



IEEE Guide for Specifications of High-Voltage Circuit Breakers (over 1000 Volts)

IEEE Power & Energy Society

Sponsored by the
IEEE Switchgear Committee



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IEEE Guide for Specifications of High-Voltage Circuit Breakers (over 1000 Volts)

Sponsor

IEEE Switchgear Committee
of the
Power & Energy Society

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Abstract: These specifications apply to all indoor and outdoor types of ac high-voltage circuit breakers rated above 1000 volts. This document is issued only as a guide for use in compiling specifications for ac high-voltage circuit breakers. The imperative mode of the language is illustrative of that used in specifications.

Keywords: capacitance current switching, circuit breaker, dielectric withstand, fast transient recovery voltage, high-voltage, indoor, initial, interrupting time, manufacturer, mechanical endurance, operating duty, outdoor, power frequency, purchaser, ratings, related capabilities, short-circuit current, short-line fault, specification.

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Introduction

This introduction is not part of IEEE Std C37.12-2008, IEEE Guide for Specifications of High-Voltage Circuit Breakers (over 1000 Volts).

This guide is a revision of ANSI C37.12™-1991. It reflects changes needed to coordinate with the IEEE Std C37.04™, IEEE Std C37.04a™, IEEE Std C37.06™, IEEE Std C37.06.1™, IEEE Std C37.09™, IEEE Std C37.010™, IEEE Std C37.011™, IEEE Std C37.012™, and IEEE Std C37.11™. It also reflects the present circuit breaker manufacturing technology.

This guide applies to all indoor and outdoor ac high-voltage circuit breakers rated above 1000 volts and is issued as a guide for use in compiling technical specifications for the purchase of ac high-voltage circuit breakers. Primarily this guide applies to the Vacuum and Sulfur Hexafluoride circuit breakers. References to older technologies such as oil, air-blast, and air-magnetic circuit breakers have been deleted since these types are not presently being offered by manufacturers. This guide is intended to assist the user in specifying proper capabilities for circuit breakers when used in conjunction with IEEE Std C37.010 (application of circuit breakers), IEEE Std C37.011 (transient recovery voltages), IEEE Std C37.012 (capacitive switching), and IEEE Std C37.015™ (reactive switching). The imperative mode of the language used for example clauses is illustrative of that used in specifications. It does not imply that this document is anything other than advisory in its scope.

The other change implemented in this guide concerns the title. It has been changed from “AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis-Specification Guide” to “Guide for Specifications of High Voltage Circuit Breakers (over 1000 Volts).” This change is consistent with similar changes in the title of other IEEE circuit breaker standards and guides.

This guide contains clauses that may be used directly in a purchaser’s specification. Alternately, users may modify example clauses to form the basis of their own specification. This guide does not contain all of the clauses that a purchaser may require for the purchase of high-voltage circuit breakers. For example, this guide makes no reference to commercial conditions that might be included in a purchaser’s complete specification. The guide also does not contain example clauses that would provide all necessary requirements for every system application or physical installation. Users of the guide are cautioned to thoroughly review each individual application when preparing a high-voltage circuit breaker specification.

Users of this guide are encouraged to review and thoroughly apply the high-voltage circuit breaker application principles identified in IEEE Std C37.010, IEEE Std C37.011, IEEE Std C37.012, and IEEE Std C37.015. These application guides have been developed to promote selection of appropriate circuit breaker features required for the successful application of high-voltage circuit breakers.

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IEEE ~~Application~~ Guide for ~~Capacitance Current Switching for~~ ~~AC~~ Specifications of High-Voltage Circuit Breakers (over 1000 Volts)

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1. Overview

1.1 Scope

This guide is for development of specifications that apply to all indoor and outdoor types of ac high-voltage circuit breakers rated above 1000 volts.

~~This application guide for capacitance current switching applies to ac high-voltage circuit breakers rated in accordance with IEEE Std C37.04™ and listed in ANSI Std C37.06. It is intended to supplement IEEE Std C37.010™. Circuit breakers rated and manufactured to meet other standards should be applied in accordance with application procedures adapted to their specific ratings.~~

1.2 Purpose

This document is intended as a guide for use in developing specifications for ac high-voltage circuit breakers. This guide is for specifications that apply to all indoor and outdoor types of ac high-voltage circuit breakers rated above 1000 volts. The imperative mode of the language is illustrative of that used in specifications. It does not imply that this document is anything other than advisory in its scope.

~~This guide is intended for general use in the application of circuit breakers for capacitance current switching. Familiarity with other American National Standards applying to circuit breakers is assumed, and provisions of those standards are indicated in this guide only when necessary for clarity in describing application requirements.~~

2. Normative references

The following referenced documents are indispensable for the application of this ~~application guide~~ document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI ~~Std~~ C37.06-2000, American National Standard ~~for~~ AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Required Capabilities.¹

[IEEE Std C37.04™-1999, IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers.](#)^{2, 3}

¹Information on references can be found in Clause 2.

²ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

IEEE Std C37.04a™, IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—[Amendment 1: Capacitance Current Switching.](#)

IEEE Std C37.09™, IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

[IEEE Std C37.09a™, IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Amendment 1: Capacitance Current Switching.](#)

IEEE Std C37.010™ [1999](#), IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

[IEEE Std C37.011™, IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers.](#)

[IEEE Std C37.012™, IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers.](#)

[IEEE Std C37.015™, IEEE Application Guide for Shunt Reactor Switching.](#)

[IEEE Std C37.10.1™, IEEE Guide for the Selection of Monitoring for Circuit Breakers.](#)

[IEEE Std C37.81™, IEEE Guide for Seismic Qualification of Class 1E Metal-Enclosed Power Switchgear Assemblies.](#)

[IEEE Std 693™, IEEE Recommended Practice for Seismic Design of Substations.](#)

[IEEE Std 1291™-1993, IEEE Guide for Partial Discharge Measurement in Power Switchgear.](#)

[NEMA 107-1987, Methods of Measurement of Radio Influence Voltage \(RIV\) of High-Voltage Apparatus.](#)⁴

[NEMA SG-4-1995, Alternating Current High-Voltage Circuit Breakers.](#)

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3. Definitions

For the purposes of this guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms*[B12] should be referenced for terms not defined in this clause.

