

IEEE Application Guide for Shunt Reactor Switching

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Abstract: Guidance for the application of ac high voltage circuit breakers for shunt reactor switching is provided. Overvoltage generation for the three cases of directly grounded, ungrounded, and neutral reactor grounded shunt reactors is addressed in terms of derivation and limitation methods. Circuit breaker specification for the purpose and the use of laboratory test results to predict field performance is also covered by this guide.

Keywords: ac high voltage circuit breakers, application, shunt reactor switching, small inductive currents, overvoltages

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Introduction

(This introduction is not a part of IEEE Std C37.015-1993, IEEE Application Guide for Shunt Reactor Switching.)

This application guide is the result of a cooperative effort between a Working Group of the IEEE High Voltage Circuit Breaker Subcommittee and a Task Force of the IEC Technical Committee 17A. The material is published by both organizations; the IEEE version being this application guide, while the IEC version (IEC TR 1233) is a technical report. The two documents differ editorially in terms of format and some terminology, but are technically identical.

The guide is based on the work of CIGRE Working Group 13.02 (refer to bibliography) and extends that work to the practical application of circuit breakers for shunt reactor switching.

The subject of shunt reactor switching is complex. The approach taken in the main text of the guide is to present a basic method for the application of circuit breakers for the purpose, which considers only load side circuit characteristics. The method is conservative and will be adequate in many instances. However, by reference to a series of notes, the general case (which incorporates the influence of the source side characteristics and the parallel capacitance of the circuit breaker) is presented. The user of this application guide is encouraged to exercise due discretion in the choice of the basic or general method for the application under consideration. Consideration should, in addition, be given to the magnetic effects associated with air core shunt reactors.

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IEEE Application Guide for Shunt Reactor Switching

1. Scope

This application guide applies to ac high voltage circuit breakers rated for shunt reactor switching.

The guide covers the specific cases of switching directly grounded shunt reactors, ungrounded shunt reactors and shunt reactors grounded through a neutral reactor. Directly grounded reactors are common on extra-high voltage (EHV) and high voltage (HV) systems, while ungrounded reactors are commonly applied on medium voltage (MV) systems. Neutral reactor grounded schemes are usually only applied on EHV systems.

Whereas this application guide is directed towards circuit breakers, it is recognized and accepted that other switching devices such as high voltage load break switches are capable of shunt reactor switching and this guide may be applied as appropriate.

2. Purpose

This guide is intended for general use in the application of ac high voltage circuit breakers for shunt reactor current switching.

Shunt reactor switching imposes a unique and severe duty on the connected system and circuit breaker. Particularly at high voltages, the current to be interrupted is generally less than 300 A, yet successful interruption is a complex interaction between the circuit breaker and the circuit. This interaction can result in significant overvoltages.

The purpose of the guide is to describe, principally for the benefit of the user, the shunt reactor switching duty, the overvoltages generated, and the control of those overvoltages. The guide further details the specification of circuit breakers and procedures to predict field performance based on test data.

3. General application conditions

3.1 Maximum voltage for application

The continuous operating voltage should not exceed the rated maximum voltage for the circuit breaker.

3.2 Frequency

The rated power system frequency is 50 Hz or 60 Hz.

3.3 Shunt reactor load current

Shunt reactor load currents are referred to generically as small inductive currents. The capability of circuit breakers to interrupt small inductive currents is generally not a concern. The circuit breaker will typically interrupt the current at the first current zero after contact parting, but may not be immediately capable of withstanding the high magnitude recovery voltages that can then appear across the contacts. This can result in a reignition followed by an additional loop of rated frequency current and successful interruption. Refer to 3.5.

3.4 Interrupting time

The interrupting time of a circuit breaker, when switching shunt reactor load currents, is the interval between energization of the trip coil and the interruption of the current in all poles on an opening operation. Refer to 3.3 and 6.8.

3.5 Transient overvoltages

An important consideration for application of circuit breakers for shunt reactor current switching are the transient overvoltages generated on interruption of the current and by subsequent reignitions. Refer to clause 4.

3.6 Fault interrupting capability

Circuit breakers applied for switching shunt reactors may or may not be required to have a fault-interrupting capability. In the latter case, the through fault capability of the circuit breaker should equal the fault level applicable to the shunt reactor location.

