

PART 2: OVERCURRENT PROTECTION OF TRANSFORMERS TRADITIONAL AND NEW FUSING PHILOSOPHIES FOR SMALL AND LARGE TRANSFORMERS

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This is the second of two articles that concern new and traditional fusing philosophies for protecting transformers. Issue 6's article (Part I) served as an introduction to the application principles that must be considered when selecting a transformer-primary fuse, in particular, the voltage rating, the short-circuit interrupting rating, and the ampere rating and speed characteristic of the fuse. It also covered how to select a transformer-primary fuse to withstand the various inrush currents it may experience in service, such as magnetizing inrush, hot-load pickup inrush, and cold-load pickup inrush. This article covers how to select a transformer-primary fuse to protect the transformer in accordance with industry-accepted through-fault protection curves, the principles of coordination as they relate to the proper selection of a primary-side fuse and power fuses, and how to protect load-side conductors and cables.

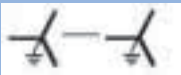


PROTECT TRANSFORMER AGAINST DAMAGING OVERCURRENTS

Fusing philosophies, as they relate specifically to secondary-fault protection, can vary significantly depending on the type of transformer under consideration. For small three-phase power transformers used on industrial, commercial, and institutional systems, and small-to-medium size three-phase power transformers used in utility substations, it is generally appropriate to use tight fusing (i.e., a low fusing ratio) to provide maximum protection to the transformer against secondary-side faults. On the other hand, for small-kVA single-phase overhead distribution transformers, larger fuse ratings are generally recommended, particularly if the arrester is mounted on the transformer tank to enhance over-voltage protection.

Three-Phase Power Transformers and Utility Substation Transformers

The most important application principle to be considered when selecting a

Table 1: Relationship Between Per-Unit Primary-Side Line Current and Per-Unit Transformer Winding Current for Various Types of Secondary Faults

Transformer Connection Type of Fault	Ratio of Per-Unit Primary-Side Line Current to Per-Unit Transformer Winding Current *		
	Three-Phase	Phase to Phase	Phase-to-Ground
	1.0	1.0	1.0
	1.0	0.87	Not applicable
	1.0	1.15	0.58

*Line current and winding current values are expressed in per unit of their respective values for a "bolted" three-phase secondary fault.

primary fuse for a three-phase power transformer is that it must protect the transformer against damage from mechanical and thermal stresses resulting from secondary-side faults that are not promptly interrupted. A properly selected primary fuse will operate to clear such a fault before the magnitude and duration of the overcurrent exceed the through-fault current duration limits recommended by the transformer manufacturer or published in the standards. Curves representing these limits can be found in ANSI/IEEE Standard C37.91-1985, "Guide for Protective Relay Applications to Power Transformers," and ANSI/IEEE C57.109-1993, "Guide for Transformer Through-Fault Current Duration."

The degree of transformer protection provided by the primary fuse should be checked for the level of fault current and type of fault (i.e., three-phase, phase-to-phase, or phase-to-ground) producing the most demanding conditions possible for each particular application, viz., those for which the ratio of the primary-side line currents to the transformer winding currents is the lowest. For these situations, one or more of the primary fuses will "see" a proportionately lower level of

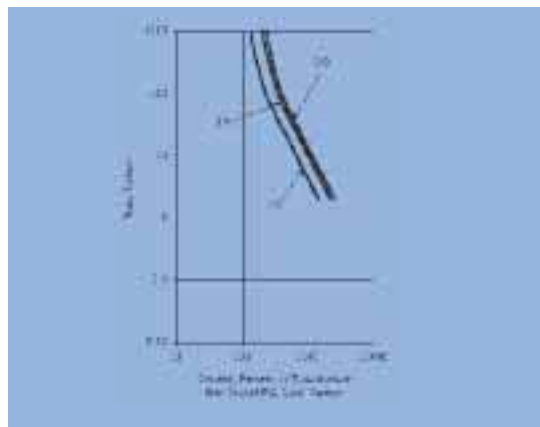


Figure 1: Infrequent-fault incident through-fault protection curves for: grounded-wye/grounded-wye transformers (A); delta/delta transformers (B); and delta/grounded-wye transformers (C).

current than will the windings and, as a consequence, the primary fuses must be carefully selected to operate fast enough to avoid damage to the transformer windings. Table 1 lists the ratio of per-unit primary-side line currents to per-unit transformer winding currents for three com-



mon transformer connections under a variety of secondary-fault conditions.

