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.

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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.

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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.

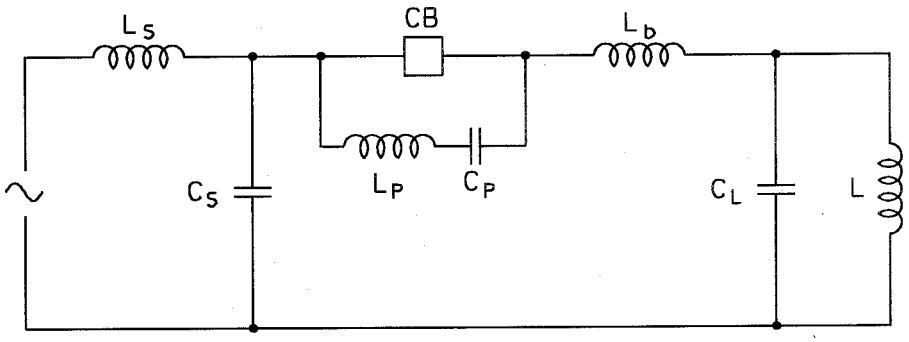
The general derivation of chopping and reignition overvoltage values, discussed in 4.2, 4.3, and 4.4, is given in annex C, while annex D discusses the oscillation modes associated with the current interruption and reignition process.

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:

a) Chopping overvoltages with frequencies up to 5 kHz
b) 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 illusrates current chopping phenomena and figure 3 defines the different overvoltage occurring at chopping and reignition.

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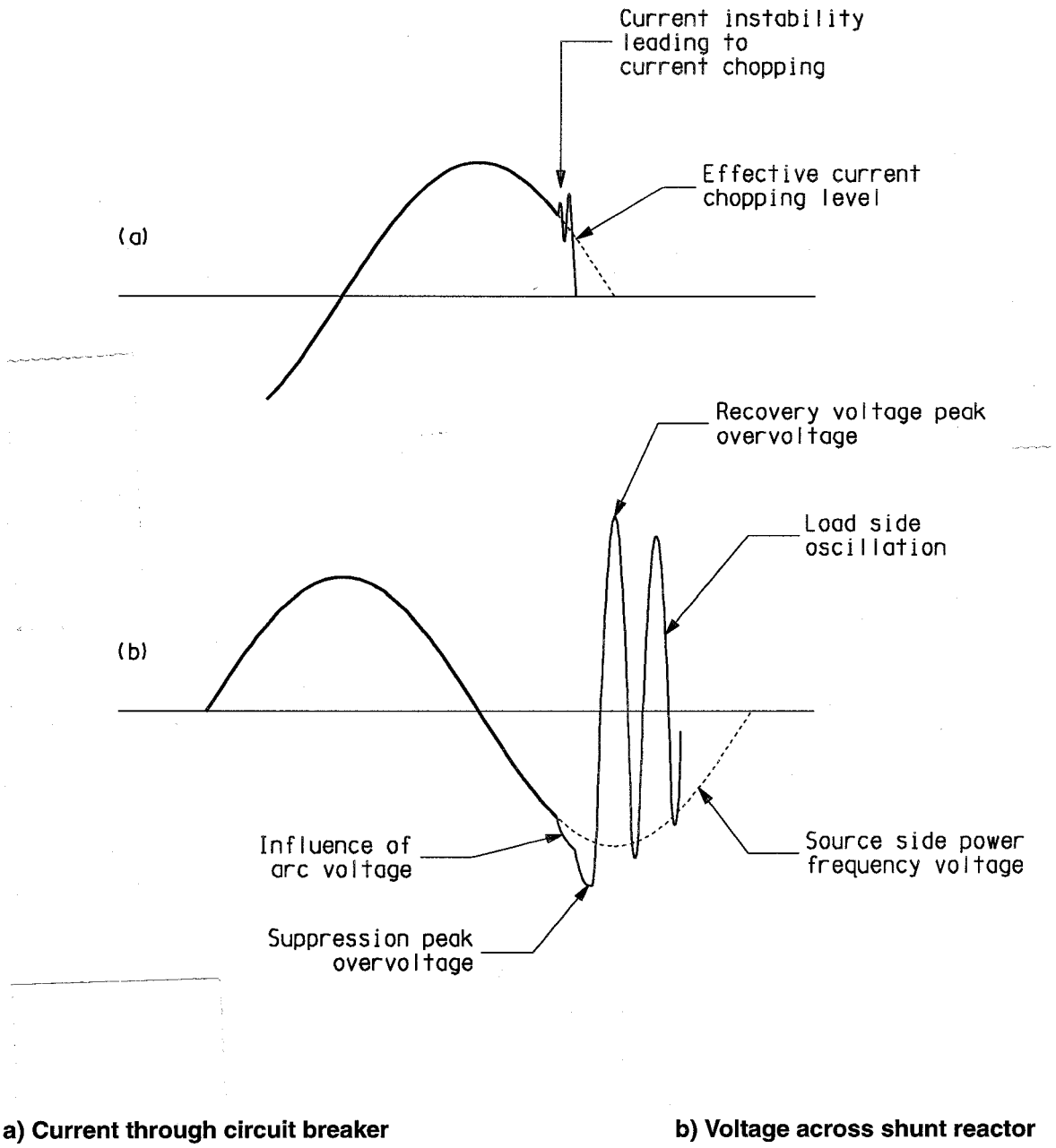

a) Current through circuit breaker **b) Voltage across shunt reactor**

Figure 2— Current chopping phenomena

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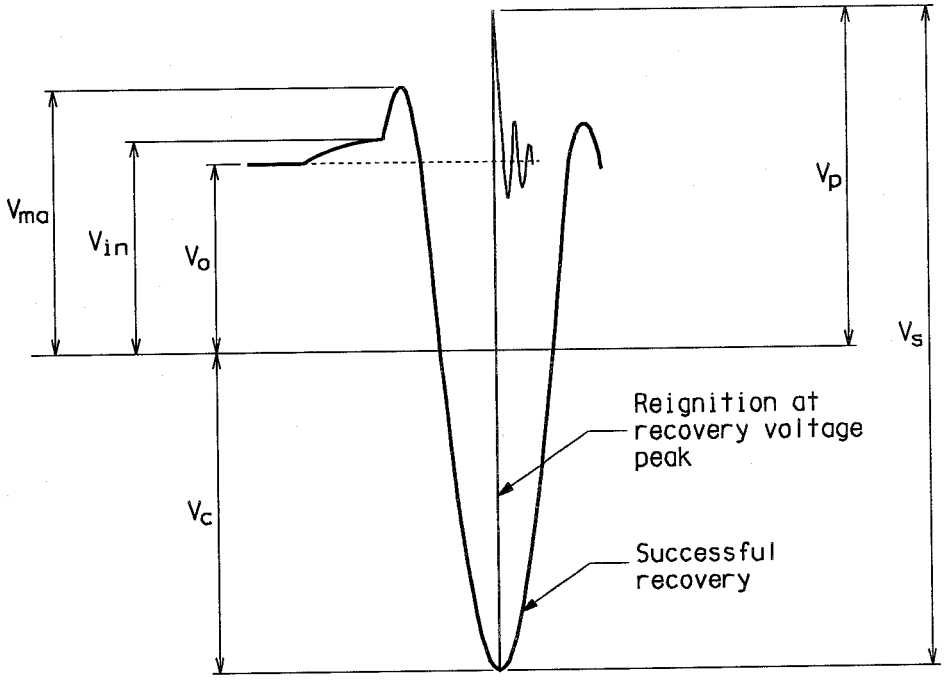

Quantity	Definition	Value in pu
V_o	Voltage across shunt reactor at instant of current interruption; arc voltage not significant	1
V_{in}	Voltage across shunt reactor at instant of current interruption; arc voltage significant	$k_{in} = \frac{V_{in}}{V_o}$
V_{ma}	Suppression peak overvoltage to ground	$k_a = \frac{V_{ma}}{V_o}$
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

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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

$$i_{ch} = \lambda\sqrt{C_t} \tag{1}$$

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	$7–10 \cdot 10^4$
Air blast	$15–25 \cdot 10^4$
SF_6	$4–17 \cdot 10^4$

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

$$C_t = C_P + \frac{C_s C_L}{C_s + C_L} \tag{2}$$

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 $C_s >> C_L$, in which case C_t is given by

$$C_t = C_p + C_L \tag{3}$$

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:

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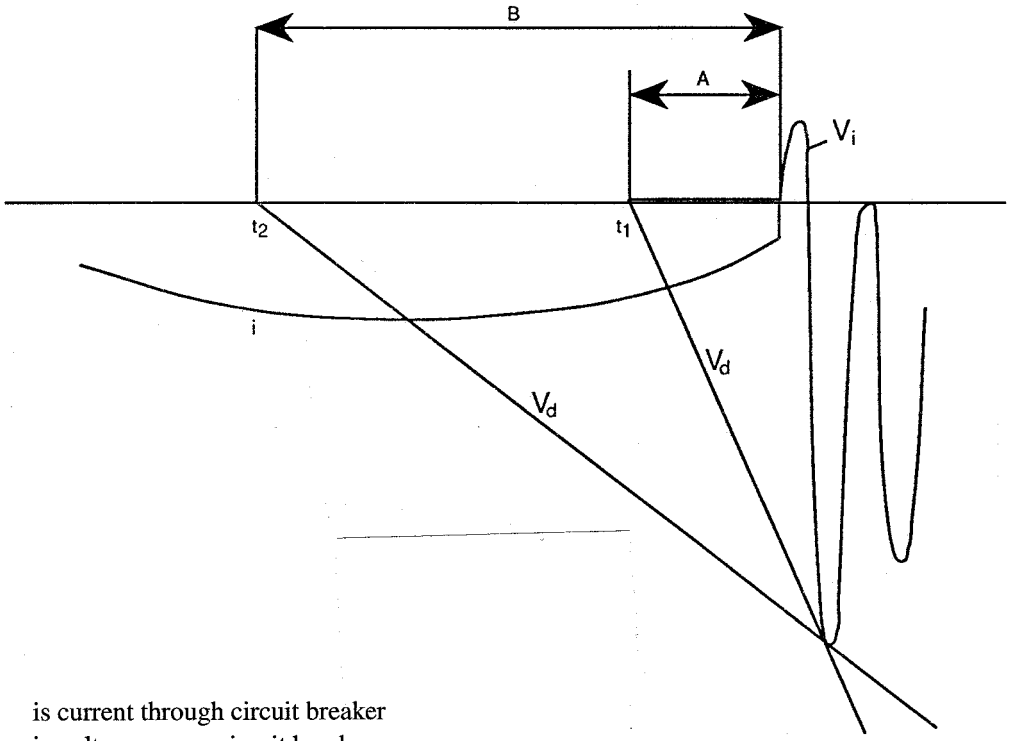
$$I_{ch} = \lambda\sqrt{NC_t} \quad (4)$$

The level of current chopping may be dependent on arcing time. This tends to be the case for SF_6 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 SF_6 puffer type that have low chopping levels, seldom reignite during the suppression peak overvoltage loop.



i is current through circuit breaker
V_i is voltage across circuit breaker
V_d is dielectric recovery of circuit breaker
t_1 is latest contact separation leading to reignition for circuit breaker with fast dielectric recovery
t_2 is latest contact separation leading to reignition for circuit breaker with slow dielectric recovery
A is reignition window for circuit breaker with fast dielectric recovery
B is reignition window for circuit breaker with slow dielectric recovery

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

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

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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:

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

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 $C_s >> C_L$ 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

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

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.

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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

$$k_p = 1 + \beta(1 + k_a) \tag{7}$$

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

$$k_s = (1 + \beta)(1 + k_a) \tag{8}$$

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.

