



IEEE Guide for the Application of Capacitive Current Switching for AC High-Voltage Circuit Breakers above 1000 V

IEEE Power and Energy Society

Developed by the
Switchgear Committee

IEEE Std C37.012™-2022
(Revision of IEEE Std C37.012-2014)

STANDARDS

IEEE Guide for the Application of Capacitive Current Switching for AC High-Voltage Circuit Breakers above 1000 V

Developed by the

Switchgear Committee
of the
IEEE Power and Energy Society

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Abstract: Guidance for the application of ac high-voltage circuit breakers switching capacitive currents is provided. The general theory of capacitive current switching and the notions of restrike, reignition, and nonsustained disruptive discharge (NSDD) are addressed in the application guide. Voltage factors used for single-phase testing as a substitute for three-phase testing are explained. The application of circuit breakers for different network conditions and different capacitive loads (capacitor banks, cables, transmission lines, and filter banks) is discussed.

Keywords: application, capacitive current switching, high-voltage circuit breakers, IEEE C37.012™, inrush current, nonsustained disruptive discharge, NSDD, overvoltages, reignition, restrike

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Introduction

This introduction is not part of IEEE Std C37.012™-2022, IEEE Guide for the Application of Capacitive Current Switching for AC High-Voltage Circuit Breakers Above 1000 V.

This application guide is a revision of IEEE Std C37.012™-2014. This revision reflects the changes made to the capacitive current switching requirements and test procedures stated in IEEE Std™ C37.04, IEEE Std™ C37.09, and IEEE Std™ C37.100.2. Furthermore, the following significant changes were made:

- The document was restructured to treat each case (capacitor bank, cable, and transmission line) in one clause.
- The basis for the calculation of inrush current was changed.
- Application limitations for allowable inrush current natural frequencies has been updated to agree with IEEE Std™ C37.012a-2020.
- Figures have been updated.
- Explanations for standard values and why certain tests are not mandatory have been moved to Annex B.

The document has been revised to incorporate the changes made in IEEE Std C37.012a-2020.

Contents

1. Overview	12
1.1 Scope	12
1.2 Purpose	12
1.3 Overview/roadmap	12
1.4 Word usage	12
2. Normative references	13
3. Definitions	13
4. General	15
5. Capacitive current switching application considerations	17
5.1 General	17
5.2 Maximum voltage for application	17
5.3 Frequency	17
5.4 Rated capacitive current	17
5.5 Voltage and power system grounding arrangement	18
5.6 Restrike probability	18
5.7 Restrike probability class of circuit breaker	19
5.8 Interrupting time	20
5.9 Transient overvoltages and overvoltage limitation	20
5.10 Inrush and outrush currents	22
6. Capacitor bank switching	23
6.1 General	23
6.2 De-energizing capacitor banks	24
6.3 Energizing capacitor banks	29
6.4 Capacitor bank application considerations	35
7. Unloaded cable switching	43
7.1 General	43
7.2 De-energizing unloaded cables	44
7.3 Energizing unloaded cables	46
7.4 Insulated Cables	51
8. Unloaded line switching	52
8.1 General	52
8.2 Considerations about line charging currents	52
8.3 Considerations about recovery voltage of unloaded transmission lines	53
8.4 De-energizing uncompensated transmission lines	54
8.5 De-energizing compensated transmission lines	57
8.6 Energizing and reenergizing transmission lines	59
9. Voltage factors for capacitive current switching tests	67
10. Other capacitive current switching application considerations	69
10.1 Switching through transformers	69
10.2 “Hidden” circuits	70
10.3 Effect of load	73
10.4 Effect of reclosing	73
10.5 Resistor thermal limitations	74
10.6 Application considerations for different circuit breaker types	74

11. Considerations of capacitive currents and recovery voltages under fault conditions	76
11.1 Voltage and current factors.....	76
11.2 Reasons for these specific tests being nonmandatory in the standard.....	77
11.3 Contribution of a capacitor bank to a fault	77
11.4 Switching transmission lines under faulted conditions.....	78
11.5 Switching capacitor banks under faulted conditions.....	79
11.6 Switching cables under faulted conditions	81
11.7 Examples of application alternatives	81
Annex A (informative) Bibliography	82
Annex B (informative) Derivation of standard values.....	84
B.1 Voltage factors	84
B.2 Why standards do not require testing under fault conditions	85
B.3 Reason for the test recovery voltage being maintained for 0.3 seconds.....	85
Annex C (informative) Document roadmap and general guidance	86
C.1 Purpose.....	86
C.2 Nature of the capacitive load to be switched.....	86
C.3 Consequences of capacitive load switching	87
C.4 Mitigation of undesired consequences of capacitive current switching	88
C.5 Cautionary notes	88

IEEE Guide for the Application of Capacitive Current Switching for AC High-Voltage Circuit Breakers above 1000 V

1. Overview

1.1 Scope

This document revises the application guide for capacitive current switching for high-voltage circuit breakers rated in accordance with IEEE Std C37.04™ and tested in accordance with IEEE Std C37.100.2™.⁶ It supplements 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 capacitive current switching. Familiarity with other US 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.

1.3 Overview/roadmap

Annex C provides a high-level overview/roadmap of key elements of this guide, and also serves as an application check list of topics to be understood and considered in applying circuit breakers to various situations involving switching of capacitive currents.

