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C37.48.1™

IEEE Guide for the Operation, Classification, Application, and Coordination of Current-Limiting Fuses with Rated Voltages 1–38 kV

IEEE Power Engineering Society

Sponsored by the
Switchgear Committee

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of the
IEEE Power Engineering Society

Approved 13 June 2002

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Abstract: Additional guidelines for application and coordination of high-voltage power- and distribution-class current-limiting fuses are provided.
Keywords: coordination, current-limiting fuses, disconnecting switches, fuse application, high voltage, high-voltages fuses, rated maximum voltage, single pole air switches, time-current-characteristics, TCC

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Introduction

(This introduction is not part of IEEE Std C37.48.1-2002, IEEE Guide for the Operation, Classification, Application and Coordination of Current-Limiting Fuses with Rated Voltages 1–38 kV.)

This guide is a new publication and is required to provide necessary additional guidelines for the application and coordination of high-voltage power- and distribution-class current-limiting fuses.

This guide was prepared by the IEEE Subcommittee on High-Voltage Fuses with cooperation from the National Electrical Manufacturers Association (NEMA).

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 C37.40-1993, IEEE Std C37.41-1994, plus the standard covering that particular device constitute a complete set of standards for each device. In addition, IEEE Std C37.48-1997 is an application, operation, and maintenance guide for all of the devices, and this guide provides additional guidelines for current-limiting fuses.

The following standards comprise this series:

ANSI C37.42-1996, American National Standard Specifications for High-Voltage Expulsion Type Distribution-Class Fuses, Cutouts, Fuse Disconnecting Switches, and Fuse Links.

ANSI C37.45-1981 (R1992), American National Standard for Specifications for Distribution Enclosed Single-Pole Air Switches.

ANSI C37.46-1981 (R1992), American National Standard for Specifications for Power Fuses and Fuse Disconnecting Switches.

ANSI C37.47-1981, American Natioinal Standard for Specifications for Distribution Fuse Disconnecting Switches, Fuse Supports, and Current-Limiting Fuses.

IEEE Std C37.40-1993, IEEE Standard Service Conditions and Definitions for High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.

IEEE Std C37.41-2000, IEEE Standard Design Tests for High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.

IEEE Std C37.48-1997, IEEE Guide for Application Operation and Maintenance of High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.

IEEE Std C37.48.1-2002, IEEE Guide for the Operation, Classification, Application, and Coordination of Current-Limiting Fuses with Rated Voltages 1–38 kV.

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IEEE Guide for the Operation, Classification, Application, and Coordination of Current-Limiting Fuses with Rated Voltages 1–38 kV

1. Scope

This guide provides information that supplements that presented in IEEE Std C37.48™-1997[1] on the application operation and maintenance of high-voltage (1–38 kV) fuses, fuse disconnection switches, and accessories for use on alternating current distribution systems. These guidelines apply to the following specific types of equipment:

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 (see types listed in 1.1).
d) Removable switch blades of the type used exclusively with power- and distribution-class fuse disconnecting switches.
e) Distribution- and power-class of current and combination current-limiting expulsion external capacitor fuses used with a capacitor unit, groups of units, or capacitor banks.

NOTE—Some of the power- and distribution-class current-limiting fuses listed above are the same as those listed in IEC 60282-1 (2002-01).

1.1 Description of fuse enclosure packages using current-limiting type indoor distribution- and power-class fuses

a) *Type 1C*—A fuse mounted in an enclosure with relatively free air circulation within the enclosure. (Example: A fuse mounted in a live front pad-mounted transformer or in a vault.)
b) *Type 2C*—A fuse mounted in a container with restricted air flow surrounding the fuse, but with relatively free air circulation within the enclosure on the outside surfaces of the enclosure. (Example: A fuse inside a canister in a vault.)
c) *Type 3C*—A fuse mounted in a container with restricted air flow surrounding the fuse but relatively free liquid circulating within the enclosure on the outside surfaces of the container. (Example: A fuse inside a canister immersed in transformer oil.)

[1]Information on references can be found in Clause 3.

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d) *Type 4C*—A combination of types 2C and 3C, where the container is partially in air and partially in liquid. (Example: A fuse inside a canister immersed in transformer oil.)
e) *Type 5C*—A fuse mounted in an enclosure, directly immersed in liquid, with relatively free liquid circulation around the fuse. (Example: An oil immersed fuse in a transformer or switchgear enclosure.)

1.2 Purpose of the document

During the process of determining the need for revising the standards to include full-range fuses, users and specifiers, both at utilities and at manufacturers, were surveyed. This survey revealed that additional information needs to be made available to the specifiers and users of all types of high-voltage current-limiting fuses. There were widespread and deep misunderstandings as to what types of current-limiting fuses were available, how to differentiate between types of current-limiting fuses, how to properly apply each type of current-limiting fuse, and how to properly handle and store fuses.

As a result, the High-Voltage Fuse Subcommittee of the IEEE Power Engineering 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 a working group on full-range fuses. It has created this additional application information to guide the application and coordination of full-range fuses.

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.

2. References

This guide shall be used in conjunction with the following publications. If the following publications are superseded by an approved revision, the revision shall apply.

ANSI C37.42-1996, American National Standard Specifications for High-Voltage Expulsion Type Distribution-Class Fuses, Cutouts, Fuse Disconnecting Switches, and Fuse Links.[2]

ANSI C37.44-1981 (R1992), American National Standard Specifications for Distribution Oil Cutouts and Fuse Links.

ANSI C37.45-1981 (R1992), American National Standard Specifications for Distribution Enclosed Single-Pole Air Switches.

[2]ANSI publications are available from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).

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ANSI C37.47-1981 (R1996), American National Standard Specifications for Distribution Fuse Disconnecting Switches, Fuse Supports, and Current-Limiting Fuses.

ANSI C37.53.1-1989, American National Standard for Switchgear—High-Voltage Current-Limiting Motor-Starter Fuses—Conformance Test Procedures.

IEC 60282-1 (2002-01), High-voltage fuses—Part 1: Current-limiting fuses.[3]

IEC 60282-2 (1997-12), High-voltage fuses—Part 2: Expulsion fuses.

IEC 60291 (1969-01), Fuse definitions.

IEC 60549 (1976-01), High-voltage fuses for the external protection of shunt power capacitors.

IEC 60644 (1979-01), Specification of high-voltage fuse-links for motor circuit applications.

IEEE Std C37.40™-1993, IEEE Standard Service Conditions and Definitions for High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.[4]

IEEE Std C37.41™-1994, IEEE Standard Design Tests for High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.

IEEE Std C37.48-1997, IEEE Guide for Application, Operation, and Maintenance of High-Voltage Fuses, Distribution Enclosed Single-Pole Air Switches, Fuse Disconnecting Switches, and Accessories.

IEEE Std C37.100™-1992, IEEE Standard Definitions for Power Switchgear.

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

IEEE Std C57.93™-1995, IEEE Guide for Installation of Liquid-Immersed Power Transformers.

IEEE Std C57.109™-1993, IEEE Guide for Transformer 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 Power Systems Analysis (IEEE Brown Book™).

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3. Fuse operation and theory

3.1 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 (1–38 kV) 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.

3.2 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, 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 C37.40-1993.

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 4 and Clause 5. 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, but that also will be discussed in 3.6.

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-characteristics (TCCs), 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 C37.41-1994. 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 C37.41-1994 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.

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

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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 is a useful concept for fuse-to-fuse and fuse-to-equipment protection and coordination, and will be discussed in more depth in 3.6.

3.3 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 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 and the total-clearing TCC tend to diverge at shorter times (higher currents), as illustrated in Figure 1A and Figure 1B.

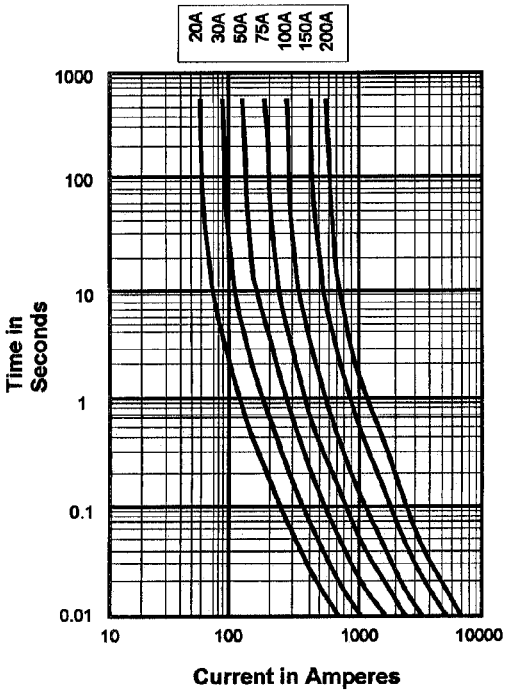

Figure 1A - Typical minimum melting curves Developed at 25°C, any variations should be positive (above and to the right of the curve)

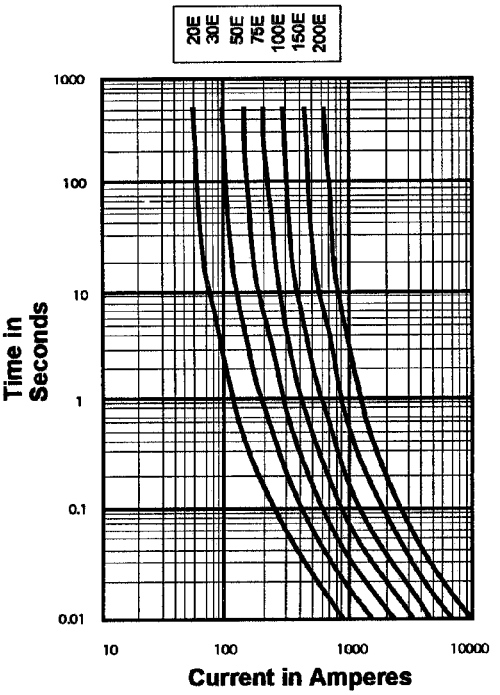

Figure 1B - Typical total clearing curves Developed at 25°C, any variations should be negative (below and to the left of the curve)

The two characteristics described above 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 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.

