



IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers

IEEE Power Engineering Society

Sponsored by the
Switchgear Committee

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Abstract: Guidance for the application of ac high-voltage circuit breakers for capacitance current switching is provided. The application guide addresses the general theory of capacitance current switching; and the notions of restrike, reignition, non-sustained disruptive discharge (NSDD), and voltage factors are explained. Application of circuit breakers for different network conditions and different capacitive loads (lines, cables, capacitor and filter banks) is treated.

Keywords: ac high-voltage circuit breakers, application, capacitance current switching, inrush currents, ~~non-sustained~~ disruptive discharge, restrike, reignition, NSDD, overvoltages

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Introduction

This introduction is not part of IEEE Std C37.012-2005, IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers.

This application guide is a revision of IEEE Std C37.012-1979. This revision reflects the changes made to the capacitive current switching requirements and test procedures stated in IEEE Std C37.04a^{TMa} and IEEE Std C37.09TM.

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Contents

1.	Overview.....	1
1.1	Scope.....	1
1.2	Purpose.....	1
2.	Normative references.....	1
3.	General.....	2
4.	General theory of capacitive current switching.....	3
4.1	De-energization of capacitive loads.....	3
4.1.1	Capacitor banks.....	3
4.1.2	No-load cables.....	6
4.1.3	No-load overhead lines.....	8
4.1.4	Voltage factors for capacitive current switching tests.....	11
4.2	Energization of capacitive loads.....	13
4.2.1	Capacitor banks.....	14
4.2.2	Cables.....	18
4.2.3	Energization and re-energization of overhead lines.....	24
5.	General application considerations.....	26
6.	Capacitance current switching application considerations.....	26
6.1	Maximum voltage for application.....	26
6.2	Frequency.....	26
6.3	Rated capacitive current.....	26
6.3.1	Overhead lines and cables.....	26
6.3.2	Capacitor and filter banks.....	27
6.4	Voltage and grounding conditions of the network.....	27
6.5	Restrike performance.....	28
6.6	Class of circuit breaker.....	28
6.7	Interrupting time.....	29
6.8	Transient overvoltages and overvoltage limitation.....	29
6.8.1	Overvoltages.....	29
6.8.2	Overtvoltage limitation.....	30
6.9	No-load overhead lines.....	30
6.9.1	Line charging current.....	30
6.9.2	Compensated overhead lines.....	32
6.9.3	No-load line recovery voltage.....	32
6.10	Capacitor banks.....	32
6.10.1	Capacitor bank current.....	32
6.10.2	Methods for calculating transient inrush currents.....	33
6.11	Cables.....	38
6.11.1	Cable inrush current.....	38
6.11.2	Alternate configurations.....	38
6.12	Switching through transformers.....	39
6.13	Unusual circuits.....	40
6.13.1	Exposure to transient inrush currents.....	41
6.13.2	Exposure to total capacitor bank discharge current.....	41
6.13.3	Exposure to capacitive switching duties during fault switching.....	43

6.14 Effect of load	43
6.15 Effect of reclosing	43
6.16 Resistor thermal limitations	44
6.17 Application considerations for different circuit breaker types	44
6.17.1 Oil circuit breakers	44
6.17.2 Vacuum circuit breakers	45
6.17.3 Sulfur hexafluoride (SF6) circuit breakers	45
6.17.4 Air-blast circuit breakers	46
7. Considerations of capacitive currents and recovery voltages under fault conditions	46
7.1 Voltage and current factors	46
7.2 Reasons for these specific tests being non-mandatory in the standard	46
7.3 Contribution of a capacitor bank to a fault	47
7.4 Switching overhead lines under faulted conditions	47
7.5 Switching capacitor banks under faulted conditions	48
7.5.1 Reference condition	49
7.5.2 Fault to neutral in one phase (one capacitor bank phase short-circuited)	49
7.5.3 Fault to ground in one phase	50
7.5.4 Other fault cases	50
7.6 Switching cables under faulted conditions	50
7.7 Examples of application alternatives	50
Annex A (informative) Bibliography	51