1.4 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{7,8}

⁶ Information on normative references can be found in Clause 2.

⁷ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁸ The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

2. Normative references

The following referenced documents are indispensable for the application of this 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.

IEEE Std C37.04™, IEEE Standard for Ratings and Requirements for AC High-Voltage Circuit Breakers with Rated Maximum Voltage Above 1000 V.^{9,10}

IEEE Std C37.09™, IEEE Standard Test Procedures for AC High-Voltage Circuit Breakers with Rated Maximum Voltage Above 1000 V.

IEEE Std C37.010™, IEEE Application Guide for AC High-Voltage Circuit Breakers > 1000 Vac Rated on a Symmetrical Current Basis.

IEEE Std C37.100.2™, IEEE Standard for Common Requirements for Testing of AC Capacitive Current Switching Devices over 1000 V.

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.¹¹

arcing time: The interval of time between the instant of the first initiation of the arc and the instant of final arc extinction in all poles.

NOTE—For switching devices that embody switching resistors, a distinction should be made between the arcing time up to the instant of the extinction of the main arc and the arcing time up to the instant of the breaking of the resistance current.¹²

back-to-back cable switching: Switching a cable in close enough electrical proximity to one or more other energized cables or capacitor banks such that the contributions from these other sources are much higher than from the normal power source.

back-to-back capacitor bank switching: Switching a capacitor bank in close enough electrical proximity to one or more other energized capacitor banks and/or cables to influence the inrush current significantly. Back-to-back inrush current magnitude is generally 20 times greater than the normal steady-state capacitor bank current.

⁹ IEEE publications are available from the Institute of Electrical and Electronics Engineers, <http://standards.ieee.org/>.

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¹¹ *IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

¹² Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

belted three-phase cables: Cables consisting of three individual insulated cores covered by a metallic sheath.

controlled closing: Operation of a switching device in such a manner that the contacts are closed at a predetermined point on a reference voltage or current wave.

controlled switching: Operation of a switching device in such a manner that the contacts are closed or opened at a predetermined point on a reference voltage or current wave.

current chopping: An interruption prior to the natural power frequency current zero of the circuit connected to the circuit breaker.

current limiting reactors: A reactor connected in series with the phase conductors for limiting the current that can flow in a circuit under short-circuit conditions or under other operating conditions, such as capacitor switching, motor starting, synchronizing, arc stabilization, and so forth.

delayed current zero: When an oscillatory current wave fails to pass through zero magnitude at least once during the oscillation.

delayed restrike: A restrike occurring at any instant after the peak recovery voltage.

effectively grounded: An expression that means grounded through a grounding connection of sufficiently low impedance (inherent or intentionally added or both) that a ground fault that may occur cannot build up voltages in excess of limits established for apparatus, circuits, or systems so grounded.

Ferranti effect: An increase in voltage occurring at the receiving end of a very long (> 200 km) ac electric power transmission line, relative to the voltage at the sending end, when the load is very small or no load is connected.

galvanic contact: An electric circuit connection made via a nonplasma or electrolytic means by intimate touching of two solid electrical conductors.

initial TRV (ITRV): A component of the transient recovery voltage that appears in the very short time immediately after current interruption. The ITRV is a result of traveling waves on the conductors adjacent to the circuit-switching device.

inrush current integral (ICI): The absolute value of the inrush current integrated over the pre-arcing duration.

interposed current transformer: Transformer that modifies the secondary current from an existing line current transformer.

interrupting time: The interval of time between energization of the trip circuit and the instant of final arc extinction on all poles of the primary arcing contacts.

noneffectively grounded: Grounded through a grounding connection of sufficient impedance (inherent or intentionally added or both) that a ground fault that might occur results in voltages in excess of limits established for apparatus, circuits, or systems as defined by an effectively grounded system.

outrush current: The transient discharge current that flows when an energized capacitor bank is initially connected to an external short circuit.

preinsertion inductors: An inductor that is inserted in parallel with each set of circuit breaker contacts during the closing stroke of the circuit breaker such that the inductor is connected in series with the capacitor (or cable or line) during the initial stage of the closing operation (i.e., before main contact closure) and then bypassed at the time of closing the main circuit breaker contacts.

preinsertion resistors: A resistor that is inserted in parallel with each set of circuit breaker contacts during the closing stroke of the circuit breaker such that the resistor is connected in series with the capacitor (or cable) during the initial stage of the closing operation (i.e., before main contact closure) and then bypassed at the time of closing the main circuit breaker contacts.

recovery voltage: The voltage that occurs across the terminals of a pole of a circuit-interrupting device upon interruption of current.

reignition: A resumption of current after initial current interruption at zero electrical degrees before 90 electrical degrees after interruption.

restrike: A resumption of current flow after initial current interruption at zero electrical degrees at or after 90 electrical degrees.

screened three-phase cables: Multiple individually insulated and grounded metallic sheaths bound together into a single ungrounded insulated cable.

single cable switching: Switching of a cable whose inrush current is limited by the inductance of the source, buswork inductance, and its own capacitance.

single capacitor bank switching: Switching of a capacitor bank whose inrush current is limited by the inductance of the source, buswork inductance, and its own capacitance. Other capacitor banks and cables are not sufficiently coupled to the bank such that inrush current magnitude is less than 20 times the steady-state capacitor bank current.

single cable switching: Switching of a cable whose inrush current is limited by the inductance of the source, buswork inductance, and its own capacitance.

shock wave limited devices: Devices by which the effects of arcing current result in an interrupter damaging shock wave.

transient limiting inductors: An inductor connected in series with the phase conductors for limiting the transient inrush current during switching or transient outrush current to faults.

transient overvoltage factor: The ratio of the transient voltage appearing between a circuit breaker disconnected terminal and the neutral of the disconnected capacitance during opening to the operating line-to-neutral crest voltage prior to opening.

transient recovery voltage (TRV): The voltage transient that occurs across the terminals of a pole of a switching device upon interruption of the current.

