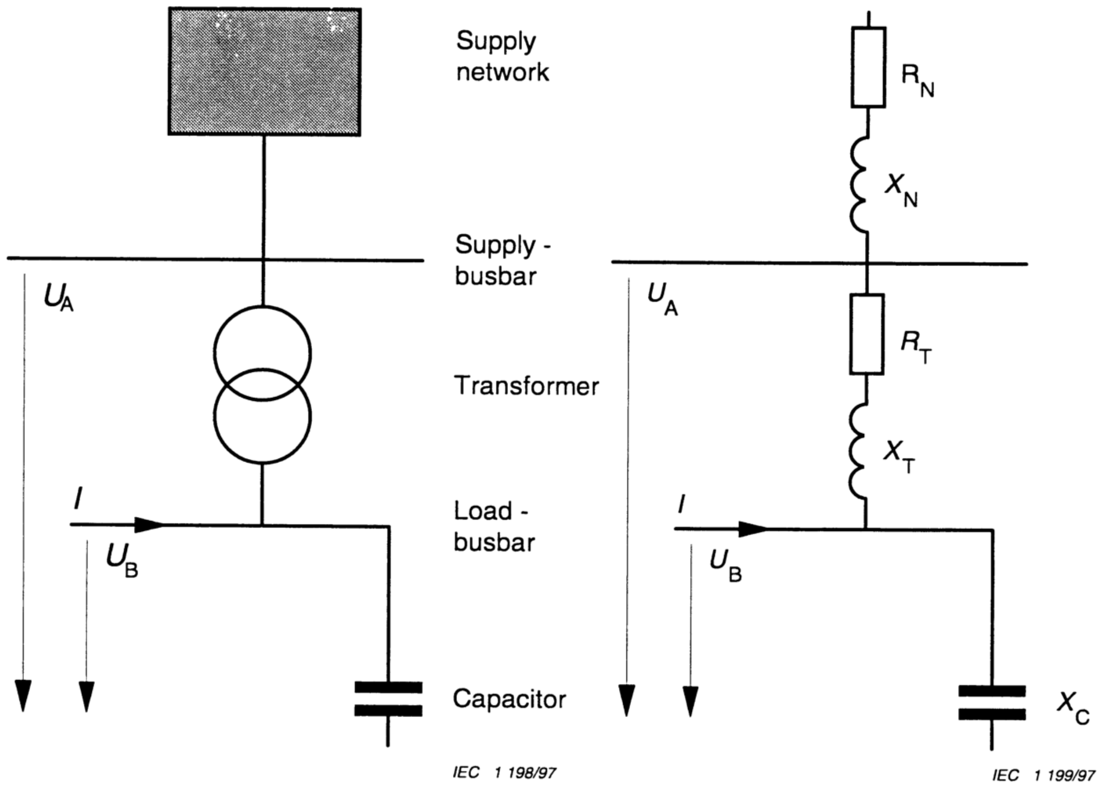

Figure 1 — Simplified network and one-line diagram

This example consists of the supply network, a supply-busbar (on the high-voltage side), a transformer, a load-busbar (on the low-voltage side) and a capacitor. The source of harmonic currents may be a drive which is controlled by a six-pulse rectifier. Harmonic voltages may be present in the network itself due to other harmonic current sources.

2.2 Supply impedance view, load-busbar impedance view

To analyze the behaviour of a network with respect to harmonics, it is useful to look, at least, at two impedances:

— the supply impedance takes the view from the supply network (see Figure 1).

This view is useful for the analysis of the capacitor and reactor load in the presence of harmonic voltages and currents on the supply-busbar, for the calculation of the branch impedance at ripple control-frequencies and for the evaluation of the resulting harmonic voltages (quality of the voltage) on the load-busbar;

— the load-busbar impedance takes the view from the load-busbar (see Figure 1).

This view is useful for the analysis of the capacitor and reactor load in the presence of harmonic current sources on the load-busbar and for the calculation of the resulting harmonic voltages (quality of the voltage) on the load-busbar.

