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Optimized overcurrent protection for pad-mounted, liquid-filled transformers

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Introduction

In order to improve system reliability and reduce the impact of overcurrent on equipment, it is essential to select a proper fuse protection package. Protection methods exist for both overhead and pad-mounted transformers, in both 1-phase and 3-phase applications. There are many variables that need to be considered to properly define a fusing package. The fusing must withstand steady-state and overload currents, normal inrush currents, and other momentary transients (due to situations such as lightning or switching surges). Conversely, the fusing package must also protect the transformer from extended overloads or excessive current due to secondary faults. The fusing must also protect the system from the effects of failures within the transformer. In order to balance these variables, it is critical to have both a proper fuse selection and coordination with other devices that comprise the power system. Due to the complexity that exists, it is preferred to use a fuse protection package that has already been established. Proper coordination is easier to maintain and reduces potential variability in coordination of the devices.

There are a variety of fusing options for single- and three-phase padmount transformers, but the industry has standardized on the two-fuse system including a Bay-O-Net (BON) expulsion fuse in series with an internally mounted backup, current-limiting fuse in deadfront applications. The BON fuse operates on secondary faults and overloads, and is an economical, easy, field-replaceable fuse. The back-up Energy Limiting Submersible Partial-range (ELSP) current-limiting fuse is mounted under-oil and is coordinated to operate on internal high-current faults only. It is not field replaceable, thus a transformer with an internal fault will have to be removed from service.

This paper will detail the two-fuse BON/ELSP fuse characteristics, options available in BON fuses (and alternately a MagneX® Interrupter), and proper coordination practices. To fully understand the Bay-O-Net fuse options requires a level of understanding of the aging effects of exposing transformers to high temperatures and loading. These effects will also be covered in detail in the last section of the paper.

Fuse definitions and characteristics

Expulsion fuse definitions and descriptions

Expulsion fuses are known as zero-waiting devices because they must wait for a natural current zero before they can interrupt the fault current. There are versions usable in air or under oil. For any fuse, the current is carried by the fusible element. The current passing through the element resistance heats the elements until they melt. The current is then carried by an arc which interacts with an ablative liner and insulating media. The gases produced during interruption cool the arc and consume the arc energy, reducing ionization. At a current zero, the arc disappears. Because the arc has been cooled the recovery of the insulation dielectric withstand capability prevents arc re-ignition and subsequent current flow. An example of an under-oil expulsion fuse is the BON fuse.

Descriptions of BON families

The first step in providing proper protection for a transformer is the selection of the correct BON fuse or low current series device. There are four main BON fuse families: Current-Sensing (353C), Dual-Sensing (358C), Dual-Element (108C), and the Hi-Amp Overload (361C) BON fuses.

The Current-Sensing BON link is either a single tin (232°C melting point) or copper (1083°C melting point) element fuse that senses only secondary faults. Because of the higher melting temperature elements (especially copper), the current sensing style of link tends to be insensitive to high oil temperatures, and is only affected by the resistive heating of the current. As a result of this insensitivity, the fuse allows transformers to carry additional overload than would be allowed with a fuse that has a lower melting temperature element.
Current sensing BON fuses require that the minimum melting current of the selected fuse, at 300 seconds, should be at least three to four times the transformer rated current. Three times rated current is used for tin elements (353C04 – C12), and 4 x rated current is used for copper elements (353C14 – C17). The current sensing links can be used up to 23 kV.

The Dual-Sensing BON link is comprised of a eutectic (145°C melting point) material, which has a relatively low melt temperature. The Dual-Sensing BON fuses provide protection against both secondary faults and high oil temperature due to transformer overloads. Because of its ability to sense and operate when there is higher oil temperature, this link aids in preserving the life of a transformer. The life expectancy of a transformer is reduced when the transformer is exposed to long-term elevated temperature. The loading recommendations for the dual sensing BON fuses provide approximately 200% of the transformer full load for two hours and 160% of the transformer full load for seven hours. This assumes that the transformer is preloaded to 75% of nameplate (normal) rating and the outside ambient temperature is 35°C. The 358C14 and smaller links may be used at any voltage below 23kV and the 358C16 and C18 are limited to 8.3kV.

