

Subject: **Application of Trans-Guard® EXT and OS Shorty Fuses**
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1. Introduction

The Trans-Guard® EXT and Trans-Guard® OS Shorty fuses, designed and manufactured by Thomas & Betts / Hi-Tech® are backup current-limiting fuses as defined in IEEE Standard C37.40™ (ANSI). These fuses are used to protect distribution equipment (transformers, capacitors, switchgear, etc.) from the potentially damaging effects of fault current and to remove faulted equipment from the system, thereby minimizing the extent of the area affected by the fault. In addition, the fuses often serve to minimize the duration of dips in the system's voltage caused by these faults. As current-limiting fuses they are capable of interrupting very high currents and are suitable almost anywhere, regardless of available fault current.

The Trans-Guard® EXT (hereafter referred to as simply EXT) is designed for applications in air, either mounted on or adjacent to the piece of equipment it is protecting. Two of the most common locations for mounting an EXT is the terminal of a cutout or directly to the high voltage bushing.

As its name implies, the Trans-Guard® OS Shorty (hereafter referred to as the OS Shorty) is an oil-submersible design and so is normally installed within the transformer or switchgear it is protecting.

Unlike the Trans-Guard® full-range current-limiting fuses manufactured by Thomas & Betts / Hi-Tech®, the EXT and OS Shorty are backup current-limiting fuses, which must always be used in series with a protective device. The protective device shall be capable of clearing currents which are sufficient to melt the element(s) of the current-limiting fuse, but are less than the backup fuse's rated minimum interrupting current (Min I/C). Expulsion fuses are particularly well suited to perform this function as they have a good low current interrupting ability. However, because they also tend to have a limited high-current interrupting ability (rated maximum interrupting current), pairing an expulsion fuse with a current-limiting backup fuse produces particularly good synergy. Therefore, because OS Shorty and EXT current-limiting fuses are usually paired with some type of expulsion fuse (cutout fuse link, Bay-O-Net fuse, etc.), this Application Bulletin will focus only on such applications and will not address coordination with any other devices. However, if another type of series device is used, for example an Elastimold® Molded Vacuum Interrupter (MVI), the same basic principles of coordination apply.

The normal procedure followed in choosing the expulsion fuse and current-limiting fuse for a particular application is to **select the expulsion fuse first**. A number of factors determine the type and current rating of expulsion fuse to be used. With a transformer, for example, factors include the overload requirements (both maximum and minimum), inrush current, and cold-load pickup currents. For a capacitor, maximum rated current, including tolerances and harmonics, and inrush currents are important considerations. The selection of expulsion fuses is beyond the scope of this bulletin, so it was written under the assumption that the expulsion fuse has already been selected and that the reader is interested only in selecting a current-limiting fuse that will coordinate properly with that expulsion fuse.

With the expulsion fuse chosen, determining the proper EXT or OS fuse for a particular application requires that one consider three main factors:

- the method by which the two fuses are to be **coordinated**
- the appropriate **voltage rating** of the current-limiting fuse
- the appropriate **current rating** of the current-limiting fuse.

Although each of these factors is discussed in separate sections of this bulletin, it will become apparent that they are significantly inter-related. Therefore, the reader is encouraged to read the whole of the

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application guide, not just the section that appears most appropriate to his or her present need. Following the sections on voltage and current rating, there is a section that briefly answers the question "When should current-limiting fuses be used?" The guide concludes with a typical step-by-step procedure for selecting an oil-submersible fuse used with an expulsion fuse in a transformer.

2. Coordination Criteria for Expulsion and Backup Current-limiting Fuses

Four fundamental areas have to be addressed to ensure that proper coordination exists between series connected backup fuses and expulsion fuses. First, each device must protect the other in its area of non-operation. Second, unless the backup fuse is to be replaced after each expulsion fuse operation, it must not be damaged during the expulsion fuse operation. Third, overload currents permitted by the expulsion fuse must not damage the backup fuse. The fourth area, while strictly speaking not directly related to the coordination with the expulsion fuse, is the requirement that the backup fuse, like the expulsion fuse, is not damaged by surges, such as transformer inrush currents. The same rules that are used to select an expulsion fuse that will withstand surges without being damaged can be applied to the backup fuse. However, this check will very rarely force one to select a larger backup fuse than would be chosen using the other coordination procedures, since if the expulsion fuse has been correctly chosen, the backup fuse usually also meets inrush requirements.

2.1 Fuses Protecting Each Other

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

2.1.1 Matched Melt Coordination: For this method of coordination, in addition to the basic coordination rules described above, one other important criterion must be met. That criterion involves ensuring that the expulsion fuse melts open any time the two-fuse combination clears an overload or fault. The characteristic curves of two fuses that achieve this coordination are depicted in figure 1. One will 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, as is shown in figure 1, this intersection may occur on the total-clearing curve of the expulsion fuse in the region where the curve is parallel to the current axis. This portion of the curve corresponds to the time representing the duration of one-half cycle, which is the minimum length of time required for an expulsion fuse to clear, no matter how high the current might be. In general, matched melt coordination will result in the minimum melting TCC of the expulsion fuse lying to the left of the minimum melting TCC of the backup fuse for all times longer than 0.01s. However, this is not a reliable method of ensuring that the expulsion fuse will melt at times shorter than 0.01s. To be certain that the expulsion fuse will always melt open at any current which causes the current-limiting fuse to operate, the minimum total I^2t let through by the current-limiting fuse should be

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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 (I^2t is a term proportional to energy, obtained by integrating the square of the current, over a particular time interval, in this case the total-clearing time of the backup fuse and the melting time of the expulsion fuse).