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All fuses also have a rated interrupting current, the highest current that a fuse has been tested to, thereby providing a demonstration of successful interruption. Some fuses also have a rated minimum interrupting current, which is the lowest current that the fuse has been tested to, thereby providing a demonstration of successful interruption, not necessarily the lowest current that it can interrupt. A fuse may not function as intended, with potentially serious results, when attempting to interrupt outside maximum and minimum interrupting rating.

3.4 Comparison of power fuses versus distribution fuses

Both current-limiting and expulsion fuses are classified by ANSI C37 standards as either power-class or distribution-class fuses. The differentiation between the two 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. Each class has its own unique set of voltage, current, and construction requirements (see ANSI C37.42, .44, .46, and .47 for examples of typical fuse requirements). Testing of each class must follow particular specifications (see IEEE Std C37.41-1994). A comparison of some of these specifications is given in Table 1. Power 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 ANSI fuse specifications

Requirement	ANSI C37.42 distribution cutouts and fuse links	ANSI C37.44 oil cutouts and fuse links	ANSI C37.46 power fuses	ANSI C37.47 distribution current-limiting fuses
Rated kV	2.6 to 38	2.6 to 15	2.8 to 169	2.8 to 27
Rated continuous current—Amps	to 200	to 200	to 700	to 200
Rated interrupting current—kA Sym.	2.6 to 16	2.2 to 7.1	1.25 to 80	12.5 to 50
X/R ratio at maximum interrupting current	1.33 to 15	2.3 to 12	≥ 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.

3.5 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.

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c) Their melting and interrupting time characteristics can be coordinated with those of other circuit overcurrent protective devices.
d) 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.
e) 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. Expulsion and other types of non-current-limiting fuses limit the fault duration, while essentially allowing the full peak of the available fault current to pass until it is interrupted at the circuit's normal current zero. 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.

Current-limiting fuses, by contrast, limit faults in magnitude and duration. 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. Thus, the fuse melting and arcing results in a high arc voltage appearing across the fuse, and 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, TRVs result. The operation of current-limiting fuses will be expanded upon in 3.6.2. The various types of current-limiting fuses include commutating as well as non-commutating, electronically actuated fuses.

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 3.6 and 3.7.

3.6 Circuit interruption and recovery

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 nonconducting 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.

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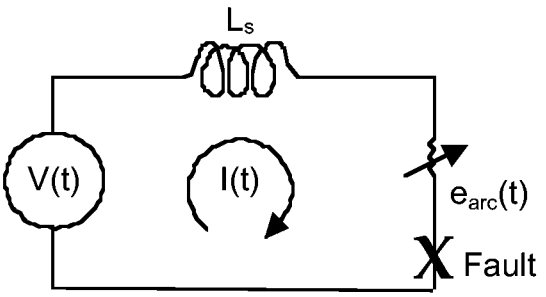

Where:

V(t) = Voltage of the source

$e_{arc}(t)$ = Arc voltage of the fuse

I(t) = Current

L_s = Source impedance

Figure 2—Simplified 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 2. 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 (1).

$$v(t) - e_{arc}(t) = L\, di/dt \quad (1)$$

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

$$i(t) = 1/L \int [v(t) - e_{arc}(t)]\, dt \quad (2)$$

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 3A and Figure 3B depict idealized arc voltages of the two primary fuse types. Figure 3A 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 3B is that of the circuit-modifying (current-limiting) fuse.

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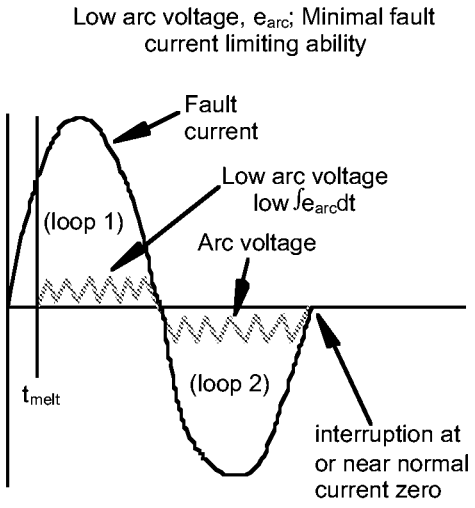

Figure 3A—Low arc voltage and $\int e_{arc}dt$

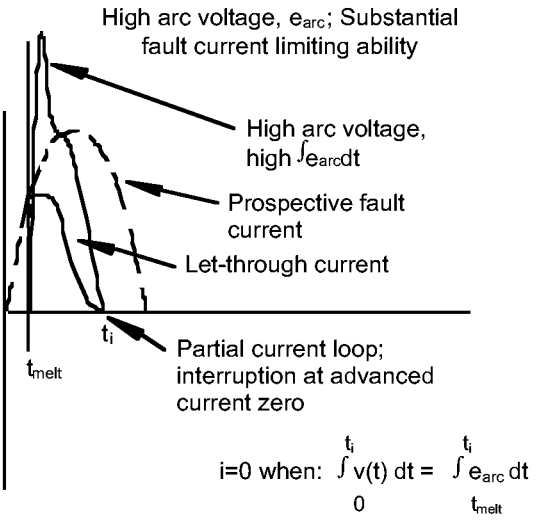

Figure 3B—High arc voltage and $\int e_{arc}dt$

3.6.1 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 4 and Figure 5 depict interruptions at normal current zeros, after which a TRV arises. These circuits are not 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. The following conditions are met for interruption at normal current zero:

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

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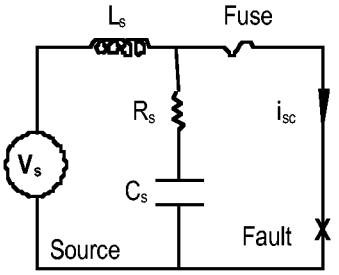

Figure 4A—Fault circuit

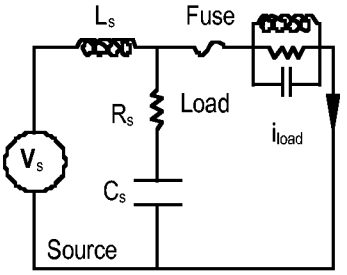

Figure 5A—Load and overload circuit

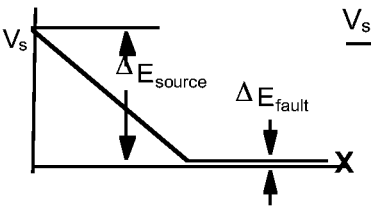

Figure 4B—

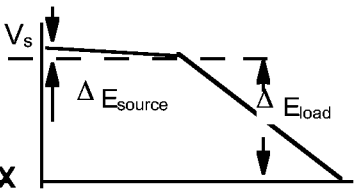

Figure 5B—

Voltage drop along circuit when current zero is reached

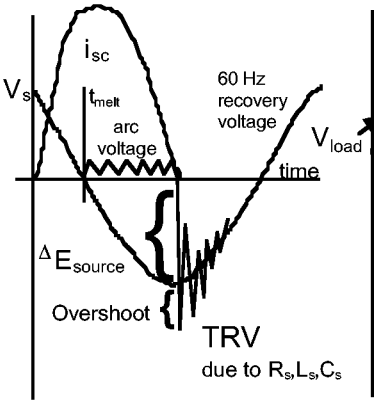

Figure 4C—

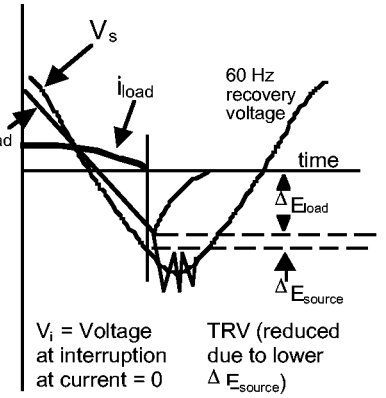

Figure 5C—

Current interruption and recovery voltages (circuit is not being modified)

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3.6.2 Interruption with circuit modification

Figure 6 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.

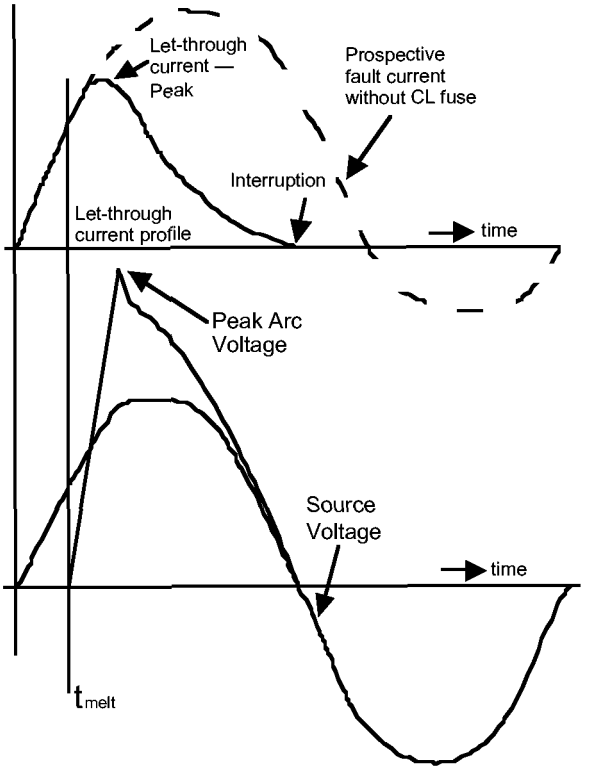

Figure 6—High current operation of a current-limiting fuse, with resulting circuit modification

If we now apply the principles of Equation (2), the large area under the arc voltage curve of Figure 3B when subtracted from the area under the system voltage curve illustrates why there is a limitation of current and subsequent reduction to zero, coinciding generally with 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 fuse arc voltage is zero.
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 C37.41-1994 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 7A and Figure 7B. Note from Equation (2) that the fault current, through a primarily inductive impedance, is

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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 7B) may be up to twice that of a fault initiated at a voltage crest (see Figure 7A). 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 3.7.1.1 through 3.7.1.8.