3.1 Purchaser or user: The organization responsible for specifying all requirements, including commercial and technical, related to purchasing equipment and accessories.

3.2 Manufacturer or Supplier: shall mean a person or corporation who is furnishing material or equipment to either Owner or Contractor or both.

3. General

~~Capacitive currents are encountered in the following cases:~~

- ~~—— Switching of no-load overhead lines~~
- ~~—— Switching of no-load cables~~
- ~~—— Switching of capacitor banks~~
- ~~—— Switching of filter banks~~

~~Interruption of capacitive currents is generally a light duty for a circuit breaker because the currents are normally a few hundred amperes. There is, however, a probability that restrikes will occur. Restrikes may lead to undesirable overvoltages or high-frequency transients affecting power quality in the network and may also cause damage to the breaking unit.~~

~~Energization of capacitive loads may lead to overvoltages or high currents. Two such cases are the switching of parallel capacitor banks and the switching of no-load lines.~~

~~The testing is designed to be representative of the service conditions up to the point of clearing, reigniting, or restriking. Because the actual value of overvoltage and transient response is totally system dependent, tests cannot replicate these effects. By providing a means of assessing the likelihood of restrike occurrence, users can determine what best suits their application. It is assumed that because capacitor switching is not the only source of overvoltage, other protection systems are employed; and in the case of unacceptable power quality for sensitive electronic equipment, a sufficiently low number of likely events are selected. A separate study of actions relative to power quality on energization should also be made.~~

~~In the selection of the rating for the circuit breaker for capacitive current switching, the following needs to be considered:~~

- a) ~~Application, i.e., overhead line, cable, capacitor bank, or filter bank~~
- b) ~~Power frequency of the network~~
- c) ~~Grounding situation of the network~~
- d) ~~Presence of single or two phase to ground faults~~

~~From the application, the restrike performance class of the circuit breaker can be determined (C1 or C2) as well as the mechanical endurance class (M1 or M2). The grounding situation of the network and the presence of single and two phase to ground faults are important factors that determine the recovery voltage across the circuit breaker, which, in turn, determines the test voltage of the circuit breaker.~~

~~The general theory of capacitive current switching is given in Clause 4, and the application and testing considerations are given in Clause 5, Clause 6, and Clause 7.~~

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4. Specification format

The developer of the specification should select a format for the specification. There are two prevalent formats although many variations are possible.

- A complete specification written for a specific circuit breaker order, or
- A set of companion documents that are to be used together. The first document is a general specification that applies to a class or classes of circuit breakers. This general specification is accompanied by a second/supplementary specification that provides only those details that are appropriate for the specific circuit breaker order. This second “rating specification” includes information such as the ratings, delivery quantities, schedule and locations, special requirements applicable to the specific order, unusual conditions and perhaps exceptions to the general specification

The specification should generally include a statement that requires the supplier to supply the circuit breaker in accordance with the Purchaser’s specification and the referenced standards. The specification should also state which standards should be applicable in the event of conflict in the standards requirements or in the event of conflict between the purchaser’s specification and the referenced standards.

The specification should identify the standards that must be followed by the supplier during the provision of the circuit breaker.

Users commonly follow the second approach, a set of companion documents, in the preparation of their specifications. This guide describes the second approach adopted by several users. However with a few modifications this specification can also be re-written as a single document specification for a specific circuit breaker order.

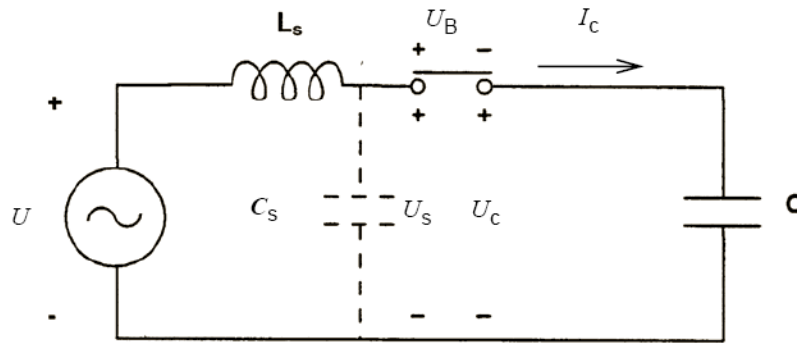
This guide includes several clauses that use the word “shall”. These clauses are included as typical sample clauses that may directly be used by the users in their specification. The other clauses with the word “should” are used to form the basis of a purchaser’s own worded clause for their specification.

4. General theory of capacitive current switching

4.1 De-energization of capacitive loads

4.1.1 Capacitor banks

The single-phase equivalent circuit shown in Figure 1 may be used to illustrate the conditions when de-energizing a capacitor bank.