NOTE—TRV is the difference between transient voltages to ground occurring on the terminals. The term transient recovery voltage is usually designated as TRV, and may refer to inherent TRV, modified inherent TRV, or actual TRV as defined elsewhere. In a multipole switching device, the term is usually applied to the voltage across the first pole to interrupt. For switching devices having several interrupting units in series, the term may be applied to the voltage across units or groups of units.

voltage step: The difference in power frequency crest voltage with the capacitive load on compared to the crest voltage with the capacitive load off.

4. General

Capacitive currents are encountered in the following cases:

- Switching of capacitor banks (Clause 6)
- Switching of unloaded cables (Clause 7)
- Switching of unloaded transmission lines (Clause 8)
- Switching of filter banks

Interruption of capacitive currents is generally a light duty for a circuit breaker because the currents are normally less than 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. Restrikes may also cause damage to the breaking unit.

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

- Inrush currents
- Overvoltages caused by the system response to the voltage collapse when energizing capacitor banks
- Overvoltages caused by traveling waves on transmission lines and cables

Product 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 system dependent, tests cannot accurately replicate these effects. By providing a means of assessing the likelihood of restrike occurrence, users can determine what best suits their application. It is common for other protection systems to be in place, such as a surge arrester application, to limit overvoltages from capacitor switching as well as other events. In the case of unacceptable power quality for sensitive electronic equipment, a separate study of actions relative to power quality on energization must 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., capacitor bank, cable or transmission line, or filter bank)
- b) Power frequency of the network
- c) Power system grounding arrangement
- d) Neutral grounding of the capacitor bank (i.e., solidly grounded, ungrounded, or impedance grounded)
- e) Presence of single- or two-phase-to-ground faults

From the application, the restrike class of the circuit breaker can be determined (i.e., class C0, class C1, or class C2). The power system grounding arrangement, neutral grounding of the capacitor bank, and the presence of single and two phase-to-ground faults are important factors that determine the recovery voltage across the circuit breaker. The recovery voltage across the circuit breaker determines the appropriate single-phase test voltage factor, k_v , which should be selected for the circuit breaker.

An interesting result following capacitive current switching is the voltage step. A capacitive load causes a voltage rise across a primarily inductive supply system. The rms voltage step is what planners use in sizing capacitor banks. For distribution, a 5% voltage change is often the maximum acceptable. For subtransmission, the voltage change limit is usually 2.5%, and for bulk power, 1% to 1.5%. Those are steady-state rules. For a “single” capacitor bank, the voltage step is inversely proportional to the square of the harmonic order of the natural inrush frequency. A 1% voltage step corresponds to a harmonic order of 10 (600 Hz at 60-Hz power frequency). A 4% voltage step corresponds to a fifth harmonic natural inrush frequency. This is a useful relation to know. The magnitude of the voltage step is system and capacitive load dependent.

5. Capacitive current switching application considerations

5.1 General

The capacitive current switching capability of the circuit breaker depends on its rated voltage, rated frequency, the particular application (transmission line, capacitor bank, etc.), and the power system grounding arrangement.

Caution should be exercised when applying older circuit breakers that have not been tested to IEEE Std C37.09 or IEEE Std C37.100.2.

5.2 Maximum voltage for application

The operating voltage should not exceed the rated maximum voltage since this is the upper limit for operation.

5.3 Frequency

The rated frequency for circuit breakers is 50 Hz or 60 Hz. As described in 6.2.2, a rated frequency of 60 Hz results in a more severe stress on the circuit breaker after current interruption since the voltage peak occurs earlier (at 8.3 ms) than in the case of 50 Hz (at 10 ms).

Special consideration should be given when comparing tests performed at 60 Hz to cover 50-Hz requirements or vice versa. The switching capability demonstrated at 60 Hz covers the requirements for 50 Hz with the same voltage factor k_c .

5.4 Rated capacitive current

The preferred values of the rated capacitive switching current are given in IEEE Std C37.04. Not all actual cases of capacitive current switching are covered by IEEE Std C37.04. The values for lines and cables cover most cases of line and cable switching. The values of the current for capacitor banks (single and back-to-back) are presented as a preferred value and three alternate values. These are intended to cover the majority of in service values but cannot cover every case.

5.4.1 Transmission lines and cables

When very long lines and cables are considered, the unloaded current may exceed that given in IEEE Std C37.04. The manufacturer should be consulted in such cases. Often currents up to the continuous current rating of the circuit breaker are acceptable.

