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

By Carey J. Cook and James K. Niemira

Over the years, both fuse manufacturers and users have generally agreed on the use of low fusing ratios* when protecting transformers against secondary-side faults and slowly evolving internal faults. This fusing philosophy is still appropriate for 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. Low fusing ratios are necessary if low-magnitude faults are to be detected and quickly cleared to minimize damage to these transformers. Protection against secondary-side faults, in particular, is extremely important when considering the critical nature of the process loads served by these transformers. Not to mention that replacement transformers are not readily available.

Recent field experience, as well as reports in the literature, suggests that a different fusing philosophy can be used when protecting small-kVA single-phase overhead distribution transformers. This change in philosophy is based, in part, on the realization that the majority of overhead transformer failures occur due to lightning surges and not due to secondary-side faults. It is also becoming clear that overhead transformers can be better protected against damage due to surges if the arrester is relocated to the transformer tank.

Moving the arrester to the transformer tank, however, makes fuses with small ampere ratings susceptible to nuisance operations because these small fuses must pass the surge current during an arrester operation. To minimize these nuisance operations, it is necessary to increase the fuse rating on overhead transformers to withstand these surges.

However, many protection engineers are concerned that the use of larger fuses may result in a reduction in the degree of protection provided against both secondary-side faults and slowly evolving internal faults. Further analysis reveals that very little protection is given up by standardizing on larger fuse ratings for these transformers, particularly if the fuses operate in a current-limiting fashion.

This article, and next month's concluding article, provides a detailed discussion of the items that must be considered when selecting a transformer primary fuse. Perhaps of interest is an expanded treatment of the inrush currents that occur when transformers are energized. Also, differences in the protection philosophy applicable to three-phase power transformers versus small kVA overhead distribution transformers will be noted, where appropriate.

APPLICATION FACTORS

As a general rule, the following factors must be considered when selecting a transformer primary fuse:

- System voltage;
- Available fault current;
- Anticipated normal loading level, including daily or repetitive peak loads, and emergency peak loads;
- Transformer inrush current, including the combined effects of magnetizing-inrush current and the energizing-inrush currents associated with connected loads — following a momentary or an extended outage;

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- The degree of protection provided to the transformer against damaging overcurrents;
- Coordination with other overcurrent protective devices; and
- Protection of load-side conductors or cables against damaging overcurrents.

A. VOLTAGE RATING

The maximum design voltage rating of the transformer primary fuse should equal or exceed the maximum phase-to-phase operating voltage level of the system. In the case of single-phase transformers, however, the maximum voltage rating of the primary fuse need only equal or exceed the maximum system phase-to-neutral voltage level, provided that the BIL rating and the leakage distance to ground of the fuse are sufficient for the application.

It is sometimes economically desirable to use phase-to-neutral rated current-limiting fuses to protect three-phase transformers.

Fuses so rated can be used on grounded-wye/grounded-wye, grounded-wye/delta, and open-wye/open-delta transformers provided that the following conditions are met:

- The probability of a primary phase-to-phase or three-phase ungrounded fault is very low.
- The fault current is high enough to ensure that two fuses will operate simultaneously by melting in less than 0.2 second.
- The load is predominantly grounded.
- A secondary breaker is employed to interrupt overloads.

B.SHORT-CIRCUIT INTERRUPTING RATING

The symmetrical short-circuit interrupting rating of the transformer primary fuse should equal or exceed the maximum available fault current at the transformer location. In addition, the interrupting rating of the fuse should be chosen with sufficient margin to accommodate anticipated increases in the interrupting duty due to system growth.

Tip: When determining the required interrupting rating of the transformer primary fuse, the X/R ratio of the system at the fuse location should be considered, since certain types of fuses may have higher-than-nominal symmetrical interrupting ratings when used in applications where the X/R ratio is less than values specified in the standards. As a result, it is often possible to use a less expensive primary fuse having a lower nominal symmetrical interrupting rating. Refer to the fuse manufacturer for details.