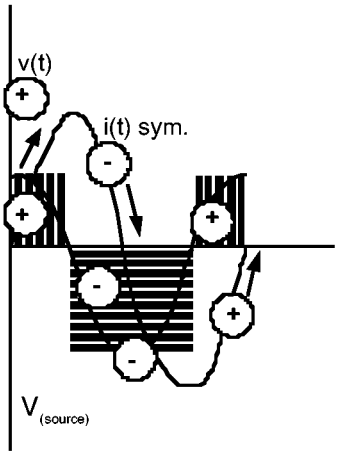

Figure 7A—Symmetrical short-circuit current

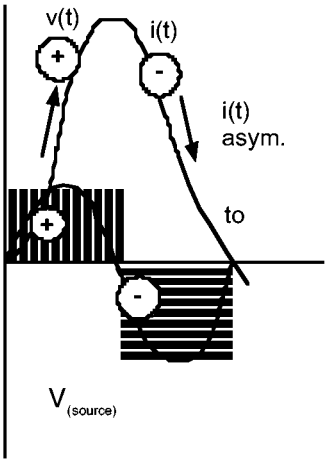

Figure 7B—Asymmetrical short-circuit current

Note: Rise of current corresponds to positive (+) area under v(t);
Decay of current corresponds to negative (-) area under v(t)

3.7 Fuse construction and operation

In the preceding paragraphs, arc voltage has been shown to be a good criterion to compare the two basic fuse types. Table 2 lists the fuse types and characteristics under high-current-interrupting conditions.

3.7.1 Current-limiting fuses

The effects of high-magnitude arc resistance and arc voltage and how they act to modify the fault circuit were reviewed in 3.6.2. This subclause 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.

3.7.1.1 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. 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

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Table 2—Fuse characteristics and types of fuses

Type of fuse characteristics	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 or more	1/8 to 1/2 cycle
Energy absorbed by fuse	Small amount	Substantial amount
Let-through I^2t	Substantial	Small
Recovery voltage	Transient—up to twice power frequency crest	Equal to power frequency crest
Subclassifications		Back-up, 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

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 voltage drop of the anode, cathode, and positive column voltage of the arc 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.

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.

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If we refer back to Figure 6, 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. 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.

3.7.1.2 Overvoltages

The insulation requirements of any electrical system and apparatus impose a limitation on the permissible magnitude of arc voltage. Table 3 gives arc voltage limits specified in ANSI C37.47-1981.

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

Rated maximum voltage (kV, RMS)	Maximum Peak Overvoltage (kV Crest)			
	From ANSI C37.47-1981		From ANSI C37.46-1981	
	Fuse rated current through 12 A	Fuse rated current over 12 A	Fuse rated current through 12 A	Fuse rated current over 12A
2.8	13	9	13	9
5.5	25	18	25	18
8.3	38	26	38	26
15.0	—	—	68	47
15.5	70	49	70	49
22	117	70	—	—
25.8	—	—	117	81
27	123	84	—	—
38.0	—	—	173	119

Control of the arc voltage is accomplished by limiting 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. As seen in Table 3, higher arc voltage limitations are permitted for the lower continuous current fuses where wire designs are prevalent.

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

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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.

3.7.1.3 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, also higher. This may limit their use in environments where heat dissipation is a problem. This is covered in greater detail in Clause 5.

3.7.1.4 Fuse vs. 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.

3.7.1.5 Energy absorption during interruption

A current-limiting fuse does not necessarily 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. Under lower fault conditions, particularly those at voltage zero initiation (high asymmetry), melting and burn back are slower while the system voltage remains high. Although the available current is lower in this case, it remains relatively high for a longer period of time. The fuse must, therefore, absorb more energy. Proper design requires that the fuse be tested under these conditions. Current-limiting fuses are often subject to maximum arc energy absorption, at a given current level, sometimes called critical current. IEEE Std C37.41-1994 requires testing at this level of current.

3.7.1.6 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 which cause current-limiting to occur. For further details regarding the three subclasses of current-limiting fuses and their different lower interrupting limits, see 4.3.

A general description for a back-up fuse is defined as being a fuse capable of interrupting all continuous currents from the rated-maximum interrupting current down to the minimum-rated interrupting current. (It should normally be applied in conjunction with a second, series interrupting device). A general-purpose fuse

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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 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.

3.7.1.7 Low current design considerations

Due to the low current interruption limitation of the back-up 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. The distribution fuse cutout is commonly applied as an add-on with back-up fuses to achieve the low-end clearing capability. As such, they must be coordinated properly. The incorporation of a low-current element section into the body of a standard current-limiting fuse is described in the following two paragraphs.

In some designs, the full-range clearing capability is achieved by integrating a current-limiting section, which is typically made up of a single or parallel silver ribbon elements embedded in sand, in series with wires forming the second section. The wires (incorporating a low melt temperature element or alloy) are 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. The wire melts on low overcurrents and interrupts like an expulsion element, but without external exhaust. This occurs prior to or in conjunction with the melting of the high-current element. For high currents, the current-limiting element embedded in sand melts and interrupts in a current-limiting mode.

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) at the normal current zero.

3.7.1.8 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.

A schematic of this type of fuse is shown in Figure 8. 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.

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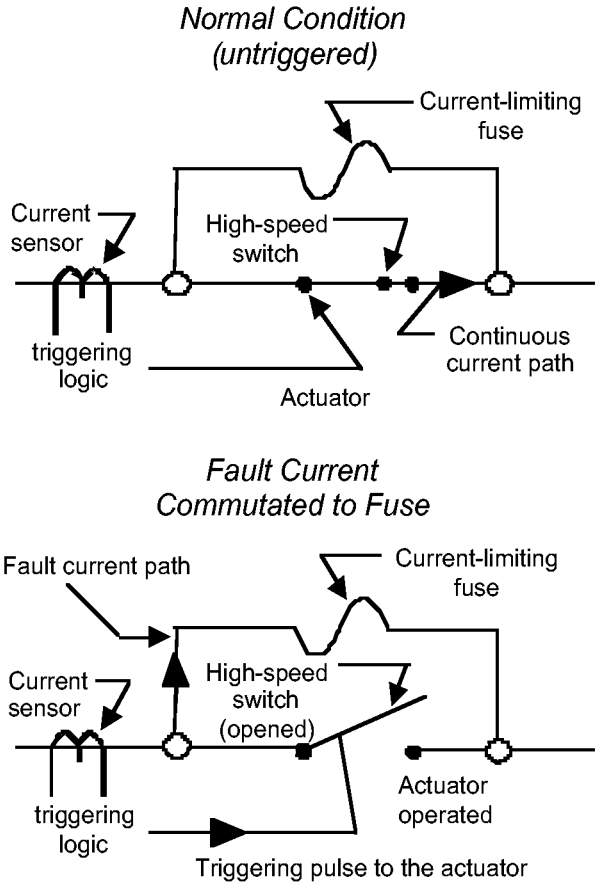

Figure 8—Operation of commutating current-limiters

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 70-1999) [B42][5] (article 100, Part B—definitions) as an overcurrent device that generally consist of a control module that provides current sensing, electronically derived TCCs, and 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 10a. 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. Other more typical fuse element features are also shown in Figure 10.

[5]The numbers in brackets correspond to those of the bibliography in Annex A.

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3.7.1.9 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 back-up fuse. Testing must confirm that failure (physical destruction) of the back-up 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.

3.7.2 Expulsion and other types of non-current-limiting fuses

As described in 3.6.1, 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 Equation (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 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 has been seen, is not necessarily true for all types of current-limiting fuses. Only fuses that include special construction features to improve their performance in low-current interrupting can reliably interrupt when exposed to low currents. Various types of expulsion and other types of non-current-limiting fuses are discussed in 3.7.2.1.

3.7.2.1 Expulsion fuses

Expulsion fuses are available in both power and distribution classifications. As the name implies, the interruption involves an expulsion action. These employ a rather short fuse element that melts to initiate the arcing process. Typically, one end of this element is fixed within the fuse tube; the other end is connected to a fuse leader or arcing rod. The arc is only moderately confined and burns in a tube or bore of gas evolving

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material. The expulsion tube is made with a gas-producing inner liner (e.g., fiber, melamine, or boric acid) and may use a reinforced outer tube. The liner is ablated by the arc and will give off gases, such as hydrogen, various hydrocarbons, or steam. This protects the tube wall from excessive erosion, while the arc burns stably with temperatures in the center as high as 20 000 °C. These gases expel the metal vapor and the leader out of the fuse tube. The movement of the leader (or arcing rod) increases the gap between the parts and is very beneficial to the dielectric recovery that occurs at current zero. The gas produced is proportional to the heat released by the arc energy. The gas flow effectively cools and deionizes the arc gap at current zero and allows the gap to withstand the TRV. This results in interruption of current flow in the circuit. Fuses that have expendable caps often have higher interrupting ratings due to the orifices at each end which can more effectively vent heat, ionized particles, and gas from inside the tube as compared to fuses with a single orifice at one end. 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 400 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 incorporate an exhaust control device (commonly called a silencer, snuffler, or condenser) that contains most of the arc-interruption products and virtually eliminates the noise accompanying the fuse's operation. These exhaust control devices do not require a reduction in the fuse's interrupting rating.

3.7.2.2 Under-oil expulsion fuses

Under-oil expulsion fuses operate on a similar principle as expulsion fuses in air (described in 3.7.2.1), except that oil is used as the dielectric medium. Melting of the element heats, vaporizes, and dissociates the oil. In many cases, the gas produced from the oil 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 oil. The interrupting phenomena and circuit conditions, such as X/R ratio and TRV characteristics, are similar to those of expulsion fuses used in air.

3.7.2.3 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.

3.7.2.4 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.

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3.7.2.5 Oil fuse cutouts

Oil fuse cutouts are devices that operate in a manner similar to under-oil expulsion fuses. The oil fuse 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.

3.7.2.6 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. 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.

4. Current-limiting fuse types, class, and definitions

4.1 Introduction

Current-limiting fuses excel at interrupting relatively high currents. However, they can experience difficulty when exposed to 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 ensure that conditions, such as transformer magnetizing inrush currents, do not result in damage to current-limiting fuse elements.