3.7 Frequency of operation

Shunt reactors are switched frequently, often daily, to control and compensate for changes in system loading and configuration. In the selection of a circuit breaker for this duty, consideration should be given to this matter.

4. Shunt reactor switching conditions

4.1 General

Three specific shunt reactor switching cases are considered in this guide. The case of directly grounded reactors is treated in detail. The cases of ungrounded reactors and neutral reactor schemes are treated in terms of relating to or deviating from the directly grounded reactor case.

Given that shunt reactor switching is interactive, characteristics of the reactor and the circuit have to be considered. Shunt reactor characteristics are discussed in annex A, while applicable system and station characteristics are discussed in annex B.

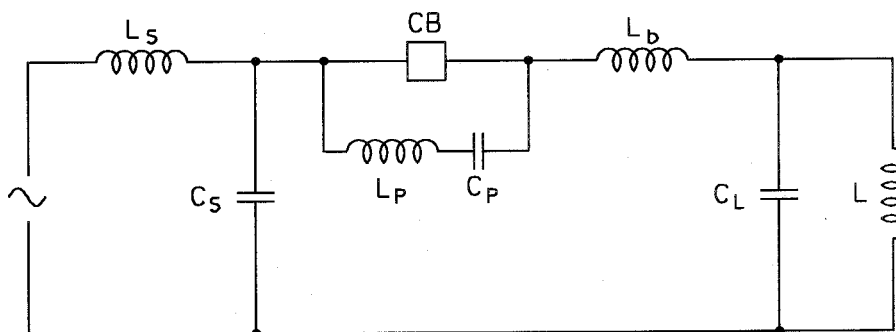
The general derivation of chopping and reignition overvoltage values, discussed in 4.2, 4.3, and 4.4, is given in annex C, while annex D discusses the oscillation modes associated with the current interruption and reignition process.

Annex E, complemented by annex F, describes how laboratory test results can be used to calculate circuit breaker performance and expected overvoltages in actual shunt reactor installations.

4.2 Directly grounded reactors

The switching of directly grounded reactors can be analyzed using the equivalent single phase circuit shown in figure 1. Basically, circuit breakers have no difficulty interrupting shunt reactor current; in fact, the current is forced prematurely to zero, a phenomenon referred to as current chopping. However, the chopping of the current and subsequent possible reignitions can result in significant transient overvoltages. The following two types of overvoltages are generated:

- Chopping overvoltages with frequencies up to 5 kHz
- Reignition overvoltages with frequencies up to several hundred kilohertz (kHz)



- L_s is the source side inductance
- C_s is the source side capacitance
- CB is the circuit breaker
- L_p, C_p is the first parallel circuit inductance and capacitance
- L_b is the connection series inductance
- C_L is the load side capacitance
- L is the shunt reactor inductance

Figure 1— Single phase equivalent circuit

Figure 2 illustrates current chopping phenomena and figure 3 defines the different overvoltage occurring at chopping and reignition.

