

INTERNATIONAL STANDARD

NORME INTERNATIONALE



**Series capacitors for power systems –
Part 1: General**

**Condensateurs série destinés à être installés sur des réseaux –
Partie 1: Généralités**



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NORME INTERNATIONALE



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Part 1: General**

**Condensateurs série destinés à être installés sur des réseaux –
Partie 1: Généralités**

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**Series capacitors for power systems –
Part 1: General**

**Condensateurs série destinés à être installés sur des réseaux –
Partie 1: Généralités**

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INTERNATIONAL ÉLECTROTECHNICAL COMMISSION

SERIES CAPACITORS FOR POWER SYSTEMS –

Part 1: General

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IEC 60143-1 edition 5.1 contains the fifth edition (2015-06) [documents 33/578/FDIS and 33/580/RVD], its corrigendum (2017-04), and its amendment 1 (2023-11) [documents 33/690/CDV and 33/693/RVC].

In this Redline version, a vertical line in the margin shows where the technical content is modified by amendment 1. Additions are in green text, deletions are in strikethrough red text. A separate Final version with all changes accepted is available in this publication.

International Standard IEC 60143-1 has been prepared by IEC technical committee 33: Power capacitors and their applications.

This fifth edition constitutes a technical revision.

The main change with respect to the previous edition is that the endurance test has been replaced by an ageing test because voltage cycling is already performed in the cold duty test. The guide section has been expanded regarding long line correction and altitude correction. In addition the insulation tables and references to other standards have been updated.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 60143 series, published under the general title *Series capacitors for power systems*, can be found on the IEC website.

The committee has decided that the contents of this document and its amendment will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

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SERIES CAPACITORS FOR POWER SYSTEMS –

Part 1: General

1 Scope and object

This part of IEC 60143 applies both to capacitor units and capacitor banks intended to be used connected in series with an a.c. transmission or distribution line or circuit forming part of an a.c. power system having a frequency of 15 Hz to 60 Hz.

The primary focus of this standard is on transmission application.

The series capacitor units and banks are usually intended for high-voltage power systems. This standard is applicable to the complete voltage range.

This standard does not apply to capacitors of the self-healing metallized dielectric type.

The following capacitors, even if connected in series with a circuit, are excluded from this standard:

- capacitors for inductive heat-generating plants (IEC 60110-1);
- capacitors for motor applications and the like (IEC 60252 (all parts));
- capacitors to be used in power electronics circuits (IEC 61071);
- capacitors for discharge lamps (IEC 61048 and IEC 61049).

For standard types of accessories such as insulators, switches, instrument transformers, external fuses, etc. see the pertinent IEC standard.

NOTE 1 Additional requirements for capacitors to be protected by internal fuses, as well as the requirements for internal fuses, are found in IEC 60143-3. See also Annex C.

NOTE 2 Additional requirements for capacitors to be protected by external fuses, as well as the requirements for external fuses, are found in Annex A and Annex C.

NOTE 3 A separate standard for series capacitor accessories (spark-gaps, varistors, discharge reactors, current-limiting damping reactors, damping resistors, circuit-breakers, etc.), IEC 60143-2, has been revised and was completed in 2012. A separate standard for internal fuses for series capacitors, IEC 60143-3 has been revised and was completed in 2013.

NOTE 4 Some information regarding fuseless capacitor units and fuseless capacitor banks is found in Annex C.

The object of this standard is:

- to formulate uniform rules regarding performance, testing and rating;
- to formulate specific safety rules;
- to serve as a guide for installation and operation.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE If there is a conflict between this standard and a standard listed below, the text of IEC 60143-1 prevails.

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at www.electropedia.org)

IEC 60060-1:2010, *High-voltage test techniques – Part 1: General definitions and test requirements*

IEC 60071-1:2006, *Insulation co-ordination – Part 1: Definitions, principles and rules*

IEC 60071-2:1996, *Insulation co-ordination – Part 2: Application guide*

IEC 60143-2:2012, *Series capacitors for power systems – Part 2: Protective equipment for series capacitor banks*

IEC 60143-3:1998, *Series capacitors for power systems – Part 3: Internal fuses*

IEC 60143-4: 2010 *Series capacitors for power systems – Part 4: Thyristor controlled series capacitors*

IEC 60549:2013, *High-voltage fuses for the external protection of shunt capacitors*

IEC 60871-1: 2014 *Shunt capacitors for a.c power systems having a rated voltage above 1000V – Part 1: General*

IEC 62271-1:2007, *High-voltage switchgear and controlgear – Part 1: Common specifications*

IEEE Std. 693:1997, *IEEE Recommended Practice for Seismic Design of Substations*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1

ambient air temperature (for capacitors)

temperature of air at the proposed location of the capacitor installation

3.2

bypass switch

device such as a switch or circuit-breaker used in parallel with a series capacitor and its overvoltage protector to shunt line current for some specified time or continuously

Note 1 to entry: This device shall also have the capability of bypassing the capacitor during specified power system fault conditions. The operation of the device is initiated by the capacitor bank control, remote control or by an operator. The device may be mounted on the platform or on the ground near the platform. Besides bypassing the capacitor, this device shall also have the capability of inserting the capacitor into a circuit carrying a specified level of current.

3.3

capacitor

word used when it is not necessary to distinguish between the different meanings of the words capacitor unit and the assembly of capacitors associated with a segment

3.4

capacitor unit

unit

assembly of one or more capacitor elements in the same container with terminals brought out

[SOURCE: IEC 60050-436:1990, 436-01-04]

3.5

(capacitor) element

device consisting essentially of two electrodes separated by a dielectric

[SOURCE: IEC 60050-436:1990, 436-01-03]

3.6

capacitor losses

active power dissipated in the capacitor

Note 1 to entry: All loss-producing components should be included. For a unit, this includes losses from the dielectric, discharge device, internal fuses (if applicable) and internal connections. For the bank, this includes losses from the units, external fuses (if applicable) and busbars. See Annex B for additional discussion.

[SOURCE: IEC 60050-436:1990, 436-04-10]

3.7

cooling air temperature

temperature of cooling air measured at the hottest position in the capacitor assembly of a segment, under rated current and steady-state conditions, midway between two units

Note 1 to entry: If only one unit is involved, it is the temperature measured at a point approximately 0,1 m away from the capacitor container and at two-thirds of the height from its base.

3.8

degree of compensation

k

degree of series compensation, k (of a line section) is

$$k = 100 (X_C / X_L) \%$$

where

X_C is the capacitive reactance of the series capacitor;

X_L is the total positive sequence inductive reactance of the transmission line section on which the series capacitor is applied.

3.9

discharge device (of a capacitor)

device connected across the terminals of the capacitor or built into the capacitor unit, capable of reducing the residual voltage across the capacitor effectively to zero after the capacitor has been disconnected from the supply

Note 1 to entry: Further requirements on the size of the discharge device are found in 8.1.

[SOURCE: IEC 60050-436:1990, 436-03-15, modified (modified definition, addition of Note 1 to entry)]

3.10

external fuse (of a capacitor)

fuse connected in series with a capacitor unit or with a group of parallel units

3.11

fuseless capacitor bank

capacitor bank without any fuses, internal or external, constructed of parallel strings of capacitor units. Each string consists of capacitor units connected in series

Note 1 to entry: See Annex C for an explanation of "string".

3.12

highest voltage of a three-phase system

highest r.m.s. phase-to-phase voltage which occurs under normal operating conditions at any time and at any point of the system

Note 1 to entry: It excludes voltage transients (such as those due to system switching) and temporary voltage variations due to abnormal system conditions (such as due to faults or sudden disconnection of large loads).

3.13

highest voltage for equipment

U_m

highest r.m.s. value of phase-to-phase voltage for which the equipment is designed in respect of its insulation as well as other characteristics which relate to this voltage in the relevant equipment standards

Note 1 to entry: This voltage is the maximum value of the highest voltage of the system for which the equipment may be used.

[SOURCE: IEC 60050-604:1987, 604-03-01]

3.14

insulation level

U_i

non-simultaneous combination of test voltages (power-frequency (U_{ipf}) or switching impulse, and lightning impulse) which characterizes the insulation of the capacitor with regard to its capability of withstanding the electric stresses between terminals and earth, between phases and between terminals and metalwork (e.g. platform) not at earth potential

3.15

internal fuse of a capacitor

fuse connected inside a capacitor unit, in series with an element or group of elements

[SOURCE: IEC 60050-436:1990, 436-03-16]

3.16

limiting voltage

U_{lim}

maximum peak of the power frequency voltage occurring between capacitor unit terminals immediately before or during operation of the overvoltage protector, divided by $\sqrt{2}$

SEE: 5.1.4

Note 1 to entry: This voltage appears either during conduction of the varistor or immediately before ignition of the spark gap.

3.17

line terminal

terminal to be connected to the power system

[SOURCE: IEC 60050-436:1990, 436-03-01, modified (modified definition)]

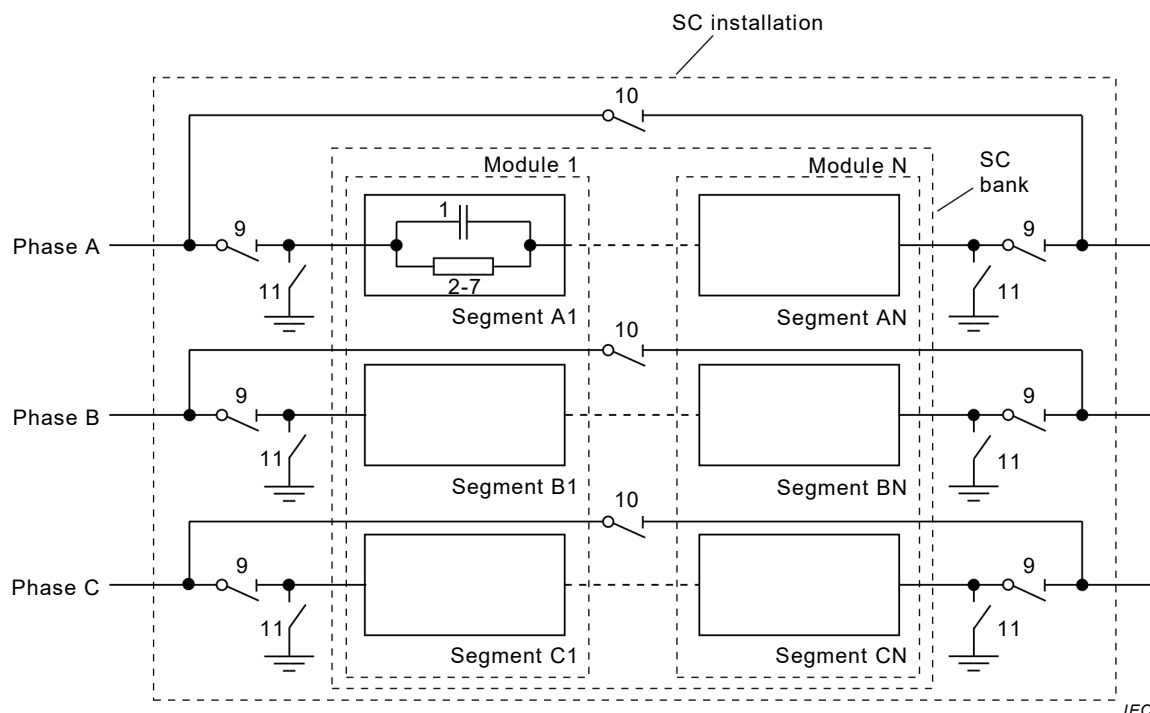
3.18

module (of a series capacitor)

switchable step of a series capacitor consisting of identical segments in each phase (see Figure 1), which furthermore are also equipped with provisions for a common operation of the bypass switch of each of these segments

Note 1 to entry: The bypass switch of a module is normally operated on a three-phase basis. However, in some applications for protection purposes, the bypass switch may be required to temporarily operate on an individual phase basis.