Coordination rules between protecting and protected devices (discussed in Clause 6) 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 a result, three different classes of current-limiting fuses have been identified and are recognized in industry standards. Each has unique operation and application characteristics. The classifications are as follows:

— Back-up type fuses
— General-purpose type fuses
— Full-range type fuses

These fuses all appear to be quite similar when viewed externally. A typical current-limiting fuse is shown in Figure 9. All have connection points to allow them to be mounted to their holder. 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. In most cases, the elements are spirally wound on a support to allow sufficient element length without requiring excessive overall outside dimensions.

The different types of fuses have slightly different internal structures to ensure that they perform as expected. For instance, back-up fuses generally use only a main fuse element, without any added structures

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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 4.4.

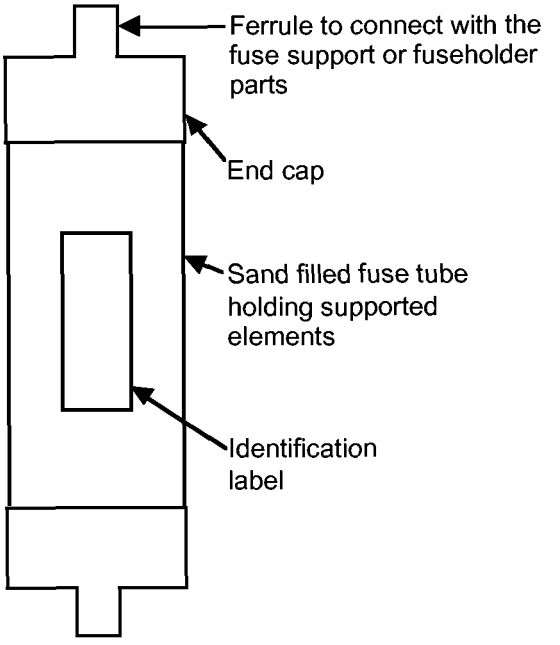

Figure 9—Typical current-limiting fuse

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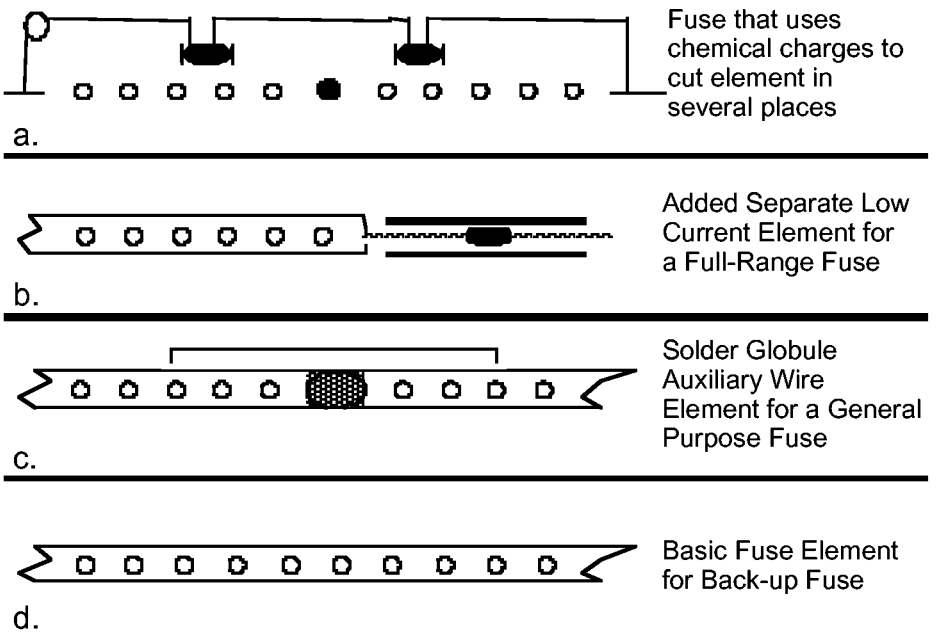

Figure 10—Construction features typical of various types of current-limiting fuse elements

4.2 Fuse class

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- 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.

4.2.1 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, especially substations that do not use current-limiting reactors to control fault current. At these locations there is very little circuit impedance should a fault occur. As a result, most of the 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. This is a difficult circuit to interrupt.

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 C37.41-1994 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 more severe duties that result from applications in or near the substation.

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4.2.2 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.

Standards require power-class fuses to be tested at an X/R ratio greater than 15. 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 those specified in the standard. Before applying current-limiting fuses to a circuit with higher X/R ratios than specified in the test standard, the manufacturer should be consulted to verify that a particular fuse is suitable for the application.

4.3 Types of current-limiting fuse

There are three types of current-limiting fuse as described in IEEE Std C37.41-1994. They are as follows:

— Back-up
— General-purpose
— Full-range

Each of these types are described in 4.3.1 through 4.3.3.

4.3.1 Back-up fuses

A back-up fuse can interrupt any current between its rated minimum interrupting current and its rated maximum interrupting current. If a back-up 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 opens 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 fulgarite. 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 fulgarite 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 back-up fuse, operates and interrupts the circuit. Because of this, a back-up 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 back-up fuse in series with another interrupting device, which will interrupt any current below the minimum rating of the back-up 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 back-up fuse element melts open. Details of how these devices are selected and coordinated are presented in Clause 5 and Clause 6 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 3.2, 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 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

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will take the fuse to melt and then interrupt the circuit at a given current (total-clearing curve). For back-up fuses, currents that are less than the minimum-rated 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 maximum interrupting rating of the fuse. This rating should not be exceeded. Other characteristics such as minimum-melt I^2t (amp^{2}sec), maximum let-through I^2t (amp^{2}sec), 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 back-up fuse. Coordination between the back-up fuse and series, low-current interrupting devices is critical to preventing damage to the back-up 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.

4.3.2 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. When using some types of general-purpose fuses in drywell canisters, for instance, the continuous current rating may require derating, as a result of the restricted air flow around the fuse. If this fuse is used in a very warm environment, for example 100 °C, in an overloaded transformer, an additional derating is usually required. After derating is factored in, the load current may be at or above the rated continuous current of the fuse. In this case, the manufacturer should be consulted and should advise the temperature and environment that the fuse was tested in to be sure there is adequate margin for the application.

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

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are extended beyond the normal 1000 second axis range, the upper limit on most TCC curves. Other application data sometimes supplied in charts and curves includes minimum-melt I^2t, maximum let-through I^2t, and peak let-through current versus available current.

4.3.3 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:

a) "Any continuous current that causes melting."
b) "At the maximum temperature specified by the manufacturer."

Basically, these 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 maximum allowable service temperature. 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 continuous current rating at the typical service temperature (25 °C typically, with a range from 10 °C to 40 °C specified as typical in the standards). This rating is based on the temperature rise of the fuse, compared with limitations detailed in standards. TCC curves, minimum melt I^2t, maximum let-through 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 protecting and protected devices. Refer to Clause 5 and Clause 6 for more details on these topics.

4.4 Current rating conventions

Many fuses will be assigned a rated continuous current, often selected from the lists of preferred values given in various 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 C37.40-1993 and without being subjected to any deterioration. This current may not, however, be the highest or lowest 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 C37.40-1993. Thus, a manufacturer may list different "allowable" current ratings for their fuses at different ambient temperatures.

ANSI 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

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designation, and may be considered a "time-current-characteristic" based rating system. Examples of TCC based rating systems are listed in the 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 (ANSI C37.47-1981).

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 a rms current in the range of 220% to 264% of the rated continuous current of the fuse unit (ANSI C37.46-1981).

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 (ANSI C37.46-1981). The maximum continuous currents for R-rated fuses are listed in ANSI C37.46-1981 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 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 proposed changes to C37 standards include 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 11, where minimum-melting characteristics 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" as defined in IEEE Std C37.40-1993, and the temperature of the surrounding fluid, in contact with the fuse enclosure package, then becomes the reference ambient temperature. Because this reduction (de-rating) will be different for different enclosure designs, the C37 standards suggest that the manufacturer of a fuse enclosure package is typically responsible for this testing.

A back-up current-limiting fuse used outdoors in series with a cutout fuse, presents another rating system. Typically, the back-up 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 back-up 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 back-up fuse coordination with low-current interrupting devices will be discussed in 6.5.2 through 6.5.5.

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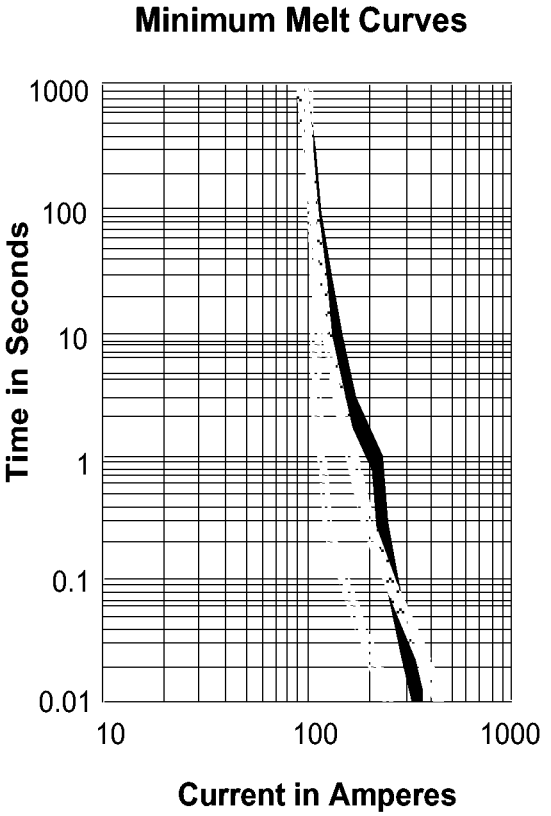

Figure 11—Curves comparing three 40A E-rated fuses of different manufacturers

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, ANSI C37.42-1996 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, and K and T links from different manufacturers may be interchangeable based on melting characteristics. K and T fuse links are the exception, however. Most fuse ratings specify only the long term melt current region. Therefore, even fuses that use the same rating system, such as an E rating may differ significantly at the shorter melt times, and are therefore seldom interchangeable from one manufacturer to another without checking the application and coordination. Caution still needs to be used to ensure that other ratings and mounting requirements also allow the fuses to be used interchangeably.