The Dual-Element BON link has similar benefits to the Dual Sensing fuse in that it preserves the life of a transformer by providing overload protection. Compared to a standard dual sensing link, the TCC curve is more vertical which provides different coordination with other devices. (Refer to Figure 2 below.) The Dual-Element fuse is an assembly of two separate materials, a lower melting temperature eutectic (145°C melting point) material, and a higher melting temperature Nichrome (about 1400°C melting point) or copper (1083°C melting point) material. The Dual-Element BON links sense overloads (high oil temperature) and secondary faults. The loading recommendation for the dual-element BON fuses are the same as those for the dual sensing and the high-amp overload links. The 108C07 and smaller links may be used at any voltage up to 23 kV and the 108C09 and C14 are limited to 15.5 kV.

The High-Amp Overload link is made of eutectic (145°C melting point) and silver (960°C melting point), with a net effective melting temperature of 145°C. As a result, it senses high oil temperature due to overloads. This family of BON fuses was designed for use in higher kVA transformers since it is able to carry higher continuous load currents. This fuse is unique in that it uses a cartridge tube that incorporates the fuse link. The loading recommendation for the high-amp overload links are the same as those for the dual-sensing and the dual element BON fuses. This can be applied up to 15.5 kV applications.

Current-limiting fuse definitions and descriptions

A full-range current-limiting fuse as defined by IEEE Std C37.40™ – 2003 standard is a fuse capable of interrupting all currents from the rated interrupting current down to the minimum continuous current that causes melting of the fusible element(s), with the fuse applied at the maximum ambient temperature specified by the fuse manufacturer. This basically means that both the high current and the low current interruption capabilities are contained within one device. Therefore this is a standalone device that does not require a low current series device.

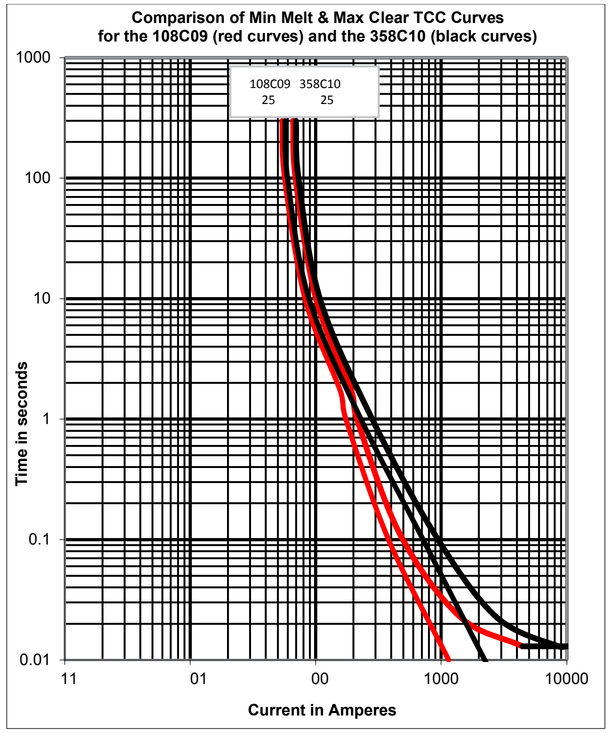

Figure 1. Comparison of dual element and dual sensing TCC curves

A backup current-limiting fuse as defined by IEEE Std C37.40™– 2003 standard is a fuse capable of interrupting all currents from the rated interrupting current down to the rated minimum interrupting current, which means that the fuse must be paired with a low current series device in order to achieve full-range protection. Two examples of backup current limiting fuses are the Companion II® fuse for overhead protection and ELSP for under-oil applications. Several examples of low current series devices are as follows: weak links, Bay-O-Net (BON) fuses, cut-out fuse links, and MagneX interrupter.

The ELSP fuse is a backup current-limiting fuse. Since the ELSP fuse is a backup fuse, it is used in series with a low current protection device, often one of the BON fuses described above. The ELSP is comprised of an element wound along a mica spider, assembled into a fiberglass/epoxy tube, and encased in sand. ELSP fuses can be connected in parallel in order to increase the current rating of the fuse. CL fuses are known as "zero-forcing" devices because during interruption they generate orders of magnitude higher resistance which drives the system current to zero without waiting for a natural current zero like with expulsion fuses. This dramatically reduces the amount of energy (I^2t) that is released from the system into the fault. This energy reduction can confine the energy released by the fault to the faulted piece of equipment. That is, the energy let through the CL fuse can be held to a level that is less than the energy needed to melt or open upstream protection. This also can prevent catastrophic failure of the faulted equipment. ELSP fuses and other CL fuses differ from expulsion type fuses in that they limit the peak current that is let through to the rest of the system. (Refer to Figure 2 below.) By limiting the peak let-through current, the magnetic forces generated by that current are reduced, thereby limiting the stress on other devices and equipment that comprise the distribution system.