The following may serve as an example: The unloaded current of a 550-kV transmission line is approximately 1.1 A/km at 50 Hz and 1.3 A/km for 60 Hz. Without considering the Ferranti effect (see 8.2), the charging current of a 500-km line would be 605 A at 50 Hz and 715 A at 60 Hz. The Ferranti effect on the line would increase the charging current, which is not covered by IEEE Std C37.04.

A higher current does not pose a problem for circuit breakers of present design, but the possible higher peak recovery voltage present on interruption could be a problem (see 8.3).

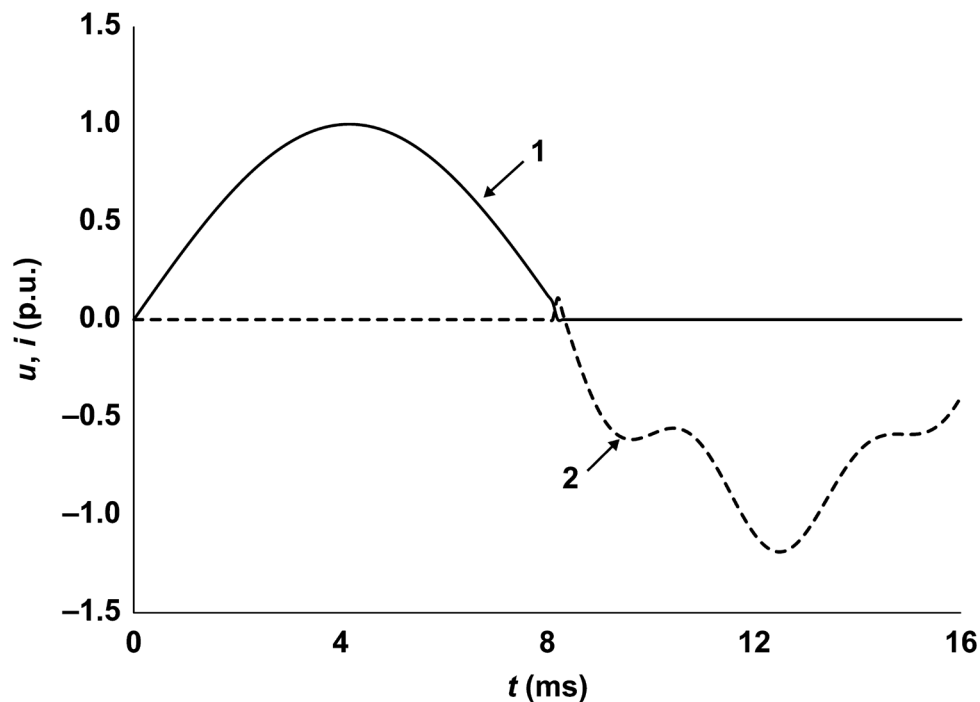
For altitudes exceeding 1000 m, the capacitive current does not have to be corrected, provided that it does not exceed the corrected rated continuous current.

5.4.2 Capacitor and filter banks

The current is dependent on the size of the capacitor banks, and line lengths to the capacitors are often short, so Ferranti effect is negligible. In certain cases, the capacitor bank considered may have a current rating higher than that given in IEEE Std C37.04. Experience has shown that capacitive current is not a limiting parameter for circuit breakers up to the continuous current rating.

5.5 Voltage and power system grounding arrangement

The recovery voltage of a harmonic filter bank may not follow a 1-cosine waveshape but may include harmonic components. The recovery voltage may have a shape as indicated in Figure 1. This case needs to be considered when making the proper choice of circuit breaker. The voltage waveshape as indicated in Figure 1 might cause occasional reignitions that may be acceptable to obtain an economical solution. If they are not acceptable, a circuit breaker of higher performance should be chosen, or controlled switching may be applied.



KEY:

- 1: Current through circuit breaker
- 2: Voltage across circuit breaker

Figure 1—Example of the recovery voltage across a filter bank circuit breaker

In IEEE Std C37.09-2018, 4.10.7 gives the multiplication factors for single-phase tests for the different conditions (see also Clause 9). They range from 1.0 for effectively grounded systems to 1.7 for ungrounded systems in the presence of single or two phase-to-ground faults.

5.6 Restrike probability

As all circuit breakers have some restrike probability in service, it is not possible to define a restrike-free circuit breaker. It is more logical to introduce the notion of a restrike classification associated with a specific test procedure (see IEEE Std C37.04 and IEEE Std C37.100.2).

The level of the restrike probability depends also on the service conditions (e.g., number of operations per year, network condition, and maintenance policy of the user). Therefore, it is impossible to introduce a common probability level related to service condition.

5.7 Restrike probability class of circuit breaker

Three classes of circuit breakers are defined for capacitive current switching in 5.8 of IEEE Std C37.04-2018. They are as follows:

- a) Class C0: Undetermined probability of restrike
- b) Class C1: Low probability of restrike
- c) Class C2: Very low probability of restrike

The intent is for class C2 to have an order of magnitude lower probability of restrike than class C1.

The main differences between the design tests and criteria for the classes are given in 4.10.9.1 and 4.10.9.2 of IEEE Std C37.09-2018 as well as IEEE Std C37.100.2. Tests in accordance with class C2 are performed on preconditioned contacts. Preconditioning consists of three interruptions with 60% of the rated short-circuit current. The total number of tests for class C2 is greater than that of class C1. The number of tests conducted near minimum arcing time are much higher for the C2 test program compared to the C1 test program.