For this reason, TCC curves are used, along with appropriate application rules, to select which fuse should be used in a given application, in addition to the fuse ampere ratings. Clause 5 and Clause 6 of this guide describe these coordination and application rules in detail.

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5. Application considerations and cautions

5.1 Electrical aspects

5.1.1 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 prevents damage to the elements and fuse assembly parts and assures 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.

5.1.2 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 back-up 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.

5.1.3 Transformer applications

5.1.3.1 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 6).

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5.1.3.2 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. Customers often turn on one light after another, attempting to "dispel the darkness." 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 could also contribute to an inrush current problem known as cold-load pick up. Since compressors have little or no head pressure, their motors are able to come up to speed rapidly enough to mitigate this problem.

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 and 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 5.1.7.

5.1.3.3 Transformer loading and overloading

IEEE Std C57.91-1995 defines the safe loading for mineral-oil-immersed overhead and pad-mounted distribution transformers, and IEEE Std C57.93-1995 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.

Generally, a transformer or fuse manufacturer will recommend fuse sizes to handle full-load and some overload 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.

5.1.3.4 Through-fault conditions

IEEE Std C57.109-1993 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

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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.

5.1.3.5 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 ANSI C37.46-1981 and ANSI C37.47-1981. System insulation must be capable of withstanding arc voltage of this magnitude.

5.1.4 Feeder and sectionalizing applications

5.1.4.1 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 5.1.3.1 for single transformers.

5.1.4.2 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 A) 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.

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5.1.4.3 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.

5.1.5 Capacitor applications

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 C37.48-1997.

5.1.5.1 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 circuits' 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 (3):

$$I = V(C/L)^{1/2}; \text{ which is based on the relationship } I^2L/2 = V^2C/2 \quad (3)$$

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 4 describes the I^2t that results from that current:

$$I^2t = 3.74E^2C^{3/2}L^{-1/2} \text{ amp}^2\text{sec} \quad (4)$$

where:

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

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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.

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{5}$$

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.

$$f_{\text{inrush}} \text{ is proportional to } \{(L_{\text{betweenbanks}})x[(C1C2)/(C1 + C2)]\}^{-1/2} \tag{6}$$

$$f_{\text{short-circuitcomponent}} \text{ is proportional to } \{(L_{\text{short-circuit}})x(C1 + C2)\}^{-1/2} \tag{7}$$

5.1.6 Voltage (potential) transformer applications

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 interrupting capacity.

5.1.6.1 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. 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, who often uses ANSI C37.46-1981 and ANSI C37.47-1981 as a basis.

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.

5.1.6.2 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. Since potential transformer burdens are lower and the construction of these transformers is different than power transformers, fuses selected solely on the basis of inrush considerations will seldom protect voltage

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transformers from overloads. The selected fuse should also withstand magnetizing inrush currents to preclude nuisance fuse operation or damage to the fuse element(s) that could result in failure of the fuse.

The inrush withstand capacity 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.

5.1.6.3 Interrupting ratings

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

5.1.7 Motor circuit protection and coordination

5.1.7.1 Function of fuses on motor-starter circuits

The function of medium-voltage, motor-starter fuses is to protect the motors from short-circuit currents. These typically are back-up type current-limiting power fuses as defined in ANSI C37.40-1993. They require a series device, such as an air or vacuum contactor, for breaking the circuit for currents below their minimum interrupting current. Fuses for this application are frequently given an R rating, as defined in ANSI C37.46-1981. The fuse designs for motor circuit protection are different than those for general-purpose or full-range fuses and back-up 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.

5.1.7.2 Selection of motor-starter fuses

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

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Items a) through e), insofar as they characteristically apply to R-rated current-limiting fuses, are briefly discussed in 5.1.7.2.1 through 5.1.7.2.5.

5.1.7.2.1 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 circuit maximum operating line-to-line voltage should be in the range of 70% to 100% of fuse rated 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. If the fuse has a voltage rating greater than system voltage it 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 ANSI C37.46-1981. 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

5.1.7.2.2 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 ANSI C37.46-1981. 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 minimum interrupting capacity of the fuse.

5.1.7.2.3 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.

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5.1.7.2.4 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 may be expressed in symmetrical or asymmetrical amperes. Annex C of IEEE Std C37.41-1994 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 (8):

$$\text{Three Phase MVA} = \sqrt{3}\ \text{(Fuse Rated Voltage in kV)} \times \text{(Fuse Rated Interrupting Capacity in kA)} \quad (8)$$

5.1.7.2.5 Pulse withstand

IEC 60644 (1979-01) 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 the following ratios:

Ratio 1: $I_{f10}/I_n \geq 3$ for $I_n \leq 100$ A

Ratio 2: $I_{f10}/I_n \geq 4$ for $I_n > 100$ A

Ratio 3: $I_{f0.1}/I_n \leq 20\ (I_n/100)^{0.25}$ for all current ratings

where:

I_n = current rating of the fuse
I_{f10} = pre-arcing current corresponding to the 10s minimum-melt time of the fuse
$I_{f0.1}$ = pre-arcing current corresponding to the 0.15 minimum-melt time of the fuse

These ratios apply to all current ratings, providing maximum short-circuit protection to associated switching devices, cables, motors, and terminal boxes. IEC 60644 (1979-01) 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 (1979-01) specifies the following two sequences of tests:

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

Figure 12 details the sequence of the two withstand tests.

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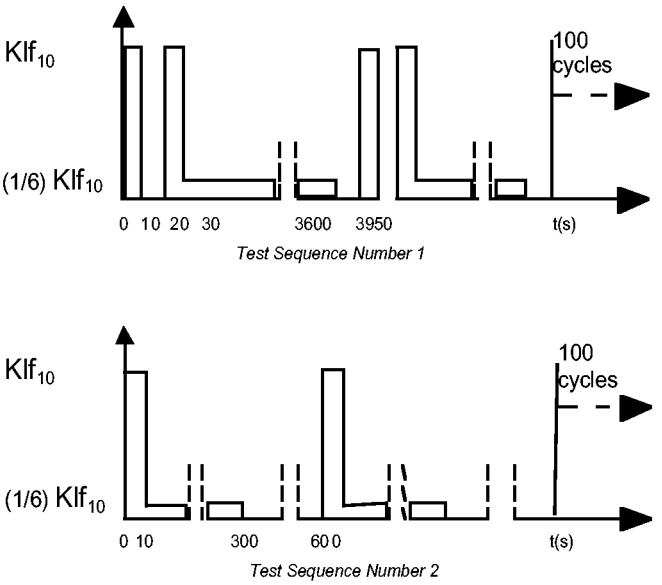

Figure 12—Withstand test sequence

5.1.8 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.

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5.1.9 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.

5.1.10 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 tape recorders.

5.2 Physical application considerations for current-limiting fuses

Before any fuse is used, consideration shall be given to the physical environment of the application. The user shall 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.

5.2.1 Fuse types/mounting for current-limiting fuses

Current-limiting fuses are typically used in conjunction with various mountings in many different applications. Subclauses 5.2.1.1 through 5.2.1.4 detail some of the more common uses and describe various ways that particular fuses are designed to meet the requirements of each application.

5.2.1.1 Under-oil current-limiting fuses

Current-limiting fuses for use under oil are completely sealed to prevent oil ingress into the fuse. IEEE Std C37.41-1994 details tests for fuse seal integrity for under-oil transformer applications. The fuse manufacturer can supply design and test information to assure a satisfactory non-leaking design.

5.2.1.2 Drywell canister mounted current-limiting fuses

Application of drywell canister enclosed current-limiting fuses under oil must take into consideration a higher air ambient, 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 C37.41-1994 contains requirements for additional testing of fuses in enclosures at temperatures over 40 °C.

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5.2.1.3 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.

5.2.1.4 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.

5.2.2 Mechanical impact considerations for current-limiting fuses

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.

5.2.2.1 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) A temperature reading of 30 °C above ambient temperature is common.
b) In some cases total measured temperatures as high as 105 °C may be normal.
c) On three-phase installations, readings on all three phases should be close if the loading is equal on all three phases.

5.2.2.2 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 shows evidence of physical damage should not be placed in service.

5.2.3 Environmental effects on ratings of current-limiting fuses

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

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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.

5.2.3.1 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 changeout 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.

5.2.3.2 Under-oil current-limiting fuse applications

Note the remarks in 5.2.1.1 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 to secure higher ampere rated fuses 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.

5.2.3.3 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.

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

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 5.2.3.4.1 and 5.2.3.4.2 detail some of the applications where caution is required due to restricted air flow.

5.2.3.4.1 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.

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5.2.3.4.2 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.

5.2.3.5 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.

5.2.3.6 Reuse of current-limiting fuses after interruption

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

6. Current-limiting fuse coordination

6.1 Tap-line coordination

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 clause will outline the requirements necessary to properly coordinate current-limiting fuses applied as tap-line protection.

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

Current-limiting fuses melt and clear overcurrent conditions according to their TCC curves. The minimum current at which the fuse melts, should be less than the minimum fault current that might develop from a fault at the end of the zone to be protected. The minimum fault current must be determined at each sectionalizing point and at the end of each zone of protection.

A term used extensively 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. In order to clarify the concept of reach, refer to Figure 13. 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.

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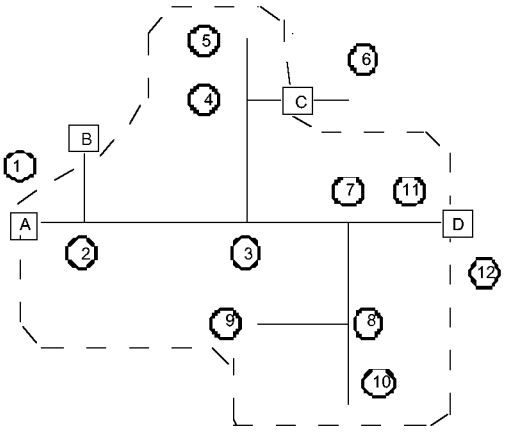

Figure 13—Reach example

The zone of protection of device "A" is shown by the dotted line. Assume that the operating current (minimum pick up value) of device "A" is 100 A, and that the minimum fault current flowing through device "A" is 450 A for a fault at point 10, which is within its zone of protection.