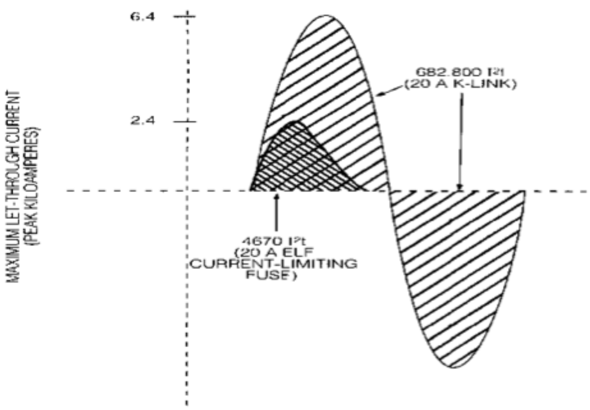

Figure 2. Differences in the amount of current let-thru between expulsion and CL fuses

Coordination overview

Fuses have typical characteristics that need to be considered including maximum current ratings, maximum operating voltages, melting time, arcing time, clearing time, fault interrupting capacity and coordination with upstream and downstream devices. Fuses within the transformer are often coordinated using matched-melt recommendations as detailed in IEEE Std C37.48™ – 2005. Matched-melt coordination guidelines were established to ensure that the low current series device or expulsion fuse will always open in the event of a fault or overload condition. Because the low current series device always opens, additional voltage withstand capability is provided. In matched-melt coordination, the CL fuse must melt in the first half-cycle of fault current at levels above the maximum interruption rating of the expulsion fuse.

Another important consideration in selecting fuses for the protection of transformers is the time-current characteristic (TCC) curves of the fuses. This is particularly important at the cross-over point, where the maximum-clear TCC curve of the low current series device crosses over the minimum-melt TCC curves of the ELSP fuse. The minimum crossover point must be greater than the maximum through-fault current allowed through the transformer. This ensures that a secondary fault, outside of the transformer will not cause operation of the ELSP fuse, which generally cannot be replaced in the field. The ELSP fuse only operates on a low impedance fault within the transformer. This prevents a line technician from re-fusing a failed transformer, improving safety. Fault current differentiation is a term that describes this relationship.

Application considerations

In addition to selecting the proper voltage-class fuse, it is important to understand the manner in which it is applied to and coordinated with other devices on the system, including transformers, capacitors, motors, reclosers, breakers and other fuses. The first item to consider in this process is the TCC Curves which are comprised of the minimum-melt and the maximum-clear curves. The minimum-melt curve defines the minimum time required at a specific current at which the fuse will begin melting and subsequently break the element current path. The maximum-clear curve defines the maximum amount of time required for the fuse to clear at a given current.

The TCC curves are used to select which fuse is to be used with the device to be protected. Generally, each type of protected device has its own set of minimum time and current levels that must be allowed to pass through the fuse. The minimum-melt TCC curve must be to the right and above the protected device key characteristic or curve when graphed. (Refer to Figure 3 below.) This will identify the smallest fuse that allows the protected device to carry its required load. Larger fuses may be selected if it is desired to allow additional overload from the protected device. TCC curves are also used to coordinate the fuses in the transformer with an upstream device or system.

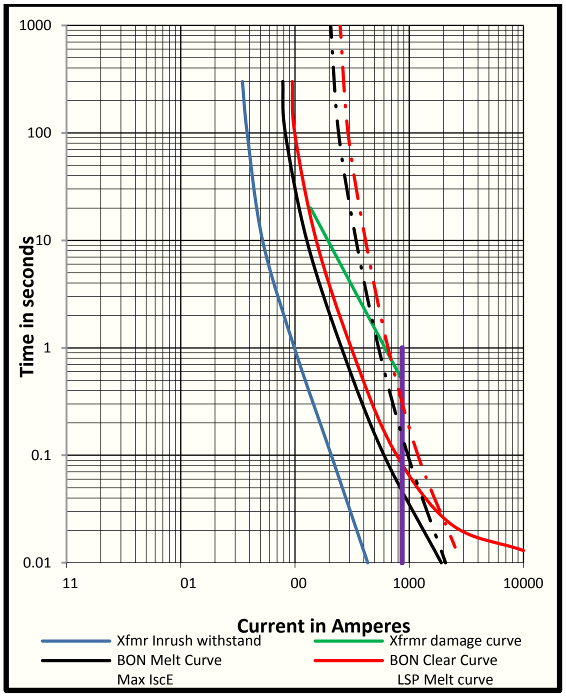

Figure 3. Minimum-melt TCC curve of BON (black curve) is to the right & above the transformer key characteristic curve (blue curve)