Note 2 to entry: Figure 1 shows a typical nomenclature of a series capacitor installation.



Key

- 1 assembly of capacitor units
- 2-7 main protective equipment (Figure 2c) and Annex D)
- 9 isolating disconnector
- 10 bypass disconnector
- 11 earth switch

NOTE 1 A SC Installation includes a SC Bank plus 9, 10 and 11.

NOTE 2 Most series capacitors are configured with a single module, unless the reactance and current requirements result in a voltage across the bank that is impractical for the supplier to achieve with one module. Normally each module has its own bypass switch, but a common bypass switch may be used for more than one module. See clause 10.2.3 for additional details.

Figure 1 – Typical nomenclature of a series capacitor installation

3.19

overvoltage protector (of a series capacitor)

quick-acting device (usually MOV or a self triggered spark gap) which limits the voltage across the capacitor to a permissible value when that value would otherwise be exceeded as a result of a circuit fault or other abnormal power system conditions

3.20

power frequency withstand voltage

U_{ipf}

wet power frequency withstand voltage of bushings and insulators

3.21

protective level

U_{pl}

magnitude of the maximum peak of the power frequency voltage appearing across the overvoltage protector during a power system fault

Note 1 to entry: The protective level may be expressed in terms of the actual peak voltage across a segment or in terms of the per unit of the peak of the rated voltage across the capacitor (see 5.1.4, 10.4 and 10.5). This voltage appears either during conduction of the varistor or immediately before ignition of the spark gap.

3.22

rated capacitance (of a capacitor)

C_N

capacitance value for which the capacitor has been designed

3.23

rated current of a capacitor

I_N

r.m.s. value of the alternating current for which the capacitor has been designed

[SOURCE: IEC 60050-436:1990, 436-01-13]

3.24

rated frequency (of a capacitor)

f_N

frequency of the system in which the capacitor is intended to be used

[SOURCE: IEC 60050-436:1990, 436-01-14, modified (modified definition)]

3.25

rated output (of a capacitor)

Q_N

reactive power derived from rated reactance and rated current

Note 1 to entry: For the bank, the rated three-phase reactive power rating in Mvar (Q_N) is defined by the equation:

$$Q_N = 3 \times I_N^2 \times X_N$$

where

I_N is the rated current, in kA;

X_N is the rated reactance, in Ω .

3.26

rated reactance (of capacitor)

X_N

reactance of each phase of the series capacitor at rated frequency and 20 °C dielectric temperature

3.27

rated voltage (of the bank)

power system phase-to-phase voltage for which the phase-to-ground insulation system is designed

3.28

rated voltage (of a capacitor)

U_N

r.m.s. value of the voltage between the terminals, derived from rated reactance and rated current $U_N = X_N \times I_N$

3.29

residual voltage (of a capacitor)

voltage remaining between terminals of a capacitor at a given time following disconnection of the supply

3.30**segment (of a series capacitor)**

single-phase assembly of groups of capacitors which has its own voltage-limiting devices and relays to protect the capacitors from overvoltages and overloads

SEE: Figure 1

Note 1 to entry: Segments are not normally separated by isolating disconnectors. More than one segment can be on the same insulated platform.

3.31**series capacitor bank (or bank)**

three-phase assembly of capacitors with the associated protection and insulated support structure

Note 1 to entry: The bank may include one or more modules (see Figure 1).

3.32**series capacitor installation**

series capacitor bank and its accessories including the bypass and isolating disconnectors

[SOURCE: IEC 60050-436:1990, 436-01-07, modified (addition of "including the bypass and isolating connectors")]

3.33**steady-state condition**

thermal equilibrium attained by the capacitor at constant output and at constant ambient air temperature

3.34**sub-segment**

portion of a segment that includes a single-phase assembly of capacitor units and an associated protective device, discharge current limiting and damping equipment, and selected protection and control functions, but does not have a dedicated by-pass switch

3.35**tangent of loss angle (of a capacitor)** **$\tan \delta$**

ratio between the equivalent series resistance and the capacitive reactance of a capacitor at specified sinusoidal alternating voltage and frequency

Note 1 to entry: Tangent of loss angle can also be expressed as the capacitor losses divided by the reactive power of the capacitor.

3.36**varistor coordinating current**

magnitude of the maximum peak of power frequency varistor current associated with the protective level

Note 1 to entry: The varistor coordinating current waveform is considered to have a virtual front time of 30 to 50 μs . The tail of the waveform is not significant in establishing the protective level voltage.

4 Service conditions**4.1 Normal service conditions**

Series capacitor banks shall be suitable for operation at their specified current, voltage, and frequency ratings and specified fault sequences under the following conditions:

- a) The elevation does not exceed 1 000 m above sea level.

- b) The indoor and outdoor ambient temperatures are within the limits specified by the purchaser.
 - c) The ice load does not exceed 19 mm (if applicable).
 - d) Wind velocities are no greater than 128 km/h.
 - e) The horizontal seismic acceleration (if applicable) of the equipment does not exceed 0,2 g and the vertical acceleration does not exceed 0,16 g when applied simultaneously at the base of the support insulators. For the purposes of this requirement, the values of acceleration are static.
- NOTE This is the “low seismic qualification level” defined in IEEE Std. 693. The seismic acceleration and the maximum wind do not have to be considered to occur simultaneously.
- f) The snow depth (if applicable) does not exceed the height of the foundations for the platform support insulators. (A typical maximum height is 1 m.)
 - g) The solar radiation does not exceed 1 000 W/m².

4.2 Ambient air temperature categories

Capacitors are classified in temperature categories, each category being specified by one number followed by one letter. The number represents the lowest ambient air temperature at which the capacitor may operate. The letter represents the upper limit of temperature variation range, having the maximum value specified in Table 1.

Table 1 – Letter symbols for upper limit of temperature range

Symbol	Ambient air temperature °C		
	Maximum	Highest mean over any period of	
		24 h	1 year
A	40	30	20
B	45	35	25
C	50	40	30
D	55	45	35

The temperature categories cover a total temperature range from –50 °C to +55 °C. The lowest ambient air temperature at which the capacitor may be operated should be chosen from the five preferred values +5 °C, –5 °C, –25 °C, –40 °C and –50 °C.

Any combination of minimum and maximum values can be chosen for the standard temperature category of a capacitor, for example –40/A or –5/C.

Table 1 is based on service conditions in which the capacitor does not influence the ambient air temperature (e.g. outdoor installations). If the capacitor influences the air temperature, the ventilation and/or choice of capacitor shall be such that the limits of Table 1 are maintained. The cooling air temperatures in such installations shall not exceed the temperature limits of Table 1 by more than 5 °C.

NOTE The temperature values according to Table 1 can be found in the meteorological temperature tables covering the installation site.

4.3 Abnormal service conditions

The application of series capacitor banks at other than the normal service conditions shall be considered as special and shall be identified in the purchaser’s specification. Examples of such conditions are as follows:

- a) Service conditions other than those listed in 4.1.
- b) Exposure to excessively abrasive and conducting dust.
- c) Exposure to salt, damaging fumes, or vapors.
- d) Swarming insects.
- e) Flocking birds.
- f) Conditions requiring over-insulation or extra leakage distance on insulators.
- g) Seismic accelerations at the “moderate or high seismic qualification levels” as defined in IEEE Std. 693.

4.4 Abnormal power system conditions

Abnormal power system conditions include:

- a) Continuous harmonic currents in the power system.
- b) The transmission line on which the series capacitor bank is located does not have phase transpositions so the reactances of each phase of the line are not approximately equal.

5 Quality requirements and tests

5.1 Test requirements for capacitor units

5.1.1 General

This clause gives the test requirements for capacitor units.

NOTE Test requirements for other equipment are found in IEC 60143-2, IEC 60143-3, IEC 60143-4 and Annex A of this standard.

Supporting insulators, switches, instrument transformers, external fuses, etc., shall be in accordance with the pertinent IEC standard.

5.1.2 Test conditions

Unless otherwise specified for a particular test or measurement, the temperature of the capacitor dielectric shall be in the range +5 °C to +35 °C. When a correction has to be applied, the reference temperature to be used is +20 °C, unless otherwise agreed between the manufacturer and the purchaser. It may be assumed that the dielectric temperature of the capacitor unit is the same as the ambient air temperature, provided that the capacitor has been left in a non-energized state in a constant ambient air temperature for an adequate period.

The a.c. tests and measurements shall be carried out at a frequency of 50 Hz or 60 Hz irrespective of the rated frequency of the capacitor unless otherwise specified.

5.1.3 Voltage limits as established by overvoltage protector

5.1.3.1 General

a) Purpose

The overvoltage protector is a quick-acting device which limits the instantaneous voltage across the series capacitor to a permissible value when that value would otherwise be exceeded as a result of a power-system fault or other abnormal network condition.