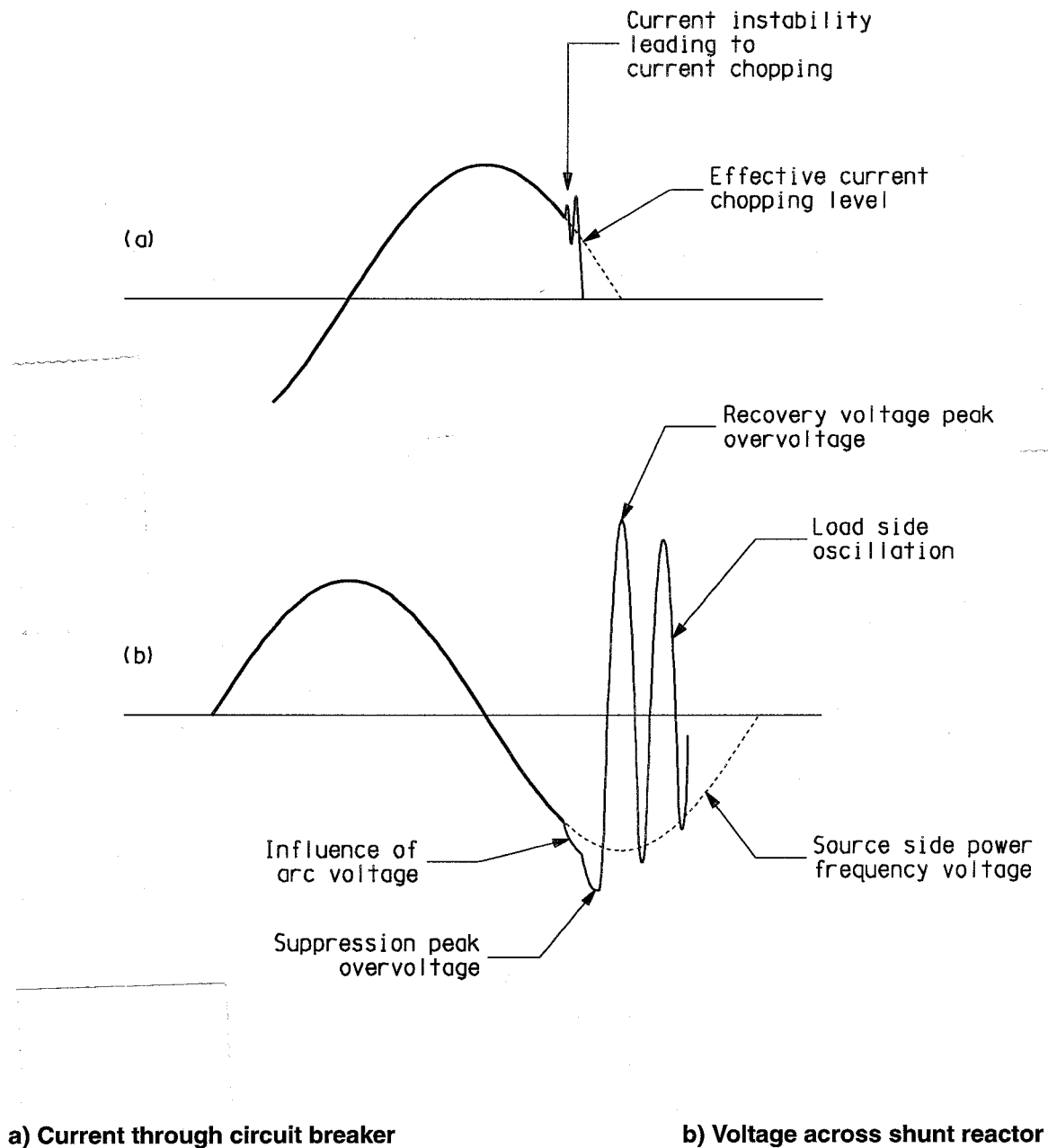
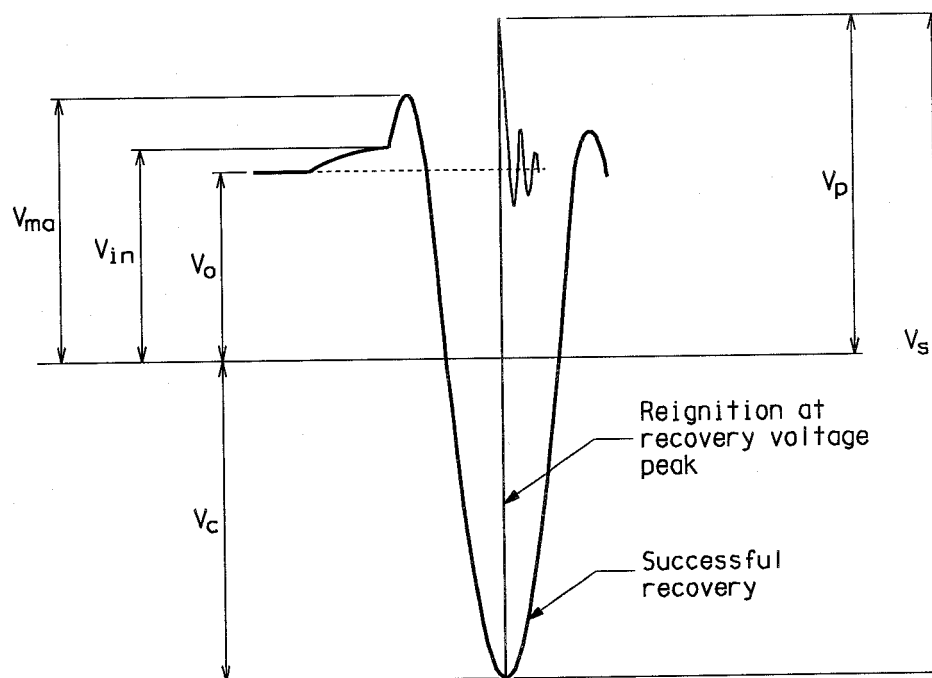