C	Capacitive load (capacitor bank)	U_c	Voltage across the capacitor bank (rms)
C_s	Source side capacitance	I_c	Capacitive current (rms)
U	Source voltage (rms)	U_s	Voltage on source side of the circuit breaker (rms)
U_B	Voltage across the circuit breaker (rms)	L_s	Source inductance

Figure 1—Single-phase equivalent circuit for capacitive current interruption

4.1.1.1 Capacitive current

The capacitive current I_c flowing in the circuit is given by Equation (1).

$$I_c = \frac{\omega_s C \times U}{1 - \omega_s^2 L_s C} = \frac{\omega_s C \times U}{1 - \frac{\omega_s^2}{\omega_l^2}} \quad (1)$$

with $\omega_l = 2\pi f_l$, where f_l is the system frequency (Hz)

$$\omega_l = \frac{1}{\sqrt{L_s C}} = 2\pi f_l \quad , \text{ where } f_l \text{ is the inrush current frequency (Hz) (see also 4.2.1)}$$

With $\omega_l \gg \omega_s$, Equation (1) transforms to $I_c = \omega_s C \times U$.

4.1.1.2 Recovery voltage

Figure 2 shows the current and voltage shapes at interruption.

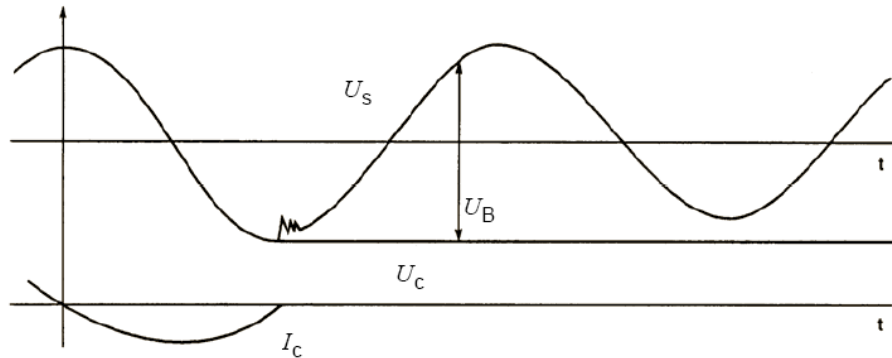


Figure 2—Voltage and current shapes at capacitive current interruption

After interruption of the current, the supply side voltage U_s will be more or less unaffected. There is only a minor decrease in amplitude, associated with the disappearance of the capacitive load. The transition to the new amplitude value is associated with a slight oscillation, the frequency of which is determined by L_s and C_s .

From the moment the current is interrupted, the charge of the capacitor bank C is trapped. The voltage U_c will, therefore, remain constant at the value it had at current zero (namely, the peak value of the supply voltage).

Together with the low current amplitude to be interrupted, the low initial rate of rise of the recovery voltage makes it extremely easy for the circuit breaker to interrupt. Some circuit breakers may interrupt even if the current zero would occur immediately after contact separation. Half a cycle after current zero, the recovery voltage has risen to an amplitude of no less than twice the peak value of the supply voltage. From this, it can easily be seen that a rated frequency of 60 Hz is more severe than 50 Hz. The circuit breaker may then not be able to withstand the high value of the recovery voltage across a relatively small contact gap. Dielectric breakdown may occur between the contacts, and current would start to flow again.

Figure 3 shows current and voltage wave shapes in a case where voltage breakdown occurs relatively close to the recovery voltage peak. The load side voltage will swing up to a voltage that ideally (without damping present) reaches three times the supply voltage peak u_p . The oscillation frequency of the current and voltage after the breakdown is determined by L_s and C (assuming $C \approx C_s$). The circuit breaker may easily interrupt the current again at one of its current zeros, with the result that the voltage across the capacitor may attain a new constant value, perhaps higher than before. Further breakdowns associated with even higher overvoltages across the load may then occur (see also Figure 4).

Voltage breakdowns at capacitive current interruption are divided into two categories:

- a) Reignitions: Voltage breakdown during the first 1/4 cycle following current interruption.
- b) Restrikes: Voltage breakdown 1/4 of a cycle or more following current interruption.

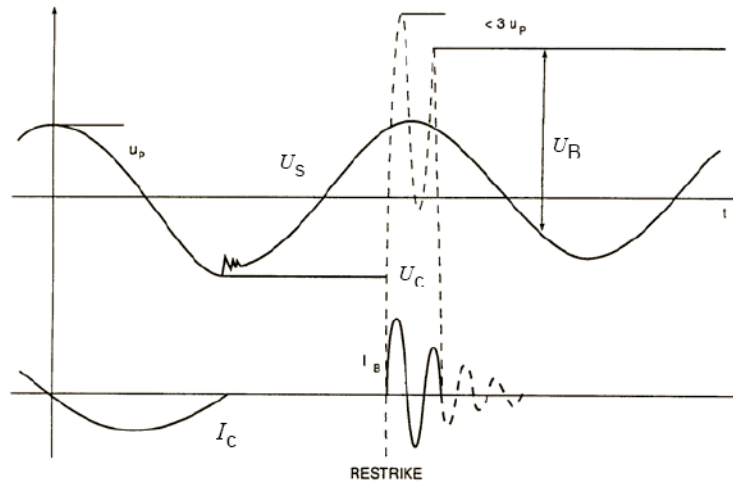
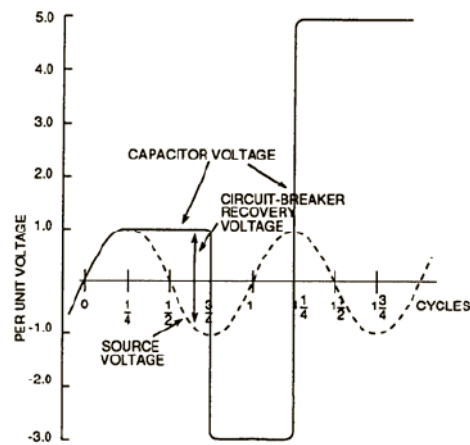


Figure 3—Voltage and current wave shapes in the case of a restrike



Key: 1 p.u. is the peak value of the phase-to-ground voltage.