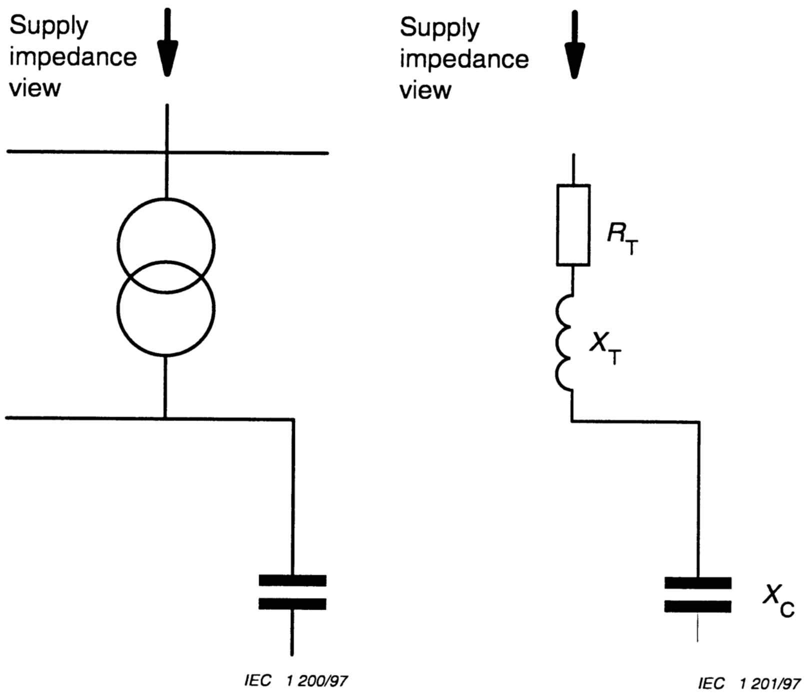

Figure 2a — Supply impedance view of a network and one-line diagram

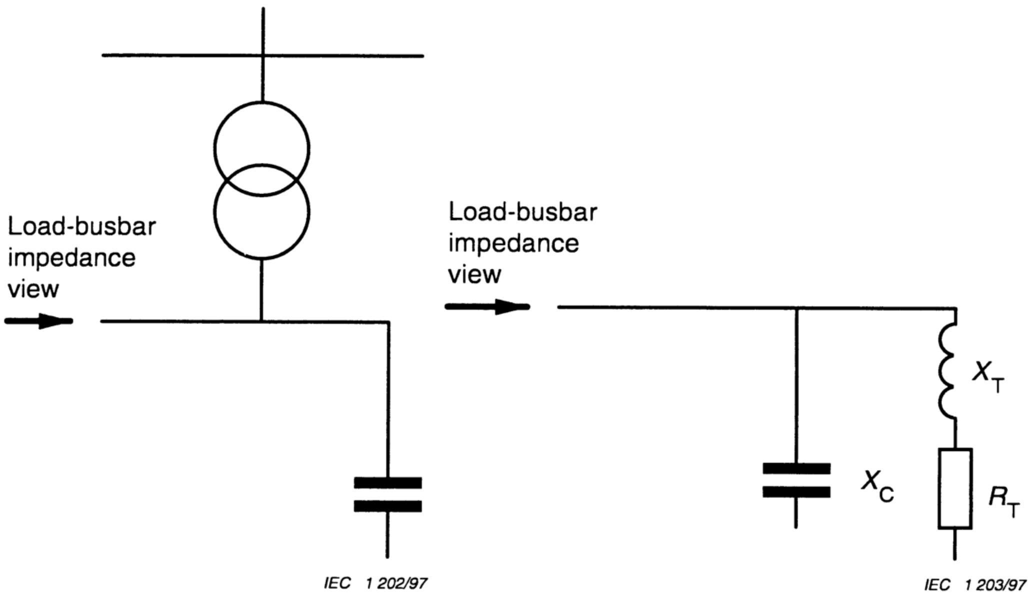

Figure 2b — Load-busbar impedance view of a network and one-line diagram

2.3 Example of a series resonance

In the following calculation example, the series connection of a transformer (inductance X_T and resistance R_T) and a capacitor is analyzed. Figure 3a shows the one-line diagram and Figure 3b shows the impedance versus harmonic order. It shows a series resonance close to the 11th harmonic. Typical numerical results of impedances, voltages and currents at characteristic harmonic frequencies in the network shown in Figure 1 with a distorted supply voltage are shown in Table 1 [8].

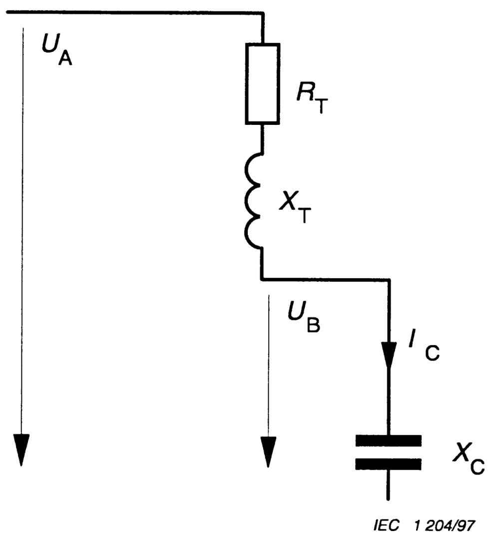

Figure 3a — One-line diagram of a series resonance circuit

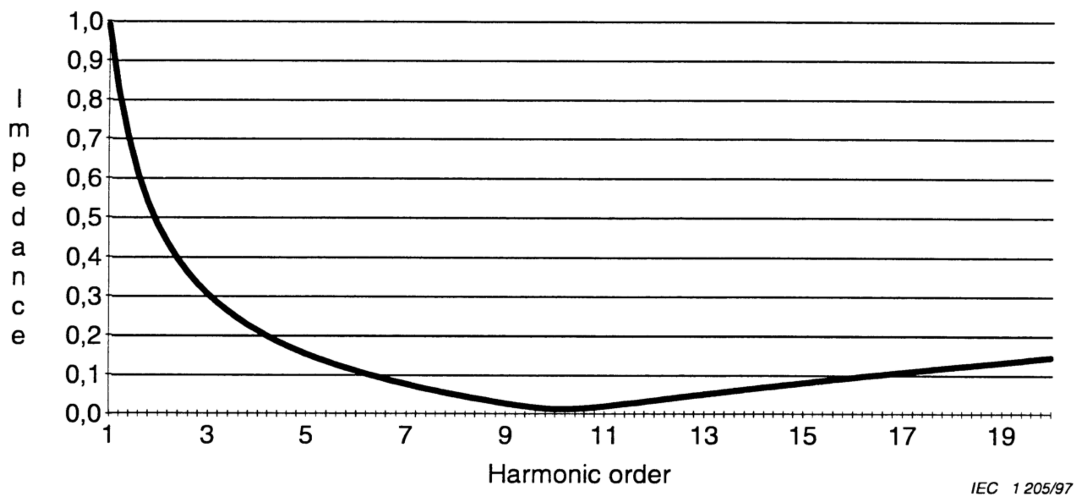

Figure 3b — Impedance in ohms versus harmonic order of the circuit shown in Figure 3a

Explanation of the symbols and values used in Figure 3a, Figure 3b and Table 1.

U_N	reference voltage (example: 3-phase 400 V)
$h = f_h/f_1$	harmonic order, f_1 fundamental frequency, f_h harmonic frequency
$X_T = X_{T1} \cdot h$	short-circuit reactance of a transformer of 1 000 kVA having an impedance voltage of 6 %
$Q_T = 8$	transformer quality factor
$X_C = X_{C1}/h$	reactance of a capacitor of 160 kvar
Z	equivalent impedance (see Figure 3a)
U_A	voltage on the supply-busbar. The values are taken from a CIGRE report about harmonics and multiplied by 60 % [8].
$U_A(\%) = (U_A/U_N) \cdot 100$	
I_c	capacitor current
I_{CN}	rated capacitor current
U_B	resulting voltage on the load-busbar
$U_B(\%) = (U_B/U_N) \cdot 100$	

Table 1 — Numerical results of impedances, voltages and currents at characteristic harmonic orders of a series resonance circuit in a network with a distorted supply voltage

h	X_T	X_C	Z	U_A	U_A(%)	I_C	U_B	U_B(%)
	Ω	Ω	Ω	V	%	A	V	%
1	0,010	– 1,000	0,990	400,0	100,0	233	404	101,0
5	0,048	– 0,200	0,152	12,0	3,0	46	16	3,9
7	0,067	– 0,143	0,076	9,6	2,4	73	18	4,5
11	0,106	– 0,091	0,020	6,0	1,5	175	28	6,9
13	0,125	– 0,077	0,050	4,8	1,2	55	7	1,8
17	0,163	– 0,059	0,106	2,4	0,6	13	1	0,3
19	0,182	– 0,053	0,132	1,9	0,5	8	1	0,2
				DF (A) % = 4,4			DF (B) % = 9,3	
$R_T = X_T/Q_T = X_T/8$ (simplified)						$I_{c\ eff.} = 313$ A		
						$I_C/I_{CN} = 1,35$		

The following can be concluded from Table 1:

— a relatively low voltage on the supply-busbar can cause a high current, if the frequency is close to the series resonance frequency.

The example at $h = 11$ results in a capacitor current of 175 A which is about 75 % of the fundamental capacitor current;

— the high current causes a high voltage drop on the load-busbar, which leads to a distortion of the sinusoidal voltage.

The example at $h = 11$ results in 6,9 % voltage distortion factor although the voltage was only 1,5 % on the supply-busbar;

— the r.m.s. current through the capacitor is 1,35 times the rated capacitor current. This is an overload condition because the normal limit is 1,3 times the rated capacitor current.

It is possible to design a capacitor which is able to withstand such a current. But this is not a solution to the problem because the voltage distortion on the load-busbar is about 7 % for a single harmonic frequency ($h = 11$) which is much higher than normal compatibility levels.

Additionally, it can be seen that magnification is not only obtained when the frequency equals the resonance frequency, but also when the frequency is close to the resonance frequency. The resonance frequency where the resulting impedance has a minimum is approximately

$$f_{res} = f_1 \sqrt{\left|\frac{X_{C1}}{X_{T1}}\right|}$$

2.4 Example of parallel resonance

In the following calculation example, the parallel connection of a transformer (inductance X_T and resistance R_T) and a capacitance is analyzed. Figure 4a shows the one-line diagram and Figure 4b shows the impedance versus harmonic order. Typical numerical results of impedances, voltages and currents at characteristic harmonic frequencies are shown in Table 2.

