Abstract – This paper examines the ways that fuses are used to protect distribution transformers and the systems to which they are connected. The common types of fuses and the performance characteristics of each type are discussed. Emphasis is given as to how proper coordination of each type of fuse with the transformer, and with each other, may be achieved. The paper attempts to cover the majority of common questions that arise when using fuses to protect distribution transformers including testing requirements for fuses, arc voltage concerns, selecting fusing for dual voltage transformers, and an explanation of "matched-melt" coordination, which can be used to fuse delta connected transformers having primary voltages as high as 34.5kV.

1 INTRODUCTION

Fuses have formed an important and cost-effective part of system and equipment protection schemes for well over a hundred years. At a casual glance, fuse technology may seem to have changed little over most of this time, and it is true that the simple elegance of the fusing principle - that of relying on an excess amount of current to melt open the conductor through which it flows and thus initiate the interruption of that current - has been the same since fuses were first introduced during the latter part of the 19th century! However, the longevity of the principle, and the device to which it gave its name, has not only been because of its brilliant simplicity ("the higher the current the faster the fuse melts"), but also because materials and design technology have kept pace with the ever-greater demands of the marketplace. In fact, one of the main drawbacks of fuses is that because their technology appears so simplistic, relatively few people fully realize what is needed to use the modern fuse effectively. Because of this, fuses have occasionally been misapplied, leading to disappointing results, and also many of the advantages they can provide have not been enjoyed as widely as they could be.

When fuses are examined in more detail, it is found that a surprising variety of types exist. Although some general types of fuses can be used in a variety of situations, many types have been designed specifically for a particular application and may therefore have attributes not possessed by other fuses. As a result, a fuse that is similar in appearance to one designed for a particular application may be quite unsuited for that application. This obviously adds to the potential for confusion on the part of the user. Because fuses form such a large subject, this paper will restrict its scope to a detailed description of types of high-voltage fuses traditionally used in or immediately adjacent to distribution transformers, although other types of fuses will be mentioned briefly. This paper will also discuss some of the aspects of fuse selection that will help the user to ensure appropriate fusing has been employed. It should be noted that "high-voltage", as defined in IEEE and IEC fuse standards refer to devices having a rated voltage over 1000V: in some circles, voltages that here will be called high-voltage may be termed "medium voltage".

2 STANDARDS

Before some specific fuses and their applications are examined, a word concerning standards is in order. Most electrical devices are covered by national, regional, and international standards, and fuses are no exception. All standards reflect the knowledge and scope of those who gather to write them (individuals, gathering under the auspices of national, regional and international bodies). Worldwide fuse applications, particularly as related to transformer protection, tend to fall into two main categories. One general type of transformer protection is related to the practice common in North America (Canada, USA and Mexico) while the other relates to the practice common in Europe. North American practice tends to use more individual transformer protection (often with the fuses mounted inside or adjacent to the transformer, with one fuse, or two series fuses, handling high and low currents). European practice commonly uses fuses in ring-main units (equipment incorporating a single fuse to handle high currents and a simple circuit breaker, mechanically tripped by the fuse, to handle low currents). Throughout the rest of the world, individual areas tend to use one or the other practice, or a combination of both. Thus individual National or Regional standards tend to reflect one of these two basic approaches, sometimes with the addition of local requirements. IEEE fuse standards have been written primarily with input from members from the US and Canada, and therefore tend to reflect the North American practices. IEC standards are world standards, and so tend to represent the “lowest common denominator” that everyone can agree upon. Because, in the past, most of those participating in IEC fuse standard development came from Europe, the standards tend to reflect primarily European practice [1]. With the latest revision of IEC 60282-1 [2] (current-limiting fuses) testing to some North American practices has been introduced, although to make such testing acceptable to European members, some “watering down” of the IEEE testing was necessary (even compared to the proposed revision of IEEE fuse test standard C37.41™ [3] currently underway, in which, based on the experience of the last 25 years, certain testing requirements have been somewhat relaxed). It is therefore important that a user who specifies that fuses shall be tested to a particular standard
ensures that the standard quoted reflects their particular needs. For example, oil-submersible current limiting fuses used in a transformer should be tested in accordance with the IEEE standard as it addresses this application specifically, with additional test requirements not present in IEC. On the other hand, if a backup fuse is being used in a ring-main unit, special testing of the striker when the fuse melts at lower currents is necessary to ensure that the fuse trips the breaker before self-destructing. In this case the additional tests are not covered by IEEE standards but are included in IEC 60282-1.

Fuse standards contain valuable information, not just for those who must test fuses (primarily their manufacturers and those who perform the testing), but for users also. It is interesting to note that those who write the current standards (users, manufacturers and testing authorities in the case of the IEEE, primarily manufacturers and testing authorities in the case of IEC) have begun to recognize that the way standards were written in the past may not be as effective today. We have recognized that many users (particularly in the case of electric utilities) do not have the depth of manpower available to them that was true 25 years ago. In addition, some testing authorities have suggested that certain newer manufacturers also are less knowledgeable concerning the testing of their product! Utility engineers now have to be more generalists, and few utilities can employ someone having a full time job involved just with fuses and fuse standards. There has therefore been a concerted effort to revise standards in such a way that they are more "user friendly" and contain more material that may be thought of as "tutorial" in nature (i.e. why a test is run not just what test is run). Of course, it must be realized that mandated standard testing can never replace a manufacturer's thorough knowledge of their own device since, as has already been suggested, standards represent the "lowest common denominator" testing. Specific examples of standards that have or will be written or revised in recent years, with the less experienced user in mind, are the IEEE standards C37.48\textsuperscript{TM} [4] (Fuse application guide) and C37.48.1\textsuperscript{TM} [5] (current-limiting fuse application guide) and the IEC project in SC32A (high-voltage fuses) to gather the application information from several different fuse standards together into one comprehensive document. It is therefore recommended that all users have access to such standards.