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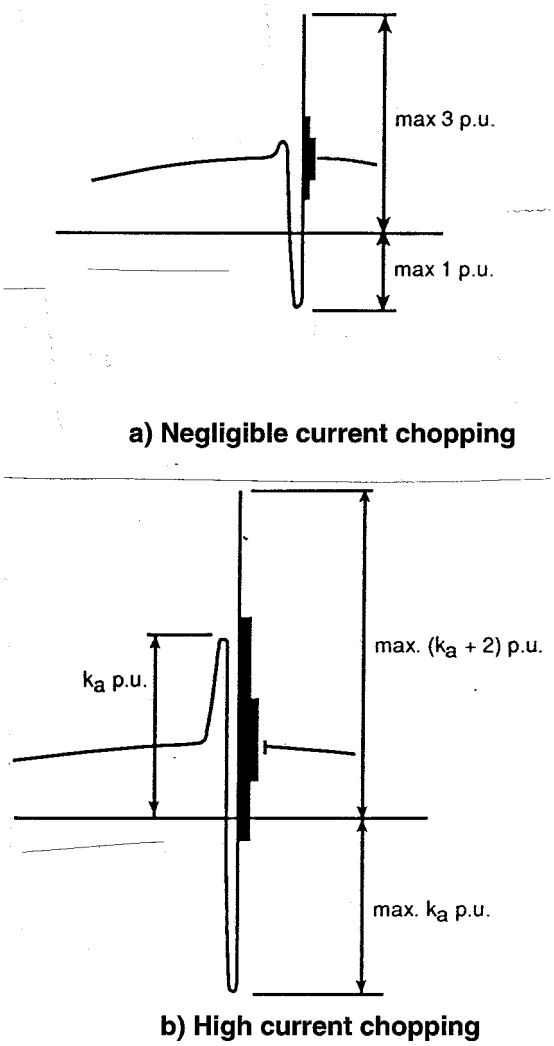

Figure 5— Maximum reignition overvoltages

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.

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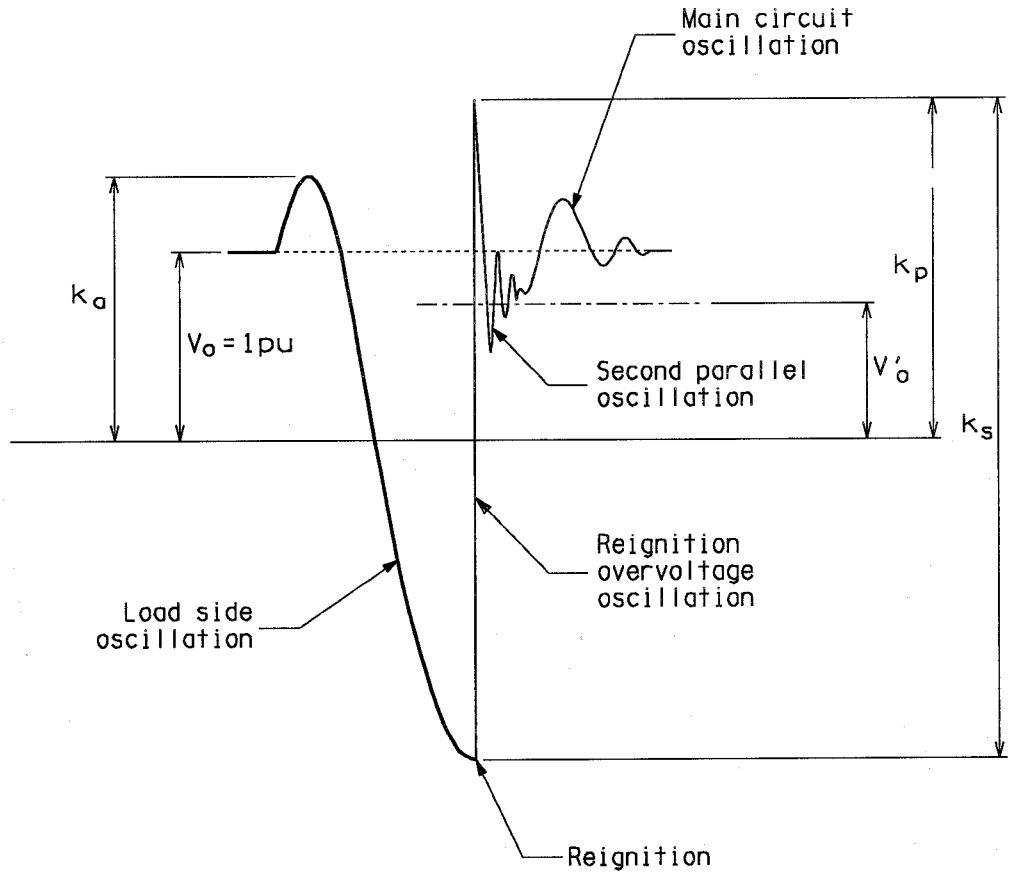
4.2.3.3 Recovery voltage across circuit breaker

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

$$k_{rv} = 1 + k_a \tag{9}$$

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

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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.

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4.3.1 Current chopping

Equation (1) is applicable to this case, as is equation (2) with $C_p = 0$, since the circuit breaker will consist of a single interrupter at this voltage level. This approach is valid because the neutral point is virtually grounded prior to first phase interruption.

4.3.2 Chopping and reignition overvoltages

The overvoltages to be considered are the chopping overvoltages to ground and the reignition overvoltage to ground and the peak-to-peak excursion.

With reference to annex C, the suppression peak overvoltage to ground is given by

$$k_a = 1.5\sqrt{1 + \left(\frac{1}{1.5}\right)\left(\frac{i_{ch}}{V_o}\right)^2\left(\frac{L}{C_L}\right)} - 0.5 \quad (10)$$

Similar to the approach taken for directly grounded reactors ($C_s >> C_L$ $C_p = 0$ and N 1), equation (10), except for vacuum circuit breakers, can be rewritten as

$$k_a = 1.5 \cdot \sqrt{1 + \frac{\lambda^2}{\omega Q}} - 0.5 \quad (11)$$

Quantities in equations (10) and (11) are as defined in 4.2.3.1.

The maximum chopping overvoltage to ground occurs at the recovery voltage peak and is given by

$$k_c = 1 + k_a \quad (12)$$

The per unit crest overvoltage to ground due to a reignition is given by

$$k_p = 1 + \beta(2 + k_a) \quad (13)$$

and the per unit crest overvoltage excursion peak-to-peak due to a reignition is given by

$$k_s = (1 + \beta)(2 + k_a) \quad (14)$$

The damping factor β for MV reactor switching applications is considered to be a maximum of 0.5.

NOTES:

1- The general equation from which equation (11) is derived is

$$k_a = 1.5\sqrt{1 + \left(\frac{\lambda^2}{\omega Q}\right)\left(\frac{C_s}{C_s + C_L}\right)} - 0.5$$

C_s and C_L both being considered significant.

2- Equations (10) and (11) do not consider the influence of arc voltage. While this approach is valid for HV and EHV applications, the arc voltage may be significant compared to the value of V_o in MV applications. With reference to figure 3, equation (10) can be modified to incorporate the influence of arc voltage giving (refer to figure 3):

$$k_a = \sqrt{(k_{in} + 0.5)^2 + 1.5\left(\frac{i_{ch}}{V_o}\right)^2 \frac{L}{C_L}} - 05$$

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Equation (11), similarly modified and with reference to note 1 above, becomes

$$k_a = \sqrt{(k_{in} + 0.5)^2 + \left(\frac{1.5\lambda^2}{\omega Q}\right)\left(\frac{C_s}{C_s + C_L}\right)} - 0.5$$

4.3.3 Recovery voltage across circuit breaker

The per unit crest recovery voltage across the circuit breaker is given by

$$k_{rv} = 2 + k_a \tag{15}$$

4.3.4 Application

In applying circuit breakers for switching ungrounded shunt reactors, consideration should be given to oscillation modes, the connection arrangement, and testing.

4.3.4.1 Oscillation modes

The frequency of the load side oscillation for the first phase to interrupt differs from that of the second and third phases to interrupt. The latter two phases interrupt virtually simultaneously.

For the first phase to interrupt and with reference to figure C.1, the frequency of the load side oscillation can be as high as 30 kHz and is given by

$$f_1 = \frac{1}{2\pi\sqrt{1.5LC_L}} \tag{16}$$

where

L is the single phase inductance of the reactor in H
C_L is the load side effective capacitance to ground in F; refer to equation (2)

The frequency of the load side oscillation after the second and third phases interrupt is given by

$$f_{2,3} = \frac{1}{2\pi\sqrt{LC_L}} \tag{17}$$

Typical oscillograms from a three-phase ungrounded reactor switching test are shown in figure 7.

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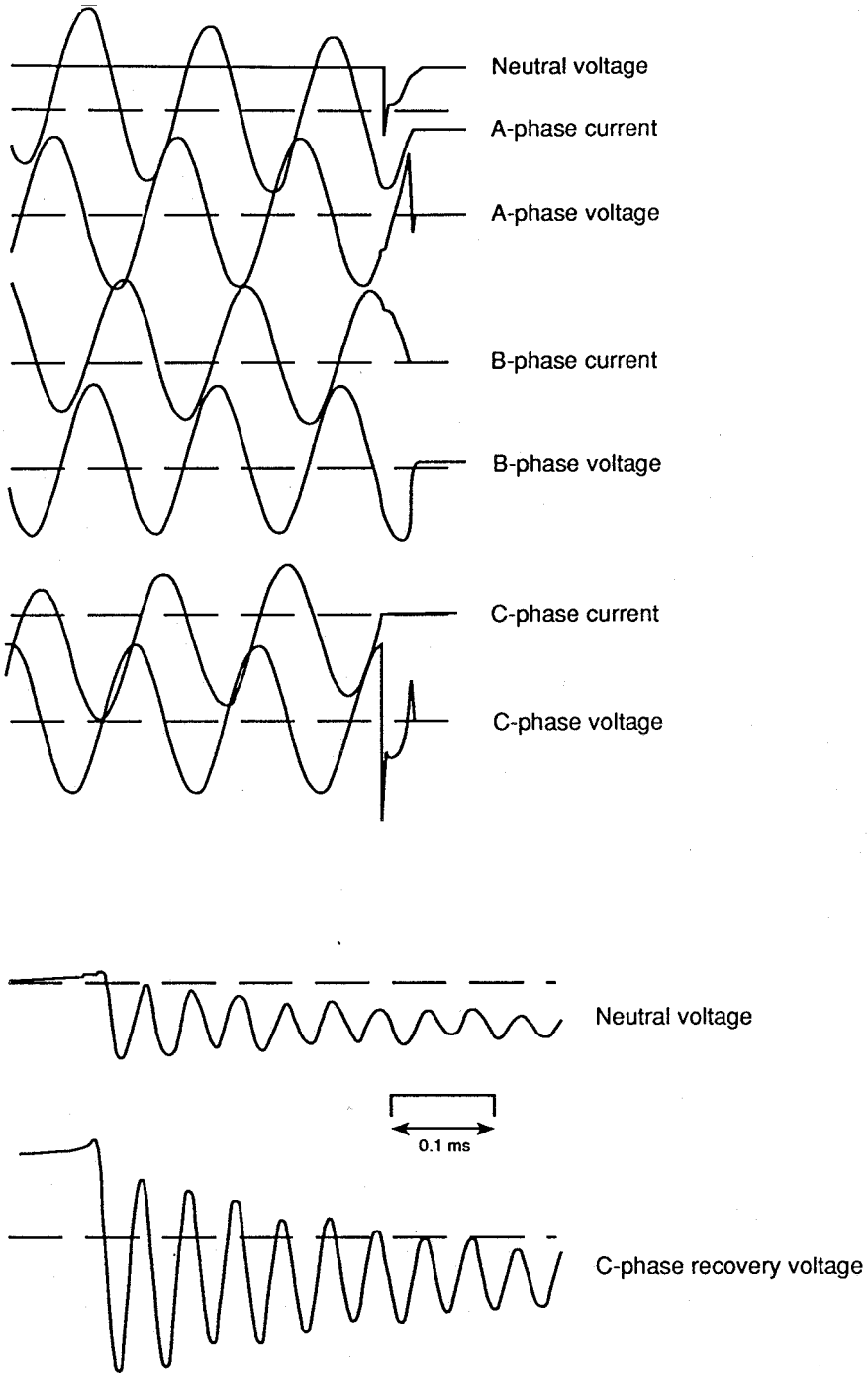

Figure 7— Test oscillogram of switching out of three-phase ungrounded shunt reactor

Phase-to-phase capacitance may be significant in this case, perhaps even purposely added. If so, then C_L in equations (16) and (17) is given by (C_G + 2Cϕ) and (C_G + 3Cϕ), respectively.