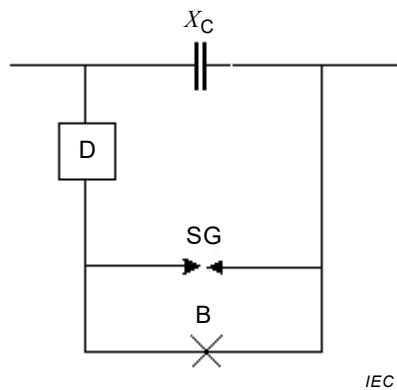
b) Classification

Three common alternatives are listed below (see Figure 2):

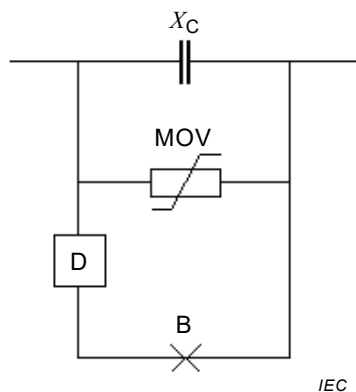
- single protective spark gap (type K1), see Figure 2a)

- varistor (gapless) (type M1), see Figure 2b)
- varistor with bypass gap (type M2), see Figure 2c)

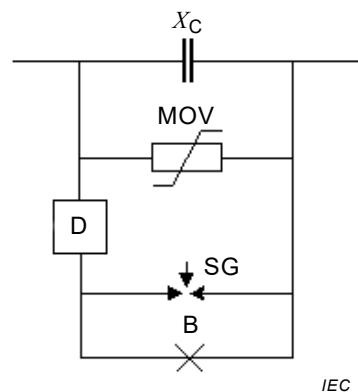
NOTE If the sparkover voltage of an overvoltage protector is dependent on air density, U_{pl} is understood to correspond to the conditions resulting in the highest sparkover voltage, i.e. to the highest air pressure and the lowest temperature. Also, the tolerance on sparkover voltage to be taken into account when determining U_{pl} .



2a) Single gap (type K1)



2b) MOV (type M1)



2c) MOV + bypass gap (type M2)

Figure 2 – Classification of overvoltage protection

5.1.3.2 Type K overvoltage protector

When the gap sparks over due to an excessive line current caused by a fault in the system, an arc is sustained until de-energizing the line or closing a bypass switch.

During arcing of the gap, the capacitor is exposed to one voltage peak whose value shall not exceed U_{pl} . The capacitor is subjected to a transient discharge once only at every operation of the gap.

5.1.3.3 Type M overvoltage protector

The varistor is permanently connected across the capacitor terminals. When the bank is operated at normal load current, a given but very low current passes through the varistor.

In the case of a fault external to the line concerned, the series capacitor becomes automatically reinserted when the fault is disconnected. Even during such a fault the series capacitor exerts a certain compensating effect. For this reason, in many cases, the U_{pl} chosen with Type M can be lower than with Type K overvoltage protectors. On the other hand,

in the event of a short-circuit at the compensated line itself, the circuit-breakers at the ends of the line will be opened.

The varistor shall be designed to withstand the thermal stresses occurring during the overload conditions and during the system swing according to 10.3, and those of the maximum line fault current.

In the event of prolonged duration of an external fault, e.g. due to malfunction of the line protection, the varistor may become thermally overloaded. Also short-circuits at the compensated line may imply such high currents that it is not economical to dimension the varistor accordingly. In order to protect the varistor in such cases, it may be bypassed by a switch or a forced, triggered spark-gap.

5.1.4 Determination of protective level voltage U_{pl} and U_{lim}

The value of a test voltage (U_t) between terminals depends on the type of the overvoltage protector and its protective level voltage U_{pl} (see 5.1.3).

The limiting voltage U_{lim} (kV r.m.s.) for the capacitor unit is related to the protective level voltage of the actual phase or segment U_{pl} (kV peak) according to equation (1).

$$U_{lim} = U_{pl} / (s \times \sqrt{2}) \quad (1)$$

where s is the number of capacitor units in series which spans U_{pl} .

Further clarifications are given in 10.4 and 10.5.

5.2 Classification of tests

5.2.1 General

Tests on equipment that constitute the capacitor bank are designated as routine tests, type tests and special tests. Additional tests are typically performed after the bank is installed. These tests are discussed in IEC 60143-2.

5.2.2 Routine tests

- a) Capacitance measurement (see 5.3)
- b) Capacitor loss measurement (see 5.4)
- c) Voltage test between terminals (see 5.5)
- d) AC voltage test between terminals and container (see 5.6)
- e) Test on internal discharge device (see 5.7)
- f) Sealing test (see 5.8)
- g) Discharge test of internal fuses (see 3.1.2 of IEC 60143-3).

The test sequence is not necessarily that indicated above.

The routine tests shall be carried out by the manufacturer on every capacitor unit before delivery.

5.2.3 Type tests

- a) Thermal stability test (see 5.9)

- b) AC voltage test between terminals and container (see 5.10)
- c) Lightning impulse voltage test between terminals and container (see 5.11).
- d) Cold duty test (see 5.12)
- e) Discharge current test (see 5.13).

The type tests are carried out in order to ensure that the capacitor unit complies with the contractual characteristics and with the operational requirements as specified in this standard.

It is not essential that all type tests are carried out on the same capacitor unit.

The above list of type tests does not indicate any test sequence.

Unless otherwise specified, every capacitor sample to which a type test will be applied shall have first withstood satisfactorily the application of all the routine tests.

When a type test has previously been successfully performed on equipment of similar design at stress or duty levels that are equal to or greater than that required for the specific application, then the manufacturer does not have to repeat the test if a written report describing the previous test is provided. The manufacturer shall also provide an explanation of how the previous test satisfies the requirements for the specific application.

New type tests shall be performed for a specific project, only if the equipment design is new or if a critical manufacturing process is new, or if it is to be applied at a higher stress or duty level than previously tested designs or if specifically contracted by the purchaser.

5.2.4 Special test (ageing test)

The special test consists of an ageing test which is to be made according to 4 of IEC TS 60871-2:2014.

The ageing test shall be carried out only after a contractual agreement between the manufacturer and purchaser.

5.3 Capacitance measurement (routine test)

5.3.1 Measuring procedure

The capacitance of each capacitor unit shall be measured at 0,9 to 1,1 times the rated voltage, using a method that excludes errors due to harmonics. Measurement at another voltage is permitted, provided that an appropriate correction factor is agreed upon between the manufacturer and purchaser.

The accuracy of the measuring method shall be such that the tolerances according to 5.3.2 can be respected. The repeatability of the measuring method shall be such that a punctured element or an operated internal fuse can be detected.

The final capacitance measurement shall be carried out after the voltage test (see 5.5). In order to reveal any change in capacitance, e.g. due to puncture of an element, or failure of an internal fuse, a preliminary capacitance measurement shall be made before the other voltage routine tests. This preliminary measurement shall be performed with a voltage not higher than $0,15 U_N$.

The manufacturer shall, on agreement, provide curves or tables showing:

- the capacitance in steady-state condition at rated output as a function of ambient air temperature within the temperature category;

- the capacitance as a function of the dielectric temperature within the temperature category.

5.3.2 Capacitance tolerance

The tolerances refer to capacitance values measured at 0,9 to 1,1 times the rated voltage under the conditions of 5.3.1.

The capacitance at reference temperature (see 5.1.2) shall not differ from the rated capacitance by more than:

- $\pm 7,5$ % for units;
- $\pm 5,0$ % for banks with a rated output less than 30 Mvar;
- $\pm 3,0$ % for banks with a rated output of 30 Mvar or more.

Furthermore, the capacitance shall not differ by more than:

- 3,0 % between any two phases or segments within the same module with a bank rated output less than 30 Mvar;
- 1,0 % between any two phases or segments within the same module with a bank rated output of 30 Mvar or more.

Closer tolerances may be required for capacitors in more critical applications.

The manufacturer shall organize the assembly of the capacitor units.

5.4 Capacitor loss measurement (routine test)

5.4.1 Measuring procedure

The capacitor losses (or $\tan \delta$) shall be measured at 0,9 to 1,1 times rated voltage using a method that excludes errors due to harmonics.

The measuring equipment should be calibrated according to IEC 60996 or to another method that will give the same or an improved accuracy.

The tangent of loss angle of impregnated low-loss dielectrics decreases considerably during the first hours of initial energization. This decrease is not correlated to the $\tan \delta$ variation with temperature. The initial $\tan \delta$ may vary also between identical units manufactured simultaneously. The final “stabilized” values are, however, usually within close limits. The $\tan \delta$ measured initially at the routine test should be regarded as a rough indication only. For contractual purposes, only measurements of units should be used which have undergone the thermal stability test before or, alternatively, units may be conditioned according to manufacturers’ practice.

5.4.2 Loss requirements

The capacitor losses refer to values measured under the conditions of 5.4.1.

The requirements regarding capacitor losses may be agreed upon between the manufacturer and purchaser.

Further information regarding capacitor losses are given in Annex B.

The manufacturer should, by agreement, provide curves or tables showing the stabilized capacitor losses (or $\tan \delta$) under steady-state condition at rated output as a function of ambient air temperature within the temperature category.

5.4.3 Losses in external fuses

Losses in external fuses shall be calculated using the nominal a.c. resistance (specified by the fuse manufacturer at 20 °C) times the square of rated capacitor current.

5.5 Voltage test between terminals (routine test)

The capacitor units shall be subjected to a d.c. test at $1,7 U_{lim}$ ($1,2 \times \sqrt{2} \times U_{lim}$) for overvoltage protectors Type K and M. The test voltage value shall not be less than $4,3 U_N$. The duration of the test shall be 10 s.

During the test, neither puncture nor flashover shall occur.

If the capacitors are to be retested, a voltage of 75 % of U_t is recommended for the re-test.

5.6 AC voltage test between terminals and container (routine test)

Capacitor units having both terminals insulated from the container shall be subjected for 10 s to an a.c. voltage test applied between the terminals (joined together) and the container. The value of the test voltage shall be chosen according to 6.1.3.2.

During the test, neither puncture nor flashover shall occur.

The test shall be performed even if one of the terminals in service is intended to be connected to the container.

Units having one terminal permanently connected to the container shall not be subjected to this test.

5.7 Test on internal discharge device (routine test)

The resistance of the internal discharge device, if any, shall be checked by a measurement. The method may be selected by the manufacturer.

The test shall be made after the voltage test of 5.5.

5.8 Sealing test (routine test)

The unit (in non-painted state) shall be exposed to a test that will effectively detect any leak of the container and bushing(s). The test procedure is left to the manufacturer, who shall describe the test method concerned.

If no procedure is stated by the manufacturer the following test procedure shall apply:

Non-energized capacitor units shall be heated throughout so that, for at least 2 h, all parts reach a temperature not less than 20 °C above the maximum value in Table 1. No leakage shall occur. It is recommended that a suitable leakage indicator should be used.