C.AMPERE RATING AND SPEED CHARACTERISTIC

The ampere rating and speed characteristic of the transformer primary fuse should be selected to (1) accommodate the normal transformer loading level, including daily or repetitive peak loads, and emergency peak loads; (2) withstand the magnetizing-inrush current associated with the energizing of an unloaded transformer, as well as the combined magnetizing- and load-inrush currents associated with the re-energization of a loaded transformer following a momentary or extended outage; (3) protect the transformer against damaging overcurrents; (4) coordinate with other overcurrent protective devices; and (5) protect load-side conductors and cables against damaging overcurrents.

ACCOMMODATE EXPECTED LOADING LEVELS

In general, the transformer primary fuse should be selected based on the anticipated normal loading schedule for the transformer, including daily or repetitive peak loads. The primary fuse ultimately selected should have a continuous loading capability, as differentiated from its ampere rating, equal to or greater than this highest anticipated loading level. Refer to the fuse manufacturer's recommendations for such loading capability values.

Conditions may occur during which the transformer will be loaded far in excess of the normal loading schedule. Such emergency peak loading typically occurs when one of two transformers (in a duplex substation, for example) is compelled, under emergency conditions, to carry the load of both transformers for a short period of time. Where emergency peak loads are contemplated, the primary fuse should have an emergency peak-load capability at least equal to the magnitude and duration of the emergency peak load. It is important to remember that the primary fuse should be selected to accommodate — not to interrupt — emergency peak loads. This requirement may result in the selection of a primary fuse ampere rating larger than would be required for a similarly rated single transformer installed alone, and therefore the degree of transformer protection provided by the primary fuse may be reduced.

Tip: The continuous, daily, and emergency peak-load capability values published for solid-material power fuses employing silver fusible elements are based on 70% preload and a 30°C ambient temperature. Peak-load capability values should be increased 0.5% for each degree centigrade that the average ambient temperature is below 30°C, and decreased 0.5% for each degree centigrade that the average ambient temperature is above 30°C. The continuous and 8-hour emergency peak-load capability values for distribution fuse links employing silver fusible elements are based on a 25°C average ambient temperature. These capabilities should be increased or decreased 0.4% for each degree centigrade that the average ambient temperature is above or below 25°C.

The published emergency peak-load capability values represent the maximum non-repetitive load that the fuse can carry without impairing its ability to perform properly. In no event should fuses be subjected to these loading levels more than twice per year in the case of power fuses, or more than 10 times over the life of a fuse link.

