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# IEEE Guide for the Application, Operation, and Coordination of High-Voltage (>1000 V) Current-Limiting Fuses

IEEE Power & Energy Society

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Switchgear Committee

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## Introduction

This introduction is not part of IEEE Std C37.48.1-2011, IEEE Guide for the Application, Operation, and Coordination of High-Voltage (>1000 V) Current-Limiting Fuses.

During the process of determining the need for revising IEEE standards to include the category of "full-range" current-limiting fuses, users and specifiers, both at utilities and at manufacturers, were surveyed. This survey revealed that additional information to that then available from fuse standards needed to be made available to the specifiers and users of all types of high-voltage current-limiting fuses to avoid confusion between the different types, and their capabilities.

As a result, the High-Voltage Fuses Subcommittee of the IEEE Power & Energy Society's Switchgear Committee established a task force to develop additional standards information that would summarize pertinent information regarding current-limiting fuses in general and full-range fuses in particular. This task force became the working group on full-range fuses. With cooperation from the National Electrical Manufacturers Association (NEMA), it created a seminar, which formed the basis of the original (2002) edition of IEEE Std C37.48.1, an IEEE guide. This document contained additional application information, to that presented in IEEE Std C37.48, to detail the application and coordination of full-range and other current-limiting fuses. This revision updates the 2002 edition.

The present revision was prepared by the Revision of Fuse Standards Working Group of the High-Voltage Fuses Subcommittee.

This guide is one of a series of complementary standards covering various types of high-voltage fuses and switches, so arranged that two of the standards apply to all devices while each of the other standards provides additional specifications for a particular device. For each device, IEEE Std C37.40™, IEEE Std C37.41™, plus the standard covering that particular device constitute a complete set of standards for each device. In addition, IEEE Std C37.48 is an application, operation, and maintenance guide for all of the devices, and this guide provides additional guidelines, more specifically for current-limiting fuses.

The following standards comprise this series:

IEEE Std C37.40™, IEEE Standard Service Conditions and Definitions for High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.

IEEE Std C37.41™, IEEE Standard Design Tests for High-Voltage (>1000 V) Fuses, Fuse and Disconnecting Cutouts, Distribution Enclosed Single- Pole Air Switches, Fuse Disconnecting Switches, and Fuse Links and Accessories Used with These Devices.

IEEE Std C37.42™, IEEE Standard Specifications for High-Voltage (>1000 V) Expulsion-Type Distribution-Class Fuses, Fuse and Disconnecting Cutouts, Fuse Disconnecting Switches, and Fuse Links and Accessories Used with These Devices.

IEEE Std C37.43™, IEEE Standard Specifications for High-Voltage Expulsion, Current-Limiting, and Combination-Type Distribution and Power Class External Fuses, with Rated Voltages from 1 kV through 38 kV, Used for the Protection of Shunt Capacitors.

IEEE Std C37.45™, IEEE Standard Specifications for High-Voltage Distribution Class Enclosed Single-Pole Air Switches with Rated Voltages from 1 kV through 8.3 kV.

IEEE Std C37.46™, IEEE Standard Specifications for High Voltage (>1000 V) Expulsion and Current-limiting Power Class Fuses and Fuse Disconnecting Switches.

IEEE Std C37.47™, IEEE Standard for Specifications for Distribution Fuse Disconnecting Switches, Fuse Supports, and Current-Limiting Fuses.

IEEE Std C37.48™, IEEE Guide for Application Operation, and Maintenance of High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.

IEEE Std C37.48.1™, IEEE Guide for the Application, Operation, and Coordination of High-Voltage (>1000 V) Current-Limiting Fuses.

## Contents

# IEEE Guide for the Application, Operation, and Coordination of High-Voltage (>1000 V) Current-Limiting Fuses



## 1. Overview

### 1.1 Scope

This guide provides information on the application, operation, and coordination of high-voltage (>1000 V) fuses and associated equipment. The information supplements that presented in IEEE Std C37.48™.[1] These guidelines apply to the following specific types of equipment, intended for use on alternating current distribution and power class systems:

a) Distribution and power class current-limiting type fuses.

b) Distribution and power class current-limiting fuse disconnecting switches.

c) Items a) and b) used in fuse enclosure packages.

d) Fuse supports of the type intended for use with distribution and power class fuses, and fuse disconnecting switches.

e) Disconnecting devices created by the use of a removable switch blade in a distribution or power class fuse support.

f) Distribution class and power class current-limiting, and combination types of external capacitor fuses used with a capacitor unit, groups of units, or capacitor banks.

g) Backup current-limiting fuses ("motor-starter fuses") used in conjunction with high-voltage Class E2 motor starters (see ANSI/UL 347 [B1][2]).

[1] Information on references can be found in Clause 2.

[2] The numbers in brackets correspond to those of the bibliography in Annex B.

## 1.2 Purpose

The purpose of this guide is to expand on aspects of the general fuse application guide, IEEE Std C37.48, in areas associated with the application and coordination of high-voltage (>1000 V) current-limiting fuses. This guide is more "tutorial" in nature than IEEE Std C37.48, and includes descriptions as to how different types of fuses work. It was developed to create a better understanding of how most fuse types operate, but with an emphasis on current-limiting fuses after the category "full-range" was added to the existing categories of "backup" and "general-purpose" current-limiting fuses.

## 1.3 Background

In order to fully understand the behavior of current-limiting fuses and the application relationship between them and other types of fuses which do not significantly limit the first peak of current (hereafter referred to as expulsion and other types of non-current-limiting fuses), a number of references to these "other" types of fuses will be made. It is not the intent of the authors of this guide to claim that any type of fuse is inherently "better" or "worse" than any other. The intent is to present design and operating characteristics of, as well as application guidelines for, current-limiting fuses. However, since such fuses are used on the same system as, and are coordinated with, expulsion and other types of non-current-limiting fuses, some discussion of their design and operating characteristics is also appropriate.

In all cases, it is of particular importance to follow the specific application guidelines published by the manufacturer of any particular device to be used. The manufacturer's guidelines should always take precedence over the opinions expressed in this guide, which are, of necessity, something of a generalization.

Some of the current-limiting type fuses listed in 1.1 are similar to those now covered in IEC 60282-1. However, differences exist in the testing requirements of IEC, IEEE, and ANSI. IEEE fuse standards primarily reflect applications common in North America and in countries that use electrical systems designed using similar principles. IEC standards tend to rely heavily on practices common in Europe. Since IEC testing differences include testing at different voltages for the same fuse rated voltage, and different or no testing for fuses intended for use in a surrounding temperature above 40 °C, the user is advised to exercise caution if devices specified and tested per IEC standards are compared with those specified and tested per IEEE and ANSI standards. The differences in test requirements may result in devices tested to IEC not being suitable for applications where devices tested to IEEE and ANSI standards are required, or vice versa.

In the headings and the text of this document, there are some areas where information is included in brackets [ ]. The information in the brackets is a term used in IEC standards that may be similar to the term used in this document, a term that is common in some parts of the world, or a term that has been used previously in IEEE or ANSI standards. Caution is again advised when making comparisons.

## 1.4 Description of fuse enclosure packages (FEPs) using current-limiting type indoor distribution-class and power-class fuses

— Type 1CL: A fuse mounted in a large enclosure with relatively free air circulation within the enclosure (e.g., a fuse mounted in a live-front pad mounted transformer or in a vault). The relevant fuse rated maximum application temperature (RMAT) is based on that of the air that is cooling the fuse. It may be noted that, if a fuse were mounted outdoors but in an ambient temperature above 40 ºC, conditions on the fuse would be the same.

— Type 2CL: A fuse mounted in a fuse container. This is a relatively small enclosure, defined as one supporting the fuse and restricting the air, gas or liquid flow surrounding the fuse (e.g., a fuse inside a canister in a transformer or a vault). However, the fluid flow (gas, liquid, or a combination

of the two) that cools the outside surface of the container has relatively free circulation. The relevant fuse RMAT is based on that of the fluid that is cooling the container. Fuses tested in accordance with IEEE C37.41 for use in air no hotter than 40 ºC that are encapsulated with solid insulation (e.g., rubber or epoxy) can be considered to be this type of FEP when so encapsulated. In this case the relevant fuse RMAT is based on that of the fluid that is cooling the encapsulated fuse.

— Type 3CL: A fuse directly immersed in liquid and mounted in an enclosure with relatively free liquid circulation around the fuse (e.g., an oil-immersed fuse in a transformer or switchgear enclosure). The relevant RMAT is based on that of the liquid that is cooling the fuse.

NOTE— In the versions of IEEE/ANSI fuse standards approved before 2008, FEPs using current-limiting fuses were designated as being of types 1C through 5C. In order to simplify FEP types, include additional types, and align with IEC practice, these types have been rationalized into three categories. Type 2CL includes the former types 2C, 3C and 4C, while type 3CL is the same as type 5C.[2]

## 2. Normative references

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

IEC 60282-1, High-voltage fuses—Part 1: Current-limiting fuses.[3]

IEEE Std C37.40™, IEEE Standard Service Conditions and Definitions for High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.[4,5]

IEEE Std C37.41™, IEEE Standard Design Tests for High-Voltage (>1000 V) Fuses, Fuse and Disconnecting Cutouts, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Fuse Links and Accessories Used with These Devices.

IEEE Std C37.42™, IEEE Standard Specifications for High-Voltage (>1000 V) Expulsion-Type Distribution-Class Fuses, Fuse and Disconnecting Cutouts, Fuse Disconnecting Switches, and Fuse Links and Accessories Used with These Devices

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IEEE Std C57.91™-1995, IEEE Guide for Loading Mineral-Oil-Immersed Transformers.

[2] Notes in text, tables, and figures of a standard are given for information only, and do not contain requirements needed to implement the standard.
[3] IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://wwwiec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.
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IEEE Std C57.93™-2007, IEEE Guide for Installation and Maintenance of Liquid-Immersed Power Transformers.

IEEE Std C57.109™-1993, IEEE Guide for Liquid-Immersed Transformers Through-Fault-Current Duration.

IEEE Std 141™-1993 (R1999), IEEE Recommended Practice for Electric Power Distribution for Industrial Plants (IEEE Red Book™ ).

IEEE Std 399™-1997, IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis (IEEE Brown Book™).

## 3. Acronyms and abbreviations

$A^2s$ ampere-squared-seconds (unit of $I^2t$)

FEP fuse enclosure package

RMAT rated maximum application temperature

TCC time-current-characteristic

## 4. Fuse operation

### 4.1 Introduction

An enormous variety of fuses are available today. They are used as a reliable means of protecting and/or limiting damage to apparatus from overcurrents in both low- and high-voltage systems. This guide is limited to high-voltage (>1000 V) current-limiting fuses intended for use in alternating current circuits.

Before different types of high-voltage fuses are examined in detail, a summary of the essential characteristics common to all fuses will be presented. These are the thermal characteristics (current rating and melting characteristics) and interrupting characteristics (voltage rating and interrupting ratings).

Discussion will then proceed to introduce a fundamental comparison of power-class versus distribution-class fuses and current-limiting versus expulsion and other types of non-current-limiting fuses.

### 4.2 Thermal characteristics

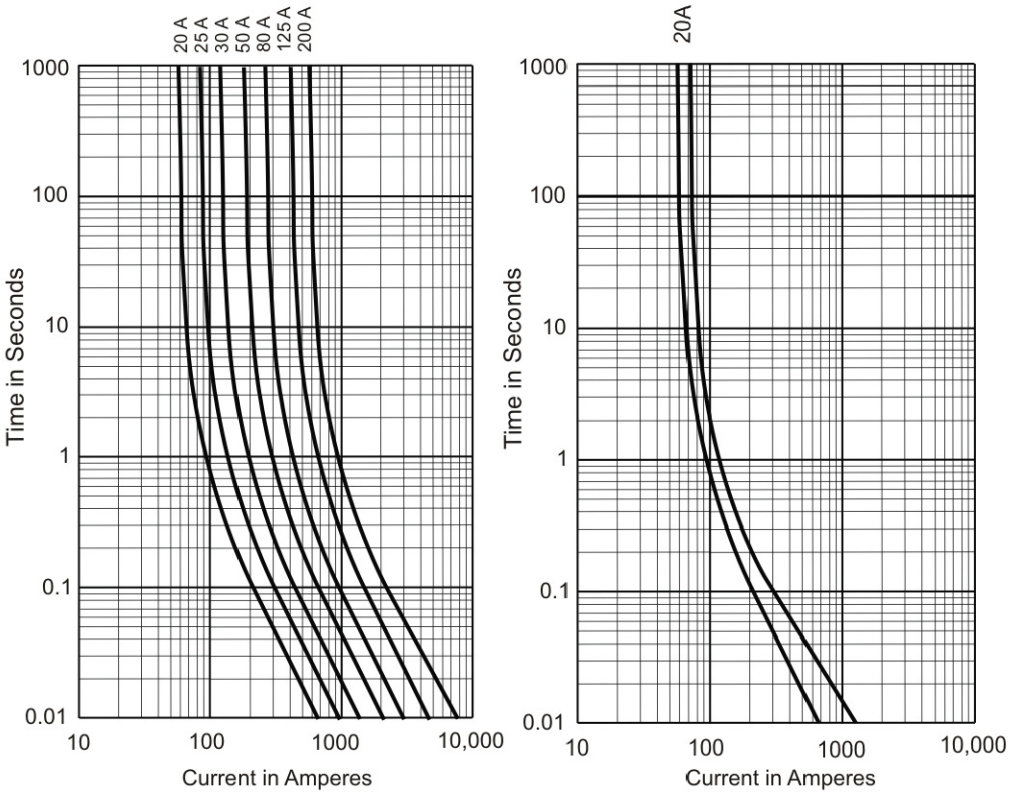
Despite the variety of types, all true fuses, by definition, are devices that open a circuit with a fusible part, which is heated and severed by current flowing through it. This fusible part is called the “element.” When current flows through a fuse, heat is generated and its element temperature rises. For a current less than or equal to its rated continuous current (the “name-plate” current rating), temperatures rise until a steady-state condition is reached in which the heat generated equals the heat dissipated. At rated continuous current, fuses conforming to the IEEE/ANSI C37 series of standards will have temperature rises within the limits specified in IEEE Std C37.40.

When a current (higher than rated continuous current) flows through the fuse, the temperature of the element will rise. For some higher currents, steady-state conditions may again be achieved, but at a higher temperature. This temperature may exceed the values specified for a fuse carrying its rated continuous

current. Whether such a situation is acceptable, or must be avoided, will depend on the fuse type and the application. A discussion of fuse types and typical applications is presented in Clause 5 and Clause 6. At some point in time, if the current has sufficient magnitude, the higher current will cause the fuse element to melt before steady-state temperature conditions are achieved. After melting, the fuse must interrupt the current, as discussed in 4.3.

For a given fuse, the relationship between the magnitude of the current that causes melting and the time needed for it to melt is given by the fuse's melting time-current-characteristic (TCC), usually shown as a TCC curve plotted on log-log graph paper. The curve is produced from time-current tests, which are specified in IEEE Std C37.41. They are performed with constant current applied to the fuse, in an ambient temperature between 20 °C and 30 °C, with the fuse carrying no initial current. IEEE Std C37.41 specifies that a melting TCC is to be drawn showing the minimum-melting time of a fuse (including an allowance for the manufacturer's minus variations—for manufacturing tolerances etc.) when carrying symmetrical current.

The typical shape of a fuse's melting TCC is shown in Figure 1A. The severing of a fuse element is caused by predominantly thermal, rather than mechanical means, so there is virtually no limit on how short the melting time can be. This very fast operation (melting) of a fuse at very high currents tends to be a distinguishing characteristic of fuses compared to most other protective devices.




**1A:** Typical minimum melting time-current-characteristic curves (for 25 °C). Any variation should be positive (above and to the right of the curves)

**1B:** Typical minimum melting and total clearing time-current-characteristic curves for a 20 A fuse. Any variation for the total clearing TCC should be negative (below and to the left of the curve).

**Figure 1—Typical minimum melting and total clearing time-current-characteristic curves**

A fuse has a long melting time at a low current because the low rate of heat input into the element is only slightly greater than the rate of heat loss from the element. As a result, the temperature of the element will increase slowly. As current increases, the melting time becomes shorter, not only because of the higher rate of heat input but also because the heat being produced in the areas with reduced cross section, and/or in the center of the elements, cannot be removed as fast as it is being produced. This gives fuses very inverse melting characteristics. At very short melting times, no heat is lost from the smallest cross section of the element. The melting $I^2t$ is, therefore, constant within this range. $I^2t$, or actually $\int i^2 dt$, is a value proportional to the heating effect of a current of a particular rms value and duration. When $I^2t$ is multiplied by a resistance value through which it "flows," the energy (heat) generated in that resistance is obtained. $I^2t$, expressed in units of ampere-squared seconds ($A^2s$), is a useful concept for fuse-to-fuse and fuse-to-equipment protection and coordination, and will be discussed in various subclauses (e.g., see 7.2.4.2).

## 4.3 Interrupting characteristics

After the fuse element melts, the fuse must interrupt the current (which continues to flow through an arc). After interruption, the fuse must withstand any immediate transient recovery voltage (TRV) condition and the subsequent steady-state recovery voltage. When a fuse melts, there will always be some period of arcing before the current is interrupted. The melting time (adjusted by an allowance for the manufacturer's plus variations for manufacturing tolerances, etc.) is added to this arcing period to obtain the total-clearing time. Total-clearing TCC curves are drawn to present this information. Normally, at long melting times, arcing as a portion of total clearing time is negligible, while at short melting times it can be significant. Thus, for a given fuse, the minimum-melting TCC curve and the total-clearing TCC curve tend to diverge at shorter times (higher currents), as illustrated in Figure 1B, which shows the minimum-melting and total-clearing time-current-characteristic curves plotted for the same fuse.

The two TCC characteristics described are used to coordinate with comparable characteristics of other fuses or protective devices to selectively isolate faulted circuits and to protect equipment. This is a very important consideration in the operation of electric systems.

In addition to TCC curves, a CL fuse manufacturer is required to present maximum and minimum $I^2t$ information for their fuses, likely to be experienced in service. In addition to "minimum melting [pre-arcing] $I^2t$" discussed in 4.2, which represents the smallest $I^2t$ to melt the fuse (at the maximum rated interrupting current, and with minimum manufacturing tolerances), the highest $I^2t$ let through by the fuse at any current that causes a current-limiting action is called the "maximum clearing $I^2t$ ". It is the sum of the melting $I^2t$ and arcing $I^2t$ (arcing $I^2t$ being that which "flows" during the time when the fuse is arcing), and can occur at any current up to the rated maximum interrupting current of the fuse, depending on fuse design. Other terms that have been commonly used for maximum clearing $I^2t$ include "maximum operating $I^2t$", "maximum let-through $I^2t$", "total $I^2t$ value", maximum total $I^2t$, and "total clearing $I^2t$". The presentation of $I^2t$ values may be in simple tabular or diagrammatic form (for example, histograms) or may employ graphical presentation with prospective current as abscissa and $I^2t$ as ordinate, both scales being logarithmic.

In addition to rated current, a fuse has a rated maximum voltage. This is the highest voltage at which the fuse is designed to operate, and it is important that a fuse not be called upon to interrupt current at a higher voltage.

A fuse manufacturer assigns a rated maximum interrupting current to a fuse, based on the highest current at which testing (per relevant standard requirements) has been performed. In addition, some fuses also have a rated minimum interrupting current. This is the lowest current that the fuse manufacturer assigns for successful interruption, based on testing, (while this is not necessarily the lowest current that it can actually interrupt, its application should not assume any lower current interrupting capability). A fuse may not function as intended, with potentially serious results, when attempting to interrupt outside its maximum and minimum interrupting rating.

## 4.4 Comparison of power fuses versus distribution fuses

Both current-limiting and expulsion fuses are classified by IEEE C37 standards as either power-class or distribution-class fuses. The differentiation between the two classes reflects the different system conditions that exist where fuses are normally applied on a power system based on specific requirements for generating sources, substations, and distribution lines. Testing of each fuse type and class must follow particular requirements detailed in IEEE Std C37.41 together with individual specification requirements listed in IEEE Std C37.42, IEEE Std C37.43, IEEE Std C37.45, IEEE Std C37.46, and IEEE Std C37.47. Such specifications include, for example, maximum peak overvoltages for current-limiting fuses and dielectric test voltages for fuse supports. A comparison of some of these specifications is given in Table 1. Power-class fuses are tested to TRVs and *X/R* ratio values more likely to be encountered in or near the generating source or substation and on three-phase circuits. Distribution fuses have specifications more closely matched with requirements of the distribution system, further away from the source or substation on single or three-phase circuits.

**Table 1—Comparison of IEEE fuse specifications**

| Requirement | IEEE Std C37.42 distribution class expulsion fuses | IEEE Std C37.46 power class expulsion and current-limiting fuses | IEEE Std C37.47 distribution class current-limiting fuses |
|---|---|---|---|
| Rated maximum voltage—kV | 5.5 to 38 | 2.8 to 169 | 2.8 to 38 |
| Rated continuous current—Amps | to 200 | to 700 | to 200 |
| Rated maximum interrupting current—kA Sym. | 0.75 to 16 | 1.25 to 80 | 12.5 to 125 |
| *X/R* ratio at rated maximum interrupting current | 1.33 to 15 | ≥ 15 | ≥10 |

Because current-limiting fuses are relatively insensitive to high *X/R* ratios, the performance difference between power-class and distribution-class current-limiting fuses is generally not significant. The basis for current-limiting fuse function, at high currents, involves inserting a high resistance into the faulted circuit, which forces the power factor of the circuit as a whole toward unity. Thus, a distribution current-limiting fuse can often be applied at or near generating sources and substations; consult the manufacturer for more information.

## 4.5 Comparison of current-limiting versus expulsion and other types of non-current-limiting fuses

All fuse types have the following characteristics, namely:

a) They can carry continuous current.

b) They are intended to interrupt abnormal overcurrents and isolate circuits. Their melting and interrupting time characteristics can be coordinated with those of other circuit overcurrent protective devices.

c) They all interrupt the circuit at a modified or normal current zero, by having a dielectric recovery that is greater than the TRV imposed by the power distribution system, thus limiting the duration of a fault or overload current.

d) They all dissipate the arc energy released in the fuse to reduce the likelihood of thermal breakdown after current zero.

However, there are other interrupting characteristics that divide fuses into separate types. The differences are primarily seen when the current is such that fuse melting occurs before the first major peak of a fault current. Expulsion and other types of non-current-limiting fuses essentially allow the full peak of the

available fault current to pass until the current is interrupted at a normal current zero of the circuit. Figure 2a shows an expulsion fuse melting under these conditions. There is no significant arc resistance and so no significant arc voltage. As a result the current that flows is almost the same as if the fuse had not melted. At the first natural current zero, the arc is extinguished (as at every current zero). If the dielectric strength of the gap in the fuse, produced by the arcing, is sufficient to withstand the circuit recovery voltage (including any transient caused by parallel circuit capacitance) the current is not re-established (as seen in Figure 2a). In practice, whether additional loops of current flow depends on factors such as the fault-current magnitude, the fault initiation timing, and the fuse size and design. Because the circuit's normal current zero is typically not close to the voltage zero, a high TRV may occur. Common examples of fuses that exhibit this behavior are expulsion, vacuum, $SF_6$, boric acid, liquid, and some electronically-actuated fuses.

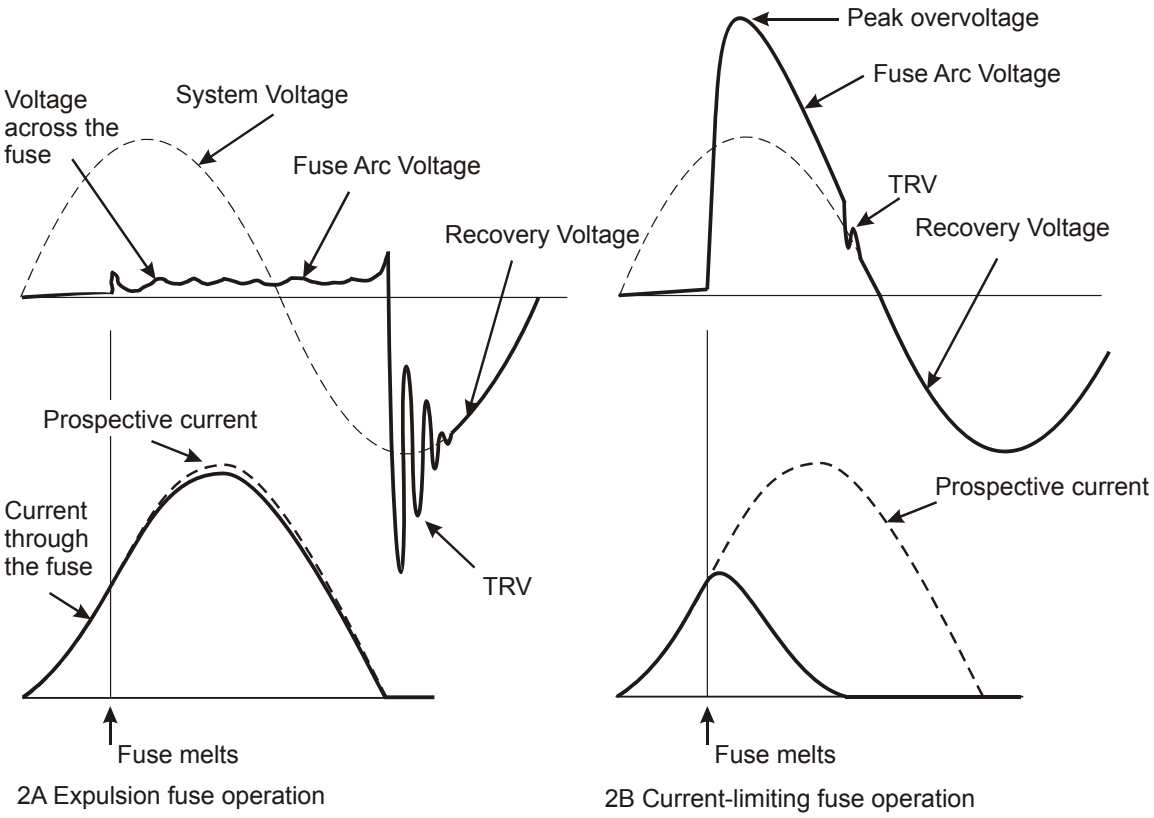



**Figure 2—Expulsion fuse and current-limiting fuse operation**

Current-limiting fuses, by contrast, can limit faults in magnitude and duration when they melt before the first major peak of the fault current. A current-limiting or "current zero forcing" fuse begins limiting the rising fault current as soon as its element melts and thus prevents the current from reaching its prospective peak value. The current-limiting action results from melting of a rather long fuse element that interacts with the constraining and cooling medium (typically sand), to introduce a quickly rising equivalent resistance into the fault circuit. Figure 2b shows a current-limiting fuse carrying a fault current that causes it to melt before the first peak. As soon as the fuse arc voltage equals the system instantaneous voltage, the current peak occurs. After this the current falls and the fuse arc voltage exceeds the system voltage because circuit inductive voltage opposes the falling current and adds to the system voltage. The fuse changes a high-current, low power factor fault circuit into a lower current, higher power factor circuit. As a result, the current is forced to near zero well before the normal current zero of the circuit and close to the voltage zero. This typically occurs within less than 1/2 cycle of the fault initiation. Because the current zero is moved close to the voltage zero, low TRVs result. The operation of current-limiting fuses will be expanded upon in 4.6.2. The various types of current-limiting fuses include commutating, as well as non-commutating, electronically actuated fuses.