Figure 2— Current chopping phenomena



Quantity	Definition	Value in pu
V_o	Voltage across shunt reactor at instant of current interruption; arc voltage not significant	1
V_{in}	Voltage across shunt reactor at instant of current interruption; arc voltage significant	$k_{in} = \frac{V_{in}}{V_o}$
V_{ma}	Suppression peak overvoltage to ground	$k_a = \frac{V_{ma}}{V_o}$
V_c	Recovery overvoltage peak to ground	$k_c = \frac{V_c}{V_o}$
V_p	Reignition overvoltage peak to ground	$k_p = \frac{V_p}{V_o}$
V_s	Reignition overvoltage excursion peak-to-peak	$k_s = \frac{V_s}{V_o}$

Figure 3— Chopping and reignition overvoltage phenomena

4.2.1 Current chopping

Current chopping is caused by arc instability, which exhibits itself in the form of a negatively damped current oscillation superimposed on the load current. The oscillation amplitude increases rapidly, creating a current zero at which the circuit breaker usually interrupts (figure 2). The frequency of the oscillation is such that current chopping can reasonably be assumed to be instantaneous.

For a single interrupter circuit breaker, the chopping current level is given by the equation

$$i_{ch} = \lambda \sqrt{C_t} \quad (1)$$

where

- i_{ch} is the current level at the instant of chopping (A)
- C_t is the total capacitance in parallel with the breaker (F)
- λ is the chopping number for a single interrupter ($AF^{-0.5}$)

The chopping number, λ , is a characteristic of the circuit breaker and is derived in laboratory tests (refer to annex E). This concept can be applied to all circuit breaker types except for vacuum circuit breakers, for which the relationship between the chopped current and the interacting capacitance is less definitive. Ranges of typical chopping numbers are given in table 1.

Table 1— Circuit breaker chopping numbers

Circuit breaker type	Chopping number (λ)
Minimum oil	7–10·10 ⁴
Air blast	15–25·10 ⁴
SF ₆	4–17·10 ⁴

C_t is given by the following equation (refer to figure 1):

$$C_t = C_p + \frac{C_s C_L}{C_s + C_L} \quad (2)$$

where

- C_p is the circuit breaker parallel capacitance (F)
- C_s is the source side capacitance to ground (F)
- C_L is the effective load side capacitance to ground (F) and given by the expression $C_G + 2C\phi$, where C_G is the summation of the load side equipment capacitances to ground (refer to annex A and annex B), and $C\phi$ is the phase-to-phase capacitance of the shunt reactor and associated connections. For many applications, $C\phi$ may not be significant compared to C_G and can be ignored.

The maximum value of C_t and the worst-case condition for overvoltage generation occurs when $C_s \gg C_L$, in which case C_t is given by

$$C_t = C_p + C_L \quad (3)$$

Equation (1) applies as noted only to circuit breakers with a single interrupter. For circuit breakers with “N” interrupting units per pole, the following equation applies:

$$I_{ch} = \lambda \sqrt{NC_t} \quad (4)$$

The level of current chopping may be dependent on arcing time. This tends to be the case for SF₆ puffer type and most air blast circuit breakers. For oil circuit breakers, however, the level of current chopping is independent of the arcing time.

Current chopping phenomena are discussed in detail in [B11], [B12], and [B13].¹

4.2.2 Reignitions

The circuit breaker, after current interruption, is stressed by the difference between the source side voltage (close to the crest of the power frequency voltage) and the load side oscillating voltage (figures 2 and 3). Circuit breakers with very high chopping levels exhibit reignitions before or at the suppression peak. Such reignitions mainly have the effect of reducing the chopping overvoltages. Circuit breakers, such as the SF₆ puffer type that have low chopping levels, seldom reignite during the suppression peak overvoltage loop.