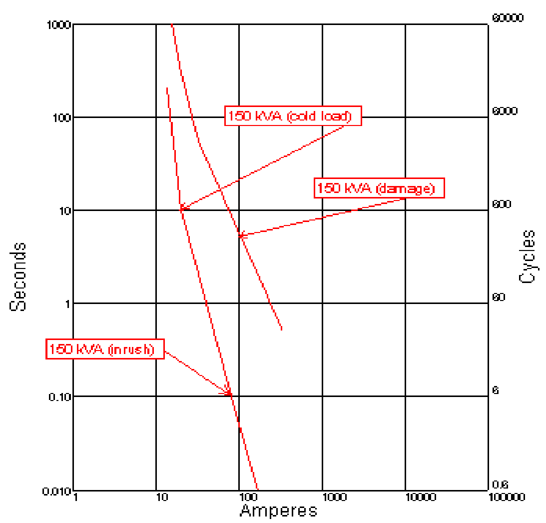

Figure 4. Plotted transformer damage, cold load pickup and in rush curves

BON fuse current rating selection

There are several things that need to be considered when selecting BON fuses. These considerations include inrush current, cold load pickup and fuse specific loading recommendations, and transformer damage curves. Specific loading recommendations are detailed above in the descriptions of each BON fuse type. The recommendations should adhere to the following rules as listed in IEEE Std C37.48.1™ – 2002:

- For inrush current, the selected fuse's minimum melt should withstand 12 x transformer full load current for 0.1 seconds, and 25 x transformer full load current for 0.01 seconds.
- For cold load pickup it is recommended that the selected fuse's minimum melt should withstand 6 x transformer full load current for 1 second, 3 x transformer full load current for 10 seconds, and 2 x transformer full load current for 900 seconds.
- Transformer damage curves indicate the current/time relationship at which the transformer may be damaged, thermally and/or mechanically, under overload and secondary fault conditions. There are two considerations: 1) heat and 2) magnetic forces.

The BON and ELSP should operate to protect the transformer against current and current durations that are greater than the values shown in the damage curves. The transformer damage curves are detailed in IEEE Std C57.109™ – 1993.

ELSP and BON fuse coordination

Once the correct BON fuse is selected, the next step is to determine the appropriate backup high current device, like the ELSP fuse, to coordinate with the BON fuse. When selecting the appropriate ELSP fuse, the six major factors to consider are:

- The maximum-thru fault current compared to the BON and ELSP fuse curves.
- The maximum thru fault is calculated as follows: Maximum thru fault current = full load current of the transformer x100 +% impedance of the transformer
- The impedance values listed in Eaton "Pad-Mounted Transformer Fusing Philosophies" S240-000-1 on page 4 (table titled – standard transformer impedances used to calculate maximum thru fault) are typical and can be used if specific impendence values are not known for a given application. For other impedance values consult the manufacturer. Then compare the minimum melting curve for the backup device (ELSP fuse) to the maximum clear curve for the BON fuse, and take note of the current at which the two curves cross. This is known as the crossover point. Ensure that the crossover point is greater than the maximum thru fault current; this will guarantee that the ELSP fuse will only open on a fault current greater than the maximum secondary fault current, i.e. a fault that is caused by a transformer failure. This is known as fault current differentiation. On a secondary fault replacing the BON link will return the unit to service. On a primary fault, replacing the BON link will not return

the unit to service, providing differentiation between a secondary and a primary fault. The first ELSP fuse that meets this criterion is the smallest ELSP that coordinates properly with the selected BON fuse; however any larger backup CL fuse would also coordinate. (Refer to Figure 5 below.)