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4.3.4.2 Connection arrangement

Given that the neutral is ungrounded, the circuit breaker can be applied on the source or neutral side of the reactor. If applied on the source side, the circuit breaker must meet at least the through fault capability associated with a bus fault and may even be required to interrupt bus faults between the circuit breaker and the reactor. For circuit breakers applied on the neutral side of the reactor, only the reactor switching duty has to be considered.

For both the source and neutral side connection arrangements, the above discussion with respect to current chopping and overvoltages applies equally. However, it is the practice of some utilities to apply two pole circuit breakers for this duty. In such a case, careful consideration should be given to the fact that, while the stress on the first pole to interrupt is as discussed above, the second pole must interrupt against the line-to-line voltage and the higher load side oscillation frequency.

It is essential that the user give serious consideration to applying surge arresters to protect the reactor and, most importantly, to protect the transformer tertiary against the reactor switching overvoltages.

4.3.4.3 Testing

Each MV shunt reactor switching application will be unique. Appropriate testing will therefore be subject to agreement between the manufacturer and the user. Depending on the terminal fault interrupting capability of the prospective circuit breaker, as discussed above, low current terminal fault interrupting capability test data may be applicable. In cases of very low capacitance values to ground and phase-to-phase, capacitance can be added either to ground or phase-to-phase to achieve a load side oscillation frequency comparable with those for low current terminal faults.

In the event that the percentage terminal fault tests data is not applicable, then the test code detailed in IEC Publication TR 1233 [B24] should be used directly or amended as necessary.

4.4 Neutral reactor grounded reactors

Neutral reactor grounded reactors are unique to EHV systems. Such schemes are applied to achieve single pole fault clearing and reclosing. The switching of such reactor schemes is a combination of the directly grounded and ungrounded reactors cases.

4.4.1 Current chopping

Equation (1) is applicable to this case. C_t is derived on the same basis as for the directly grounded reactor case [refer to equation (2)]. As noted for the ungrounded reactor case, the neutral point is virtually grounded prior to first phase interruption.

4.4.2 Chopping and reignition overvoltages

With reference to annex C, the suppression peak overvoltage to ground is given by

$$k_a = (1+K)\sqrt{1+\frac{1}{1+K}\left(\frac{i_{ch}}{V_o}\right)^2\left(\frac{L}{C_L}\right)} - K \qquad (18)$$

Similar to the approach taken for directly grounded reactors ($C_s > C_L$ and ignoring C_p), equation (18) can be rewritten as

$$k_a = (1+K)\sqrt{1+\left(\frac{1}{1+K}\right)\left(\frac{3N\lambda^2}{2\omega Q}\right)} - K \qquad (19)$$

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Quantities in equations (18) and (19) are as defined in 4.2.3.1 and in annex C.

The maximum chopping overvoltage-to-ground occurs at the recovery voltage peak and is given by

$$k_c = 2K + k_a \tag{20}$$

The per unit crest overvoltage-to-ground due to a reignition is given by

$$k_p = 1 + \beta(1 + 2K + k_a) \tag{21}$$

and the per unit crest overvoltage excursion peak-to-peak due to a reignition is given by

$$k_s = (1 + \beta)(1 + 2K + k_a) \tag{22}$$

The damping factor B can be considered to be 0.5 as for the directly grounded reactor case.

NOTE — The general equation from which equation (19) is derived is

$$k_a = (1 + K)\sqrt{1 + \frac{1}{(1 + K)}\left(\frac{3N\lambda^2}{2\omega Q}\right)\frac{C_t}{C_L}} - K$$

C_s and C_L being considered significant and C_t given by equation (2).

4.4.3 Recovery voltage across circuit breaker

The per unit crest recovery voltage across the circuit breaker is given by

$$k_{rv} = 1 + 2K + k_a \tag{23}$$

4.4.4 Application

In applying circuit breakers to switch neutral reactor grounded reactors, consideration should be given to the connection arrangement, oscillation modes and testing.

4.4.4.1 Connection arrangement

Due to the presence of the neutral reactor, the recovery voltage across the breaker will be higher when compared to the directly grounded reactor case by a factor of 2*K* assuming a suppression peak overvoltage of similar magnitude [compare equations (9) and (23)]. If surge arresters are applied across the circuit breaker, this voltage can be limited to the same value as for the directly grounded case (refer to 5.3). Another way to limit this voltage is to ground the neutral prior to switching out the reactor with a single-pole disconnect switch connected across the neutral reactor.

In this context, surge arresters are usually provided at the neutral point to protect the neutral reactor. This arrester, depending on its rating, may operate during the reactor switching, and thus will have some influence on the voltage across the breaker, but not necessarily on the first recovery voltage peak. The user can review the effect of this arrester through computer simulation.

4.4.4.2 Oscillation modes

The load side oscillation that occurs after the first phase clears is a single frequency oscillation and is given by

$$f_1 = \frac{1}{2\pi\sqrt{(1 + K)LC_L}} \tag{24}$$

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This frequency is $1/\sqrt{1+K}$ times lower than that for the directly grounded shunt reactor case (refer to annex D). After clearing of the second phase, and subsequent clearing of the third phase, the phase oscillations consist of a fundamental frequency modulated by a second lower frequency. Figure 8, from an actual field test on a neutral reactor grounded reactor scheme, illustrates the complexity of the oscillation modes for this case.

4.4.4.3 Testing

The testing of a circuit breaker for this application should involve a three-phase test but may be difficult, if not impossible, to achieve. A two-part test can be considered as follows. The first-part test should be performed at the applicable reactor current to establish the characteristics of the breaker for the directly grounded reactor case. Based on this test and the derived breaker characteristics, the second-part test is performed at a higher voltage calculated to reflect the expected performance and stress in the field installation including a voltage distribution factor [refer to equation (23) and annex E]. This test is important to demonstrate that no reignitions will occur at a second current zero due to the higher voltage across the interrupter.

The requirements for the above tests will be influenced by measures taken to limit the reactor switching overvoltages (refer to 5.3).

5. Limitation of overvoltages

5.1 General

The overvoltages described in clause 4. cannot be totally eliminated. However, the overvoltages can be limited to acceptable values. This limitation is determined by the influence of the shunt reactor surge arrester protection and the auxiliary equipment that can be applied to the circuit breaker to limit the overvoltages.

5.2 Shunt reactor surge arrester protection

Shunt reactors are normally protected by surge arresters. At least a 25% protective margin is recommended between the maximum protective level of the arrester and the insulation level of the reactor. This margin is easily attained with both modern metal-oxide surge arresters and the non-linear resistor type surge arresters with series gaps. A typical 500 kV shunt reactor installation (1550 kV BIL, 1275 kV switching surge) would incorporate a 396 kV rated surge arrester with a maximum switching impulse protective level of about 800 kV peak. While many new reactor installations will incorporate metal oxide type surge arresters, gapped type surge arresters are still in common use in some countries and also need to be considered.

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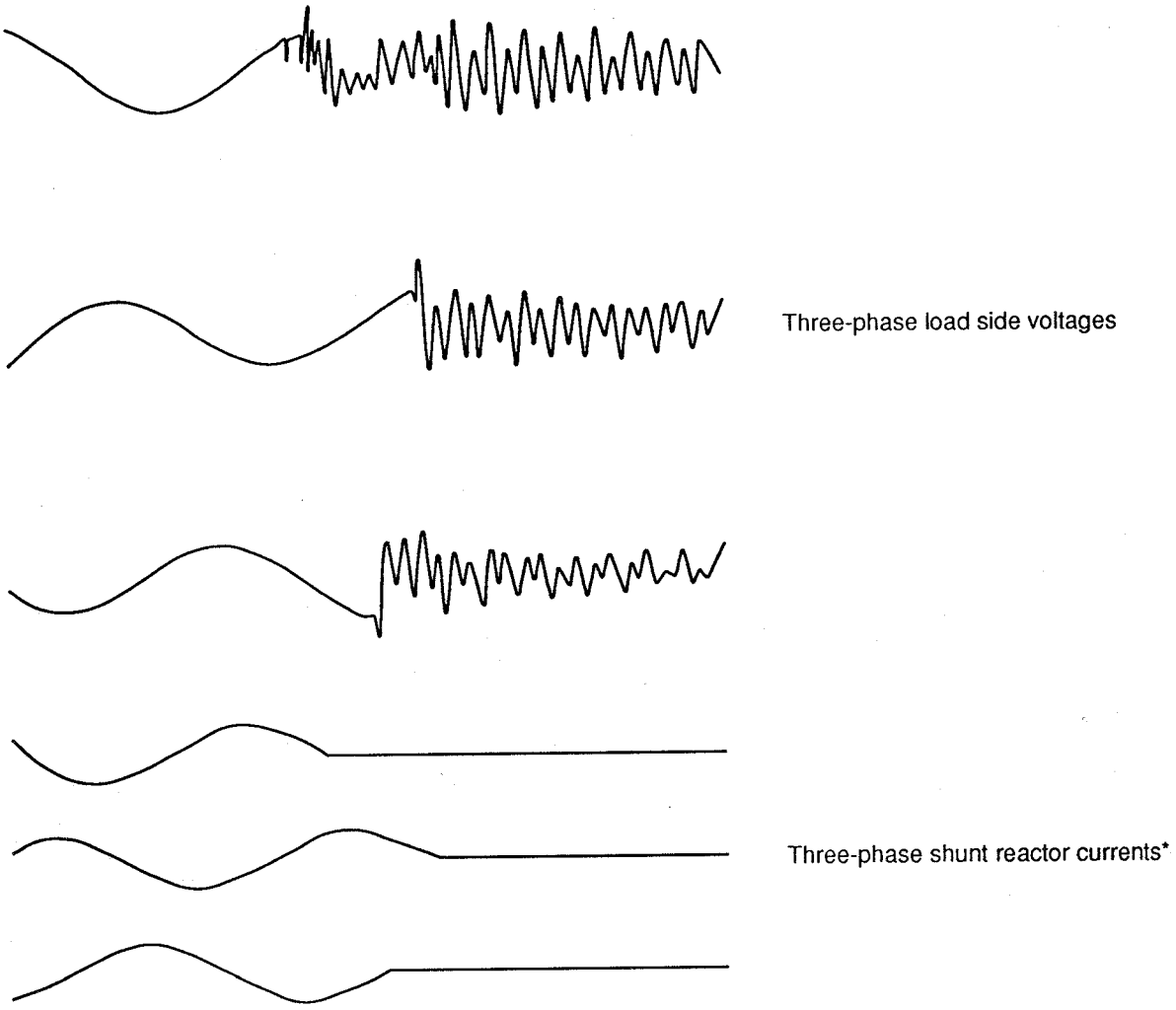

* Note that the measured polarity of the current traces is reversed compared to the actual polarity.

Figure 8— Field oscillogram of switching out of three-phase neutral reactor grounded shunt reactor

5.2.1 Metal oxide surge arresters

Metal oxide surge arresters are rated on the basis of ability to absorb a rated amount of energy and to subsequently withstand the immediate application of rated voltage for 10 s. Such an arrester is a voltage dependent non-linear resistor without gaps and operates by limiting the voltage to its voltage—current characteristic, i.e., it essentially clips the voltage. Since no series gaps are involved, the arrester starts to conduct at a much lower voltage level than the gapped type. The current drawn by the arrester due to chopping overvoltages will not exceed 20 A in most cases.

In the event that the circuit breaker chops sufficient current to produce a chopping overvoltage (suppression peak or recovery overvoltage peak) that exceeds the voltage—current characteristic of the arrester, thearrester will conduct current but only so long as the prospective voltage exceeds that of the arrester characteristic. The arrester will thus discharge a fraction of the load side energy and the load side voltage will continue to oscillate. The possibility of a reignition is not eliminated, but it is reduced since the recovery voltage peak is less than its prospective value. An example of such an arrester operation without reignition is shown in figure 9. Note the clipping of the suppression peak

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overvoltage. If the suppression peak overvoltage is less than the arrester characteristic, the arrester will not operate, but may operate for the eventual higher reignition overvoltages and limit the peak-to-peak voltage excursions to a maximum of twice the protective level.