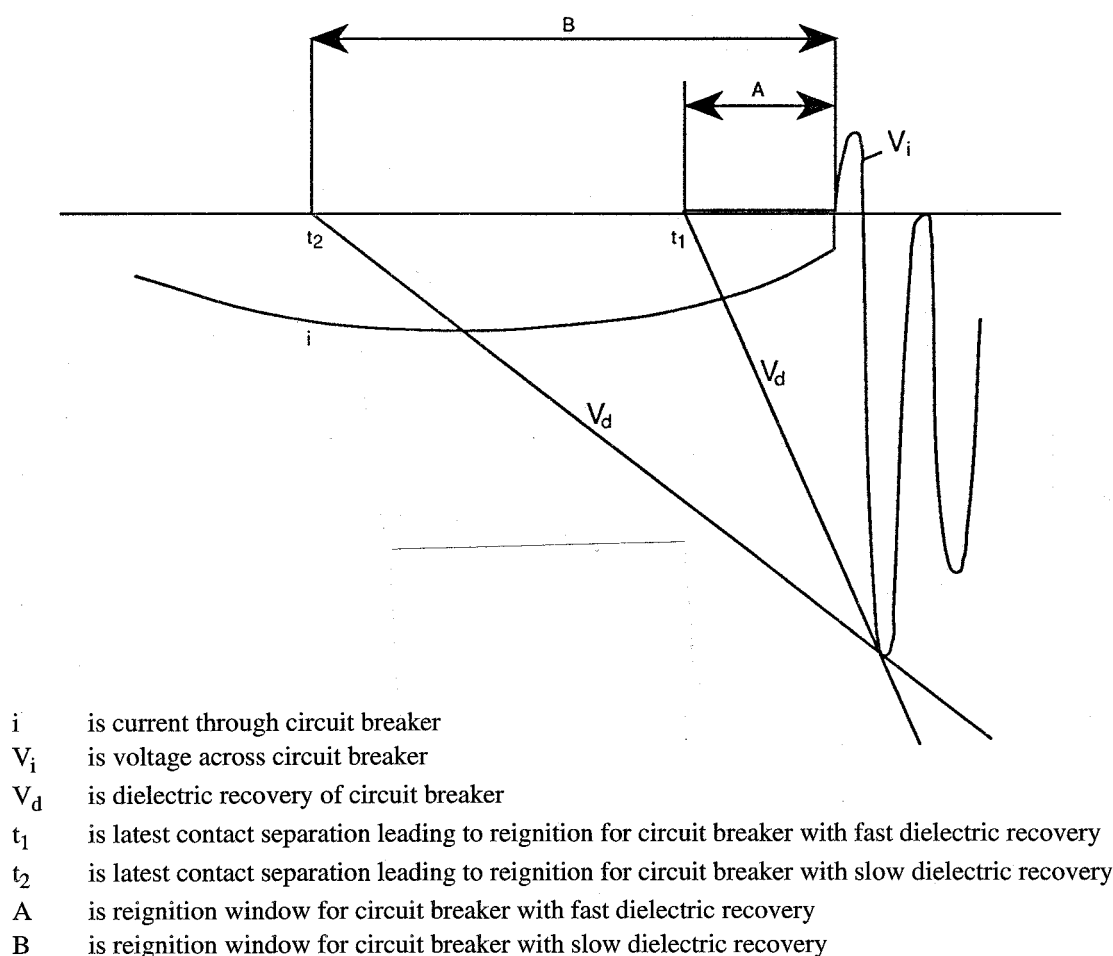


Figure 4— Reignition windows

At the recovery voltage peak, the circuit breaker is stressed by a voltage that approaches the chopping overvoltage plus the peak of the source side voltage. If the circuit breaker does not reignite before or at this point, then the interruption

¹The numbers in brackets correspond to those of the references in clause 7.

is successful. If, however, the instant of contact parting is such that the contact gap does not yet have sufficient dielectric strength, then a reignition will occur (refer to figure 4). All circuit breakers will reignite when the interruption occurs with a small contact gap. The reignition “window” will be narrow or wide depending on the rate of rise of voltage withstand capability of the increasing contact gap, i.e., the design of the circuit breaker (interrupting medium, contact velocity, electrode design, etc.). Reignition-free interruption can practically be achieved only through control action (refer to 5.3).

4.2.3 Overvoltages

Two types of overvoltages are to be considered—chopping overvoltages and reignition overvoltages.

4.2.3.1 Chopping overvoltages

The energy trapped in the load side inductance and capacitance at the instant of chopping will oscillate between the inductance and the parallel capacitance. The frequency of the oscillation is of the order of 1 to 5 kHz at high voltages and is determined by the natural frequency of the reactor load circuit, i.e., the reactor itself and all equipment connected between the circuit breaker and the reactor (refer to annexes A and B).