For a more thorough explanation of fuse theory, see Annex A.

The energy released into the fault is proportional to the duration of the fault and square of the fault current (or $I^2t$). This energy is primarily responsible for the destructive effects of faults. Current-limiting fuses significantly reduce these effects. Mechanical forces due to magnetic effects of peak currents are also limited. The reduced fault current and duration result in lower stress on all of the equipment that makes up the protected circuit when a fault is cleared by a current-limiting fuse. Other distinguishing characteristics of current-limiting fuses are that they are virtually noiseless and do not usually discharge arc products. For some applications, these factors are an important consideration in fuse selection. Additional features provided by each fuse type are referenced in 4.6.

## 4.6 Fuse construction and operation

### 4.6.1 General

In the preceding paragraphs, arc voltage has been shown to be the primary criterion that differentiates various types of fuse. Table 2 compares other characteristics (under high-current-interrupting conditions) for various types of fuse.

**Table 2— Fuse characteristics and types of fuses**

| Characteristic | Expulsion, vacuum, oil fuse cutout, $SF_6$ | Current-limiting, commutating, current-limiters, triggered fuses |
|---|---|---|
| Arc voltage | Lower | Higher |
| Circuit modifying | No | Yes |
| Current zero shifting | No | Yes |
| Max. interrupting current | Lower | Higher |
| Let-through current | Full available current | Current is limited |
| Fault duration | One loop (1/2 cycle) or more | 1/8 to 1/2 cycle |
| Energy absorbed by fuse | Small amount | Substantial amount |
| Clearing $I^2t$ | Substantial | Small |
| Recovery voltage | Transient—up to twice power frequency crest | Equal to power frequency crest |
| Sub-classifications | | Backup, general-purpose, full-range (apply to current-limiting only) |
| Continuous operating loss | Low | Higher for standard CLF; Lower for commutating current-limiters and triggered fuses |
| Continuous current rating | Higher | Lower for standard CLF; Higher for commutating current-limiters and triggered fuses |

### 4.6.2 Current-limiting fuses

#### 4.6.2.1 General

The effects of high-magnitude arc resistance and arc voltage and how they act to modify the fault circuit were reviewed in 4.5. Subclause 4.6.2 reviews the means by which this resistance and arc voltage are achieved and controlled in the design of current-limiting fuses. It also reviews various types and classes of these devices.

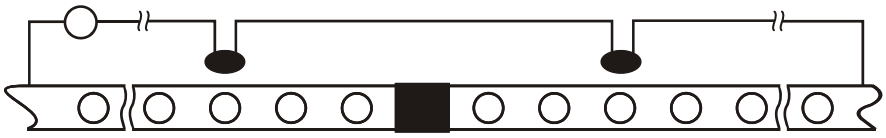
#### 4.6.2.2 The fusible element and establishment of high arc voltage

The conducting, fusible elements of current-limiting fuses are commonly made of high conductivity materials such as silver or copper, which are supported within the fuse body and surrounded with high-purity quartz sand. A section of a typical current-limiting fuse element is shown in Figure 3a. When a current-limiting fuse melts at high fault currents the conducting element is segmented into many portions. This segmenting will occur at holes or notches that form restrictions in the current path of the conducting elements. These restrictions are common in higher continuous current designs. Uniform cross section elements (such as wire elements), common in lower continuous current designs, melt and form a multiplicity of bead-like segments. The melted portions of the element are vaporized and diffused into the surrounding sand. At each segment an arc will form. The sum of the voltage drop components of the arc (anode, cathode, and positive column voltage) are referred to as the arc voltage. The arc voltage of a current-limiting fuse is the sum of the arc voltages of the individual arcs. By comparison, expulsion and other types of non-current-limiting fuses generally employ one arc gap.

a. Basic fuse element for a backup fuse

b. Typical “dual element” design for a full-range fuse, with added low current element.

c. Element with a solder overlay and auxiliary arcing wire for a general-purpose fuse.



d. Element for full-range fuse that uses pyrotechnic charges to cut element in several places.

**Figure 3—Construction features typical of various types of current-limiting fuse elements**

In the case of a current-limiting fuse, the arcs are highly confined, constricted and cooled by the surrounding sand. This constriction and effective cooling leads to a high arc voltage, and a high ratio of arc resistance to arc length, which, together with substantial element lengths leads to a high arc resistance. This greatly impedes the continuing flow of fault current. The surrounding sand is melted by the intense heat of the arc, thus absorbing large amounts of energy. If the arc voltage from one melted point is multiplied by the number of segments formed in the fuse, we find that a very substantial arc voltage can be produced. Immediately after melting, the arc voltage is primarily a function of the number of melted segments and associated arcs. The peak arc voltage occurs shortly thereafter and is also a function of arc length, as well as the number of arcs.

If we refer back to Figure 2B, we can see how the magnitude and the area under the arc voltage curve determines how quickly the total current can be reduced and the current zero moved. The fuse design should maintain the high arc voltage during the interrupting process to maximize the current reduction and limit the fault damage. This is made possible by continued burn back of the element between the segments and continued heat transfer from the molten and vaporized fuse element into the sand. Because of the high resistance imposed by the current-limiting fuse, the current is brought nearly back into phase with the system voltage. In time, the remainder of the fuse element may melt to form a single arc, reducing arc voltage somewhat. Also, increasing arc length only partly compensates for the reduced heat transfer to the now heated surroundings, so that the arc voltage tends to decrease with time until the arc ceases to exist. At this point, resistance increases rapidly, and the fuse must withstand a recovery voltage equal to system voltage.

#### 4.6.2.3 Overvoltages

The insulation requirements of any electrical system and apparatus impose a limitation on the permissible magnitude of an arc voltage. Table 3 gives arc voltage limits specified in IEEE Std C37.46 and IEEE Std C37.47.

**Table 3—Maximum permissible overvoltages for distribution-class and power-class current-limiting fuses**

| Rated maximum voltage (kV, RMS) | Maximum Peak Overvoltage (kV, peak) | | | |
|---|---|---|---|---|
| | From IEEE Std C37.47 | | From IEEE Std C37.46 | |
| | Fuse rated current through 12 A | Fuse rated current over 12 A | Fuse rated current through 12 A | Fuse rated current over 12A |
| 2.54 – 2.8 | 13 | 9 | 13 | 9 |
| 5.08 – 5.5 | 25 | 18 | 25 | 18 |
| 8.3 | 38 | 26 | 38 | 26 |
| 15.0 – 17.2 | — | — | 68 | 47 |
| 15.5 – 17.2 | 70 | 49 | 70 | 49 |
| 23 (21-22) | 105 | 72 | 105 | 72 |
| 25.8 | — | — | 117 | 81 |
| 27 | 123 | 84 | 123 | 84 |
| 38.0 | 173 | 119 | 173 | 119 |

Control of the arc voltage is accomplished by limiting the element length and the number of arc initiating restrictions, and subsequent arcing segments, in ribbon element fuses. For a wire element fuse the arc voltage is controlled essentially by its length and diameter (multiple series sections of different diameters can be used to control arc voltage). As seen in Table 3, higher arc voltage limitations are permitted for the lower continuous current fuses where wire designs are prevalent. However, it should be borne in mind that the permitted high values usually persist for a much shorter duration than do the lower values produced by higher current rating fuses.

Accordingly, the permissible peak arc voltages are approximately three times the system rms voltage for fuses with rated currents over 12 A and approximately five times rated rms voltage for fuses with lower rated currents. Experience has shown this is an acceptable number complying with insulation requirements while resulting in rapid current limitation and relatively low energy let-through during the interruption process.

Consideration of peak overvoltage can be important when applying current-limiting fuses and lightning arresters on the same circuit (see 7.5). The overvoltage produced by a current limiting fuse could cause the arrester to begin to conduct, placing thermal stress on the arrester. The values detailed in Table 3 result in a level of stress low enough for the arrester to withstand. The lower voltage, longer duration voltage peak for higher current rating fuses and the higher voltage, shorter duration voltage peak for small current ratings have demonstrated, through testing and years of field experience that arresters and current-limiting fuses work well together.

#### 4.6.2.4 Heat dissipation

To obtain high arc voltage during interruption, current-limiting fuses use relatively long fuse elements with comparatively high resistance, as contrasted with the shorter element used in expulsion and other types of non-current-limiting fuses. The continuous losses of the former are, therefore, higher. This may limit their use in environments where heat dissipation is a problem. This is covered in greater detail in Clause 6.

#### 4.6.2.5 Fuse voltage versus system voltage

Successful interruption by a current-limiting fuse requires that the arcing resistance of the fuse be sufficient to modify the fault circuit and create a timely current zero. This means that the fuse element and fuse arc voltage must be configured for a particular circuit voltage. A current-limiting fuse must never be applied such that it is required to interrupt a voltage higher than its rated maximum voltage. If it is applied at a higher voltage, the result is likely to be a failure to interrupt, usually accompanied by physical destruction of the fuse. Conversely, caution should also be used when applying current-limiting fuses at voltages substantially below their rating in order to avoid overvoltage damage to power system components. This is because certain fuse designs (particularly those employing wire type elements) produce arc voltages substantially independent of the applied voltages. Other designs, while producing a lower arc voltage at a reduced applied voltage, may still produce significantly higher arc voltage than fuses designed specifically for the lower voltages. Before applying fuses at voltages substantially below their rating, consult the manufacturer.

#### 4.6.2.6 Energy absorption during interruption

A current-limiting fuse does not normally absorb maximum energy at the rated maximum interrupting current, but often at a substantially lower value of fault current. Under maximum fault conditions, the fuse element melts quickly and produces a sharp reduction of the available fault current, limiting the arc energy. As the prospective current is reduced (at the same *X/R*), circuit inductance is higher and the circuit stored energy at the start of arcing ($\frac{1}{2}L\,i^2$) is higher. Under severe circuit conditions, particularly those at voltage zero initiation (high asymmetry), melting and burn back are slower while the system voltage is near its

maximum at the start of the arcing, reducing the rate of decrease of current. Although the peak current through the fuse is lower with reducing prospective current, the current remains relatively high for a longer period of time. The fuse must, therefore, absorb more energy. When the prospective current is sufficiently low, most of the arcing occurs after the peak of the system voltage, making interruption for the fuse easier and reducing arc energy. Current-limiting fuses therefore tend to exhibit maximum arc energy absorption, around a particular current level, sometimes called "critical current". IEEE Std C37.41 specifies testing at this level of current (often termed "$I_2$").

#### 4.6.2.7 Low-current interrupting limitations

When a fuse element, designed to successfully interrupt high currents, is melted by a relatively low current, the fuse may experience difficulty interrupting. This is because, at high currents, all the series restrictions in a notched element, or the whole length of a wire element, tends to melt nearly simultaneously. At a much lower current, the element may melt in only one location, producing a low arc voltage. Although a single arc will elongate with subsequent cycles of arcing, and its resistance and arc voltage will increase, it has been found that with most practical designs of fuses, a single plain element in quartz sand will be unable to successfully interrupt against a system voltage higher than a few thousand volts, under these conditions. As a result, a higher element current density, which produces multiple arcs, is necessary for successful interruption with such a fuse. For this reason, many fuse designs exhibit a minimum interrupting rating, as has been mentioned previously. However, numerous techniques have been developed to enable current-limiting fuses to interrupt currents lower than those that cause a current-limiting action to occur, leading to three classes of current-limiting fuse.

A backup current-limiting fuse (see 5.3.2) is defined as being a fuse capable of interrupting all (continuous) currents from its rated maximum interrupting current down to its rated minimum interrupting current. (It should normally be applied in conjunction with a second, series interrupting device). A general-purpose fuse (see 5.3.3) is capable of interrupting all currents from the rated maximum interrupting current down to the current that causes melting of the fusible element in 1 hour. A full-range fuse (see 5.3.4) is capable of interrupting all continuous currents from the rated maximum interrupting current down to the minimum continuous current that causes melting of the fusible element(s), with the fuse applied at the maximum ambient temperature specified by the fuse manufacturer. For further details regarding the three subclasses of current-limiting fuses and their different lower interrupting limits, see 5.3.

#### 4.6.2.8 Low current design considerations

Due to the low current interruption limitation of the backup fuse, another interrupting means is necessary to clear overload and lower fault current levels. This is generally accomplished with a series combination of a current-limiting element with a low arc voltage device capable of interrupting these low currents. This may be done either as an add-on device (switch or low arc voltage fuse) or as a section incorporated into the fuse itself. For overhead applications, a distribution fuse cutout is commonly applied as an add-on with backup fuses to achieve the low-end clearing capability, while in liquid filled enclosures (e.g., transformers) liquid-submerged expulsion fuses are often used as the additional device. When series devices are used, they must be coordinated properly. The incorporation of a low-current interrupting capability into the body of a current-limiting fuse is described in the following two paragraphs.

In some popular designs, the full-range clearing capability is achieved by the use of the "dual element" principle (see Figure 3b). This type of fuse integrates a current-limiting section for interrupting high currents, which is typically made up of single or parallel silver or copper ribbon elements, in series with a second element, typically using wires, for low current interruption. The wires (incorporating a low melting temperature section) are typically contained in a heavy wall silicone rubber sleeving. This entire assembly is placed inside the sand-filled tube and has the appearance of a typical current-limiting fuse. For high currents, the current-limiting element embedded in sand melts and interrupts in a current-limiting mode, while for low overcurrents, the wire element melts and interrupts like an expulsion element, but without external exhaust. For intermediate currents either or both series elements melt. The area where primary

interrupting duty changes from one element to the other is called the "cross-over" region, and IEEE Std C37.41 contains additional testing requirements in this region to assist in determining that such fuses are capable of interrupting all currents.

In general-purpose fuses, low-current clearing may be achieved by similar or alternative means. Some alternative techniques cause multiple sections of the main element to be selectively melted in order to create sufficient "gap(s)" that the current can be interrupted at a current zero (Figure 3c shows one method of doing this, using an auxiliary element to create three gaps). Gas-evolving materials are also commonly used to increase the effectiveness of created gaps, allowing a smaller number of gaps to achieve current interruption.

#### 4.6.2.9 Other current-limiting fuse types

Numerous fuse types, classes, and designations exist, which are referred to as current-limiting fuses. One variety is commonly referred to as commutating current-limiters, triggered current-limiters, or electronically-actuated fuses. These devices carry the continuous current through an alternate, very low impedance path compared to the typical fuse element. The result is a higher continuous current rating than traditional current-limiting fuses may achieve.

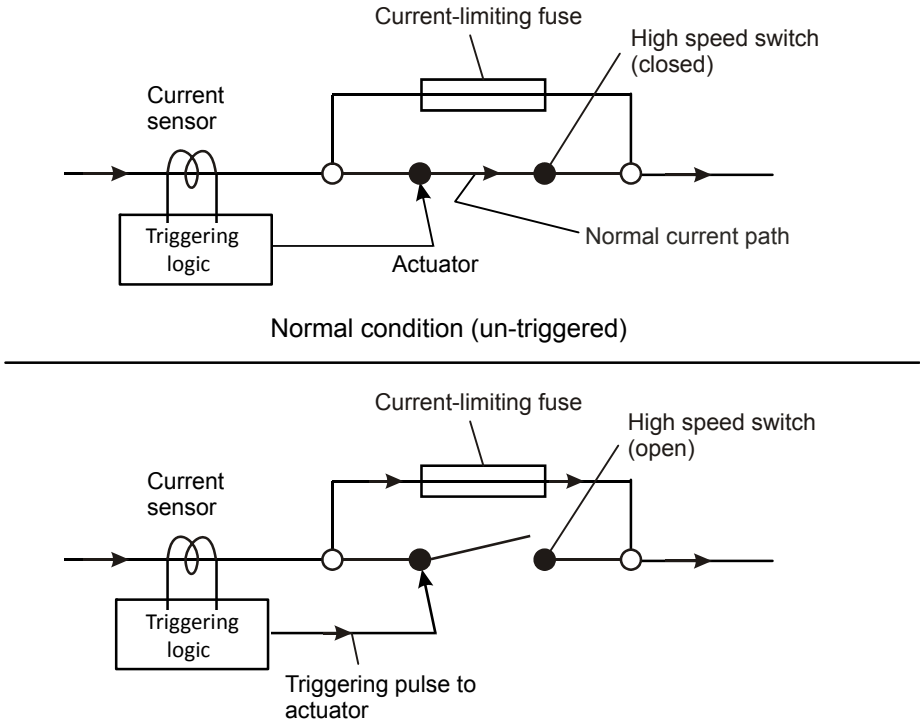



**Figure 4—Operation of communicating current-limiters**

A schematic of this type of fuse is shown in Figure 4. Upon occurrence of a fault, the continuous current path is opened and the fault current is commutated to a parallel current-limiting fuse, before the first peak. The shunt fuse, of traditional current-limiting design, interrupts the circuit. These devices typically employ electronic sensing to initiate operation and sealed pyrotechnics to achieve high-speed switching of the main conductor. The electronics may also be used to selectively initiate interruption in a non-current-limiting fashion.

Another variety of fuse is non-commutating, but uses electronics to trigger an opening of the fuse element at a number of points. This permits alteration of the low-current TCCs. Operation in the current-limiting region is unchanged.

Electronically actuated fuses are defined in the National Electrical Code® (NEC®) (NFPA 70) [B50] (article 100, Part II — definitions) as an overcurrent protective device that generally consist of a control module that provides current sensing, electronically derived TCCs, energy to control tripping, and an interrupting module that interrupts current when an overcurrent occurs. Electronically-actuated fuses may or may not operate in a current-limiting fashion, depending on the type of control selected.

Another type of fuse element is shown in Figure 3d. The fuse element has an overcurrent sensor (the black dot) which produces the fuse's TCC. A number of pyrotechnic chemical charges are located at strategic points along the element. These charges are fired by passing current through them at the desired time. Under normal conditions, this circuit is isolated by a spark gap. When the main element opens, the fuse's arc voltage breaks down the gap, and fires the charges, cutting the element to create the series arcs required to interrupt low currents.

#### 4.6.2.10 Indicating current-limiting fuses

For many applications, it is desirable to have indication when a fuse has operated. This indication can take several forms—from simple visual indication, to the tripping of auxiliary equipment or a drop open function. Visual indication is normally achieved by use of a spring-loaded "button" held down by a high-resistance wire that is connected in parallel with the main elements. When the main elements melt, current flows through this indicator wire, causing it to melt and release the spring-operated indicator. A version using a heavier spring can be used to operate a trip bar or a microswitch that can trip a switch or circuit breaker. With some designs, this arrangement is used to take care of the interruption of currents below the minimum interrupting rating of a backup fuse. Testing must confirm that failure (physical destruction) of the backup fuse does not take place during the time that the fuse is arcing while waiting for the indicator to trip the switch, and for the switch to interrupt the current. Tripping a switch, or causing a drop-open action for a general-purpose fuse may require a more forceful indicator, or "striker." One type of striker uses a small explosive charge, initiated with a wire similar to that used to release an indicator. The explosion drives a pointed striker with sufficient force to push it through the fuse end cap. Such a design is often favored for use with sealed fuses.

### 4.6.3 Expulsion and other types of non-current-limiting fuses

#### 4.6.3.1 General

As described in 4.5, expulsion and other types of non-current-limiting fuses do not significantly modify the circuit. This implies a rather low arc voltage compared to the source voltage of the system [see Annex A Equation (A.2)]. A fuse that works on this principle must wait for a normal current zero before it can attempt to interrupt the current. The low arc voltage is due to a short fuse element and generally a singular arc burning in a relatively unconstricted environment. In this case, the heat transfer from the arc to its surroundings is low compared to the current-limiting fuse, and this contributes to the low arc voltage, on the order of only a few hundred volts.

Expulsion and other types of non-current-limiting fuses allow passage of virtually the full crest of fault current prior to interruption at a normal current zero. Anything that increases the magnitude of the first major loop of an asymmetrical fault current makes interruption harder. Since the magnitude of this first major loop is a function of available fault current, the *X/R* ratio of the system and the degree of asymmetry of the current, these fuse types are more sensitive to high *X/R* ratios than are current-limiting fuses.

In addition to being sensitive to *X/R* ratio, expulsion and other types of non-current-limiting fuses are sensitive to TRV. They do not introduce the high resistance of the current-limiting fuse to provide a phase shift while clearing. Therefore, the normal current zero occurs near the time of a system voltage crest. Upon reaching a current zero, they must be capable of dielectric recovery at a rate and to a magnitude greater than the TRV characteristic of the system. The TRV typically involves an overshoot of up to twice the power frequency voltage. If the recovery conditions are not met at the first current zero, the device will conduct a second loop of fault current and usually interrupts at the following current zero.

Because of their typical applications, expulsion and other types of non-current-limiting fuses have been designed to interrupt any current from the overload current at which the element melts up to their maximum fault rating. This, as previously discussed, is not necessarily true for all types of current-limiting fuses where only fuses that include special construction features to improve their low-current interrupting capability can reliably interrupt when exposed to low currents. Various types of expulsion and other types of non-current-limiting fuses are discussed in 4.6.3.2.

#### 4.6.3.2 Expulsion fuses in air

Expulsion fuses are available in both power and distribution classifications. As the name implies, the interruption involves an expulsion action. These fuses employ a rather short fuse element that melts to initiate the arcing process. The most common type of distribution class expulsion fuse is the fuse cutout, which uses a replaceable fuse-link mounted in a fuseholder, and the most common type of power class expulsion fuse is the boric acid fuse, which normally uses a replaceable refill unit. In an expulsion fuse, the arc is only moderately confined and burns in a tube or bore of gas evolving material that normally uses a reinforcing outer tube. The gas evolution protects the tube wall from excessive erosion, while the arc burns stably with temperatures in the center as high as 20 000 °C. In the case of a single vented fuse cutout, the upper end of the element is fixed within the fuse tube and the other end is connected to a fuse leader that is expelled from the tube during arcing. A double vented cutout has an expendable cap that allows the upper part of the fuse link to be expelled at higher fault currents and therefore gas is also released from this area. In a boric acid fuse, typically the fuse element is connected at its upper end to an arcing rod (which draws the arc through a boric acid block, evolving steam to provide the expulsion action. These expulsion gases expel parts and the metal vapor out of the fuse tube. The movement of the leader (cutout) or arcing rod (boric acid power fuse) increases the gap between the parts and is very beneficial to the dielectric recovery that occurs immediately after current zero. The amount of gas produced is proportional to the heat released by the arc. The gas flow effectively cools and deionizes the area inside the tube and at current zero allows the gap between live parts to withstand the TRV. This results in interruption of current flow in the circuit.

Various methods are used to increase the interrupting capability of cutouts. In some cases, an extender rod is used to move the element down the fuse holder tube, reducing the internal pressure generated within the tube by allowing the high pressure gas generated by the arc to be more easily vented. Another method to increase the interrupting capacity is to put a conductive sleeve (typically copper or bronze) inside the top of the fuse tube to effectively move the arc lower in the fuse tube. Fuseholder tubes that have expendable caps often have higher interrupting ratings due to the orifices at each end (often known as “double vented”) that can more effectively vent heat, ionized particles, and gas from inside the tube as compared to fuseholder tubes with a single orifice at one end (often known as “single vented”). An advantage of such “single-venting” types is that there is no emission of ionised gas in an upward direction which could impinge on adjacent overhead lines.

Expulsion fuses under some conditions expel solid materials at high velocities upon fault current interruption. This should be considered in the mounting location of the device.

Expulsion fuses are principally used outdoors at distribution, sub-transmission, and transmission voltages. They are commonly used at distribution voltages less than or equal to 34.5 kV, and in current ratings up to 720 A. Expulsion fuses can be used in outdoor pole-top or station-style mountings as well as in indoor mountings installed in metal-enclosed switchgear, indoor vaults, and pad mounted gear. Indoor mountings for boric acid fuses incorporate an exhaust control device that contains most of the arc-interruption

products and virtually eliminates the noise accompanying the fuse's operation. Some exhaust control devices do not require a reduction in the fuse's interrupting rating.

#### 4.6.3.3 Liquid-submerged expulsion fuses

Liquid-submerged expulsion fuses operate on a similar principle as expulsion fuses in air (described in 4.6.3.2), except that liquid (most commonly oil or an oil substitute) is used as the dielectric medium. Melting of the element heats, vaporizes, and dissociates the liquid. In many cases, the gas produced from the liquid is sufficient to complete the interruption process. At higher currents, the fuse tube wall also supplies gas to facilitate the interruption process. The gas vents into a bulk tank containing the fuse and, typically, other components under liquid. The interrupting phenomena and circuit conditions, such as *X/R* ratio and TRV characteristics, are similar to those of expulsion fuses used in air.

#### 4.6.3.4 $SF_6$ fuses

$SF_6$ fuses employ a tube filled with sulfur hexafluoride gas dielectric, axial contacts joined by the fuse element, and a conducting surface on a part of the inner wall. Upon melting of the fusible element, arcing is initiated and transferred from one central contact to the conducting surface on the wall. The conductor on the wall is connected in series with a coil, which now carries the fault current. This imposes a magnetic field that rapidly rotates, thereby lengthening and cooling the arc in the $SF_6$ gas. Upon reaching a current zero, the dielectric recovers and the circuit is interrupted. This design must withstand the same asymmetrical current and TRV criteria as expulsion fuses used in air. It is believed that this fuse type is no longer being manufactured.

#### 4.6.3.5 Vacuum fuses

Vacuum fuses typically have a very short fusible element attached to two opposing arc rotating plates that are mounted inside of a vacuum bottle. When the element melts and the interrupting process begins, the arc column is typically at a few atmospheres of pressure with the outer regions of the bottle, internal to the bottle, at about negative one atmosphere. As the arc burns, metal particles, vapor, and ionized particles are drawn to the outer region and deposited on the cool metal parts in this area. Depending on the current magnitude, there can be one or more rotating arcs within the vacuum bottle. As the current approaches zero, any multiple arcs combine into a single arc. As the current decreases, less heat is created. Eventually, the heat transferred to the metal plates matches and exceeds the heat being produced by the arc, and the production of arc by-products ceases. At current zero, the gap between these plates forms a clean, high vacuum medium, with a dielectric recovery voltage withstand greater than the TRV of the system and current flow ceases. Vacuum fuses have *X/R* ratios and recovery conditions similar to those seen by expulsion fuses. It is believed that this fuse type is no longer being manufactured.