Figures

Figure 1—Single-phase equivalent circuit for capacitive current interruption	3
Figure 2—Voltage and current shapes at capacitive current interruption	4
Figure 3—Voltage and current wave shapes in the case of a restrike	5
Figure 4—Theoretical maximum voltage buildup by successive restrikes	5
Figure 5—Recovery voltage of the first pole-to-clear at interruption of a three-phase ungrounded capacitive load.....	6
Figure 6—Cross section of a high-voltage cable.....	7
Figure 7—Screened cable with equivalent circuit.....	8
Figure 8—Belted cable with equivalent circuit.....	8
Figure 9—Recovery voltage peak in the first pole-to-clear as a function of $C1/C0$, delayed interruption of the second phase	9
Figure 10—Typical current and voltage relations for a compensated line.....	10
Figure 11—Half cycle of recovery voltage	11
Figure 12—Recovery voltage on first pole-to-clear for three-phase interruption: capacitor bank with isolated neutral (50 Hz).....	13
Figure 13—Parallel capacitor banks.....	15
Figure 14—Typical circuit for back-to-back switching	20
Figure 15—Equivalent circuit for back-to-back cable switching.....	22
Figure 16—Bank-to-cable switching circuit.....	23
Figure 17—Equivalent bank-to-cable switching circuit.....	23
Figure 18—Energization of no-load lines: basic phenomena.....	25
Figure 19—Pre-insertion resistors and their function.....	25
Figure 20—Example of the recovery voltage across a filter bank circuit breaker	27
Figure 21—RMS charging current versus system voltage for different line configurations at 60 Hz	31
Figure 22—Typical circuit for back-to-back switching	34
Figure 23—Example of 115 kV system	36
Figure 24—Voltage and current relations for capacitor switching through interposed transformer.....	40
Figure 25—Station illustrating large transient inrush currents through circuit breakers from parallel capacitor banks	42
Figure 26—Fault in the vicinity of a capacitor bank.....	47
Figure 27—Recovery voltage and current for first pole-to-clear when faulted phase is the second pole-to-clear.....	48
Figure 28—Reference condition.....	49

Tables

Table 1—Voltage factors for single-phase capacitive current switching tests..... 12

Table 2—Inrush current and frequency for switching capacitor banks..... 33

Table 3—Typical values of inductance between capacitor banks..... 35

Table 4—Frequency and current amplitude relations..... 39

IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers

1. Overview

1.1 Scope

This application guide for capacitance current switching applies to ac high-voltage circuit breakers rated in accordance with IEEE Std C37.04™¹ 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 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. 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, American National Standard for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis – Preferred Ratings and Related Required Capabilities.²

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 C37.04™, IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.^{3, 4}

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

IEEE Std C37.010™, IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis.

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.

³IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, Piscataway, NJ 08854, USA (<http://standards.ieee.org/>).

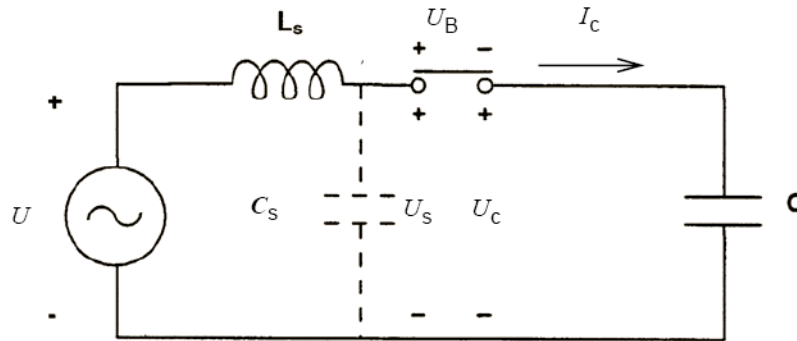
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4. General theory of capacitive current switching

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

$$\omega_s = 2\pi f_s, \text{ where } f_s \text{ is the system frequency (Hz)}$$

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

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.