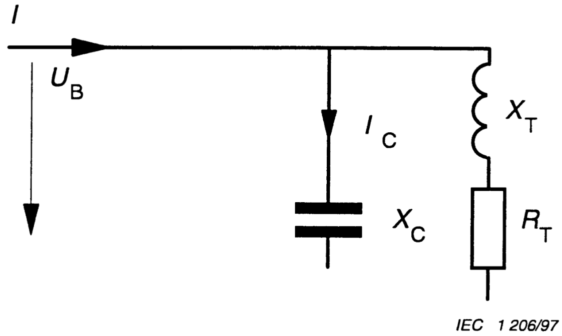

Figure 4a — One-line diagram of a parallel resonance circuit

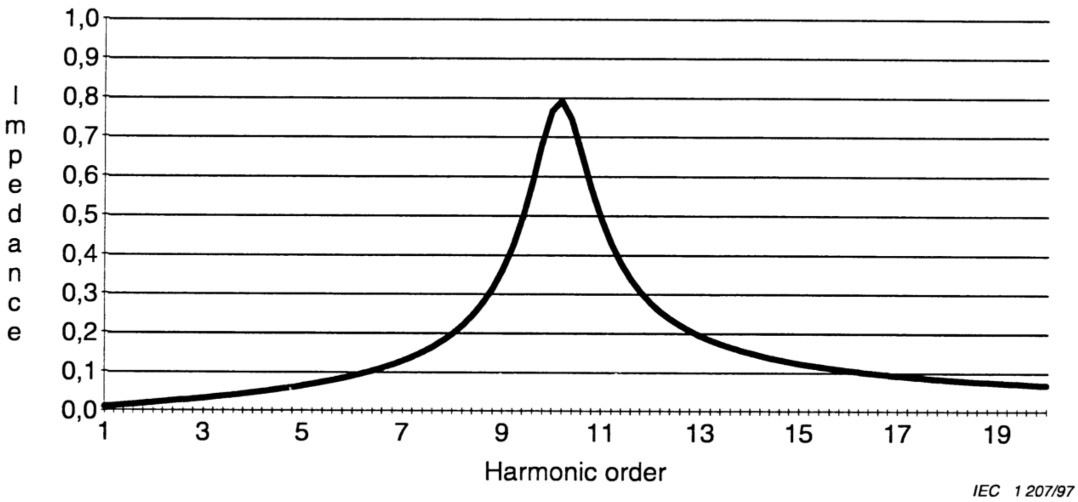

Figure 4b — Impedance in ohms versus harmonic order of the circuit shown in Figure 4a

Explanation of the symbols and values used in Figure 4a, Figure 4b and Table 2.

U_N	reference voltage (example: 3-phase 400 V)
$h = f_h/f_1$	harmonic order, f_1 fundamental frequency, f_h harmonic frequency
$X_T = X_{T1} \cdot h$	short-circuit reactance of a transformer of 1 000 kVA having an impedance voltage of 6 %
$Q_T = 8$	transformer quality-factor

$X_C = X_{C1}/h$	reactance of a capacitor of 160 kvar
Z	equivalent impedance (see Figure 4a)
I, I(%)	current on the load-busbar. The values are the theoretical values of a 300 kVA drive
U_B	resulting voltage on the load-busbar
$U_B(\%) = (U_B/U_N) \cdot 100$	
I_C	capacitor current
I_{CN}	rated capacitor current

Table 2 — Numerical results of impedances, voltages and currents at characteristic harmonic orders of a parallel resonance circuit in the presence of a harmonic current source

h	X_T Ω	X_C Ω	Z Ω	I A	I(%) %	U_B V	U_B(%) %	I_C A
1	0,010	– ,000	0,010	433	100,0	—	—	231
5	0,048	– 0,200	0,064	87	20,0	10	2,4	28
7	0,067	– 0,143	0,127	62	14,3	14	3,4	55
11	0,106	– 0,091	0,490	39	9,1	33	8,3	212
13	0,125	– 0,077	0,192	33	7,7	11	2,8	83
17	0,163	– 0,059	0,091	25	5,9	4	1,0	39
19	0,182	– 0,053	0,073	23	5,3	3	0,7	32
						DF(B) % = 9,8		
$R_T = X_T/Q_T = X_T/8$ (simplified)								$I_{c\ eff.}$ = 334 A
								I_C/I_{CN} = 1,45

The following can be concluded from Table 2:

— a relatively low current on the load-busbar can cause a high capacitor current, if the frequency is close to the parallel resonance frequency.

The example at h = 11 results in a capacitor current of 212 A which is more than 90 % of the fundamental capacitor current, although the harmonic current was only 39 A on the load-busbar;

— the high current causes a high voltage drop on the load-busbar, which leads to a distortion of the sinusoidal voltage.

The example at h = 11 results in 8,3 % voltage distortion factor;

— the r.m.s. current through the capacitor is 1,45 times the rated capacitor current. This is an overload condition because the normal limit is 1,3 times the rated capacitor current.

It is possible to design a capacitor which is able to withstand such a current. But this is not a solution to the problem because the voltage distortion on the load-busbar is about 8 % for a single harmonic frequency which is much higher than normal compatibility levels.

Additionally, it can be seen that magnification is not only obtained when the frequency equals the resonance frequency, but also when the frequency is close to the resonance frequency. The resonance frequency where the resulting impedance has a maximum is approximately:

$$f_{res} = f_1 \sqrt{\left|\frac{X_{C1}}{X_{T1}}\right|}$$

NOTE In practice, the network impedance is connected in series to the transformer impedance. This will affect the resonance frequency and the voltage and current amplitudes to a certain extent.

2.5 Solutions to avoid resonances

The principal method used to avoid resonance problems is to keep the resonance frequency as far away as possible from the harmonic frequencies which have considerable amplitudes.

This can be done by changing the inductance or the capacitance of the network components. However, there is little latitude, if a particular network configuration is defined by the power supply and reactive power compensation. In particular when an automatic capacitor bank is to be used, many resonance conditions have to be considered.

The most common solution to avoid resonance problems is to connect a reactor in series with the capacitor, tuned to a series resonance frequency which is below the lowest frequency of the harmonic voltages and currents in the network. Below the tuning frequency, the impedance of the capacitor-reactor-connection is capacitive, above the tuning frequency, it is inductive. The interaction of the network inductance and the (inductive) impedance of the capacitor-reactor-connection can no longer create a resonance condition, neither a series or a parallel resonance, at the frequencies of the harmonic voltages and currents in the network. The reactor may be specified by its relative impedance:

$$p = \frac{|X_{L1}|}{|X_{C1}|}$$

The tuning order is:

$$\frac{f_{LC}}{f_1} = \sqrt{\frac{1}{p}}$$

In most networks, the 5th harmonic is the lowest frequency with a considerable amplitude. For such networks, it is useful to choose a capacitor-reactor-connection with a tuning frequency below $5 \cdot f_1$, i.e. $p > 4$ %.