3 FUSE TYPES

3.1 Introduction

All protection schemes require full-range protection, in the sense that protection from both high and low currents is needed (sometimes the low current protection is needed for a fuse that cannot interrupt low currents). In the case of transformer protection, a single fuse, a combination of fuses, or a combination of fuse and circuit breaker is used to provide this. The devices can be in or adjacent to the transformer, or can be in a remote location. When more than one device is used, and there is virtually always more than one protective device between generation and the end user, issues of coordination between devices become relevant. An exhaustive study of all possible combinations of protective devices would occupy more space than is available here, however, the basic principles of coordination tend to be the same for all schemes. The most common protection methods for distribution transformers up to around 3000kVA will be discussed in detail in this paper.

All conventional fuses, after melting, continue to carry the current in the form of an arc for some period of time. Fuses can be divided into two basic types depending on how, during arcing, they influence the current that causes them to melt in a very short time (less than about 5 ms). The two types are called “current-limiting” and “non-current-limiting”.

3.2 Non-Current-limiting fuses

Non-current-limiting fuses arc, after melting, until at least the next natural current zero. They introduce very little resistance during arcing, so if they melt before the first peak of a high fault current, this peak is not significantly affected (that is they limit the duration of a fault current, but not its magnitude). The most common type of non-current-limiting fuse is the expulsion fuse (other less common types not discussed in this paper include vacuum and SF\textsubscript{6} filled devices). Expulsion fuses use a relatively short element suspended in a tube, made of, or lined with, a material that will evolve gas under the action of an arc. There are many types of expulsion fuse. Two of the most common types are cutout fuses, which are used on overhead systems to protect pole-type transformers, and bayonet fuses (shown in Figure 1), which are primarily used on underground systems in pad-mounted transformers.

Cutout fuses use a fuse link, consisting of a short element in a small diameter tube connected to a braided conductor that is installed under tension in a cutout fuse tube. When the fuse link melts a mechanism is released, which causes the cutout to drop open after interruption. Bayonet fuses have an
element that is made from a low, or high, melting point material (e.g. tin or copper) that is mounted in a cartridge that can be replaced from outside the transformer. Another common transformer expulsion fuse, termed a protective link, cartridge, or weak-link fuse, operates in a similar manner and is mounted on a terminal board or bushing. Because they are less easily replaced after operation than the bayonet fuse, they are less popular (probably 90% of fused pad-mount transformer in North America use bayonet fuses). However they do tend to have higher voltage and interrupting ratings, and other advantages discussed later. For each of these types, arc products from the fuse liner (and from oil around the element in the case of bayonets or weak-link fuses) are blown out of the open tube. The de-ionizing effect of this expulsion action produces a gap that can withstand system recovery voltage after the arc is extinguished at the current zero. With a high fault current this can happen in one loop, see figure 2.

With a lower current, the gap may be insufficient to withstand the transient recovery voltage (TRV) and may require two or more loops of arcing to establish sufficient withstand. This is shown in figure 3.

The amount of tube burning and gas production depends on the current level, so it becomes harder for a fuse to interrupt as the current increases. Therefore expulsion fuses in general tend to have a relatively limited rated maximum interrupting current. Although designs of expulsion fuse are available with interrupting ratings as high as 20,000A, such fuses require an elaborate construction. The typical, relatively inexpensive, expulsion fuses like bayonets and weak links that can be used inside transformers usually have interrupting ratings between about 600A and 3500A. Interrupting rating tends to decrease with increasing voltage, so the interrupting rating of some expulsion fuses at quite common system voltages can be too low for them to be used alone. X/R also affects the maximum Interrupting rating. Higher fault X/R values can produce more asymmetry – off-set – increasing the severity of a particular rms available current. Also, of course, more severe TRV values after a current zero make it harder for the fuse to interrupt (also related to X/R). However, while expulsion fuses can struggle in more severe circuits at higher currents, they are very good at interrupting lower currents.

3.3 Current-limiting fuses

3.3.1 General

The other main type of fuse is the current-limiting (CL) fuse. CL fuses usually consist of long elements wound around a former or “core” (to make the fuse compact), enclosed in a body that is filled with quartz sand. Figure 4 shows a “cut-away” view of such a fuse.

The element, typically made from one or more ribbons of high melting point material (silver or copper), has multiple areas of reduced cross-section. At a high current these restrictions melt virtually simultaneously, rapidly introducing a significant resistance into the circuit. This causes the current to quickly reduce to zero, and prevents the fault current from having the opportunity to reach its normal peak value (hence the “current-limiting” name). This action is shown in figure 5.
Because of the rapid current reduction, the voltage across the fuse during arcing (arc voltage) exceeds the system voltage (the difference being made up by the circuit’s inductive di/dt).

The element and its restrictions are therefore optimized in a CL fuse to control this voltage to an acceptable limit. It is very important to note that no fuse, expulsion or current-limiting, should be exposed to a recovery voltage that exceeds its rated maximum voltage (test voltage), or failure to interrupt can result (often in a spectacular fashion).