5.9 Thermal stability test (type test)

5.9.1 Measuring procedure

The capacitor unit subjected to the test shall be placed between two barrier units with the same rating and energized at the same voltage as the test capacitor. The barrier units shall have almost the same container dimensions as the unit under test. Alternatively, two dummy capacitors both containing resistors may be used as barrier units. Dissipation in the resistors shall be adjusted to such a value that the case temperatures of the dummy capacitors are

equal to or higher than those of the test capacitor. The temperature of the units shall be measured at "equal" spots which shall not be exposed to direct heat radiation from another unit. The separation between the units shall be equal to or less than the normal spacing. The assembly shall be placed in still air, in a heated enclosure, in the most unfavourable thermal position according to the manufacturer's instructions for mounting on site.

The ambient air temperature shall be maintained at the appropriate value shown in Table 2 (tolerance ± 2 °C). It shall be checked by means of a thermometer having a thermal time constant of approximately 1 h. This thermometer shall be shielded so that it is exposed to the minimum possible thermal radiation from the energized sample and the energized barrier units.

**Table 2 – Ambient air temperature
in thermal stability test**

Symbol	Temperature °C
A	40
B	45
C	50
D	55

The test capacitor shall be subjected to an a.c. voltage of substantially sinusoidal form for a period of at least 48 h. The magnitude of the voltage shall be kept constant throughout the test. Its value shall be derived from the measured capacitance (see 5.3.1) to give a calculated output of the capacitor equal to 1,44 times the rated output. The test value 1,44 Q_N is related to the 8 h overload current 1,1 I_N according to 7.1. If this 8 h overcurrent has been increased, the factor 1,44 shall be correspondingly increased in square (see also 10.3.2).

During the last 6 h, the temperature of the container shall be measured at least four times. Throughout this period of 6 h, the temperature rise shall not increase by more than 1 K. Should a greater change be observed, the test may be continued until the above requirement is met for four consecutive measurements during a subsequent 6 h period.

Before and after the test, the capacitance shall be measured (see 5.3.1) within the temperature range according to 5.1.2 and the two measurements shall be corrected to the same dielectric temperature.

The difference between the two measurements shall be less than that which would correspond to a puncture of an element or which would initiate operation of an internal fuse. When interpreting the results of the measurements, the following factors shall be taken into account:

- the repeatability of the measurements;
- the fact that internal change in dielectric may cause a small change of capacitance, without puncture of any element or operation of an internal fuse having occurred. When checking whether the temperature conditions are satisfactory, voltage fluctuation, frequency and ambient air temperature during the test should be taken into account. For this reason, it is advisable to plot these parameters and the temperature rise of the container as a function of time.

Units intended for 60 Hz installation may be tested with 50 Hz and vice versa, provided that the specified output is applied. For units rated below 50 Hz, the test conditions should be agreed between the manufacturer and purchaser.

5.9.2 Capacitor loss measurement

The capacitor losses (or $\tan \delta$) shall be measured at the end of the thermal stability test. The measuring voltage shall be that of the thermal stability test. Otherwise subclause 5.4.1 applies.

The value of $\tan \delta$ measured shall not exceed the value declared by the manufacturer or the value agreed upon between the manufacturer and purchaser.

5.10 AC voltage test between terminals and container (type test)

Capacitor units having both terminals insulated from the container shall be subjected to a test voltage applied for 1 min between the terminals joined together and the container. The value of the test voltage shall be chosen according to 6.1.3.2.

Units having one terminal permanently connected to the container shall also be subjected to a 1 min a.c. voltage test between the terminals to check the adequacy of the insulation to container. The test voltage is proportional to the rated voltage and is calculated according to 6.1.3.3. Whenever the voltage of this test exceeds the dielectric test requirement, the test unit's dielectric composition may be modified, for example by increasing the number of elements in series, to avoid dielectric failure. However, the insulation to container shall not be changed. Alternatively, this test may be completed, using a similar unit with two isolated terminals having the same insulation to the container.

The test is dry for units to be used indoors. For units to be used outdoors, it is performed in artificial rain (IEC 60060-1). The position of the bushings when subjected to a test in artificial rain shall correspond to their position in service.

During the test, neither puncture nor flashover shall occur.

Units intended for outdoor installation may be subjected to a dry test only if the manufacturer can supply a separate type test report showing that the bushings will withstand the wet test voltage for 1 min. The position of the bushing in this separate type test should correspond to the service position.

5.11 Lightning impulse voltage test between terminals and container (type test)

This test is applicable only to units having all terminals insulated from the container, and with the containers connected to earth (ground).

The lightning impulse test shall be made in accordance with IEC 60060-1 but with a waveform of 1,2/50 μ s to 5/50 μ s having a crest value corresponding to the insulation level of the unit according to 6.1.1.

Fifteen impulses of positive polarity followed by 15 impulses of negative polarity shall be applied between bushings joined together and the container. After the change of polarity, it is permissible to apply some impulses of lower amplitude before the application of the test impulses.

The capacitor is considered to have passed the test if

- no internal puncture has occurred,
- not more than two external flashovers occurred at each polarity,
- the waveshape has revealed no irregularities or no significant deviation from recordings at reduced test voltage.

5.12 Cold duty test (type test)

The objective of this test is to demonstrate that the capacitors of the bank can withstand an overvoltage at the protective level followed by an overcurrent condition with the capacitors initially at the lowest ambient temperature.

The voltages applied during this test shall be at power frequency and the waveform substantially sinusoidal. The test circuit shall be suitably damped to reduce transients that exceed the prescribed power frequency voltages.

The cold duty test may be performed on either a standard unit or on a special unit having the characteristics described in IEC 60871-1, sub-clauses 16.5.2 and 16.5.3.

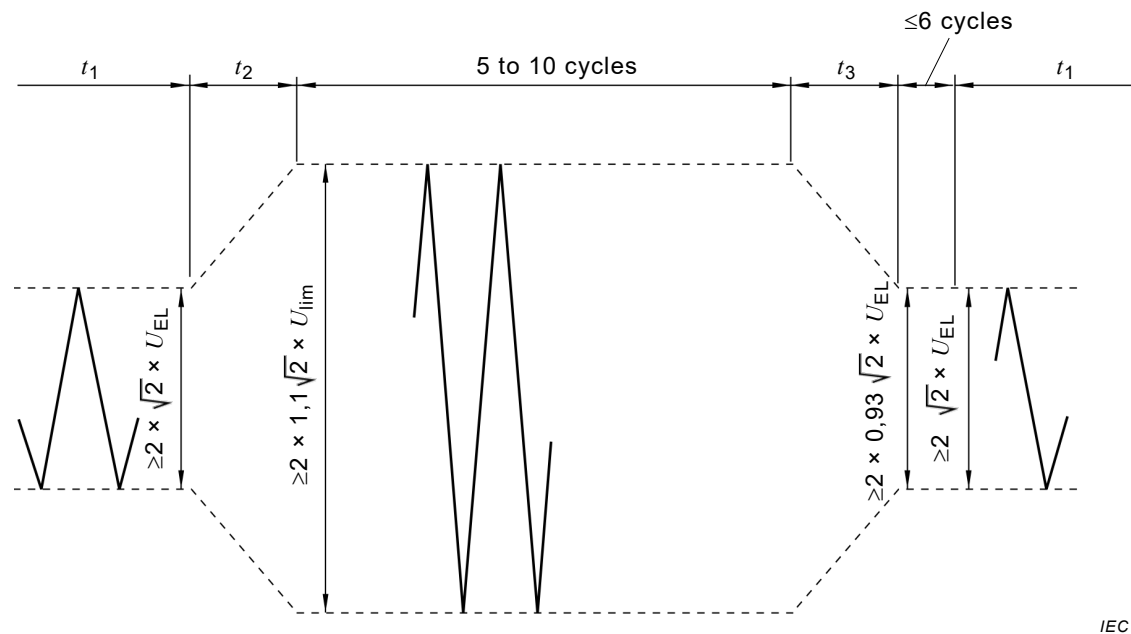
To prepare for the test, the test unit shall be placed in a refrigerator and the unit cooled until the dielectric temperature is equal to or lower than the lowest temperature of the temperature category.

Within 10 min after being removed from the refrigerator, the unit shall be exposed to U_{EL} (between terminals) for 30 s. Thereafter, an overvoltage of $1,1 U_{lim}$ (but at least $2,25 U_N$) shall be applied without any voltage interruption for a period of 5 to 10 cycles. After this the overvoltage of U_{EL} is maintained again without any voltage interruption (Figure 3) for an interval of 1,5 min to 2 min. Then another equal overvoltage sequence shall be applied, and so on until 50 power frequency overvoltage periods of $1,1 U_{lim}$ followed by U_{EL} have been applied (see Figure 3).

After the last overvoltage period at $1,1 U_{lim}$, a voltage of U_{EL} shall be maintained for a time of 30 min.

The magnitude of U_{EL} shall be either $1,2 U_N$ or the voltage corresponding to the maximum 30 min overload condition following system disturbances (see Clause 7 and 10.3.1) whichever is higher.

Before and after the test, the capacitance shall be measured according to 5.3.1 and the two measurements shall be corrected to the same dielectric temperature (see 5.1.2). There shall be no significant change of capacitance for these measurements and, in any case, it shall be less than the change corresponding to the puncture of an element or the operation of an internal fuse. When interpreting the results of the measurements, the factors stated in 5.9.1 shall be taken into account.



The time t_1 is the interval of 1,5 min to 2 min between two consecutive overvoltage applications. The times t_2 and t_3 depend on the test circuit parameters and should be as short as possible.

Figure 3 – Time and amplitude limits for an overvoltage period waveform

5.13 Discharge current test (type test)

This test includes discharges with two different sets of parameters. The first test is intended to demonstrate that the units can withstand the stresses that may occur during the rare instance of a flashover that bypasses the damping circuit. The second test is intended to demonstrate that the units can withstand the discharge current associated with operation of the gap or closure of the bypass switch.

NOTE The discharge frequency should approximate that of the application.

For the first test, the capacitor unit shall be charged to a d.c. voltage of $\sqrt{2} U_{lim}$ and then discharged once through a circuit having an impedance as low as possible. The discharge circuit may be implemented with a small fuse wire or a shorting switch.

For the second test, the same unit shall then be charged to a d.c. voltage of $1,6 U_{lim}$ ($1,1 \times \sqrt{2} U_{lim}$) and discharged through a circuit which satisfies the following conditions:

- the peak value of the discharge current shall be not less than 110 % of that resulting from conduction of the gap or the closure of the bypass switch;
- the I^2t of the discharge current shall be at least 10 % more than that associated with the conduction of the gap or the closure of the bypass switch (see IEC 60143-2).