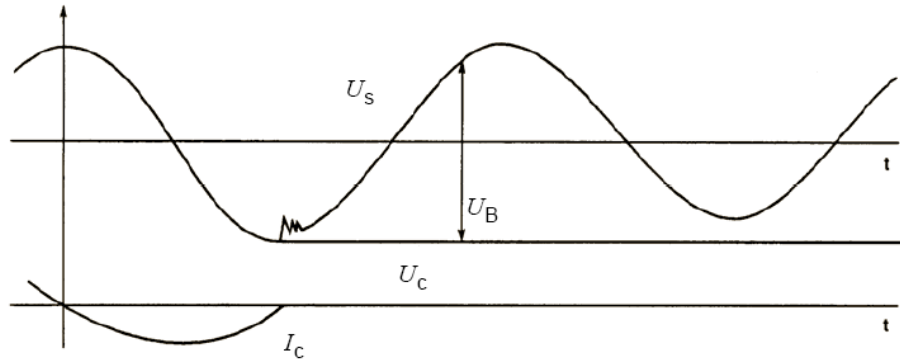


Figure 2—Voltage and current shapes at capacitive current interruption

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.

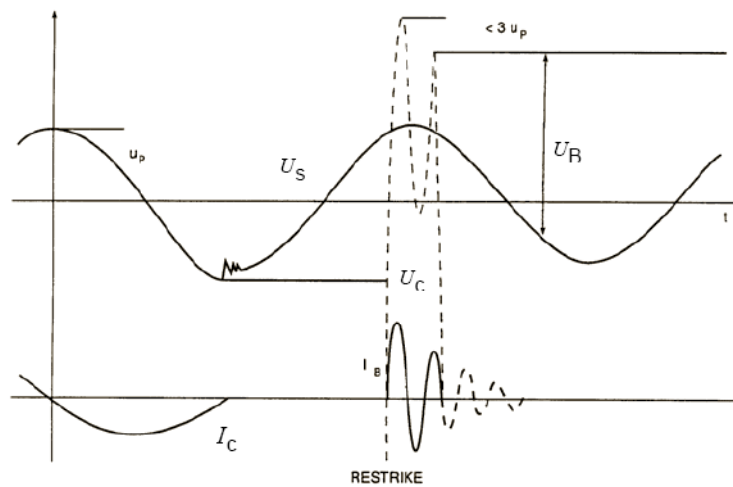
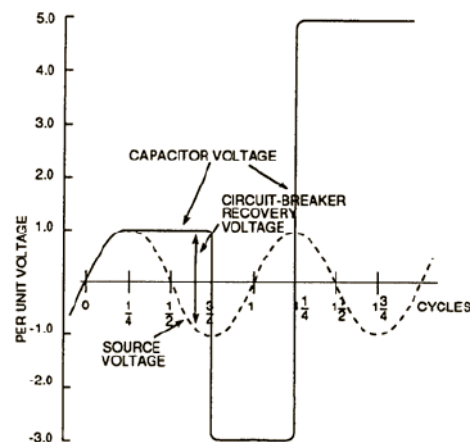


Figure 3—Voltage and current wave shapes in the case of a restrike



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).

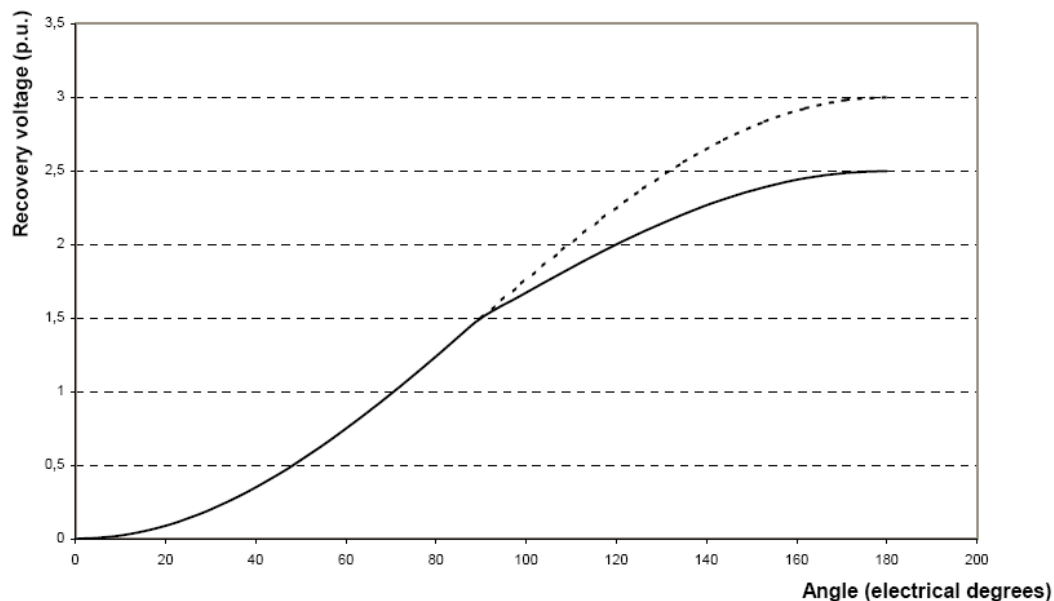


Figure 5—Recovery voltage of the first pole-to-clear at interruption of a three-phase ungrounded capacitive load

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).