All fuses work well at reduced voltage; however, in the case of current-limiting fuses, the arc voltage does not decline in proportion to the system voltage. Care should therefore be exercised if a CL fuse is used at less than about 70% of its rated voltage, to ensure that insulation and arresters are not compromised. An exception tends to be for applications below 8.3kV where 8.3kV fuses have been used (primarily due to the scarcity of lower voltage CL fuses) for many years without problems. The fuse manufacturer can supply a curve showing arc voltage reduction with system voltage reduction (figure 6). This is of importance when fusing dual voltage transformers (see 6.1).

![Figure 6: Reduction of CL fuse arc voltage as system voltage is reduced.](image)

As described, a CL fuse is extremely good at interrupting high currents. Standard testing includes tests at the fuse’s Rated Maximum Interrupting Current (commonly termed “max I/C”), and also referred to as I₁, or Test Duty 1. CL fuses are also tested at a lower current (I₂, Test Duty 2, or “critical current”). This current depends on the design and current rating of the fuse, and approximates the maximum arc energy (absorbed energy) for that fuse. These two tests ensure that the tested design can interrupt any current that causes a current-limiting action to occur. CL fuse rated maximum I/C values tend to be very high, normally 50,000A symmetrical, unless test station limitations require a lower value. Because a CL fuse introduces a high resistance into the circuit upon arcing, current and voltage are pulled into phase, so circuit X/R and TRV have much less influence than for expulsion fuses. While testing standards require X/R values to be at least 10 for distribution class fuses, higher values (often 25 or more) are often used when testing at high currents for convenience or due to test station limitations. While current-limiting fuses are very good at interrupting high currents, they are not always as good at interrupting lower currents. This has led to the introduction of three categories of CL fuse, based on their ability to interrupt low currents: backup, general purpose, and full-range.

### 3.3.2 Backup CL fuses

A fuse that uses a simple punched strip element in quartz sand, as shown in figure 4, is normally classed as a backup fuse. If the current is so low that only one notch melts, the current cannot be interrupted at any significant voltage. Such a fuse therefore has a minimum current that will result in enough series notches melting together to produce current interruption. This current is termed the fuse’s rated minimum interrupting current (commonly “minimum I/C”). A backup fuse interrupting such a current is shown in figure 7.

![Figure 7: Current-limiting fuse interrupting lower current, requiring more than one loop of arcing.](image)

The waveforms are similar to an expulsion fuse interrupting low current except that, when multiple parallel elements are used, current switching between the elements occurs, and the voltage across the fuse during arcing tends to be higher, reducing the severity of the inherent TRV. Backup fuses are tested at this current, termed I₃, or Test Duty 3, and so can interrupt any current between their minimum and maximum I/C. A backup fuse must always be used in conjunction with some other device that will operate at a current below its minimum I/C to prevent the backup fuse from continuing to arc until it is destroyed and possibly causing an eventful failure of an otherwise undamaged transformer. Since expulsion fuses
clear low currents well, but have a limited maximum I/C, pairing an expulsion fuse with a backup CL fuse makes a lot of sense. This technique is often termed the “two-fuse” approach. Each fuse protects the other in its area of vulnerability; the expulsion fuse protects the backup fuse at low currents, and the backup fuse protects the expulsion fuse at high currents. There are two main types of backup fuses used on North American style distribution systems; oil-submersible backup fuses, which are used in conjunction with bayonet or weak link expulsion fuses to protect pad-mount transformers, and external backup fuses, which are used with fuse cutouts to protect transformers on overhead systems. The “two-fuse” approach to protection is the most common form of transformer protection in North America, unless fault currents are so low that an expulsion fuse alone is used. The coordination of backup fuses and expulsion fuses will therefore form a substantial part of this paper (see 5.2 & 5.3).

3.3.3 General Purpose fuses

To address the limited low current interruption ability of simple CL fuses, a significant number of techniques have been used, including multiple elements, gas evolving materials and auxiliary elements. It is too extensive a subject to cover here [6]; however, whatever the technique used, if the minimum I/C of a fuse can be reduced to the point where a fuse can interrupt a current that causes it to melt in an hour or more, the fuse is classed as a General Purpose fuse. Such fuses can handle many overload situations, without the need for a second device, hence the name. However, the test requirements were developed when wire elements were common, and melting Time-Current Characteristic (TCC) curves were substantially vertical at one hour. While wire element fuses could not melt with currents much lower than that causing them to melt in one hour, overloading could still damage them. They therefore had to be coordinated with other protection to prevent them from being exposed to such currents, if they were possible. When ribbons replaced wires in order to get higher fuse current ratings and improved TCC shapes, general purpose fuses could now melt at times longer than one hour, as the TCC curves did not become vertical until perhaps 10,000s. Designs that could still work at these longer times were developed, usually employing gas-evolving materials to help with low current interruption. Unfortunately, when some of these designs were used inside transformers by employing “dry well” canister fuseholders, certain ratings experienced problems due to gas condensation, etc. [7] This led to a move away from such applications, and more towards the “two-fuse” approach introduced in 3.3.2.