This discharge shall be repeated 10 times at intervals of less than 20 s. Within 10 min after the last discharge, the unit shall be subjected to a voltage test between terminals according to 5.5.

Before and after the test, the capacitance shall be measured according to 5.3.1 and the two measurements shall be corrected to the same dielectric temperature (see 5.1.2). There shall be no significant change of capacitance at these measurements and, in any case, it shall be less than the change corresponding to the puncture of an element or to the operation of an internal fuse. When interpreting the results of the measurements, the factors stated in 5.9.1 shall be taken into account.

6 Insulation level

6.1 Insulation voltages

6.1.1 Standard values

The insulation withstand voltages of the capacitor units and of the capacitor installation shall be chosen from the standard values prescribed in IEC 60071-1 and IEC 60071-2.

The standardized values of the highest voltage for equipment are divided into two ranges:

- a) **Range I:** Above 1 kV to 245 kV included. This range covers both transmission and distribution systems. The different operational aspects, therefore, shall be taken into account in the selection of the rated insulation level of the equipment.
- b) **Range II:** Above 245 kV. This range covers mainly transmission systems. The association of standard withstand voltages with the highest voltage for equipment has been standardized to benefit from the experience gained from the operation of systems designed according to IEC standards and to enhance standardization.

Standard withstand voltages are associated with the highest voltage for equipment according to Table 3 for range I and Table 4 for range II.

The purchaser shall specify which of the alternative test voltages shall be applied.

NOTE In North America other values of U_m and of rated withstand voltages are in use. Table 5 contains such values which, however, do not constitute IEC standard insulation levels.

6.1.2 Insulation to earth and between phases

The test voltages shall be selected among the standard values in accordance with 6.1.1.

For installations at altitudes exceeding 1 000 m, an increased insulation may be required.

NOTE The insulation level to earth applies not only to the platform insulators, but also to other series capacitor equipment between phase and earth such as ground mounted bypass switch, communication insulator, disconnectors etc.

6.1.3 Insulation levels for insulators and equipment on the platform

6.1.3.1 General requirements

The insulation levels for insulators and series capacitor equipment mounted on the supporting platform are in reference to the platform.

For installations at altitudes exceeding 1 000 m, higher insulation levels may be required.

The insulation level of the insulators and equipment on the platform shall be selected based on the protective level established by the overvoltage protector using equation (2) below. The equation applies to the insulation across the entire segment using the protective level of that segment. It also applies to the insulation within the segment using the pro-rated protective level across that part of the segment.

$$U_{ipf} \geq 1,2 U_{pl} / \sqrt{2} \quad (2)$$

where

U_{ipf} is the power frequency withstand voltage (r.m.s.);

U_{pl} is the peak voltage magnitude of the protective level.

The required power frequency withstand voltage is derived from the protective level. A standard insulation level is then selected from Table 3 or table 5 by comparing the short time power frequency withstand voltage stated in the table with the required value. The first column in the tables (highest voltage for equipment) shall not be used to select a standard insulation level.

6.1.3.2 Capacitor units

Capacitor units mounted on insulated platforms, or otherwise insulated from earth, shall withstand the power frequency voltage between terminals and container according to equations (3) or (4). The higher value according to equations (3) or (4) shall apply.

$$U_{ipf(n)} \geq U_{ipf} \times n/s \quad (3)$$

$$U_{ipf(n)} \geq 2,5 \times n \times U_N \quad (4)$$

where

U_N is the rated voltage of the capacitor unit;

s is the total number of capacitor units in series of the actual segment;

n is the number of capacitor units in series relative to the metal rack to which the containers are connected (e.g. if six units are series connected in one rack with the centre point connected to the rack, $n = 3$).

Capacitor units having their containers connected to earth shall withstand full insulation according to 6.1.1 between terminals and container.

NOTE The equations for $U_{ipf(n)}$ above refer to the insulation between terminals and container of the capacitor unit. The equations do not apply to the test voltage of the capacitor dielectric, for which the equations in Clause 5 apply.

6.1.3.3 Capacitor racks

Any inter-rack insulation, e.g. support insulators between racks, shall withstand the power frequency withstand voltage according to equations (3) and (4). The higher value according to equations (3) or (4) shall apply. In this case n corresponds to the number of units which span across the insulation in question.

6.1.3.4 Support insulators and other equipment on the platform

The insulation levels for equipment mounted on the platform shall be selected according to the procedure outlined in 6.1.3.1 and by applying equation (2) and (3), if not otherwise stated in the subclauses below. In this case n corresponds to the number of capacitor units which span across the insulation in question.

a) Bus insulators

The insulation class of the insulators supporting the different buses on the platform shall be selected based on the above relationship. The insulator voltage class is determined by selecting an insulator with an equivalent or greater power frequency withstand voltage in accordance with Table 3. In this process the left column of the table is not used.

b) Equipment insulators

In general, the power frequency insulation level of the equipment on the platform shall be established by equation (3) and by applying the procedure described for bus insulators, with some exceptions.

c) Bypass switch

The insulation level across the interrupter of the bypass switch shall be based on the relationships defined above.

d) Varistor

The enclosure of the varistor shall have a power frequency wet withstand voltage based on the above equation. It is not required that the specific level selected be a standard value from Table 3.

e) Bypass gap

The insulators used in the bypass gap shall be based on the relationships defined above, taking into account the portion of the segment voltage to which the bypass gap is exposed. Intermediate assemblies can experience high transients during the normal breakdown process and shall be designed for these conditions. In addition, the withstand level of the power gap and any trigger circuit shall be coordinated to withstand all system disturbances without breaking under power system conditions for which they are inappropriate.

f) Discharge current limiting and damping equipment

The insulators used to support the discharge current limiting circuit from the platform shall be based on the relationships defined above, taking into account the portion of the segment voltage to which these insulators are exposed.

The insulation level across the discharge current limiting circuit shall be selected based on instantaneous voltage appearing across the circuit when the bypass gap sparks over or the bypass switch closes. The power frequency withstand of the required insulation class shall be at least $1,2/\sqrt{2}$ times this instantaneous voltage. The LIWL (lightning impulse withstand level) (BIL) (basic lightning impulse insulation level) of the circuit is then selected from the tables. However it must be recognized that the voltage that appears across the circuit when the bypass gap conducts or the bypass switch closes is of a much higher frequency than 50 Hz or 60 Hz and that the duration is very brief. At 50 Hz or 60 Hz, the magnitude of impedance of the circuit is usually very small, making it virtually impossible to perform a power frequency voltage withstand test at the selected level. On the other hand, the circuit can be easily tested with an impulse. As a result, the primary focus of the insulation across the circuit is its LIWL (BIL).

g) Current transformers and optical current transducers

The insulation level of the current transformers and the optical current transducers shall be based on the relationships defined above.

Table 3 – Standard insulation levels for range I ($1 \text{ kV} < U_m \leq 245 \text{ kV}$)

(reproduced from IEC 60071-1:2006, Table 2)

Highest voltage for equipment (U_m) kV (r.m.s. value)	Standard rated short-duration power-frequency withstand voltage kV (r.m.s. value)	Standard rated lightning impulse withstand voltage kV (peak value)
3,6	10	20 40
7,2	20	40 60
12	28	60 75 95
17,5 ^a	38	75 95
24	50	95 125 145
36	70	145 170
52 ^a	95	250
72,5	140	325
100 ^b	(150) 185	(380) 450
123	(185) 230	(450) 550
145	(185) 230 275	(450) 550 650
170 ^a	(230) 275 325	(550) 650 750
245	(275) (325) 360 395 460	(650) (750) 850 950 1 050

NOTE If values in brackets are considered insufficient to prove that the required phase-to-phase withstand voltages are met, additional phase-to-phase withstand voltage tests are needed.

^a These U_m are non preferred values in IEC 60038 and thus no most frequently combinations standardized in apparatus standards are given.

^b This U_m value is not mentioned in IEC 60038 but it has been introduced in range I in some apparatus standards.

Table 4 – Standard insulation levels for range II ($U_m > 245$ kV) (1 of 2)

(reproduced from IEC 60071-1:2006, Table 3)

Highest voltage for equipment U_m kV (r.m.s. value)	Standard rated switching impulse withstand voltage			Standard rated lightning impulse withstand voltage ^b kV (peak value)
	Longitudinal insulation ^a kV (peak value)	Phase-to-earth kV (peak value)	Phase-to-phase (ratio to the phase-to-earth peak value)	
300 ^c	750	750	1,50	850
				950
	750	850	1,50	950
				1 050
362	850	850	1,50	950
				1 050
	850	950	1,50	1 050
				1 175
420	850	850	1,60	1 050
				1 175
	950	950	1,50	1 175
				1 300
	950	1050	1,50	1 300
				1 425
550	950	950	1,70	1 175
				1 300
	950	1 050	1,60	1 300
				1 425
	950 1 050	1 175	1,50	1 425
				1 550
800	1 175	1 300	1,70	1 675
				1 800
	1 175	1 425	1,70	1 800
				1 950
	1 175 1 300	1 550	1,60	1 950
				2 100
1 100	–	1 425 ^d	–	1 950
				2 100
	1 425	1 550	1,70	2 100
				2 250
	1 550	1 675	1,65	2 250
				2 400
	1 675	1 800	1,6	2 400
				2 550

Table 4 (2 of 2)

Highest voltage for equipment U_m kV (r.m.s. value)	Standard rated switching impulse withstand voltage			Standard rated lightning impulse withstand voltage ^b kV (peak value)
	Longitudinal insulation ^a kV (peak value)	Phase-to-earth kV (peak value)	Phase-to-phase (ratio to the phase-to-earth peak value)	
1 200	1 550	1 675	1,70	2 100
				2 250
	1 675	1 800	1,65	2 250
				2 400
	1 800	1 950	1,60	2 550
				2 700
^a Value of the impulse voltage component of the relevant combined test while the peak value of the power-frequency component of opposite polarity is $U_m \times \sqrt{2} / \sqrt{3}$.				
^b These values apply as for phase-to-earth and phase-to-phase insulation as well; for longitudinal insulation they apply as the standard rated lightning impulse component of the combined standard rated withstand voltage, while the peak value of the power-frequency component of opposite polarity is $0,7 \times U_m \times \sqrt{2} / \sqrt{3}$.				
^c This U_m is a non-preferred value in IEC 60038.				
^d This value is only applicable to the phase-to-earth insulation of single phase equipment not exposed to air.				