#### 4.6.3.6 Distribution Oil cutouts

Distribution oil cutouts are devices that operate in a manner similar to under-oil expulsion fuses. The oil cutout typically contains a fuse carrier (tube) mounted on a rotating structure with contacts on each end, so that it may be used as a load breaking switch as well as a protective device. The contacts, fuse carrier, and element are under oil in a vessel capable of withstanding very substantial pressures. Upon melting of the element, its ends are blown out of the carrier by a jet of vaporized oil. Hydrogen gas evolved by the dissociated oil cools the arc zone and causes rapid deionization of the gases in the arc zone, which results in interruption of the circuit at a current zero. The carrier may also provide ablative effects to assist in the interruption process. Distribution class oil cutouts were devices formerly covered by IEEE/ANSI standards. However, ANSI C37.44-1981 [B1], which covered specifications for such devices, has been withdrawn.

Since these devices are now considered obsolete, testing for oil cutouts was removed from IEEE Std C37.41 with the 2008 revision.

#### 4.6.3.7 Liquid fuses

Liquid fuses are applied in air, but use a liquid to facilitate arc interruption. They usually consist of a glass tube sealed with ferrules at each end. The tube is filled with an arc extinguishing liquid, usually tetrachloroethylene and trichloroethylene. A short element, usually a wire or notched strip, is connected to one end of the fuse. The element is held in tension by a spring. A flexible lead connects the element to the lower ferrule. When the element melts, the spring draws the arc through the liquid. As the arc is extended, it interacts with the liquid to interrupt the current at the normal current zero of the circuit. To relieve the tube of excessive pressure, the fuse is fitted with a diaphragm at the upper end, which is ejected for all but the most modest of faults. These fuses can only be used outdoors. Current breaking capacities of liquid fuses are limited. Liquid fuses experience *X/R* ratios and recovery conditions similar to those seen by expulsion fuses.

# 5. Current-limiting fuse types, class, and definitions

## 5.1 Introduction

Current-limiting fuses excel at interrupting relatively high currents. However, they can experience difficulty when exposed to certain transient currents. If the transients are of a sufficient magnitude to cause damage to the elements, without sufficient duration to complete the interruption process, failure can result. This concern drives the application rules and guidelines to reduce the risk that conditions, such as transformer magnetizing inrush currents, will result in damage to current-limiting fuse elements.

Coordination rules between devices described as being “downstream” (closer to the load) and “upstream” (closer to the source) (see 7.1) have also been developed to prevent damage by limiting the application of the fuse to appropriate locations on the system.

Current-limiting fuses have different capabilities in interrupting low-magnitude currents, as described in 4.6.2.7. As a result, current-limiting fuses are divided into three classes recognized in industry standards

- Backup type fuses
- General-purpose type fuses
- Full-range type fuses

Because these fuses may appear to be quite similar (or even identical) when viewed externally, care must be taken when replacing fuses that have operated (“blown”). A typical current-limiting fuse is shown in Figure 5. All have connection points to allow them to be connected into a circuit. Some fuses are fitted with ferrules, enabling the fuse to be mounted in clips or fuseholders, while other fuses use bolted connections. Some fuses are intended for use in fuse supports (usually having terminals attached to insulators) while others can be hung from power lines or attached to cutouts or bushings. All have some form of cap and tube to hold the elements, element supports, sand, and other parts. All come with some form of identification, either in the form of a label or as a marking on the fuse cap (see Figure 5A).

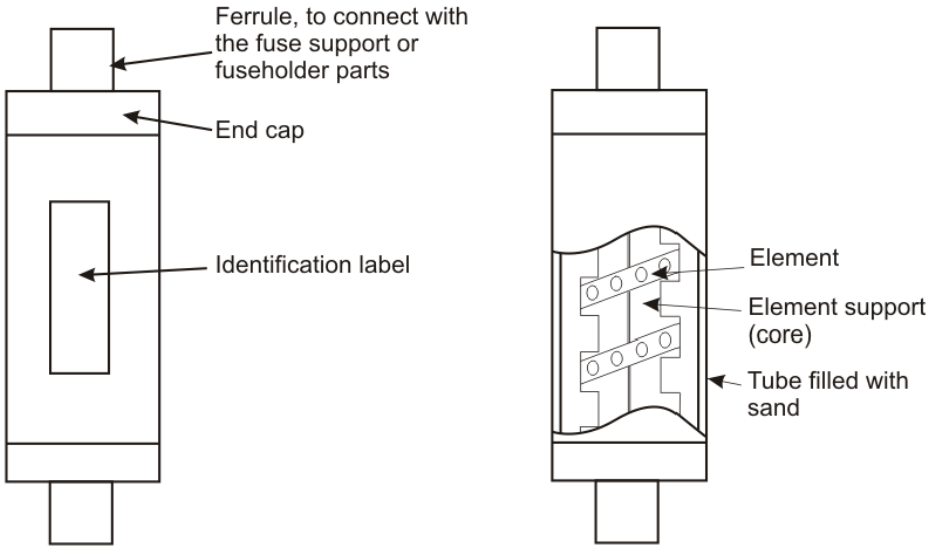



Figure 5A Figure 5B

**Figure 5—Typical current-limiting fuse construction**

In most cases, the fuse elements are spirally wound on a support (see Figure 5B) to allow sufficient element length without requiring excessive overall outside dimensions. The different types of fuses have different internal structures to enable appropriate low current operation. For instance, backup fuses generally use only a main fuse element, without any added structures designed to improve performance in the low-current interrupting region. General-purpose fuses may add auxiliary elements and special solder globules that force melting and create multiple arcing points to aid in the low-current interrupting process. Other fuses may include gas evolving spiders (fuse winding supports), or series low-current interrupting sections packaged within the fuse body to create full-range designs. Each performs slightly differently and has different application requirements and advantages that are discussed in 5.3.

## 5.2 Fuse class

### 5.2.1 Introduction

In addition to classification by low-current interrupting capability, current-limiting fuses are classified according to where they are used on the system. The technical committees writing the C37 standards have surveyed the industry and written the standards to reflect typical reported circuit conditions. This resulted in two descriptions of fuse types (power-class and distribution-class). Each fuse type was given different test requirements to address the requirements in accordance with where the fuse is located, in relationship to the substation, on the system.

### 5.2.2 Power-class current-limiting fuses

Power-class current-limiting fuses are designed and tested to allow their use on feeders and locations in or close to the substation, or other areas that tend to have higher fault circuit X/R values and/or higher dielectric requirements, at these locations there is very little conductor impedance. Should a fault occur, most of the fault circuit impedance results from the inductance of the transformer feeding the circuit with almost no resistance. A low power factor, high inductive reactance to resistance ratio, (*X/R*) circuit results.

On this type of circuit, the current is out of phase with the voltage, and the current zero occurs close to the voltage peak.

During the interruption process, current-limiting fuses insert a significant resistance into the circuit as they provide current-limitation. This dynamically-increasing resistance changes the circuit from one that has a high *X/R* ratio into one that has a low *X/R* ratio. As a result, current-limiting fuses are generally not very sensitive to the circuit *X/R* ratio. IEEE Std C37.41 requires that power-class current-limiting fuses be tested on circuits with a higher *X/R* ratio than distribution-class current-limiting fuses to reflect the somewhat more severe duties that result from applications in or near the substation. Standards require power-class current-limiting fuses to be tested at an *X/R* ratio not less than 15.

### 5.2.3 Distribution-class current-limiting fuses

Distribution-class current-limiting fuses are used at locations that are some distance from the substation. As a result, there is additional resistance in the circuit, due to the conductor resistance. With larger conductors the resistance will be lower, resulting in the need for longer distances to reduce *X/R* ratios significantly. As the *X/R* ratio of the circuit is reduced, so is the stress on the fuse as it interrupts.

Distribution-class fuses are tested on circuits with *X/R* ratios not less than 10. Because of test lab limitations, some manufacturers may test current-limiting fuses on circuits with *X/R* ratios significantly higher than the minimums specified in the standard (both for power-class and distribution-class fuses). However, before applying current-limiting fuses to a circuit with an *X/R* ratio any higher than specified in the test standard for the class of fuse, the manufacturer should be consulted to verify that a particular fuse is suitable for the application.

## 5.3 Types of current-limiting fuse

### 5.3.1 General

There are three types of current-limiting fuse defined in IEEE Std C37.40, and with test requirements specified in IEEE Std C37.41. They are as follows:

— Backup

— General-purpose

— Full-range

Each of these types is described in 5.3.2 through 5.3.4.

Fuse designs of any of these three types may be suitable for use in an enclosure, thus creating a fuse enclosure package (FEP see 1.4). This will normally expose a fuse to immediate surrounding temperatures above 40 °C. Such a fuse or FEP is therefore assigned a rated maximum application temperature (RMAT), and the fuse is subjected to additional testing in an enclosure at this elevated temperature. In addition, the fuse and/or FEP manufacturer provides information on the effects of the enclosure and elevated temperature on the rated continuous current of the fuse, and the effect (if significant) on the TCC of the fuse.

### 5.3.2 Backup fuses

A backup fuse can interrupt any current between its rated minimum interrupting current and its rated maximum interrupting current. If a backup fuse is melted open at a current level less than its minimum interrupting rating, the fuse is not required to, and may not successfully, interrupt the circuit. In this case, the fuse melts open at only a few places, often a single point, along the length of the element. Burn back of the element proceeds very slowly, as the arc heat causes the sand to melt and form a resistive fulgurite. During arcing conditions, a large amount of heat is released in a limited area within the fuse. This heat can prevent the sand and the resultant fulgurite formed in the sand from developing dielectric properties needed to withstand circuit voltage. As a result, the fuse may fail to interrupt the current and be destroyed as it attempts to clear.

The high amount of heat released can also attack an organic fuse tube, carbonizing it, and making it incapable of withstanding voltage. Therefore, arcing will continue until another protective device, connected in series with the backup fuse, operates and interrupts the circuit. Because of this, a backup fuse is limited to applications where it will not be called on to interrupt currents that are less than its rated minimum interrupting current.

In most cases, this is accomplished by using a backup fuse in series with another interrupting device, which will interrupt any current below the minimum rating of the backup fuse. The series device may be another fuse or other type of circuit interrupting device. In some cases, these currents may be interrupted by a switch that is tripped when the backup fuse element melts open. Details of how these devices are selected and coordinated are presented in Clause 6 and Clause 7 of this guide.

The rated minimum interrupting current that the fuse will interrupt, as defined by the standards and testing experience, is required to be marked directly on the fuse. It is also listed in the catalog literature supplied by the manufacturer.

As discussed earlier, in 4.2, the response of a given fuse to a current is usually shown on TCC curves. These TCC curves are drawn on special log-log graph paper (with scales as specified in IEEE Std C37.41) and usually display the minimum length of time that is required to cause the element to melt at a given current (minimum-melting curve) and the maximum time it will take the fuse to melt and then interrupt the circuit at a given current (total-clearing curve). For backup fuses, currents that are less than the rated minimum interrupting current, but will still melt the element, are often shown as a dashed or broken line on the minimum-melting TCC curve. Currents less than the minimum current the fuse can interrupt are usually not shown on the total-clearing curve since the fuse cannot reliably interrupt those currents.

The fuse manufacturer also provides the rated maximum interrupting current of the fuse. This rating should not be exceeded. Other characteristics such as minimum-melt $I^2t$ ($A^2s$), maximum clearing $I^2t$ ($A^2s$), and charts of peak let-through current versus available current are generally available. This data provides needed information to properly apply and coordinate these fuses.

Caution should be exercised when replacing a backup fuse. Coordination between the backup fuse and series, low-current interrupting devices is critical to preventing damage to the backup fuse and associated equipment. Therefore, replacement of either protective device with one of a different rating or one supplied by a different manufacturer should be done only after a careful review of the total protection scheme to be sure that coordination is maintained.

Backup fuses used in an enclosure may experience a reduction in their allowable continuous current (see 5.4), but changes to their TCC are usually small, and often negligible. This is because the elements of backup fuses are usually made from high melting point materials (such as silver or copper).

### 5.3.3 General-purpose fuses

A general-purpose fuse is defined by standards as a device that can interrupt any fault current between a current that will cause the fuse to melt in not less than one hour and its rated maximum interrupting current. Typically, these fuses are used for transformer through-fault protection, or to protect the system from the effects of a high-current, low-impedance fault.

Because this type of fuse can interrupt currents quite small in relation to its rating, it usually does not require any series device to be used with it. Care should be taken so that the fuse is not called upon to interrupt overload currents that are below its one-hour melt current.

In addition, some general-purpose fuse designs should not be subjected to currents between the rated continuous current and their one-hour melt current, even if such a current does not result in melting. Operating the fuse in this zone can lead to fuse deterioration, which might later prevent the fuse from interrupting successfully at currents it could otherwise clear.

One method of ensuring that the general-purpose fuse is not overloaded, or required to interrupt overload conditions, is to apply the fuse in conjunction with load or temperature sensing devices, such as a secondary or primary breaker, in oil-filled distribution transformers. This prevents the fuse from melting open as a result of overloads or very long duration, low current, transformer through faults. Breakers must be selected so that they will interrupt the current going through the transformer before the general-purpose fuse, mounted to the primary of the transformer, is damaged. A secondary breaker will not protect the transformer fuse from being damaged from a high-impedance primary fault.

When this type of fuse is used, care must be exercised to be sure that any derating of the fuse, caused by elevated temperature around the fuse or restricted air flow, is included in the selection process. For example, if a general-purpose fuse is used in a drywell canister, in a transformer, the allowable continuous current rating may be reduced as a result of both the restricted air flow around the fuse and also because of elevated temperatures surrounding the canister. Because general-purpose fuses normally include element features that cause them to melt at a lower temperature than a backup fuse, the TCC, particularly at longer melting times, is normally affected much more than for a backup fuse (that is, the one hour melting current is reduced), A fuse of an appropriate current rating must therefore be chosen after taking into account any derating factors. It should also be noted that IEEE Std C37.41 requires that the low current testing of a general-purpose fuse, intended for use in an enclosure, includes tests in an enclosure, and at appropriate temperature to simulate worst case conditions (i.e., it must be shown that it can interrupt the reduced one-hour current). The highest surrounding temperature (RMAT see 1.4) and type of enclosure that a fuse is intended for is therefore specified by the fuse manufacturer and/or the enclosure manufacturer.

Although not required by standards, some fuse manufacturers can provide the one-hour capability of each general-purpose fuse (this is sometimes known as the minimum current required for successful interruption and is sometimes expressed as a percentage of the fuse's continuous current rating) and the maximum temperature in which the fuse may be used. This may be done in table form or taken from TCC curves, which are required to be published to 3600 s. Other application data sometimes supplied in charts and curves includes minimum-melt $I^2t$, maximum clearing $I^2t$, and peak let-through current versus available current.

### 5.3.4 Full-range fuses

A full-range fuse, as defined by standards, can interrupt any continuous current between the minimum current that can cause melting of its elements, with the fuse applied at the maximum temperature specified by the manufacturer, and its rated maximum interrupting current.

There are two key components in this description. They are as follows:

— Any continuous current that causes melting.

— At the maximum temperature specified by the manufacturer.

Full-range fuses are normally intended for use in enclosures and/or at elevated temperatures. The maximum temperature specified by the manufacturer is called the fuse's rated maximum application temperature (RMAT). The RMAT is the maximum ambient temperature at which a device is suitable for use. An interrupting device shall be capable of withstanding this temperature without any deterioration that would inhibit its ability to interrupt the circuit. Therefore, when the RMAT is higher than 40 °C, the low current tests (termed test duty 3 or $I_3$) are performed at the RMAT and/or in an enclosure. Also, additional high current testing is required.

The two components, put together, result in a fuse that can interrupt any continuous current that causes melting, as long as the maximum use temperatures are not exceeded. Of course, other criteria such as voltage ratings and continuous current ratings must also be used in selecting a fuse for a given application.

Because a full-range fuse can interrupt any continuous current that causes melting, it does not require any other associated device to protect it from overloads or high-impedance faults, as long as the ambient temperature surrounding the fuse does not exceed its maximum use temperature. No minimum-interrupting level is specified, since the fuse should be capable of interrupting any continuous current that melts the elements when used at or below its RMAT. Full-range fuses can be used to protect against both faults and overloads. As a result, a key rating is the maximum allowable ambient temperature around the fuse.

Another common application parameter for full-range fuses is the allowable continuous current at various service temperatures (often including temperatures above 40 °C). This rating may be based on the temperature rise of the fuse, compared with limitations detailed in standards, but some designs run at temperature rises well below the maximum permitted, their current rating being limited by their long time melting current. This design characteristic may allow manufacturers to specify use in enclosures at elevated temperatures without deterioration of contacts or fuse components occurring. Such data may be in the form of a table, or a derating factor that depends on ambient temperature. TCC curves, minimum melting $I^2t$, maximum clearing $I^2t$, and peak let-through current versus available current charts and tables are also often supplied.

Normal current-limiting fuse application guides must be followed with full-range fuses. These fuses can also experience difficulty if exposed to transient overcurrent conditions. Therefore, factors such as transformer magnetizing inrush current levels need to be considered, as do coordination rules with other downstream and upstream devices. Refer to Clause 6 and Clause 7 for more details on these topics.

## 5.4 Current rating conventions

Many fuses will be assigned a rated continuous current, often selected from the lists of preferred values given in various IEEE C37 documents. This current rating is used to identify the fuse and shows that it can carry at least that many amperes of current in a 40 °C ambient temperature, without exceeding the contact and insulation temperature rises specified in IEEE Std C37.40 and without being subjected to any deterioration. This current may not, however, be the highest current that the fuse can carry continuously. Therefore, fuses may also be assigned an "allowable continuous current", which is the maximum current they can carry continuously in a specified ambient temperature without exceeding the total temperature specified in IEEE Std C37.40. Thus, a manufacturer may list different "allowable" current ratings for their fuses at different ambient temperatures. It should be noted that, in some cases, temperature rise may not be the limiting factor in assigning the rated continuous current or allowable continuous current to a fuse.

IEEE C37 standards detail additional characteristics that permit certain fuses to carry designations such as "C," "E," and "R" after its ampere rating, e.g., "40E." The criterion for such a designation is that the fuse's melting TCCs must be linked to its current rating. The rules for such linkage are different for each designation, and may be considered a "time-current-characteristic" based rating system. Examples of TCC based rating systems are listed in the IEEE C37 standards and summarized in the following paragraphs.

For a C-rated fuse, the fusible element shall melt in 1000 s at an rms current in the range of 170% to 240% of the rated continuous current of the fuse unit (IEEE Std C37.47).

For E-rated fuses rated 100 A or smaller, the fuse shall melt in 300 s at an rms current in the range of 200% to 240% of the rated continuous current of the fuse unit. Fuses larger than 100 A shall melt in 600 s, at an rms current in the range of 220% to 264% of the rated continuous current of the fuse unit (IEEE Std C37.46).

R-rated fuses will melt in the range of 15 s to 35 s at a value of current equal to 100 times the R-rating (IEEE Std C37.46). The maximum continuous currents for R-rated fuses are listed in IEEE Std C37.46 at ambient temperatures of 40 °C and 55 °C.

It is important to note that these C, E, and R criteria were originally proposed as a method of achieving some measure of fuse interchangeability, and for many years IEEE C37 standards listed these requirements under the heading of "Interchangeability Requirements." However, it is now recognized that these letter designations provide virtually no help to a user and changes to IEEE C37 standards have included removal of any suggestion that these requirements are for interchangeability. There are two reasons for this. First, take as an example the C rating. Two fuses with the same C ratings could have minimum-melt currents at 1000 s as different as 1.4:1 and still each meet the criterion. Secondly, the fuse melting characteristics at times longer and shorter than the designated time can be whatever the manufacturer desires, and different fuses need bear no similarity. This is illustrated in Figure 6, where melting time-current- characteristic curves (minimum and maximum) of three different E-rated fuses are plotted. It can thus be seen that the only way to decide which fuse may be substituted for another must be on the basis of examining a fuse's melting characteristics in the light of the application.

When a fuse is used in an enclosure at elevated temperatures, its melting current may be reduced. The reduction in melting current, and also "rated" current, is a function of the type of fuse, any restriction of cooling medium fluid flow around the fuse, and the type and temperature of the cooling medium fluid surrounding it. For example, the heat transfer characteristics of air and oil are quite different. The fuse, fuse container if used, and the enclosure become a "fuse enclosure package" (FEP) as defined in IEEE Std C37 .40, and the temperature of the surrounding fluid, in contact with the fuse enclosure package, then becomes the reference ambient temperature (RMAT for the fuse/FEP). Because this reduction (de-rating) will be different for different enclosure designs, the IEEE C37 standards suggest that the manufacturer of an FEP is typically responsible for this testing.

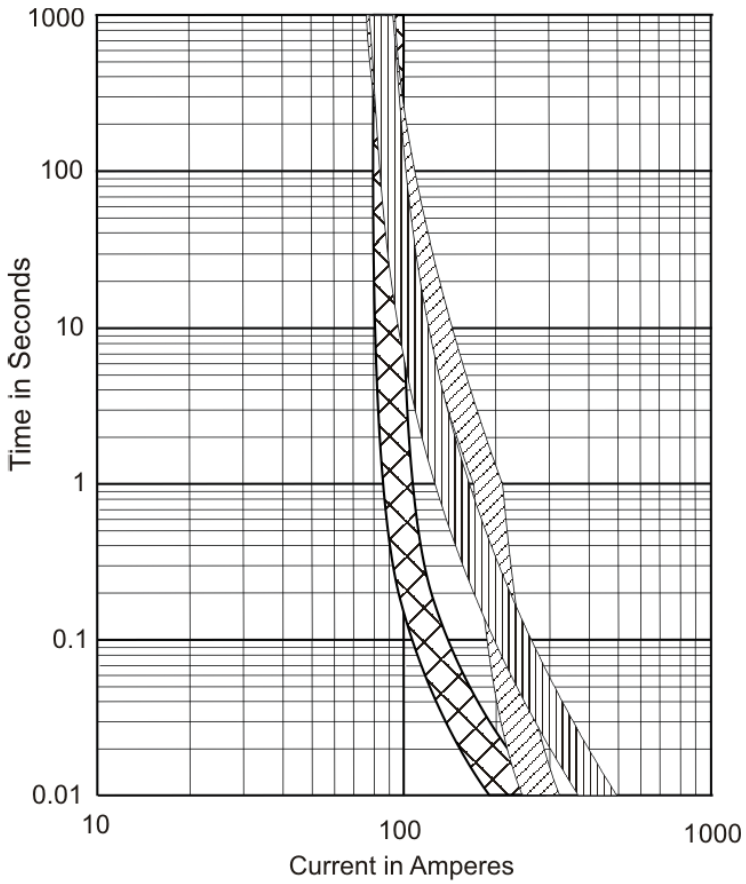



**Figure 6—Melting TCC Curves, comparing three 40A E-rated fuses of different manufactures**

A backup current-limiting fuse used outdoors in series with a cutout fuse, presents another rating system. Typically, the backup fuse is given the same continuous current rating as that of the largest fuse link that may be used in the series-connected cutout fuse, while meeting coordination rules. For instance, a backup outdoor fuse that can be used in series with a maximum of a 12-"K" style expulsion fuse link is rated as a "K-12" or "12K". Details of backup fuse coordination with low-current interrupting devices will be discussed in 7.4.

Some fuse rating conventions, such as "T" or "K" ratings used for expulsion fuse links, may use both long-time and short-time check points or gates to establish the rating. For instance, IEEE Std C37.42 describes the requirement for the long term melting current at 300 or 600 s, for both K and T links, in a manner similar to that used for C or E rated fuses. However, the T and K fuses also specify a melting current range at two other times, 10 s and 0.1 s. The current at 0.1 s is typically 6 to 8 times the long-term melt current for a K- style fuse and 10 to 13 times for a T-style fuse link. Because both the short- and long-time melt current of these links is specified, fuse selection is made easier. Backup fuses that are designed to coordinate with a K or T link are therefore normally interchangeable between manufacturers. However, in a multi-phase system, care must be taken if backup fuses are being used in a manner that assumes that under some fault conditions two backup fuses will be effectively in series and will share the phase-to-phase voltage (see 6.1.8). For two fuses to share the voltage, they must arc simultaneously. Consequently, fuses in all phases should be of the same fuse rating, be from the same manufacturer, and be the same model or type of fuse.

# 6. Application considerations and cautions

## 6.1 Electrical aspects

### 6.1.1 Response of current-limiting fuse to steady-state conditions—overview

Fuses are selected for an application such that they are capable of carrying load currents and some permissible overload currents, and are able to respond by opening and interrupting all currents above a given value caused by faults or by extended duration overloads. Under normal circumstances, the specified ambient temperature of fuses shall not be exceeded. This reduces the risk of damage to the elements and fuse assembly parts and assists in assuring that the interrupting capability is not impaired.

While current-limiting fuses may have a higher resistance and therefore a higher watt loss than expulsion fuses, the larger diameter, length, and large end caps all act to hold the temperature in an acceptable range.

### 6.1.2 Response of current-limiting fuse to overcurrent conditions—overview

If a fuse is subjected to currents above its rated current, circumstances may occur that are detrimental to its successful operation. If a transient condition causes partial melting of a fusible element, this damage may cause the fuse to melt open at a current less than it can safely interrupt. In the case of a general-purpose or backup fuse, for example, damage to the fuse, including rupture of the casing, may follow. If a current-limiting fuse is damaged by transient currents, the fusible element may open at only one or two locations. Arcing starts at these locations and failure of the fuse can result. To prevent this, the circuit should be evaluated for temporary overcurrent or inrush currents and the fuse selected accordingly.

Under normal conditions, the fuse must sense overcurrent and operate according to a predetermined TCC, and interrupt any normal overcurrent within the fuse's minimum and maximum interrupting capability, which causes the element to open. If the prospective fault current is quite high, the current-limiting fuse will greatly reduce the magnitude and time duration of the fault current, reducing the likelihood of damage to associated equipment from these high-fault currents.

### 6.1.3 Transformer applications

#### 6.1.3.1 Inrush considerations

Current-limiting fuses may be subject to damage if inrush currents cause partial melting of the fusible element(s). Inrush currents due to energizing a transformer can be high and require checking as part of the normal selection and coordination procedure.