With respect to energy absorption, the arrester absorbs only a fraction of the energy stored in the reactor at the instant of chopping and it is of no significance.

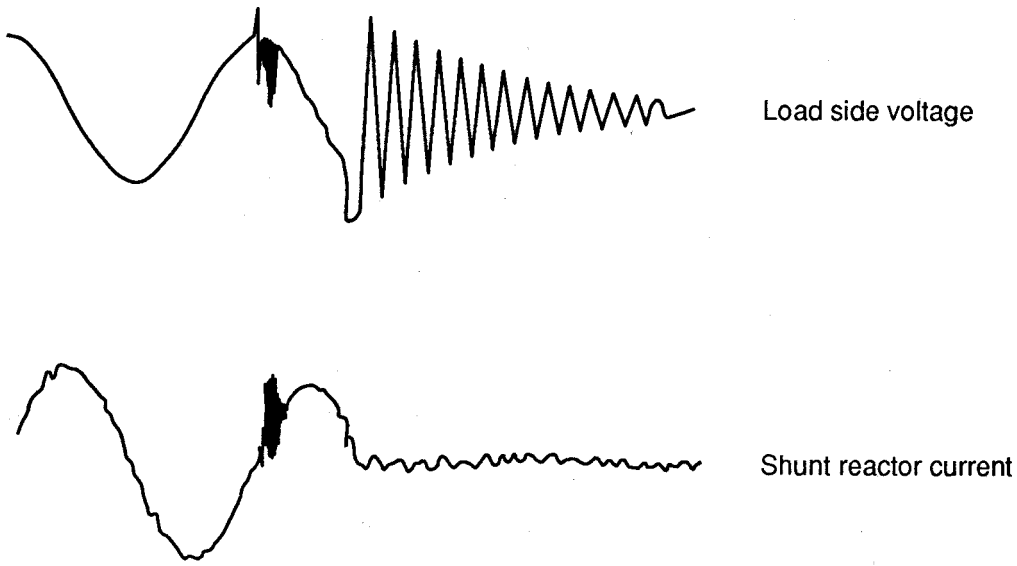

Figure 9— Interruption of shunt reactor current with suppression peak overvoltage limited by metal oxide surge arrester

5.2.2 Gapped surge arresters

The rated voltage of a non-linear resistor-type surge arrester with series gaps is the maximum permissible rms value of normal frequency voltage at which it is designed to operate correctly. At this voltage, the arrester is able to discharge an overvoltage and reseal, i.e., interrupt the power frequency follow current. The rated voltage is usually selected to be equal to the highest power frequency voltage, which can occur between the arrester terminals under temporary overvoltage conditions.

The overvoltage protection provided by this type of arrester is characterized both by the sparkover characteristics of its series gaps and the residual voltage of the non-linear resistors and gap voltage during passage of discharge current. Since the prospective arrester discharge current due to arrester operation when switching shunt reactors is low, the sparkover voltage characteristics of the arrester will determine the maximum overvoltage. The duration of voltage rise will be from a few μs (reignition overvoltages) to hundreds of μs (chopping overvoltages), which means that sparkover voltages for the standard 1.2/50 μs lightning impulse as well as switching surges have to be considered.

In the event that the circuit breaker chops sufficient current to produce a suppression peak overvoltage that equals or exceeds the sparkover voltage of the arrester, the arrester will operate discharging the load side circuit energy and reducing the load side voltage essentially to zero. An example of such a case is shown in figure 10. In this case, the 500 kV reactor is protected by a 420 kV rated arrester, which operates at 950 kV peak at the applicable time. Note the discharge of the current trapped in the reactor through the arrester.

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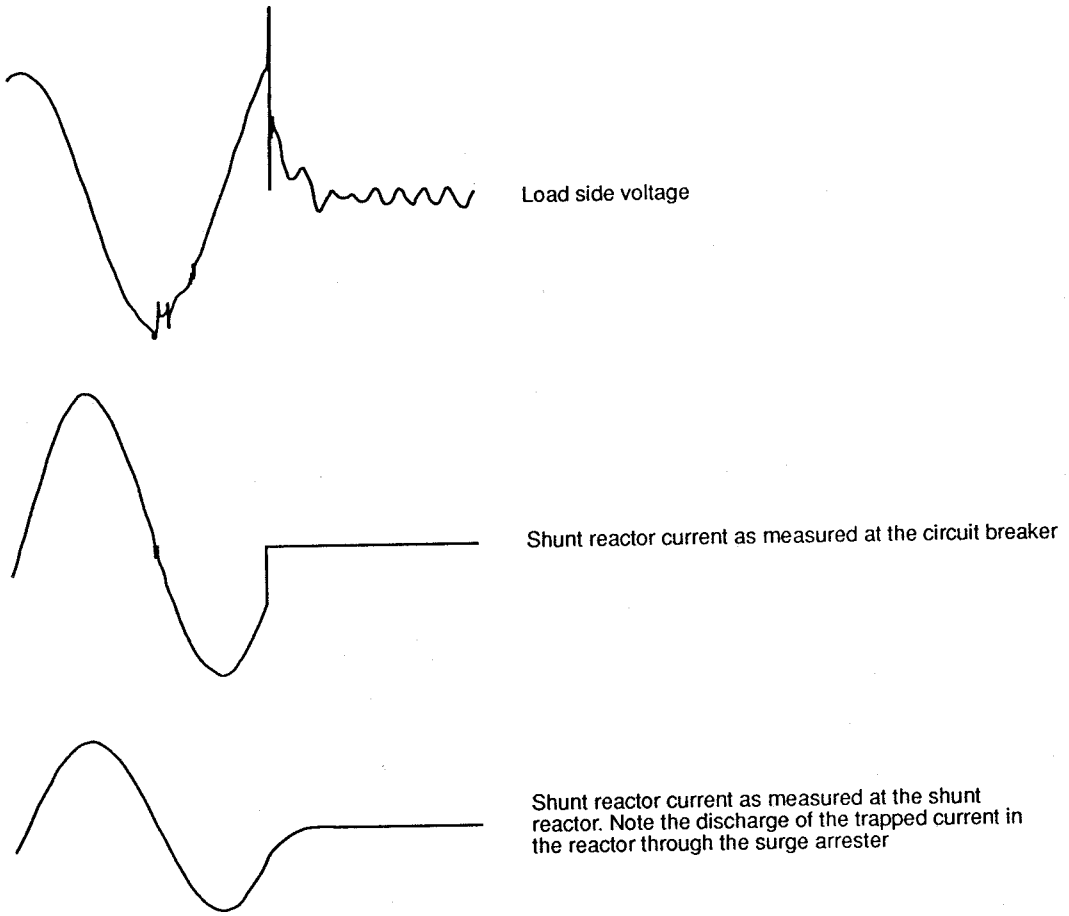

Figure 10— Interruption of shunt reactor current with suppression peak overvoltage limited by a gapped surge arrester

For the case of high chopping overvoltage causing arrester operation, the possibility of reignitions is essentially eliminated. If, however, the chopping overvoltage peak is less than the arrester protective level, the arrester will not operate. This is the case for circuit breakers, which chop low levels of current, e.g., SF_6 puffer-type circuit breakers. The arrester will still protect the reactor against the higher reignition overvoltages. The maximum peak-to-peak voltage excursions are then limited to about twice the arrester protection level.

The energy stored in the reactor at the instant of current chopping, even for the highest possible chopped currents, is an order of magnitude less than the line discharge energy absorption capability of the arrester, and is of no significance.

5.3 Circuit breaker auxiliary equipment

The auxiliary equipment that can be applied to the circuit breaker to limit overvoltages includes opening resistors, metal oxide surge arresters, and synchronous opening control devices.

5.3.1 Opening resistors

High chopping overvoltages can be limited by the addition of opening resistors and associated resistor switches connected across the main interrupter of the circuit breaker. The main interrupters of the circuit breaker will still chop the current, but now only a commutation to the resistor circuit is taking place, i.e., no current interruption and therefore

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no, or very limited overvoltages will occur depending on the ohmic value of the resistor. Interruption of the current occurs on the resistor switch, providing a much softer interruption and low chopping currents.

The value of the opening resistors should be chosen to be of the same order as the ohmic reactance of the reactor. Resistor values of several thousand ohms are common and the insertion of the resistor causes a significant phase shifting of the current. Current zero is advanced relative to the voltage peak, and interruption thus occurs at a lower point on the voltage wave. The chopping overvoltages are reduced relatively as are the magnitude and probability of reignition overvoltages.

5.3.2 Metal oxide arresters

Metal oxide surge arresters can be used to limit reignition overvoltages. The arrester is applied across the circuit breaker in the same manner as a grading capacitor and essentially limits the voltage across the circuit breaker to its voltage-current characteristic. A typical interruption of reactor current for this case is shown in figure 11. The effect of the arrester applied across the circuit breaker can be summarized as follows:

Chopping overvoltages are limited to

$$k_a \leq 1 + k_{arr} \tag{25}$$

$$k_c \leq k_{arr} - 1 \tag{26}$$

$$k_{rv} \leq k_{arr} \tag{27}$$

Reignition transients are limited to:

$$k_p \leq 1 + \beta k_{arr} \tag{28}$$

$$k_s \leq k_{arr}(1 + \beta) \tag{29}$$

where

k_{arr} is the protective level of the arrester expressed in pu of V_o.

5.3.3 Synchronous opening control devices

Reignitions in modern circuit breakers can be eliminated by means of synchronized opening of the circuit breaker. This method applies to circuit breakers with minimum arcing times sufficiently less than one half-cycle to permit accurate and consistent contact parting at a point-on-wave to ensure a greater than minimum arcing time and successful interruption at the first current zero after contact parting. For example, in figure 4, contact parting should occur at times earlier than t_1 and t_2 as applicable.

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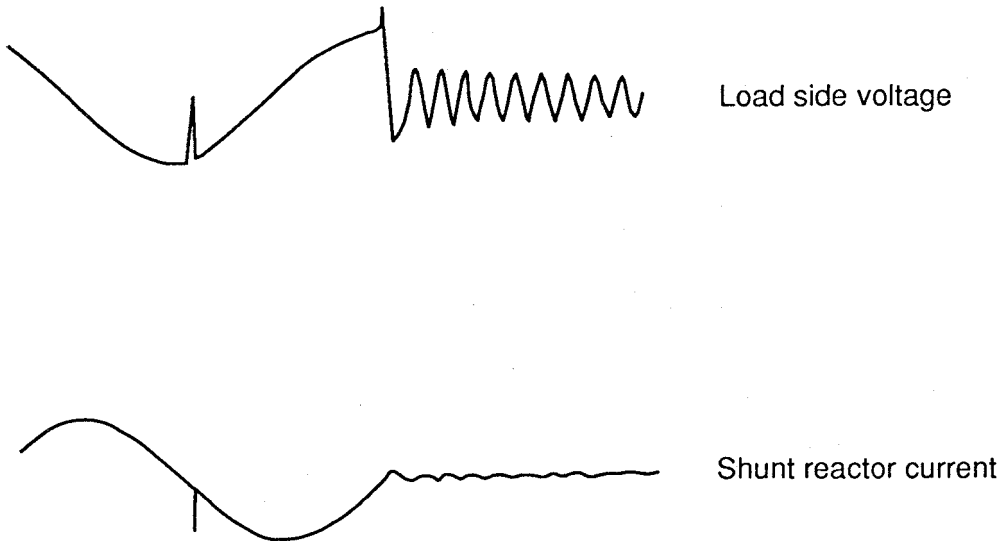

Figure 11— Interruption of shunt reactor current by a circuit breaker equipped with a parallel metal oxide surge arrester

A special circuit breaker synchronous control device is required together with a source side voltage transformer or CVT for timing reference. An adaptive control may be used to compensate for any changes in mechanical timing due to ambient temperature or wear and tear. However, the moderate timing accuracy required will usually not necessitate adaptive control.

Both three-pole and single-pole operation can be accommodated.

6. Circuit breaker specification

On the basis that the dedicated purpose of the circuit breaker is to switch a shunt reactor only, the characteristics discussed in the following subclauses should be specified by the user.

6.1 Dielectric withstand capability

The quantities to be stated, as applicable, are maximum system voltage, ac voltage withstand level, and lightning and switching impulse withstand levels. These values should be at least equal to those for any circuit breaker applied at the applicable system voltage. Special consideration should be given to the recovery voltage across the circuit breaker, particularly under wet conditions (refer to 6.10 and annex E).