3.3.4 Full-Range fuses

When it was realized that applications existed where a fuse not only needed to be able to clear any current that caused it to melt, but also needed to be able to do this at elevated temperatures and in enclosures, appropriate testing was introduced into fuse standards. A Full-Range Fuse is defined as one that can interrupt any continuous current that causes it to melt, at a surrounding temperature equal to the maximum specified by the fuse manufacturer (rated maximum application temperature, or RMAT). As a consequence of the method of testing, most properly tested full-range fuses can be overloaded, without damage, until they melt and interrupt. For fuses used inside transformers (either directly in the oil or in a canister fuseholder) the usually assigned RMAT is 140°C. This outstanding performance is typically achieved by incorporating the “two-fuse” approach into a single fuse body, as shown in figure 8.

Figure 8: Full-Range fuse using the “dual-element” approach.

The fuse uses two series connected types of element (such fuses are usually termed “dual-element”). Here an expulsion type element (a silver wire in a silicone rubber sleeve) connects two high current strip elements. The low current section incorporates a short tin section, which initiates melting at lower currents. The fuse is sealed, so the small amount of gas generated in the sleeve, that creates the expulsion process, is contained within the fuse. This permits submersible canisters to be used if necessary.

4 TRANSFORMER PROTECTION

The primary function of a fuse is to remove a faulted device from the power system (protect the system). In some cases, overload protection for the transformer is desired, and so a fuse that responds to transformer oil temperature as well as current is then preferable. As available fault currents continue to rise, it is also becoming increasingly important to remove a faulted transformer in a way that minimizes the chance of an eventful transformer failure. In addition to performing these functions, it is also necessary that the fuses be selected such that anticipated inrush currents and cold load pick-up currents will not damage them.

Manufacturer’s literature normally provides recommendations for fuse selection. However it is difficult for manufacturers to anticipate every eventuality, and special cases exist. While normally under such special circumstances one would obtain
recommendations from the fuse manufacturer, it is helpful to understand the principles of the selection process, in order to make sure that the manufacturer is supplied with all of the relevant information. In the case of protecting a transformer with a full-range fuse, a single fuse is chosen during the selection process. In the case of "two-fuse" coordination, normally the expulsion fuse is chosen first, and then a suitably coordinated backup fuse is selected to complete the protection.

The fuse selection and coordination process will be examined in two parts. The first will look at the selection of current rating, without regard to voltage, and then the second part will discuss the appropriate voltage rating for the fuses, based on typical transformer configurations.

5 FUSE CURRENT RATING SELECTION

5.1 Expulsion and Full-Range CL fuses

We will first examine the selection of an expulsion fuse or full-range CL fuse, since the techniques are similar. In general, the smallest fuse that will meet the customer’s requirements is selected, in order to minimize the extent of an outage (preferably just to the affected transformer) and minimize the risk of eventful failure. However, it is important that the selected fuse is large enough that nuisance operation will not occur due to damaging surge currents.

Rules to achieve fuse coordination with inrush, etc. are well established, and figure 9 shows the usual inrush and cold-load pickup points together with a minimum melt TCC for an expulsion fuse (a full-range fuse TCC will look similar, and use the same rules, except that the curve will become asymptotic to the time axis at a much longer time, approximately 10,000s).

The specified points must lie on, or to the left of the minimum melt TCC ("safety" margins have been built in). Internal transformer secondary circuit breakers are less common than they used to be, but if they are being used, then sufficient margin should be left between the breaker curve (adjusted for turns ratio) and the primary fuse. A frequently used rule for this is to shift the primary fuse’s minimum melting TCC to 75% of time and compare this with the total clearing TCC of the secondary device. The total clearing TCC must lie to the left of the shifted minimum melt TCC to achieve coordination. If the secondary device is inside the transformer, and uses a thermal trip, coordination with an internal primary device is normally maintained as oil temperature rises since the secondary breaker curve shifts as much or more than the primary fuse TCC. However, care must be exercised if an external secondary breaker (or a secondary fuse) is to be compared with an internal primary fuse, since the secondary device’s characteristic would then be independent of the transformer oil temperature. In such an instance it is sometimes necessary to shift the minimum melting TCC of the internal primary fuse by some factor to make sure that it will still coordinate with the external secondary protective device under overload conditions when the temperature of the oil is elevated. The amount that an internal primary fuse curve shifts will depend on what the melting portion of the element is made from. The melting characteristic of silver and copper elements change very little as oil temperature increases, while lower melting point materials such as tin or eutectic can shift significantly. In fact it is this latter characteristic that provides transformer overload protection, when it is needed. However, even when overload protection is not a priority and a utility wants to keep a transformer functioning under severe overload conditions, the effect of curve shift is still important, and must be considered when selecting an expulsion fuse that will allow a particular overload capability.