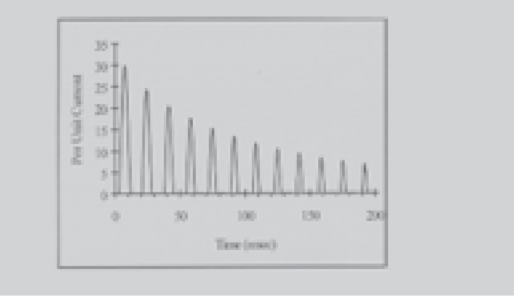

Figure 1

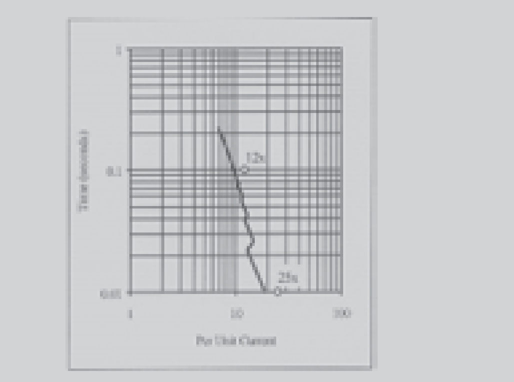

Figure 2

WITHSTAND INRUSH CURRENTS

When an unloaded distribution or power transformer is energized, there occurs a short-duration inrush of magnetizing current which the transformer primary fuse must be capable of withstanding without operating (or, in the case of certain types of fuses, without sustaining damage to their fusible elements). A conservative estimate of the integrated heating effect on the primary fuse as a result of this inrush current is roughly equivalent to a current having a magnitude of 12 times the primary full-load current of the transformer for a duration of 0.1 second, and 25 times for 0.01 second. An example of the magnetizing-inrush current for a small overhead distribution transformer is shown in Figure 1. This example is from a laboratory test and is the highest inrush obtained from tests performed on this transformer. The inrush that occurs on any particular energization will depend, among other things, on the residual magnetism of the transformer core as well as the instantaneous voltage when the transformer is energized. Since these two parameters are unknown and uncontrollable, the fuse must be sized to withstand the maximum inrush that can occur under worst-case energization. The minimum-melting curve of the primary fuse should be such that the fuse will not operate as a result of this magnetizing-inrush current.

The integrated rms equivalent of the inrush current from Figure1 is shown in Figure 2, along with the 'standard' inrush points. Note that the standard inrush points are higher than the actual rms equivalent of the inrush current. As mentioned, these standard inrush points result in a conservative estimate of the magnetizing-inrush current. Sizing the transformer-primary fuse such that its minimum-melting curve is above these standard inrush points will avoid an unnecessary fuse operation, but can occasionally cause coordination problems with upstream protective devices, or it may result in compromising the protection of the transformer because of the large rating selected.

On these occasions, the use of a smaller fuse rating is desirable and can be justified by a better estimate of the heating equivalent of the magnetizing-inrush current.

Actual magnetizing-inrush current also depends on the transformer rating and the available fault current. Because of the voltage drop across the source impedance during the inrush period, the inrush current will be less when the transformer is supplied from a weak source as compared to a strong source. Also, for small overhead distribution transformers the peak inrush current can be as high as 30 times the rated rms current, while for larger substation-type transformers the inrush peak will be lower, but the inrush duration longer. Figure 3 illustrates the maximum magnetizing inrush rms equivalent as a function of transformer size. Note that the per-unit inrush current is lower for the larger transformer sizes (actual amperes of inrush current is, of course, higher for the larger transformers). The strength of the source relative to the transformer full-load current is indicated by the ratio of the transformer full-load current to the source available fault current; a strong source will be able to

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supply a high fault current and will result in a lower ratio of full-load current to fault current.

The transformer-primary fuse must also be capable of withstanding the inrush current that occurs when a transformer that is carrying load experiences a momentary loss of source voltage, followed by re-energization (such as occurs when a source-side circuit breaker operates to clear a temporary fault, and then automatically recloses). In this case, the inrush current is made up of two components: the magnetizing-inrush current of the transformer and the inrush current associated with the connected loads. The ability of the primary fuse to withstand this combined magnetizing- and load-inrush current is referred to as 'hot-load pickup' capability.

The integrated heating effect on the transformer-primary fuse as a result of the hot-load pickup current is equivalent to a current having a magnitude of between 12 and 15 times the primary full-load current of the transformer for a duration of 0.1 second. Here again, the minimum-melting curve of the fuse (adjusted for preload) should exceed the magnitude and duration of the combined inrush current. This is again a conservative estimate of the inrush, and the advantages of using a smaller fuse can sometimes be obtained by recognizing certain mitigating factors. First, this hot-load inrush phenomenon is usually not applicable to transformers serving predominantly industrial loads such as a factory. Because the manufacturing processes will generally require equipment and machines to be restarted in an orderly sequence, not all of the loads are immediately restarted as soon as power is restored. Also, in industrial applications the transformers are typically sized to carry continuously the maximum expected demand load, with the result that they are often actually loaded to perhaps only half or less of rated power. Second, as with magnetizing inrush, the ability of the source to supply current, limited by the source impedance, will limit the magnitude of the hot-load inrush current.