From Table 1, it is clear that a phase-to-phase secondary fault on a delta/delta connected transformer and a phase-to-ground secondary fault on a delta/grounded-wye connected transformer produce the most demanding conditions possible for those particular transformer connections, since the per-unit primary-side line currents are less than the per-unit transformer winding currents. Accordingly, to ensure proper transformer protection for these two situations, it is necessary to “shift” the appropriate through-fault protection curve to the left (i.e., in terms of current) by the ratio of the per-unit primary-side line current to the per-unit transformer winding current listed in Table 1. The shifted through-fault protection curve will then be in terms of the primary-side line current and, as such, will be directly comparable with the total-clearing curve of the primary fuse. For the grounded-wye / grounded-wye connected transformer, the per-unit primary-side line currents and the per-unit transformer winding currents are the same, hence the base (unshifted) through-fault protection curve applies.

Figure 1 illustrates the infrequent-fault incidence through-fault protection curve applicable to a grounded-wye/grounded-wye connected transformer (Curve A), as well as through-fault protection curves shifted to reflect the two situations discussed above. Curve B represents Curve A shifted to reflect the reduced level of current (0.87 per unit) flowing in two primary lines during a phase-to-phase secondary fault on a delta/delta connected transformer. Similarly, Curve C represents Curve A adjusted to reflect the reduced level of current (0.58 per unit) flowing in two primary lines during a phase-to-ground secondary fault

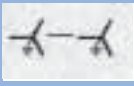
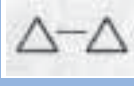
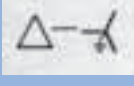
on a delta/grounded-wye connected transformer.

Tip: For a delta/wye connected transformer with its neutral grounded through a significant impedance, the ratio of per-unit line current to per-unit winding current for a phase-to-ground secondary fault is the same as that discussed above for a delta/grounded-wye connected transformer. However, since the impedance in the neutral limits the mag-

fault protection curve at the current level corresponding to the maximum three-phase secondary-fault current as determined solely by the transformer impedance (i.e., an infinite source is assumed).

Another aspect of transformer protection involves low-current overloads. Low-voltage protective devices such as circuit breakers and current-limiting fuses are designed to provide overload protection for the transformer by operat-

Table 2: Secondary Fault Currents Reflected to Primary Lines

Transformer Connection	Impedance	Arcing Phase-to-Ground Fault*	Maximum Primary-Side Line Current for Various Types of Secondary Faults, Percent of Transformer Full-Load Current		
			Three-Phase	Phase-to-Phase	Phase-to-Ground
	4%	1000%	2500%	2180%	2500%
	5.5%	✖	1820	1580	1820
	5.75%	700	1740	1510	1740
	6.5%	✖	1540	1340	1540
	8%	500	1250	1090	1250
	4%	N/A	2500	2180	N/A
	5.5%		1820	1580	
	5.75%		1740	1510	
	6.5%		1540	1340	
	8%		1250	1090	
	4%	580	2500	2500	1450
	5.5%	✖	1820	1820	1050
	5.75%	400	1740	1740	1010
	6.5%	✖	1540	1540	890
	8%	290	1250	1250	730

N/A: Not applicable. *Commonly accepted arcing-fault-current values for secondary-switchboard and other nearby faults. ✖ For transformers with medium-voltage secondaries (2.4 kV or 4.16 kV); the entries in the “Phase-to-Ground” column apply.

nitude of the phase-to-ground fault current to levels well below the level of current which will damage the transformer, the phase-to-ground through-fault protection curve is of no concern and may be ignored. Accordingly, the base (unshifted) through-fault protection curve, applicable to multiphase secondary faults, should be used for this transformer.