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

which, in this example, would equal

$$\frac{450\text{A}}{100\text{A}} \quad \text{or} \quad \frac{4.5}{1}$$

To determine the reach of any device on a circuit, it is necessary to know the minimum value of current for which the device will operate. 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 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. Tests show that phase-to-earth faults are often of low magnitude, typically less than 100 A, and may be less than 20 A. Refer to IEEE Tutorial 90EH0310-3PWR [B23].

At least one major utility uses a 3/1 reach 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 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 value, the circuit may need to be re-engineered.

6.2.1 General-purpose current-limiting fuse reach

Ideally, the current-limiting fuse should be able to interrupt the lowest value of fault current expected within its zone of protection. The reach capability of a fuse is largely dependent on the fuse design. Some general-purpose current-limiting fuses can be damaged if they are subjected to a continuous current above their continuous current rating and below their minimum-melt and clear rating (given by manufacturer). For these fuses, the overload current heats up the fuse causing damage to its body or its holder before the fuse can melt

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and interrupt the current. Therefore, this limitation 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 overcurrent 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.

6.2.2 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.

6.3 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 5.1.3.1, 5.1.3.2, 5.1.4.1, 5.1.4.2, and 5.1.6.1.

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.

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6.4 Time margins between time-current-characteristics

For a fuse that is protected by another fuse, the intersection of the minimum-melt TCC curve of the protected fuse, modified as detailed below, and the total-clear TCC curve of the down-stream protecting fuse should be greater than the maximum available fault current at the location of the upstream protected fuse. (See Figure 14 for clarification of protected and protecting).

Per Standard IEEE Std C37.48-1997, a value of 75% of the minimum-melting time of the protected 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 protected fuse with the total-clear time of the protecting fuse is to align the four-second line of the protected fuse TCC minimum-melt curve with the three-second line of the protecting 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.

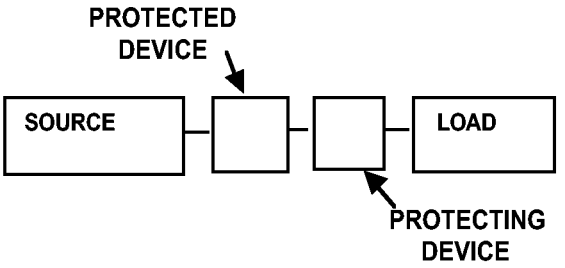

Figure 14—Block diagram of protection scheme

For a recloser that is protected by a fuse (see 6.5.4) 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.

To prevent an unnecessary time delay operation of the recloser, there should be a 0.2 s margin required between the total-clearing curve of a protecting fuse and the time delay curve of the protected 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 6.5.5), the time delay curve of the recloser multiplied by the recloser "K" factor (see 6.5.5) shall be below and to the left of the 75% minimum-melt curve of the protected fuse when they are plotted on the same voltage base. No additional margin is required.

6.5 Coordinating current-limiting fuses with other protective devices

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.

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In the examples in the following subclauses, 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.

6.5.1 Current-limiting fuse/Current-limiting fuse coordination

As with expulsion fuse to expulsion fuse coordination, the protecting fuse must clear the maximum fault current at its location before the protected fuse is damaged. To prevent damage to the protected fuse, the total-clearing time of the protecting 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 protecting 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 protecting fuse is of sufficient magnitude, i.e., to the right of where the protected 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 protected fuse should be greater than the total-clear (let-through) I^2t of the protecting fuse. This is referred to as "I^2t coordination." The manufacturer's values for minimum-melt I^2t and total-clear (let-through) 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 coordination between a 125 A full-range current-limiting fuse (CLF) and a 65 A general-purpose CLF as shown in Figure 15. Also, verify that the 125 A CLF has adequate reach for its zone of protection.

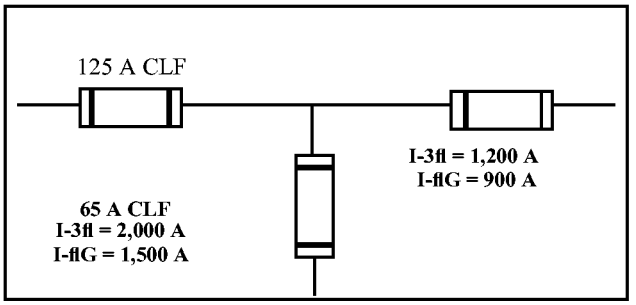

Figure 15—Current-limiting fuse/Current-limiting fuse example

The TCC curves for this combination are also illustrated in Figure 16. Before drawing the fuse TCC curves, verify that the 125 A CLF has adequate reach. The 125 A CLF shall reach to the device at point (3) of Figure 13, where the fault current of 900 A is the lowest protection.

For a full-range current-limiting fuse, the fault current (including 3/1 reach) should be sufficient to melt the fuse in 300 s or less. The 125 A CLF melts at approximately 280 A in 300 s. For a 3/1 reach, the current at the end of the zone protected by the 125 A CLF should be at least 280 × 3 or 840 A. Since the fault current at the point under review is 900 A, the 125 A CLF has adequate reach.

To check TCC curve coordination, draw the 75% minimum-melt curve for the 125 A CLF and the total-clear curve for the 125 A CLF. Note that the curves intersect at approximately 3100 A. Therefore, since the maximum fault current at 65 A CLF does not exceed 3100 A, time coordination exists. Since the TCC curves intersect above the 0.01 s line, I^2t coordination does not need to be checked.

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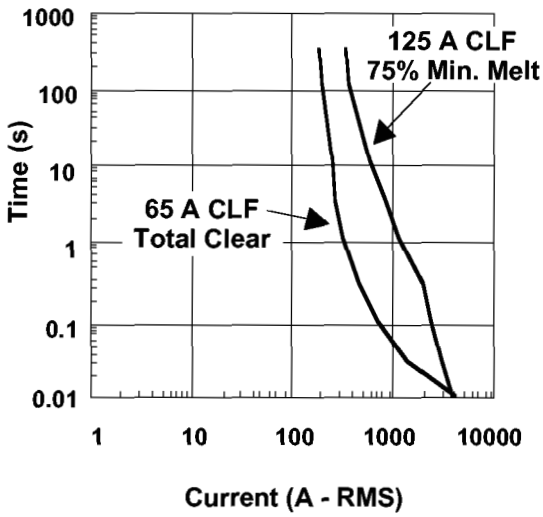

Figure 16—Current-limiting fuse/Current-limiting fuse TCC curve example

6.5.2 Current-limiting fuse/Expulsion fuse coordination

In this coordination scheme, the total clearing TCC curve of the expulsion (protecting) fuse should be compared with the adjusted (reduced to 75% in time) minimum-melting TCC curve of the current-limiting (protected) 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), which is generally labeled "Minimum Time for Safe Coordination." As a result of this convergence, the total-clear curve of the expulsion fuse will always cross the melt curve of the protected fuse. Therefore, this method will provide coordination only up to a finite current level.

An example of current-limiting fuse/expulsion fuse coordination is as follows: check coordination between a 90 A full-range current-limiting fuse and a 40 A expulsion fuse link as shown in Figure 17. Also, verify that the 90 A current-limiting fuse has adequate reach for its zone of protection. The TCC curves for this combination are illustrated in Figure 18.

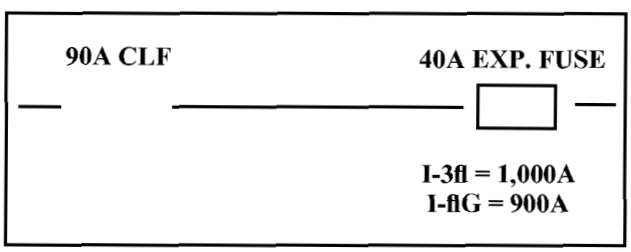

Figure 17—Current-limiting fuse/Expulsion fuse example

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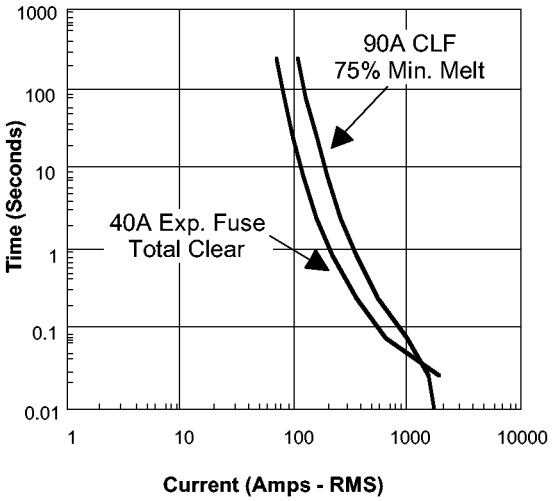

Figure 18—Current-limiting fuse/Expulsion fuse TCC curve example

Before drawing the fuse TCC curves, verify that the 90 A current-limiting fuse has adequate reach. The 90 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 (including 3/1 reach) should be sufficient to melt the fuse in 300 s or less. The 90 A current-limiting fuse melts at approximately 105 A in 5 min. For a 3/1 reach, the current at the end of the zone protected by the 90 A current-limiting fuse should be at least 105 × 3 or 315 A. Since the fault current at the location of the 40 A fuse link is 900 A, the 90 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 90 A fuse. The curves intersect at approximately 1200 A. Therefore, since the maximum fault current at the 40 A fuse link is 1000 A, time coordination exists.

6.5.3 Expulsion fuse/Current-limiting fuse coordination

The total-clearing TCC curve of the current-limiting (protecting) fuse must lie to the left of the adjusted (typically downward to 75% in time) minimum-melting TCC curve of the expulsion (protected) 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 total clear I^2t of the current-limiting fuse must be verified to be less than the calculated minimum melt I^2t of the expulsion fuse, adjusted for preload.