6.2 Interrupting current rating

Circuit breakers used to switch shunt reactors connected to buses are normally required to clear reactor zone faults. The circuit breakers should thus have fault interrupting and associated capabilities suitable for the purpose. For circuit breakers used to switch shunt reactors connected to transmission lines, fault-interrupting capability may not be a requirement, but the short-time and momentary current capability of the circuit breakers shall equal those applicable to the circuit breakers providing fault current protection for the shunt reactor zone.

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6.3 Shunt reactor rating

The shunt reactor rating should be stated in terms of Mvar and rated voltage. For example, a three-phase shunt reactor applied on a 500 kV system might be rated 135 Mvar at 525 kV.

6.4 Shunt reactor current

The shunt reactor current to be interrupted is that derived from the shunt reactor rating. For the example given in 6.3, the shunt reactor current is 148.5 A rms.

6.5 Load side circuit characteristics

The load side circuit characteristics to be stated by the user are the inductance L of the shunt reactor (5.41 H for the example in 6.3) and the total capacitance C_L of the circuit. C_L is the capacitance contributed by the shunt reactor and all connected equipment, including buswork and supporting insulators between the circuit breaker and the shunt reactor. Refer to annexes A and B.

6.6 Overvoltage limitations

The suppression peak overvoltage (k_a) limitation (2% value; refer to annex E) should be stated. It is recommended that a k_a of 2 pu be used for EHV and HV applications and 2.5 pu for medium voltage applications.

NOTE — Reignition overvoltages (k_p) are dependent on the interaction between the circuit breaker and the user's system and load side circuit arrangement, and should not be stated as a circuit breaker requirement. Reignition overvoltage levels can be calculated as described in clause 4. and in annex E.

6.7 Grounding arrangement

For the grounding arrangement, directly grounded, ungrounded, or neutral reactor grounded should be stated. For the neutral reactor grounded case, the inductance of the neutral reactor shall also be stated.

6.8 Interrupting time

Shunt reactor switching is a normally routine, rather than a protective (three-phase switching of bank for reactor fault) switching operation. Additionally, the interrupting times of different devices will vary dependent mainly on mechanical opening time. Unless there is a particular reason for doing so, the user should not specify an interrupting time, but may wish to state some limitation with respect to simultaneity between poles and interrupters for multi-break circuit breakers. Where synchronous control opening devices are applied, consideration should be given to the repeatability of the mechanical opening time.

6.9 Mechanical endurance

Given that shunt reactors are switched frequently, the number of required close-open operations before maintenance is necessary should be stated. A mechanical endurance type test should be performed to verify the endurance capability of the circuit breaker.

6.10 Additional information

In addition to other necessary technical data, the following additional information should be requested for evaluation of the suitability of the circuit breaker for the application:

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a) Reactor switching test report complete with test circuit details, measured arcing times and associated chopping overvoltage and chopped current values (if measured)
b) Analysis of the above test report results as described in annex E
c) Evidence (test report or other documentation) of applicable withstand capability across the circuit breaker
d) Details of auxiliary equipment provided with the circuit breaker for the purpose.

7. Bibliography

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Annex A Shunt reactor characteristics

(Informative)

At 60 kV and above, shunt reactors are directly connected to station buses or to transmission line terminations and are grounded directly or through a neutral reactor (sometimes referred to as a four reactor scheme). At voltages below 60 kV, reactors are commonly connected to system transformer tertiary windings and are usually ungrounded.

A.1 Shunt reactors rated 60 kV and above

The majority of the installed shunt reactors at 60 kV and above are in the 30 to 300 MVA (three-phase) range. The largest single phase units have ratings of 125 MVA or 375 MVA as a three-phase group.

The characteristics of shunt reactors depends to a great extent on the design, which can be

— 3-legged gapped iron-core
— 5-legged gapped iron-core
— shell type gapped iron-core
— coreless (air-core)

Table A.1 gives some typical shunt reactor characteristics in the range 60 to 765 kV [B14] .

Table A.1 —HV and EHV shunt reactor electrical characteristics

Rated voltage (kV)	Rating (Mvar)	Normal frequency (Hz)	Rated current (A)	Inductance (H)	Capacitance (nF)	Natural frequency (kHz)
765	150–300	60	113–226	5.17–10.35	1.7–4.0	1.1–1.7
735	330	60	259	4.34	4.1	1.2
525	135	60	148	5.43	1.8–4.0	1.1–1.6
400	120–200	50	173–289	2.55–4.25	1.9–3.2	1.4–2.3
236	125	60	306	1.18	2.1	3.2
132	55	50	240	1.0	1.3	4.4
115	25	60	126	1.4	2.9	2.5
60	20	60	190	0.48	2.0	5.1

In the range 60 to 245 kV, reactors are most commonly oil-filled and have three-legged gapped cores with layer, continuous disc or interleaved disc windings. Future reactors in the range 69 to 145 kV will tend to be air-core dry coil units.

At 300 to 500 kV, reactors are single-phase or three-phase units with three-legged, five-legged or shell-type cores (with the wound core legs gapped). The windings are of the layer, continuous disc, or interleaved disc type.

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At 735 kV and 765 kV reactors are almost exclusively banks of single-phase units with similar constructions as for 500 kV single-phase units.

The effective capacitance values of the reactors are dependent on the design and construction. For oil-filled units, the capacitance is composed of bushing capacitance, winding series capacitance, and winding capacitances to ground or to shields. Bushing capacitances range from 500 to 800 pF.

Effective winding capacitances vary from a minimum of about 1200 pF to a maximum of about 3500 pF; layer windings having the lowest values and interleaved disc windings the highest values. For dry coil units, no bushings are involved and capacitance is that due to windings to ground and winding series capacitance. Both of these values are low; the latter so because of the large number of turns inherent in such coils, and the effective capacitance is in the range 300 to 500 pF.

For general reactor switching application and laboratory testing purposes, oil-filled reactors can reasonably be assumed to have a capacitance of at least 2000 pF. This will give natural frequencies of 1 to 5 kHz for reactors rated 69 to 765 kV, the lower frequencies being applicable at the higher voltages.

A.2 Shunt reactors rated below 60 kV

Shunt reactors rated below 60 kV are either oil-filled, three-legged iron core units, or dry coil units. Table A.2 gives some typical shunt reactor characteristics in this range [B14] .

Table A.2 —Medium voltage reactor electrical characteristics

Rated voltage (kV)	Rating (Mvar)	Normal frequency (Hz)	Rated current (A)	Inductance (mH)	Capacitance* (nF)	Natural frequency† (kHz)
36	35–100	50/60	560–1600	98–34	2	9.3–15.8
24	35–100	50/60	840–2400	44–15	2	14–23.7
17.5	40–80	50/60	1400–2600	20–10	2	20.6–29
12	40–75	50/60	1900–3600	10–5	2	29–41

*Oil-filled reactor effective capacitance to ground ignoring internal capacitive coupling between phases.
†Applicable to first-pole to-clear.

Table A.2 illustrates the wide range of current and natural frequency applicable in this voltage range. For dry coil reactor units, the capacitance to ground is in the range 300 to 500 pF and the corresponding natural frequencies will be two to three times those given in table A.2.

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Annex B System and station characteristics

(Informative)

System (source) and station characteristics interact with the circuit breaker during the switching of shunt reactors and must be considered in the application of circuit breakers for this purpose.

B.1 System characteristics

The system characteristics, which impact on reactor switching are the source inductance and the source side capacitance. The source inductance can be derived from the prevailing short-circuit level at the station. The source side capacitance is in general very much greater than the load side capacitance. For circuit breaker type testing purposes, the former capacitance is assumed to be at least ten (10) times greater than the latter.

B.2 Station characteristics

Directly connected shunt reactors are connected either to station busbars or to overhead lines. A worldwide survey has shown that connection to busbars is three times more common than the connection to lines. The characteristics that are of relevance are the inductance of the connecting bus or line and any capacitances in addition to that of the reactor. Typical values are given in table B.1.

Table B.1 —Connection characteristics for shunt reactor installations

Connection	Inductance μH/m	Capacitance pF/m
Busbar/line	1	10
Cable	0.2–0.5	200–400
GIS	0.2	60

The inductance of even the longest connection lengths (150 to 200 m) is not significant compared to the inductance of high voltage reactors, but does influence the reignition process. The capacitance of long busbar/line lengths (up to 170 m reported), and relatively short cable or GIS lengths is significant compared to that of the reactor and should be considered. Additionally, other connected equipment between the circuit breaker and the reactor will also contribute to the overall load side capacitance and should be considered. Capacitance values for such equipment are given in table B.2.

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Table B.2 —Capacitance values of various station equipment

Equipment	Capacitance* nF
Capacitor voltage transformers	2–16
Current transformers	0.15–0.45
Voltage transformers	0.15–0.45
Surge arresters	0.08–0.12
Disconnect switches	0.06–0.20
Bus support insulators	0.01
GIS air entrance bushings –SF_6	0.03–0.15
–Condenser	0.10–1
–Epoxy	0.10–1

*Variation is with voltage rating.

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Annex C General derivation of chopping and reignition overvoltages due to shunt reactor switching

(Informative)

C.1 General

The purpose of this annex is to provide the basis for the derivation of the chopping and reignition overvoltage equations given in 4.2, 4.3, and 4.4. The equations for the three cases of directly grounded, ungrounded and neutral reactor grounded shunt reactors can be derived from the general case shown in figure C.1.

C.2 Chopping overvoltages

The general schematic for chopping and reignition overvoltages is shown in figure C.2. Prior to interruption of current on any phase, the neutral of the reactor is at ground potential due to the symmetry of the voltage and circuit. When the first phase clears the neutral potential shifts through a transient oscillation towards a bias voltage K pu dependent on the grounding arrangement. The mean value of the shifted neutral voltage decays to zero in a time also dependent on the grounding arrangement.

The load side oscillation of the first phase-to-clear will oscillate around the shifted neutral voltage. Current chopping adds energy to this oscillation, the degree of chopping determining the magnitude of the overvoltage. The suppression peak overvoltage k_a in per unit (pu) of the phase-to-ground peak voltage V_o is given by

$$k_a = (1 + K)\sqrt{1 + \frac{1}{1 + K}\left(\frac{i_{ch}}{V_o}\right)^2 \frac{L}{C_L}} - K \qquad \text{(C.1)}$$

where

$$K = \frac{1}{2 + \frac{L}{L_N}}$$

i_{ch} is chopped current level (A)
V_o is system voltage to ground (V_{peak}) at the instant of current interruption
L is main reactor inductance (H)
L_N is neutral reactor inductance (H)
C_L is effective load side capacitance to ground (F) [refer to 4.2.1, equation (2)].