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

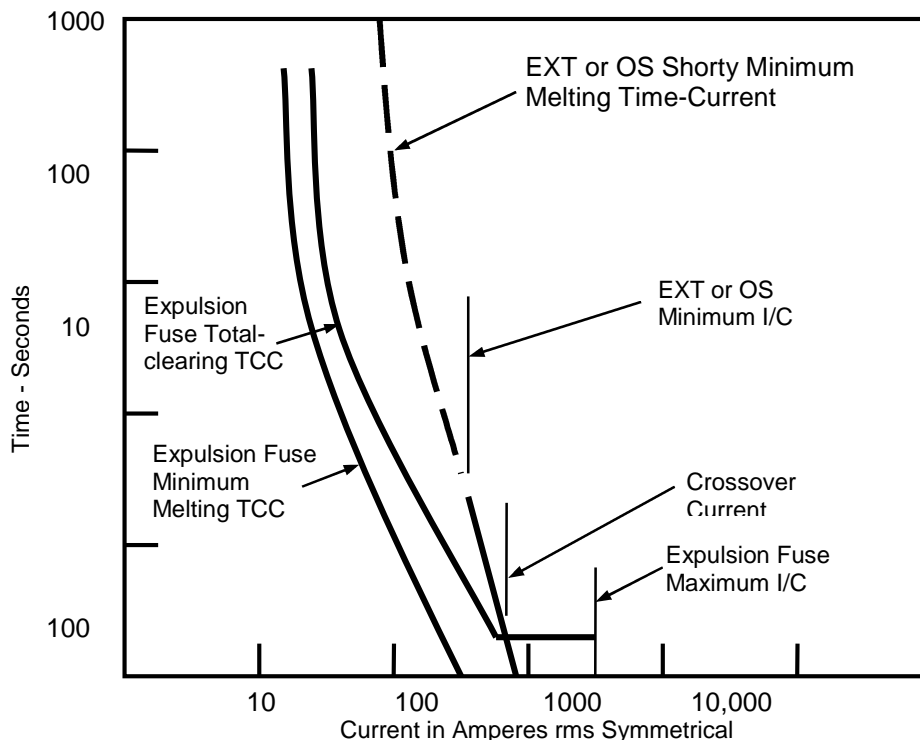


Figure 1. Matched Melt Coordination

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 expulsion fuse manufacturer does not normally publish the former. However, it can be readily calculated from the expulsion fuse's minimum melting TCC curve (the curve

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that represents the lowest value of symmetrical sinusoidal current that will cause the fuse to melt at a given time). One method of calculation that can be used when the expulsion fuse curves have been drawn following IEEE recommended guidelines involves first determining the current corresponding to the value of time representing the fewest whole number of quarter-cycles. For example, this might be the current corresponding to three (3) quarter cycles (.0125 seconds). Once the current has been determined from the expulsion fuse's minimum melting curve, it should be increased by an appropriate factor to take into account variations resulting from manufacturing tolerances. In the case of expulsion fuses having silver elements, this factor is 10%. For fuses with elements made from other materials, this factor is normally 20%. After the current has been corrected to allow for manufacturing tolerances, the maximum melting I^2t of the expulsion fuse can be calculated by first squaring this current and then multiplying that value by the time (expressed in seconds) that was the basis for determining the current. Obviously, should the expulsion fuse manufacturer publish a value for the fuse's maximum melting I^2t , that value should be used rather than the value that one would obtain from the previously described procedure.

The principal advantage of the matched-melt method is that the expulsion fuse will melt open even if the current-limiting fuse does the actual clearing. Thus, it is the approach that is almost always used with EXT fuses applied in series with cutouts. The melting open of the cutout link allows the fuse holder to drop open. This, in turn, does two things. It provides a visual indication as to the location of the fault that caused the fuses to operate and also serves to remove the voltage stress from the current-limiting fuse that 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 would be the case 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 re-fused and energized, or if an expulsion fuse within a transformer was larger than it should have been and did not melt, relatively short backup 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 been able to withstand system voltage for as long as several months, even in severe coastal environments.

Another advantage of this coordination method is that in most three-phase applications, the voltage rating of the backup current-limiting fuse need only be equal to the system's line-to-neutral voltage provided that the voltage rating of the expulsion fuse is at least equal to the system's line-to-line voltage. For this reason, matched melt coordination is sometimes used with OS Shorty fuses. Section 3.2, on voltage rating, discusses this issue in greater detail.

2.1.2 Time-Current Curve Crossover Coordination: This method of coordination, illustrated in Figure 2, is frequently used with the OS Shorty fuses, but is hardly ever used with the EXT fuses. Due to the location of the point of intersection of the expulsion fuse's total-clearing curve and the current-limiting fuse's minimum melting curve with this method of coordination, the current-limiting fuse may, under fault current conditions, melt and clear without letting through sufficient energy to melt the expulsion fuse. This is why time-current curve coordination is rarely used in applying the EXT fuse and is also 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 this method of coordination. The principal criterion to be satisfied is that the previously discussed crossover point must correspond to a current which is greater than the rated minimum interrupting current of the current-limiting fuse, but less than the rated maximum interrupting current of the expulsion fuse. The manufacturers of the expulsion fuse and the current-limiting fuse should publish values for these performance characteristics.