Figure 4—Theoretical maximum voltage buildup by successive restrikes

Another phenomenon, which has been observed predominantly on vacuum circuit breakers, may occur during capacitive current and short circuit breaking current tests, but also at lower currents and voltages. This phenomenon is known as a *non-sustained disruptive discharge* (NSDD).

An NSDD is defined as a disruptive discharge associated with current interruption that does not result in the resumption of power frequency current or, in the case of capacitive current interruption, does not result in current at the natural frequency of the circuit.

NOTE—Oscillations following NSDDs are associated with the parasitic capacitance and inductance local to, or of, the circuit breaker itself. NSDDs may also involve the stray capacitance to ground of nearby equipment.

Restrikes will lead to overvoltages across the capacitive load (maximum 3 p.u. for a single restrike, where 1 p.u. is the peak value of the phase to ground voltage) while reignitions will not produce any overvoltages (maximum 1 p.u. theoretically). Reignitions are acceptable, but they may cause power quality problems, as they represent a temporary short circuit.

In reality, there are no restrike free circuit breakers. It would take an infinite number of test shots to verify this. For this reason, the concept of restrike performance was introduced in IEEE Std C37.04a.

When interrupting small capacitive currents, some circuit breaker types may exhibit current chopping. Current chopping is a distortion of the current prior to current zero and is usually caused by the high arc voltage. Different types of circuit breakers have varying degrees of current chopping.

Current chopping will cause an interruption prior to the current zero of the power frequency current. In other words, the trapped charge on the capacitive load will not be at its peak. This case results in a lower recovery voltage peak and a lower stress on the contact gap of the circuit breaker.

The recovery voltages in three phase circuits are more complicated than in the single phase case. Figure 5 shows as an example the recovery voltage of the first pole to clear in a case with an ungrounded capacitive load. For the first pole to clear, the recovery voltage initially has a shape that would lead to a peak value equal to three times the supply voltage peak (dotted line). When the two last poles interrupt 90° after the first, there is, however, a discontinuity in the slope, and the final peak value for the first pole to clear is 2.5 times the supply voltage peak (see also 4.1.4).

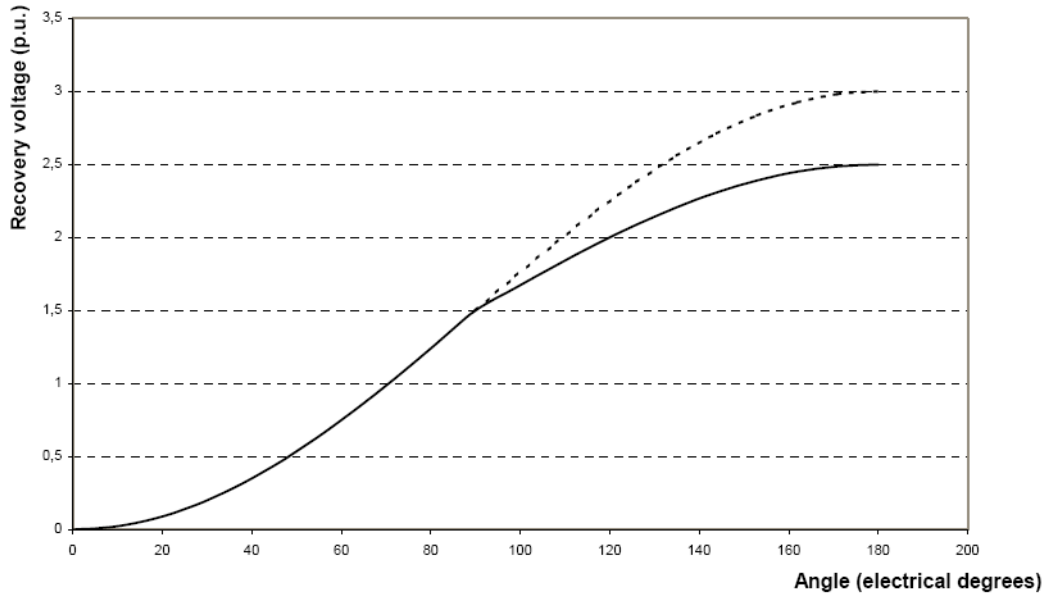


Figure 5—Recovery voltage of the first pole to clear at interruption of a three-phase ungrounded capacitive load

4.1.2 No-load cables

4.1.2.1 Cable charging current

The cable charging current is a function of the following characteristics:

- System voltage
- Cable geometry
- Insulation dielectric constant
- Cable length

The shunt capacitive reactance can be obtained from the cable manufacturer; or, if the physical constants of the cable are known, the shunt capacitive reactance can be calculated (see Gabrielle, et al. [B6])⁵. For single-conductor and three-conductor shielded cables (for the different cable configurations, see Figure 8 and Figure 7), the shunt capacitive reactance can be written as shown in Equation (2):

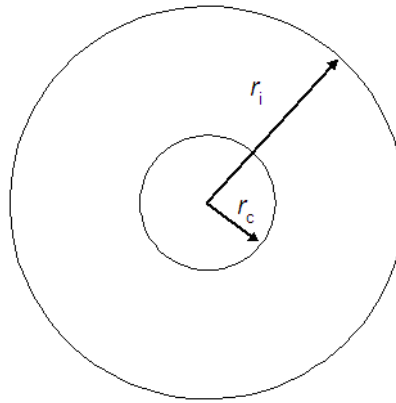


Figure 6—Cross section of a high-voltage cable

$$X_c = \frac{0,3495}{f_s \epsilon_r} \ln \frac{r_i}{r_c} \text{ (M}\Omega \text{ per phase per km)}^6 \quad (2)$$

where

f_s is the system frequency (Hz)

ϵ_r is the dielectric constant of cable dielectric material (F/m)

r_i is the inside radius of shield (mm)

r_c is the conductor radius (mm)

Using the capacitive reactance, the cable charging current can be calculated and compared with the rated cable charging current of the circuit breaker given in ANSI Std C37.06. If the calculation exceeds the rating, the manufacturer should be consulted. Before an application can be made, the inrush current rating should also be checked (see 6.11.1).