When a relatively limited transformer overload capability is desired, bayonet or weak link expulsion fuses that use a low melting point material are used. Expulsion links that use a eutectic element that melts at about 145ºC are normally termed “dual sensing” or “dual element”. The transformer oil temperature has a significant effect on the minimum melting TCC of such fuses. In fact, the links would
melt open at an oil temperature of 145°C even if no current flowed through the link. This of course is not possible, but it serves to illustrate the effectiveness of these links in responding to oil temperature. What actually does happen is that at a transformer overload, the fuse element will rise to a temperature above that of the oil surrounding the link. If this temperature were above the element melting temperature, the fuse would operate, but if it is not, the transformer will carry the overload until the oil temperature rises to the point where the oil + element temperature rise equals the melting temperature. At this time the fuse will operate. It is possible, therefore, to estimate from the published minimum melting TCC of the link at 25°C what current will cause it to melt at a particular oil temperature, if the element material is known. Manufacturer's published tables have already done this for common transformer types. Dual element and dual sensing links are typically selected to permit about 160% load for 7 hours. Other types of links that use higher melting point materials are sized to permit 3 to 4 times full load current for 300s. Some ratings of these “current sensing” or “fault sensing” links use copper or copper alloy elements that have so high a melting temperature, they are almost unaffected by oil temperature. Other links use tin elements. When this is the case, fuse melting will be somewhat dependent on oil temperature and a measure of overload protection is possible. Again, published information will take this into account. Full-range fuses that employ a tin section also respond to oil temperature whether they are mounted in a canister fuse holder or directly immersed in oil. In the case of the fuse shown in figure 8, the long time minimum melting TCC curve will shift to the left by 2% if the fuse is used in a canister, and an additional 0.2% for each degree C that the oil temperature is above 25°C (at which the curve is published). For example, in 100°C oil, a fuse having a minimum melting current (at 10,000s) of 52A, has this reduced to 51A by enclosing it in a canister surrounded by oil, and then by 75 x 0.2 = 15%, i.e. to 43.3A, due to the 75°C rise in oil temperature. Thus a transformer having a rated current of 21A can carry approximately 200% of rated current at an oil temperature of 100°C without the fuse melting. Manufacturer’s literature usually has application tables that list two columns of full-range fuses for each standard transformer. For an oil temperature of 100°C, one column lists a fuse that will permit between 160% and 200% of transformer rated current, the other between 200% and 300% of rated current.

5.2 Time-Current Curve Coordination

5.2.1 General

Having selected a suitable expulsion fuse, the next step in creating a “two-fuse” protection scheme is to appropriately coordinate a backup fuse. The most common method of coordinating an expulsion fuse with an oil-submersible current-limiting backup fuse is to use what is known as time-current curve coordination (TCC coordination). The total clearing TCC of the expulsion fuse and the minimum melting TCC of the backup fuse are used for this.

Note – Most of the difference between minimum melt and total clearing TCC curves, at times of more than 1s, is due to manufacturing tolerances. Standards require that the maximum melting curve not be more than 20% greater (in terms of current) than the minimum. Arcing is added to the “maximum melting TCC” to produce the total clearing TCC, but arcing time is only significant at very short melting times. If an “average” clearing TCC is published for a fuse, this must be shifted 10% to the right to give an approximation of its total clearing TCC.

Several different coordination criteria must be met to ensure a successful “two fuse” scheme.

5.2.2 Mutual protection

The first criterion concerns the arrangement whereby each fuse protects the other in its area of non-operation. Figure 10 shows the TCC curves for an expulsion fuse crossing that of the backup fuse.

![Figure 10: Coordination of expulsion fuse and backup fuse.](image-url)
crosses the minimum melting TCC of the backup fuse at a current equal to or greater than the backup fuse’s rated minimum interrupting current. To protect the expulsion fuse from attempting to interrupt at a current higher than its rated maximum interrupting current, the crossing of the two curves should also occur at a current below the expulsion fuse’s max I/C.

In the case of larger sized transformers, this latter constraint may not be possible. However, provided that the minimum I/C of the backup fuse is lower than the expulsion fuse’s maximum I/C, fusing may still be possible. At currents above the max I/C of the expulsion fuse, the expulsion fuse will arc until the backup fuse melts and interrupts. In the case of an internal cartridge fuse, the additional arcing will increase the severity of the fault inside the transformer (which has failed anyway - see later) and so may be acceptable. However, in the case of a bayonet fuse, the additional arcing may or may not be acceptable. If the arc energy dissipated in the bayonet before the backup fuse clears is no higher than it can withstand, this should be acceptable (e.g. if at a high voltage the bayonet fuse cannot interrupt a particular current, but the energy, limited by the backup fuse operation, is no higher than the fuse would see when successfully interrupting a higher current at a lower voltage). If however the energy is sufficient to severely damage the bayonet assembly, this may not be acceptable. This is because under these circumstances the pullout bayonet assembly could be “launched” from its holder with force. Only the user is in a position to determine if the convenience of the bayonet over a fixed expulsion fuse warrants the operating practices required to deal with this eventuality.

5.2.3 Bolted secondary fault coordination

The purpose of the backup fuse is to provide transformer protection in the case of high current faults, with an emphasis on significantly reducing the risk of an “eventful” failure. Even if the fault current is less than the expulsion fuse max I/C, the energy let through by the expulsion fuse at high currents is many times more than that let through by a CL fuse, and so could still lead to an eventful failure (particularly in the case of pole-type transformers). Because oil-submersible backup fuses need only to operate in the event of an internal transformer failure, they do not have to be field replaceable. It is therefore important that a fault external to the transformer (the worst case being a bolted secondary fault) causes the expulsion fuse to operate without melting, or more importantly damaging, the backup fuse. This is achieved by leaving a suitable margin between the expulsion fuse total clearing TCC and the backup fuse minimum melt TCC, at a current equal to the bolted secondary fault current. A commonly used margin (that appears in the IEEE Fuse Guide C37.48) is to ensure that at a time equal to the expulsion fuse bolted secondary fault current clearing time, the backup fuse minimum melting current is at least 125% of the bolted secondary fault current. This is shown in figure 11. The 25% margin prevents element damage, and also takes care of the situation where the transformer has taps. The bolted secondary fault current should be calculated from the transformer nominal kVA and voltage, and its minimum impedance. It may be noted that this is equivalent to shifting the backup fuse’s minimum melting TCC by 20%, in terms of current (reducing the current by 20%), creating a “no damage” curve for the fuse.