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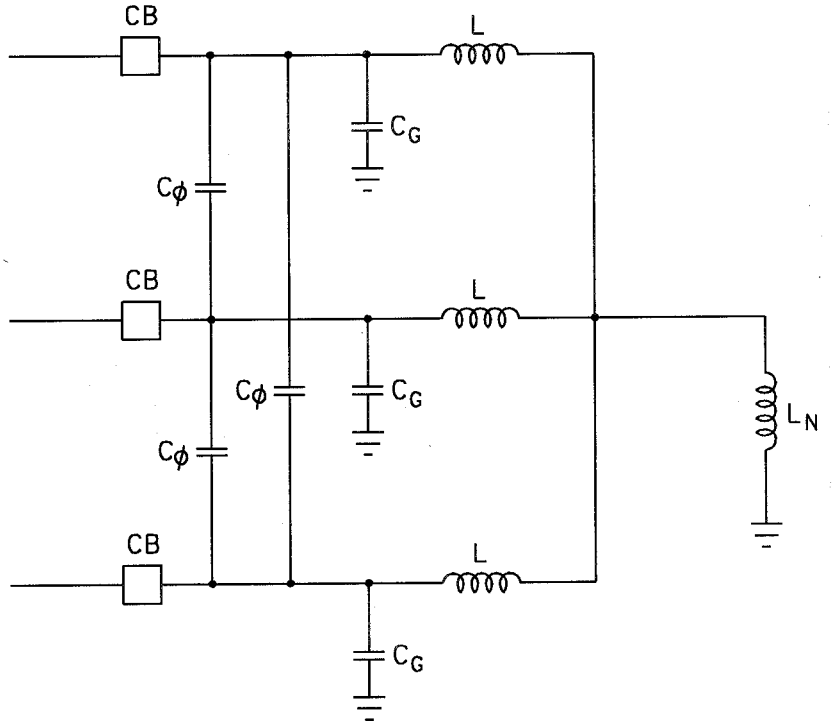

Figure C.1 —General case for shunt reactor switching

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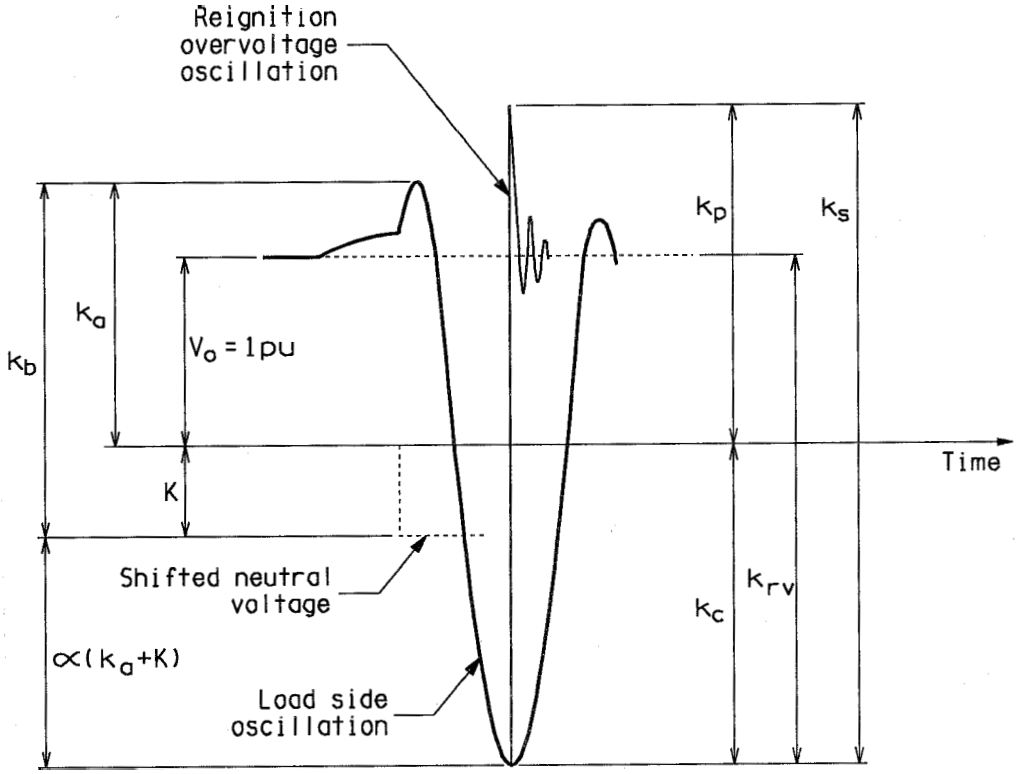

Figure C.2 —General schematic for chopping and reignition overvoltages

For directly grounded reactors (K=0), equation (C.1) can be applied to clearing on any phase. For ungrounded or reactor grounded reactors, the equation applies only to the first-phase-to-clear. For these latter cases and considering the second and third phase to clear, there is either no or lower neutral shift, and additionally the released inductively stored energy at current chopping is lower. For these reasons, it can be assumed that the chopping overvoltages are lower for the second and third phases to clear unless the chopping current level is significantly higher than for the first-phase-to-clear.

The magnitude of the suppression peak overvoltage relative to the shifted neutral voltage k_b is given by

$$k_b = k_a + K \tag{C.2}$$

and the magnitude of the overvoltage to ground at the recovery peak k_c, is given by

$$k_c = K + \alpha(k_a + K) \tag{C.3}$$

where

α is the damping factor associated with the chopping overvoltage oscillations.

The peak recovery voltage across the circuit breaker k_{rv} is given by

$$k_{rv} = 1 + K + \alpha(k_a + K) \tag{C.4}$$

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For the different reactor grounding arrangements, the following equations apply:

For *directly grounded* reactors:

$K = 0$

$\alpha = 1$ (zero damping)

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

$k_b = k_a$

$k_c = k_a$

$k_{rv} = 1 + k_a$

For *ungrounded* reactors:

$K = 0.5$

$\alpha = 1$ (zero damping)

$$k_a = 1.5\sqrt{1 + \frac{1}{1.5}\left(\frac{i_{ch}}{V_o}\right)^2 \frac{L}{C_L}} - 0.5$$

$k_b = k_a + 0.5$

$k_c = k_a + 1$

$k_{rv} = k_a + 2$

For *neutral reactor grounded* reactors:

K = as for application

$\alpha = 1$ (zero damping)

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

$k_b = k_a + K$

$k_c = k_a + 2K$

$k_{rv} = 1 + k_a + 2K$

C.3 Reignition overvoltages

With reference to figure C.2, the maximum reignition overvoltage to ground k_p is given by

$$K_p = 1 + \beta[1 + K + \alpha(k_a + K)] \qquad \text{(C.5)}$$

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where

β is the damping factor associated with the reignition overvoltage oscillation and can be assumed to be 0.5.

The maximum reignition overvoltage excursion peak to peak k_s is given by

$$k_s = (1 + \beta)[1 + K + \alpha(k_a + K)] \quad \text{(C.6)}$$

For *directly* grounded reactors:

$K = 0$

$\alpha = 1$ (zero damping)

k_a = as noted in subclause C.2 for this case

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

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

For *ungrounded* reactors:

$K = 0.5$

$\alpha = 1$ (worst case)

k_a = as noted in subclause C.2 for this case

$k_p = 1 + \beta\ (k_a + 2)$

$k_s = (1 + \beta)\ (k_a + 2)$

For *neutral reactor grounded* reactors:

k = as for application

$\alpha = 1$

k_a = as noted in subclause C.2 for this case

$k_p = 1 + \beta\ (1 + k_a + 2K)$

$k_s = (1 + \beta)\ (1 + k_a + 2K)$

NOTES:

1 — Equations (C.3) through (C.6) include the damping factor α and the conservative approach is to assume $\alpha = 1$. In reality, however, some damping will occur and a damping factor α of 0.9 or less is appropriate.

2 — Equations (C.1) through (C.6) do not consider the influence of arc voltage. The influence of the arc voltage is not significant for HV or EHV circuit breakers, but can be significant for MV circuit breakers. Refer to 4.3.

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3 — Equation C.1) does not consider neutral to ground capacitance. Experience with ungrounded and neutral reactor grounded installations indicates that the neutral-to-ground capacitance is not significant and can be ignored. On this basis, the load side oscillation in general is single frequency.

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Annex D Oscillation modes

(Informative)

D.1 General

The following discussion is applicable to the directly grounded reactor case and reference should be made to figure 1. The oscillation modes applicable to ungrounded and reactor grounded reactors are discussed in 4.3 and 4.4, respectively.

Four different oscillation modes occur during the interruption and reignition process. These modes and associated frequency ranges are listed in table D.1.

Table D.1 —Oscillation modes and frequency ranges

Oscillation mode	Frequency range
Load side	1–5 kHz*
First parallel	1–10 MHz
Second parallel	50–1000 kHz
Main circuit	2–20 kHz

*Range applicable to oil-filled reactors; for dry coil reactors the upper limit may be two to three times higher.

D.2 Load side oscillations

A successful interruption results in the slowly decaying load side oscillation with the trapped energy oscillating between the inductance and capacitance of the load side circuit. The frequency of the oscillation is given by

$$f_L = \frac{1}{2\pi\sqrt{LC_L}} \tag{D.1}$$

This oscillation may be modulated due to phase interaction (refer to D.4).

D.3 Reignition oscillations

Three different oscillation circuits are involved in reignitions. A “first parallel” oscillation occurs when C_P discharges through the circuit breaker; the frequency of this oscillation is

$$f_{p1} = \frac{1}{2\pi\sqrt{L_p C_p}} \tag{D.2}$$

and is in the order of 1 to 10 MHz.

The circuit breaker will not interrupt the current associated with the “first parallel” oscillation. A “second parallel” oscillation (reignition overvoltage oscillation) will follow, as a result of which, the voltages across C_s, and C_L are equalized, i.e., the voltage across the circuit breaker is reduced to zero for an instant. The frequency of the “second parallel” oscillation is given by

$$f_{p2} = \frac{1}{2\pi}\sqrt{\frac{C_L + C_s}{L_b C_L C_s}} \tag{D.3}$$

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and is in the range 50 to 1000 kHz.

The circuit breaker may interrupt the current associated with the “second parallel” oscillation. If it does not, then a “main circuit” oscillation develops. This oscillation involves the total circuit and generally leads to a new loop of current. Neglecting L_b (since it is small compared to L_s and L), the frequency of the “main circuit” oscillation is given by

$$f_m = \frac{1}{2\pi}\sqrt{\frac{L_s + L}{L_s L(C_s + C_L)}} \tag{D.4}$$

and is in the range 5 to 20 kHz. It should be noted that equation (D.4) describes the main circuit oscillation in its simplest possible form. In reality, the oscillation is a composite of a number of oscillation modes dependent on the reactor installation and the local and remote configuration of the system.

Load side, second parallel, and main circuit oscillations are shown schematically in figure 6. Note that if $C_s >> C_L$, no main circuit oscillation will occur.

All circuit breakers will exhibit reignitions when switching reactors. The voltage at which the reignitions occur (given a certain rate of change of the recovery voltage) is a characteristic of the circuit breaker. The frequency of occurrence of reignitions is dependent on the breaker characteristics and the circuit (the circuit breaker reacts at a certain imposed voltage, but sustaining the reaction depends on the circuit).

It should be noted that reignitions involve an energy exchange. Prior to the reignition, the load side energy alternates between electromagnetic and electrostatic energy. During the “first parallel” oscillation, the electrostatic energy stored in C_p is dissipated with no exchange between the source and load sides. During the “second parallel,” oscillation electrostatic energy is exchanged between C_s and C_L. During the “main circuit” oscillation, all circuit elements are involved and the energy exchange is both electromagnetic and electrostatic.

D.4 Interaction between phases

The interaction between phases during the switching of shunt reactors is a complex subject. This is particularly the case for medium voltage transformer tertiary connected reactors where the interaction can influence the interruption process. For the case of directly and neutral reactor grounded reactors in the range 60 kV and above, the interaction influences only the load side recovery voltage oscillation.

Due to mutual coupling between the individual phases, the interaction manifests itself in the form of beating of the recovery voltage oscillation. The degree of beating is dependent on the length of the connection between the circuit breaker and the reactor and on the type of reactor. When the circuit breaker is located close to the reactor, the interaction is minimal or nonexistent and the recovery voltage oscillation is a clean exponentially decaying sinusoidal function (refer to figure D.1). For longer connection lengths between the circuit breaker and the reactor, beating of the recovery oscillation will occur (refer to figure D.2). The effect is stochastic and varies even with fixed contact parting times. With regard to the reactors, if the units are single-phase, no interaction occurs due to the reactors. If, however, the units are three-phase (in one tank), the phase-to-phase coupling is significant and results in beating such that the maximum recovery voltage peak can occur late in the oscillation.

For purposes of this application guide, the interaction between phases is not a concern because the interaction does not influence the recovery voltage in the region between current interruption and the occurrence of the recovery voltage peak. If the circuit breaker successfully withstands the recovery voltage peak, then no reignition will occur later even if subsequent peaks exceed the chopping overvoltage peak value due to beating.

The probability of high overvoltages occurring due to superposition of transients from adjacent phases is considered to be remote.