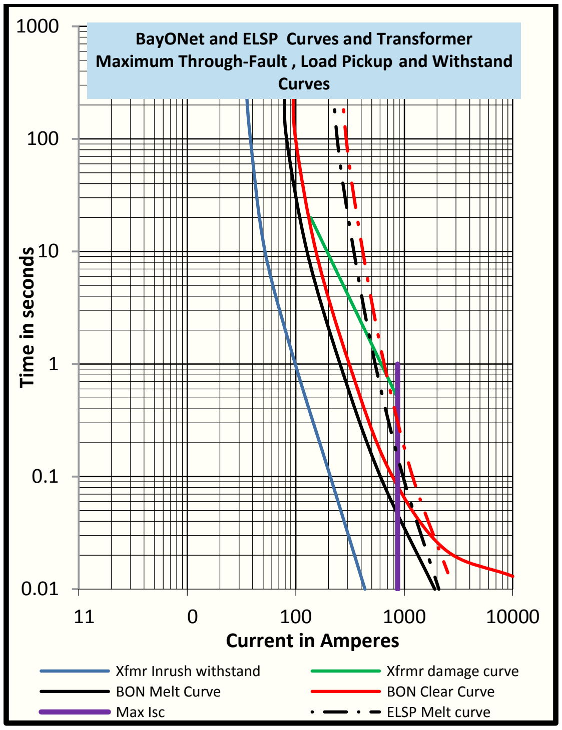

Figure 5. BON and ELSP coordination using smallest ELSP fuse

- Compare the minimum rated interrupting current of the selected ELSP to the crossover current.
- Verify that the BON and ELSP TCC curves do not crossover in the long-time region of the curves.
- It is important to ensure that there is no long-term crossover between the BON maximum clear curve and the ELSP minimum melt curve because this may cause the ELSP to attempt to interrupt current, below its minimum melt current or to be exposed to potentially damaging overloads prior to the BON fuse's operation. One way of ensuring this is to check the maximum clear current of the BON fuse which must be less than or equal to 90% of the backup CL fuse's minimum melt current at 300 seconds. When proper coordination is achieved the low current series device should operate first. The only time that the backup CL fuse should operate would be for internal transformer faults, winding failures, and other similar failures where the transformer would need to be pulled from service.
- The BON maximum interrupting rating should be higher than the crossover current.
- Ideally, this will provide additional margin to the coordination scheme by ensuring that the BON and ELSP fuses overlap in the areas that they provide protection.
- Match-Melt Coordination considerations
- Match-melt coordination is important because it ensures that the low current series device or expulsion fuse will always open in the event of a fault or overload condition. Because the low current series device always opens, it will have the system voltage across it. This is in addition to being across the CL fuse, thus augmenting the ability of the protection package to withstand system recovery line-to-line or line-to-ground voltage.
- For instances where these conditions are not fully met, under unusual circumstances it may still be possible to use BON and ELSP fuses successfully. A careful review of the coordination should take place between the manufacturer and the end user.

In some cases a user may not wish to use an ELSP fuse. In those cases an isolation link should be used to provide additional high current protection during re-fusing and switching. Unlike other backup devices isolation links do not have interrupting ratings, are coordinated to operate at higher current levels (similar to those experienced during a transformer failure) and will melt open during a transformer failure. This prevents a faulted transformer from being re-energized. Isolation links are used in series with a BON fuse or other low current series device. They should be coordinated with the BON fuses similar to how ELSP fuses are coordinated; the minimum melt TCC of the isolation link should cross the maximum clear curve of the BON fuse at a point greater than the maximum-thru-fault current.

The key reason CL fuses are important to incorporate in the protection of systems is because they allow for the prevention of catastrophic failures by dramatically reducing the amount of current let-thru to the rest of the system after a high current fault. This can prevent tank rupture and other similar failures.

Voltage class selection rules

In all cases the rated voltage of the fuse should exceed the system voltage at the point of application. For single-phase applications, the voltage rating of the fuse must be greater than the L-G rating of the system. For three-phase, there are two connection schemes that affect the voltage rating of the fuse. One is Wye connected transformers; use of the L-G rated fuses is generally acceptable. If the transformer experiences a phase-to-phase fault without involving ground or if there is a Delta secondary load that is greater than 40 to 60% of the total load, a phase-to-phase (L-L) rated fuse may be required. For units connected with a Delta primary or secondary, L-L rated fuses are required.