![Figure 11: Safety margins for fuse coordination.](image)

5.2.4 Overload

The safety margin discussed in 5.2.3 also applies for any current lower than the bolted secondary fault current. Clearly any current at which the expulsion fuse should operate must not damage the backup fuse. Otherwise, after the expulsion fuse has been replaced, the damaged backup fuse could melt at a current that it cannot interrupt, and subsequently fail. Therefore the 25% margin should also be used at the top of the expulsion fuse curve, and anywhere in between, should the expulsion fuse curve have a “knee” in it (this occurs when dual element links, having two different elements in
series, are used). An additional consideration is that the rated continuous current of the backup fuse should not be exceeded by any overload that can persist for a significant time. Fuses have a relatively short thermal time constant, and respond quite rapidly to currents. However, oil-submersible backup fuses frequently can carry more than their "name plate" rating in 85ºC oil and, fortunately, most applications use a backup fuse that has a significantly higher current rating than the transformer rated current, due to the coordination criteria discussed.

5.3 Matched-melt Coordination

Fuses coordinated using the criteria in 5.2.2, 5.2.3, and 5.2.4 are said to be coordinated using "Time-current curve" coordination. This provides satisfactory coordination, and, as stated, is the most common method used for the two-fuse approach. However there is a second method, termed "matched-melt" coordination that requires all of the criteria already discussed and adds one more. This additional criterion ensures that the expulsion fuse always melts open, even if it is the backup CL fuse that is doing the interruption.

$I^2t$ is a term frequently used in association with fuses and their coordination, particularly when considering high currents. $I^2t$ (strictly $\int \frac{di}{dt}$) is related to energy. When an $I^2t$ value is multiplied by the resistance through which the current flows, the result is the energy dissipated in that resistance. The reason for its use with fuses is that, at very short melting times, the $I^2t$ to melt a fuse element tends towards a fixed value. Further more, most CL fuses tend to let through a reasonably constant $I^2t$ value when in their current limiting mode, independent of fault current. Clearly, if the minimum melt $I^2t$ of the backup CL fuse is more than the maximum melt $I^2t$ of the expulsion fuse (using minimum and maximum tolerances) the CL fuse could not melt without melting the expulsion fuse also. To use this as the criterion would be rather restrictive, however, and excellent results have been achieved by having the minimum melt $I^2t$ of the backup fuse at least half of the maximum melt $I^2t$ of the expulsion fuse. This is because, at most practical melting times, the CL fuse does have a higher melt $I^2t$ than its minimum, and because a fuse cannot interrupt current without some arcing, which will add additional $I^2t$.

The most common occurrence of matched melt coordination is when an external backup fuse is used with a cutout (often used to protect pole-type transformers). In this case the primary reason for the matched melt coordination is to ensure that the cutout always drops open. This gives visual indication of the fuse operation, and also removes recovery voltage from the backup fuse, enabling it to be made shorter (since it does not require the appropriate creep distance for withstanding system voltage). While match-melt coordination of fuses can appear to be a difficult process (since the maximum melt $I^2t$ of the expulsion fuse is not a published value and must be estimated from its minimum melting time-current characteristic), selecting an external backup fuse to coordinate with a particular size of cutout fuse is actually quite easy. External backup fuse manufacturers rate their fuses by the largest type K cutout link that the fuse will match-melt coordinate with. For example, a 25K backup fuse will match-melt coordinate, and can therefore be used with, any type K cutout fuse link that has a rating of 25K or lower. For those using other types of cutout fuse links, the appropriate external backup fuse can be selected from tables published in the backup fuse manufacturer's literature, thereby simplifying the coordination process.

While match-melt coordination is most commonly used with cutouts and external backup fuses, there are occasions when it is also used to coordinate the fuses used in pad-mounted transformers. The reason for this will be explored when fuse voltages are discussed in 6. Methods of achieving matched-melt coordination for this application are discussed in IEEE Standard C37.48 and in backup fuse manufacturers' literature. However, it is suggested that, in most cases, the backup fuse manufacturer be consulted for their specific recommendations.

6 FUSE VOLTAGE RATING SELECTION

6.1 Single-Phase Applications

Selection of fuse voltage rating in this case is quite straightforward. The rated maximum voltage of the expulsion fuse and backup fuse, or full-range fuse, must be equal to or greater than the maximum applied voltage (normally system line-to-neutral voltage, unless a transformer is connected line to line on a delta system). It should be noted that if a fuse has been tested to IEC standards, rather than IEEE standards, then it may be necessary to have the fuse rated voltage at least 115% of the maximum system voltage, as IEC testing is based on fuses for use in a grounded three phase system. It may be noted that some manufacturer's fuses have been tested at voltages in excess of the standard "preferred" values, by which the fuses are normally known (e.g. an 8.3kV fuse may have a rated maximum voltage of 10kV, but is listed as an 8.3kV nominal fuse).