Table 5 – Typical insulation levels for platform-to-ground insulators (1 of 2)

(insulation levels based on IEEE Standard C62.82.1-2010)

Maximum system voltage (phase-to-phase) V_m kV, rms	Basic lightning impulse insulation level (phase-to-ground) BIL kV, crest	Low-frequency, short-duration withstand voltage ^a (phase-to-ground) kV, rms
15	95 110	34
26.2	125 150	40 50
36.2	150 200	50 70
48.3	250	95
72.5	250 350	95 140
121	350 450 550	140 185 230
145	450 550 650	185 230 275
169	550 650 750	230 275 325
242	650 750 825 900 975 1050	275 325 360 395 480

Table 5 (2 of 2)

Maximum system voltage (phase-to-phase) V_m kV, rms	Basic lightning impulse insulation level (phase-to-ground) BIL kV, peak	Basic switching impulse insulation level ^a (phase-to-ground) BSL kV, peak
362	900 975 1050 1175 1300	650 750 825 900 975 1050
420	1050 1175 1300 1425	850 950 1050
550	1300 1425 1550 1675 1800	1175 1300 1425 1550
800	1800 1925 2050	1300 1425 1550 1675 1800
1200	2100 2250 2400 2550 2700	1675 1800 1950

^a See specific BIL/BSL relationship in relevant apparatus standard. Preferred values are provided in 4.6.

6.2 Creepage distance

The recommendations given in Table 1 of IEC 60071-2:1996 shall apply. The purchaser shall specify which one of the pollution levels, or specific creepage distance, shall be applicable.

In Table 6, specific creepage distances are given for the different pollution levels according to Table 1 of IEC 60071-2:1996. (For more detailed description of the pollution levels, see IEC 60071-2.) The creepage distance is calculated by multiplying the general nominal specific creepage distance in the fourth column with the rated voltage across the insulation in question. The values in Table 6, column 4 are generally applicable for any voltage, i.e. phase-phase, phase-earth or any voltages within a phase segment.

If the 30 min overload current (I_{30}) exceeds 1,35 pu, the creepage distances shall be increased linearly in proportion to ($I_{30}/1,35$ pu).

Table 6 – Specific creepage distances

Pollution level	Examples of environments (further details in IEC 60071-2:1996, Table 1)	Minimum nominal specific creepage distance according to (IEC 60071-2:1996, Table 1) mm/kV	General nominal specific creepage distance mm/kV
I Light	No or low density of industries or houses Agriculture or mountain areas Locations at least 10 km to 20 km from the sea	16	28
II Medium	Industries not producing particularly polluting smoke High density of houses and/or industries but subjected to frequent winds and/or rainfall Wind from the sea but not too close to the coasts	20	35
III Heavy	High density of industries and suburbs of large cities, producing pollution Areas close to the sea	25	44
IV Very heavy	Industrial smoke producing conductive deposits Areas very close to the sea and exposed to sea-spray (salt) Desert areas	31	54
The general nominal specific creepage distances in Table 6, Column 4, are obtained from values in IEC 60071-2:1996, Table 1, multiplied by $\sqrt{3}$. The values in IEC 60071-2:1996 (Column 3) are based on the highest voltage for equipment (see 3.13) but should be applied on phase-ground insulations. When applying any of these nominal specific creepage distances on phase-phase insulations, the values shall be multiplied by $\sqrt{3}$. A more general approach is to apply the values in Column 4 to the voltage across any insulation path within the bank.			

6.3 Air clearances

Recommendations for selection of air clearance distance are found in IEC 60071-2:1996, Annex A. Minimum clearances have been determined for different electrode configurations. The minimum clearances specified are determined with a conservative approach, taking into account practical experience, economy, and size of practical equipment in the range below 1 m clearance. These clearances are intended solely to address insulation coordination requirements. Safety requirements may result in substantially larger clearances.

Table 7, taken from IEC 60071-2, shall be used for phase-to-phase and phase-to-earth insulation for which lightning impulse withstand voltage is defined.

Table 8 and Table 9, taken from IEC 60071-2, shall be used for phase-to-earth and phase-to-phase insulation for which switching impulse withstand voltage is defined.

For selection of proper air clearance across insulation paths where only an a.c. voltage withstand requirement applies, e.g. for platform-mounted equipment, the recommendations in Annex G of IEC 60071-2:1996 shall be used. Minimum air clearance versus a.c. power frequency withstand voltage, according to Figure 4, shall apply if no other more detailed requirements are specified.

Application example: Calculation of insulation level, creepage distance and air clearance

A series capacitor (SC) is rated $X_{CN} = 43 \, \Omega$ and $I_{CN} = 1\,500 \, \text{A}$. The 30 min overload current is 1,35 pu. The SC is protected by a ZnO varistor with a protective level equal to 2,2 pu. The pollution level is level II, medium, according to Table 6. Calculate the insulation level, the creepage distance and the air clearance for the support insulator of the high-voltage busbar on the platform.

Solution:

The rated voltage $U_{CN} = 43 \times 1,5 = 64,5 \, \text{kV r.m.s.}$

The protective level voltage $U_{pl} = \sqrt{2} \times 2,2 \, U_{CN} = 200,7 \, \text{kV peak (see 10.5).}$

a) Insulation level

According to 6.1.3.1, equation (2) the following is valid:

$$U_{ipf} \geq 1,2 \, U_{pl} / \sqrt{2} = 170,3 \, \text{kV r.m.s.}$$

According to Table 3, the insulation level for the high-voltage busbar insulator is selected as 185 kV r.m.s. for power frequency withstand voltage and as 450 kV peak for lightning impulse withstand voltage.

b) Creepage distance

According to 6.2, Table 6, the following is valid:

The creepage distance l is: $l = 35 \, U_{CN} = 2\,258 \, \text{mm.}$

c) Air clearance

According to Figure 4, the following is valid:

The air clearance corresponding to 170,3 kV r.m.s. is 580 mm.

**Table 7 – Correlation between standard lightning impulse withstand voltages
and minimum air clearances**

(reproduced from IEC 60071-2:1996, Table A.1)

Standard lightning impulse withstand voltage kV	Minimum clearance mm	
	Rod-structure	Conductor structure
20	60	
40	60	
60	90	
75	120	
95	160	
125	220	
145	270	
170	320	
250	480	
325	630	
380	750	
450	900	
550	1 100	
650	1 300	
750	1 500	
850	1 700	1 600
950	1 900	1 700
1 050	2 100	1 900
1 175	2 350	2 200
1 300	2 600	2 400
1 425	2 850	2 600
1 550	3 100	2 900
1 675	3 350	3 100
1 800	3 600	3 300
1 950	3 900	3 600
2 100	4 200	3 900

NOTE The standard lightning impulse is applicable phase-to-phase and phase-to-earth.
For phase-to-earth, the minimum clearance for conductor-structure and rod-structure is applicable.
For phase-to-phase, the minimum clearance for rod-structure is applicable.

Table 8 – Correlation between standard switching impulse withstand voltages and minimum phase-to-earth air clearances

(reproduced from IEC 60071-2:1996, Table A.2)

Standard switching impulse withstand-voltages kV	Minimal phase-to-earth	
	Conductor-structure	Rod-structure
750	1 600	1 900
850	1 800	2 400
950	2 200	2 900
1050	2 600	3 400
1175	3 100	4 100
1300	3 600	4 800
1425	4 200	5 600
1550	4 900	6 400

Table 9 – Correlation between standard switching impulse withstand voltages and minimum phase-to-phase air clearances

(reproduced from IEC 60071-2:1996, Table A.3)

Standard switching impulse withstand-voltages kV			Minimum phase-to-phase clearances mm	
Phase-to-earth kV	Phase to phase value Phase-to-earth value	Phase to phase kV	Conductor-conductor parallel	Rod-conductor
750	1,5	1 125	2300	2 600
850	1,5	1 275	2 600	3 100
850	1,6	1 360	2 900	3 400
950	1,5	1 425	3 100	3 600
950	1,7	1 615	3 700	4 300
1050	1,5	1 575	3 600	4 200
1050	1,6	1 680	3 900	4 600
1175	1,5	1 763	4 200	5 000
1300	1,7	2 210	6 100	7 400
1425	1,7	2 423	7 200	9 000
1550	1,6	2 480	7 600	9 400