When a transformer is energized, relatively high inrush currents may occur, depending upon the residual flux in the core and the voltage at the instant of closing the circuit. Tests with typical transformers, as well as many years of experience in applying both current-limiting and expulsion fuses for transformer applications, have produced a generally accepted set of guidelines for fuse selection. These guidelines consider the typical first loop current value, as well as the rms value over the duration of a typical inrush current. The guidelines are in the form of two time-current points, and are expressed as multiples of transformer rated full-load current. The first is 25 times rated current for 0.01 s; the second is 12 times rated current for 0.1 s. These points are compared to the fuse's minimum-melting TCC. If at these points, the fuse characteristic lies above and to the right, then the fuse is considered to be capable of properly withstanding the magnetizing-current inrush of the transformer. Since the 12 times and 25 times figures

include safety factors, no further margin between these points and the fuse curve is normally considered necessary (unlike margins used when fuse to fuse coordination is attempted, as described in Clause 7).

#### 6.1.3.2 Pick-up considerations

Cold-load pick up is a transient current condition that occurs upon energizing a circuit after it has been deenergized for 2 min or longer. Fuses used in certain applications, such as protecting pumps, can experience elevated currents after outage times as short as 6 s. Tests have shown that large fans can draw six times rated current for 60 s. On residential circuits, cold-load currents can cause problems because load diversity has been lost. Refrigerators, air circulating fans, air conditioner compressors and/or heat pumps, water pumps, etc., are all ready to cycle on. The combined starting currents of these devices contribute to a period of higher than normal current termed cold-load pick up. After an outage of several minutes, compressors have little or no head pressure, so their motors are able to come up to speed with a normal starting current. On non-residential circuits, the opportunity for staged restoration of loads tends to mitigate the pick-up problem somewhat.

Another problem, commonly referred to as sympathetic tripping, arises on a momentary dip in voltage, due to a fault on another part of the system, which is then cleared in a matter of cycles, allowing the subject area voltage to be restored to normal. During the voltage dip, voltage in parts of the system drop to a point that compressor motors stall. When full voltage is restored, the large compressor motors cannot come up to speed due to high head pressure. Locked rotor currents exist until the thermal overload on the compressor motor trips. Tests on circuits subject to this phenomenon indicate approximately 2.7 times pre-fault current for about 7 s. The 2.7 multiplier results from all motors being instantaneously energized (some contactors have not had a chance to open), with a loss of diversity. Low power factor locked rotor conditions combine with the inductance in the secondary, the transformer, the lateral, the main feeder, and the substation to cause low voltage on the motor terminals and the overcurrent. Seven seconds is the approximate time it takes for the thermal overloads on motors with locked rotor currents to trip open.

The distinction between sympathetic operation and cold-load pick up arises in part from the operating time of control relays and contactors. In most cases, there is enough randomness in closing to allow the relatively small, single-phase air conditioning motors to come up to speed, at normal voltage, in much less than one second, since there is no head pressure.

A commonly used rule of thumb for application is that the fuse should be selected so that the minimum-melting TCC curve lies to the right of the points corresponding to six times rated full-load current for one second, three times rated for 10 s, and 2 times rated full-load current for 15 min.

Repeated starting currents from heavily loaded motors can cause unusual stresses on a current-limiting fuse element; special designs for motor-starter applications have been produced to handle this special application. This is discussed in 6.1.7.

#### 6.1.3.3 Transformer loading and overloading

IEEE Std C57.91 defines the safe loading for mineral-oil-immersed overhead and pad-mounted distribution transformers, and IEEE Std C57.93 defines safe loading for mineral-oil-immersed power transformers. These standards detail the potential loss of transformer life for various load levels and durations. The information is given in a series of equations and in tabular form. The data in the tables can also be graphed and expressed as a safe loading curve. The fuse's total-clearing TCCs should lie to the left of the safe loading curve to provide adequate protection. For many distribution transformer applications, typical fusing methods and transformer loading (overloading) requirements are such that it may not be possible to prevent loss of transformer life, due to the long term effects of overloading, by using fuses alone. The use of internal expulsion fuses that employ elements sensitive to liquid temperature may help alleviate this situation, but even the use of such fuses may not provide full overload protection under all circumstances.

Generally, a transformer or fuse manufacturer will recommend fuse sizes to handle full-load and some over-load currents without fuse operation or damage. The ambient temperature that the fuse encounters during the overloading will depend on how the fuse is being applied.

#### 6.1.3.4 Through-fault conditions

IEEE Std C57.109 presents a through-fault duration guide. The fuse's total-clearing TCCs should lie to the left of the through-fault duration curve for complete protection. Secondary faults, when reflected to the primary winding that the current-limiting fuse would be protecting, are typically of magnitudes to operate the fuse in 0.02 s to 1.0 s; thus, little or no current-limiting action would occur. Therefore, the fuse must have low-current interrupting ability to handle this duty.

#### 6.1.3.5 Maximum arc voltage levels

Inherent TRV characteristics are determined by the system layout and components. Current-limiting fuses produce a high resistance during operation, quickly reducing the current, and altering the circuit TRV characteristics. The interaction of the circuit inductance and the rapidly changing current causes a significant overvoltage. The maximum voltage that can be expected during operation of a current-limiting fuse is specified in IEEE Std C37.46 and IEEE Std C37.47, and summarized in Table 3. System insulation must be capable of withstanding arc voltage of this magnitude.

### 6.1.4 Feeder and sectionalizing applications

#### 6.1.4.1 Inrush considerations

Inrush current into a distribution circuit for the first few cycles can be very high due to magnetizing current for transformers that have high residual magnetic flux in the core and maximum energizing flux. This coupled with incandescent lighting inrush and locked-rotor inrush into motors (plus some out-of-phase residual flux) should be considered by the user. Transformer magnetizing current may be quite high for an individual transformer, but when the transformer is only one of many in the circuit being energized; one would not expect the magnetizing inrush current in the circuit to equal the sum of the maximum magnetizing inrush current experienced by each transformer. Inrush currents that are quite high could result in a voltage drop that would act to reduce the inrush currents.

For instance, if ten 50 kVA transformers were being energized simultaneously for a total of 500 kVA, an inrush current of 20 times transformer rated current would represent a connected load of 10 000 kVA at that instant. Some distribution circuits would experience appreciable voltage dip during this period, and thus significantly reduce the inrush magnitude. However, since it may be difficult to determine which circuits are capable of producing and sustaining the higher inrush currents for varying numbers of transformers being applied, the conservative approach would be to utilize the connected kVA and the multipliers discussed in 6.1.3.1 for single transformers.

#### 6.1.4.2 Load pick-up considerations

Experience has shown that if a distribution sectionalizing fuse was carrying no more than 30% of its rated current at the time of a power failure, power has not been off for more than one hour, and no significant changes in the load have taken place, then there should be no problem with inrush currents.

A fuse operation may result when the connected load current is between 30% and 50% of the fuse rating. Above 50%, the circuit should be sectionalized to pick up only a part of the load. It is not recommended that bypass jumpers be put around a fuse to avoid sectionalizing the circuit.

A more important factor for selecting a sectionalizing fuse could be that of cold-load pick up. After an extended outage period, many applied loads are ready to start up as soon as the transformers are re-energized. Some of these loads, such as motors, can have current requirements of 5 to 10 times the normal running current for a period of time ranging into seconds. Published literature (see the bibliography in Annex B) on this subject indicates that the sectionalizing fuse should be capable of handling about 6 times the peak load current prior to the outages for one second, three times the peak load current prior to the outages for 10 s, and 2 times this value for 15 min.

#### 6.1.4.3 Fault conditions

The interrupting rating of the fuse should be higher than the available fault current. These interrupting ratings are specified by the fuse manufacturer. A sectionalizing fuse typically would be required to interrupt high fault currents since the transformer fuse or protective device would sense and interrupt transformer secondary faults and abnormally high overload currents. While the transformer fuse is also expected to respond to low level overcurrents, it must be capable of interrupting those currents. If a current-limiting fuse is needed, a full-range or general-purpose fuse may be required.

### 6.1.5 Shunt Capacitor applications

#### 6.1.5.1 General

The main function of the capacitor fuse is to protect the distribution system from failed capacitors and faults that occur within capacitors banks. The capacitor fuse cannot prevent the capacitor from failing. When the capacitor does fail, the fuse should remove it from the system before case rupture occurs. Ideally the fuse should also clear before upstream protective devices operate or are damaged.

While capacitors are considered constant current devices, they are subject to overcurrents in actual operation on a system. These are caused by over-capacitance (manufacturing tolerance), operation at higher than rated voltage, and system harmonic currents.

Overvoltage increases the current into a capacitor linearly with voltage change. Excessive voltage may also cause an increase in third harmonic current from over-excited transformers. Standards allow operation at 10% overvoltage and a 15% over-capacitance. These two factors increase rated current by 25%. Harmonic currents depend on system conditions and are difficult to predict. Generally, an additional allowance of 5% to 10% of rated current is used. For additional information, see IEEE Std C37.48.

#### 6.1.5.2 Transient currents

##### 6.1.5.2.1 Capacitor inrush considerations

While being energized, capacitor banks may initially appear as a short-circuit. The capacitor bank charging current (or inrush current) will be limited by the circuit's impedance and depend on the system voltage phase angle at which the bank is initially energized.

The fuse's minimum-melt $I^2t$ must be larger than the inrush $I^2t$. The $I^2t$ of the inrush current can be estimated with good accuracy. The initial magnitude of the inrush current, without any consideration for damping due to system resistance can be calculated, using Equation (1):

$I = E(C/L)^{1/2}$, which is based on the relationship $I^2L/2 = E^2C/2$ (1)

The inrush energy enters the capacitor by way of a high-frequency damped sinusoidal current, whose initial magnitude is determined by the system voltage, inductance, and surge impedance. The high-frequency resistance, a value much greater than the 60 Hz circuit resistance, and one that can only be empirically determined, causes damping of the high-frequency inrush current. A typically severe, and therefore conservative, inrush current is one having a first peak that is 90% of that for an undamped current, with subsequent 1/2 cycle peaks that should be 81% of each preceding peak. Equation (2) describes the $I^2t$ that results from that current:

$I^2t = 3.74\ E^2\ C^{3/2}\ L^{-1/2}\ \mathrm{A^2s}$ (2)

where:

$E$ = phase to ground peak voltage in volts,
$C$ = Phase capacitance of bank in farads,
$L$ = Source circuit inductance in henries.

It has been found that in some circumstances a full analysis of the capacitor circuit (a driven RLC circuit) is required to determine $I^2t$ at longer times (e.g., 0.03 s) when inrush $I^2t$ may be closer to the $I^2t$ characteristic of a fuse. This can occur with expulsion fuses that have a "fast" TCC curve shape (e.g., K links) or current-limiting fuses with a similar curve shape.

A capacitor with no initial charge (has not been energized in the previous 5 min) results in an initial instantaneous inrush current unaffected by an existing charge. This transient current diminishes as the capacitor charges until eventually the current is equal to VωC. The transient current has a frequency proportional to the reciprocal of the square root of the product of capacitance and the short-circuit inductance.

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (3)$$

Excessive switching may degrade the characteristics of a fuse as repeated inrush currents can cause localized heating and movement of the elements within the sand. Considerations for inrush conditions in single bank applications are as follows:

a) Energizing a capacitor during recloser/breaker operations with short (measured in cycles) "open" time may result in higher inrush currents if the charge trapped on the capacitor is of a polarity opposite to the circuit voltage at the moment of energizing.

b) Energizing a capacitor bank on a circuit that has an energized bank already in service causes the instantaneous current to be a function of the impedance between the two banks as well as the short-circuit current from the source. The frequency of the inrush current has two components, one resulting from the inrush characteristics of the bank and the other from the short-circuit characteristics of the circuit. The following equations express these relationships.

$f_{\text{inrush}}$ is proportional to $\{(L_{\text{between banks}}) \times [(C1C2)/(C1 + C2)]\}^{-1/2}$ (4)

$f_{\text{short-circuit component}}$ is proportional to $\{(L_{\text{short-circuit}}) \times (C1 + C2)\}^{-1/2}$ (5)

#### 6.1.5.2.2 Capacitor "outrush" considerations

The most onerous transient current consideration for most capacitor fuses is actually the "outrush" current from an isolated capacitor bank, at the peak of maximum operating voltage, into a nearby system fault. Where there are multiple capacitor banks at one location, the most onerous discharge may be associated with a worst case restrike of a capacitor switch. The fuse should be selected so that this outrush current will not damage the fusible elements. If this condition is met, normal capacitor energization or capacitor bank against bank switching will not be a problem.

In making this determination, note that the frequency of the discharge is higher than power frequency (e.g., 1000 Hz). Due to various phenomena associated with high frequencies, it is normal to leave a greater margin between the outrush $I^2t$ and the minimum melting $I^2t$ of the fuse than is customary when coordinating power frequency surges. In the absence of specific advice from the fuse manufacturer, a margin of 4:1, or even 6:1, between fuse minimum melting $I^2t$ and outrush $I^2t$ may be appropriate when the current transient is of short magnitude.

In the case of outrush, the transient $I^2t$ is the energy in Joules stored in the capacitor at the instant of the initiation of the fault, divided by the resistance of the discharge circuit ($I^2t$ = stored energy/R). While the capacitor energy may be calculated as 1/2 C $E^2$, for 60 Hz capacitors it is also about 2.65 Joules per kvar for a capacitor operating at rated voltage. (For capacitors operating above or below rated voltage, this value should be multiplied by the square of the per unit of rated voltage at which the capacitor is operating).

The effective resistance of the discharge circuit is not the 60 Hertz resistance, but the resistance at the discharge frequency. This can be estimated from the Q (or X/R ratio) of the discharge circuit. The circuit reactance, X is given by: $X = (L/C)^{1/2}$. The circuit resistance R is given by R = X/Q, and the $I^2t$ is the energy times the Q, divided by $(L/C)^{1/2}$.

For Equation (2) in 6.1.5.2.1, the Q is about 7.5, not a very conservative value. While it may be typical, a value of 15 would be a more conservative approach. If there is a high Q, low loss, reactor in the discharge circuit, a value of 25 may be appropriate.

### 6.1.5.3 Capacitor fuse voltage rating

IEEE Std C37.48 contains advice concerning voltage selection for line and unit capacitor fuses. It refers to the necessity of considering the maximum power-frequency system voltage, including any system overvoltage. The following paragraph discusses a source of overvoltage that may not always be considered, and that applies to expulsion fuses as well as current-limiting fuses.

When a shunt capacitor is used in a power system, the leading (capacitive) current it draws has the effect of increasing system voltage at the point where it is connected. This is because the current produces a voltage rise as it flows through the circuit reactance. While this is usually desirable for maintaining a satisfactory operating voltage level (and often the reason that shunt capacitors are used), excessive capacitive current can cause an unwanted voltage increase. Excessive capacitive current usually occurs due to the failure of capacitor elements or units that are in series with other capacitor elements or units (and/or the operation of unit fuses). A failure produces a significant increase in voltage across the remaining series elements or units, resulting in increased capacitive current flow through them. This higher than normal current, can produce an increase in system voltage.

Capacitors are usually required to operate satisfactorily at up to 10 % above their rated voltage, so capacitor banks normally use protection that limits overvoltage to 10%. Testing to IEEE Std C37.41 produces an increase in circuit voltage, due to the switching of the capacitance that produces the desired capacitive prospective current. While the rise is supposed to represent a typical circuit voltage increase, there is no guarantee that a given fuse has been tested in a circuit that gives the maximum possible voltage rise (it may

have been less). Therefore the "capacitive voltage rating" is set no higher than the power frequency recovery voltage (the same voltage as if the test had been with an inductive current). Because of this, the maximum circuit voltage, or internal bank voltage, that a fuse must be able to interrupt against, even under conditions of capacitor failure, must be known in order to choose the correct capacitor fuse rated voltage. The fuse rated voltage must be equal to or higher than this maximum voltage. Thus if, for example, the capacitor bank overvoltage protection is set at 10% above nominal capacitor voltage, a fuse should be chosen having a rated voltage at least 10% above the capacitor voltage.

### 6.1.6 Potential [voltage] transformer applications

#### 6.1.6.1 General

Current-limiting fuses are used to protect the power system by isolating failed potential transformers from the system. Since potential transformers are installed at the substation bus and their kVA ratings are lower than power or distribution transformers, they require fuses that combine low continuous current ratings with high rated maximum interrupting current.

#### 6.1.6.2 Voltage rating

Some manufacturers recommend the fuse's rated voltage be 100% to 140% of the maximum system line-to-line voltage to which the fuse is to be applied. This range of application voltage is recommended because the current-limiting action of the fuse is characterized by the generation of arc voltage which should coordinate with system and circuit insulation levels. Since the current ratings are low, and often use wire elements (see 4.6.2.3), for some designs switching voltages can be high. Other manufacturers feel that application at lower system voltage is acceptable for their design of fuse. The maximum voltage permitted for each fuse rating is its maximum voltage rating, assigned by the manufacturer.

For separately mounted fuses where over-insulation is required, the fuse is selected on the basis of actual service voltage. The fuse can be mounted with insulators of a higher voltage rating, providing additional insulation to ground.

#### 6.1.6.3 Current rating

To provide maximum protection against damage to other equipment in the event of a failure of the potential transformer, it is usually necessary to select the smallest fuse that will not result in nuisance fuse operations. The selected fuse should withstand magnetizing inrush currents to preclude nuisance fuse operation or damage to the fuse element(s) that could result in failure of the fuse. Since potential transformer burdens are lower and the construction of these transformers is different from power transformers, fuses selected solely on the basis of inrush considerations will seldom protect potential transformers from overloads.

The inrush withstand capability of the fuse is readily available from the manufacturer in the form of minimum-melting $I^2t$ values. The inrush current of the potential transformer can be recorded with an oscillograph and the $I^2t$ calculated, or the $I^2t$ value can be obtained from the potential transformer manufacturer. For satisfactory fuse application and for preventing nuisance fuse operations, it is clear that the fuse's melt $I^2t$ should exceed the transformer magnetizing inrush $I^2t$, with a reasonable margin of safety. This safety margin, expressed as a multiplying factor, is dependent on the method used to connect the voltage transformer to the system bus. Empirically, for delta connected transformers with three line fuses, or for open delta transformers with three line fuses, the multiplying factor is 4.5. That is, the $I^2t$ of the fuse should be equal to or greater than 4.5 times the transformer's inrush $I^2t$. For single-phase units, open delta units with four fuses, or delta units with six fuses, this multiplying factor is 1.5. The inrush $I^2t$ of the

voltage transformer increases rapidly with an increase in applied voltage. In requesting $I^2t$ values from transformer manufacturers, the voltage specified should be the maximum expected in service.

In some applications, particularly in underground cable circuits, there is a possibility that the inherent capacitance of the circuit will give rise to a discharge current through the primary windings of the potential transformer connected to the bus. The magnitude and duration of the discharge currents may be calculated from the circuit constants. Caution should be used to ensure that the fuse will not operate under these conditions.

#### 6.1.6.4 Interrupting ratings

The rated maximum interrupting current of a fuse at rated voltage should be equal to or greater than the maximum available fault current from the system at the point of fuse installation.

#### 6.1.6.5 Partial discharge

One concern with voltage transformer fuses is the effect of partial discharge on the fuse elements, in this case commonly termed "corona". Partial discharge normally occurs because of sharp edges of energized apparatus parts. This sharp edge creates high voltage stress to ground, or other energized components, in air or other dielectric medium, producing electrical breakdown of this medium. In the case of a voltage transformer fuse, the “sharp edge” is the very small diameter element that is usually used, and the insulation is the air in the voids of the filler material. Radio influence voltage (RIV) measurements are made to determine the extent of radio interference generated by this corona. Normally the concern with corona (other than radio interference) is the damaging effect it can have on non-restorable insulation. In the case of a voltage transformer fuse, however, the insulation is self-restoring, so there is no damage, but what is of concern is the effect on the fuse element itself. Because of the delicate nature of the elements used in the very low current rating fuses needed for voltage transformers (often less than one ampere) any appreciable partial discharge will lead to the element being damaged (the element material is removed, ion by ion, and deposited on the fuse filler and body). Suitable fuse mounting, to avoid the onset of partial discharge, is therefore important; primarily of concern is the location of ground planes near to the fuse.

### 6.1.7 Motor circuit protection and coordination

#### 6.1.7.1 Function of fuses on motor-starter circuits

The function of motor-starter fuses (often termed “medium voltage” fuses) is to protect the motors from short-circuit currents. These typically are backup type current-limiting power fuses as defined in IEEE Std C37.40. They require a series device, such as an air or vacuum contactor, for breaking the circuit for currents below their rated minimum interrupting current. Fuses for this application are frequently given an R rating, as defined in IEEE Std C37.46. The fuse designs for motor circuit protection are different than those for general-purpose or full-range fuses and backup fuses used for transformer applications. Motor-starter fuses use special elements that are designed to withstand the currents that result from frequent starting and stopping of the motors. They must withstand the surge currents associated with this application.

#### 6.1.7.2 Selection of motor-starter fuses

##### 6.1.7.2.1 General

Coordination of motor-starter components and fuses to protect the fuse against unnecessary operation is accomplished by matching the thermal relay or other devices' characteristics with the characteristics of the fuse. In the selection of current-limiting fuses for a particular application, it is important to consider all of the factors that affect the installation, such as, motor full-load current, motor locked-rotor current, fault current at the location, and the overload relay characteristics to assure a properly coordinated installation. Generally, the following important factors should be fully considered:

a) Voltage rating

b) Current rating

c) Frequency rating

d) Interrupting rating

e) Pulse withstand

f) Location

Items a) through e), insofar as they characteristically apply to R-rated current-limiting fuses, are briefly discussed in 6.1.7.2.2 through 6.1.7.2.6.

##### 6.1.7.2.2 Voltage ratings

In selecting the fuse voltage rating for a three-phase delta connected motor, the maximum line-to-line voltage of the system should not exceed the rated maximum voltage of the fuse, regardless of the system grounding conditions. In these cases, the fuse rated voltage should be in the range of 100% to approximately 140% of circuit maximum operating line-to-line voltage. . In many instances, line-to-ground rated fuses may be used on three-phase grounded-wye connected motors supplied from a grounded-wye system. A fuse that has a voltage rating greater than system voltage will interrupt successfully, but limitations imposed by the arc voltage of the fuse must be considered in selecting the fuse. Permitted arc voltages for current-limiting power-class fuses are specified in IEEE Std C37.46. In general, the system must be capable of withstanding the arc voltage generated by the fuse as it interrupts.

In terms of NEMA Standard motor voltages, examples of the fuses that are applicable are shown in Table 4.

**Table 4— Nominal system, motor and fuse voltages**

| Nominal power system voltage (V) | Motor nameplate voltage (V) | Fuse rated voltage (V) |
|---|---|---|
| 2400 | 2300 | 3540 |
| 4160 | 4000 | 5080 |

##### 6.1.7.2.3 Current ratings

When selecting fuse units for a particular application, proper allowance must be made for the maximum anticipated overload current expected. This is more critical than the nameplate rating of the motor. The maximum continuous currents for these fuses are specified in IEEE Std C37.46. In application, care should

be taken to avoid having the current in the circuit too closely approach the minimum-melting TCC of the fuse. If the fuse melts or is damaged by a current below its minimum interrupting current, failure of the fuse may result.

The R designation specifies a narrow window on the TCCs for the fuse curves to lie within. This does not mean that all R-rated fuses have the same shape of time-current-characteristics. Hence, it is necessary to coordinate the fuse with the contactor or thermal relay characteristics. This ensures the devices coordinate properly, that is, the fuse protects the contactor against currents that are above the maximum interrupting capacity of the contactor and the contactor protects the fuse against exposure to currents below the rated minimum interrupting current of the fuse.

#### 6.1.7.2.4 Frequency ratings

In North America, motor-starter fuses are normally designed for 60 Hz application. In many cases, they can be also applied in 50 Hz circuits. However, the fuse manufacturer should be consulted before applying current-limiting fuses at frequencies other than 60 Hz.

#### 6.1.7.2.5 Interrupting ratings

The interrupting ratings of motor-starter fuses should equal or exceed the maximum available short-circuit duty at the point in the system where the fuses are installed. The available short-circuit current at the fuse's location is expressed in symmetrical amperes. Older fuses may have rated maximum interrupting ratings expressed in asymmetrical amperes. Annex C of IEEE Std C37.41 gives the relationship between the symmetrical and asymmetrical values based on the *X/R* ratio of the circuit. In some instances, the three-phase fault level may be available from the system planning studies. The three-phase interrupting capacity may be calculated by Equation (6):

Three Phase MVA = √3 (Fuse Rated Voltage in kV) × (Fuse Rated maximum interrupting current in kA) (6)

#### 6.1.7.2.6 Pulse withstand

IEC 60644 [B25] specifies pulse withstand requirements testing and guidance for selection of fuse links. In order to provide maximum withstand capabilities (pulse withstand) against motor starting current; it specifies that the pre-arcing (melting) time-current-characteristics of fuses for motor circuit applications be within the following limits:

$I_{f_{10}} / I_{\mathrm{r}} \geq 3$ for $I_{\mathrm{r}} \leq 100\ \mathrm{A}$

$I_{f_{10}} / I_{\mathrm{r}} \geq 4$ for $I_{\mathrm{r}} > 100\ \mathrm{A}$

$I_{f_{0,1}} / I_{\mathrm{r}} \leq 20\left(I_{\mathrm{r}}/100\right)^{0.25}$ for all current ratings

where:

$I_{\mathrm{r}}$ = current rating of the fuse

$I_{f10}$ and $I_{f_{0.1}}$ = pre-arcing (melting) currents corresponding to 10 s and 0.1 s respectively, expressed as mean values with maximum tolerances of ± 20%.

These ratios apply to all current ratings, providing maximum short-circuit protection to associated switching devices, cables, motors, and terminal boxes. IEC 60644 also introduces a term, the "*K*" factor. The "*K*" factor (less than unity) defines an overload characteristic to which the fuse may be repeatedly subjected, under specified motor starting conditions, and other specified motor-operating overloads, without deterioration. The value of "*K*" is chosen at 10 s. Unless otherwise stated by the manufacturer, this is valid from 5 s to 60 s for a frequency of up to six starts per hour and for no more than two consecutive starts. The overload characteristic is obtained by multiplying the minimum-melting time characteristic by "*K*."

IEC 60644 specifies the following two sequences of tests:

a) To withstand without deterioration starting pulses in rapid succession due for example to abnormal conditions, such as those occurring during commissioning of the equipment

b) To withstand without deterioration a large number of motor starts in normal service conditions

The standard therefore specifies two sequences of tests representative of these conditions: 100 cycles corresponding to abnormal service conditions; 2000 cycles corresponding to normal service conditions. It is expected that a fuse-link which passes these tests will have a good behaviour during satisfactory life duration.