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The principal advantage of the time-current curve crossover method, compared to matched melt coordination, is that it normally permits the use of a backup fuse having a smaller current rating. This can be significant in several regards. First, the lower the current-limiting fuse's current rating is, the less energy it is apt to let through under fault conditions. Obviously, the lower the energy that is let through by the current-limiting fuse, the better the protection will be against eventual failure and the less the fault will affect the rest of the distribution system. Second, the lower the current rating of the current-limiting fuse, the smaller it is apt to be and the less space it is apt to require for installation. Finally, when this method of coordination is used rather than matched melt coordination, fuse protection can be extended to larger transformers (KVA).

One problem that can occur with larger kVA transformers is that, sometimes, there is no suitable under-oil expulsion fuse available to achieve curve crossover at a current below the expulsion fuse's rated maximum I/C. This may be because coordination requirements demand that a large backup fuse be used, and usually occurs at higher voltages, where the maximum interrupting current of expulsion fuses tends to be lower. Such an application could lead to the situation in which the expulsion fuse has to arc at a current higher than its rated maximum I/C until the backup fuse melts and interrupts the current. If the expulsion fuse is an internal "weak-link" or "protective link" type fuse, this is of no great concern, since it just adds to the arcing already present in the transformer due to the fault. However, extended arcing of "bay-o-net" type links could produce severe damage to the draw-out assembly, possibly causing ejection of the assembly from the transformer. If this imposes unacceptable operational limitations, a weak-link type should be used, or in some cases, instead of using a bay-o-net fuse, an externally mounted cutout or power-fuse at the riser pole can be coordinated with the internal backup fuse.

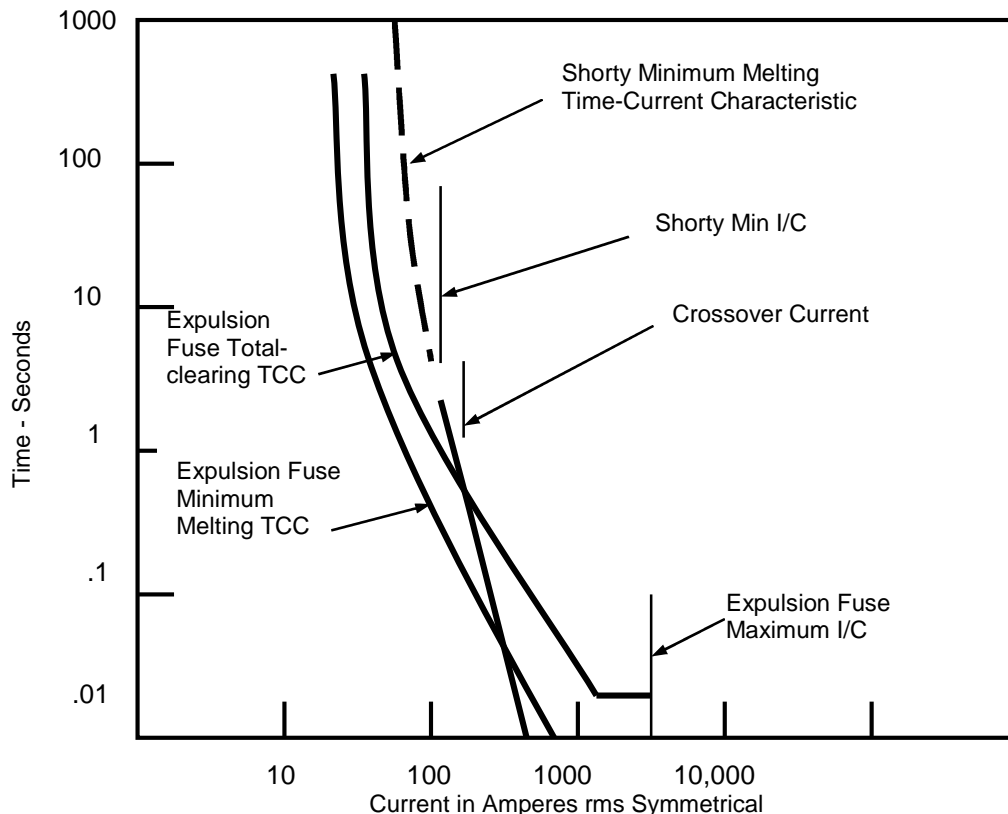


Figure 2. Time-Current Curve Crossover Coordination

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2.2 Prevention of Damage to the Backup Current-Limiting Fuse

When fuses are used to protect a transformer, there is another selection criterion that is particularly important from the standpoint of serviceability and operability. It involves currents up to the value corresponding to a bolted fault at the secondary terminals of the transformer (that is a fault limited only by the transformer's impedance). If at all possible, a current-limiting fuse should be chosen such that this current is less than the current corresponding to the crossover point of the expulsion fuse's total-clearing curve and the backup fuse's minimum melt curve by an appropriate margin. This ensures that the backup fuse does not melt with, and more importantly is not damaged by, a fault external to the transformer. A damaged backup fuse could later melt at a current below its minimum I/C and fail to interrupt this current. The "appropriate margin" will therefore now be discussed; the concepts that are covered in this section and section 2.3 are illustrated in Figure 3.

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

Two different methods can be used to determine the extent of the margin that needs to exist between the minimum melting curve and the no-damage curve for backup fuses manufactured by Thomas & Betts / Hi-Tech®. The more traditional and most frequently used method involves setting the no-damage current equal to 80% of the current shown on the minimum melting curve for any particular melting time. Since proper coordination between the backup current limiting fuse and the series expulsion fuse requires that the current limiting fuse not be damaged by any current equal to or less than the bolted secondary fault current, this method requires that the calculated bolted secondary fault current be no greater than 80% of the current-limiting fuse minimum melting current at a time corresponding to the total-clearing time of the expulsion fuse. Conversely, the backup fuse's minimum melt current must equal at least 125% of the calculated bolted secondary fault current at a time corresponding to the expulsion fuse's total-clearing time.