Although the through-fault protection curves are only a guide, they are recommended as a criterion against which to measure the degree of transformer protection provided by the primary fuse. To meet this criterion for high-magnitude secondary-side faults, the total-clearing curve of the primary fuse should pass below the point (historically called the ANSI Point) on the appropriate through-

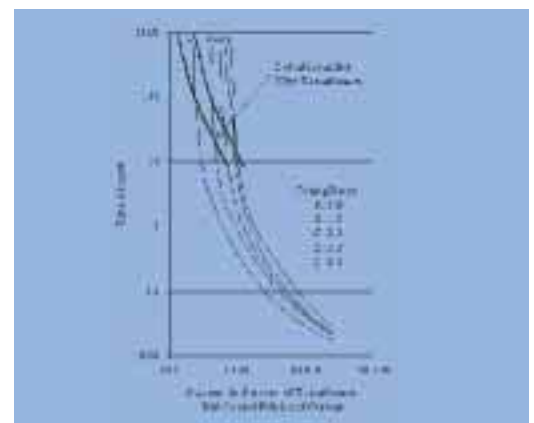


Figure 2: The effect of fusing ratios on the degree of protection provided by a delta/grounded-wye connected transformer against a phase-to-ground secondary fault.

ing at currents only slightly larger than their minimum-pickup settings or ampere ratings. In contrast, medium-voltage fuses are not intended to provide overload protection. Accordingly, the total-clearing curve of the primary fuse will cross the through-fault protection curve at some low level of current. Because the primary fuse does not provide overload protection for the transformer, this should not be a concern; however, efforts should be made to keep the current value at which the two curves intersect as low as possible to maximize protection for the transformer against secondary-side faults.

The through-fault protection curve for a delta/grounded-wye connected transformer can be used to illustrate these principles for primary-side fuses. See Figure 2. The total-clearing curves for primary fuses with a fusing ratio of 1.0, 1.5, or 2.0 all pass below the ANSI Point of the delta/grounded-wye connected transformer's through-fault protection curve. The total-clearing curve for primary fuses with a fusing ratio of 2.5 or 3.0 pass completely above and to the right of the through-fault protection curve and, thus, would not provide any protection for the transformer for a phase-to-ground secondary fault. Since the object of primary fusing is to provide protection for the transformer against all types of secondary faults, primary fuses having total-clearing curves that pass above the ANSI Point would be considered unacceptable.

The primary fuse having the lowest fusing ratio of the three fuses that pass beneath the ANSI Point will provide the maximum protection for the transformer against secondary faults located between the transformer and the secondary-side overcurrent protective device — as well as maximum backup protection for the transformer in the event the secondary-side overcurrent protective device fails to operate, or operates too slowly due to an incorrect (higher) rating or setting.

From Figure 2, it may be seen that a primary fuse with a fusing ratio of 1.0 will provide protection for a delta/grounded-wye connected transformer against phase-to-ground secondary faults producing currents as low as 230 per cent of the full-load current of the transformer, as reflected on the primary side. When the fusing ratio is 2.5, however, protection for the transformer is provided only when secondary faults produce primary-side line currents exceeding 670 per cent of the transformer full-load current.