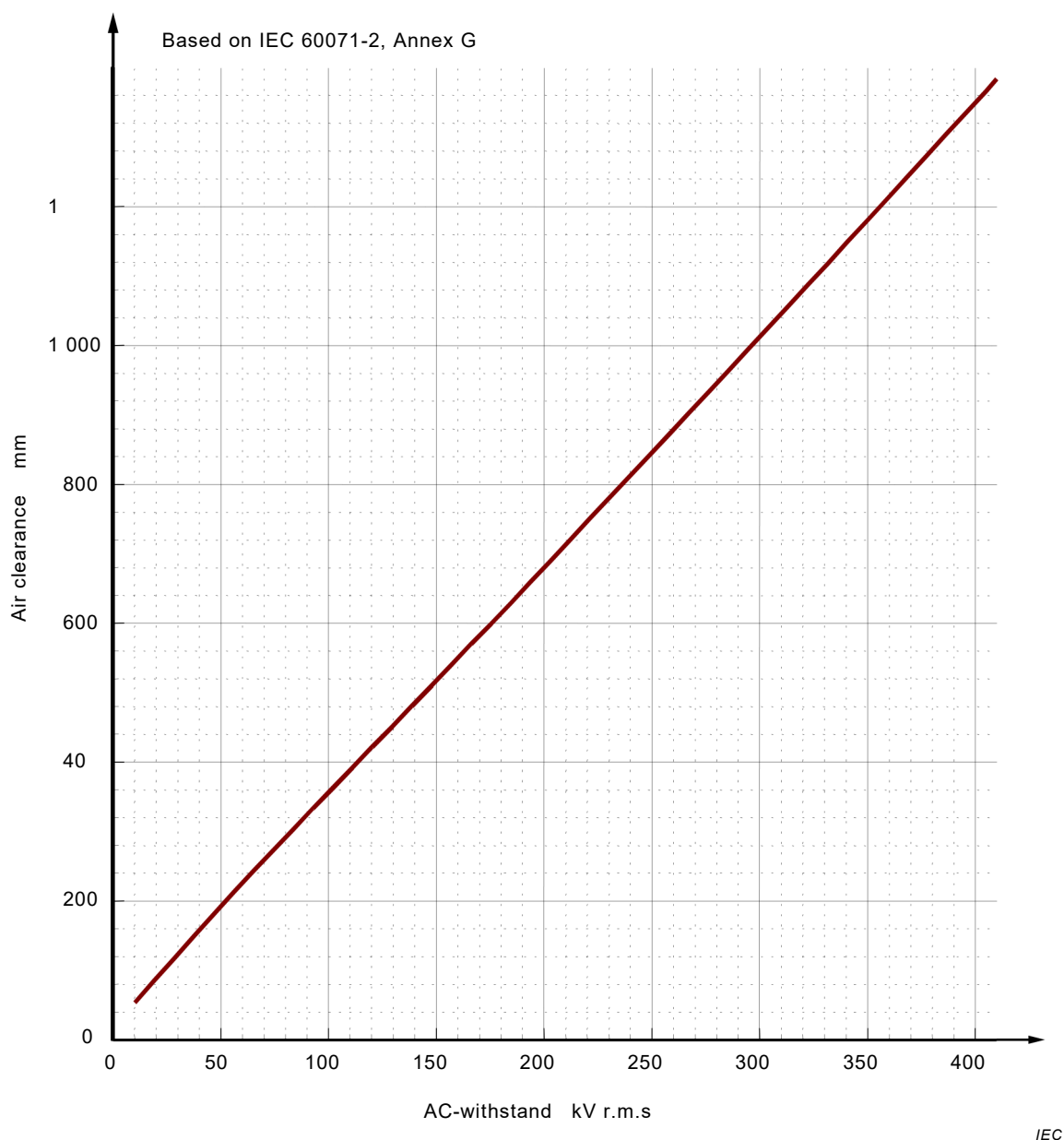


Figure 4 – Air clearance versus a.c. power frequency withstand voltage

7 Overloads, overvoltages and duty cycles

7.1 Currents

The series capacitor bank shall be capable of withstanding the rated continuous current, system swing currents, emergency loading, power system faults and, in some applications, harmonic currents. Some of these conditions are illustrated in 10.3. These quantities are generally specified by the purchaser.

7.2 Transient overvoltages

Series capacitors shall be suitable for repeated operations at transient overvoltages, e.g. caused by power system faults, with the highest possible value U_{pl} that is expected to occur across the capacitor terminals. The transient overvoltage is normally limited by an overvoltage protector (see 5.1.3, 5.1.4 and 10.5). The expected magnitude of the overvoltage shall be

agreed upon between the manufacturer and the purchaser. The purchaser shall give the estimated repetition rate.

7.3 Duty cycles

The series capacitor equipment shall be designed to withstand the required sequences of faults, system swing currents, emergency loading and continuous currents, as specified by the purchaser. These sequences form the duty cycles that all of the components of the bank shall be designed to withstand. The duty cycle shall be consistent with the manner in which the surrounding power system will be operated for both internal and external faults. The purchaser shall define duty cycles for faults of normal and extended durations and for faults of different types (three-phase and single-phase). Phase-to-phase faults shall be considered if specifically defined by the purchaser as these can be decisive for the energy rating of the varistor. Examples of typical duty cycles are found in 4.4 of IEC 60143-2:2012. See also 10.5 of this standard.

Although the focus of this subclause is duty cycles involving faults on the power system, it is understood that the bank shall be designed to operate for other events such as insertion and reinsertion under the conditions defined by the purchaser.

8 Safety requirements

8.1 Discharge device

Each capacitor unit or group of parallel units shall be provided with a means for discharging the residual voltage to 75 V or less from $\sqrt{2} U_N$. The maximum discharge time is 10 min for the capacitor unit or group of parallel units. There shall be no switch, fuse or any other isolating device between the capacitor unit(s) and the discharge device (external device).

The discharge circuits shall have adequate current-carrying and energy absorbing capacity to discharge the capacitor from a voltage level equal to U_{pl} and for auto-reclosing of the line and the series capacitor bank.

A discharge device is not a substitute for short-circuiting the capacitor terminals together and to earth before handling.

In certain countries, a shorter discharge time and a lower residual voltage are required. In this case, the purchaser should inform the manufacturer.

NOTE 1 Operating conditions above the rated voltage may cause a residual voltage over 75 V after 10 min.

NOTE 2 A fault in a unit cleared by a fuse, or a flashover across part of the bank can produce local residual charges inside the segment which cannot be cleared within the specified time by means of a discharge device connected between the terminals of the segment.

NOTE 3 The service requirements may require that the phase or segment should be equipped with an additional discharge device external to the capacitor units.

8.2 Container connection

To enable the potential of the metal container of a capacitor unit to be fixed, and to be able to carry the fault current in the event of a breakdown to the container, the container shall be provided with connection means suited for a bolt with a screw size of at least M 10 or equivalent (e.g. brackets with unpainted mounting surface).

8.3 Protection of the environment

When capacitors contain materials (e.g. polychlorinated biphenyls) that must not be dispersed into the environment, the legal requirements of the country concerned shall be followed (see Annex E).

8.4 Other safety requirements

The purchaser shall specify at the time of enquiry any special requirements with regard to the safety regulations applicable in the country in which the capacitor is to be installed.

9 Markings and instruction books

9.1 Markings of the unit

9.1.1 Rating plate

The following information shall be given on the rating plate of each capacitor unit:

- a) Name of manufacturer.
- b) Identification number and year of manufacture; the year may be a part of the identification number or be in code form.
- c) Rated current, I_N , in amperes.
- d) Rated capacitance, C_N , in microfarads.
- e) Rated frequency, f_N , in hertz.
- f) Rated voltage U_N in volts or kilovolts.
- g) Rated output, Q_N , in kilovars.
- h) Limiting voltage, U_{lim} , in volts or kilovolts.
- i) Temperature category.
- j) Discharge device, if internal, shall be indicated by wording or by the symbol  or by the rated resistance in kilohms or megohms.
- k) Insulation level, U_i , in kilovolts.
- l) Internal fuses, if included, shall be indicated by wording or by the symbol  (IEC 60417:2002-10).
- m) Chemical or trade name of impregnant; this indication may alternatively be stated on the warning plate (see 9.1.2).
- n) Reference to IEC 60143-1 (plus the year of issue).

A place shall be reserved for the measured capacitance (see 5.3.1). This value may be indicated in one of the following ways:

- as an absolute capacitance value which may replace the rated capacitance;
- as a difference ΔC between the measured and the rated capacitance indicated, for example, by symbols for the capacitance deviation ranges as follows:
 - ++ for ΔC between +7,5 % and +4,5 %
 - + for ΔC between +4,5 % and +1,5 %
 - +– for ΔC between +1,5 % and –1,5 %
 - for ΔC between –1,5 % and –4,5 %
 - for ΔC between –4,5 % and –7,5 %.

The insulation level can be marked by means of two numbers separated by a stroke, the first number giving rated short duration power-frequency withstand voltage in kilovolts and the

second number giving rated lightning impulse withstand voltage in kilovolts, e.g. 28/75 kV. For units having one terminal permanently connected to the container and not tested according to 5.10 and 5.11, this information is not applicable.

9.1.2 Warning plate

If the capacitor unit contains material which may pollute the environment or may be hazardous in any other way (e.g. inflammability), the unit shall be provided with a label or otherwise marked according to the relevant laws of the country of the user. The purchaser shall inform the manufacturer about such law(s) (see Annex E).

9.2 Markings of the bank

9.2.1 Instruction sheet or rating plate

The following minimum information shall be given by the manufacturer in an instruction sheet or, alternatively, by contractual agreement, on a rating plate:

- a) Name of manufacturer.
- b) Rated output Q_N (e.g. 3×10 Mvar).
- c) Reactance of each phase.
- d) Rated current I_N .
- e) Permissible overcurrent during 30 min (see 10.3).
- f) Rated voltage U_N .
- g) Protective level voltage U_{pl} .
- h) Insulation level with respect to earth.
- i) Time to discharge the phase from $\sqrt{2} U_N$ to 75 V.
- j) Type of overvoltage protector (see 5.1.3).

If further information is given in an instruction sheet, the rating plate (or another plate, if a rating plate does not exist) shall bear reference to this instruction sheet.

If the capacitor bank consists of series-connected segments, items c), f), g) and i) shall be related to each segment.

The insulation level can be marked by means of two numbers separated by a stroke, the first number giving the rated short duration power-frequency withstand voltage (for $U_m < 300$ kV) or the rated switching impulse withstand voltage (for $U_m \geq 300$ kV) in kilovolts, and the second number giving the rated lightning impulse withstand voltage in kilovolts, e.g. 185/450 kV.

9.2.2 Warning plate

Subclause 9.1.2 is also valid for the bank.

9.3 Instruction book

The following minimum information shall be provided in the instruction book for the series capacitor bank:

- a) Name of supplier
- b) Overall bank
 - summary of ratings
 - layout drawings
- c) Power equipment

- description
 - ratings
 - outline drawings
 - maintenance procedures
 - spare parts
- d) Protection and control
- description of operation
 - schematics
 - maintenance procedures
 - testing procedures
 - spare parts.

10 Guide for selection of ratings, installation and operation

10.1 General

Since series capacitors reduce the inductive line reactance, and thereby decrease the phase angle between the voltages at the ends of the line, they are used in long transmission lines to improve voltage regulation and system stability, and thus increase transmission capacity of the line. They are also used for governing the active power distribution between lines working in parallel, thereby reducing the total transmission losses.

Because of their automatic and instantaneous response, series capacitors are used in distribution lines to reduce rapid voltage fluctuations due to load variation. See reference [3]. Consequently, the voltage conditions in the system are improved in most cases.

Because of the fluctuating line current, series capacitors are subjected to much greater variation of the voltage between terminals than shunt capacitors. When a short-circuit occurs in the system, this voltage may be so high that capacitor units designed to withstand it would be uneconomical. Therefore, such overvoltages are in most cases limited by an overvoltage protector which bypasses the phase or segment.

The effect of series capacitors on the system and their operating conditions are different in almost every application. To attain the best technical and economic results, each particular case should be studied individually in cooperation between the manufacturer and purchaser according to the criteria indicated in this clause and the result of the studies shall form part of the contract information.

10.2 Reactance per line, rated reactance per bank and number of modules per bank

10.2.1 Capacitive reactance per line

Typically, the series compensation in a transmission line is selected as a fixed percentage of the line inductive reactance. This percentage is selected from system power flow, system stability, short-circuit and subsynchronous resonance (SSR) studies (see 10.8.3) based on:

- voltages at key substations;
- voltage profile along the line;
- system dynamic stability requirements;
- power flow on parallel paths;
- SSR considerations for nearby, non-hydro turbine generators.