It must be noted that the behavior of the circuit breaker during the transient discharge after the first restrike during design test may be different than under real network conditions since the energies involved in a laboratory test circuit will be different compared to the real network conditions. Because of this shortcoming in the test conditions, although class C0 requires that multiple restrikes not be observed, this same result cannot be assured in real networks. The overvoltage protection on the capacitor bank used for the type test may be different from the overvoltage protection in the network. This may result in different voltage stresses to the test object. This may also influence possible damages within the interrupting unit.

It must be noted that selection by the user among classes C0, C1, and C2 depends on the following:

- The service conditions
- The number of capacitive current switching operations expected per year
- The consequences of any restrike for:
 - The network generally restrike overvoltages are a minor concern at distribution voltages < 38 kV)
 - The circuit breaker (very difficult to evaluate in service)

Class C0 may be acceptable where restrikes are not a concern (often for distribution line capacitors < 38 kV).

Class C1 is often considered acceptable for circuit breakers with a voltage rating of 100 kV and below and circuit breakers applied for infrequent switching of transmission lines and cables.

Class C2 is recommended for capacitor bank circuit breakers and those used on frequently switched (i.e., more than 30 times per year) transmission lines and cables.

5.8 Interrupting time

The interrupting time of a circuit breaker on capacitive current switching is the interval between the energizing of the trip circuit at rated control voltage and the interruption of the main circuit in all poles on an opening operation. For some circuit breakers, the time required for interruption of capacitive currents may be greater than the rated interrupting time (e.g., oil circuit breakers). For circuit breakers equipped with opening resistors, the interrupting time of the resistor current may be longer.

5.9 Transient overvoltages and overvoltage limitation

An important consideration for application of circuit breakers for capacitive current switching is the transient overvoltage that may be generated by restrikes during the opening operation. The *transient overvoltage factor* is defined as the ratio of the transient voltage appearing between a circuit breaker disconnected terminal and the neutral of the disconnected capacitance during opening to the operating line-to-neutral crest voltage prior to opening.

The selection of the class (see 5.7) of circuit breaker to be applied should be coordinated with the insulation capability of other components on the system.

5.9.1 Overvoltages

When switching capacitive currents, transients are generated. These transients are associated with the restrikes that may occur when de-energizing a capacitive load and with the energization of capacitive loads. These transients may cause the following:

- Insulation degradation and possible failure of the substation equipment
- Operation of surge arresters
- Interference in the control wiring of the substation
- Increase in step potentials in substations (transient ground rise)
- Undesired tripping or damage to sensitive electronic equipment

The magnetic fields associated with high inrush currents during back-to-back switching in either the unloaded transmission line conductors or the grounding grid during back-to-back switching can induce voltages in control cables by both capacitive and electromagnetic coupling. These induced voltages can be minimized by shielding the cables and using a radial configuration for circuits (i.e., circuits completely contained within one cable so that inductive loops are not formed). Metal-oxide varistors may also be used on control circuits to limit control circuit voltages.

5.9.1.1 Switching of capacitor banks

The switching of capacitor banks is associated with voltage and current transients (see Clause 6). As most class C1 and C2 circuit breakers have a low probability of restrike, the majority of the switching transients will be generated when energizing capacitor bank(s). The effects of the transients will exhibit themselves locally and at remote locations on the power system.

The high-frequency transient inrush current associated with back-to-back switching can stress other equipment in the circuit as well as the circuit breaker. Wound-type current transformers will have turn-to-turn insulation stressed because of the high rates of rise of current and the resulting voltage that is developed across inductance in the circuit.

5.9.1.1.1 Local effects

Local effects of the transients include the following:

- Voltage transients resulting in dielectric stresses on nearby equipment
- Electrical, mechanical, and electromechanical forces caused by the inrush current
- Transient ground potential rise of the grounding system caused by the inrush current

5.9.1.1.2 Remote effects

Remote effects of the transients included the following:

- Transfer of capacitively coupled fast transients through transformer windings
- Reflections of traveling wave transients on open-ended lines or transformer-terminated lines
- Excitation of near resonant portions of the power system by the oscillatory transient frequency

5.9.1.2 Switching of lines and cables

When energizing lines and cables, higher overvoltages may be created if the line or cable is precharged as a result of a preceding breaking operation (i.e., in the case of an auto-reclosing). These overvoltages may result in damage of insulation.

5.9.2 Overvoltage limitation

There are several means available to reduce the overvoltages generated by the switching of capacitive currents (see also IEEE Std C37.010):

- *Current limiting reactors* or *transient limiting inductors (TLIs)* are sometimes used to reduce the current transients associated with back-to-back switching. They do not limit the remote overvoltages.
- *Preinsertion resistors* limit the inrush current and remote overvoltages. They are a basic solution widely used on transmission circuit breakers. They are usually fitted on circuit breakers and, therefore, add to the complexity of the equipment. Depending on the design, the added complexity may or may not result in a reduced availability of the equipment (see also 10.5).
- *Preinsertion reactors* also limit the inrush current and remote overvoltages. They are usually fitted on circuit switchers and their effect on complexity and availability of the equipment is sometimes equivalent to preinsertion resistors, depending on the design of the devices.
- *Point-on-wave controlled closing* reduces the magnitude of the inrush current by closing the contacts at a point when the voltage across the contacts is close to zero. Both overvoltages and current transients can be reduced, remote and local. The controller used for this purpose adds to the complexity of the equipment and can influence its availability.
- *Surge arresters* limit the magnitude of the transient overvoltages to the arrester's maximum switching surge protective level at the surge arrester terminals.