If the network is loaded with strong 3rd harmonic voltages between phases as occurs for example with single phase rectifiers and overexcited transformers, the tuning frequency shall be below $3 \cdot f_1$, i.e. $p > 11$ %.

In the following examples of Figure 5a, Figure 5b, Figure 6a, Figure 6b and Table 3 and Table 4 the same values are used as before, but with a capacitor-reactor-connection tuned to $3{,}78 \cdot f_1$, with a $p = 7$ % reactor and compensation power at power frequency as before.

2.5.1 Capacitor-reactor connection: series resonance

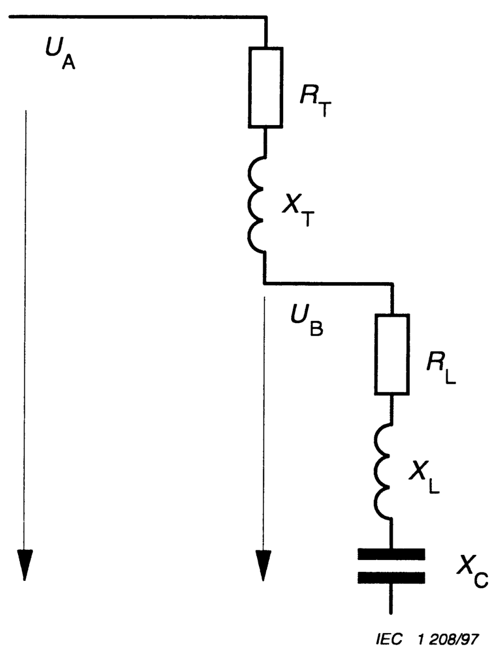

Figure 5a — One-line diagram of a series resonance circuit with capacitor-reactor connection

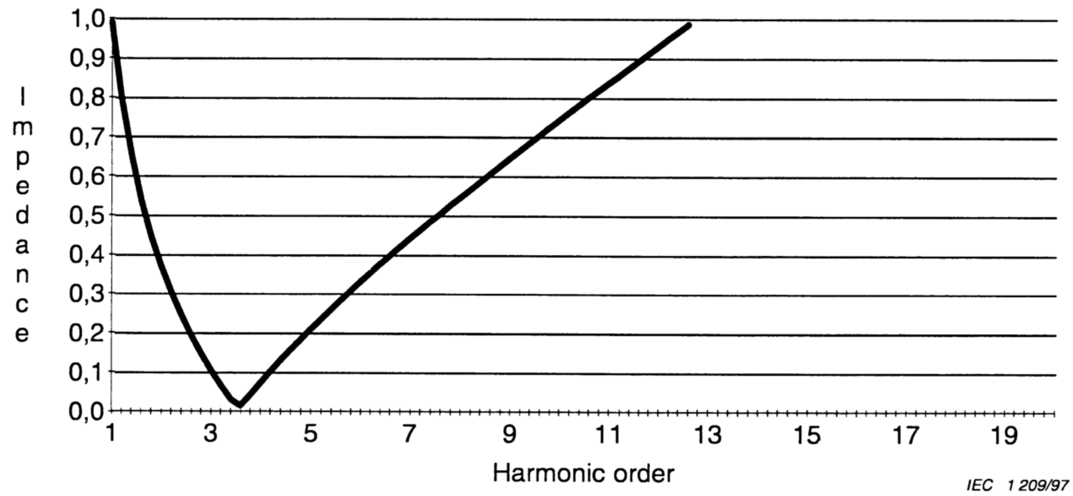

Figure 5b — Impedance in ohms versus harmonic order *h* of the circuit shown in Figure 5a

Explanation of the symbols and values used in Figure 5a, Figure 5b and Table 3.

U_N	reference voltage (example: 3-phase 400 V)
$h = f_h/f_1$	harmonic order, f_1 fundamental frequency, f_h harmonic frequency
$X_T = X_{T1} \cdot h$	short-circuit reactance of a transformer of 1 000 kVA having an impedance voltage of 6 %
$Q_T = 8$	transformer quality factor
$X_L + X_C$	reactance of a capacitor with a p = 7 % reactor for 160 kvar compensation power
$Q_L = 30$	reactor quality factor
Z	equivalent impedance (see Figure 5a)
U_A	voltage on the supply-busbar. The values are taken from a CIGRE report about harmonics and multiplied by 60 % [8]
$U_A(\%) = (U_A/U_N) \cdot 100$	
I_C	capacitor current
I_{CN}	rated capacitor current
U_B	resulting voltage on the load-busbar
$U_B(\%) = (U_a/U_N) \cdot 100$	

Table 3 — Numerical results of impedances, voltages and currents at characteristic harmonic orders of a series resonance circuit with a capacitor-reactor-connection in a network with distorted supply voltage

h	X_T	$X_C + X_L$	Z	U_A	U_A(%)	I_C	U_B	U_B(%)
	Ω	Ω	Ω	V	%	A	V	%
1	0,010	– 1,000	0,990	400,0	100,0	233	404	101,0
5	0,048	0,161	0,212	12,0	3,0	33	9	2,3
7	0,067	0,373	0,443	9,6	2,4	13	8	2,0
11	0,106	0,730	0,840	6,0	1,5	4	5	1,3
13	0,125	0,896	1,026	4,8	1,2	3	4	1,0
17	0,163	1,216	1,386	2,4	0,6	1	2	0,5
19	0,182	1,374	1,563	1,9	0,5	1	2	0,4
				DF (A) % = 4,4			DF (B) % = 3,5	
$R_T = X_T/Q_T = X_T/8$ (simplified)						$I_{C\ eff.}$ = 236 A		
$R_L = X_L/Q_L = X_L/30$ (simplified)						I_C/I_{CN} = 1,02		

The following can be concluded from Table 3:

— a resonance-problem with an amplification of voltages and currents is avoided with the capacitor-reactor connection;

— the voltage distortion factor on the load-busbar is 3,5 % while that in the example of Table 1 is 9,3 %. The power quality is improved in this respect.

2.5.2 Capacitor-reactor connection: parallel resonance

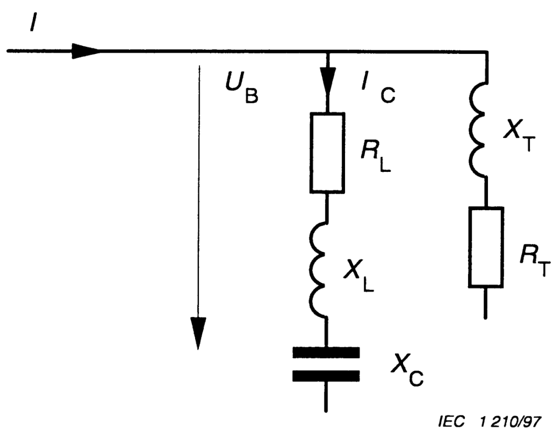

Figure 6a — One-line diagram of a parallel resonance circuit with capacitor-reactor connection