Figure 7 details the sequence of the two withstand tests, carried out on the same fuse.

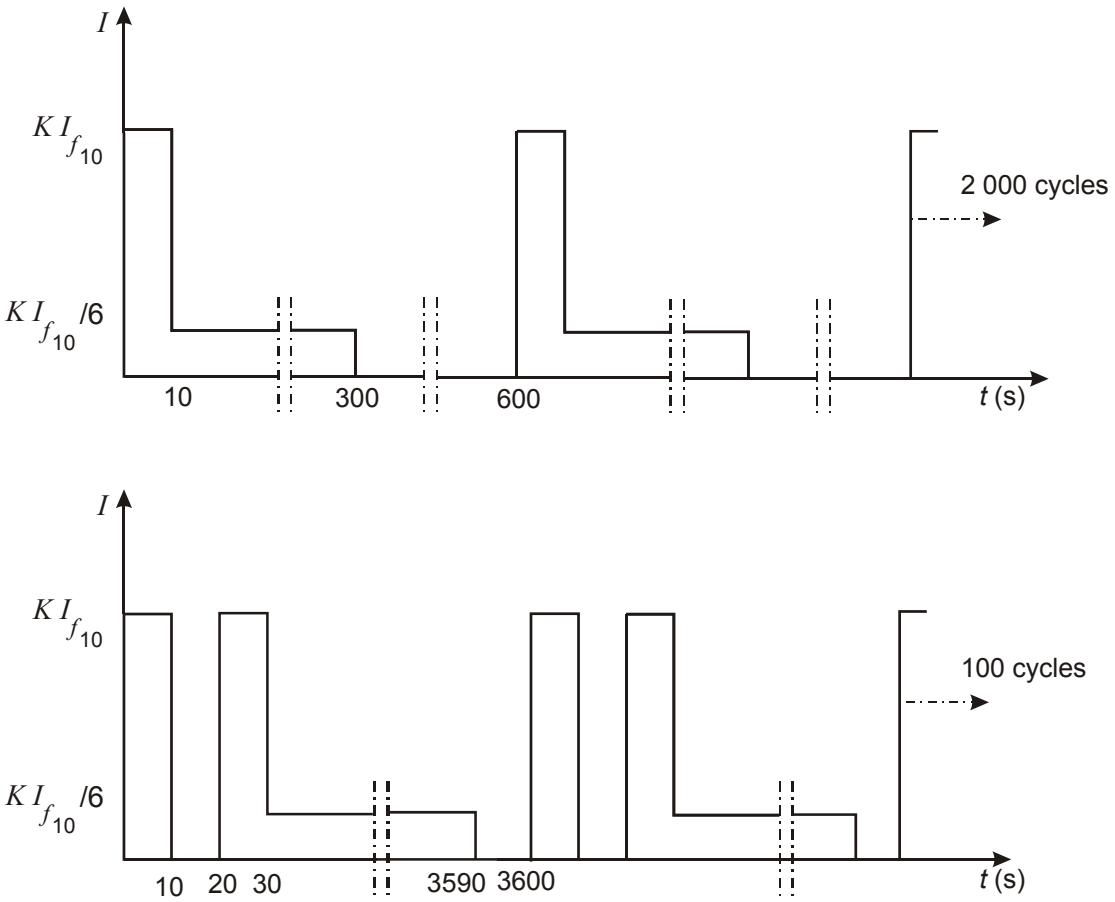



**Figure 7—Withstand test sequences**

### 6.1.8 System voltage considerations

A current-limiting fuse that has a maximum design voltage equal to or higher than the maximum system voltage that the fuse may encounter during its interrupting duty should be used. Because a current-limiting fuse generates high arc voltage, it is also advisable to select a fuse voltage rating only slightly higher than the system voltage. Some manufacturers recommend the fuse's rated voltage be 100% to 140% of the maximum system line-to-line voltage to which the fuse is to be applied. For single phase applications, the voltage rating of the fuse should always be higher than the system line-to-ground voltage. On ungrounded or delta circuits, use line-to-line voltage rated fuses. On uni-grounded systems, use line-to-line voltage rated fuses, unless a system study shows a lower voltage rating may be used. With effectively grounded neutral systems, use a fuse with a phase-to-neutral voltage rating.

In applications where the three-phase load is delta connected, it is recommended that the design voltage rating of the fuse exceeds the maximum line-to-line voltage of the system, regardless of system grounding conditions. For three-phase applications in GrdY/GrdY systems, an evaluation in many instances will show that the use of line-to-ground rated fuses will be permissible, or even desirable, since it results in a smaller, less expensive fuse, which produces lower arc voltage.

General practice would require a phase-to-phase voltage rating for the fuse. However, if the system is such that only high fault currents could occur and both (or all three) phase fuses would operate simultaneously, the fuses could be of a phase-to-ground rating. This is because current-limiting fuses, when operating in their current-limiting mode, tend to share voltage quite equally. However, if low fault currents and excessive overload currents could occur, variation in TCCs could cause one fuse to provide the complete interruption function and thus see full phase-to-phase voltage. The selected fuse should be rated adequately for this condition.

### 6.1.9 Fuse replacement

Considerations regarding fuse changeout after a single fuse operation on three-phase applications include the following:

a) If one fuse of a three-phase group operates, there is a possibility that another phase was involved and, while it did not operate, its fuse may be damaged. Unless the user can positively rule out this possibility, then all fuses in a three-phase set should be replaced when one has operated.

b) An example of a situation in which a multi-phase fault can be ruled out is in the case in which the fault location can be positively identified and only the phase with the operated fuse was present at the fault site.

c) For capacitor banks that use capacitor line fuses (group fuses) the following conditions apply. On a grounded-wye capacitor bank, if one fuse operates there is no need to replace the other two fuses. On an ungrounded-wye capacitor bank, if one fuse operates the other two fuses may be damaged since they have been subjected to 3 times normal current when the capacitor shorted (which caused the first fuse to operate). On delta connected banks, usually two fuses operate simultaneously and there is no need to replace the third. If a second fuse did not operate, then after the faulted capacitor is identified (and isolated), the second fuse, on the other line bushing of the faulted capacitor unit, should be replaced.

### 6.1.10 Current-limiting fuses and power quality issues

High magnitude faults can depress the voltage at the substation bus, affecting all feeders that emanate from that substation transformer. Voltage sags that are of sufficient magnitude and last long enough will affect the operation of sensitive electronic equipment such as machine tools, computers, clocks, and video recorders. Once a current-limiting fuse begins to arc, and its arc voltage equals the system voltage, the voltage depression on the system ceases (and voltage generally becomes higher than normal due to the fuse

arc voltage see 4.5 and 4.6.2.2). Current-limiting fuses are therefore very effective at reducing the duration of voltage sags caused by high fault currents.

## 6.2 Physical application considerations for current-limiting fuses

### 6.2.1 General

Before any fuse is used, consideration shall be given to the physical environment of the application. The user should be cautious and choose a fuse that is appropriate for the physical environment in which it will be used. Improper selection and application of a fuse can result in damage to the fuse and associated equipment.

### 6.2.2 Fuse types/mounting for current-limiting fuses

#### 6.2.2.1 General

Current-limiting fuses are typically used in conjunction with various mountings in many different applications. Subclauses 6.2.2.2 through 6.2.2.5 detail some of the more common uses and describe various ways that particular fuses are designed to meet the requirements of each application.

#### 6.2.2.2 Liquid immersible current-limiting fuses

Current-limiting fuses for use in insulating liquid are completely sealed to prevent liquid ingress into the fuse. IEEE Std C37.41 details liquid-tightness tests for fuse seal integrity. Fuses are tested at their rated maximum application temperature (see 5.3.1) so some designs are suitable for under-oil transformer applications. The fuse manufacturer can supply design and test information to assure a satisfactory non-leaking design.

#### 6.2.2.3 Fuse container mounted current-limiting fuses

A current-limiting fuse may be mounted in a fuse container. This is a relatively small enclosure, defined as one supporting the fuse and restricting the air, gas, or liquid flow surrounding the fuse. Common applications include “drywell” canisters that enable a fuse that may not be sealed, to be used under liquid in a transformer. Other canisters may be insulated with air, $SF_6$, or solid insulation. Application of current-limiting fuses in a container must take into consideration a higher air ambient, surrounding the fuse, as well as the possibility of elevated temperatures surrounding the container such as where fuse drywells are placed in the top oil of a loaded transformer, which often reaches 105 °C and perhaps as high as 135 °C under overload conditions. IEEE Std C37.41 contains requirements for additional interrupting tests for fuses in enclosures at temperatures over 40 °C. The most common type of fuse used in a container is the Full-range type, although General-purpose types have also been used for this application.

#### 6.2.2.4 Application of current-limiting fuses indoors

Fuses designed for indoor applications may not be suitable for outdoor applications and should not be so applied unless approved for such use by the manufacturer. Indoor fuses may not be suitable for application in enclosures in which the outdoor air circulates freely into the enclosure. Circulating fog, moisture, and condensation under adverse weather or other application conditions, such as dust and particle accumulation

on insulating surfaces, may degrade the dielectric withstand capability of the device and its supporting structures.

Fuses should be applied indoors in protective enclosures suitable for preventing contaminant build-up that could result in tracking or flashover of the fuse tube following an overcurrent interruption.

#### 6.2.2.5 Application of current-limiting fuses outdoors

Fuses for outdoor use must be of a design that can resist deterioration of the tube due to weathering, ultraviolet, and ozone, and should be capable of withstanding system voltage for a period of time sufficient for locating and correcting the overcurrent problem that caused the fuse to operate. Fuses designed for outdoor use should be suitable for indoor applications unless the fuses emit ionized gases during the interrupting process. Outdoor fuses are often longer than indoor types and/or utilize special weather resistant coatings since they are exposed to contaminants that may accumulate on the body of the fuse.

### 6.2.3 Mechanical impact considerations for current-limiting fuses

#### 6.2.3.1 General

Due to their somewhat fragile nature, care must be exercised in packaging, shipping, and handling of current-limiting fuses. Fuses that are mishandled may look undamaged, since the exterior portions are intact. However, elements and fuse supports may be broken. This breakage could result in a failure to interrupt a fault current or inability to withstand voltage.

#### 6.2.3.2 Normal operation of current-limiting fuses

A normal operation of a current-limiting fuse will not produce excessive external forces on the mounting or surrounding parts. In addition, there is comparatively little noise or reaction when a current-limiting fuse operates. One way of evaluating current-limiting fuses while they are in use is to use infrared test equipment. This approach is becoming more common. Since current-limiting fuses are heat producing devices and run hotter than other types of fuses, the following factors are appropriate to consider when using this equipment:

a) Infrared test equipment may indicates that the fuse elements themselves may experience temperatures well in excess of 100 °C, under normal operating conditions.

b) Usual service conditions include ambient temperatures between –30 °C and 40 °C. The 40 °C application temperature is the reference used for temperature rise calculations. These devices also may be applied with maximum application temperatures above 40 °C, as long as the application temperature does not exceed the fuse's assigned maximum application temperature.

c) In some cases total measured temperatures of the external fuse components may be as high as 220 °C for the fuse tube and 115 °C for bolted electrical contacts that have silver plating (maximum temperatures are 105 °C for those with tin planting and 90 °C for bare copper or copper alloy contacts, while spring loaded contacts are approximately 10 °C less).

d) On three-phase installations, readings on all three phases should be close if the loading is equal on all three phases.

#### 6.2.3.3 Damage (dropping)

The user should not permit a current-limiting fuse to be subjected to mechanical shock that could result from dropping or throwing the fuse. This could cause damage to fuse elements and alter the fuse's rating or impair its interrupting capability. Any current-limiting fuse that has been subject to high impact and/or shows evidence of physical damage should not be placed in service.

### 6.2.4 Environmental effects on ratings of current-limiting fuses

#### 6.2.4.1 General

The user should recognize that some organic insulating materials may degrade under exposure to ultraviolet radiation and/or ozone. Both are present in outdoor applications, and protection needs to be provided for by the manufacturer and considered by the user in this application. In addition, fuses used outdoors are exposed to contaminants, pollutants, rain, snow, fog, smog, and other conditions (e.g., very high temperatures from direct sunlight or freezing conditions). All of these can affect the fuse's ability to interrupt a circuit and withstand voltage. The manufacturer designs the fuse so that it can withstand these conditions and ensures that it has an adequate sealing system. Only fuses specifically designed for outdoor use should be applied outdoors. If there is a question, the fuse manufacturer should be consulted.

#### 6.2.4.2 Drywell applications of current-limiting fuses

Drywell canisters are utilized to provide access to a current-limiting fuse in a transformer or switchgear housing and permit change out in the event of a fuse operation. The fuse is generally of the standard indoor current-limiting design. Drywell applications may have an impact on a current-limiting fuse's current carrying rating. Not only must heat be transferred from the current-limiting fuse to air in the container, but the heat must also be transferred from the container to its surrounding medium. Fuses used in drywell applications need to be rated for such applications and the current carrying rating may be different than for non-drywell applications. For example, the long-time melting current may be a derated value compared to that where the fuse is applied with free air movement.

#### 6.2.4.3 Under-oil current-limiting fuse applications

Note the remarks in 6.2.2.2 regarding current-limiting fuses. Fuses must be rated for application under-oil or in other fluid. The user should be aware that if oil enters the fuse, improper fuse operation or a failure of the fuse to clear the fault current and interrupt the circuit may result.

Current-limiting fuses designed for direct oil immersion have excellent heat transfer means by the liquid oil. Thus, the long-time melt current may be higher than with the same fuse in air, at the same ambient temperature. As such it may be possible for the fuse manufacturer to assign a higher ampere rating to fuses for use in an under-oil design than in a drywell or in-air design. However, if the fuse is applied inside a transformer, the oil temperature may reach much higher ambient temperatures, which must be considered for determining the maximum overloading permissible.

#### 6.2.4.4 Use of current-limiting fuses near adjacent heat sources

Adjacent heat sources may raise the temperature of the fuse to an unacceptable level that may affect the fuse rating. The manufacturer should be consulted for advice under such conditions. Furthermore, the design of the current-limiting fuse may differ between manufacturers so that the advice from one manufacturer may not be applicable to a replacement product from another manufacturer.

#### 6.2.4.5 Use of current-limiting fuses where there is restricted air flow/cooling

##### 6.2.4.5.1 General

Restricted air flow will reduce the ability of the environment to act as a sink for the heat produced by the current flowing through the current-limiting fuse over a long period of time. Since the fuse cannot dissipate heat as effectively, a derating of the continuous current-carrying rating may result. Subclauses 6.2.4.5.2 and 6.2.4.5.3 detail some of the applications where caution is required due to restricted air flow.

##### 6.2.4.5.2 Use of current-limiting fuses in vaults

Current-limiting fuses in vaults should be rated for the highest ambient temperature anticipated in the vault. If the vault also contains other heat producing devices, such as transformers, then increased ventilating areas may be required. The size of the vault may also influence the air circulation within the vault. A small enclosed vault may trap excess heat and reduce the heat transfer from the fuse, which, as a result, may need to be derated.

##### 6.2.4.5.3 Use of current-limiting fuses in enclosures

Vented outdoor enclosures will be affected by solar heating and therefore, it may be necessary to derate any current-limiting fuses used in the enclosure. Non-vented or poorly vented outdoor enclosures may also require a further derating of the fuse. Consult the manufacturer. Also, note that replacement fuses from another manufacturer may have a different derating factor due to a different design.

#### 6.2.4.6 Use of current-limiting fuses in hazardous environments/conditions

Current-limiting fuses typically do not emit ionized gases from the arc extinguishing process and may be suitable for use where combustible gas may be present in the area surrounding the fuse. The manufacturer should be consulted for all such applications. Without the emission of ionized gases, mounting locations are less restrictive. Caution may still need to be exercised to ensure that disconnecting the fuse does not result in a small arc that could ignite combustible gases. In like manner, operation of indicators or striker pins could result in small external arcs that may pose a problem in some applications.

#### 6.2.4.7 Reuse of current-limiting fuses after interruption

Reuse or rebuilding of a current-limiting fuse is not recommended without the express approval of the manufacturer.

# 7. Current-limiting fuse coordination

## 7.1 General

In general, when two protective devices are in series, it is desirable for the downstream device (the one closest to the load or fault) to operate without causing operation of the upstream device (if this is a fuse, without melting, or damaging, it). This generally limits an outage to the fewest number of customers. It may be said that the downstream device is protecting the upstream device, and some literature may call

them the "protecting" and "protected" devices, respectively, rather than the "downstream" and "upstream" devices. Figure 8 illustrates this concept for fuses.

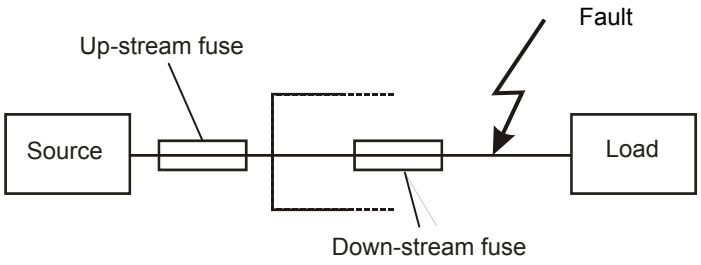



**Figure 8—Description of the terms upstream and downstream fuse**

To achieve this coordination therefore requires that the intersection of the minimum-melt TCC curve of the upstream fuse, modified as detailed below, and the total-clear TCC curve of the downstream fuse should be at a current higher than the maximum available fault current at the location of the downstream fuse.

Per IEEE Std C37.48, a value of 75% of the minimum-melting time of the upstream fuse should be used to make allowance for most operating variables, such as preheating of the fuse element by load and normal variations in ambient temperature. A convenient way to plot the 75% of the minimum-melting time of the upstream fuse with the total-clear time of the downstream fuse is to align the four-second line of the upstream fuse TCC minimum-melt curve with the three-second line of the downstream fuse TCC total clear curve. The shifting of the minimum-melt TCC curve downward to 75% in time results in a curve that will be referred to as "the 75% minimum-melt curve" in subsequent clauses. Another method is to allow a 10% safety-margin in current for any value of time.

When current-limiting fuse coordination at times of less than 0.01 s is required, $I^2t$ characteristics are used as will be explained in subsequent sub-clauses.

For a recloser that is being protected by a downstream fuse (see 7.2.4.5) in overhead applications, the fast (A) curve of the recloser should be below and to the left of the 75% minimum-melt curve of the fuse for all possible fault currents, in order that the fuse not be damaged by a temporary fault. In this case it is the recloser that is actually protecting the fuse.

To prevent an unnecessary time delay operation of the recloser, and possible fuse damage, there should be a 0.2 s margin required between the total-clearing TCC curve of a downstream fuse and the time delay curve of the upstream recloser. On underground circuits, faults will most likely be permanent in nature. Therefore, it is unnecessary for the recloser to reach through the fuse and trip instantaneously for a fault on the load-side of the fuse. Typically, in these situations, the recloser's instantaneous trip would be defeated.

For a fuse protected by a recloser (usually in a step-up or step-down transformer bank situation, see example in 7.2.4.6 ), the time delay curve of the recloser multiplied by the recloser "K" factor shall be below and to the left of the minimum-melt curve of the upstream fuse when they are plotted on the same voltage base. No additional margin is required.

## 7.2 Tap-line coordination

### 7.2.1 General

For many years, current-limiting fuses have been used for tap-line protection of overhead and underground distribution circuits. In addition to the current-limiting aspects of these fuses, they are used because of their

effectively noiseless operation and their high interrupting capabilities. Applying current-limiting fuses as tap-line protection requires considerations not typically encountered with other overcurrent protective devices. With most overcurrent protection devices, miscoordination only results in the nuisance operation of a source-side device. Miscoordination of current-limiting fuses, however, may not only result in the nuisance operation of the fuse but also may result in the failure of the fuse. This sub-clause will outline the requirements necessary to properly coordinate current-limiting fuses applied as tap-line protection.

### 7.2.2 Determining the zone of protection for current-limiting fuses (reach)

#### 7.2.2.1 General

Current-limiting fuses melt and clear overcurrent conditions according to their TCC curves. The minimum current that produces successful fuse melting and interrupting, should be less than the minimum fault current that might develop from a fault at the end of the zone to be protected (the end of the line or the next downstream protection device). The minimum fault current must be determined at each sectionalizing point and at the end of each zone of protection.

A term used in coordination and overcurrent protection work is “reach.” Reach is a measure of the ability of a protective device to sense a fault condition within its zone of protection. It was developed in the context of devices, such as reclosers, that have a clearly defined pick-up value – if a certain current is not available the device will not operate. The word was originally used to describe the ability of a recloser to “reach” beyond the next fuse and operate without the fuse melting. However it is now also used for fuses, and has particular relevance for those fuses having a defined minimum interrupting capability. Such fuses include general-purpose CL fuses that should not generally be subjected to currents between their rated current and their one-hour melting current.

In order to clarify the concept of reach, refer to Figure 9. Consider device A as the device for which a calculation of the reach is desired. Fault current calculation methods are described in IEEE Std 141-1993 and IEEE Std 399-1997.

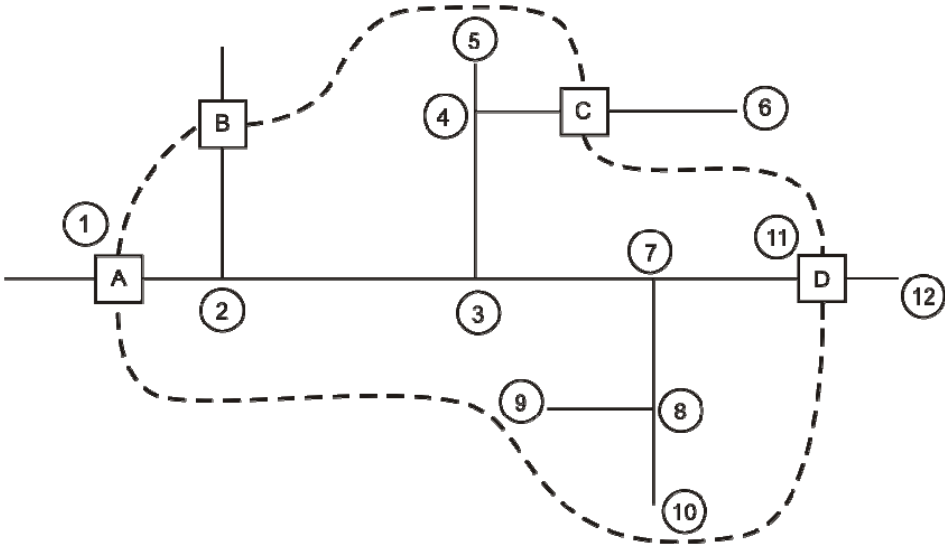



**Figure 9— Reach example**

The zone of protection of device “A” is shown by the dotted line. It terminates at other protective devices (“B”, “C”, etc.) and the end of the radial taps. Assume that the desired operating current (minimum pick up value) of device “A” is 100 A. This is a current that gives a required operating time – for a general-purpose

fuse it might be the minimum one hour melting current. While a fuse may be capable of melting in several hours (e.g., a full-range CL fuse) it is not normally desirable to permit a fault to exist for that long. An appropriate maximum time may therefore be chosen for the minimum device operating current, e.g., 300 s (all fuses have TCC curves drawn to 300 s) or a user might want a shorter maximum fault time. The current is calculated for various points within the zone of protection of the fuse. In the example the lowest prospective current in the zone is at point 10, which produces 300A flowing through fuse "A".

Clearly 300 A would cause the fuse to operate in less than the maximum desired time (for this example 300 s). However, typically, fault currents on distribution circuits are calculated for bolted faults (relatively low resistance faults). In actuality, upwards of 90% of all faults encountered on overhead distribution circuits are temporary in nature (e.g., tree limbs brushing conductors), and many such faults have high resistance, thereby significantly reducing the magnitude of fault current. The possibility of reduced values of fault current must be taken into account when sizing a protective device to reach to the end of its zone of protection. A user can therefore use their experience to determine how much less current there can be, and incorporate an operating margin into the calculation. Typically factors of 3 or less are used. In the above example, the reach margin is :

$$\text{Reach margin} = \frac{\text{(min. fault current through device within zone of protection )}}{\text{(min. current to operate protective device)}}$$

which, in this example, would equal

$$\frac{300\text{ A}}{100\text{ A}} \quad \text{or} \quad \frac{3}{1}$$

This is normally an acceptable margin (it also allows for some errors in calculating the prospective current).

Experience shows that faults are normally either of low impedance, giving currents similar to calculated values, or are of such high impedance that it is very difficult to detect with upstream fuses. Utilities with this experience therefore tend to use lower reach margins.

At least one major utility uses a 3/1 reach margin as the criterion for sizing protective devices. Another major utility states in their standards, "hesitancy to raise ground trip settings for fear of losing the ability to sense low- level ground faults is usually not warranted." Actual field experience with modern protective devices in distribution applications reinforces the belief that measured line-to-ground fault values are either very close to calculated values or much too small to relay effectively using even the most conservative relaying practices. One major utility uses a reach margin of 1.67/1 for phase devices and 2/1 for ground devices. Of course, devices must also be sized based on the full-load current that the device must carry. When the full-load current prevents obtaining the minimum reach margin, the circuit may need to be re-engineered.

#### 7.2.2.2 General-purpose current-limiting fuse reach

It is clear that a general-purpose fuse will be subjected to a fault current at the end of its zone of protection; however it should also be able to interrupt the lowest value of fault current anticipated. Some general-purpose current-limiting fuses can be damaged if they are subjected to a continuous current above their rated continuous current and below their one-hour melting current (given by manufacturer). Either the fuse may melt at a current too low for it to interrupt, or the overload current heats up the fuse causing damage to the fuse components or its holder before the fuse can melt and interrupt the current. Therefore, the reach capability of a general-purpose fuse is largely dependent on its design. Any limitation on overloading must be considered when determining the reach for these fuses.

For example, one manufacturer of a general-purpose current-limiting fuse states that the fuse will carry 100% of the E rating continuously without damage. However, in order to melt and clear properly, the over-

current must be at least 220% of the fuse's E rating. If this fuse is subjected to a continuous current in excess of its rating (up to 220%), it may sustain damage to its fuse body and possibly fail before the element can melt and clear. Therefore, the minimum allowable fault current at the end of the zone of protection to obtain a 3/1 reach with this general-purpose current-limiting fuse would be, Fuse E rating × 2.2 × 3.0 or Fuse E rating × 6.6.

#### 7.2.2.3 Full-range current-limiting fuse reach

The concept of reach, in the case of full-range current-limiting fuses, becomes almost arbitrary considering the low-current interrupting capability of the fuse. However, consideration should be given to whether the fuse will interrupt the low values of fault current before other devices in the system are adversely affected.