The results of published studies [1] [2] [3] indicate that under arcing conditions, secondary-switchboard and other nearby faults on 480/277Y-volt circuits may have magnitudes as low as 38 per cent to 40 per cent of the maximum available phase-to-ground fault current at the point of the fault. This corresponds to 290 per cent of the full-load current of the transformer in Figure 2, as seen by the primary fuse. Hence, a primary fuse with a fusing ratio of 1.0 will provide protection for the transformer against an arcing phase-to-ground fault, since the primary fuse will operate at as low as 230 per cent of the full-load current of the transformer. A primary fuse with a fusing ratio only slightly higher than 1.0, though, may have a total-clearing current in excess of 290 per cent of the full-load current of the transformer, and thus may not provide protection for the transformer against a phase-to-ground fault under arcing conditions. A primary fuse with a fusing ratio only slightly higher

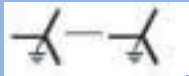

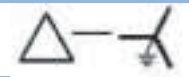
than 1.0 will, however, protect the transformer against permanent or metallic phase-to-ground secondary faults as well as other types of secondary faults, including arcing phase-to-ground secondary faults that escalate to multiphase secondary faults.

Tip: You can determine if the primary fuse will protect against an arcing secondary-side fault by referring to Table 2 which lists primary-side line current values for various types of secondary-side faults and for various transformer connections and impedances, expressed in percent of the transformer full-load current. The desired protection is obtained if the current value at which the total-clearing curve of the primary fuse intersects the transformer through-fault protection curve is less than the values shown in Table 2.

Small-kVA Overhead Distribution Transformers

In the past, the fusing philosophy applied to small-kVA single-phase overhead distribution transformers was similar to the fusing philosophy applied to larger transformers, that is, the smallest practical fuse link rating was used, subject only to loading considerations. Recently, however, this philosophy has changed to one of protecting the system from a failed transformer and protecting against catastrophic failure of the transformer rather than protecting the transformer itself from overcurrents. This shift

Table 3: Relationship Between Per-Unit Primary-Side Line Current and Per-Unit Secondary-Side Line Current for Various Types of Secondary Faults

Transformer Connection	Ratio of Per-Unit Primary-Side Line Current to Per-Unit Secondary-Side Line Current *		
Type of Fault	Three-Phase	Phase to Phase	Phase-to-Ground
	1.0	1.0	1.0
	1.0	1.0	Not applicable
	1.0	1.15	0.58

*Primary-side and secondary-side line current values are expressed in per unit of their respective values for a "bolted" three-phase secondary fault.

in philosophy is due in large part to the realization that most overhead distribution transformer failures occur due to lightning-induced surges and not secondary-side faults.

One way to provide better overvoltage protection is to relocate the arrester from the cross-arm and mount it directly to the transformer tank. This location eliminates 3 to 4 feet of lead connecting the arrester to the transformer tank, which reduces the $L \times di/dt$ voltage surge seen by the transformer when the arrester operates.

Moving the arrester to the transformer tank, however, makes small-rated fuse links susceptible to nuisance opera-

tions because these small links must pass the surge current during an arrester operation. Therefore, to provide better overvoltage protection without increasing nuisance fuse operations, it is necessary to increase the fuse link rating to withstand these surges. The only apparent downside to the use of larger fuse ratings is a reduced level of overload, secondary-fault, and internal-fault protection provided for the transformer. However, further analysis reveals that very little protection is given up by standardizing on larger fuse ratings. Consider the following:

- Overload protection for the transformer is difficult to justify as the

economics of overhead distribution systems necessitate the loading of transformers significantly beyond their nameplate ratings.

- Where covered secondary conductor is used, secondary faults are rare. With covered conductor the possibility of faults due to mid-span tree, animal, or human contact is significantly reduced.
- The rare faults that do occur on the secondary conductor will generally not sustain the arc. These faults tend to be self clearing due to the low 120/208-volt driving voltage. In addition, when aluminum secondary conductor is used, faults tend to burn back the conductor which further helps to extinguish the arc.
- A bolted fault at the service drop of the nearest house will be low enough in magnitude, due to the impedance of the conductor, that a primary fuse — even one with a low fusing ratio — would not likely detect the fault.