The second, generally less conservative although, in some situations, more accurate method for establishing the no-damage curve is sometimes used when, for example, circumstances demand the use of a smaller fuse than is suggested by using the first method. In this method it is important to use the minimum transformer impedance to calculate the bolted secondary fault current. The no-damage current is then set to be at least 10% less than the backup fuse's minimum melt current, for any particular melting time, but in addition, the non-damage curve's time must be equal to, or less than, 50% of the backup fuse's minimum melting time, for any current. Therefore when using this method, the backup fuse is chosen such that the total-clearing time of the expulsion fuse, at the bolted secondary fault current of the transformer, should be no more than 50% of the melting time of the backup fuse. In addition, the bolted secondary fault current should not be more than 90% of the minimum melting current of the backup fuse at a time corresponding to the clearing time of the expulsion fuse, at the bolted secondary fault current.

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

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2.3 Overload Protection for the Backup Fuse

Another aspect of coordination that must be checked before one can be sure that the two fuses are coordinated properly involves making certain that the current-limiting fuse will not melt or be damaged as a result of overloads. Two conditions must be met to be sure that this won't happen.

First, for all currents less than the bolted secondary fault current down to a current corresponding to the long-time melting of the expulsion fuse (i.e. to approximately 1000 seconds or more), the total-clearing curve of the expulsion fuse should not cross the no-damage curve discussed in 2.2. This is particularly important for "dual-element" expulsion fuses that may have a "knee" that causes the curve to approach the backup fuse minimum melting curve at times longer than those considered during the coordination described in 2.2 above. In other words, for all expulsion fuse clearing times between the value corresponding to the clearing time at the bolted secondary fault current and 1,000 seconds or more, the corresponding current on the expulsion fuse's total-clearing curve should be no more than 80% of the corresponding current on the current-limiting fuse's minimum melting curve, using the first method described in 2.2. If the second method is used, the current should be less than 90% of the corresponding current on the minimum melting curve and the time should be less than 50% of the melting time of the backup fuse at that current. Since backup fuses curves are only drawn to 1000s, the 50% melting time cannot be used for expulsion fuse clearing times over 500s; for these times, the 80% criterion should be used.

The second condition to be satisfied is that under pre-loaded conditions, the maximum current that the expulsion fuse can carry without melting for a relatively long period of time (i.e. greater than five minutes) must be less than the maximum continuous current rating of the current-limiting fuse. When the expulsion fuse is located inside equipment, such as a transformer, any shifting of the curve caused by temperatures produced by overload conditions should be taken into account when this criterion is examined. For example, some types of expulsion fuses experience a significant shift in their total-clearing TCC curve at elevated temperatures. A "dual" element type fuse in oil at 100°C can have its long time melting characteristic shifted, in terms of current, to about 60% of the values published at 25°C. Overload protection for the backup fuse can also be provided by secondary protection.

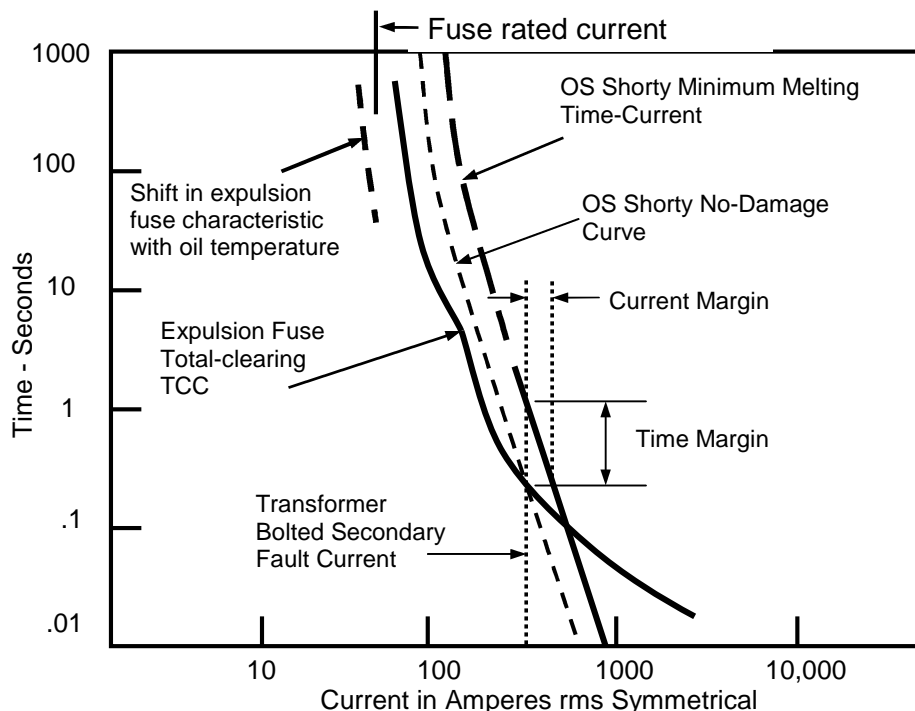


Figure 3 Bolted Secondary Fault Current and Overload Coordination

2.4 Inrush Considerations for the Backup Fuse

As explained earlier, the rules used to protect backup fuses from inrush damage are similar to those used for expulsion fuses. The chosen backup fuse should therefore be checked for the same inrush requirements as were used to pick the expulsion fuse, although this is seldom an issue.