One utility's approach is to limit the melting time for a full-range current-limiting fuse at the minimum fault current (including 3/1 reach) within its zone of protection to 300 s or less. This current value can be determined from the minimum-melt TCC curves for the fuse. This helps reduce the likelihood of long-time "burning" of the fault before the fuse interrupts.

To determine reach, the current at which the fuse melts in 300 s or less must be determined. From the minimum-melt TCC curve for one manufacturer's 100 A fuse it can be shown that a current of approximately 220 A will melt the fuse in 300 s. Therefore, to obtain a 3/1 reach, the minimum allowable fault current at the end of the zone protected by this fuse would be as follows: 220 A (current to melt at 300 s) times 3.0 or 660 A. Again, the full-range fuse will satisfactorily interrupt lower currents; however, the above criterion will limit the melt time.

### 7.2.3 Selecting minimum fuse current ratings

Fuses should be sized based on total connected nameplate kVA, magnetizing inrush, and the anticipated peak load conditions as discussed in 6.1.3.1, 6.1.3.2, 6.1.4.1, and 6.1.4.2.

Since magnetizing inrush is a high current for a short duration, the element may melt open where the fuse element has a minimal cross-sectional area. Partial melting of a fuse element may reduce the continuous current capability of the fuse and its ability to withstand additional surges. Depending on the design of the fuse, this could lead to overheating and eventual fuse failure, or the fuse may be melted by a current that does not allow it to clear successfully. Because of this, sizing a current-limiting fuse properly for magnetizing inrush is extremely important.

To evaluate the loading capability of the fuses most used on a distribution system, each fuse's minimum-melt curve should be compared with the magnetizing inrush and the cold-load pick up characteristics of the transformer or circuit it is protecting. The value of current at which the fuse's minimum-melt curve lies completely to the right of each of these points for each case, i.e., cold-load pick up and magnetizing inrush, can be tabulated.

Since the shape of the minimum-melt curve for each fuse varies, some fuses are more suitable for withstanding cold-load pick up than magnetizing inrush and vice versa. This necessitates looking at each fuse individually instead of using a rule-of-thumb such as sizing a fuse for 1.5 times to 2 times the connected load current.

### 7.2.4 Coordinating current-limiting fuses with other protective devices

#### 7.2.4.1 General

Applying current-limiting fuses as tap-line protection requires their coordination with a variety of devices. This subclause will discuss coordination requirements for current-limiting fuses with some of the more commonly used distribution circuit overcurrent protection devices.

In the examples in the following sub-clauses, it has been assumed that all of the other application requirements such as voltage rating, continuous load capability, inrush capability, and interrupting capability have been met.

#### 7.2.4.2 Current-limiting fuse/Current-limiting fuse coordination

The downstream fuse must clear the maximum fault current at its location before the upstream fuse is damaged. To prevent damage to the upstream fuse, the total-clearing time of the downstream fuse should be less than 75% of the minimum-melting time of the protected fuse for all current up to the maximum fault current where the downstream fuse is located.

With higher fault currents, current-limiting fuses are capable of interrupting in less than 0.01 s, which is the shortest time shown on fuse TCC curves. If the TCC curves of the two fuses do not intersect above the 0.01 second line and the fault current at the downstream fuse is of sufficient magnitude, i.e., to the right of where the upstream fuse melt curve crosses the 0.01 second line, coordination in the current-limiting range must be confirmed. For this coordination, 75% of the minimum-melt $I^2t$ for the upstream fuse should be greater than the maximum clearing $I^2t$ of the downstream fuse. This is referred to as "$I^2t$ coordination." The manufacturer's values for minimum-melt $I^2t$ and maximum clearing $I^2t$ of current-limiting fuses should be published and readily available.

An example of current-limiting fuse/current-limiting fuse coordination is as follows: check the coordination between a 125 A full-range current-limiting fuse (CLF) and a 65 A general-purpose CLF as shown at point "A" in Figure 10. Also, verify that the 125 A CLF will be able to operate correctly with faults between it and the 65A fuse (i.e., in its zone of protection).

The TCC curves for this combination are illustrated in Figure 11. Before comparing the fuse TCC curves, verify that the 125 A CLF has adequate reach (can operate with a fault at point "A"). At point "A", the phase to ground prospective current $I_P$ is 900 A (assuming a bolted fault that is a fault having no impedance). A full-range current-limiting fuse can break any current that causes it to melt, so it will operate with a current corresponding to the top of its published minimum pre-arcing TCC curve. However a fault persisting for hours would not be desirable so a Utility will likely pick a shorter time for which they would like fuse operation. If a time of 300 s is chosen as a desirable maximum, the 300 s current for the 125 A fuse is 300 A. Since the phase-to-ground fault current at the 65 A fuse is 900 A, the fuse will melt in less than 300 s. However, another consideration is the fact that actual fault currents will be somewhat less than the calculated value, as a result of fault impedance. In this example, the current could be one third less (a "reach margin" of 3 see 7.2.2.1) and still operate the fuse in less than 300 s.

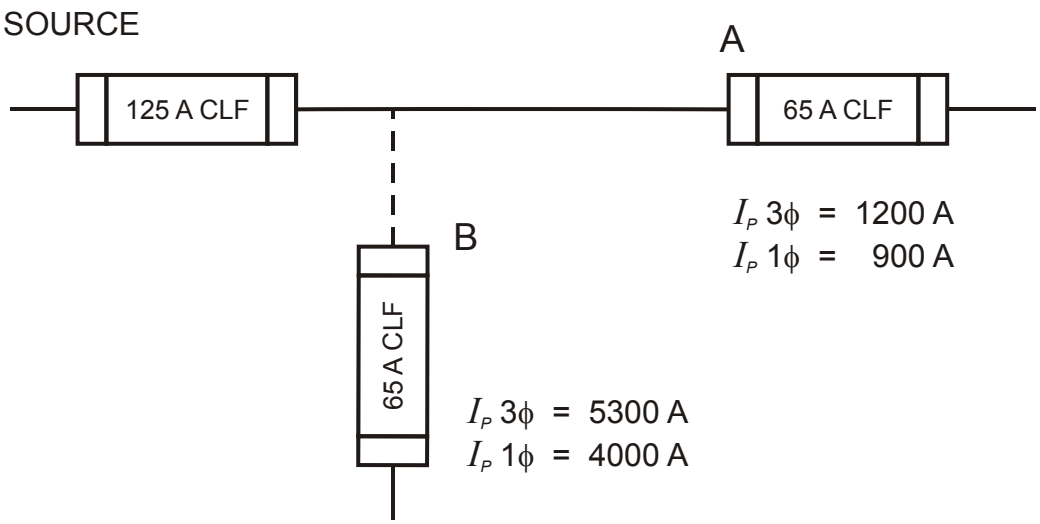



**Figure 10—Current-limiting fuse/Current-limiting fuse example**

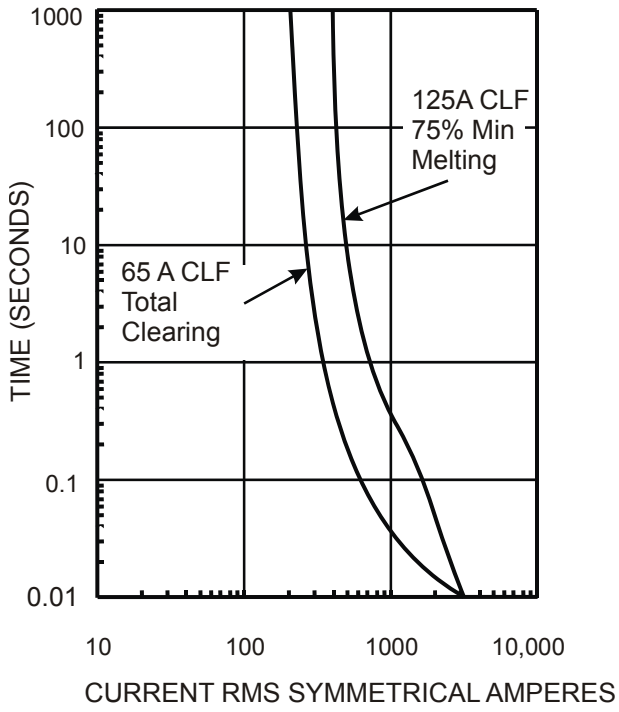



**Figure 11—Current-limiting fuse/Current-limiting fuse TCC curve example**

To check TCC curve coordination between the 125 A and 65 A fuse, draw the 75% minimum-melt curve for the 125 A CLF and the total-clear curve for the 65 A CLF. Note that the curves intersect at approximately 3100 A, and at a time below 0.01 s. Therefore, since the maximum fault current at the 65 A CLF does not exceed 3100 A, time coordination exists. Because the prospective current is less than the point at which the 125A TCC curve crosses the 0.01 s line, $I^2t$ coordination does not need to be checked.

Had the prospective fault current at the 65 A fuse been higher, 4000A for example (position B in Figure 10), then $I^2t$ coordination would have to be checked. The maximum clearing $I^2t$ for the 65 A fuse is 100,000 $A^2s$, while the minimum melting $I^2t$ for the 125 A fuse is 100,800 $A^2s$. In this case, $I^2t$ coordination at 4000A would not be achieved (100,000 $A^2s$ > 0.75 × 101,000 $A^2s$ = 75,750 $A^2s$). If a 150A fuse could be used instead of the 125A fuse (with a melting $I^2t$ of 136,000 $A^2s$) then this would be acceptable (100,000 $A^2s$ < 0.75 × 136,000 $A^2s$ = 102,000 $A^2s$). Reach would still be acceptable because although the 300 s current would be higher (at 350 A) the prospective fault current is also higher. Coordination of the larger 150A fuse with upstream protection would also need to be checked.

#### 7.2.4.3 Current-limiting fuse to Expulsion fuse coordination

In this coordination, the current-limiting fuse is the upstream device. Therefore, the total clearing TCC curve of the expulsion (downstream) fuse should be compared with the adjusted (reduced to 75% in time) minimum-melting TCC curve of the current-limiting (upstream) fuse. Since expulsion fuses clear the circuit at a normally occurring current zero following melting of the element, the minimum total-clearing time for high fault currents, is 0.5 to 0.8 of a cycle depending on the point on the voltage wave that the fault begins. Therefore, the family of total-clearing TCC curves for an expulsion fuse eventually converge on a horizontal line at 0.8 of a cycle (0.014 s). As a result of this convergence, the total-clearing TCC curve of the expulsion fuse will always cross the melt curve of the current-limiting fuse. Therefore, this fuse arrangement can only achieve coordination up to a certain current level, where the two curves cross.

An example of current-limiting fuse/expulsion fuse coordination is as follows: check coordination between a 100 A full-range current-limiting fuse and a 40 A expulsion fuse link as shown in Figure 12. Also, verify that the 100 A current-limiting fuse has adequate "reach" (see 7.2.2) for its zone of protection. The TCC curves for this combination are illustrated in Figure 13.

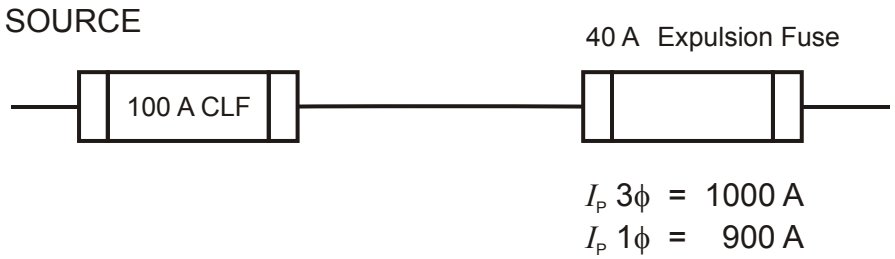



**Figure 12— Current-limiting fuse/Expulsion fuse example**

Before comparing the fuse TCC curves, verify that the 100 A current-limiting fuse has adequate reach. The 100 A fuse must reach to the location of the 40 A fuse link where the calculated fault current of 900 A is the lowest within its zone of protection. For a full-range current-limiting fuse, the fault current should be sufficient to melt the fuse in 300 s or less. The 100 A current-limiting fuse melts at approximately 220 A in 5 min. The ratio between the prospective current at the end of the zone protected by the 100 A current-limiting fuse and the 300 s fuse pre-arcing current is 900/220 = 4.1. This is higher than most normally used reach factors, so the 100 A current-limiting fuse has adequate reach.

To check coordination, draw the total-clear curve of the 40 A fuse link and the 75% minimum-melt curve of the 100 A fuse. The curves intersect at approximately 2800 A. Therefore, since the maximum fault current at the 40 A fuse link is 1000 A, time coordination exists. Had the prospective current been over 2800A, coordination could not be guaranteed and operation of the expulsion fuse could damage the elements of the current-limiting fuse.

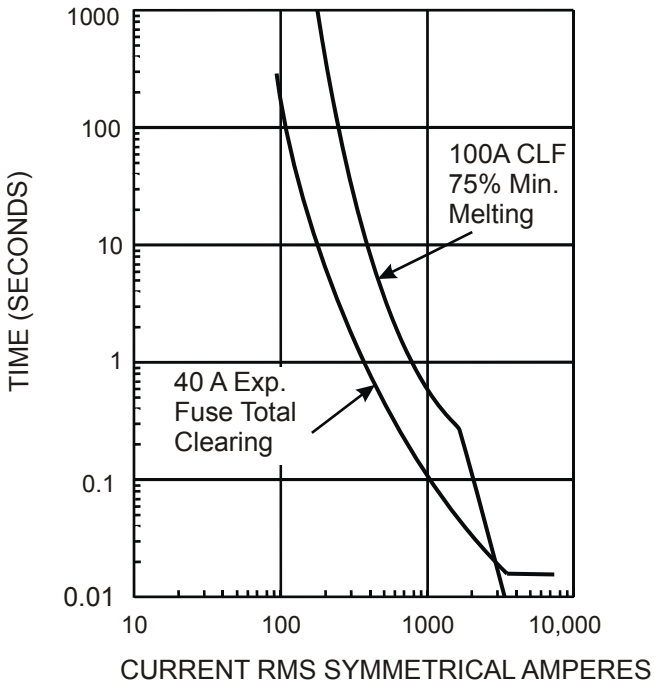



**Figure 13—Current-limiting fuse/Expulsion fuse TCC curve example**

#### 7.2.4.4 Expulsion fuse to Current-limiting fuse coordination

In this coordination, the expulsion fuse is the upstream device. The total-clearing TCC curve of the current-limiting (downstream) fuse must lie to the left of the adjusted (typically downward to 75% in time) minimum-melting TCC curve of the expulsion (upstream) fuse for all current values up to the maximum fault current available at the location of the current-limiting fuse. In addition, if the maximum available fault current at the location of the current-limiting fuse is greater than the current where the current-limiting fuse total-clear curve crosses the 0.01 second line, the maximum clearing $I^2t$ of the current-limiting fuse must be verified to be less than the calculated minimum melting $I^2t$ of the expulsion fuse, adjusted for preloading.

The minimum melting $I^2t$ for the expulsion fuse can be obtained by squaring the minimum melting current of the expulsion fuse at 0.0125 s and multiplying this value by 0.0125 s. Of course, if the manufacturer's $I^2t$ data is available, it should be used.

An example of expulsion fuse/current-limiting fuse coordination is as follows: check coordination between a 150 A fuse link and a general-purpose 80 A CLF as shown in Figure 14. The TCC curves for this combination are illustrated in Figure 15.

To check TCC curve coordination, draw the total-clearing curve of the 80 A current-limiting fuse and the 75% minimum-melt curve of the 150 A fuse link. The curves do not intersect; therefore, TCC curve coordination exists.

Since the maximum available fault current of 5000 A is greater than the current value where the 80 A CLF total-clear curve crosses the 0.01 second line, the maximum clearing $I^2t$ of the 80 A CLF is compared with 75% of the minimum melting $I^2t$ of the 150 A fuse link; the maximum clearing $I^2t$ of the 80 A is 181 000 $A^2s$, as specified by the manufacturer. The minimum melting curve for the 150 A fuse link crosses the 0.0125 second line at approximately 7000 A; therefore,

$(7000)^2 \times (0.0125) \times (0.75) = 460\ 000\ A^2s$ and $181\ 000\ A^2s < 460\ 000\ A^2s$. Since the 80 A CLF maximum clearing $I^2t$ is less than the minimum $I^2t$ of the 150 A fuse link's 75% minimum melting curve, $I^2t$ coordination exists.

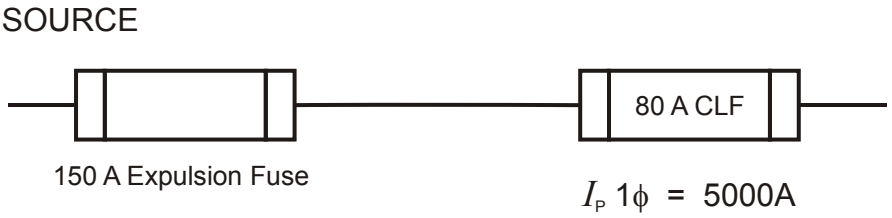



**Figure 14—Expulsion fuse/Current-limiting fuse example**

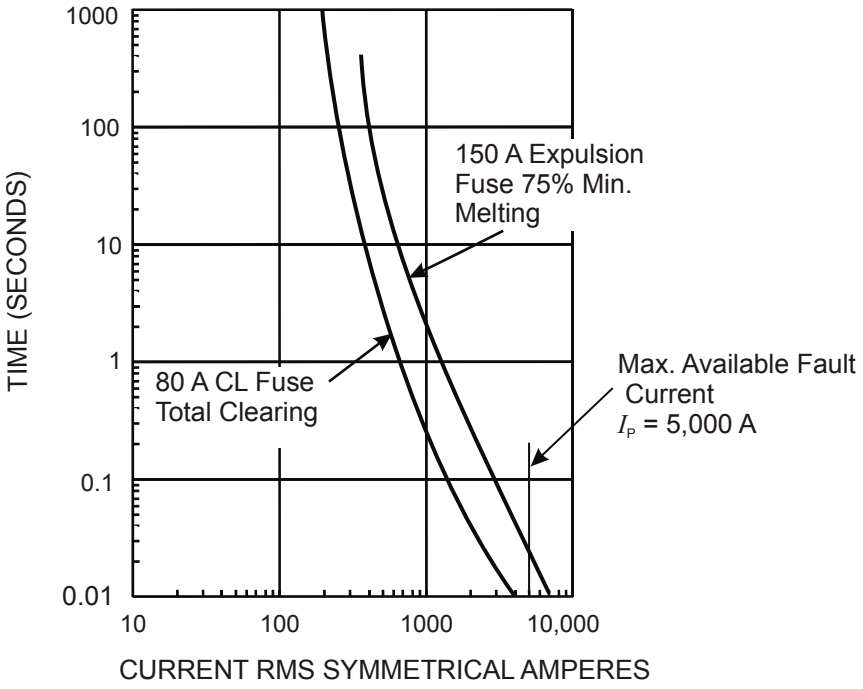



**Figure 15—Expulsion fuse/Current-limiting fuse TCC curve example**

### 7.2.4.5 Recloser/Current-limiting fuse coordination

With coordination of reclosers and load-side current-limiting fuses, the possibility of reclosing into a partially melted current-limiting fuse should be avoided, since the fuse may not satisfactorily interrupt if the element melts while picking up normal line current after a successful reclose. Two scenarios exists requiring different approaches in the application of recloser-current-limiting fuse coordination.

The first scenario occurs when the recloser and fuse are both applied on overhead circuits. In this case, it is common for the recloser to protect the fuse from temporary faults and still have the fuse blow for permanent faults. The recloser should reach through the fuse and trip instantaneously for a fault on the load side of the fuse before the fuse starts to melt. This requires that the crossover of the recloser "A" curve and the 75% minimum-melt curve of the fuse be to the right of the maximum fault current at the location of the

fuse. Once the recloser closes back into the circuit, if the fault is permanent, the fuse should melt and clear before the first time delayed operation of the recloser. This requires that the fuse total-clearing TCC curve be below the recloser "B" curve up to the maximum fault current level at the fuse. If the fault is temporary, the recloser will successfully reclose.

In the second scenario, the recloser is applied on an overhead circuit that has underground dips that are protected by current-limiting fuses. On underground systems or circuits, faults will most likely be permanent in nature. Typically, in these situations, the recloser's instantaneous trip would be defeated. The decision to defeat the instantaneous trip depends on the amount of overhead line exposure and whether overhead fuse taps are also present, making fuse operation during temporary faults undesirable. On totally underground circuits, reclosing is not normally used since the faults are usually permanent and reclosing only causes the fault to be re-energized without restoring service. In situations where the recloser is protecting an overhead circuit that has underground laterals protected by current-limiting fuses, the instantaneous trip of the recloser may be retained if, for faults beyond the current-limiting fuses, the fuses can adequately clear before the recloser trips and interrupts.

One recommended way to meet this requirement is to ensure that the available fault current at the end of the zone protected by the current-limiting fuse is higher than the current at the 0.01 second point of the current- limiting fuse's total-clearing TCC curve. Since most faults on underground systems are of low impedance, the available current should be near the calculated value. If this condition cannot be met, then consideration should be given to eliminating the instantaneous trip curve of the recloser.

An example of recloser/current-limiting fuse coordination is as follows: to determine if a 100 A full-range current-limiting fuse will coordinate with a 160 A recloser (as shown in Figure 16) with one instantaneous trip curve "A" and two time delay trip curves "B," draw the curves and observe the intersection points. Figure 17 illustrates typical TCC curves for this combination. Depending on the application, there are two ways this problem may be approached.


**Figure 16—Recloser/Current-limiting fuse example**

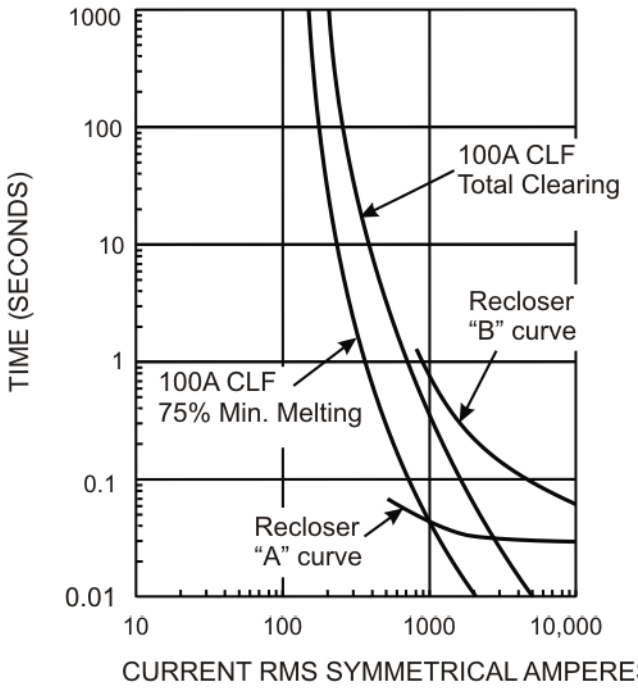



**Figure 17—Recloser/Current-limiting fuse TCC curve example**

If the current-limiting fuse is protecting overhead circuits, the recloser should reach through the fuse and trip instantaneously for a fault on the load side of the fuse, before the fuse starts to melt. This requires that the crossover of the recloser "A" curve and the 75% minimum-melt curve of the fuse be to the right of the maximum fault current at the location of the fuse. In this example, as the curves are drawn, coordination will exist if the maximum fault current at the fuse is 1000 A or less.

If the current-limiting fuse is protecting underground circuits where only permanent faults are expected, the current-limiting fuse total-clearing TCC curve should cross the 0.01 second line to the left of the maximum fault current at the end of the zone protected by the fuse. In this example, as drawn, the fault current must be approximately 5 000 A or higher for coordination to exist. If the fault current is not sufficiently high, then the recloser instantaneous trip should be removed to make sure the fuse totally clears, avoiding a partial melting condition. Studies have shown on overhead systems that a high percentage of faults are temporary in nature and "fuse saving" schemes are commonly used.

However, another protection scheme that is gaining in popularity is coordination that minimizes momentary outages. For many customers, in today's environment, with electronic clocks, computers, DVRs, and other electronic devices, a momentary outage is approaching the same importance as a sustained outage. The scenario described above subjects a substantial number of customers to momentary outages. It may be possible to limit the number of customers exposed to momentary outages by not using the instantaneous recloser settings. With one or two time delay curves programmed into the recloser, faults on the load side of the fuse will simply blow the fuse.

The advantages of this coordination scheme are as follows:

— None of the customers on the load side of the recloser are subjected to a momentary outage for a fault on the load side of one of the tap fuses.

— The problem area for temporary faults is easily identified, because, in this scheme, the fuse will always blow.

The fault can then be found during a subsequent patrol and inspection of the circuit. The decision on which scheme to choose will likely depend on such factors as the incidence of customer complaints, the type of exposure (e.g., trees, lightning) on the line being protected, and the accessibility of the line(s) being protected. On long rural lines where there is substantial line impedance between the fault and the source, the voltage dip during fuse clearing may be enough to appear as a temporary outage to some of the customers on the circuit because of the long clearing time of the fuse at the reduced fault current level. In this case, the number of customers exposed to the momentary outages did not change even though the instantaneous recloser settings are not used. Another consideration is that, if the fuse clears all temporary faults, the actual cause of the fault may not be visually apparent (tree brushing line, lightning flashing over an insulator, etc.). By keeping the instantaneous trip of the recloser, the faults are not generally cleared by the fuse unless it is permanent, in which case the cause is probably easier to find.

#### 7.2.4.6 Current-limiting fuse/Recloser (step-down) coordination

This combination is typical for protection of step-up or step-down transformers. For the step-down application, it is generally desired that the recloser on the low side of the step-down transformer operate to lock out without damaging or blowing the high-side fuse.

There are two approaches that can be used to check coordination. A conservative approach would be to add up all the recloser times for the fast and time delay curves to generate a composite curve to compare with the fuse 75% minimum melt curve. This approach ignores any fuse cooling that would occur during the recloser open times as it goes through its reclosing sequence. As such, it is very conservative.

A more realistic approach is to recognize the cooling of the fuse during the recloser open times. The longer the recloser is open, before reclosing, throughout its operating sequence, the more time the fuse has to cool before the next fault current is applied. Conversely, if the recloser closes very quickly in its sequence, the fuse has little time to cool and so will melt more quickly. Multiplying factors called “K” factors were developed specifically for tin element expulsion fuse links. These are applied (time multiplied by the “K” factor) to the time delay curve of a recloser (see Table 5). The “K” factors incorporate the cumulative heating resulting from the recloser operations (fault current), the cooling from the recloser open times, the fuse link 75% minimum melt “damage” curve, and recloser timing tolerances.