4.1.2.2 Recovery voltage

The recovery voltage is equal to that of a capacitor bank (see 4.1.1.2).

⁵Number in brackets correspond to the numbers in the bibliography in Annex A.

⁶When using the quantity megaohm per phase per kilometer, it should be remembered that the shunt capacitive reactance in megaohms for more than 1 km decreases because the capacitance increases. For more than 1 km of line, therefore, the value of shunt capacitive reactance as given in Equation (2) should be divided by the number of kilometers of line.

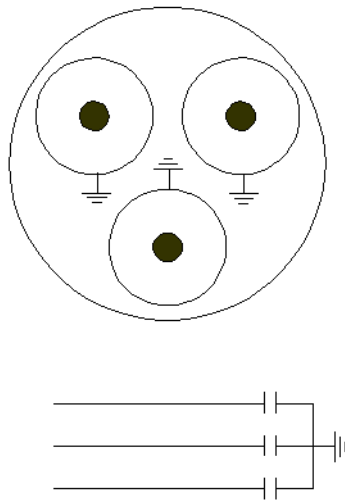


Figure 7—Screened cable with equivalent circuit

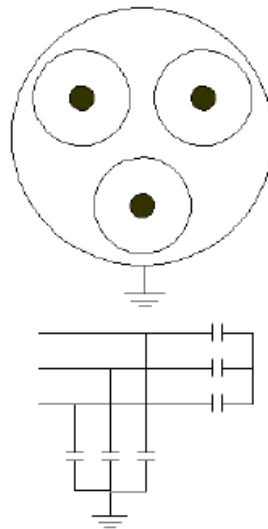


Figure 8—Belted cable with equivalent circuit

4.1.3 No-load overhead lines

4.1.3.1 Uncompensated overhead lines

4.1.3.1.1 Line charging current

A no-load overhead line can generally be represented by a capacitance. In the case of short lines (< 200 km), this capacitance can be considered concentrated. However, in the case of long lines, it must be considered distributed. Typical capacitance values vary from 9.1 nF/km per phase for single conductor overhead lines to 14 nF/km per phase for four conductor bundle overhead lines (see also CIGRE Technical Brochure 47 [B1]).

Due to the distributed nature of the inductance and the capacitance of the line, the peak value of the power frequency voltage at the remote (or receiving) end is higher than that at the circuit breaker (sending) end of the line. This effect is called the *Ferranti effect*. For a line length of 500 km, the voltage increase is approximately 4% and for a line of 200 km, approximately 1%. The Ferranti effect is not considered for line lengths below 200 km.

4.1.3.1.2 Recovery voltage

Overhead lines have capacitance both between phases and to ground. Figure 9 shows the peak value of the recovery voltage in the first pole to clear as a function of the capacitance ratio C_1/C_0 (positive to zero sequence capacitance). It has been assumed that the amplitude approaches 3 p.u. The conditions for this case are as follows:

- No capacitance to ground
- Delayed interruption of the second phase

An example of the voltages in such a case is given in Figure 5. The other extreme, $C_1 = C_0$, is the case where each phase has capacitance to ground only. The recovery voltage peak is then 2 p.u. as in a single phase case.

Overhead lines typically have C_1/C_0 ratios in the order of 2.0. In this case, Figure 9 shows that the recovery voltage peak is approximately 2.4 p.u.

While Figure 5 and Figure 9 assume a delayed interruption of the second phase, when the second and third phases interrupt 90° after the first, the maximum recovery voltage peak is 2.4 p.u. one half cycle after interruption (see 4.1.4).

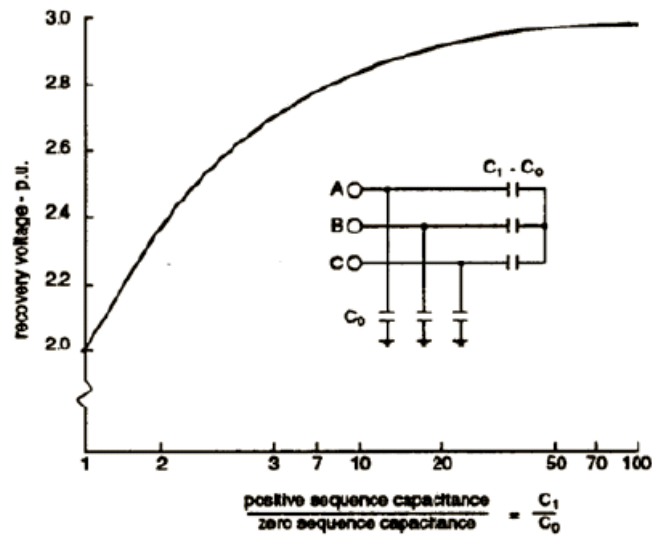


Figure 9—Recovery voltage peak in the first pole-to-clear as a function of C_1/C_0 , delayed interruption of the second phase

When the characteristics of the voltage in service (e.g., shape and peak value) deviate from those of the test voltage, the restrike probability may increase or decrease. For example, if the line is compensated, the line-side component is not a trapped voltage resulting from the trapped charge, but a voltage oscillating with a frequency determined by the compensating reactors and the line-side capacitance (see 4.1.3.2).