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3. Determining the Appropriate Voltage Rating

3.1 Single-Phase Applications

In these applications, the situation is quite clear and simple. The rated maximum voltage of the EXT or the OS Shorty fuse must be equal to or greater than the maximum applied (system line-to-neutral) voltage. It should be noted that some Thomas & Betts / Hi-Tech® fuses have a rated maximum voltage (the voltage at which they are tested in accordance with IEEE Std C37.41™) that is higher than their nominal voltage (a preferred voltage value listed in the standards). The rated maximum voltage for each fuse is listed in the individual product brochures and certified test reports.

In **dual voltage transformers** in which a single fuse is used for both voltages, the fuse must have a voltage rating equal to or greater than the higher of the two transformer primary voltages (although it must have a current rating appropriate for the lower voltage situation). When the transformer is being used at the lower voltage, the only concern is about the arc voltage that the fuse will develop when it operates. This is similar to the situation that exists if, for example, an 8.3 kV fuse is used on a 2.4 kV system. A detailed discussion of that issue occurs in section 3.3.

3.2 Three-phase Applications

There are a number of factors that make the selection of proper voltage rating in a three-phase application, making the selection process more complicated than for a single-phase applications. 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 bulletin 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 interest to the most readers. If there is a question concerning a situation not covered in this bulletin, please contact the company for advice.

For many three-phase applications, it is possible to coordinate the expulsion fuse and the current-limiting fuse such that a current-limiting fuse having a voltage rating corresponding to the line-to-neutral voltage can be used. This is particularly so when matched melt coordination is used.

With matched melt coordination, 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. 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 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 the individual rated voltage of each. 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.

Tests have shown that two series connected current-limiting fuses share voltage well when they are operating in the current-limiting mode. Thus, 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, the two fuses cannot be relied upon to share the interrupting duty. Although tests on some designs of general purpose current-limiting fuses have shown that two fuses in series shared the

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interrupting duty up to melt times as long as 0.3 seconds, some test data suggests that two backup current-limiting fuses will not share the interrupting duty for melt times longer than equivalent to a few loops of current. Therefore, 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 a few loops of current, the use of line-to-neutral rated current-limiting fuses should be restricted to grounded-wye/grounded-wye transformers where a fault persisting for more than a few loops would likely involve ground. The only exception to this practice is when additional testing has been performed on a given L-N rated backup fuse design to show that it is capable of interrupting L-L faults from currents causing melting in a few loops down to the maximum interrupting current of the expulsion fuse. When such testing has been performed, it is usually possible to use L-N rated backup fuses even when the current-limiting fuses are not in their current-limiting mode at the maximum interrupting current of the expulsion fuse.

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. The overriding assumption made when using match-melt coordination to enable the use of L-N rated current-limiting fuses is that a single current-limiting backup fuse will not be called upon to interrupt a current higher than that causing melting in approximately one loop of current (that is where the fuse is operating under severe duty conditions). Conditions that could cause this to occur are quite rare, but are discussed in fuse standards. Three conditions where this could occur are if a three phase primary fault that does not involve ground can occur, 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, or 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. For more information on this subject, contact the company.

When time-current curve crossover coordination is used, both the current-limiting fuses and the expulsion fuses normally should be rated line-to-line, except on grounded-wye/grounded-wye transformers. 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 to confirm how the system will perform.

In the case of grounded-wye/grounded-wye transformers having a grounded load of at least 50%, the recovery voltage across each fuse sharing the interruption duty is normally within its rated maximum voltage, even when the fuses were selected on the basis of line-to-neutral voltage. Even if the melting time is long enough so as to make sharing unlikely, there should not be a problem because by then the fault should involve ground since in this coordination scheme, the current-limiting fuse should be selected so as to melt only when there is a fault within the transformer. Obviously, once ground becomes involved, the fuses only have to clear against the system's line-to-neutral voltage.

3.3 Fuses at Reduced Voltage

As mentioned previously, current-limiting fuses may, for various reasons, be used at a voltage well below their rated voltage. Although the fuses will interrupt quite satisfactorily at any voltage below their rated voltage, the normal practice is to avoid using them at less than about 70% of their rated voltage due to concerns that they will generate too high of an arc voltage when they operate. This arc voltage is the over-voltage that is produced by the fuse when in its current-limiting mode, and is the result of the fuse inserting a high resistance into the circuit. It is what produces the current-limiting action. The over-voltage is provided by the inductance of the circuit, which tries to maintain the flow of current. The variables responsible for determining the magnitude of this over-voltage are quite complex and are a function of

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both the circuit parameters and the fuse design. Fuses with wire elements generally exhibit an arc voltage that is relatively independent of the supply voltage. However, the notched-ribbon elements used in the EXT and the OS Shorty fuses do produce less arc voltage at reduced supply voltages.

Tests have shown that there is not a linear relationship between supply voltage and arc voltage. The relationship that exists was determined through testing and is illustrated in Figure 4. Using the curve in Figure 4, one can determine, for example, that if a 23 kV fuse that produces a maximum arc voltage of 66kV at 23kV, were used at 7.2 kV, it would produce an arc voltage of 39kV. Thus, although the supply voltage (7.2 kV) is only 31% of the rated voltage, the fuse generates approximately 60% of the arc voltage that would appear if it had been used at its design voltage.

By comparison, an 8.3kV rated fuse would produce an arc voltage of about 25kV when used at 7.2kV. Whether the higher arc voltage would present a problem is dependent upon the "spark over" levels of "upstream" arresters and the impulse withstand ability of the insulation systems in source-side equipment. For system voltages below 8kV, including 2.4kV, backup fuses rated at 8.3kV have been extensively used, without any problems. This is because backup fuses having a rated maximum voltage of less than 8.3kV are uncommon.