5.10 Inrush and outrush currents

Figure 2 and Figure 3 illustrate example network configurations resulting in inrush and outrush currents and are discussed in more detail in the following paragraphs.

Inrush current is the transient charging current that flows when energizing capacitive loads or elements. These transient charging currents stress the capacitive load switching device during a making operation. Figure 2 shows a network configuration resulting in an inrush current where Circuit Breaker 5 is closed to energize the capacitor behind Circuit Breaker 5 and the transient charging current from connected elements behind all the other circuit breakers flow through the capacitive load switching device that energizes the capacitor (i.e., Circuit Breaker 5). Outrush current is the transient discharge current that flows when charged capacitive loads or elements are discharged as a result of the high-voltage capacitive element terminal being connected to neutral or ground. Most often this is because of a fault occurring or a result of a nearby station circuit breaker closing into an existing fault. The circuit breaker closing into the fault can be in the same station as the capacitive element or, in more unusual circumstances, located in another nearby station. The key point here is that the circuit breaker involved could be a station circuit breaker that may or may not be intended for use in capacitive current making such as a general-purpose oil circuit breaker. Figure 3 shows a network configuration resulting in an outrush current where Circuit Breaker 3 closes into a fault and the transient discharge current from connected elements behind all the other circuit breakers flows through the station circuit breaker that closed into the fault (i.e., Circuit Breaker 3).

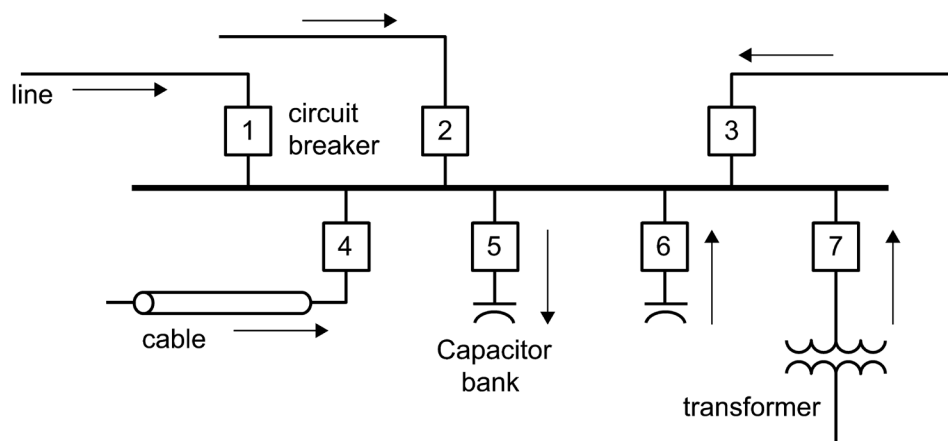


Figure 2—Illustration of inrush current where Circuit Breaker 5 switches a capacitor

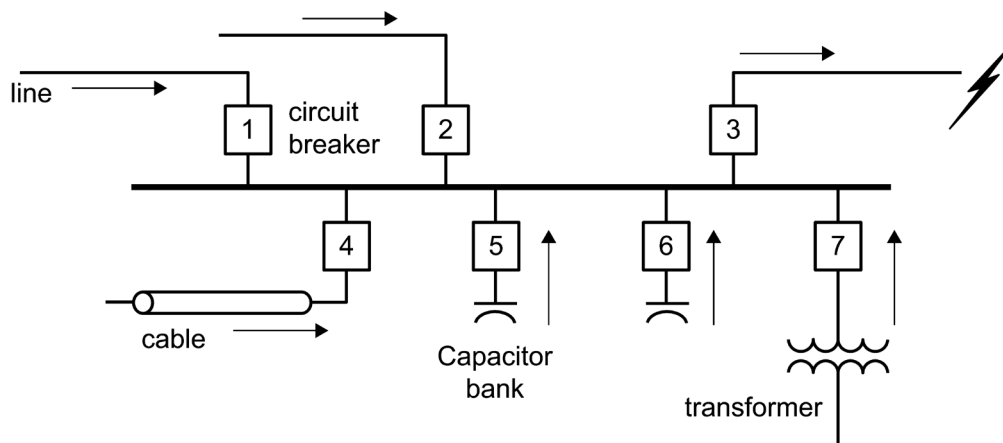


Figure 3—Illustration of outrush current where Circuit Breaker 3 closes into a fault

Subclause 10.2.2 speaks of total capacitive discharge into a short circuit. When a fault occurs, capacitive elements will discharge into the fault, but when the circuit breaker between the capacitor bank and the fault is fully closed, the circuit breaker is usually not in jeopardy. The switching device outrush current issue occurs when a circuit breaker closes into a fault with significant charged capacitance behind it (e.g., a reclose operation or a closing when safety grounds are left on by mistake). This can occur on circuit breakers that are not intended to be used for capacitive current making. Oil circuit breakers in particular are sensitive not just to the peak current magnitude of the outrush current but also to the di/dt . In such outrush cases, it may be necessary to limit the magnitude and/or the di/dt of the outrush current, depending on the capabilities of the circuit breaker which could potentially close into a fault (see also 10.2.2). These requirements are reflected in past versions of circuit breaker standards. Nevertheless, if oil circuit breakers are still present in the station, these factors and the limits in former versions of the standards should be considered when developing new applications that may also involve older general-purpose circuit breakers.