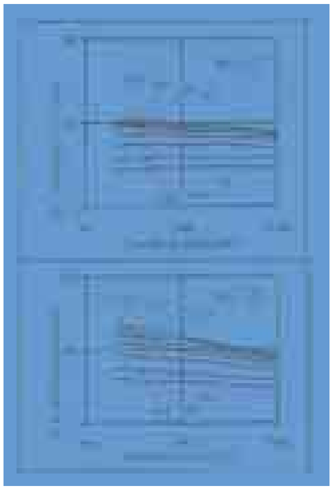

Figure 3

The final type of inrush currents to which the transformer-primary fuse will be exposed are long-duration overcurrents that occur due to the loss of load diversity following an extended outage (30 minutes or more). These long-duration overcurrents are referred to as 'cold-load pickup.' The cold-load pickup phenomenon is typically associated with utility distribution transformer loading practices, where the transformers are often sized for the average peak load rather than the maximum expected peak load, thereby exposing the transformers to overcurrents of up to 30 minutes duration following re-energization. This phenomenon occurs since large electrical loads such as air conditioners, refrigerators, and electric heaters are thermostatically controlled and cycle on and off at random times relative to one another such that only a fraction of total possible load is connected to the system at any one time. After an extended loss of power, many more of the thermostatically controlled devices will be outside of their respective set-point limits with the result that, as soon as power is restored, the thermostats will demand power for their controlled equipment.

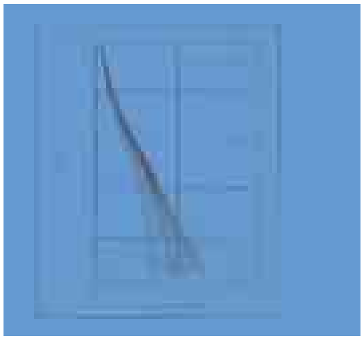

Figure 4

To avoid a nuisance operation of the transformer-primary fuse, it must be capable of withstanding the magnetizing-inrush current of the transformer superimposed on the transient overcurrent associated with picking up cold, the expected overload current associated with the total kVA connected. The time-integrated heating effect of the cold-load current profile on thermally responsive devices, such as fuses, is usually represented by the following equivalent multiples of transformer nominal rated load current:

6 x nominal load current for one second;
3 x nominal load current for up to 10 seconds; and
2 x nominal load current for up to 15 minutes.

The ability of the transformer primary fuse to withstand the combined magnetizing- and load-inrush current associated with an extended outage is referred to as its cold-load pickup capability. Here again, the cold-load inrush will be ameliorated by the source impedance and, if

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the source is weak, use of a smaller fuse rating may often be justified. Equivalent rms current representing the cold-load inrush that can be expected from small distribution transformers (50 to 225 kVA) is illustrated in Figure 4. Standard cold-load pickup points are also illustrated. For larger transformers (up to 1000 kVA) the cold-load pickup profile differs slightly only in the short time region (less than 0.1 seconds) from that illustrated in Figure 4; this is because the difference in the magnetizing-inrush current with transformer size has a greater influence when the inrush current is integrated over this short time period.

Tip: In contrast to residential loads, transformers applied in industrial, commercial, and institutional power systems are usually sized to accommodate maximum peak demand load without being overloaded. As a result, these transformers are often actually loaded to only a small fraction of their rated power — perhaps only one-half or less. For this reason, and the requirement for an orderly re-starting of equipment, the combined magnetizing- and load-inrush currents associated with the energizing of these transformers following an extended outage is no more severe than the inrush currents encountered under hot-load pickup conditions. Accordingly, cold-load pickup need not be considered when selecting the ratings and settings of primary fuses for transformers applied on industrial, commercial, and institutional power systems.

Next month's article will discuss protecting the transformer in accordance with industry-accepted through-fault current duration guide curves, and how to coordinate the transformer-primary fuse with both secondary-side and primary-side overcurrent protective devices.

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[1] Fusing ratio is defined as the ratio of the transformer primary fuse ampere rating to the transformer self-cooled full-load current. **ET**