**Table 5—Multiplying factors for given sequence (“K” factors)**

| Open time in seconds | 2-Fast 2-Delayed | 1-Fast 3-Delayed | 4-Delayed | 1-Fast 2-Delayed |
|---|---|---|---|---|
| 0.5 | 2.6 | 3.1 | 3.5 | 2.5 |
| 1.0 | 2.1 | 2.5 | 2.7 | 2.0 |
| 1.5 | 1.85 | 2.1 | 2.2 | 1.8 |
| 2.0 | 1.7 | 1.8 | 1.9 | 1.65 |
| 4.0 | 1.4 | 1.4 | 1.45 | 1.35 |
| 10.0 | 1.35 | 1.35 | 1.35 | 1.35 |

As mentioned previously, the “K” factors were applicable to the heating and cooling effects for tin element expulsion fuse links. They also depend on timing of the delay trip and the open time of the recloser. For some current-limiting fuse designs, where the heat is rapidly transferred from a notched area of the element into the surrounding medium or the larger, and therefore cooler, cross-sectional area of the element itself, the open time of the recloser may be sufficient to provide adequate cooling and the “K” factor may be near unity. For specific cases, it is suggested that this be discussed with the recloser and fuse manufacturers.

Coordination exists when the minimum-melt curve of the fuse lies above this adjusted curve. For example, if the "B" curve of a recloser clears a 1000 A fault in 0.1 s, and the "K" factor is 1.7, then the melt time from the fuse's minimum-melt curve must be greater than 0.17 s at 1000 A [i.e., (1.7) × (0.1)].

An example of fuse-recloser (stepdown) coordination is as follows: Coordination between the high-side fuse and the low-side recloser on a 2500 kVA, 34.5 kV to 12.47 kV grounded wye-grounded wye stepdown transformer is shown in Figure 18. The high-side fuse for this transformer is an 80 A CLF. A single-phase 140A recloser is set with an operation sequence of one fast (A) and two time delay (B) curves and a 2 s open time to best suit the needs for protecting the low-side of the step down transformer. Check coordination of the recloser with the high-side fuse.

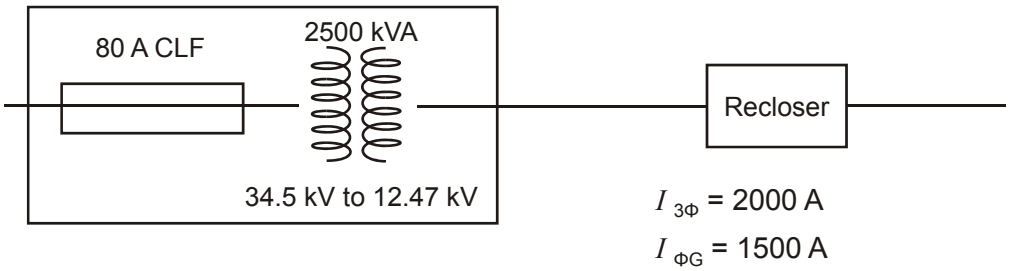



**Figure 18—Current-limiting fuse/Recloser example**

The fuse and recloser are applied at different voltage bases, therefore, the characteristics of one of the devices will have to be reflected through the transformer turns ratio. For this example, the fuse minimum-melt TCC curve has been reflected to the low side of the transformer. To accomplish this, multiply the current values of the fuse minimum-melt curve by the ratio of the primary voltage to the secondary voltage or 34.5/12.47.

Compare the minimum-melt curve of the 80 A CLF reflected to the low-side of the transformer to the recloser "B" curve multiplied by its "K" factor. In this case, a conservative value of 1.65 (i.e., a factor that is used for tin element expulsion fuse links, which tend to cool more slowly than current-limiting fuses) was selected as the "K" factor, since a value for this current-limiting fuse was not available. As shown in Figure 19, coordination exists since the minimum-melt curve for the 80 A current-limiting fuse is slower than 1.65 times the 140 A recloser "B" curve up to the maximum available fault current of 2000 A at the location of the 140 A recloser.

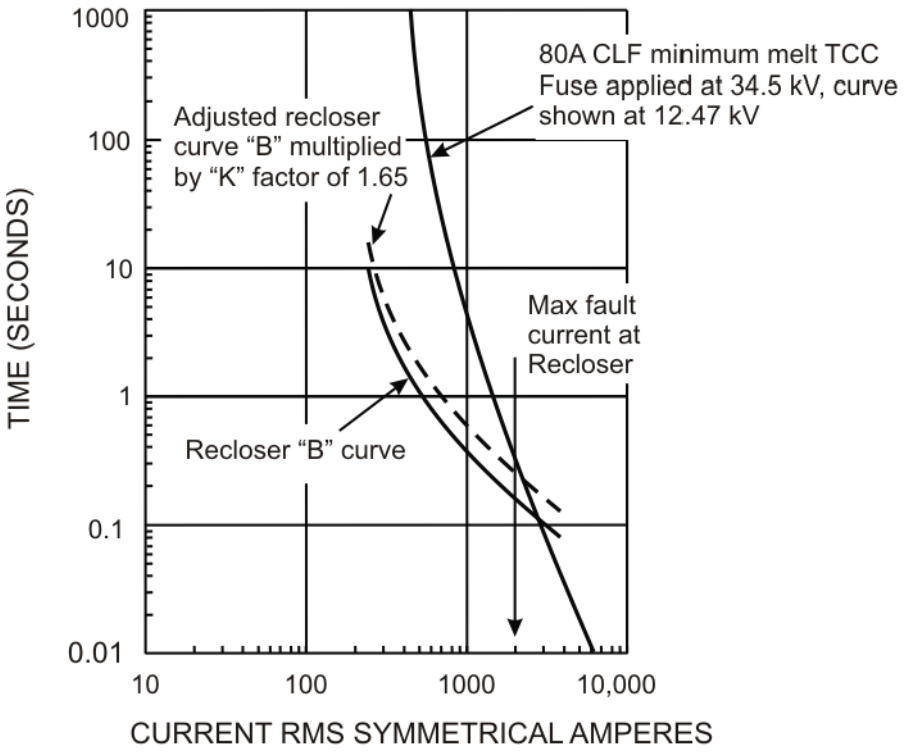



**Figure 19—Current-limiting fuse/Recloser TCC curve example**

## 7.3 Coordination of motor-starter current-limiting fuses and other protective devices

In applying a fuse to motor-starting equipment, it is necessary to coordinate the fuse and the motor-starter components so that the fuse will be protected against unnecessary operation during motor starting or expected overload conditions. In a properly coordinated protection scheme, the thermal or overload relays will protect the motor for currents below the maximum interrupting rating of the contactor and the fuse will protect the motor from short-circuit currents.

An example of proper coordination between motor starter current-limiting fuses and other protective devices is as follows: A 2400 V, 625 kW (700 hp) motor is chosen for this study. The full load current at rated voltage for this motor is 151 A. A current transformer with a ratio of 200/5 has been chosen to trip the thermal relays. The CT secondary current for the rated motor full load current is 3.775 A. The thermal overload relay for this application has a rated tripping current of 4.68 A. Thus, the thermal relay will not pick up during normal motor operation. The relay tripping current translates to 187 A on the primary circuit. A schematic layout of the system is presented in Figure 20. For this motor (NEMA Code F), the locked rotor current is 800 A and the starting time is 0.2 s. The relay's tripping characteristics should lie to the right of this point to avoid nuisance contactor tripping during starting. The locked rotor current of 800 A is adjusted to 880 A to account for variation in supply voltage. For this application, if the motor has not started within 5 s, the thermal overload relay will open the contactor between 5 to 10 s. A 6R fuse will not withstand the 880 A starting current since it will melt in about one second. A 9R fuse will not melt open because the relay will open the contactor for all long-time low currents, thus protecting the fuse from melting below its rated minimum interrupting current. The fuse (9R) will open and interrupt the circuit for all currents above the current where the two curves intersect, thus protecting the contactor from interrupting currents beyond its capacity. The normal range of interrupting capacity for contactors is 4000 to 6000 A. Thus, in this study, the two devices together provide protection to the motors for the entire range from overloads to the maximum interruption current (rms symmetrical) of 50 000 A. The 9R fuse can carry the

full-load current of the motor since it has a continuous current rating of 200 A in an ambient temperature of 40 °C.

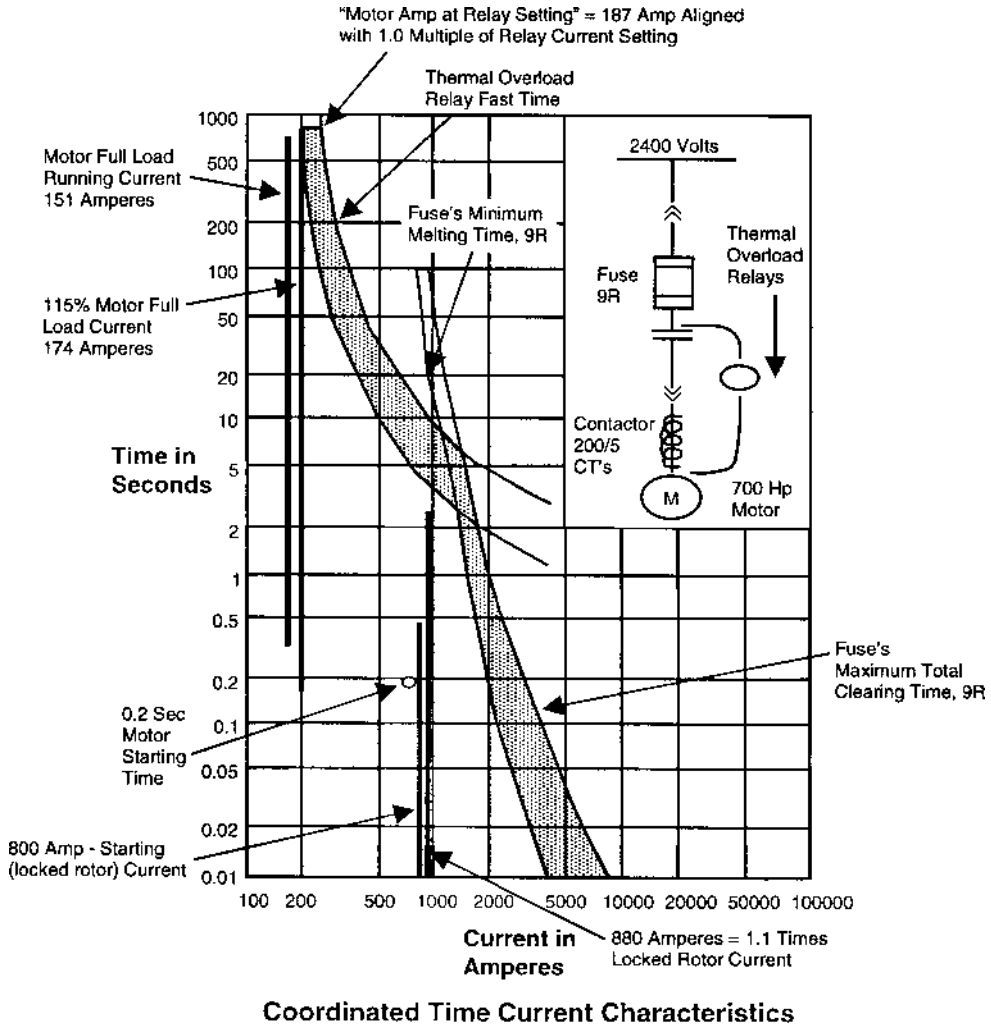



**Figure 20—Schematic of motor protection system**

## 7.4 Backup current-limiting fuse coordination

### 7.4.1 General

A backup fuse can interrupt any current between its rated minimum interrupting current and its rated maximum interrupting current. If a backup fuse is melted open at a current less than its minimum interrupting rating, the fuse may not interrupt the circuit. Because of this, a backup fuse should not be used in applications where it will be required to interrupt currents less than its rated minimum interrupting current. This leads to particularly rigorous coordination rules being needed for the successful application of backup fuses. The backup fuse is always applied in series with another interrupting device that will interrupt currents below its rated minimum interrupting current. The series device may be another fuse or a breaker. In some cases, currents below the fuse's rated minimum interrupting current may be interrupted by a device that is tripped by a striker, deployed when the backup fuse's element(s) melt open and begin to arc. This device is coordinated to protect the backup fuse from failure. Special testing of the fuse (not covered

in the IEEE C37 series of fuse standards) is necessary for this type of coordination to be successful (see IEC 60282-1). More commonly, expulsion fuses are used with backup fuses to achieve the necessary low current interrupting capability.

A backup fuse used outdoors in series with a fuse cutout presents a special case of coordination. Typically, backup fuses used in this application are rated by the largest expulsion fuse link with which they may be used, while still meeting coordination rules. For example a backup fuse that can be used with a 12 A type K expulsion fuse link may be designated as being a 12K coordinating fuse.

For all types of backup fuses, the fuse manufacturer's recommendations for application should be followed. If the manufacturer's recommendations are not available, some of the following coordination information may apply.

Four fundamental areas have to be addressed to ensure that proper coordination exists between backup fuses and series-connected low current interrupting devices. Because the series connected device is frequently an expulsion fuse, this is the series device that will be discussed in the following paragraphs. However, the protection principles involved are the same for other series devices.

First, each fuse must protect the other in its area of non-operation; second, unless the backup fuse is to be replaced after each expulsion fuse operation it must not be damaged by such an operation; and third, overload currents must not damage the backup fuse. The fourth area, strictly speaking, is not directly related to the coordination with the expulsion fuse, but it is the requirement that the backup fuse, like the expulsion fuse, is not damaged by surges, such as transformer inrush current. The same rules that are used to select an expulsion fuse for this requirement also apply to the backup fuse, and so this area will not be discussed further. However, it may be noted that if the expulsion fuse has been correctly chosen, a backup fuse that coordinates correctly with it usually meets those same surge requirements.

### 7.4.2 Devices protecting each other

#### 7.4.2.1 General

Primary coordination between the series expulsion fuse and the backup current-limiting fuse ensures that the two will work together to clear all currents from the lowest current that will cause the expulsion fuse's element to melt up to the current corresponding to the rated maximum interrupting current of the current-limiting fuse. Achieving this primary coordination requires that when the appropriate time-current-characteristic curves for the two devices are overlaid, **the total clearing time-current-characteristic curve of the expulsion fuse must cross the minimum melting time-current-characteristic curve of the current-limiting fuse at a point corresponding to a current that is greater than the minimum interrupting rating of the current-limiting fuse, but less than the maximum interrupting rating of the expulsion fuse.** When this occurs, each fuse protects the other fuse in its zone of "vulnerability." The curves must always cross at a current higher than the minimum interrupting rating of the backup fuse, or it may be called upon to try and interrupt a current that it cannot. Depending upon the relative location of the two curves, one of two different types of coordination will exist. These two methods of coordination are commonly referred to as "matched melt" coordination and "time-current curve crossover" coordination, although matched melt coordination should in fact be considered a form of time-current curve crossover coordination with some additional requirements. Figure 21 and Figure 22 illustrate the principles involved.

#### 7.4.2.2 Matched-melt coordination

For this method of coordination, in addition to the basic coordination rules described above, another criterion must be met. This is to ensure that the expulsion fuse melts open any time the two-fuse combination clears an overload or fault. In general, matched melt coordination will result in the minimum

melting time-current-characteristic of the expulsion fuse lying to the left of the minimum melting TCC of the backup fuse for all times longer than 0.01s, as shown in Figure 21. However, this is not a reliable method of ensuring that the expulsion fuse will melt at times shorter than 0.01s. To be certain that the expulsion fuse will always melt open at any current which causes the current-limiting fuse to operate, the minimum clearing $I^2t$ let through by the current-limiting fuse should be equal to, or greater than, the maximum melting $I^2t$ of the series expulsion fuse., at 0.01s and less. It is this criterion from which the method's name is derived.

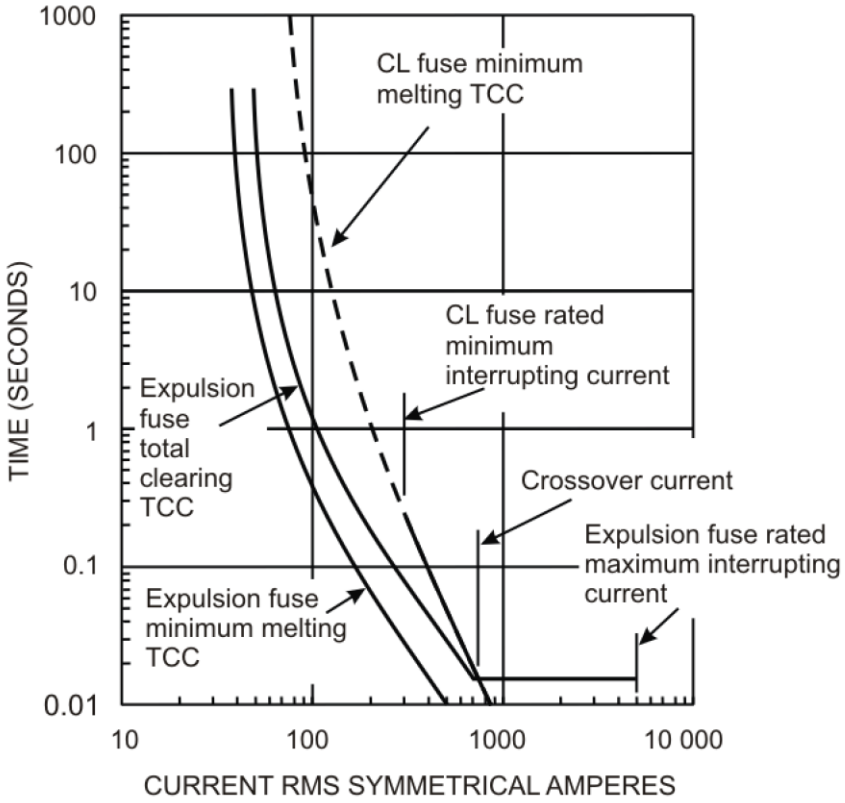



**Figure 21—Matched-melt coordination example**

One conservative approach to ensuring that the current-limiting fuse will let through sufficient energy to melt open the expulsion fuse is to choose a current-limiting fuse having a minimum melting $I^2t$ greater than the maximum melting $I^2t$ of the expulsion fuse used in series with it. However, a more practical approach is to take into account the fact that the current-limiting fuse will, under almost all practical circumstances, let through more $I^2t$ than its minimum melting $I^2t$. Minimum melting $I^2t$ values correspond to very short fuse melting times, and worst-case manufacturing tolerances. Therefore, not only will the actual $I^2t$ that causes melting likely be higher than the published minimum values, additional $I^2t$ will be let through as a result of the current during the arcing that occurs after melting, and which continues until the fuse has cleared. Experience has shown that excellent coordination can be realized as long as the maximum melting $I^2t$ of the expulsion fuse does not exceed approximately twice the minimum melting $I^2t$ of the current-limiting fuse. The only circumstances under which such an approach could result in the failure of the expulsion fuse to melt open is if a very short duration surge of current (e.g., a lightning surge) were to occur and its magnitude just happened to be such that the $I^2t$ of the surge exceeded the melting $I^2t$ of the current-limiting fuse, but was less than the melting $I^2t$ of the expulsion fuse. Obviously, such a situation would very rarely develop, and thus need not be a significant consideration in selecting the best current-limiting fuse for a particular application.

As is obvious from the preceding discussion, in order to use the matched-melt method of coordination, one must know the values of the short-time maximum melting $I^2t$ for the expulsion fuse and the minimum melting $I^2t$ for the current-limiting fuse. Although the latter is usually included in the performance data published by the current-limiting fuse manufacturer, the expulsion fuse manufacturer does not normally publish the former. However, it can be readily calculated from the expulsion fuse's minimum melting time-current-characteristic curve. One method of calculation involves first determining the current corresponding to the value of time representing the fewest whole number of quarter-cycles. For many published curves this might be the current corresponding to three (3) quarter cycles (0.0125 s). Once the current has been determined from the expulsion fuse's minimum melting curve, it should be increased by an appropriate factor to take into account variations resulting from manufacturing tolerances. In the case of expulsion fuses having silver elements, this factor is 10%. For fuses with elements made from other materials, this factor is normally 20%. After the current has been corrected to allow for manufacturing tolerances, the maximum melting $I^2t$ of the expulsion fuse can be calculated by first squaring this current and then multiplying that value by the time (expressed in seconds) that was the basis for determining the current. Obviously, should the expulsion fuse manufacturer publish a value for the fuse's maximum melting $I^2t$, that value should be used rather than the value that one would obtain from the previously described procedure.

The principal advantage of the matched-melt method is that the expulsion fuse will melt open even if the current-limiting fuse does the actual clearing. This is the approach that should be used with those backup current-limiting fuses that may not have a long-term voltage withstand capability. When applied in series with a fuse cutout, the melting open of the cutout link ensures that the fuseholder will always drop open. Having the cutout drop open provides a visual indication as to the location of the fault that caused the fuses to operate and also serves to remove the voltage stress from the current-limiting fuse which has operated. The latter function is also accomplished by any other type of expulsion fuse that would be used in series with the current-limiting fuse. Therefore, when the current-limiting fuse is properly coordinated with any series-connected expulsion fuse using the matched-melt method, the current-limiting fuse is not likely to have the system's voltage impressed across it after it has operated.

Another advantage of this coordination method is that in most three-phase applications, the voltage rating of the backup current-limiting fuse need only be equal to the system's line-to-neutral voltage as long as the voltage rating of the expulsion fuse is equal to the system's line-to-line voltage. This is the main reason why this coordination method is sometimes used with the under-oil backup current-limiting fuse.

#### 7.4.2.3 Time-current curve (or melt-clear) crossover coordination

The second method for coordinating backup current-limiting fuses is referred to as time-current curve crossover coordination. This method of coordination is frequently used with under-oil backup current-limiting fuses, and is illustrated in Figure 22. In the example shown, the minimum melting TCC curve of the expulsion fuses crosses the minimum melting TCC curve of the expulsion fuse at a time longer than 0.01 s, making it less likely that the combination would meet the requirements for matched melt coordination. When a fault current is higher than this crossover point, the current-limiting fuse may melt and clear without letting through sufficient energy to melt the expulsion fuse. Time-current curve crossover coordination is rarely used in applying outdoor backup current-limiting fuses, since there is no assurance that a series cutout would melt and drop open using this method. If the cutout does not open, full voltage can be impressed on a weathered outdoor backup fuse that may no longer have full voltage withstand capability.

Because of the location of the intersection or crossover point of the expulsion fuse’s total clearing TCC curve and the backup fuse’s minimum melting TCC curve, one need not be concerned with the melting $I^2t$ values of the two fuses when using this method of coordination. The principal criterion to be satisfied is that the previously discussed crossover point must correspond to a current which is greater than the rated minimum interrupting current of the current-limiting fuse, but less than the rated maximum interrupting current of the expulsion fuse. The manufacturers of the expulsion fuse and the current-limiting fuse are required to publish values for these performance characteristics.

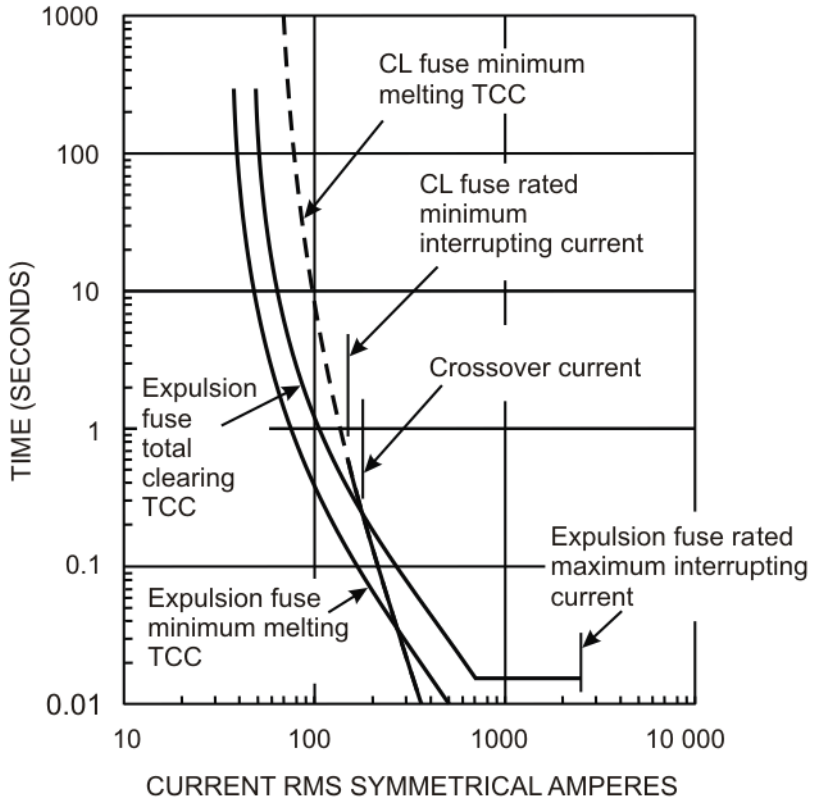



**Figure 22—Time-current curve crossover coordination example**

The principal advantage of the time-current curve crossover method, compared to matched melt coordination, is that it normally permits the use of a fuse having a smaller current rating. This can be significant in several regards.

First, the lower the current-limiting fuse's current rating is, the less energy it is apt to let through under fault conditions. Obviously, the lower the energy that is let through by the current-limiting fuse, the better the protection will be against eventful failure anywhere on the system that is protected by the current-limiting fuse. In addition, the fault will have less effect on the rest of the distribution system as voltage drops are minimized.

Second, the lower the current rating of the current-limiting fuse, the smaller it is apt to be and the less space it is apt to require for installation.

Third, when this method of coordination is used rather than matched melt coordination, often the largest available backup fuse rating can then be used to protect larger transformers.

### 7.4.3 Prevention of damage to the backup current-limiting fuse

For applications of backup current-limiting fuses on the primaries of transformers, there is another selection criterion that is particularly important from the standpoint of serviceability and operability. The concepts to be discussed are illustrated in Figure 23, and involve currents up to the value corresponding to a bolted fault at the secondary terminals of the transformer (that is a fault limited only by the transformer's impedance). A current-limiting fuse should be chosen such that this current is less than the current corresponding to the crossover point of the expulsion fuse's total-clearing curve and the backup fuse's minimum melt curve by an appropriate margin. This ensures that the backup fuse does not melt with, and more importantly is not damaged by, a fault external to the transformer. A damaged backup fuse could later

melt at a current below its rated minimum interrupting current and fail to interrupt this current. The "appropriate margin" will therefore now be discussed.