If the C_1/C_0 ratio is greater than 2, higher voltages may be coupled to the first pole to clear, resulting in increased probability of restrike. In this case, the manufacturer should also be consulted because circuit breaker designs are sensitive to both current magnitude and recovery voltage waveshapes.

4.1.3.2 Shunt compensated overhead lines

Long overhead lines are often compensated with shunt reactors to reduce the charging current of the line. The compensation factor (k_1) of an overhead line is given by the ratio of the capacitive reactance of the line ($X_{C, \text{line}}$) to the inductive reactance ($X_{L, \text{reactor}}$) of the compensating reactor, as in Equation (3).

$$k_1 = \frac{X_{C, \text{line}}}{X_{L, \text{reactor}}}$$

If $X_{L, \text{reactor}} > X_{C, \text{line}}$, the line is called *undercompensated*. A line with $X_{L, \text{reactor}} < X_{C, \text{line}}$ is called *overcompensated*.

4.1.3.2.1 Line charging current

The compensated line charging current is given by

$$I_{lc} = I'_c(1 - k_1)$$

where

I_{le} is the line charging current of the compensated line (A) (rms)

I_e' is the line charging current of the uncompensated line (A) (rms)

k_l is the compensation factor

Assuming a line compensated at 60% (i.e., $k_l = 0.60$), the line charging current is as follows:

$$I_{le} = I_e' (1 - 0.6) = 0.4 I_e' \text{ or } 40\% \text{ of the uncompensated value}$$

4.1.3.2.2 Recovery voltage

If the line is compensated, the line-side component of the recovery voltage is no longer a dc voltage, but an oscillation of which the frequency is determined by the compensating reactor and the line capacitance.

The resonant frequency is approximated by Equation (4):

$$f_l \approx \frac{1}{2\pi\sqrt{LC}} = f_s \sqrt{\frac{X_{C, \text{line}}}{X_{L, \text{reactor}}}} = f_s \sqrt{k_l} \quad (4)$$

where

f_l is the resonance frequency of the compensated line (Hz)

L is the inductance of the reactor (H)

C is the total capacitance of the line (F)

f_s is the system frequency (Hz)

k_l is the compensation factor

In other words, the resonance frequency of a compensated line is dependent on the degree of compensation. Because the compensation usually is less than 1, this resonance frequency is less than the system frequency, resulting in a reduction of the recovery voltage. Typical current and voltage waveshapes are given in Figure 10.

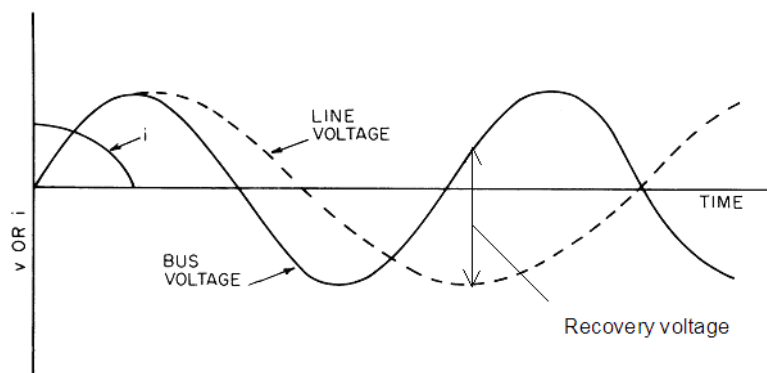


Figure 10—Typical current and voltage relations for a compensated line

The first half cycle of recovery voltage is, for this example, as shown in Figure 11. Compensation thus results in a decrease of the probability of restrike at a particular current. Under these conditions, improved performance may result, and the circuit breaker becomes restrike free or possibly able to interrupt higher values of charging current. The manufacturer should be consulted on applications that markedly alter the recovery voltage.

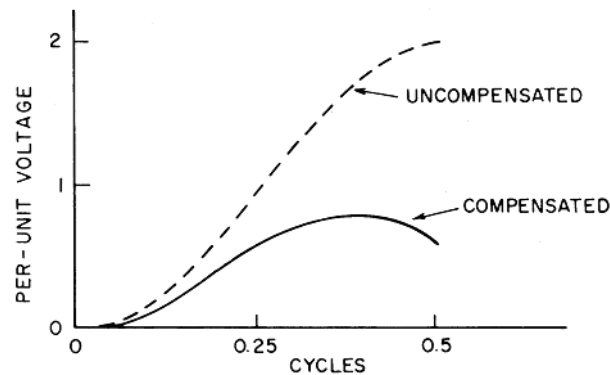


Figure 11—Half cycle of recovery voltage

4.1.3.3 Switching the charging currents of long overhead lines

Very long overhead lines in excess of 300 km, even those of simple construction type, present a special case not covered by the requirements of 4.10.7 of IEEE Std C37.09 or its notes. Where such long lines are to be switched, consideration should be given to the higher value of peak transient recovery voltage (TRV) present on interruption. Some idea of the ability of a particular circuit breaker for making and breaking this requirement can be gained by considering any out of phase switching evidence that may exist. Such evidence will usually provide adequate demonstration of the elevated TRV; and, although the current values for the out of phase duty are higher than the charging current of the line, they may be considered comparable for providing background evidence for this special duty. However, such limited demonstration of capability as the out of phase test cannot be considered satisfactory for demonstration purposes for an overhead line switching duty. For full compliance, evidence will be required to satisfy the capacitive current switching requirements of 4.10 of IEEE Std C37.09, but to the elevated values required by the specific application.