The first peak of the oscillation has the same polarity as the system voltage at the time of interruption. This chopping overvoltage is referred to commonly as the suppression peak overvoltage (refer to figures 2 and 3). The second peak of the oscillation has a polarity opposite to that of the system voltage at the time of interruption, and that chopping overvoltage is referred to as the recovery voltage peak overvoltage. For directly grounded reactor installations, the recovery voltage peak overvoltage is equal to or less than the suppression peak overvoltage (refer to annex C). The magnitude of the suppression peak overvoltage (k_a in pu) is given by the following equation:

$$k_a = \sqrt{1 + \left(\frac{i_{ch}}{V_o}\right)^2 \frac{L}{C_L}} \quad (5)$$

where

i_{ch}	is the chopped current level (A)
V_o	is the peak voltage (V) across shunt reactor at the instant of current interruption
L	is the reactor inductance (H)
C_L	is the load side effective capacitance to ground (F), refer to equation (2)

Equation (5) assumes that the arc voltage of the circuit breaker prior to current chopping is negligible in comparison to V_o , which is generally the case for HV and EHV shunt reactor switching.

For a given application (fixed V_o , L , and C_L), when $C_s \gg C_L$ and C_p is negligible, the overvoltage is dependent on i_{ch} only. Equation (5), except for vacuum circuit breakers, can then be rewritten as

$$k_a = \sqrt{1 + \frac{3N\lambda^2}{2\omega Q}} \quad (6)$$

where

Q	is three-phase reactor rating (V · A)
λ	is the chopping number ($AF^{-0.5}$) for a single interrupter
ω	is $2\pi f$ = angular rated power system frequency
N	is the number of interrupting units in series per pole

The chopping overvoltage is thus only dependent on the chopping number and the reactive power of the reactor.

Since the damping is usually small, the oscillation on the load side will result in a recovery voltage peak overvoltage of nearly the same magnitude as the suppression peak overvoltage. The load side oscillation will slowly decay in amplitude due to the damping.

The stress on the reactor due to current chopping is determined by the highest peak voltage to ground, which is the suppression peak overvoltage at the frequency of the load side oscillation. Due to the comparatively low frequency, the overvoltage is evenly distributed across the winding, which results in low interturn voltages.

NOTE — The general equation from which equation (6) is derived is

$$k_a = \sqrt{1 + \frac{3N\lambda^2}{2\omega Q} \cdot \frac{C_t}{C_L}}$$

where C_t is as given by equation (2). Equation (6) can be used as a reasonably conservative approach in most cases. However, for those cases where actual C_s , and/or C_p values must be considered, then the general equation should be used.

4.2.3.2 Reignition overvoltages

When a reignition occurs, the load side voltage rapidly tends toward the source side voltage, but overshoots producing a reignition overvoltage (refer to figure 3). Figure 5 shows the maximum attainable overvoltages without damping for a reignition at the recovery voltage peak. With damping considered, the maximum magnitude of the reignition overvoltage to ground (k_p pu) is given by the equation

$$k_p = 1 + \beta(1 + k_a) \quad (7)$$

where

β is a damping factor whose value will not normally exceed 0.5.

The voltage breakdown at a reignition creates a steep voltage transient that is imposed on the reactor. The front time varies from less than one microsecond to several microseconds. Since the voltage breakdown in the circuit breaker is practically instantaneous, the steepness is solely determined by the frequency of the second parallel oscillation circuit (refer to annex D), which in turn is dependent on the system/station layout. This steep transient may be unevenly distributed across the reactor winding, stressing the entrance turns in particular with high interturn overvoltages.

The peak-to-peak excursion voltage of the reignition transient (k_s pu) is given by

$$k_s = (1 + \beta)(1 + k_a) \quad (8)$$

It is important to note that the value of k_a applicable to equations (7) and (8) is that for the current zero at which the reignition occurs.