Although not published by the fuse manufacturer, one can envision a "no-damage" characteristic curve, which lies slightly below and to the left of the minimum melting curve of a backup current-limiting fuse. The separation between the published minimum melting curve and the imaginary no-damage curve represents a margin of safety and is intended to compensate for various factors associated with real life (practical) applications. Some factors affect the accuracy of the calculation of the bolted secondary fault current. These include the tolerances on the transformer impedance, system line voltage fluctuations, and the use of taps. Other factors involve actual damage to the fuse element(s), caused by partial melting and mechanical stress, which can occur prior to the complete severing of the element. Only after the element(s) completely melt open can arcing be initiated, indicating the end of the "melting time", and it is this time that is used to plot the TCC curve.

If the fuse manufacturer has a recommended margin, this should be used. In the absence of appropriate information, a commonly used method involves setting the no-damage current equal to 80% of the current shown on the minimum melting curve for any particular melting time. Since proper coordination between the backup current-limiting fuse and the series expulsion fuse requires that the current-limiting fuse not be damaged by any current equal to or less than the bolted secondary fault current, this method requires that the calculated bolted secondary fault current be no greater than 80% of the current-limiting fuse minimum melting current at a time corresponding to the total-clearing time of the expulsion fuse (with a current equal to the bolted secondary fault current). Conversely, the backup fuse's minimum melt current must equal at least 125% of the calculated bolted secondary fault current at a time corresponding to the expulsion fuse's total-clearing time at that current.

When a backup current-limiting fuse has been chosen using appropriate bolted secondary fault current coordination, it is not necessary to provide access to permit a current-limiting fuse located inside the transformer to be replaced "in the field". If bolted secondary fault coordination is **not** achieved, then **the backup fuse must also be replaced** any time the expulsion fuse operates.

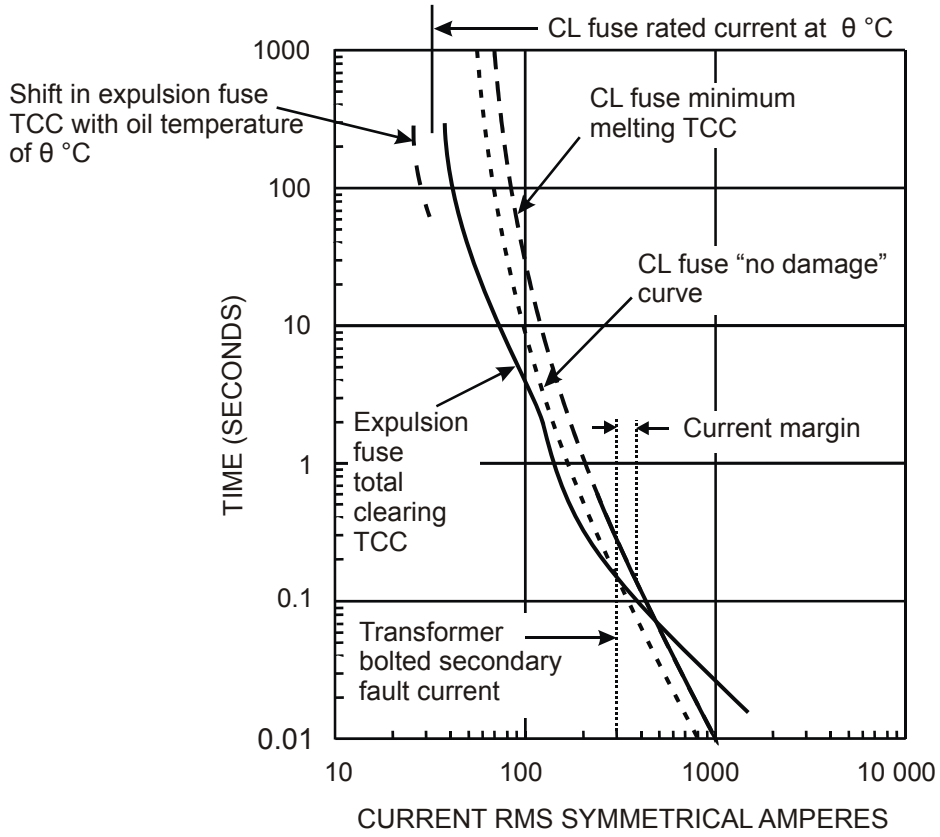



**Figure 23—Fuse "no-damage" margin**

### 7.4.4 Overload protection for the backup current-limiting fuse

There is another aspect of coordination that must be considered before one can be sure that a backup fuse is properly coordinated. This requires that checks be made to show that the backup current-limiting fuse will not melt or be damaged as a result of overloads. This is also illustrated in Figure 23. First, when the backup fuse is used for transformer protection, the total-clearing TCC curve of the expulsion fuse should not cross the no-damage curve discussed in 7.4.3, for all currents below the bolted secondary fault current of the transformer. This is particularly important for "dual-element" expulsion fuses that may have a "knee" that causes the curve to approach the backup fuse minimum melting curve at times longer than those considered during the coordination described in 7.4.3. In other words, for all expulsion fuse clearing times from the value corresponding to the clearing time at the bolted secondary fault current up to 1000 seconds or more, the corresponding current on the expulsion fuse's total-clearing TCC curve should be no more than 80% of the corresponding current on the current-limiting fuse's minimum melting curve (unless the fuse manufacturer specifies a different no-damage criterion). Preloading should not affect this coordination as any shifting to the left of the characteristic curves due to $I^2R$ heating of the fuse elements, or ambient oil temperature rise will be as much or more for the expulsion fuse as for the current-limiting fuse.

The second condition to be satisfied is that under pre-loaded conditions, the maximum current that the expulsion fuse can carry without melting for a relatively long period of time (i.e., greater than five minutes) must be less than the maximum continuous current rating of the current-limiting fuse. When the expulsion fuse is located inside equipment, such as a transformer, any shifting of the curve caused by temperatures produced by overload conditions should be taken into account when this criterion is examined. For example, some types of expulsion fuses experience a significant shift in their total-clearing TCC curve at elevated temperatures. A "dual" element type fuse in oil at 100 ºC can have its long time melting

characteristic shifted, in terms of current, to about 60% of the values published at 25 ºC. Overload protection for the backup fuse can also be provided by secondary protection.

## 7.5 Coordinating current-limiting fuses with arresters

Since current-limiting fuses generate a substantial peak arc voltage during fault interruption, consideration has to be given to their coordination with source side arresters. While transformer and other equipment insulation does not appear to be adversely affected by the operation of current-limiting fuses, the peak arc voltage may be high enough to drive a source-side arrester into conduction. The energy from the system during the high arc voltage phase of the fuse clearing may, under certain rare circumstances, exceed the capability of the arrester. With the advent of MOV arresters this situation is rare, since even if a fuse arc voltage causes an arrester to conduct (for example, with a low current rating wire element fuse) the peak of the arc voltage is brief and the MOV arrester quickly stops conducting. On the occasions when arrester conduction occurs with a silicon carbide "gapped" arrester, the resistance of distribution arresters is high enough so that damage to the arrester would not be expected. Experience with applying current-limiting fuses over the past several years indicates that problems of arrester damage as a result of fuse operation have been rare.

An arrester on the load side of the current-limiting fuse is not vulnerable because it is neither exposed to the peak arc voltage generated by the fuse nor is it subject to the possibility of excessive energy from the system. Thus, it may be desirable to have the current-limiting fuses on the source side of the arrester for a transformer installation, recognizing that other arresters on the source side of the fuse may remain vulnerable. The disadvantage of this arrangement is that lightning surges passing through the arrester also pass through the CL fuse (and expulsion fuse if a cutout/backup fuse combination is used). Occasional lightning surges will be large enough to cause nuisance operation of the fuse(s).

# Annex A

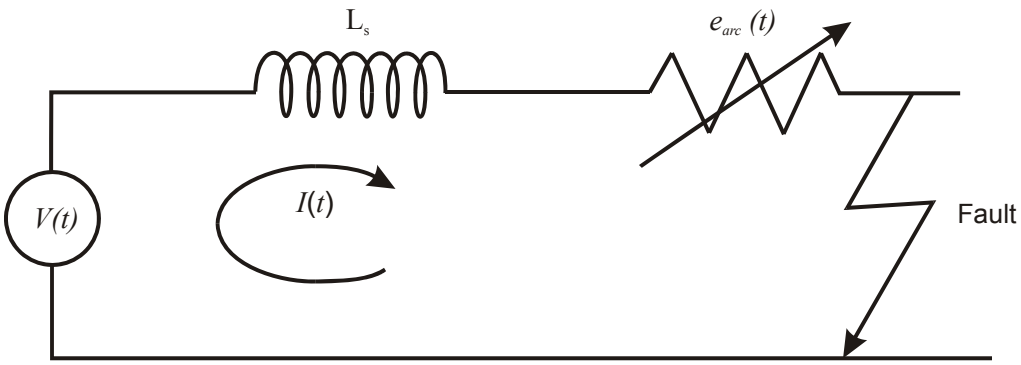
(informative)

# Theoretical treatment of current interruption by a fuse

## A.1 Introduction

During normal circuit conditions, a fuse does not appreciably affect the flow of current in a given circuit. Interruption of current in an electric circuit by a fuse requires the opening of a fusible element, a transition to a non-conducting state, and the ability to withstand the transient and steady-state circuit recovery voltages. Circuits can be inductive, capacitive, or resistive. This discussion is limited to highly inductive fault circuits and to abnormally overloaded circuits with a power factor of less than one.

Depending on the current-interruption technique employed by a fuse, it may or may not significantly modify the characteristics of the circuit that it protects during the interruption process. In principle, current-limiting fuses are energy absorbing, arc constricting devices, which appreciably modify the circuit during the interruption process to force an early current zero when interrupting high magnitude faults. By comparison, expulsion and other types of non-current-limiting fuses do not constrict the arc to the same degree and therefore do not significantly modify the circuit during the interruption process. As such, they wait for a normal current zero to occur before interrupting the circuit. Current-limiting fuses, when interrupting overload and lower-level fault currents, well below their maximum interrupting rating, may also function as non-circuit-modifying devices.




Where:
$V(t)$ = source voltage
$e_{arc}(t)$ = arc voltage of the fuse
$I(t)$ = current
$L_s$ = source impedance

**Figure A.1—Simpllified fault-current circuit**

The interruption process begins upon melting of the fuse element and establishing of an arc across the associated gap. The ability to modify the circuit during the interruption process is a function of the arc resistance and associated arc voltage of the fuse once it has melted. The effect may be demonstrated with the aid of the simplified fault circuit in Figure A.1. The voltage of the source is designated v(t). Generally,

one can assume that the primary impedance of this source is reactive and is based upon its inductance L. The arc of the melted fuse element has some variable magnitude of resistance and associated arc voltage, e arc (t). Two basic equations can aid in understanding the interactions. The loop equation can be written as Equation (A.1).

$$V(t) - e_{arc}(t) = L_s \, di/dt \quad \text{(A.1)}$$

Accordingly, the introduction of a relatively low arc voltage has little circuit modifying effect. When solved for current we have Equation (A.2).

$$I(t) = 1/L_s \int [V(t) - e_{arc}(t)] \, dt \quad \text{(A.2)}$$

This equation illustrates the following concepts:

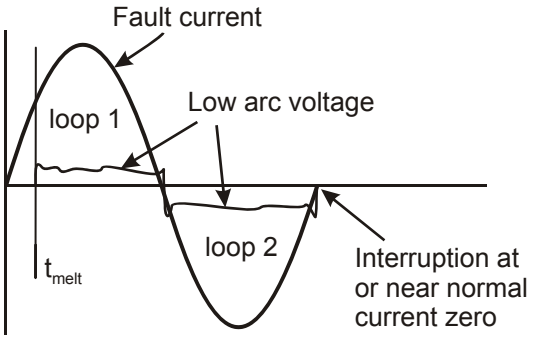
a) The current is proportional to the area under the voltage traces, specifically, their difference. The inductance provides a stored energy and the necessary voltage to sustain the current even though the instantaneous arc voltage of the fuse may momentarily exceed that of the source.

b) A higher source voltage will yield a higher prospective fault current.

c) A higher fuse arc voltage sustained over time will result in greater limitation of that fault current.

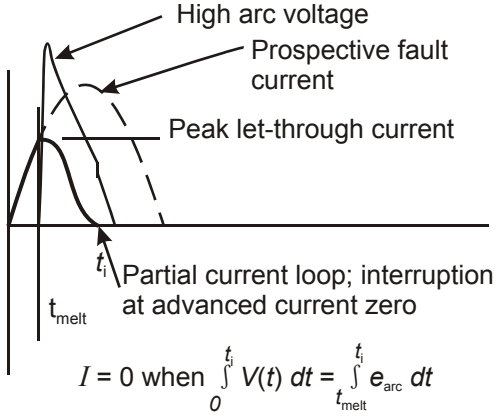
d) Current is inversely proportional to the inductance, and therefore, a smaller inductance will produce a higher available prospective fault current.

Figure A.2a and Figure A.2b depict idealized arc voltages of the two primary fuse types. Figure A.2a is that of the non-circuit-modifying (non-current-limiting) fuse with a relatively low arc voltage. This figure indicates that the fuse has not forced a change in current zero. The occurrence of a second loop of fault current is dependent on the fault-current magnitude, the fault initiation timing, and the fuse size. Figure A.2b is that of the circuit-modifying (current-limiting) fuse.




Low arc voltage $e_{arc}$. Minimal fault current limiting ability

**Figure A.2a— Low arc voltage and $\int e_{arc} dt$**




High Arc voltage $e_{arc}$. Substantial fault current limiting ability.

**Figure A.2b— High arc voltage and $\int e_{arc} dt$**

## A.2 Interruption without circuit modification

Expulsion and other types of non-current-limiting fuses have been defined as low arc voltage devices, which do not appreciably modify the circuit during interruption. By virtue of the low arc voltage, these devices do not significantly limit the magnitude of the fault current. Instead they conduct to a normal current zero for the existing circuit conditions and recover dielectrically at that time to achieve an interruption.

Since the current zero does not coincide with a voltage zero of the source, the fuse must recover against a TRV of that system. In theory, the TRV can reach a level of twice the power frequency recovery voltage. For interruption to occur, sufficient gap length and deionization must be achieved. Depending on the interrupting characteristic of a particular fuse, the interruption may or may not occur at the first current zero.

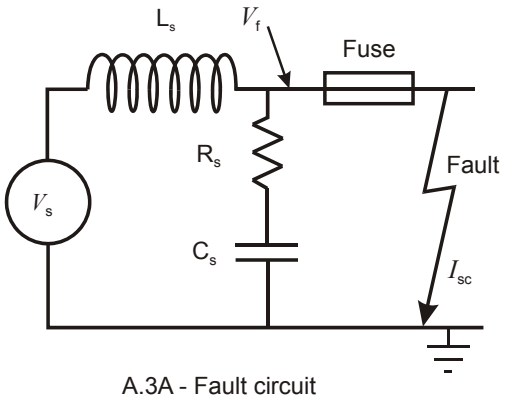
Figure A.3 and Figure A.4 depict interruptions at normal current zeros, after which a TRV arises. Figure A.3 shows the situation for a fault current of high magnitude where most of the circuit impedance lies up-stream of the fuse. Figure A.3A shows the circuit, Figure A.3B shows the voltage drop along the circuit at a current zero, and Figure A.3C shows the TRV following the current interruption. Figure A.4 shows the situation where the fuse melts as a result of an overload, in which the majority of the circuit impedance is down-stream of the fuse, with Figure A.4A, Figure A.4B, and Figure A.4C showing similar information to the equivalent parts of Figure A.3. These circuits are not significantly modified by the interrupting device. This is typical of interruption by expulsion and other types of non-current-limiting fuses; interruption of current-limiting fuses in the non-current-limiting mode (melt times greater than .01 s) also typically interrupt in this manner, although sometimes with a more significant arc voltage. The following conditions are met for interruption at normal current zero:

a) Essentially the full magnitude of fault current has passed (see Figure A.3C).

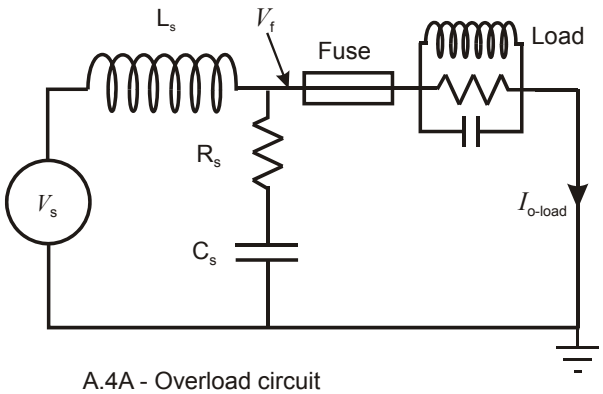
b) The energy stored in the circuit's inductance has been returned to the source and absorbed by the system (and fault) resistance. It is now virtually zero.

c) The system voltage at interruption is at some substantial value, typically near the maximum.

d) As the arc chamber of the fuse recovers dielectrically, it must withstand the TRV of the system, which is now imposed across its terminals.

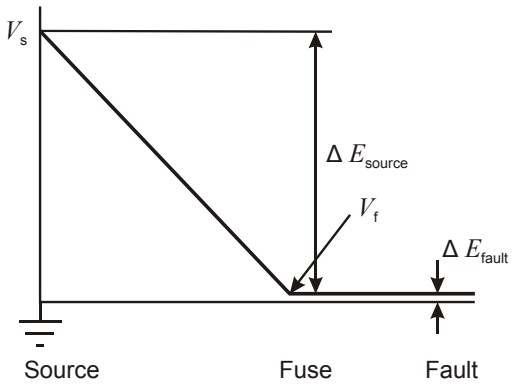



A.3A - Fault circuit

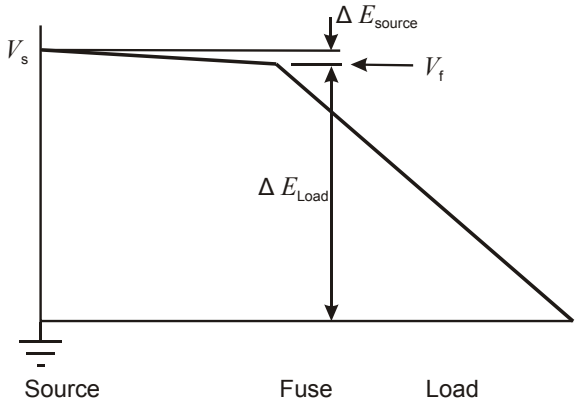



A.4A - Overload circuit

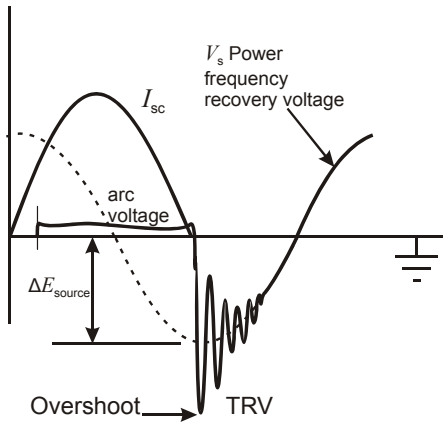
Where:
$V_s$ = source voltage, $V_f$ = Voltage at source side of fuse, relative to ground
$L_s$ = source impedance
$R_s$, $C_s$ = stray resistance and capacitance, that, with $L_s$, produces TRV
$I_{sc}$ = Short circuit current, $I_{o\text{-}load}$ = Overload current



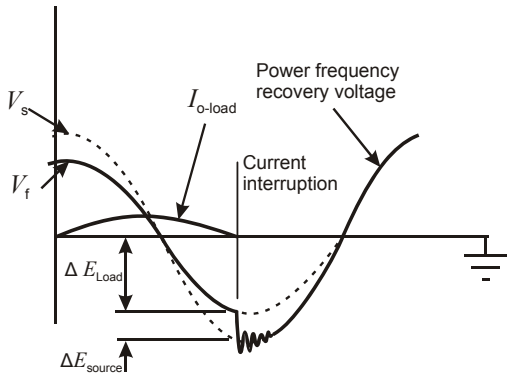

A.3B - Voltage drop along fault circuit (at current zero)




A.4B - Voltage drop along overload circuit (at current zero)




A.3C - Current interruption and recovery voltage waveforms




A.4C - Current interruption and recovery voltage waveforms

**Figure A.3— Recovery voltage for high current interruption**

**Figure A.4— Recovery voltage for low current interruption**

## A.3 Interruption with circuit modification

Figure A.4 shows how the circuit is interrupted by a current-limiting fuse having a high arc voltage. The arc is highly resistive, though non-linear with respect to current. If the resistive arc impedance is substantially greater than the system inductive impedance, a dynamic condition is established during the interruption process whereby the power factor of the circuit changes from being primarily inductive to primarily resistive. The current is thereby shifted back toward becoming more in phase with system voltage.

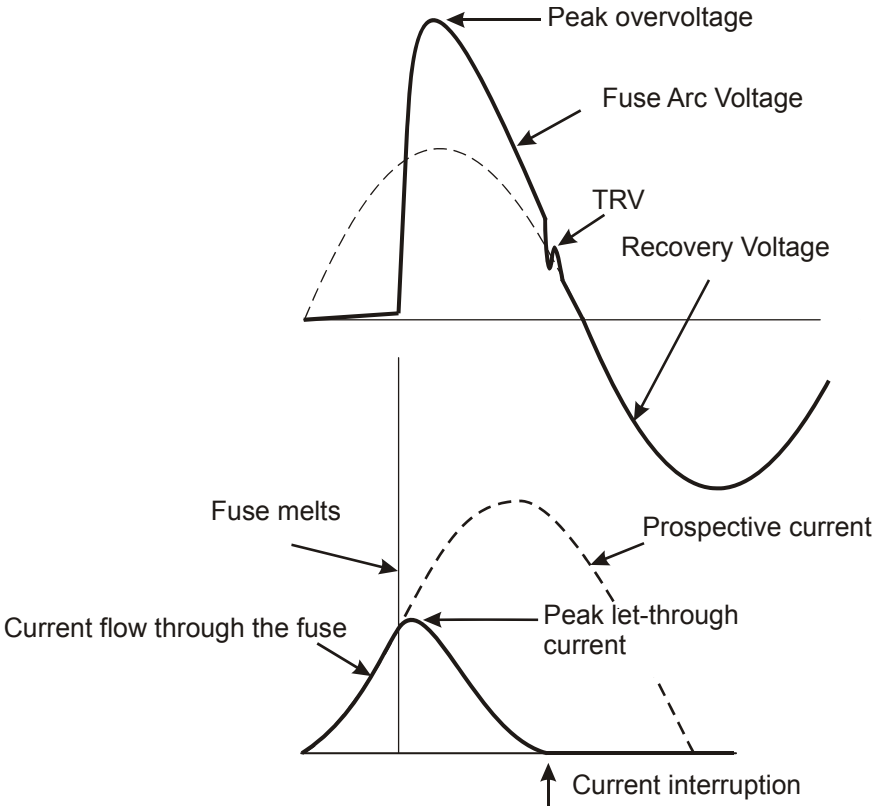



**Figure A.5—High-current operation of a current-limiting fuse, with resulting circuit modification**

If we now apply the principles of Equation (2), the large area under the arc voltage curve of Figure A.5 when subtracted from the area under the system voltage curve illustrates why there is a limitation of current and subsequent reduction to zero, generally close to the voltage zero. At this newly "created" current zero, the following conditions have been reached:

a) The system voltage is close to zero.

b) The stored energy of the inductance has been absorbed, primarily by the fuse, and is now at zero.

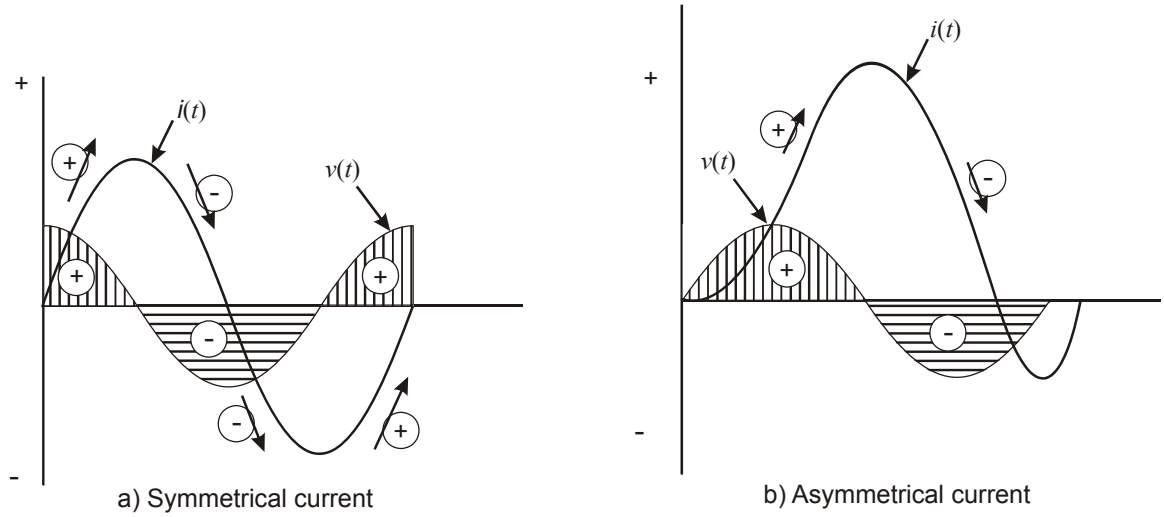
c) The voltage across the fuse equals the system voltage.

d) No significant TRV will develop.

e) The magnitude of fault current has been limited to a peak value only slightly higher than the instantaneous value at which the fuse begins to arc.

The preceding example indicated an asymmetrical fault, normally the worst case condition for a current-limiting fuse, since it has to interrupt against an increasing supply voltage. IEEE Std C37.41 specifies worst case conditions during fuse interruption. A prospective fault current may be symmetrical or asymmetrical depending on the fault initiation point in time on the source voltage wave. This is depicted in Figure A.6a and Figure A.6b. Note from Equation (2) that the fault current, through a primarily inductive impedance, is related to the integral of the voltage (the area under the voltage trace). The prospective current crest for a fault initiation at a voltage zero (See Figure A.6b) may be up to twice that of a fault initiated at a voltage crest (see Figure A.6a). The criteria for circuit modification during interruption remain essentially the same in both cases.

We see that the fault current characteristics can be modified by controlling the arc voltage of a fuse. This is a function of the fuse design, which is expanded upon in 4.6.2.2 through 4.6.2.9.




Increase of current in + direction corresponds to positive area (+) under $v(t)$;
decay of current in + direction corresponds to negative area (-) under $v(t)$.
The reverse is true for current in the - direction.

**Figure A.6—Symmetrical and asymmetrical current**

# Annex B

(informative)

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