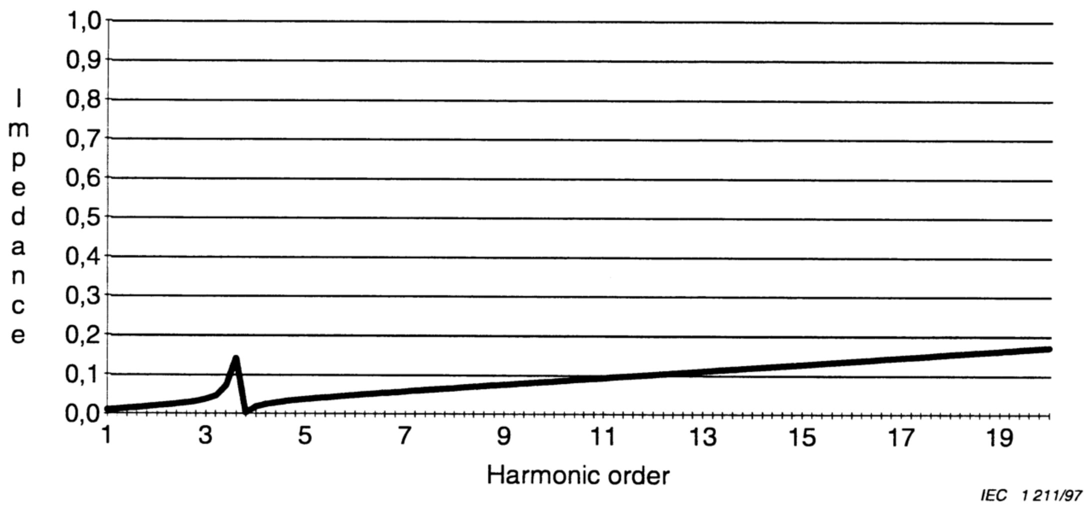

Figure 6b — Impedance in ohms versus harmonic order of the circuit shown in Figure 6a

Explanation of the symbols and values used in Figure 6a, Figure 6b and Table 4.

U_N	reference voltage (example: 3-phase 400 V)
$h = f_h/f_1$	harmonic order, f_1 fundamental frequency, f_h harmonic frequency
$X_T = X_{T1} \cdot h$	short-circuit reactance of a transformer of 1 000 kVA having an impedance voltage of 6 %
$Q_T = 8$	transformer quality-factor
$X_L + X_C$	reactance of a capacitor with a p = 7 % reactor for 160 kvar compensation power
$Q_L = 30$	reactor quality-factor
Z	equivalent impedance (see Figure 6a)
I, I(%)	current on the load-busbar. The values are the theoretical values of a 300 kVA drive.
U_B	resulting voltage on the load-busbar
$U_B(\%) = (U_B/U_N) \cdot 100$	
I_C	capacitor current
I_{CN}	rated capacitor current

Table 4 — Numerical results of impedances, voltages and currents at characteristic harmonic orders of a parallel resonance circuit with a capacitor-reactor connection in the presence of a harmonic current source

h	X_T	$X_L + X_C$	Z	I	I(%)	U_B	U_B(%)	I_C
	Ω	Ω	Ω	A	%	V	%	A
1	0,010	–1,000	0,010	433	100,0	–	–	231
5	0,048	0,161	0,037	87	20,0	6	1,4	20
7	0,067	0,373	0,057	62	14,3	6	1,5	10
11	0,106	0,730	0,093	39	9,1	6	1,6	5
13	0,125	0,896	0,110	33	7,7	6	1,6	4
17	0,163	1,216	0,145	25	5,9	6	1,6	3
19	0,182	1,374	0,162	23	5,3	6	1,6	3
						DF (B)% = 3,8		
$R_T = X_T/Q_T = X_T/8$ (simplified)								$I_{C\ eff.} = 232$ A
$R_L = X_L/Q_L = X_L/30$ (simplified)								$I_C/I_{CN} = 1,01$

The following can be concluded from Table 4:

— a resonance problem with an amplification of voltages and currents is avoided with the capacitor-reactor connection;

— the voltage distortion factor on the load-busbar is 3,8 % while that in the example of Table 2 is 9,8 %. The power quality is improved in this respect.

NOTE In practice, the network impedance is connected in series to the transformer impedance. This will affect the resonance frequency and the voltage and current amplitudes to a certain extent.

3 Shunt capacitors and filters for networks having a voltage up to and including 1 000 V

3.1 Introduction

Three methods of utilising shunt capacitors on the low voltage network are described below together with an indication of the precautions to be taken in each case.

To design a power factor correction installation, all network configurations including exceptional and emergency arrangements as well as possible future extensions should be considered.

3.2 Shunt capacitors

This type of power factor correction installation can be used when it is not necessary to take measures to avoid resonance problems or to reduce harmonics. This is generally the case when the resonant frequency given by the network inductance and the capacitance of the power factor correction installation is relatively high and the harmonic content of the network (i.e. bus voltage and harmonic currents generated by the loads) is very low.

It should however be understood that the total resulting capacitance of all power factor correction installations connected to the low voltage side of one distribution transformer determines the possibility of a harmonic resonance problem. Avoiding such problems when the power factor correction installation is already in service can be more difficult and costly than at the original installation time as it is often not possible to re-use existing capacitors, frames, etc.

3.3 Detuned filter

As shown in **2.5**, an effective way to prevent harmonic resonance problems from a technical as well as an economical point of view is to connect a reactor in series with each phase of each capacitor step of the power factor correction installation.

This type of power factor correction installation (detuned filter) also gives the advantage of reducing the harmonic voltages in the network by absorbing part of the harmonic currents with an order higher than the tuning frequency of the reactor-capacitor arrangement.

The choice of the tuning frequency of the reactor-capacitor arrangement depends on the magnitudes and frequencies of the harmonic currents circulated in the network, and on the signal frequency of a ripple control installation if any (see **3.6**).

Typically, reactors cannot be added to existing capacitors to make a detuned filter as the installed capacitors may not be rated for the additional voltage and/or current caused by the added series reactor.

Normally, a power factor correction installation having series reactors shall not be mixed with an equipment without series reactor. Care should also be taken when a detuned filter is extended by equipment having a different tuning frequency. In both cases problems can occur due to unequal sharing of the harmonic load and possible overloading of one filter or part of it.

3.4 Tuned filter

To keep the harmonic voltages in the network to an acceptable level, a tuned filter may have to be considered as mentioned in **1.4.1**. The filters act as a load on the harmonic generator absorbing the harmonic currents and thus reducing the harmonic voltage increases. When assessing the requirements of the tuned filter it is important to consider the complete network system.

To design a tuned filter it is necessary to know the harmonic impedance values of the network, especially the impedance of the distribution transformer as well as the frequency spectrum of the harmonic source(s) and the harmonic voltages in the high voltage network.

A tuned filter comprises one or more tuned filter units (series connection of reactor and capacitor on each phase) each tuned to give a relatively low impedance at the considered harmonic frequency compared to the impedance of the network at the same frequency. Harmonic currents are thus mainly absorbed by this filter. At the network frequency the filter acts as a capacitor providing power factor correction.

Generally, tuned filter units need to be designed for the odd harmonic orders except multiples of 3, i.e. 5, 7, 11, 13, 17, 19, etc. in increasing order. Usually, in low voltage installations the third harmonic needs not be considered as it only appears between phase and neutral and most of the power factor correction installations are connected between phases (no connection to the neutral). However, in the case of unbalanced load, a third harmonic filter unit may be considered.