Finally, the cost of the equipment should be considered as the cost of series compensation will increase as the series compensation level is increased.

Higher series compensation can generally improve system performance but may require costly mitigation measures for SSR, if the compensation is close to non-hydro turbine generators with an SSR risk. Based on these considerations, a fixed level of series compensation is selected in the first place.

For several parallel paths or transmission lines, the series compensation level is selected to avoid unequal power flows. However, in some cases, series compensation may be used to optimize power flow on parallel lines with unequal line current ratings, to attract more power to the preferred line or path.

The per cent compensation can be anywhere from 20 % to 80 % of the line impedance. Series compensation is generally needed on long transmission lines for improving system stability and voltage profiles. It may be applied on short lines to balance the power flows. The series compensation range is kept below 100 % as it is desirable that the line appears as a net inductive reactance and to keep the resonant of the transmission line below the system synchronous frequency. A 50 % line compensation on a 300 km long line with 0,3 Ω/km

positive sequence line impedance would require 45 Ω of series capacitive impedance ($0,5 \times 300 \text{ km} \times 0,3 \Omega = 45 \Omega$). This is the “capacitive reactance” of the series capacitors installed for series compensating the line.

In general, most of the transmission lines on which series capacitors have been installed are constructed with phase transpositions so that the inductive reactances of the phases are approximately equal. The reactances of the series capacitor banks are manufactured to be approximately equal so that the net reactances of the phases of the compensated line are also approximately equal. This approach minimizes negative sequence currents. The application of series capacitors in non-transposed lines is possible. However, selection of the reactance and the current ratings for each phase requires careful consideration. The purchaser should indicate in the specification if the line is not transposed.

10.2.2 Number of series capacitor banks in a transmission line

The number of banks in a line is dependent on the length of the line, the percentage compensation and the line current. There are no standard values of reactance for series capacitor banks. If the line is long and the compensation level and current levels are both high, the desired capacitive reactance per line is generally installed either as two banks, one at each line terminal, or as a single bank in the mid-section of the line. Mid-line location generally gives a lower through fault current and requires a smaller varistor rating compared to line end location. This is done to maintain a reasonably acceptable voltage profile on the transmission line and in some cases to limit the voltage across a single series capacitor bank. During high power transfer conditions, series capacitors generally cause a step increase of the voltage on the transmission line. Basically, the line inductive reactance causes a voltage drop when the power has a lagging reactive current component, which is usually the case under high loading conditions. This same current through the capacitive reactance of a series capacitor bank causes a step voltage increase at the bank location. By splitting the series capacitive reactance and putting it at two locations on the line, the step voltage increase can be split into half, thereby avoiding excessive voltage increases in the line voltage profile. Under light load conditions, the flow of line charging current (capacitive) through the series capacitor will result in a voltage drop. More than one bank per line also means that all of the compensation in the line is not lost if one of the banks is out of service.

In applications where the line is shorter or the compensation level is lower or the rated current is lower, usually only one bank per line is applied.

10.2.3 Number of modules in a capacitor bank

Most series capacitor banks are configured with a single module. This is usually the most economical design, unless the reactance and current requirements result in a voltage across

the bank that is impractical for the supplier to achieve with one module. Then the supplier may choose to configure the bank with two modules.

However, in some cases, it may be desirable to split the bank into two modules to achieve better power flow control on the power system. The advantages of the power flow control may outweigh the extra equipment costs associated with a two module bank. In addition, a bank with two modules can provide partial compensation if the other module has to be bypassed. However, with a two module bank it is not possible to maintain the equipment on the platform of one of the modules without taking the entire bank out of service.

The purchaser should indicate in the specification if more than one module per bank is required.

10.2.4 Future requirements for series capacitors

When selecting the rating of the series capacitor bank, the future requirements such as higher percentage compensation, higher power transfer, higher fault currents etc. should be considered.

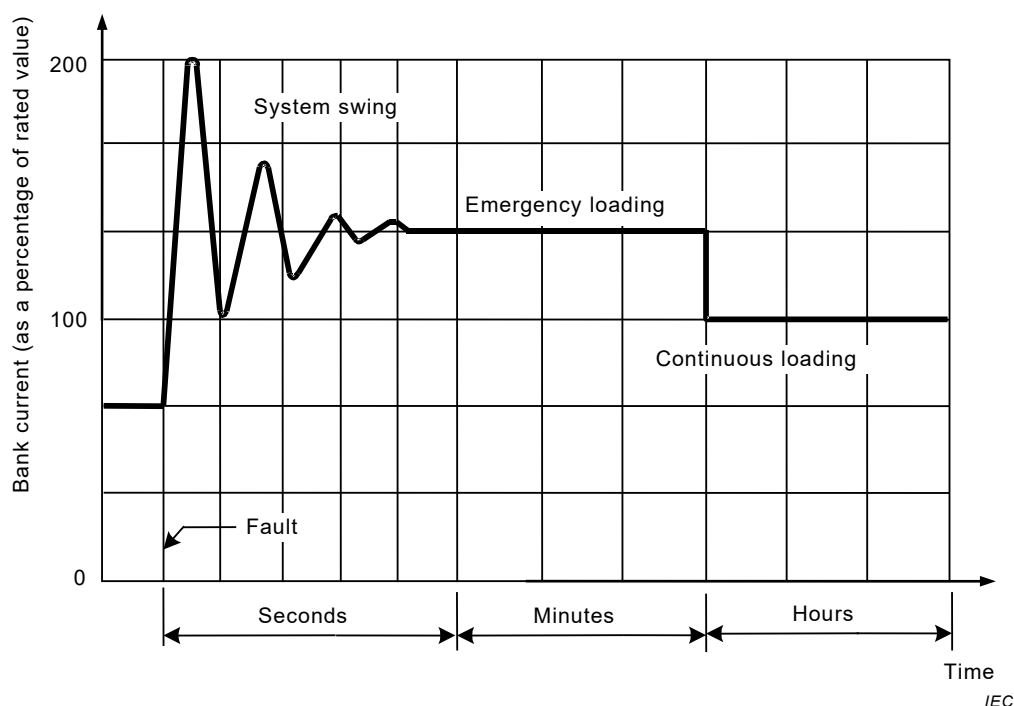
The purchaser should indicate in the specification the degree to which the bank, as initially supplied, must accommodate these future operating requirements.

10.3 Current ratings for the bank

10.3.1 General

The purchaser should specify the continuous, emergency and swing currents required by the application. These currents should be defined for the bank in the inserted condition. For the bypassed condition, the continuous and emergency currents should also be specified, as they are usually different from those for the inserted condition.

These currents and their respective time periods are illustrated in Figure 5.



NOTE The fault current is not shown.

Figure 5 – Typical current-time profile of an inserted capacitor bank following the fault and clearing of parallel line

10.3.2 Typical bank overload and swing current capabilities

Since a series capacitor bank is located in series with the line, it can be exposed to a wide range of currents. As a result, banks are specified to have at least the three current ratings in Table 10. Listed for each category are the typical magnitudes of the currents in per unit of bank rating and the typical time frame for the currents. To achieve the optimum design, the purchaser should analyse the requirements of the power system and specify the current ratings of the bank based on those requirements.

Table 10 – Typical bank overload and swing current capabilities

Current	Duration	Typical range per unit pu	Most common values per unit pu
Rated	Continuous	1,0	1,0
1,1 × Rated	8 h in a 12 h period	1,1	1,1
Emergency overload (I_{EL})	30 min	1,2 to 1,6	1,35
	10 min	1,4 to 1,7	1,50
Swing	1 s to 10 s	1,7 to 2,5	1,7 to 2,0

In some cases, the emergency loading is defined for a 10 min or for a 4 h period at correspondingly higher and lower per unit values than are shown in Table 10. The 30 min emergency overload is most commonly specified. A capacitor may be reasonably expected to withstand, during normal service life, a total of 300 such overloads. The protection and control

system of the bank will typically limit the overload to the specified value by closing the bypass switch.

The value specified for the 30 min overload can affect the design and cost of the capacitor and the varistor. To achieve 30 min overload currents above 1,6 pu, the manufacturer is likely to be forced to increase the continuous current capability of the capacitor units. In addition, the protective level of the bank is likely to be forced higher.

It should be noted that the 30 min overload current (I_{EL}) specified by the purchaser will be used to establish the voltage (U_{EL}) for the capacitor unit “cold duty test” and the varistor “energy withstand and power frequency voltage stability test” (see IEC 60143-2), unless otherwise specified by the purchaser.

10.3.3 Analysis to determine the continuous and emergency overload current rating

The continuous and emergency overload current ratings of a series capacitor bank are usually selected from one of the following three approaches:

- The power system is assumed to have its worst practical sustained contingencies and maximum power transfer through the bank is analysed using a power flow computer program. The bank is selected to have a continuous rating associated with this contingency power transfer. With this approach the bank may not need to have any significant emergency overload rating because higher currents are not practical.
- The power system is assumed to be normal and the maximum power transfer through the bank is analysed using a power flow program. The bank is selected to have a continuous current rating associated with this normal power transfer. The emergency current rating is established by analysing the current through the bank during system contingencies, especially the outage of parallel circuits. This rating should come directly from this study. However, if such outages result in a ratio of the emergency current rating to the continuous rating that is higher than the top of the range in Table 10, the continuous current rating of the bank should be increased accordingly. Due regard shall be taken to the duration of the emergency current.
- The continuous rating of the bank is selected to be equal to the maximum thermal loading current of the transmission line. In this case, the emergency loading of the bank may be selected to be consistent with the temporary thermal overload capability of the line. Again, if the ratio of the emergency current rating to the continuous rating is higher than the top of range in Table 10, the continuous current rating of the bank should be increased.

10.3.4 Analysis to determine the swing current rating

The swing current is usually determined by using a dynamic stability computer program. The analysis is performed for faults and power system contingencies that result in the highest swing current in the bank. It is especially important to consider the outage of parallel circuits.

If the currents are below 1,7 pu of the continuous rating of the bank, the impact on the design of the bank will be small. Currents above 1,7 pu can have a significant affect on the design and therefore the magnitude and waveform of the current shall be carefully defined in the specification.

10.4 Overvoltage protection requirements

In general, it is recommended that the supplier be permitted to select the protective level to best optimize the equipment. However, if the purchaser has analysed such power system considerations as SSR or line breaker TRV (see 10.8) and has an established requirement for the protective level, that requirement should be included in the specification. Typical protective levels range between 2,0 pu and 2,5 pu for Type M overvoltage protectors and higher for Type K overvoltage protectors (see 5.1.3).