It should be noted that the published maximum arc voltage values correspond to those that occur at the maximum interrupting current of the fuses. At fault currents less than approximately 20,000 amperes, typical arc voltages would be 5% - 10% less than those observed at the maximum interrupting current.

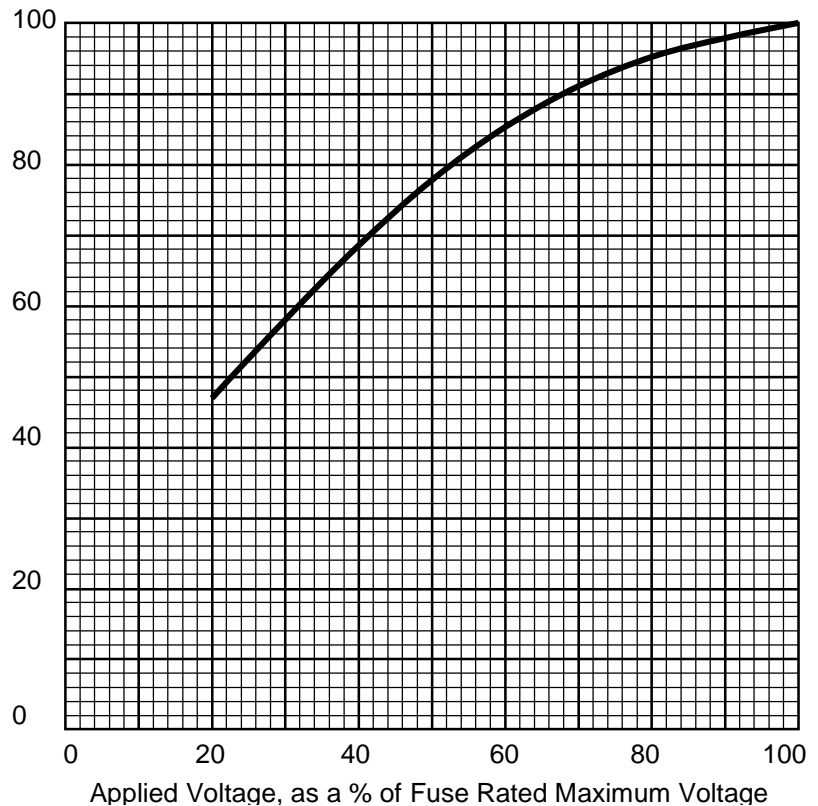


Figure 4: Effect of a Reduced Applied Voltage on the Fuse Maximum Arc Voltage

4. Determining the Appropriate Current Rating

For most Trans-Guard® OS Shorty and EXT applications, fuse selection is based more on its melting characteristics, using the coordination rules discussed earlier, than on its current rating. However, there are times when the current carrying ability of the fuse is important and must be known. The "name-plate" current rating of Trans-Guard fuses is expressed in terms of K-link coordination in the case of the EXT fuse, and in amperes for the OS Shorty fuse. In past printings of this guide, OS Shorty fuses were assigned "C" current ratings. The "C" rating had been referenced in ANSI C37.47 under the heading of "interchangeability requirements" and signified that a fuse would melt at 1000s with a current between 170% and 240% of the fuse's continuous current rating. Because this single point on the time current curve did not make identically rated fuses from different manufacturers interchangeable, the latest version

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of C37.47 no longer uses the term "interchangeability requirements". In keeping with the spirit of the latest C37.47, the use of "C" ratings for our oil-submersible fuses has therefore been discontinued.

The K-rating of the EXT fuse corresponds to the maximum size K-rated expulsion fuse that the EXT will coordinate with. Thus, it has no significance except when coordinating with a K-rated expulsion link. EXT fuses can also be coordinated with other types of links, such as T, N, QA, etc.. The important current rating in selecting the proper EXT for a particular application is the maximum continuous current. Since these fuses have little overload capability due to their short thermal time constant, the fuse must be selected such that either the application or the series-connected expulsion fuse will prevent the fuse from "seeing" a current greater than its maximum continuous current rating for longer than a few minutes.

The maximum continuous current ratings for EXT fuses are based on a 40°C air environment while the OS Shorty fuses will carry at least their "nameplate" current rating, continuously, in an 85°C oil environment. The maximum permissible ambient oil temperature for the OS Shorty fuses is 140°C (termed the fuse's Rated Maximum Ambient Temperature, RMAT). At such an ambient temperature, the fuse's maximum continuous current rating must be reduced by approximately 25%. The reduction at other ambient temperatures can be calculated by using a reduction factor of .4% per degree C for each degree C the temperature is above 85°C.

When a single current-limiting fuse is used with dual voltage transformers, its current rating must be chosen so as to coordinate with the expulsion fuse used at the lower of the two transformer voltages.

Higher current ratings can often be obtained through the use of two current-limiting fuses connected in parallel. However, when this is done care must be taken to ensure that the resistances of the current paths through the two fuses are nearly equal in order to facilitate good current sharing between the two fuses. This is particularly important in the case of fault clearing since parallel fuses may not equally share the interrupting duty. For this reason, only fuse designs that have been short-circuit tested as parallel combinations should be applied in this manner. The Trans-Guard® fuses tested as parallel combinations and therefore suitable for applications requiring parallel fuses are listed in the appropriate brochures.