Some users may be concerned about rare or occasional switching operations from one end on a long line. This case can occur during the early development stages of a system when intermediate substations may not be fully equipped or may even be by passed. In such cases, it may be appropriate to consider the out of phase capability in relation to the combined load presented by the lines. If satisfactory for the current and voltage conditions, then specific testing for the severe capacitive current switching duty of IEEE Std C37.09 would not be necessary at the enhanced levels of the extended line. They would be required for the switching duty of the individual lines, as normal. There is an obvious risk associated with such operation, and this acceptance of the out of phase evidence is possible only if the operating regime for such an extended line length condition is infrequent. Infrequent operation is often likely to be the case for such development stages of a system.

4.1.4 Voltage factors for capacitive current switching tests

Depending on the capacity of a high-power laboratory, capacitive current switching tests may be performed as three phase tests or single phase tests. For the higher voltages (i.e., 362 kV, 420 kV, 550 kV, and 800 kV), unit tests are sometimes made.

Especially when single phase tests are made to cover three phase application, the test voltage shall reflect the application of the circuit breaker in the system. One of the factors influencing this is the grounding situation of the network. The other is the presence of single or two phase faults.

In 4.10.7 of IEEE Std C37.09, the voltage factors shown in Table 1 are given for single phase tests. The test voltage measured at the circuit breaker location prior to interruption shall not be less than the product of the rated voltage $U_r/\sqrt{3}$ and the voltage factors given in Table 1.

Table 1—Voltage factors for single-phase capacitive current switching tests

Voltage factor (k_e)	Application
1.0	Tests corresponding to normal service in effectively grounded neutral systems without significant mutual influence of adjacent phases of the capacitive circuit, typically capacitor banks with effectively grounded neutral and screened cables.
1.2	Test on belted cables and line charging current switching ^a corresponding to normal service conditions in effectively grounded neutral systems for rated voltages 72.5 kV and above.
1.4	— Breaking during normal service conditions in systems having a ungrounded neutral including screened cables;^a — Breaking of capacitor banks ungrounded neutral; — Test on belted cables and line charging current switching^b corresponding to normal service conditions in effectively grounded systems for rated voltages less than 72.5 kV; — Breaking in the presence of single or two phase-to-ground faults in systems having a solidly grounded neutral.
1.7	Tests corresponding to breaking in ungrounded systems in the presence of single or two phase-to-ground faults. ^c
NOTE 1—The voltage factors for line charging current switching tests of 1.2 and 1.4 are applicable to single circuit line construction. Requirements for multiple overhead line constructions may be greater than these factors. NOTE 2—The 1.4 factor is a compromise and is valid for breaking capacitive currents in ungrounded systems, where the second and third poles to clear interrupt 90° after the first. NOTE 3—When the nonsimultaneity of contact separation in the different poles of the circuit breaker exceeds 1/6th of a cycle of rated frequency, it is recommended to raise the voltage factor or to make only three phase tests. Such circuit breakers fall outside the scope of IEEE Std C37.09.	

^aWhen a significant capacitance to ground on the source side is present, the factor will be reduced. ^bUnder the condition that the line can be replaced partly or fully by a concentrated capacitor bank. ^cThe factor 1.7 is derived from the fact that the healthy phase sees the phase-to-phase voltage.

The voltage factor 1.4 is explained as follows: When the current in the first pole is interrupted, the voltage across the circuit breaker will rise as if the voltage factor would have been 1.5. When the second and third poles interrupt 90° later, there is a discontinuity; and the recovery voltage across the first pole to clear will follow a 1-cosine wave with a voltage factor of 1.25. The recovery voltage is indicated by the solid line in Figure 12. By using a voltage factor of 1.25 (dotted line in Figure 12), the initial portion of the

recovery voltage across the first pole is not adequately covered. Using a voltage factor of 1.5 will result in too high a stress. A voltage factor of 1.4 as indicated by the dashed curve in Figure 12 is a compromise that adequately covers the actual recovery voltage.

Careful consideration should be given to these voltage factors when circuit breakers are relocated to other parts of the system where the application is different from that of the original location.

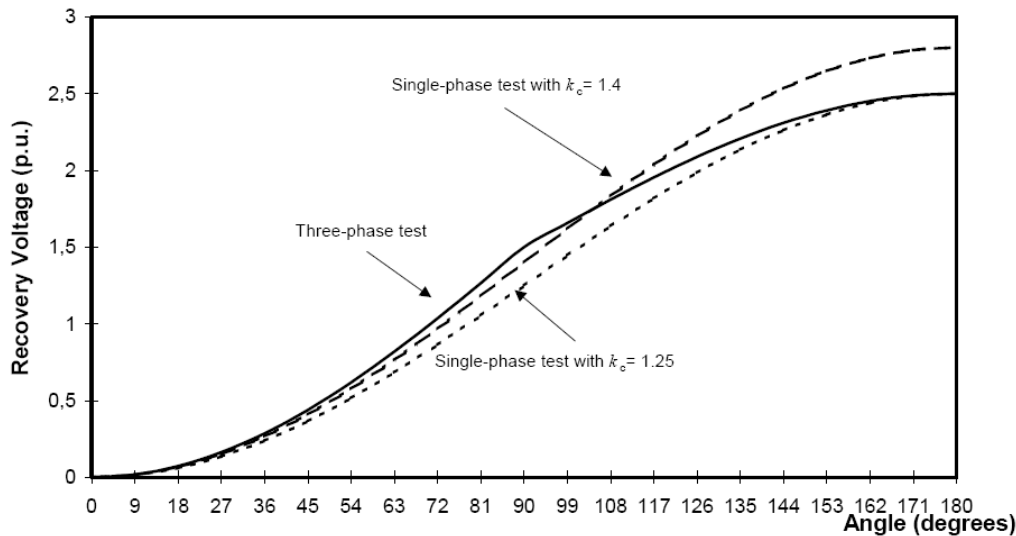


Figure 12—Recovery voltage on first pole-to-clear for three-phase interruption: capacitor bank with isolated neutral (50-Hz)

The voltage factors specified in Table 1 are associated with single circuit line constructions and are chosen to accommodate all known physical arrangements of the conductors of such circuits. Note 1 to Table 1 indicates that switching in the case of multiple overhead line constructions that have parallel circuits may require a voltage factor greater than 1.2 and 1.4. The reason for the higher voltage factor is because such circuits are likely to have an enhancement to the line-side residual voltage following interruption. The enhancement is associated with the coupling (pick-up) from the parallel circuit and may add a power frequency peak voltage of up to 0.2 p.u., depending upon the geometry of the conductor systems of the two circuits.