Perhaps a greater concern than secondary-fault protection is the need to protect overhead distribution transformers from catastrophic failure due to internal faults that begin as low-current faults, and then quickly escalate to the full available fault current. One recent paper[4] studied internal transformer faults and concluded that this type of fault signature is indeed common. Interestingly, the authors also concluded that small rated fuses in general, and even surge-tolerant fuses with dual-element melting characteristics in particular, are no better at detecting internal winding faults than are larger rated fuses having the same lightning surge-withstand characteristics. In addition, fuse limiters or backup current-limiting fuses were found to be very effective at minimizing the energy into the faulted transformer, and are recommended when surge tolerant fuses are used. Lastly, pressure relief devices are clearly recommended to limit tank pressure during an evolving fault should a high-current fault develop.

COORDINATE WITH OTHER PROTECTIVE DEVICES

In addition to protecting the transformer against faults, internal or otherwise, it is also important that the primary fuse coordinate with overcurrent protective devices on both the primary side and the secondary side of the transformer. The following sections describe how proper coordination is achieved both between the primary fuse and secondary-side protective equipment, and between the primary fuse and source-side protective devices.

Coordination Between the Primary Fuse and 480/277Y-Volt Secondary-Side Overcurrent Protective Devices

Coordination between the transformer primary fuse and the feeder protective device is typically checked for the level of fault current and for the type of fault (i.e., three-phase, phase-to-phase, or phase-to-ground) producing the most demanding conditions possible for the transformer in each application. From the standpoint of coordination, the most demanding conditions possible are those where the per-unit line current on the primary side of the transformer is greater than the per-unit line current on the secondary side of the transformer. For this situation, the primary-side device carries more current, relatively, than does the secondary-side overcurrent protective device. Accordingly, an allowance must be made before checking for proper coordination between the two devices. Table 3 lists the ratio of per-unit primary-side line current to per-unit secondary-side line current for the same transformer connections and types of secondary faults discussed earlier.

For a phase-to-phase secondary fault not involving ground on a delta/grounded-wye connected transformer, the per-unit primary-side line current in one phase is the same as that resulting from a three-phase secondary fault, while the secondary-side line current is only 0.87 per unit of the three-phase secondary fault-current value (hence, the ratio, as listed in Table 3, is 1.0/0.87, or 1.15). To compensate for the line-current differential inherent to the delta/grounded-wye connected transformer, it is generally recommended that a 15 per cent margin in terms of current (or an equivalent margin in terms of time) be maintained between the total-clearing curve of the feeder protective device and the minimum-melting curve of the primary fuse. This is illustrated in Figure 3 for a low-voltage feeder circuit breaker.

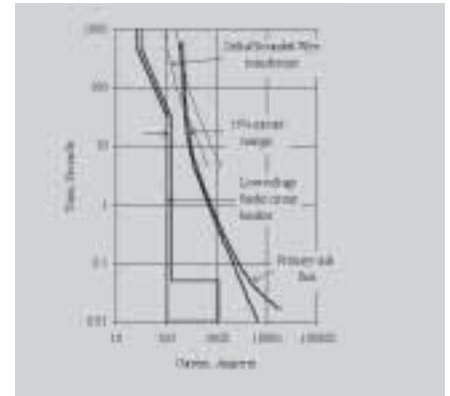


Figure 3: Application of 15% current margin between time-current curves of primary fuse and low-voltage current-limiting fuse.

Tip: The only exception to this recommendation is Class E-2 high-voltage industrial control equipment, where the 15 per cent current margin is not required since the point of influence of this margin (where the curves for this device and the primary-side device are the closest to each other) occurs at approximately 20 seconds, before which time a medium-voltage phase-to-phase ungrounded fault would likely have propagated to ground. This current margin is therefore not required to ensure proper coordination for faults involving ground in this type of equipment.

Occasionally, it may be deemed necessary to coordinate the transformer primary fuse with a main secondary-side protective device. In this case, the primary fuse will operate to protect the transformer against a fault located between the transformer and the main secondary protective device and will further serve as a backup to the main device - operating in the event the main secondary protective device either fails to operate due to a malfunction, or operates too slowly due to incorrect (higher) ratings or settings.