The main area of complication with single-phase applications (and this also can apply to three phase applications) is that of dual voltage transformers in which the same backup fuse is to be used at both voltages. In this case the CL fuse must have a voltage rating equal to or greater than the higher of the two transformer primary voltages, and a current rating that will coordinate with the expulsion fuse to be used for the lower voltage situation. Normally the
expulsion fuse is changed between the two voltages, a relatively simple task if bayonet fuses are used since the same fuse assembly is suitable for all voltages below 23kV (although the links have different max I/C values at different voltages). When the transformer is being used at the lower voltage, the only concern that results from using the same backup fuse at both voltages is with the arc voltage that the fuse will develop when it operates. A detailed discussion of that issue occurs in section 3.3.1.

6.2 Three-phase Applications

6.2.1 Introduction

Before beginning the discussions concerning selecting the proper voltage rating for fuses in three-phase applications, it should be noted that the selection process is much more difficult than for single-phase applications and that the selection is apt to be influenced by a number of different factors. Among these factors are the design of the transformer (delta or wye), the nature of the connected load, the method of coordination to be used, operating experience and practices, and the ratings of the available expulsion and current-limiting fuses. Due to the number of factors involved and the complexity of the selection process in these applications, this paper cannot address all possible combinations and permutations of these factors. It instead focuses on those situations that the authors believe to be of the most general interest, and fuse manufacturers should be contacted for additional information.

6.2.2 Delta connected transformers

Delta connected transformers produce L-L voltages across primary fuses for a variety of faults. [8] It is therefore normal to use L-L rated fuses. However if one uses the two-fuse approach, and if the expulsion fuse is rated line-to-line, it is often possible to coordinate the expulsion fuse and the current-limiting fuse using matched-melt coordination so that a current-limiting fuse having a voltage rating corresponding to the system line-to-neutral voltage can be used. In practice, this is seldom done where L-L rated backup CL fuses are available, but often becomes the only way that higher voltage transformers can be fused.

As discussed in 5.3, matched-melt coordination ensures sufficient $I^2t$ will be let through by the current-limiting fuse(s) to melt open the expulsion fuse(s). If the fault is a line-to-neutral fault, the line-to-neutral rated current-limiting and the line-to-line rated expulsion fuse combination obviously should have no difficulty in clearing, as both fuses have voltage ratings equal to or greater than the voltage that they would have to clear against. Even if the fault is transient (e.g. a flashover) and a L-L recovery voltage appears across the operated fuses, the L-L rated expulsion fuse could block the voltage if the backup fuse proved to be inadequate for the task. In the case of line-to-line faults, the situation becomes more complicated. If the magnitude of the fault current is less than the interrupting rating of the expulsion fuses, the two expulsion fuses that would “see” the fault (one from each phase) should have no difficulty in clearing it. If the fault current exceeds the rated maximum I/C of the expulsion fuse and doesn't involve ground, two current-limiting fuses in series with two expulsion fuses will be attempting to interrupt the fault current. If the two current-limiting fuses share the interrupting duty, they will be able to clear despite the fact that they must do so against a voltage that exceeds each's individual rated voltage. In addition, the fact that the line-to-line rated expulsion fuses will have melted open means that the system's line-to-line voltage will not be impressed across the line-to-neutral rated current-limiting fuses after the clearing has occurred.

Testing and many years of experience support this. Tests have shown that two series connected current-limiting fuses share voltage well when they both melt in the first loop of current (i.e. when they are operating in their current-limiting mode or at currents a little less). Thus, it has long been assumed that as long as the interrupting rating of the expulsion fuse is at or above the point at which the current-limiting fuses go into their current-limiting mode, there should be no question as to whether the two current-limiting fuses share the interrupting duty. However, if the interrupting rating is such that the current-limiting fuses would take several cycles to melt when subjected to such a current, there was no guarantee that the two fuses would share the interrupting duty. In fact recent test data [9] has shown that two backup current-limiting fuses, of a particular design, will not share the interrupting duty for melt times longer than equivalent to a few loops of current. This would imply that, unless the current corresponding to the maximum interrupting current of the expulsion fuse is high enough to cause the current-limiting fuses to melt within one or two loops of current, L-L rated backup fuses should be used. However, the same testing referred to previously also showed that, at currents below those causing the backup fuse to operate in its current-limiting mode, a single L-N rated fuse was capable of interrupting L-L faults. This was shown to be true from currents causing melting in a few loops down to currents well below the maximum interrupting current of the expulsion fuse. This is because the “rated” maximum voltage of a backup fuse is established under the most severe conditions, i.e. $I_2$ and $I_1$, and the light duty conditions below $I_2$ are easier for the fuse. Such testing has been performed on certain 23kV rated backup fuses that have been shown to be capable of interrupting in a 37kV circuit from a current well below the maximum interrupting rating of 35kV.
expulsion fuses (1200A) up to a current at which a single fuse can interrupt alone or two fuses in series will melt in the same loop and share the duty. This enables 34.5kV delta connected transformers to be fused up to 2600kVA, using L-L expulsion fuses and L-N rated backup fuses. The backup fuse manufacturer must be consulted for such applications.

Wind farm applications often utilize delta-connected transformers at 35kV and use the fusing described in the preceding paragraph. Wind farm applications at any voltage, where the transformers are acting to step-up the voltage from the wind turbine and connect them to the power system, present certain challenges to system protection. Although the conventional “cold-load pickup” points for an expulsion fuse on the HV side have no real meaning in such applications, it is important that the expulsion fuses still be chosen to withstand such overloads, as wind gusts can impose significant surges on the fuses. It is also important that, in the event of a fault that causes operation of the transformer fuses, the generator be isolated from the low voltage side of the transformer as quickly as possible. If the generator and system voltage are not held in phase, up to double voltage could be imposed across the operated fuses. For this reason, the two-fuse approach using matched melt coordination is particularly helpful, especially when cartridge expulsion fuses are used that produce a large, under oil, isolation gap. For this reason, full-range fuses are not usually recommended for this type of application.