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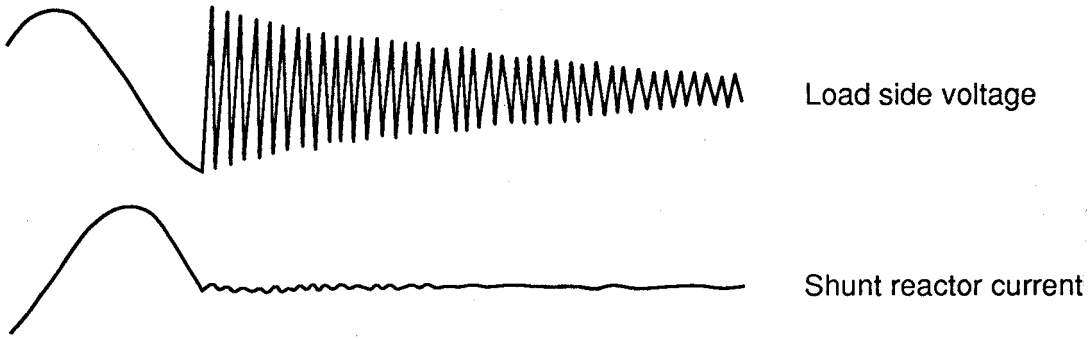

Figure D.1 —Load side oscillation with circuit breaker located close to shunt reactor

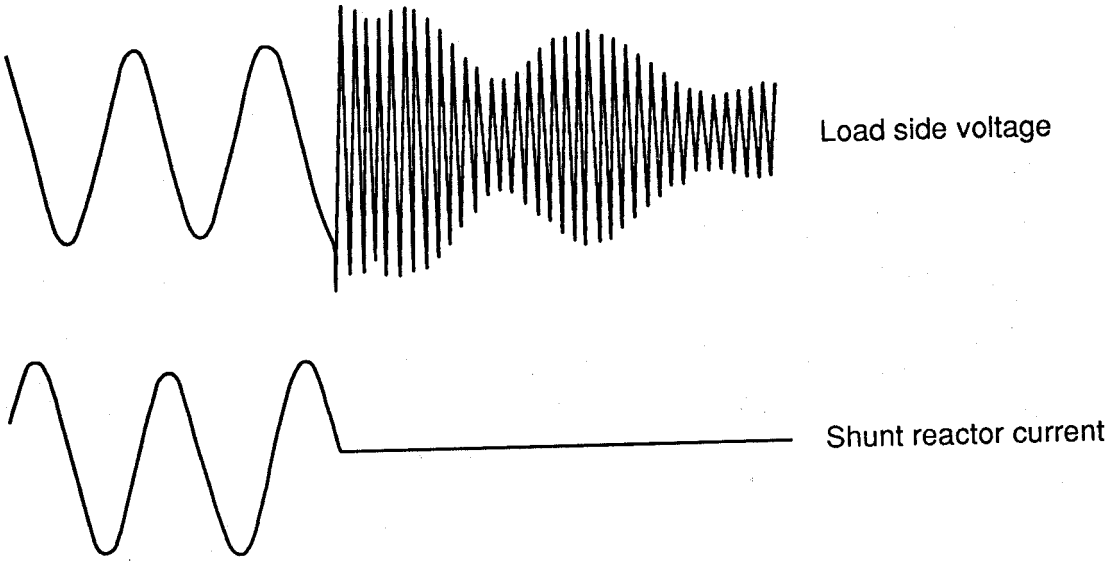

Figure D.2 —Load side oscillation with circuit breaker located remote from shunt reactor

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Annex E Application of laboratory test results to actual shunt reactor installations (Informative)

E.1 General

The purpose of this annex is to describe the procedure based on laboratory tests results, estimate the overvoltage levels that will occur in actual shunt reactor installations, and determine the suitability of a particular circuit breaker for the application.

The procedure described applies principally to EHV and HV shunt reactor installations with directly grounded neutrals. The procedure may however be applied with suitable adaptation to the ungrounded and neutral reactor grounded cases as discussed in 4.3 and 4.4. Due to the statistical nature of overvoltage generation, it is necessary to apply statistical methods to estimate the risk for overvoltages at or above certain levels. Applicable statistical formulas are given in annex F for convenience.

E.2 Overvoltage estimation procedures

E.2.1 Chopping number of one interrupter

The main characteristic evaluated in the laboratory test is the chopping number (λ) for a single interrupter circuit breaker. The chopping number is an inherent characteristic of the circuit breaker and is usually independent of the circuit. The chopping number can therefore be used to estimate the behavior of the circuit breaker in other circuits than the test circuit.

The chopping number varies statistically and must be expressed in terms of a mean value, standard deviation and, if applicable, dependence on arcing time. The chopping number for a single interrupter circuit breaker is defined by

$$\lambda = \frac{i_{ch}}{\sqrt{C_t}} \tag{E.1}$$

where

i_{ch} is the chopped current value
C_t is the total capacitance in parallel with the circuit breaker (refer to 4.2.1).

The value of chopped current should, if possible, be directly measured for each test shot and current zero at which interruption is attempted or achieved. If actual measurement is not possible, then i_{ch} for directly grounded reactors can be calculated using the following equation:

$$i_{ch} = V_o\sqrt{\frac{C_L}{L}(k_a^2 - 1)} \tag{E.2}$$

and λ is then calculated using equation (E.1).

Equation (E.2) does not include the influence of arc voltage and is valid for HV and EHV circuit breakers. For MV circuit breakers, the arc voltage may be significant and i_{ch} is derived, based on a single phase test, using

$$i_{ch} = V_o\sqrt{\frac{C_L}{L}(k_a^2 - k_{in}^2)} \tag{E.3}$$

If the MV circuit breaker test is performed on a three-phase ungrounded basis, the corresponding equation is

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$$i_{ch} = V_o\sqrt{\frac{2C_L}{3L}[(k_a + 0.5)^2 - (k_{in} + 0.5)^2]} \quad \text{(E.4)}$$

The factor k_{in} and other quantities are as defined in 4.2 and 4.3.

The values of i_{ch} and λ will vary statistically from test to test. If the values show no clear dependence on the arcing time, the statistical variation is usually a normal distribution. On this basis, the mean value, λ_{mean}, and the standard deviation σ are calculated.

In the event that i_{ch} and λ exhibit a clear dependence on arcing time, a linear relationship can be assumed as a first approximation

$$\lambda_{mean} = A + Bt_a \quad \text{(E.5)}$$

where t_a is the arcing time

The constants A and B can be derived by performing a linear regression. The dispersion around the regression line will probably be wide and therefore it is necessary to also derive the standard deviation of the regression line (generally referred to as the standard error of estimate). Refer to E.3 and annex F.

E.2.2 Estimation of chopping overvoltages in shunt reactor installations

For the first case, where the chopping number is independent of the arcing time, the maximum chopping number for one interrupter is given by

$$\lambda_{max} = \lambda_{mean} + 2\sigma \quad \text{(E.6)}$$

Statistically, this is the 2% value, i.e., the value that will be exceeded in less than 2% of the switching operations.

To estimate the maximum chopping overvoltages, λ_{max} is inserted in equation (E.7),

$$k_{amax} = (1 + K)\sqrt{1 + \frac{3N\lambda_{max}^2}{2\omega Q(1 + K)}} - K \quad \text{(E.7)}$$

where

k_{amax} is the maximum suppression peak overvoltage (2% value) in pu
ω is the angular power frequency (377 radians/s at 60 Hz)
Q is the three-phase reactive power of the reactor in VA
K is the neutral voltage shift in pu
N is the number of interrupting units in series per pole

the assumption being that $C_s >> C_L$, C_p is negligible and arc voltage is not a consideration. If these assumptions do not apply, refer to 4.2, 4.3, or 4.4 and associated notes, as applicable.

For the second case, where the chopping number is dependent on arcing time, the maximum chopping number will occur at the maximum arcing time. The maximum chopping number (2% value) for a single interrupter is given by

$$\lambda_{max} = A + Bt_{amax} + 2S_e \quad \text{(E.8)}$$

where

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S_e is the standard error of estimate.

The maximum chopping overvoltage is calculated using equation (E.7).

E.2.3 Estimation of reignition overvoltages in shunt reactor installations

It is important to note that overvoltages occurring in laboratory tests due to reignitions have no relevance for the estimation of reignition overvoltages in actual shunt reactor installations. Estimated reignition overvoltage levels are derived on the basis described in annex C.

For the case where the chopping number is independent of arcing time, reignition overvoltages k_p and k_s are given by

$$k_{pmax} = 1 + \beta(1 + 2K + k_{amaxr}) \quad \text{(E.9)}$$

$$k_{smax} = (1 + \beta)(1 + 2K + k_{amaxr}) \quad \text{(E.10)}$$

where

k_{pmax} is the maximum reignition overvoltage to ground (2% value) in pu
k_{smax} is the maximum reignition overvoltage peak-to-peak excursion (2% value) in pu
k_{amaxr} is the maximum expression peak overvoltage value in pu derived using equation (E.7) following which reignition occurs
β is 0.5

For circuit breakers whose chopping numbers vary with arcing time, the applicable k_a, value is that obtained at the longest arcing time (t_{ar}) resulting in a reignition. t_{ar} can generally be considered as t_{amax} less one-half cycle. The applicable maximum chopping number is thus,

$$\lambda_{maxr} = A + Bt_{ar} + 2S_e \quad \text{(E.11)}$$

This value is then used in equation (E.7) to derive k_{amaxr}. Finally, k_{pmax} and k_{smax} are derived using equation (E.9) and equation (E.10), respectively.

E.2.4 Evaluation of recovery voltage stress across circuit breaker

The maximum recovery voltage across the circuit breaker (k_{rvmax}) in per-unit value is given by the following:

for directly grounded reactors (refer to 4.2)

$$k_{rvmax} = 1 + k_{amax} \quad \text{(E.12)}$$

for ungrounded reactors (refer to 4.3)

$$k_{rvmax} = 2 + k_{amax} \quad \text{(E.13)}$$

for neutral reactor grounded reactors (refer to 4.4)

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$$k_{rvmax} = 1 + 2k + k_{amax} \quad \text{(E.14)}$$

E.3 Case studies

The case studies are based on laboratory tests carried out on a single interrupter SF_6 circuit breaker in a single phase 50 Hz test at 98 A and 175 kV. The tests are analyzed as described in E.2 and are then applied to predict performance in a field installation with and without overvoltage limitation measures applied.

The arrangement for the laboratory test was as shown in figure E.1. The test interrupter was complete with a grading capacitor of 1600 pF. The chopped current values were not measured, but are derived using equation (E.2) where

C_L is 7520 pF
L is 5.68 H
V_o is $0.098 \cdot 314 \cdot 5.68 \cdot$ = 247 kV crest

Thus,

$$i_{ch} = 9\sqrt{k_a^2 - 1}$$

where

k_a is the measured suppression peak overvoltage value

The chopping number k is then calculated.

$$\lambda = \frac{i_{ch}}{\sqrt{C_t}} = \frac{i_{ch}}{\sqrt{7520 + 1600}} = 10471\, i_{ch}$$

The test and calculation results are tabulated in table E.1.

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Table E.1 —Single interrupter laboratory test values

t_a (ms)	k_a (pu)	i_{ch} (A)	λ ($A/F^{0.5}$)
6.2	1.26	6.9	72 239
5.3	1.09	3.9	40 872
4.3	1.07	3.4	35 873
11.9	1.4	8.8	92 335
11	1.42	9.1	95 008
10.3	1.38	8.6	90 050
9.4	1.32	7.7	80 627
8	1.24	6.6	69 108
7.3	1.2	5.9	61 779
6.2	1.18	5.6	59 033
5.2	1.09	3.9	40 872
4	1.08	3.7	38 442
11.6	1.38	8.6	89 621
10.8	1.49	9.9	104 094
10.3	1.41	8.8	92 335
9.2	1.24	6.6	69 097
8.2	1.2	6	62 511
7.1	1.22	6.3	65 860
3.8	1.08	3.7	38 442
12.9	1.34	8	84 058
4	1.07	3.4	35 873
3.9	1.12	4.5	47 532
4.1	1.09	3.9	40 872
4	1.07	3.4	35 873

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t_a (ms)	k_a (pu)	i_{ch} (A)	λ ($A/F^{0.5}$)
13.3	1.51	10.2	106 623
3.7	1.05	2.9	30 171
12.6	1.49	9.9	104 094
4.9	1.1	4.1	43 186
13.3	1.62	11.5	120 109
12.9	1.39	8.7	90 983
13.2	1.51	10.2	106 623
13.2	1.5	10	105 362
13.2	1.56	10.8	112 835
13.2	1.4	8.8	92 335

The derived chopping numbers are plotted against arcing time in figure E.2. A linear regression analysis, using the equations given in annex F or a computer spreadsheet program, gives the following equation:

$\lambda_{mean} = 10031 + 7226\ t_a$

and

$S_e = 8079$

This result is applied to predict the performance of a circuit breaker with two interrupters applied on a 60 Hz, 500 kV system to switch out a 525 kV, 135 Mvar shunt reactor. Performance is considered first for the directly grounded case without overvoltage limitation measures applied, with a surge arrester applied across the circuit breaker and finally, with controlled opening applied. Performance is then considered in a similar manner for the case where the neutral is grounded through a 1600 Ω neutral reactor.