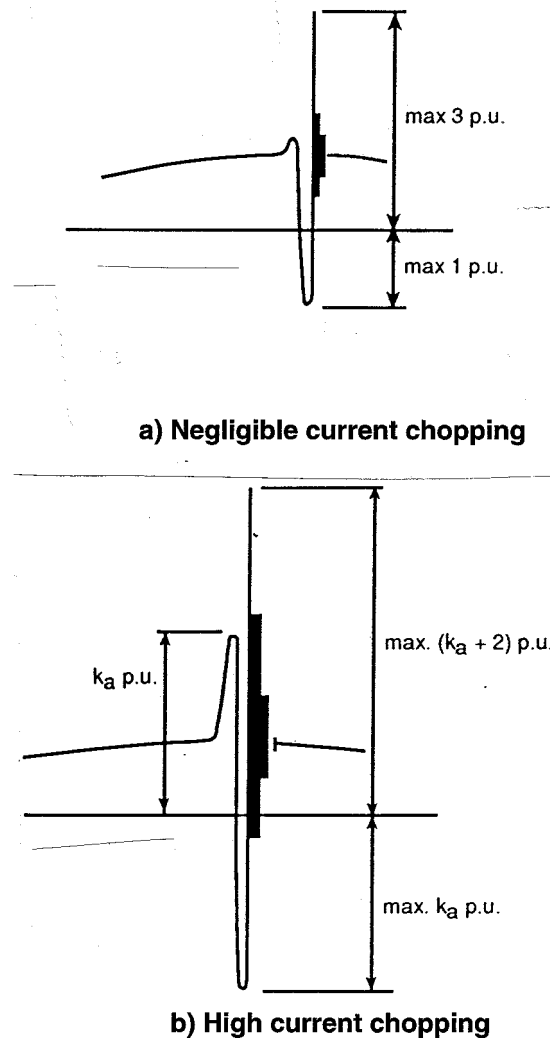


Figure 5— Maximum reignition overvoltages

NOTE — Equations (7) and (8) also reflect a conservative approach since C_s is assumed to dominate over C_L . If this is not the case, additional damping will occur due to the redistribution of charge between C_s and C_L . With reference to figure 6, it can be shown that

$$k_p = (1 + \beta) \frac{C_s}{(C_s + C_L)} (1 + k_a) - k_a$$

and

$$k_s = (1 + \beta) \frac{C_s}{(C_s + C_L)} (1 + k_a)$$

giving lower reignition overvoltage peak and excursion values than if C_s was considered dominant.

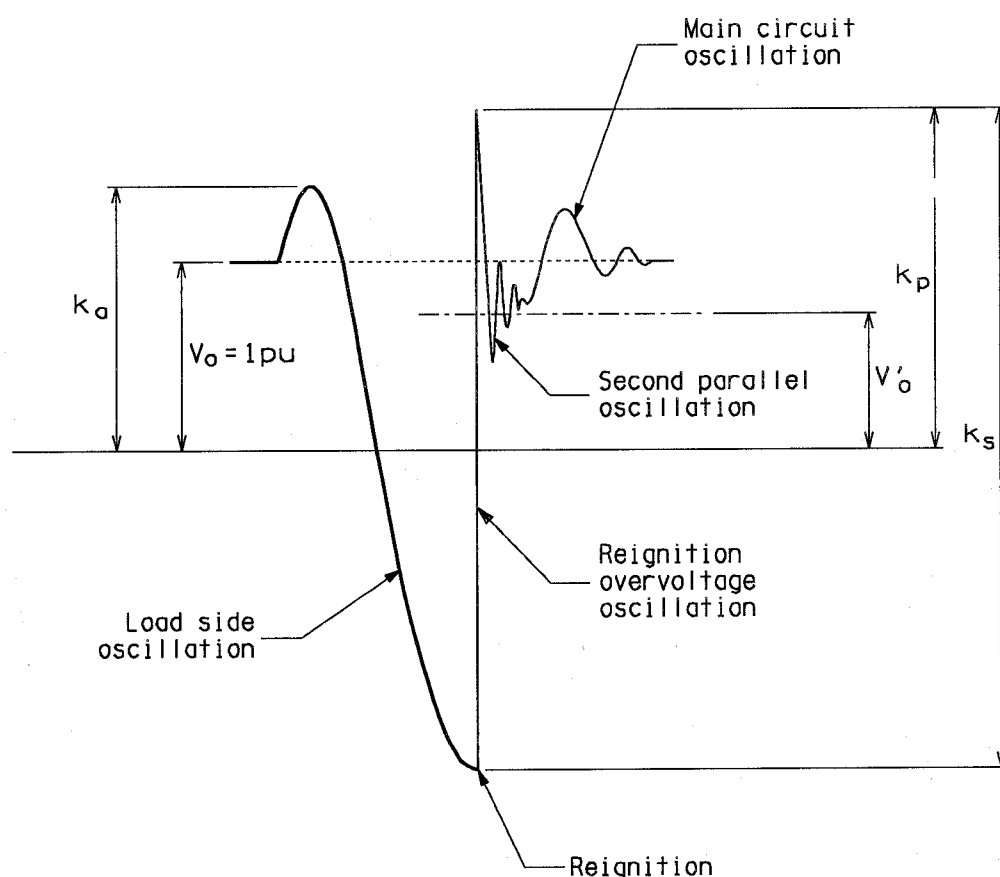
Refer also to the note in 4.2.3.1.