The minimum-melt I^2t for the expulsion fuse can be obtained by squaring the minimum-melt current of the expulsion fuse at 0.01 s and multiplying this value by 0.01 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 19. The TCC curves for this combination are illustrated in Figure 20.

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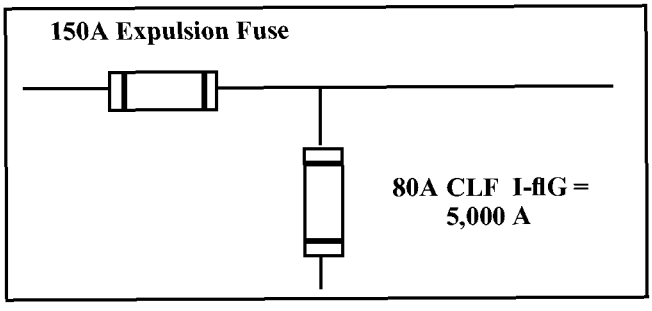

Figure 19—Expulsion fuse/Current-limiting fuse example

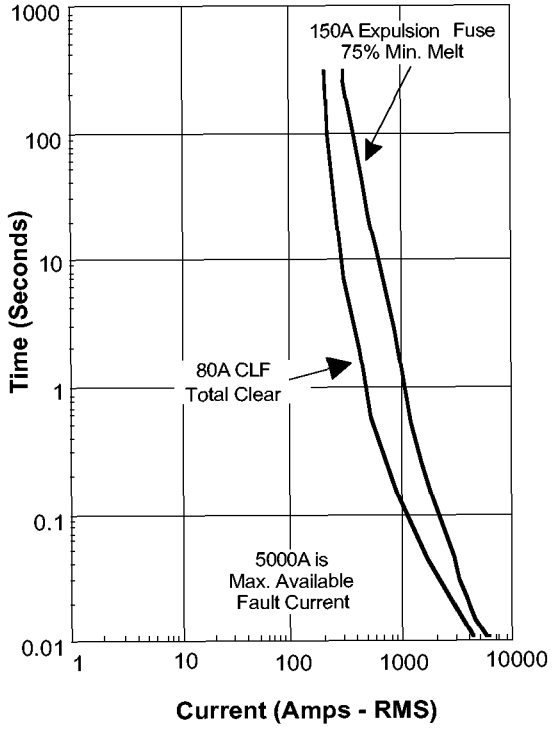

Figure 20—Expulsion fuse/Current-limiting fuse TCC curve example

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 total-clear I^2t of the 80 A CLF shall be compared with 75% of the minimum-melt I^2t of the 150 A fuse link; the total-clear I^2t of the 80 A is 181 000 amp^{2}sec, as specified by the manufacturer. The minimum-melt curve for the 150 A fuse link crosses the 0.01 second line at approximately 6100 A; therefore,

$$(6100)^2 \times (0.01) \times (0.75) = 279\,000 \text{ amp}^2\text{sec} \quad \text{and} \quad 181\,000 \text{ amp}^2\text{sec} < 279\,000 \text{ amp}^2\text{sec}$$

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Since the 80 A CLF total-clear I^2t is less than the minimum I^2t of the 150 A fuse link's 75% minimum-melt curve, I^2t coordination exists.

6.5.4 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 exist 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 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 90 A full-range current-limiting fuse will coordinate with a 160 A recloser (as shown in Figure 21) with one instantaneous trip curve "A" and two time delay trip curves "B," draw the curves and observe the intersection points. Figure 22 illustrates typical TCC curves for this combination. Depending on the application, there are two ways this problem may be approached.



Figure 21—Recloser/Current-limiting fuse example

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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.

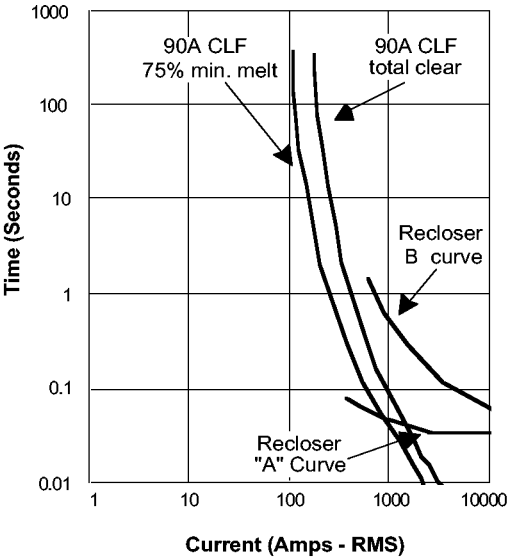

Figure 22—Recloser/Current-limiting fuse TCC curve example

If the current-limiting fuse is protecting underground circuits where only permanent faults are expected, the current-limiting fuse total-clearing 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 6000 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, VCRs, 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

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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.

6.5.5 Current-limiting fuse/Recloser (step-down) coordination

This combination should only be used to protect 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 blowing the high-side fuse.

Time coordination is based on the cumulative heating of the fuse as the recloser closes back in on faults. Different types of fuses cool at a different rate once the recloser opens. Multiplying ("K") factors were developed to reflect this cumulative heating effect as it is applied to expulsion fuse links for specific recloser trip times and reclosing time intervals as shown in Table 5. The heating and cooling of the element depends on the length of time the element is exposed to the fault (heating) as well as the length of time between each reclosing (cooling). "K" factors increase the time of the time delay TCC of the recloser to give it a large apparent clearing time.

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 expulsion fuse links. They also depend on timing of the delay trip and the open time of the recloser. For some 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 75% 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 75% minimum-melt curve must be greater than 0.17 s [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 23. The high-side fuse for this transformer is an 80 A CLF. A single-phase recloser with an operation sequence of one fast (A) and two time delay (B) curves and a 2 s open time has

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been selected 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.

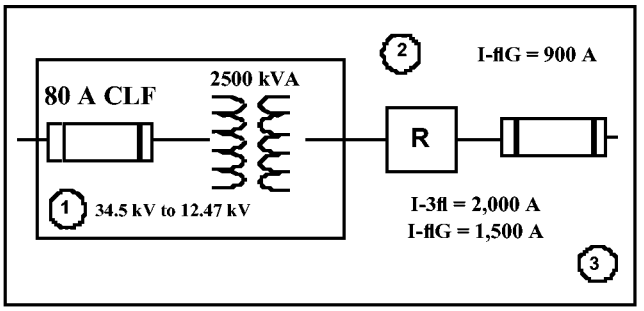

Figure 23—Current-limiting fuse/Recloser example

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 75% minimum-melt curve has been reflected to the low side of the transformer. To accomplish this, multiply the current values of the fuse 75% minimum-melt by the ratio of the primary voltage to the secondary voltage or 34.5/12.47.

Compare the 75% minimum-melt curve of the 80 A CLF reflected to the low-side of the transformer to the composite 1A-2B curve of the recloser multiplied by its "K" factor. In this case, a conservative value of 1.65 (i.e., a factor that is used for standard speed fuse link, which cool more slowly) was selected as the "K" factor since a value for this current-limiting fuse was not available. As shown in Figure 24, coordination exists since the 75% 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.

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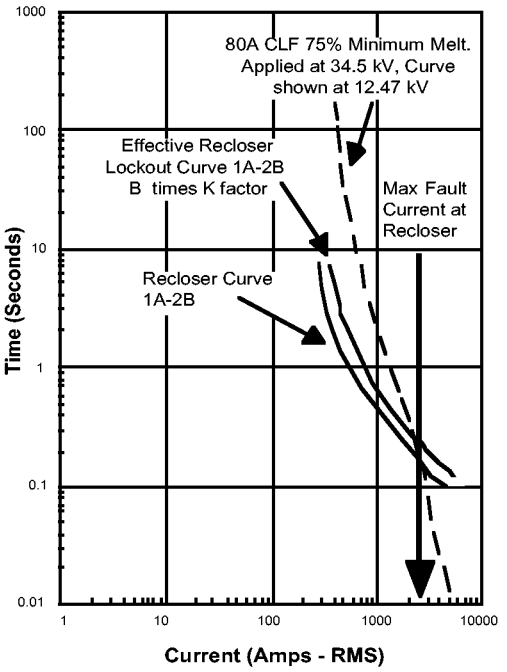

Figure 24—Current-limiting fuse/Recloser TCC curve example

6.5.6 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, 520 kV (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 25. 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 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

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(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.