Case 1: Directly grounded shunt reactor

Option 1.1: Without overvoltage limitation measures applied

The maximum chopping overvoltage will occur at the maximum arcing time. The maximum arcing time in the laboratory was 13.3 ms at 50 Hz, giving a corresponding value at 60 Hz of 11.6 ms. From equation (E.8), $\lambda_{max} = 10\ 031 + 7226 \cdot 11.6 + 2 \cdot 8079 = 11 \cdot 10^4$

Using equation (E.7),

$$k_{amax} = \sqrt{1 + \frac{3 \cdot (2)(11 \cdot 10^4)^2}{2 \cdot 377 \cdot 135 \cdot 10^6}}$$

$$= 1.31$$

$$k_{rvmax} = 1 + 1.31$$

$$= 2.31 \text{ pu}$$

To calculate the magnitude of the reignition overvoltages, from equation (E.11),

$\lambda_{maxr} = 10032 + 7226\ (11.6–8.33) + 2 \cdot 8079$

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$= 4.98 \cdot 10^4$

From equation (E.7),

$$k_{amaxr} = \sqrt{1 + \frac{3 \cdot (2)(4.98 \cdot 10^4)^2}{2 \cdot 377 \cdot 135 \cdot 10^6}}$$

$= 1.07$ pu

From equations (E.9) and (E.10),

$k_p = 1 + 0.5\ (1 + 1.07)$

$= 2.04$ pu

$k_s = (1 + 0.5)\ (1 + 1.07)$

$= 3.1$ pu

Option 1.2: Metal oxide surge arrester applied across the circuit breaker

The surge arrester is taken to have a protective level k_{arr} equal to 1.6 pu (refer to 5.3.2). The effect of the surge arrester on the circuit breaker is to limit the reignition voltage and tends to reduce the arcing time. The maximum arcing time will thus be 11.6 ms or less. Therefore

$k_{amax} \leq 1.31$ pu

$k_{rvmax} = 1.6$ pu

$k_{pmax} \leq 1 + 0.5 \cdot (1.6)$

≤ 1.8 pu

$k_{smax} \leq 1.6\ (1 + 0.5)$

≤ 2.4 pu

Option 1.3: Controlled opening applied to the circuit breaker

With controlled opening applied to the circuit breaker, the maximum chopping overvoltage is determined by the arcing time setting of the synchronizer to achieve no reignitions. A setting at 5 ms arcing time will allow some variation in mechanical opening time since the maximum arcing time with reignitions was 3.9 ms in the laboratory tests.

Again, from equation (E.8),

$\lambda_{max} = 10{,}031 + 7226 \cdot 5 + 2 \cdot 8079$

$= 6.23 \cdot 10^4$

$k_{amax} = 1.11$ pu

$k_{rvmax} = 2.11$

$k_{pmax} = 0$ pu

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k_{smax} = 0 pu

Case 2: Neutral reactor grounded shunt reactor

The inductance of the neutral reactor L_N is 4.24 H, L being 5.43 H. With reference to annex C,

$$K = \frac{1}{\frac{5.43}{4.24} + 2}$$

$$= 0.3$$

Option 2.1: Without overvoltage limitation measures applied.

From equation (E.7),

$$k_{amxax} = 1.3\sqrt{1 + \frac{3 \cdot (2)(11 \cdot 10^4)^2}{2 \cdot 377 \cdot 135 \cdot 10^6 \cdot 1.3}} - 0.3$$

$$= 1.32$$

$$k_{cmax} = 2 \cdot 0.3 + 1.32$$

$$= 1.92 \text{ pu}$$

$$k_{rvmax} = 1 + 1.92$$

$$= 2.92 \text{ pu}$$

From equation (7),

$$k_{amaxr} = 1.3\sqrt{1 + \frac{3 \cdot (2)(4.98 \cdot 10^4)^2}{2 \cdot 377 \cdot 135 \cdot 10^6 \cdot 1.3}} - 0.3$$

$$= 1.07 \text{ pu}$$

From equations (E.9) and (E.10),

$k_p = 1 + 0.5\ (1 + 2 \cdot 0.3 + 1.07)$

$= 2.33$ pu

$k_s = (1 + 0.5)\ (1 + 2 \cdot 0.3 + 1.07)$

$= 4$ pu

Option 2.2: Metal oxide surge arrester applied across the circuit breaker

The surge arrester is identical to that applied in option 1.2 above.

$k_{amax} \leq 1.32$ pu

$k_{cmax} \leq 0.6$

$k_{rvmax} = 1.6$ pu

$k_{pmax} \leq 1.8$ pu

$k_{smax} \leq 2.4$ pu

Option 2.3: Controlled opening applied to the circuit breaker

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$\lambda_{max} = 6.23 \cdot 10^4 k_a = 1.1$ pu

$k_{cmax} = 1.7$ pu

$k_{rvmax} = 2.7$ pu

$k_{pmax} = 0$ pu

$k_{smax} = 0$ pu

Case 1 overvoltage predictions are summarized in table E.2.

Table E.2 —Case 1 predicted overvoltage values

Option	Overvoltage (pu)			
	k_{amax}	k_{rvmax}	k_{pmax}	k_{smax}
1.1	1.31	2.31	2.04	3.1
1.2	≤ 1.31	1.6	≤ 1.8	≤ 2.4
1.3	1.11	2.11	0	0

The wet bias switching surge capability across the circuit breaker is 3.15 pu (1350 kV, 1 pu = 525 pu = $525\sqrt{2/3} = 428$ kV crest). Taking the position that the maximum allowable voltage across the circuit breaker shall not exceed 80% (i.e. 2.52 pu) of the withstand capability, the following can be concluded:

a) No overvoltage limitation measures are essential for the application of the proposed circuit breaker.
b) Some shunt reactor surge arrester operations will occur (protective level approximately 2 pu). The shunt reactor will be exposed to a maximum voltage excursion of 3.1 pu.
c) The relative merit of applying Options 1.2 and 1.3 is evident, both in terms of impact on the circuit breaker and the shunt reactor, respectively.

Case 2 overvoltage predictions are summarized in table E.3.

Table E.3 —Case 2 predicted overvoltage values

Option	Overvoltage				
	k_{amax}	k_{cmax}	k_{rvmax}	k_{pmax}	k_{smax}
2.1	1.32	1.92	2.92	2.33	4.0
2.2	≤ 1.31	≤ 0.6	1.6	≤ 1.8	≤ 2.4
2.3	1.1	1.7	2.7	0	0

Applying the same 2.52 pu maximum allowable voltage across the circuit breaker, the following can be concluded:

a) The circuit cannot be applied without some form of overvoltage limitation.
b) Option 2.2 can be applied without any further measures.
c) Option 2.3 can only be applied if the neutral reactor is bypassed prior to opening the circuit breaker, i.e. switching duty becomes identical to case 1, option 1.3.

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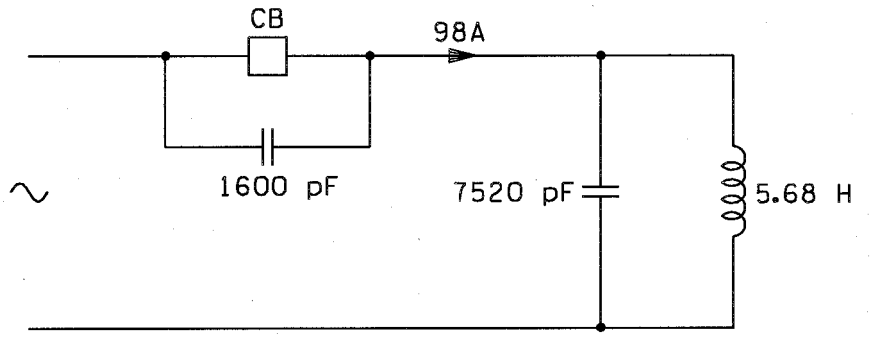

Figure E.1 —Case study laboratory test circuit

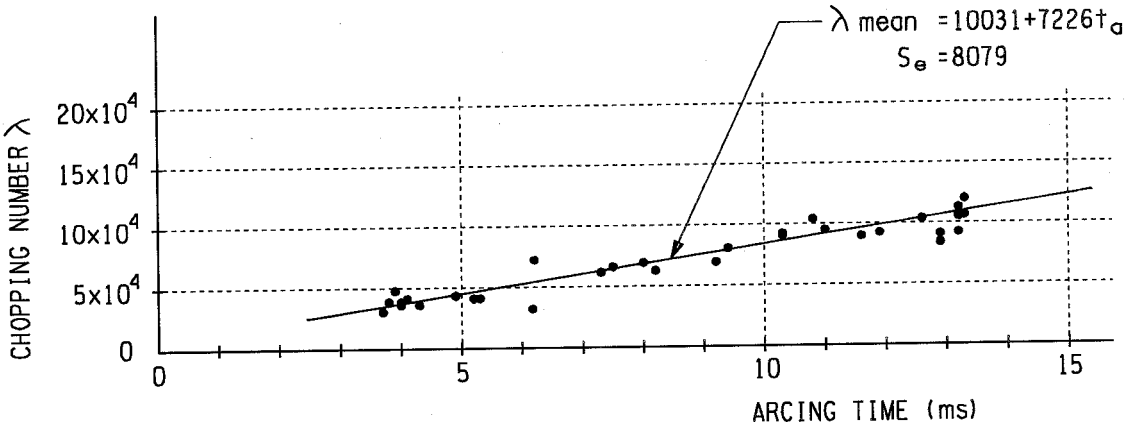

Figure E.2 —Linear regression analysis of test points derived in laboratory test

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Annex F Statistical formulas for derivation of chopping and reignition overvoltages (Informative)

F.1 General

The purpose of the annex is to provide, for convenience, the statistical formulas used in the derivation of chopping and reignition overvoltages.

F.2 Chopping number independent of arcing time

With reference to equation (E.4),

$$\lambda_{mean} = \frac{1}{n}\sum_{i=1}^{n}\lambda_i \tag{F.1}$$

and

$$\sigma^2 = \frac{n\sum_{i=1}^{n}\lambda_i^2 - \left(\sum_{i=1}^{n}\lambda_i\right)^2}{n(n-1)} \tag{F.2}$$

where

n is the number of test shots
λ_i is the chopping number corresponding to the ith test shot

F.3 Chopping number dependent on arcing time

Calculate values for S_{xx}, S_{yy}, and S_{xy} as follows:

$$S_{xx} = n\sum_{i=1}^{n}t_{ai}^2 - \left(\sum_{i=1}^{n}t_{ai}\right)^2$$

$$S_{yy} = n\sum_{i=1}^{n}\lambda_i^2 - \left(\sum_{i=1}^{n}\lambda_i\right)^2$$

$$S_{xy} = n\sum_{i=1}^{n}t_{ai}\lambda_i - \left(\sum_{i=1}^{n}t_{ai}\right)\left(\sum_{i=1}^{n}\lambda_i\right)$$

where n and λi are as noted above and t_{ai} is the arcing time corresponding to the ith test shot.

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With reference to equation (E.8),

$$B = \frac{S_{xy}}{S_{xx}} \tag{F.3}$$

$$A = \frac{1}{n}\sum_{i=1}^{n} \lambda_i - \left(\frac{B}{n}\right)\sum_{i=1}^{n} t_{ai} \tag{F.4}$$

$$S_e^2 = \frac{1}{n(n-2)}(S_{yy} - B^2 S_{xx}) \tag{F.5}$$

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Annex G Bibliography for the annexes

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