Normally, the following are valid:

— the reactive power rating at network frequency of each tuned filter unit decreases with increasing harmonic order;

— all tuned filter units of a filter are switched together. If, however, it is necessary to switch the tuned filter units independently, they should be switched on in ascending order 5, 7, 11, etc. and switched off in the reverse order;

— the rated tuning frequency of a filter unit is generally chosen slightly lower than the harmonic frequency. Thus, the impedance of the tuned filter unit is inductive at the harmonic frequency.

Care should be taken to fit tuned filters to individual items of equipment connected to the low voltage side of the same distribution transformer in order to avoid problems. Parallel connected filter units for one harmonic order will not have exactly the same resonance frequency due to the tolerances of the components causing problems, for example, due to unequal sharing of the harmonic load and/or to parallel resonances between tuned filters. In such cases it could be useful to use additional contacts to connect together the points between reactors and capacitors of each phase of the filter units for the same harmonic order which are in service.

3.5 Components selection

A low voltage power factor correction installation is usually installed indoors and normally consists of some or all of the following components:

— capacitors;

— reactors (for example in case of filters);

— contactors and/or circuit-breakers;

— short-circuit protection (fuses or circuit-breaker).

The determination of ratings for these components is usually based on the calculated stresses during worst service conditions. Harmonic currents generated by the electrical loads and any harmonic current or voltage existing on the network have to be considered when designing power factor correction installation and/or filter.

It should be checked that the manufacturing tolerances, the influence of temperature and ageing, the operation of internal or external fuses if any, the possible non-linearity of the filter components as well as the variation of the network frequency will not cause unacceptable repercussions on the function of the filter.

3.5.1 Capacitors

The capacitor units or bank are the fundamental part in each power factor correction installation and/or filter. A thorough study should therefore be performed in order to obtain optimal capacitor design.

The capacitor current consists of fundamental and harmonic frequency components. As the magnitude of harmonic components may be very high, especially in a tuned filter, it is necessary to take them into account when defining rated values of the capacitors.

For filters the voltage increase on the capacitor caused by the series connection of the reactor should be considered.

3.5.2 Reactors

The reactor current consists of fundamental and harmonic frequency components. As the magnitude of harmonic components may be very high, especially in a tuned filter, it is necessary to take them into account when defining rated values of the reactors.

The reactor shall be designed for the thermal load due to the maximum fundamental and harmonic currents.

Manufacturing tolerance for the inductance of the reactor is to be taken into account in filter design. A value of ± 3 % is acceptable for most filter applications.

The reactor shall be able to withstand the short-circuit current which can occur during fault conditions as well as the switching current and voltage.

The inductance value of the reactor shall not vary by more than 5 % from rated current to the highest loading given by the peak value of the current or voltage (induction caused by the arithmetic sum of the maximum fundamental and harmonic currents or voltages).

When using reactors with an iron core (which is the normal case in low voltage filters), care should be taken to avoid saturation problems (important change of inductance value, ferro-resonance occurring during switching operations and leading to overloading of components, etc).

The losses of the reactors should be considered.

3.5.3 Contactors and/or circuit-breakers

The switching of power factor correction installations requires some special features of the switching device. The following aspects shall be therefore considered:

- — the contactor and circuit-breaker shall be restrike-free and adapted for capacitors;
- — the rated voltage of the contactor and circuit-breaker shall be equal to or higher than the maximum network voltage with the power factor correction installation and/or filter in service;
- — the contactor and circuit-breaker shall be designed for continuous current (including harmonics) which can pass the power factor correction installation and/or filter at maximum source voltage, maximum frequency and extreme tolerances of the components, especially capacitor and reactor;
- — the interrupting rating of circuit-breaker shall be equal to or greater than the short-circuit current which can occur on the power factor correction installation and/or filter side;
- — the contactor and circuit-breaker shall have sufficient short-time current rating to withstand both system short-circuit faults and inrush currents associated with energizing;
- — the type of the contactor and circuit-breaker shall be selected with respect to the expected frequency of switching operations.

3.5.4 Short-circuit protection (fuses)

The rated voltage of the short-circuit protection shall be equal to or greater than the maximum network voltage with the power factor correction installation and/or filter in service.

The short-circuit protection shall be designed for continuous current (including harmonics) which can pass the power factor correction installation and/or filter at maximum source voltage, maximum frequency and extreme tolerances of the components, especially capacitor and reactor.

The interrupting rating shall be equal to or greater than the short-circuit current which can occur on the power factor correction installation and/or filter.

The short-circuit protection shall have sufficient short-time current rating to withstand both system short-circuit faults and inrush currents associated with energizing.

3.6 Disturbance of ripple control installations by shunt capacitors and filters

The influence of the power factor correction installations and filters on the ripple control installation is described below, for each method of use of shunt capacitors.

3.6.1 Shunt capacitors

For audio frequency signals injected into the high voltage network by a ripple control installation the capacitance of the power factor correction installation forms a series resonant circuit with the inductance of the distribution transformer. When the resonance frequency of this circuit is the same as or close to the signal frequency problems could occur. The voltage of the signal in the low voltage network may be increased to an unacceptable level, and the impedance, at this frequency, in the high voltage network may be reduced leading to additional loading of the ripple control signal generator. When the resonance frequency is much lower than that of the ripple control signal the voltage of this signal may be reduced to an unacceptable level.

An example of this is shown in Figure 7b and Figure 7c for a transformer-capacitor arrangement corresponding to Figure 7a for four different ripple control signal frequencies. Close to the resonance frequency the impedance of the arrangement is much lower than the nominal load impedance which may lead to an overloading of the ripple control generator. On the other hand, the ripple control signal voltage can be increased or reduced to levels which may disturb the ripple control receivers.

Explanation of the symbols used in Figure 7a, Figure 7b and Figure 7c:

Z_{RC}	impedance at ripple control frequency of transformer-capacitor arrangement
Z_1	nominal load impedance at network frequency
S	transformer rating
ε_k	impedance voltage of the transformer in per cent
Q	shunt capacitor rating
U_{RC}	ripple control signal voltage in the low voltage network
U_{RCO}	ripple control signal voltage when no shunt capacitor is connected
f_{RC}	ripple control signal frequency
Q_{RC}	quality factor of the transformer at ripple control signal frequency

3.6.2 Detuned filter

Reactors connected in series with the capacitors of power factor correction installations prevent such disturbances of the ripple control installation if the resonance frequency of the reactor-capacitor arrangement is lower than and far enough from the ripple control signal frequency.

From Figure 5b, for example, it can be seen that for a frequency ratio h between ripple control signal frequency and a network frequency of about 10 (for example for a signal frequency of 492 Hz in a 50 Hz network) the impedance at signal frequency is not very different from the impedance at fundamental frequency. So there may be practically no influence on the ripple control installation. For a frequency ratio h in the range of about 2 to 6, the impedance is relatively low. Consequently the signal voltage in the low voltage network and the impedance in the high voltage network at ripple control frequency will be reduced. So the correct function of the ripple control installation could be affected.