5. When Should Current-limiting Fuses be Used?

Current-limiting fuses are installed for two main reasons, both stemming from the fact that the whole of the first loop of fault current (at least) must flow through an expulsion fuse before it can interrupt. This means that the rated maximum interrupting current of many types of expulsion fuses are quite low. The first and most obvious reason for using a current-limiting fuse is therefore because the interrupting rating of an expulsion fuse is inadequate for the point on the system where the fuse protection is to be provided. While this inadequacy usually simply stems from the published rated maximum interrupting current of the expulsion fuse not being as great as the available fault current, it may also be the result of a high system X/R or TRV, reducing the interrupting ability of the expulsion fuse to a value well below its published value. For example, the use of current-limiting reactors or high impedance transformers to limit the available fault currents may produce a system X/R high enough to significantly reduce the interrupting capability of the expulsion fuse. Because of their very high interrupting ratings and the fact that the current-limiting fuses are relative insensitive to both X/R and TRV, current-limiting fuses are ideal for such applications.

The second reason for using current-limiting fuses is the outstanding energy limitation that they provide. The precise point at which this energy limitation becomes critically important is difficult to pinpoint as the arc energy withstand of different types of distribution equipment cannot be accurately predicted. For example, although there is a cover retention test for pole-type transformers included in the ANSI Standards for that product, the purpose of the test is to establish a common test condition under which the various manufacturers can test their transformers in order to determine if their designs satisfy the minimum arc energy withstand requirements. This test does not provide any indication as to either the

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magnitude of the fault current or the amount of I^2t that is apt to produce cover "blowing" under any other circumstances since the relationship between fault energy and I^2t is a function of the arc resistance. However, tests have demonstrated conclusively that a current-limiting fuse with a low I^2t let-through provides effective protection against eventful transformer or capacitor failure in almost all situations. On the other hand, laboratory tests have shown that when only expulsion fuses are used, transformer covers can be blown off with available fault currents in the range of 2,000 to 3,000 amperes. Figure 5 illustrates a curve that may be used to estimate the I^2t let-through by an expulsion fuse clearing at the end of one "loop" of current. The I^2t in the first loop of a fully asymmetrical fault current is given by the following expression:

$$I^2t = K \times 10^{-3} \times I_{rms}^2 \quad (\text{equation 1})$$

- * K is determined from Figure 5 for a particular circuit X/R
- * I_{rms} is the magnitude of the available fault current (Amperes, rms symmetrical).

From this expression it can be seen that with an available current of only 2,000 amps, the first loop I^2t can be as much as $140 \times 10^3 \text{ A}^2\text{-sec.}$ for an X/R of 10. By comparison, a 15.5 kV, 12 K EXT limits the I^2t let-through to $10 \times 10^3 \text{ A}^2\text{-sec.}$ for any fault up to 50,000-amperes. Of course, if the expulsion fuse takes more than one loop to interrupt, the I^2t differential is even higher.

In addition to providing protection to the equipment the current-limiting fuse is mounted in, on, or adjacent to, it also serves to reduce the stresses that develop throughout the system when faults occur. This may be observed in a variety of ways including much shorter dips in the system voltage and reduced through-fault duty for substation transformers.

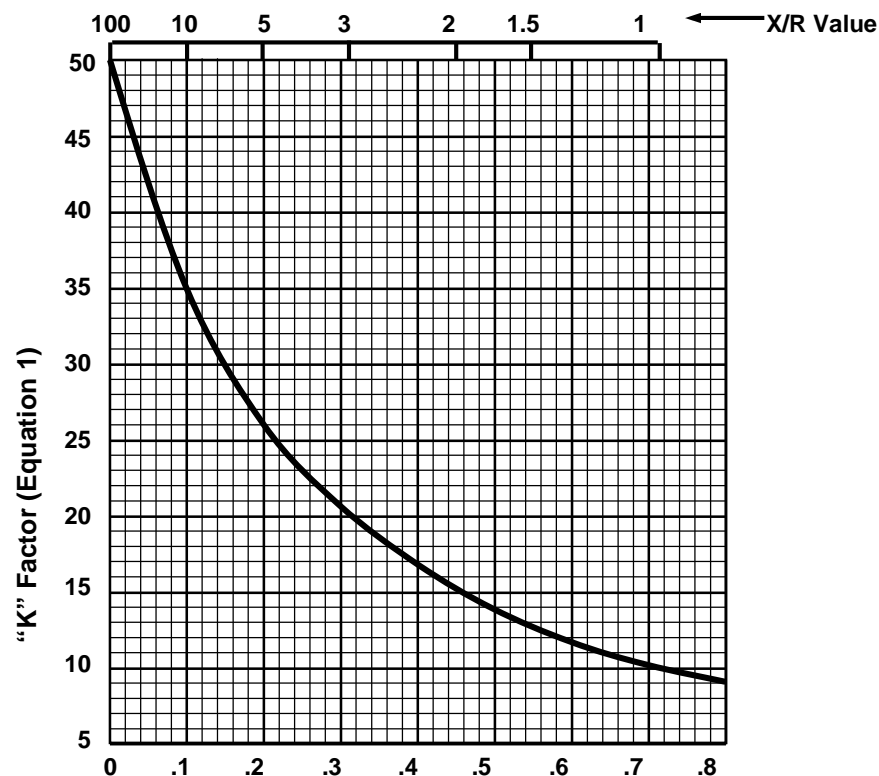


Figure 5: I^2t "K" factor; Dependence on Circuit Power Factor (X/R ratio)

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6. Typical Step-by-step Backup Current-Limiting Fuse Selection Procedure

The selection procedure for a backup fuse, illustrated in Figure 6, is designed to achieve coordination such that it operates only in the event of an internal transformer fault and it will not be damaged by any overload or low-level fault current. The bolted secondary fault current coordination uses the first method discussed in 2.2. The expulsion fuse is chosen first using usual selection procedures.