Summary

BON and ELSP fuses have been used for decades with good success. As there is turnover in the engineering communities at both manufacturers and utility users, a restatement of the general application considerations is helpful. Eaton is uniquely positioned to provide this restatement since CPS both manufactures transformers and offers the most comprehensive line of transformer fuses and protection devices. This paper provides such a restatement.

Below, this paper also presents a new tool, developed from well accepted industry standards and practices that provide a simple way to select and then present the TCC curves, the transformer characteristic curves and the long term melt curves of the optimum fuses for each application. It also can be used to assess, using a wide-range of assumptions such as levels of preloading and ambient temperatures, transformer life.

Cooper TransFusion™ coordination program

Eaton completed development of a software program to allow assessment of interactions between the fuse and the transformer to aid in the selection of a fuse protection package. Initially, this tool determines the smallest BON link for the selected BON fuse family. It can also be used to select a 1ø, 3ø Y-Y or 3ø Δ MagneX device. This program requires the kVA size, voltage, and percent impedance to be entered. This data is then used to calculate the full load current and maximum through-fault current of the transformer. A user can also enter the ambient temperature and percent preload on the transformer, along with the transformer class, 55° or 65° C rise.

The program initially selects the smallest BON fuse that meets inrush requirements. It also has the flexibility to identify the second, third, or fourth largest fuse of the desired type, should a larger fuse be desired. This allows comparison and selection of the best fit for the long-term protection of the transformer. For example, the recommended standard practice is that a dual sensing BON fuse should allow a two-per-unit load for two hours and a 1.6 per unit load for seven hours. The smallest fuse may not allow that level of loading. Using the selection of larger fuses, a comparison can be to select the best fuse.

The program also provides the catalog number for the minimum size ELSP that coordinates with the BON. The selection program then displays two charts. One of the charts displays the transformer inrush curve, the transformer damage curve, and the maximum through-fault curve. It also displays the minimum-melt and maximum-total-clearing TCC curve for the BON and ELSP. This allows the user to verify that the coordination is correct, and that the vcrossover point has a current rating that is greater than the maximum through-fault of the specific transformer.

The second chart presents the long time loading (at 0.5, 1, 2, 4, 7, and 24 hours) allowed before the minimum melting or tripping of the fuse or MagneX. This chart shows the per unit current allowed through the fuse for long times. Smaller fuses reduce the time and/or current required to open the fuse. Therefore, smaller fuses also reduce the heat released in the transformer.

IEEE Std C57.91 - 1995/Cor 1-2002 is an excellent document to illustrate and allow understanding of the effects of the heat released by overloads in an oil-filled distribution transformer. The hotter the transformer is, the shorter its expected life. The TransFusion™ coordination program provides the ability to assess the minimum level of overload allowed by a specific fuse in a specific transformer. As a result, the program allows assessment of comparative protection provided by different types and sizes of low current protective devices. This information makes it easier to understand the consequences of fuse selection. It also lays the ground work for studying the loss of transformer insulation life.

In all cases, the fuse must withstand normal inrush requirements, based on the nominal temperature TCC curves. The inrush requirements are:

- 25 x the full load current at 0.01 s
- 12 x the full load current at 0.1 s
- 6 x the full load current at 1 s
- 3 x the full load current at 10 s
- 2 x the full load current at 900 s (For wire element expulsion fuses the minimum melting current from the TCC curves at 300 s or 600 s may be used.)

These points can be graphed to form an inrush curve. If expulsion fuses are used alone, the minimum melt curve must be to the right of the inrush curve. (Refer to Figure 6.) For two fuse applications, where the BON fuse provides the long-term overload or secondary fault protection, and the ELSP protects against high current faults, the composite melt curve for the two fuses must be to the right of the inrush curve. If the BON fuse meets inrush requirements, typically the composite curves will also meet the inrush curve requirements. After verifying that the TCC curves meet inrush requirements, the interaction of the two fuses and the transformer can be evaluated, using overload curves as shown in Figure 7.

This set of figures shows fuses that meet the minimum application requirements; at the same time they allow significantly different long-term overloads. The overload curves show that a 353C12 current sensing fuse will allow a relatively flat long-term load. A 358C12 dual sensing fuse will allow lower levels of long-term loading. The overload chart also shows two additional sizes, the second and third largest dual sensing fuses. The 358C14 fuse will allow significantly higher short-term curves while limiting the long-term overload to levels that are actually less than those allowed by the 353C12. The 358C16 fuses allow even higher short-term overloads while providing similar long-term loading. This provides added information to guide an engineer specifying fuses in the selection of a specific fuse. A 358C14 seems to provide the best balance.