If the resonance frequency of the reactor-capacitor arrangement is higher than the ripple control signal frequency the impedance at signal frequency is capacitive. This may lead to resonance with the inductive impedance of the distribution transformer and thus disturb the ripple control installation in a similar way as explained in **3.6.1** for a capacitor installation without reactors.

3.6.3 Tuned filter

Tuned filters may influence the signal of ripple control installations. The impedance of a tuned filter unit is capacitive for all frequencies lower than the resonance frequency and inductive for all higher frequencies. The impedance of the distribution transformer contributes, in the first case, to reduce the impedance at ripple control signal frequency in the high voltage network and, in the second case, to reduce the ripple control signal voltage in the low voltage network. In both cases, the ripple control installation may be disturbed.

If the ripple control signal frequency is between the resonance frequencies of two tuned filter units, total or partial compensation of the inductive impedance with respect to the capacitive impedance of the two filters may give a relatively high impedance at ripple control signal frequency. Disturbance may also be avoided, for example, by careful choice of the tuning frequencies and/or the capacitance and inductance values of the tuned filter units.

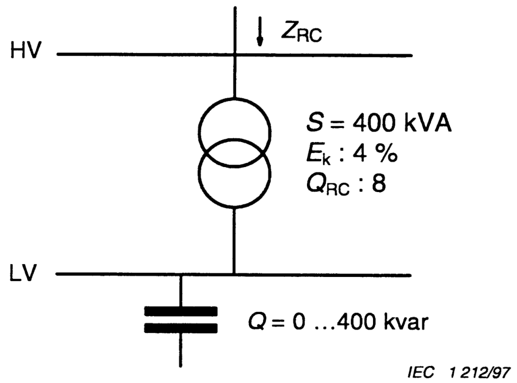

Figure 7a — One-line diagram of transformer-capacitor arrangement

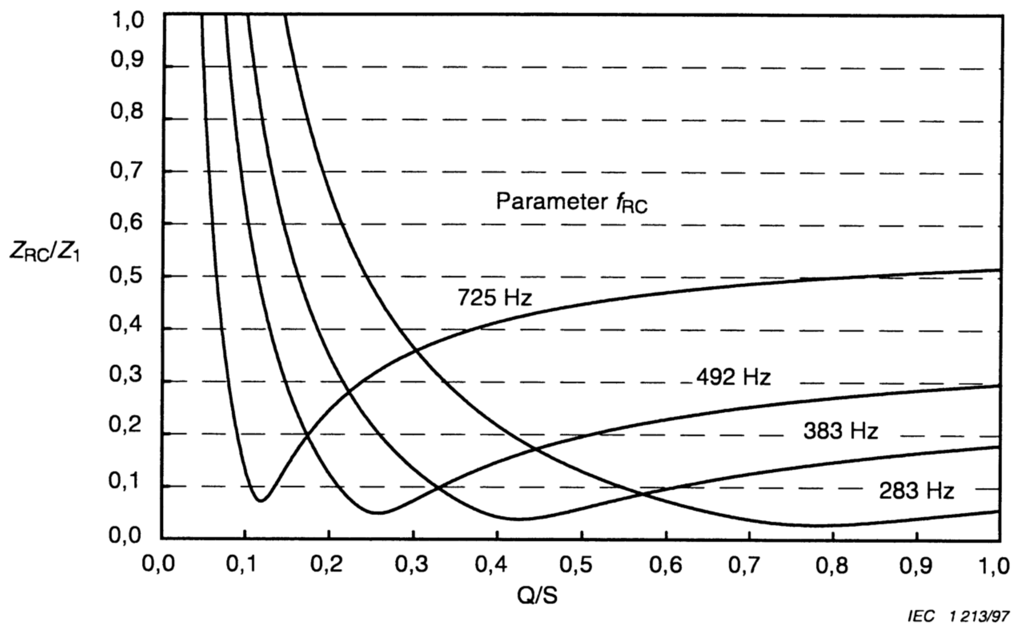

Figure 7b — Relative impedance Z_{RC}/Z_1

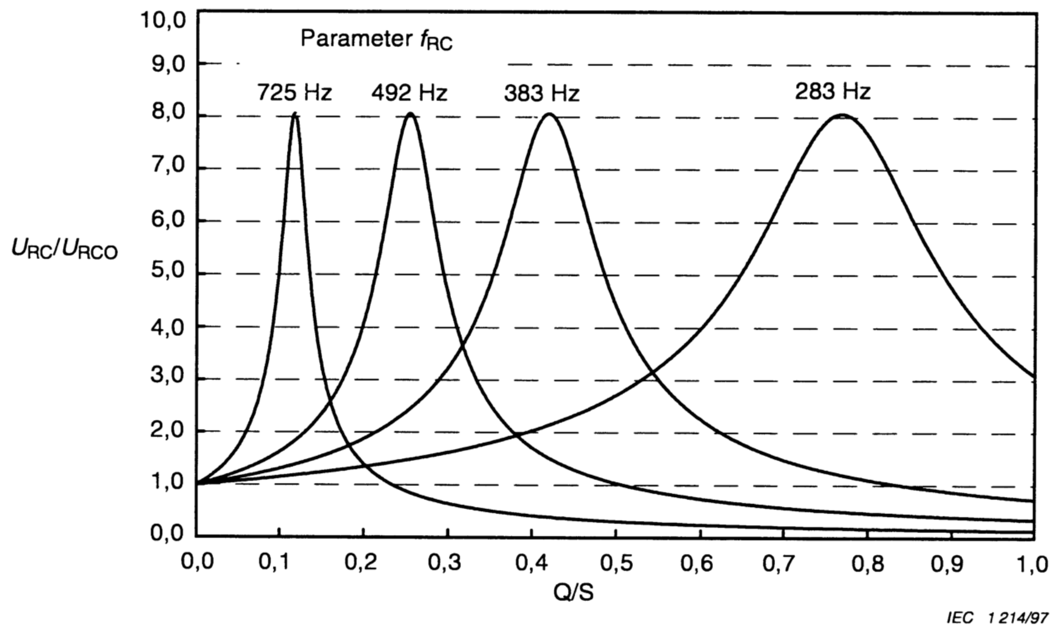

Figure 7c — Relative signal voltage U_{RC}/U_{RCO}

4 Shunt capacitors and filters for networks having a voltage above 1 000 V

4.1 Introduction

All the principles described in the low voltage section also apply to high voltage networks. There are however specific requirements applicable to this voltage.

4.2 Specific requirements

The system configuration and, consequently, the short-circuit power are generally variable in high voltage networks. Variations shall be considered for all conditions when designing equipment.

High voltage power factor correction equipment may be installed indoors or outdoors, the following having an effect on the design:

— adverse atmospheric conditions, pollution, etc, requiring increased creepage and clearance distances;

— climatic conditions;

— mechanical stress, seismic forces;

— solar radiation.

Harmonics generated by the electrical loads and any harmonics existing on the network have to be considered when designing power factor correction installations.

4.3 Choice of power factor correction installation

A network analysis should be carried out to determine the most appropriate equipment to be installed. Whenever possible existing harmonic distortion should be measured although the interpretation of the results should be considered with care.