- 1) Calculate the transformer rated line current I_R , and bolted secondary fault current (A), using the transformer impedance Z%, ($A = I_R/Z \times 100$).
- 2) Multiply fault current (A) by 1.25 = (B).
- 3) Overlay chosen expulsion fuse total-clearing curve and backup fuse minimum melt curves, and observe time (T) at which expulsion fuse clears with current (A).
- 4) Choose a backup fuse with a minimum melting current (C) at time (T) such that $C > B$. Note the backup fuse minimum interrupting rating (D).
- 5) Observe current (E) at which the two fuse characteristics cross. If (E) is not equal to or greater than (D), choose a CL fuse with a characteristic further to the right which meets this criterion.
- 6) Current (E) should be less than the maximum interrupting rating of the expulsion fuse (F). If this is not the case, damage will occur to the expulsion fuse when it attempts to clear higher current, and the bayonet assembly may become a projectile. Either, choose a different or larger expulsion fuse, or be aware of operational limitations caused by such a potential problem.
- 7) Observe expulsion fuse total-clearing current (G) at 300 - 600 seconds.
- 8) Multiply current (G) by 1.25 = (H).
- 9) Observe backup fuse 1000 second melting current (I).
- 10) If (I) is not equal to or greater than (H), choose a larger backup fuse to prevent backup fuse damage with overload/secondary fault currents.

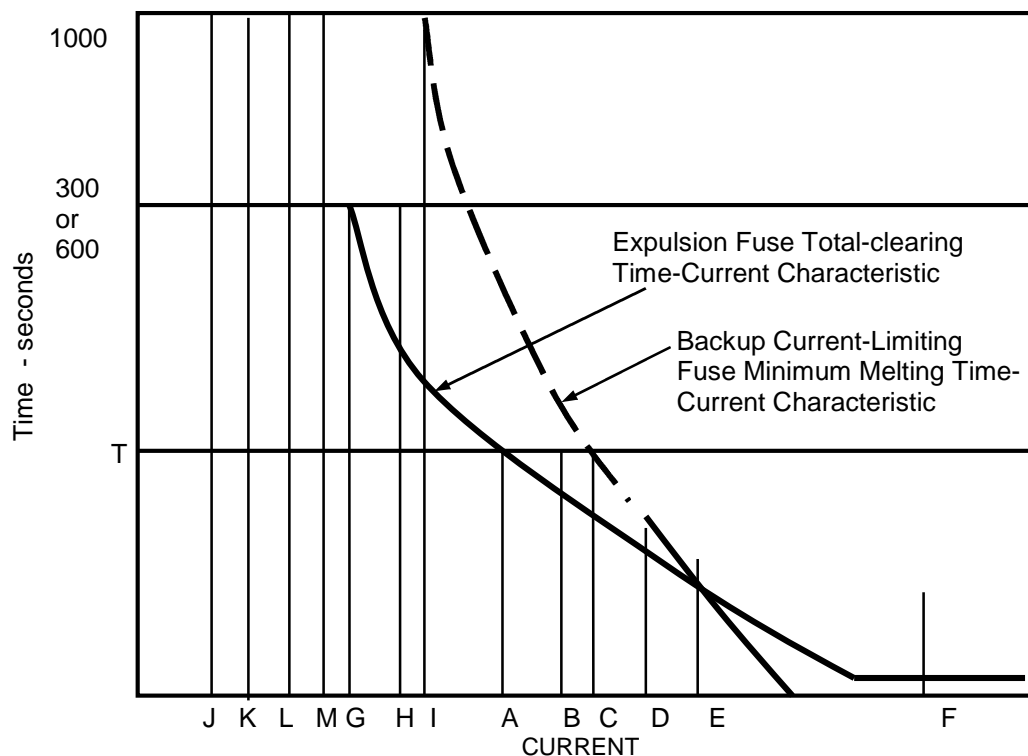


Figure 6: Coordination Example

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- 11) Check for a "knee" in the expulsion fuse curve. If, between currents (A) and (G), for any given time the backup fuse melting current is less than 125% of the expulsion fuse total-clearing current, a larger backup fuse must be chosen to meet this criterion.
- 12) Calculate the maximum possible continuous transformer overload current (J) (limited, for example, by secondary protection) or the overload melting current of the expulsion link (K) (taking account of curve shifting due to increasing oil temperature) or the secondary breaker maximum clearing current (L) under overload oil temperature conditions.
- 13) The lowest current (J), (K), or (L) should be less than the maximum rated current of the backup fuse (M), taking into account any de-rating due to oil temperature, to ensure that the backup fuse is not damaged by overloading.
- 14) Check that the transformer inrush current points ($12xI_R$ at 0.1s and $25xI_R$ at .010s) lie on, or to the left, of the minimum melting TCC of the backup fuse.
- 15) Voltage Rating of the fuses:

Single-phase requires the voltage rating of the expulsion and backup fuses to be greater than or equal to the maximum L-N voltage that will occur in service.

Three-phase, involving delta or only effectively grounded transformers, requires the use of L-L rated expulsion and backup fuses, unless matched melt coordination is used in which case it is usually possible to use a L-N rated backup fuse with a L-L rated expulsion fuse. See Section 3.2 for more information.

In the case of grounded-wye/grounded-wye systems, L-N rated expulsion and backup fuses can often be used, provided faults not involving ground will not persist for more than a few cycles, and at least 50% of the load is grounded.

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