It should also be stated that significant damaging outrush events are rare and in order to be serious, particularly at system voltages below 100 kV, require that the involved fault be located quite near to the station. The higher the system voltage, the further out from the station a fault could be and still result in a damaging outrush current. Considering all of this, a risk analysis is an appropriate undertaking as part of a design application development. Such analysis should also consider any requirements of the utility regulator—which may demand that certain limits be satisfied, regardless of risk/probability requirements.

Transient limiting inductors (TLIs) can be used to limit outrush current di/dt and magnitude and, therefore, are often a good solution, but, of course, they are not without additional cost and potential complications, such as increasing the transient recovery voltage (TRV) imposed on the circuit breaker. This too can be solved with a capacitor-to-ground or capacitor-and-surge arrester across the TLI, but also with additional cost. In summary, the limitations of oil circuit breakers, if present, need to be considered along with the particular application risks and associated mitigation costs to arrive at a good engineering solution.

A risk analysis needs to be done to compare the rare likelihood of a damaging outrush current to the cost of mitigation with TLIs. Consideration needs to be given to unintended consequences of having TLIs in the circuit, which are as follows:

- There is increased voltage on the capacitors and possible shortened capacitor life.
- A shunt harmonic filter branch is being created, which may cause harmonic overload of the capacitive load (particularly capacitor banks and long cables).
- With a possible fault where the TLI is the majority of the fault impedance, a TLI can result in a fast TRV that gas circuit breakers may not be able to withstand.

These need to be considered in addition to the additional cost of installing TLIs.

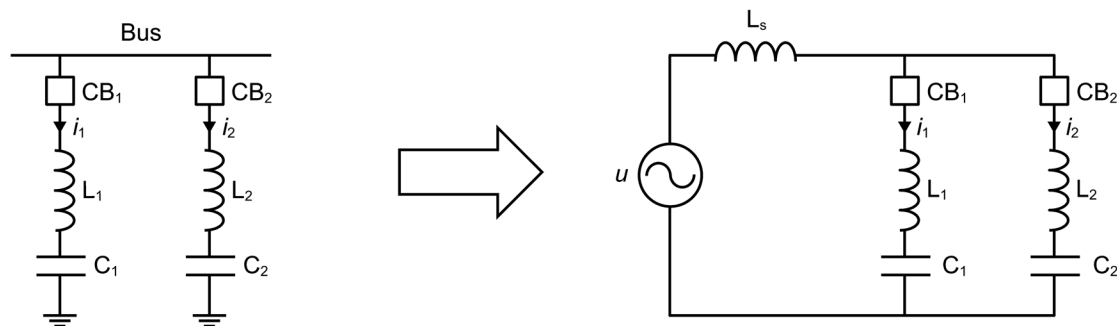
6. Capacitor bank switching

6.1 General

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.

To describe the phenomena associated with capacitor bank switching, a general single-phase equivalent circuit is shown in Figure 4. The figure shows a single-line diagram of the case in which two capacitor banks (C_1 and C_2) are connected in back-to-back to a busbar. L_1 and L_2 represent the stray inductance (or

stray inductance plus additional inductance added such as a TLI). The inductance L_s of the source network will often be several orders of magnitude higher than that of L_1 or L_2 .



KEY:

u	Source voltage	i_1, i_2	Capacitive currents
L_s	Source inductance	L_1, L_2	Inductance between capacitor bank 1 and 2 and bus, respectively
CB ₁	Circuit breaker	C_1, C_2	Capacitor bank 1 and 2
CB ₂	Circuit breaker, open for single capacitor bank switching, closed for back-to-back capacitor bank switching		

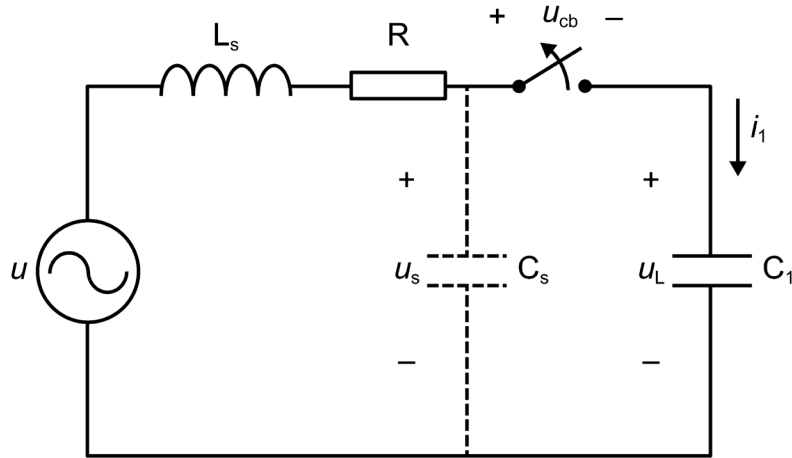
Figure 4—General circuit for capacitor bank switching

Single capacitor bank switching occurs when C_1 is switched and C_2 is not connected in the circuit described in Figure 4. The circuit, then, consists of the source inductance L_s in series with the capacitor bank C_1 . The inductance L_1 can be disregarded here since the value of the source inductance $L_s \gg L_1$.