The network analysis should take into account the following points:

— all network configurations should be considered, including exceptional and emergency arrangements as well as possible future extensions. Special attention shall be paid to electrical machines (generators, synchronous compensators), cable capacitance, line impedance, etc.;

— harmonic generation (distortion ratios) obtained in all the different working configurations. This should take into account the existing harmonic sources on the system. Measurements and/or calculation of the harmonic currents is necessary. Figures deduced from harmonic voltage distortion alone are not accurate as harmonics are generated by current not by voltage sources. When the user plans to install a filter on a system which is not separated from the utilities network by an interposing transformer or another significant impedance, the effect of all other shunt capacitors and filters on the network have to be considered;

— existing power factor correction installations, detuned and tuned filters;

— the influence of power factor correction installations and filters on ripple control installations shall be investigated to ensure that system malfunction does not occur.

4.4 Type of filters

Filter systems of 1st, 2nd, and 3rd order are usually considered (see Figure 8a, Figure 8b, Figure 8c, Figure 8d and Figure 8e). The order of a filter can be determined by the number of reactive components in the circuit. Damping circuits may be considered due to technical and/or economical reasons. If a damped filter is used, loss evaluation is necessary. The most frequently used harmonic orders for filter tuning are 5, 7, 11, 13, 17, 19, 23, 25.

When a harmonic distortion limit has to be guaranteed, account shall be taken of capacitor and reactor manufacturing tolerances. With filters it is not always possible to maintain both the harmonic distortion and the power factor within given limits.

4.5 Filter components selection

A high voltage filter normally consists of the following components:

— circuit-breaker;

— capacitors;

— reactors;

— resistors;

— protection equipment.

The determination of ratings for these components is usually based on the calculated stresses during worst service conditions. Harmonic currents generated by the electrical loads and any harmonic current or voltage existing an the network have to be considered when designing power factor correction or filter installation.

It should be checked that the manufacturing tolerances, the influence of temperature and ageing, the operation of internal or external fuses if any, the possible non-linearity of the filter components as well as the variations of the network frequency will not unacceptably influence the function of the filter.

4.5.1 Circuit-breaker

The switching of filters requires some special features of the switching device. The following aspects shall therefore be considered:

— the circuit-breaker shall be restrike-free;

— the rated voltage of the circuit-breaker shall be equal to or higher than the maximum network voltage with the filter in service;

— the circuit-breaker shall be designed for continuous current which can pass the filter at maximum source voltage, maximum frequency and capacitance deviation;

— the interrupting capacity shall be equal to or greater than the short-circuit current which can occur on the filter side of the circuit-breaker;

— the circuit-breaker shall have sufficient short-time current rating to withstand both system short-circuit faults and inrush currents associated with energizing;

— the type of the circuit-breaker shall be selected with respect to the expected frequency of switching operations.

4.5.2 Capacitors

The capacitor bank is the fundamental part in each filter equipment. A thorough study should therefore be performed in order to obtain optimum capacitor design.

The filter current consists of fundamental and harmonic frequency components. As the magnitude of harmonic components may be very high, it is necessary to take them into account when defining rated data of the capacitors.

The following definitions and designing criteria are specific to filter capacitors:

— rated capacitor voltage, rated capacitor current and tolerances: see the relevant capacitor standard;

— the ratings of a capacitor should make allowances for element failure or fuse operation and should co-ordinate with filter protection. During service, if the capacitance change exceeds the acceptable range for the filter, the filter should be disconnected from the system.

4.5.3 Reactors

When selecting filter reactors, the following aspects shall be considered:

— thermal load due to the maximum fundamental and harmonic currents;

— manufacturing tolerance of inductance: for most filter applications ± 3 % is acceptable. In special cases adjustment taps may be required;

— short-circuit current which can occur during fault conditions;

— linear characteristic within the current and frequency ranges;

— the effects of eddy current losses in adjacent metallic parts, for example equipment frame, earthing system and building structural steel.

4.5.4 Resistors

When selecting filter resistors, the following aspects should be considered:

— total r.m.s. current through the resistor;

— inductance of the resistor;

— manufacturing tolerance and temperature coefficient of the resistance.

4.5.5 Relay protection

The protection system normally consists of:

— harmonic overload protection;

— overcurrent protection;

— earth fault protection;

— undervoltage protection;

— unbalance protection of the capacitor bank.

4.6 Disturbance of ripple control installations by shunt capacitors and filters

The influence of power factor correction installations and filters on ripple control installations shall be investigated to ensure that system malfunction does not occur.

The tuning frequencies of the power factor correction installation should not be the same as the ripple control signal frequency, but far enough from it. Due to the inductive impedance of the line between the injection point of the ripple control installation and the power factor correction installation, the ripple control signal voltage may be reduced or increased. It will be reduced if the impedance of the power factor correction installation is inductive at ripple control signal frequency and increased if it is capacitive. It should be ensured that the influence on the ripple control signal voltage is within acceptable limits, referring to the general requirements of **3.6**.

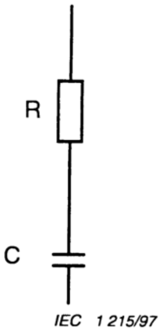

Figure 8a – 1st order filter

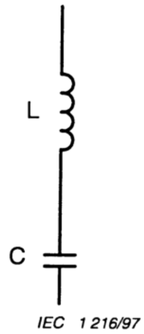

Figure 8b – 2nd order filter – band-pass filter

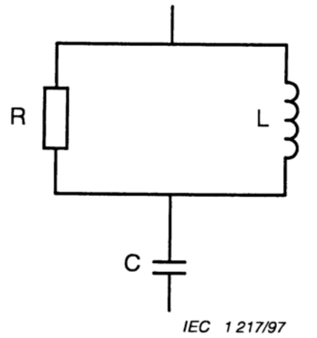

Figure 8c – 2nd order filter – damped filter with resistive element

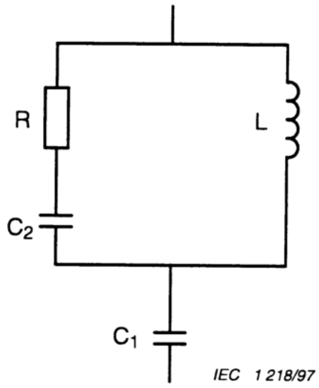

Figure 8d – 3rd order filter – damped filter

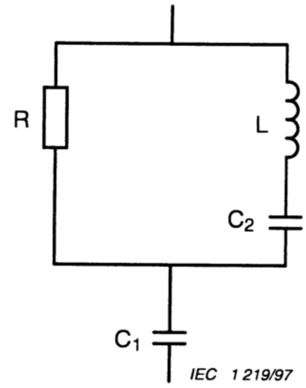

Figure 8e – 3rd order filter – C type

Figure 8 — Types of filters for high-voltage applications

Annex A (informative)
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IEC 61000-2-2:1990, *Electromagnetic compatibility (EMC) — Part 2: Environment — Section 2: Compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems.*

Annex ZA (normative) Normative references to international publications with their corresponding European publications

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies (including amendments).

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60050(131)	1978	International Electrotechnical Vocabulary (IEV) Chapter 131: Electric and magnetic circuits	—	—
IEC 60050(161)	1990	Chapter 161: Electromagnetic compatibility	—	—

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