In addition, the effect of these changes on the line-side voltage, following interruption by the first pole-to-clear, does affect the shape of the TRV across that opening pole. Consideration of this effect may require additional testing if the existing factor does not adequately cover the combined effects. Alternatively, the higher of the given values, e.g., 1.4 for 1.2, can be selected to encompass the specific waveshape.

On occasion, utilities have specified a voltage factor of 1.3 instead of 1.2 for their double circuit lines.

4.2 Energization of capacitive loads

Energization of capacitive loads is usually associated with transient voltages and currents. Those transients are the following:

- Inrush currents
- Overvoltages caused by the system response to the voltage dip when energizing capacitor banks (see 4.2.1)
- Overvoltages caused by traveling waves on transmission lines and cables

In 4.2.1 through 4.2.3, the phenomena associated with the energization of capacitor banks, lines, and cables are treated.

4.2.1 Capacitor banks

Because the use of capacitor banks for compensation purposes is increasing, it is common that more than one capacitor bank is connected to the same bus. This practice has no influence on the conditions at interruption. The current at closing (i.e., inrush current), however, is affected to a high degree. Two different situations may occur:

- a) The capacitor bank is energized from a bus that does not have other capacitor banks energized. This situation is called *isolated capacitor bank switching*.
- b) The capacitor bank is energized from a bus that has other capacitor banks energized. This situation is called *back-to-back capacitor bank switching*.

The conditions for isolated and back-to-back capacitor bank switching are given in 4.2.1.1 and 4.2.1.2. Even energized capacitor banks in nearby substations may contribute to the inrush current so that a back-to-back situation occurs.

Especially the second case may give rise to an inrush current of very high amplitude and frequency, which sometimes has to be limited in order not to be harmful to the circuit breaker, the capacitor banks, and/or the network. The magnitude and frequency of this inrush current is a function of the following:

- Applied voltage (point on the voltage wave at closing)
- Capacitance of the circuit
- Inductance in the circuit (amount and location)
- Any charge on the capacitor bank at the instant of closing
- Any damping of the circuit due to closing resistors or other resistances in the circuit

It is assumed that the capacitor bank is discharged prior to energization. This assumption is reasonable, as capacitor units are fitted with discharging resistors that will discharge the capacitor bank. Typical discharge times are in the order of 5 min.

The transient inrush current to an isolated bank is less than the available short-circuit current at the capacitor bank terminals. It rarely exceeds 20 times the rated current of the capacitor bank at a frequency that approaches 1 kHz. Because a circuit breaker must meet the making current requirements of the system, transient inrush current is not a limiting factor in isolated capacitor bank applications.

When capacitor banks are switched back to back (i.e., when one bank is switched while another bank is connected to the same bus), transient currents of prospective high magnitude and with a high natural frequency may flow between the banks on closing of the circuit breaker. The effects are similar to that of a restrike on opening. This oscillatory current is limited only by the impedance of the capacitor bank and the circuit between the energized bank or banks and the switched bank. This transient current usually decays to zero in a fraction of a cycle of the system frequency. In the case of back-to-back switching, the component supplied by the source is at a lower frequency; therefore, small it may be neglected.

4.2.1.1 Isolated capacitor bank

A bank of shunt capacitors is considered isolated when the inrush current on energization is limited by the inductance of the source and the capacitance of the bank being energized. A capacitor bank is also considered isolated if the maximum rate of change, with respect to time, of transient inrush current on energizing an uncharged bank does not exceed the maximum rate of change of the symmetrical short-circuit current at the voltage at which the current is applied. The limiting value is equal to Equation (5).

$$\left(\frac{di_i}{dt} \right)_{\max} = \omega_s I_{sc} \sqrt{2} \quad (5)$$

where

$\left(\frac{di_i}{dt} \right)_{\max}$ — is the maximum rate of change of inrush current (A/s)

I_{sc} — is the rated rms short-circuit current (A)

$\omega_s = 2\pi f_s$ — is the angular system frequency (rad/s) and f_s is the power frequency (Hz)

The single phase equivalent of a circuit where two capacitor banks are connected to a busbar is shown in Figure 13. L_1 and L_2 represent the stray inductance (or stray inductance plus additional damping inductance). The inductance L_s of the supply network will be several orders of magnitude higher than L_1 and L_2 :

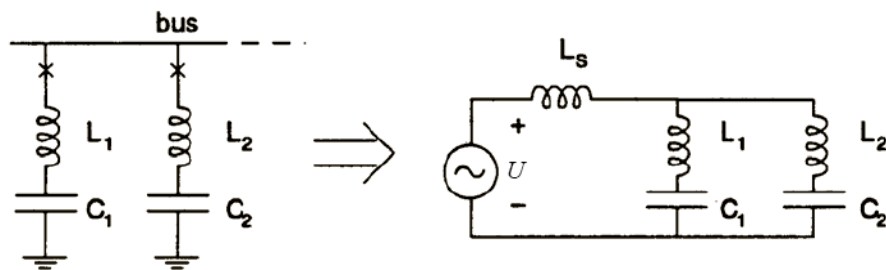


Figure 13—Parallel capacitor banks