The Cooper TransFusion™ coordination program is a free, web-based, easy-to-use coordination tool that makes finding the right ELSP or BON fuses, and MagneX Interrupter effortless. It can be found at http://www.coopertransfusion.com

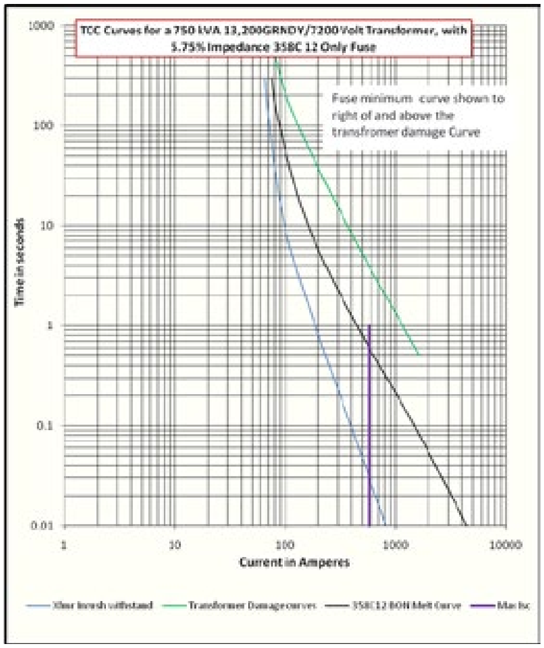

Figure 6. Minimum-melt BON fuse curve shown to the right of and above the transformer damage curve

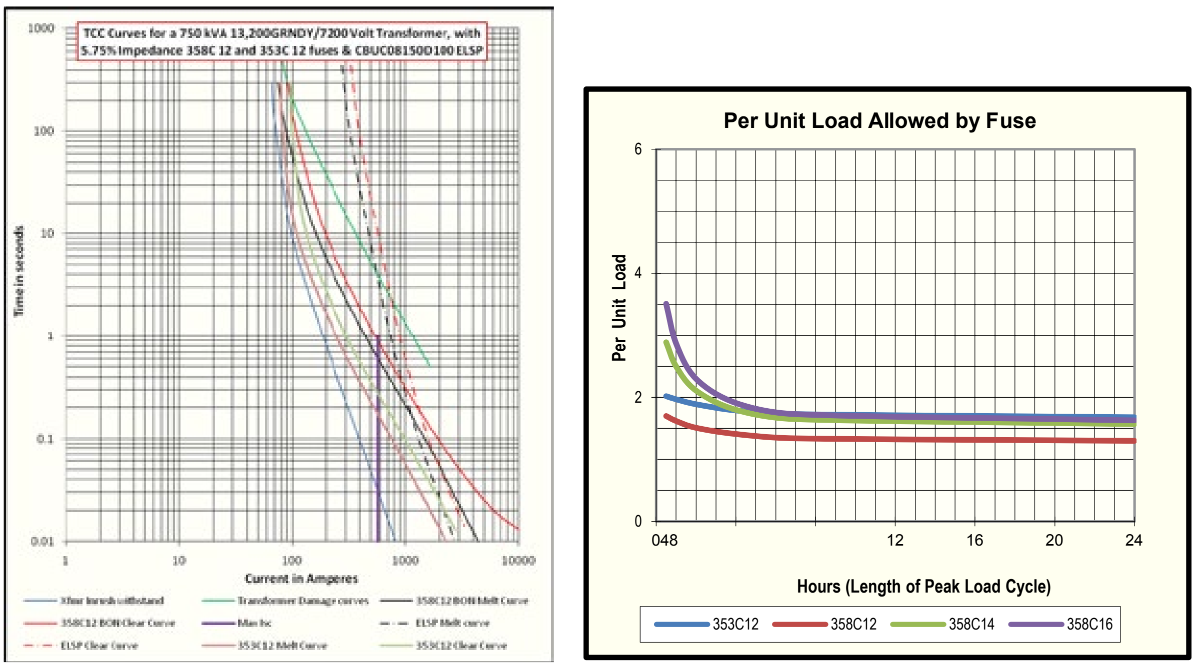

Figure 7. Transformer coordination and long-term overload curves for 358C and 353C fuses

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