4.2.3.3 Recovery voltage across circuit breaker

Following interruption, the circuit breaker is stressed by the difference between the source side voltage and the load side voltage. If no reignition occurs, the per unit crest value of this recovery voltage (k_{rv}) is given by

$$k_{rv} = 1 + k_a \quad (9)$$

For testing purposes, this is the minimum recovery voltage that must be achieved in the test circuit. For application purposes, this value should be compared with the withstand capability across the circuit breaker as discussed in annex E.



V_o is power frequency crest voltage across shunt reactor at instant of current interruption

k_a is suppression peak overvoltage in pu of V_o

k_p is reignition overvoltage peak to ground in pu of V_o

k_s is reignition overvoltage excursion in pu of V_o

$$\frac{V'_o}{V_o} = \frac{C_s}{C_s + C_L} \left(1 - k_a \frac{C_L}{C_s} \right)$$

Figure 6— Reignition at recovery voltage peak for a circuit with low supply side capacitance

4.2.4 Related phenomena

There are a number of phenomena related to shunt reactor switching, which may impact on the success of the current interruption and should be recognized. These phenomena include oscillation modes, high frequency current interruption, energizing transients, and voltage escalation.

4.2.4.1 Oscillation modes

A number of different oscillation modes occur during the interruption and reignition process. These voltage and associated current modes are discussed in annex D.

4.2.4.2 High-frequency current interruption

The occurrence of a reignition results in several modes of current oscillations (annex D). These oscillations are superimposed on the reestablishing of load current and may produce current zeros at which the circuit breaker will attempt to interrupt. The ability to interrupt at these high-frequency current zeros is dependent on the type of circuit breaker and on the frequency and damping of the oscillation. The subject is discussed in detail in [B25]. Refer also to 4.2.4.3 below.

4.2.4.3 Voltage escalation

In the event that a new interruption occurs during the first, second, or main circuit oscillation modes, the load side oscillation will start again. Due to energy transfer between the source and load sides, the oscillating energy may have changed. A new reignition may occur close to the recovery voltage peak, and if the energy has increased, the reignition voltage may be higher than at the first reignition. This procedure may be repeated several times, giving multiple reignitions with increasing overvoltage magnitude. This is referred to as “voltage escalation” and is a significant characteristic of vacuum circuit breakers due to their ability to interrupt high frequency currents. Voltage escalation may also occur on other circuit breaker types, particularly where the frequency of the reignition transient is low, i.e., less than approximately 100 kHz (refer to [B25]).

4.2.4.4 Shunt reactor energizing transients

Energizing (switching-in) a shunt reactor is a situation similar to the occurrence of a reignition. However, the breakdown voltage across the circuit breaker will not exceed 1 pu for directly grounded reactors, and the peak value of the energizing transient will be 1.5 pu or less.

NOTE — For ungrounded reactors, this transient is maximum for the second pole to make, the peak value being 1.73 pu assuming β equals 0.5.

Reactor surge arrester operation may occur if the switching device has a slow closing speed resulting in multiple restriking and possible voltage escalation (refer to 4.2.4.3).

4.3 Ungrounded reactors

The switching of MV ungrounded reactors, generally connected to the tertiaries of system transformer, differs from the case of directly grounded HV and EHV reactors in that the current to be interrupted is several times to an order of magnitude higher than that in the latter case (refer to annex A). On this basis, while the current to be interrupted may still be small relative to the terminal fault interrupting capability of the circuit breaker, the reactor current will approach or equal the continuous current rating of the circuit breaker. The ungrounded reactor switching case is therefore influenced by the ability of the breaker to interrupt the current and withstand the recovery voltage without reignition. The case can reasonably be described as being equivalent to or approaching that of a low current level terminal fault.