Back-to-back capacitor bank switching occurs when switching C_1 with C_2 being in service or vice versa.

6.2 De-energizing capacitor banks

The single-phase equivalent circuit for de-energization of a capacitor bank is shown in Figure 5, which is derived from Figure 4 when C_2 is not connected.



KEY:

C_1	Capacitive load (capacitor bank)	u_L	Load side voltage (rms value)
C_s	Source side capacitance (stray capacitance)	i_1	Capacitive current (rms value)
u	Source voltage (rms value)	L_s	Source inductance
u_{cb}	Voltage across the circuit breaker (rms value)	u_s	Voltage on source side of the circuit breaker (rms value)

Figure 5—Single-phase equivalent circuit for capacitive current interruption

6.2.1 Capacitive current

The capacitive current i_1 flowing in the circuit is given by Equation (1):

$$i_1 = \frac{\omega_s C_1 \times u}{1 - \omega_s^2 L_s C_1} = \frac{\omega_s C_1 \times u}{1 - \frac{\omega_s^2}{\omega_1^2}} \quad (1)$$

where:

C_1	is the capacitance of capacitor bank C_1 (F)
$\omega_s = 2\pi f_s$	is the system frequency (rad/s), where f_s is the system frequency in Hz
$\omega_1 = \frac{1}{\sqrt{L_s C_1}} = 2\pi f_1$	is the inrush current frequency during energization (rad/s), where f_1 is the inrush current frequency in Hz (see also 6.3.2)
L_s	is the source inductance (H)

With $\omega_1 \gg \omega_s$, Equation (1) transforms to $i_1 = \omega_s C_1 \times u$.

6.2.2 Recovery voltage

Figure 6 shows the current and voltage shapes at interruption.

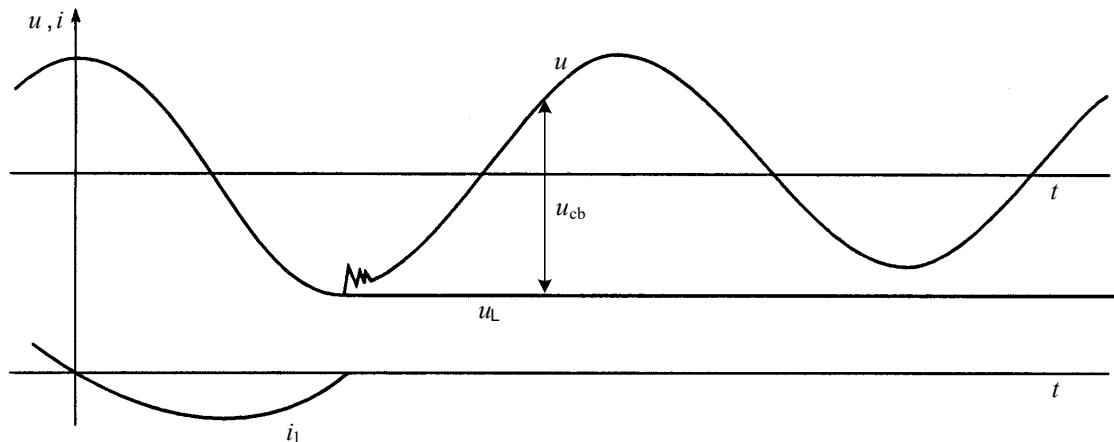


Figure 6—Voltage and current shapes at capacitive current interruption

After interruption of the current, the source voltage u will be more or less unaffected. There is only a minor decrease in amplitude (voltage step) 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_1 is trapped. The voltage u_L will, therefore, remain constant at the value it had at current zero (namely the peak value of the source voltage). This results in a recovery voltage across the open gap of the circuit breaker with a frequency equal to the power frequency of the source and a voltage peak no less than twice the peak value of the source voltage. The voltage peak will occur earlier in a 60-Hz system versus a 50-Hz system; therefore, 60 Hz presents a more severe condition.

The low current amplitude and the low initial rate-of-rise of the recovery voltage makes it extremely easy for the circuit breaker to initially interrupt the current. Some circuit breakers may interrupt even if the current zero would occur immediately after contact separation. In this case, the circuit breaker may then not be able to withstand the high value of the recovery voltage across a relatively small contact gap, which would result in dielectric breakdown and current would start to flow again.

Figure 7 shows current and voltage waveshapes in a case where voltage breakdown occurs relatively close to the recovery voltage peak. The load side voltage recovers through an oscillation, the amplitude of which ideally (without damping present) reaches three times the source voltage peak u_p . The oscillation frequency of the current and voltage after the breakdown is determined by L_s and C_1 (assuming $C_1 \gg C_s$). The circuit breaker may easily interrupt the transient 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 8).