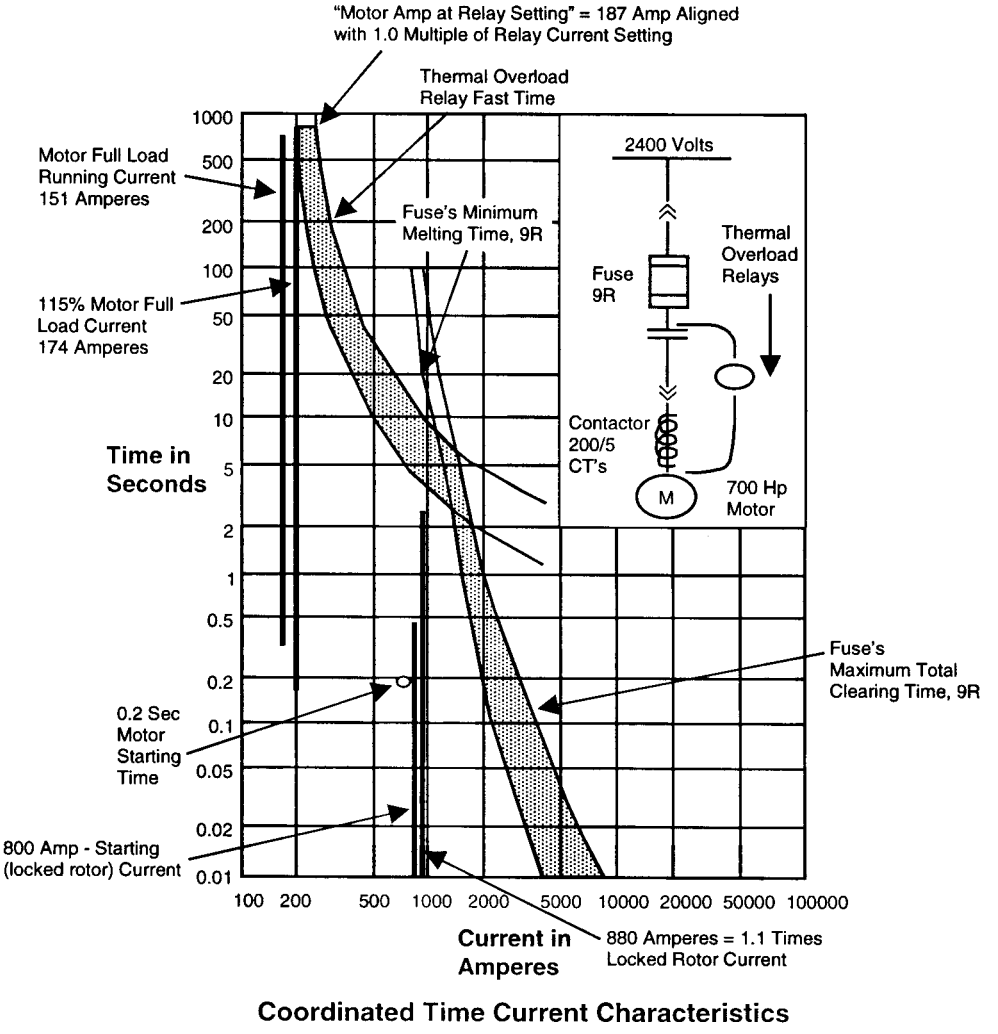

Figure 25—Schematic of motor protection system

6.6 Coordinating with back-up current-limiting fuses

Since back-up current-limiting fuses have a minimum interrupting capability, as discussed in 4.3.1, they must be used in conjunction with another device that will interrupt the currents below their minimum interrupting capability. This subclause will discuss two methods of coordinating a back-up current-limiting fuse in combination with an expulsion fuse, namely, matched-melt coordination, and time-current curve crossover coordination.

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6.6.1 Matched-melt coordination

This method of coordination, in which the expulsion fuse melts open any time the two fuse combination clears an overload or fault, is depicted in Figure 26. Note that the intersection of the expulsion fuse's total clearing TCC curve and the minimum-melting TCC curve of the current-limiting fuse occurs at a very short time. In some cases this intersection may occur on the total-clearing time-current curve of the expulsion fuse in the region where the curve is parallel to the current axis. This portion of the curve corresponds to a time duration of one-half cycle, which is the minimum length of time required for an expulsion fuse to clear. To be certain that the expulsion fuse will always melt open at any current that causes the current-limiting fuse to operate, the minimum I^2t let-through of the current-limiting fuse should be equal to or greater than the maximum-melt I^2t of the expulsion fuse. It is this criterion from which the method's name is derived.

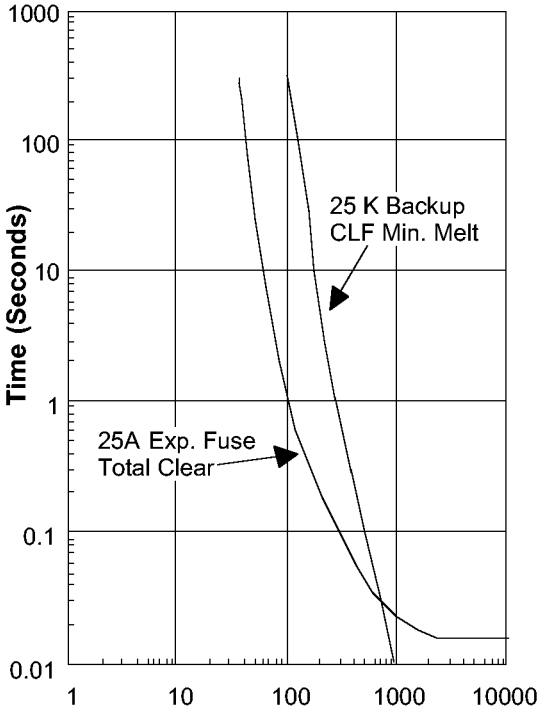

Figure 26—Matched melt coordination TCC curve example

While choosing a current-limiting fuse having a minimum-melting I^2t greater than the maximum I^2t melting of the expulsion fuse is conservative, another, 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. Not only will the I^2t that causes melting likely be higher than the minimum-melting I^2t, additional I^2t will be let through as a result of 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

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was less than the melting I^2t of the expulsion fuse. Obviously, such a situation would very rarely develop, although an expulsion fuse that is incorrectly selected (too large) can increase the probability. Because the probability is so low, this is not usually 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 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 former is not normally published by expulsion fuse manufacturers. However, it can be readily calculated from the expulsion fuse's minimum-melting TCC 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 is the current corresponding to 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 that have 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. Therefore, it is the approach that is almost always used with back-up current-limiting fuses, which are frequently applied in series with cutouts. The melting open of the cutout link allows the fuseholder to drop open. This, in turn, does the following two things:

1) It provides a visual indication as to the location of the fault that caused the fuses to operate.
2) It 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. This allows the designer to make certain ratings of the current-limiting fuse physically smaller than they would be if the fuses had to be capable of withstanding full system voltage indefinitely.

However, even if the system voltage were to be impressed across a "blown" fuse (due to the cutout being refused and closed back in, or if the expulsion fuse within the transformer was larger than it should have been), relatively short back-up current-limiting fuses have been shown to successfully withstand voltage for long periods of time without tracking taking place. Well-weathered fuses have been reported to have withstood voltage for as long as several months, even in severe coastal environments. Where the current-limiting fuse has operated, restoring the expulsion fuse does not restore service. Because of this, unless the fuse is installed on a capacitor bank, where there is no connected customer loads, the continued loss of service will lead to quick fuse replacement.

Another advantage of this coordination method is that, in three-phase applications, the voltage rating of the back-up 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 back-up current-limiting fuse.

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6.6.2 Time-current curve (or melt-clear) crossover coordination

Time-current curve crossover coordination, illustrated in Figure 27, is frequently used with under-oil back-up current-limiting fuses, but is hardly ever used with outdoor back-up current-limiting fuses. With this method of coordination, the location of the point of intersection of the expulsion fuse's total-clearing curve and the current-limiting fuse's minimum-melting curve under certain fault current conditions, may result in the current-limiting fuse melting and clearing without letting through sufficient energy to melt the expulsion fuse.

This is why time-current crossover curve coordination is rarely used in applying the outdoor back-up current-limiting fuse, and is what differentiates this method of coordination from the matched-melt method. Because of the location of this intersection or crossover point, one need not be concerned with the melt I^2t values of the two fuses when using the crossover method of coordination.

The principal criterion to be satisfied is that the previously discussed crossover point must correspond 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. The manufacturers of the expulsion fuse and the current-limiting fuse should publish values for these performance characteristics.

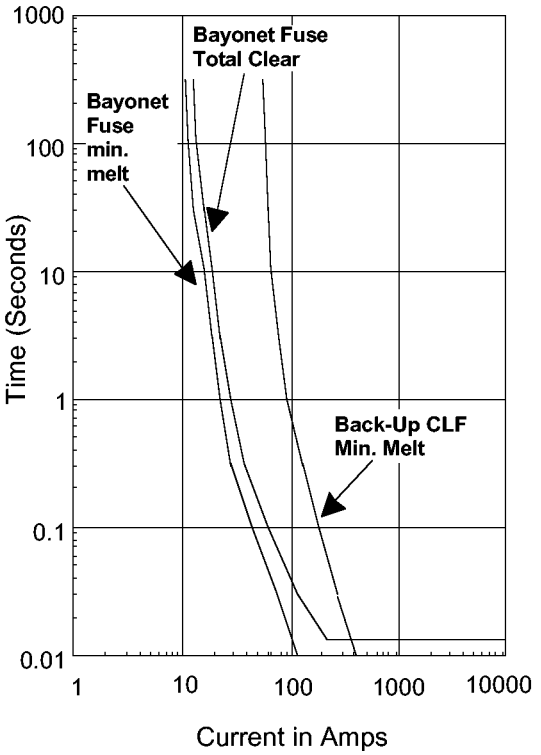

Figure 27—Time-current curve crossover coordination example

For applications of back-up current-limiting fuses on the primaries of transformers, another selection criterion that is important from the standpoint of serviceability and operability involves the current associated with a bolted-fault at the secondary terminals of the transformer. If possible, a current-limiting fuse should be chosen such that this current is less than the current corresponding to the crossover point.

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More specifically, one needs to first locate the point in time on the expulsion fuse's total-clearing curve that corresponds to the bolted-fault current. After this point has been located, next determine the current on the minimum-melting curve of the current-limiting fuse that corresponds to this time. If that current equals at least 125% of the bolted-fault current, the current-limiting fuse should only melt in the case of an internal transformer fault. Therefore, it is not necessary to provide access for replacing the current-limiting fuse in the "field."

As was the case with matched-melt coordination, it is important that the expulsion fuse's total-clearing curve not recross the current-limiting fuse's minimum-melting curve in the long-time region, which would allow the current-limiting fuse to respond to a current below its rated minimum interrupting current.

A suitable coordination margin is considered to exist if, in the long-time region of the curves, the current-limiting fuse's minimum-melting current at any given time equals at least 125% of the current determined from the expulsion fuse's total-clearing curve at that same time. Preloading should not affect this, as any shifting to the left of the characteristic curves due to I^2R heating of the fuse element(s) or ambient oil temperature rise will be as much or more for the expulsion fuse as for the current-limiting fuse.

The principal advantage of the time-current curve crossover method is that it normally permits the use of a lower current-rated fuse than does the matched-melt method. This can be significant in several regards.

First, the lower the current-limiting fuse's current rating is, the less energy it will 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 usually is apt to be and the less space it will require for installation. This method of coordination, allows extension of current-limiting fuse protection to larger kVA transformers.

6.7 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.

An arrester on the load side of the current-limiting fuse is not vulnerable, i.e., 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.

On the occasions when arrester conduction occurs, 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.

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Annex A

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