The method for establishing coordination between the transformer primary fuse and the main secondary protective device is essentially the same as that described previously for a feeder circuit breaker or fuse, except for the handling of the current margin (or equivalent time margin) for the phase-to-phase secondary fault not involving ground on a delta-wye connected transformer. For this particular fault, the point of influence of the 15 per cent current margin (or equivalent time margin) typically occurs at a relatively low current (and long duration) for low-voltage circuit breakers and low-voltage current-limiting fuses. The probability of occurrence of a low-magnitude long-duration phase-to-phase secondary fault not

involving ground located between the feeder protective devices and the main secondary protective device is extremely remote. Such low-magnitude long-duration faults typically occur on a feeder some distance from the transformer, and thus are cleared by the feeder protective device.

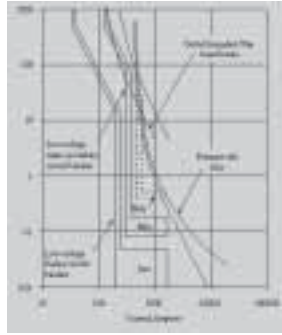


Figure 4: Coordination between primary fuse and low-voltage main-secondary circuit breaker can often be obtained by lowering the short-time pickup current and/or the short-time delay setting.

Accordingly, it is not necessary to maintain the 15 per cent current margin (or equivalent time margin) when coordinating low-voltage main secondary current-limiting fuses with the primary fuse. For medium-voltage circuit breakers, the point of influence of the 15 per cent current margin (or equivalent time margin) occurs at a very high current — on the order of the maximum three-phase secondary fault-current level. Accordingly, this margin must be retained when coordinating medium-voltage main secondary circuit breakers with the primary fuse.

Since main secondary circuit breakers or fuses typically have high ampere ratings or settings, difficulties are sometimes experienced in simultaneously obtaining protection for the transformer against secondary-side faults in accordance with the through-fault protection curves discussed earlier, and complete coordination between the primary fuse and the main secondary protective device. If this situation is encountered, it is recommended that the ampere rating or settings of the main secondary protective device be investigated to see if a reduction is possible, rather than accepting a larger than necessary primary fuse ampere rating, which would result in reduced transformer protection.

This point is illustrated in Figure 4 for a low-voltage main secondary circuit breaker, wherein a transformer-primary fuse does not coordinate with the main secondary circuit breaker over the full range of applicable currents. Coordination between the two devices has not been obtained with the short-time pickup current of the main secondary circuit breaker set at 12,000 amperes (4X), and with the short-time delay setting on the “Maximum.” Clearly, by reducing the short-time pickup setting from 4X to 3X or even 2.5X, and by reducing the short-time delay setting from “Maximum” to “Minimum,” coordination between the main secondary circuit breaker and the primary fuse will be obtained. (The time-current curve for the main secondary circuit breaker adjusted to reflect lower short-time pickup and short-time delay settings is illustrated by solid lines.) Lack of complete coordination of the type illustrated in Figure 4 can frequently be corrected by making such adjustments.

Tip: If it is not practicable to reduce the ampere rating or settings of the main secondary-side protective device, as discussed in the example above, incomplete coordination between the primary-side protective device and the main secondary-side device should be accepted in order to obtain better transformer protection. Even if these circumstances are encountered, coordination will typically be given up over only one or two very small ranges of current.

Coordination Between Primary-Side and Source-Side Overcurrent Protective Devices

After the transformer primary fuse has been selected to provide the maximum degree of protection for the transformer and to coordinate with secondary-side protective devices, it is necessary to consider coordination with source-side protective devices. To achieve coordination with a source-side protective device, the total-clearing time of the primary fuse must be less than the minimum-melting time of a source-side fuse, or the minimum-operating time of a source-side relay, for all currents up to the maximum available fault current at the location of the primary fuse. In establishing such coordination, no adjustments must be made to the total-clearing curve of the primary fuse.