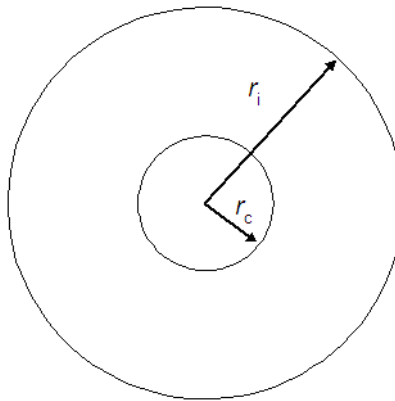


Figure 6—Cross section of a high-voltage cable

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

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.

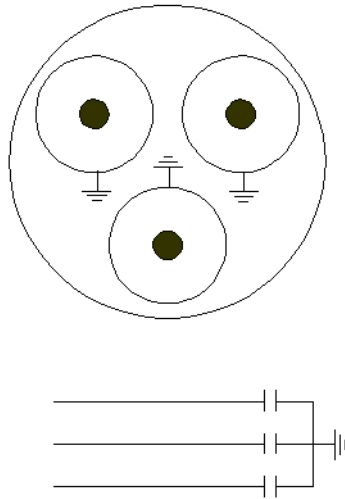


Figure 7—Screened cable with equivalent circuit

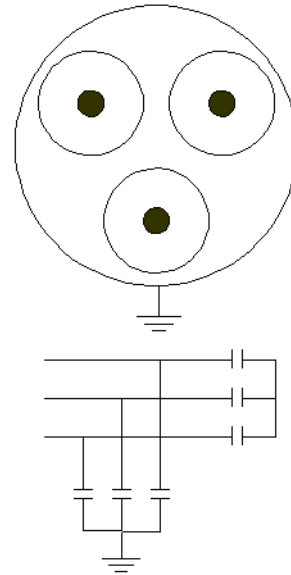


Figure 8—Belted cable with equivalent circuit

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).

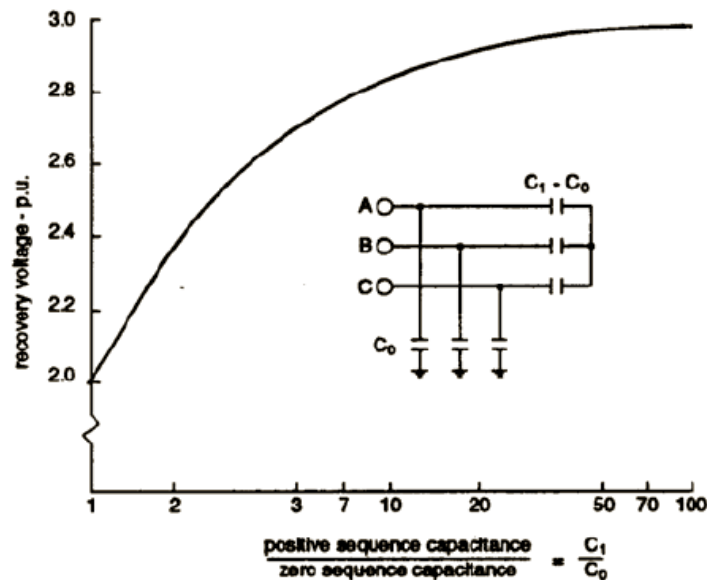


Figure 9—Recovery voltage peak in the first pole-to-clear as a function of C_1/C_0 , delayed interruption of the second phase

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).

$$k_1 = \frac{X_{C, \text{line}}}{X_{L, \text{reactor}}} \quad (3)$$

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 $I_{IC} = I'_C(1 - k_1)$