When only time-current curve crossover coordination is used for two-fuse protection, both the current-limiting fuses and the expulsion fuses normally should be rated line-to-line, except on grounded-wye/grounded-wye transformers having less than 50% delta connected load (6.2.3). The reason why this coordination is more restrictive than matched-melt coordination is that one cannot be sure that the current-limiting fuses will let through sufficient energy to melt open the series connected expulsion fuse(s). In this case, even if the two current-limiting fuses share the interrupting duty and successfully clear a line-to-line fault in excess of the maximum interrupting rating of the expulsion fuse, one cannot be certain that a voltage that may be as high as the system’s line-to-line voltage will not be impressed across the fuses after they have cleared. If this were to occur, there is insufficient test data or experience to be certain that the fuses would not subsequently fail.

6.2.3 Grounded-wye/Grounded-wye connected transformers

In the case of grounded-wye/grounded-wye transformers, having at least 50% grounded load, full-range fuses, or in the case of the two-fuse system both expulsion and backup CL fuses, are often chosen based on the system’s L-N voltage. The reason for the 50% grounded load limit is that 50% grounded load produces a recovery voltage in an open phase of approximately 115% of the L-N voltage [8] and preferred fuse voltages are normally at least 15% higher than typical system L-N voltages. In the case of a high current line-to-line fault not involving ground that causes fuses to operate in their current-limiting mode, two fuses in series (or sets of fuses) share the duty. They easily interrupt the current, and then the recovery voltage impressed across the fuse(s) in each phase is normally within their rated maximum voltage. If the melting time is long enough so as to make sharing of series fuses unlikely, the assumption is that by then the fault should involve ground. Obviously, once ground becomes involved, the fuses only have to clear against the system’s line-to-neutral voltage. It must be emphasized, however, that a substantial part of the load must be grounded. If the load is predominately ungrounded, or if the % of grounded load is not known, L-L rated fuses should be used.

6.2.4 Assumptions

It should be noted that all three-phase fusing schemes that employ fuses having a voltage rating less than the system’s L-L voltage require that certain assumptions are valid. For grounded-wye/grounded-wye systems, some of these have been discussed in 6.2.3. For all systems, there is an overriding assumption that a single fuse will not be called upon to interrupt a line-to-line voltage except in the case of a tested backup CL fuse discussed in 6.2.2. Even here, there is a restriction that a single fuse must not be called upon to interrupt in its current-limiting mode (that is at severe duty conditions when the current is higher than that causing melting in approximately one loop of current). Conditions that could cause this to occur are quite rare, but are discussed in fuse standards. Three conditions where this could occur are:

1) If a three phase primary fault that does not involve ground can occur

2) If a system has an isolated neutral or is resonant grounded and does not have protection that will operate when a single ground fault occurs and (or before such protection can operate) a second phase fails to ground with one fault upstream of the fuses and the other downstream

3) If a system is such that a neutral shift can occur that would produce a higher than normal voltage across the fuse during a high current L-N fault.

7 CONCLUSIONS

Fuses of various types have provided improved system and equipment protection for many years.
For transformer protection, expulsion fuses alone have long provided inexpensive an effective protection where fault currents are modest, as well as the availability of overload protection, where improved transformer life is desired at the cost of disconnecting a customer. Where available fault currents are higher, and the risk and inconvenience of an eventful failure (or just an oil spill from damaged accessories) is undesirable, current-limiting fuses provide outstanding protection at a reasonable cost. The combination of an under oil expulsion fuse and a backup current-limiting fuse (two-fuse approach) is a popular option and the ease and low cost of replacing the expulsion link in a bayonet type expulsion fuse is often favored over using a Full-Range fuse. However, Full-Range fuses provide greater flexibility of mounting, keep arc products out of the transformer oil, and do not need the coordination of two fuses (and the potential for incorrect link replacement compromising the coordination with the backup fuse). Typical mounting arrangements include: mounted in overhead applications; mounted under oil; in a canister that allows ease of replacement and the option of load make/break; in the elbows of separable connectors (particularly where the retrofitting of a fuse is needed); in solid insulation switchgear or connections (as a Molded Current-Limiting Fuse); or clip mounted in associated switchgear.

Although attempts have been made to assess the energy withstand of various types of transformer [10] in order to determine appropriate \( I^2t \) limits for the use of CL fuses in particular sizes of transformer, this has proved difficult as the transformer arc energy is proportional to \( I^2t \) times arc resistance, which depends on the length of the internal fault arc. However, what has been found is that current-limiting fuses tend to let through an \( I^2t \) having an order of magnitude less than that necessary to cause tank failure, so the use of any appropriately sized fuse seems to provide good transformer protection under nearly all practical circumstances.

This paper has attempted to cover some of the more popular questions and typical applications concerned with protecting a power system from a failure associated with a transformer and its components, and minimizing the impact on the public from such events. Fortunately such failures are rare, but even more fortunately, “eventful” versions of such failures are even rarer. The reasons for this surely lie, at least partly, in the extensive use and continued development of fuses and their application.

REFERENCES