Certain adjustments, however, must be made to the minimum operating time-current curves of source-side protective devices. Specifically, the minimum response curves for source-side relays must be adjusted for overtravel and tolerance, and minimum-melting curves of source-side power fuses must be adjusted to reflect the assumed pre-fault load, elevated ambient temperature and, for certain types of fuses, damageability.

Earlier it was recommended that the smallest practicable ampere rating or setting for the primary fuse be selected in order to maximize transformer protection. Such a selection will also greatly facilitate coordination with source-side protective devices since the lower total-clearing time-current curve associated with the primary fuse will more easily fit below the time-current curve of the source-side protective device.

If difficulties in coordination with source-side protective devices are encountered, the ratings of the primary fuse should be restudied to verify that the smallest practicable ampere rating has indeed been selected. This may involve a reconsideration of the ratings and settings of the secondary-side protective devices with which coordination was previously obtained.

PROTECT LOAD-SIDE CONDUCTORS AND CABLES

The final principle to be considered when selecting a transformer primary fuse is that it must protect the conductors or cables between the primary fuse and the transformer against damage due to excessive overcurrents. In general, the size of

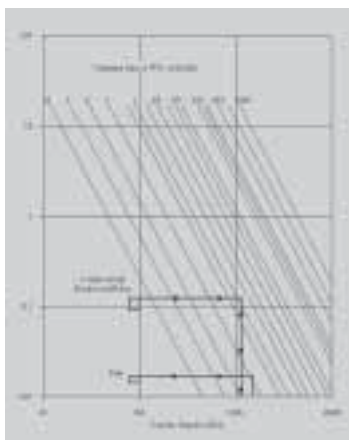


Figure 5: Damage curve for rubber-insulated aluminum conductors with initial temperature of 75°C and final temperature of 200°C.

the conductor or cable is determined by considering its ampacity, as well as its behavior under short-circuit conditions. Selection of the conductor size from the standpoint of its continuous current-carrying capability is easily done by reference to ampacity tables found in sources such as the National Electrical Code. Similarly, conductor or cable sizes capable of withstanding available short-circuit currents can easily be selected from industry-accepted curves, such as those contained in the IEEE Buff Book, or those distributed by conductor or cable man-

ufacturers. As a general rule, power fuses, which operate in as little as one cycle for high-magnitude faults, will protect conductors or cables one or more sizes smaller than will relay-actuated circuit breakers. This is illustrated in Figure 5 for rubber-insulated aluminum conductors with initial temperature of 75°C and final temperature of 200°C. As noted in Figure 5, for a 10,000-ampere fault, the circuit breaker will protect cables sized 1/0 or larger. By comparison, a power fuse will protect cables two sizes smaller, or #2 AWG.

SUMMARY

This series of articles should be useful as a reference source detailing the often contradictory factors that must be considered when selecting a transformer-primary fuse. The first article showed that the industry "standard" points used to represent inrush currents are sufficiently conservative such that a fuse having a smaller ampere rating can often be used in cases where the initial fuse selection does not properly coordinate with other protective devices, or where the degree of transformer protection is not acceptable.

As detailed in the second article, secondary-fault protection is critical on small three-phase power transformers used on industrial, commercial, and institutional power systems, and small-to-medium size three-phase power transformers used in utility substations, because of the expense and long lead times involved in repairing or replacing these transformers. Small-kVA overhead distribution transformers, on the other hand, will not likely see secondary faults, and the rare faults that do occur will not likely be detected and cleared by

the primary fuse in any case. The predominant cause of failure of small overhead distribution transformers is insulation failure due to lightning-induced overvoltages. These transformers are inexpensive and readily available.

Thus, a larger fuse rating, used in combination with a tank-mounted surge arrester, can provide better transformer protection than the smaller fuse link ratings traditionally recommended.

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