REDUCING ARC FLASH ENERGIES ON TRANSFORMER SECONDARIES

By Mike Lang, Principal Field Engineer and
Dave Komm, Technical Services Supervisor

I. INTRODUCTION

Arc flash incident energy calculations are frequently above 40 cal/cm^2 for equipment connected directly to the secondary side of power transformers due to existing electrical system designs and transformer fuse protection practices. Many companies use this value as the upper limit for energized work. Consequently these companies must now insist on outages to perform routine tasks on this equipment. When the equipment is switchgear feeding large processes, the downtime cost of a task such as racking in and closing a power circuit breaker can be tens of thousands of dollars.

E-Rated Medium Voltage fuses, used on transformer primaries, have reliably fulfilled the protection objectives of isolating failed transformers from the electrical system, protecting the transformer from through faults, protecting cables connected to the transformer, and limiting damage for faults on the transformer primary. Current-limiting E-Rated fuses have been particularly effective at limiting the damage that occurs from transformer primary faults such as winding failures, bushing failures, and insulation breakdown [1]. For these faults, E-Rated current-limiting fuses dramatically limit the destructive energy delivered to the fault by clearing in less than ½ cycle while preventing the fault current from reaching its first ½ cycle peak value. Current-limiting fuses also have the high ampere interrupting ratings needed for fault current levels typically found in industrial power systems.

Part of the problem of high arc flash energies is that the ampere rating of these fuses is often found near the upper limit identified in article NEC 450.3. The larger sizes easily ensure that magnetizing inrush currents of the transformer do not cause nuisance openings and that there is good coordination with secondary over current protective devices. Fuses of these ampere ratings will be current-limiting for primary faults but will have extremely long clearing times for secondary arcing faults as will be shown in the example of the following section.

When using a smaller ampere rating of the same fuse type is not enough to adequately reduce arc flash energies, it can be useful to consider other fuse types. In some cases, it is possible to reduce energies below 20 cal/cm^2 and maintain reliable operation by using a fuse with different time current characteristics. This Tech Topic will identify the factors that need to be considered to reduce arc flash energies and still provide reliable protection of the transformer and conductors.

II. EXAMPLE DETAILS

The example depicted in Figure 1 highlights 480V switchgear where incident energy calculations exceed 40 cal/cm^2. In this situation, the switchgear must be de-energized by opening the transformer primary switch to perform many typical maintenance actions such as racking out a feeder breaker. Since opening the primary switch will de-energize all the unaffected circuits in the switchgear, the cost of downtime associated with this safety practice can be so costly that improvements have to be made to the protection scheme to drastically reduce the incident energy.

In this example, the arc flash incident energy calculation for the switchgear is based upon the clearing time of the primary fuse. The blue "X" on the time current curve in Figure 2 illustrates that the fuse's clearing time for a secondary arcing fault of 11,322 amps at the 480V switchgear (394A through primary fuse) will be in excess of the 2 second calculation limit suggested by IEEE1584 [3]. The resultant incident energy calculation, shown in Figure 1, is 73 cal/cm^2 at the switchgear.

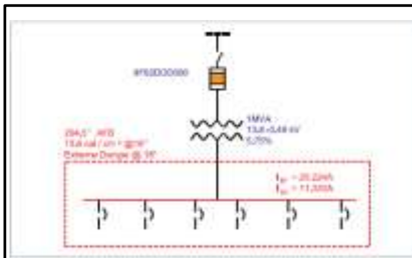

Figure 1: Switchgear with no main fed by 1000KVA transformer. Short circuit protection for switchgear bus is provided by primary fuse.

The relevant calculations are as follows:

- The **bolted fault current** available at the primary of the transformer is determined by the system impedance to the primary of the transformer. In this example the calculation at the 13,800V side of the transformer yields 20,918A. For primary faults of this magnitude, the primary fuse will be in its current-limiting mode and clear the fault in less than a ½ cycle.
- The **bolted fault current** available at the 480V switchgear is determined by the impedance of the transformer as well as the system impedance to the primary of the transformer and size/length of conductors from the transformer to the 480V switchgear. In this example, the calculation yields 20,224A and is shown as IBF in Figure 1. Based on the transformer turns ratio, the current through the primary fuse is 703A.
- The **arc fault current**, in the event of an arc flash in the 480V switchgear, will be significantly less due to the added impedance of the arc. Using IEEE 1584 equations, the arc fault current is a function of the bolted fault current and it is shown as I_{arc} = 11,322A in Figure 1. Based on the transformer turns ratio the current through the primary fuse is 394A.
- The **incident energy (IE) calculations** using IEEE 1584 equations require the expected duration (t) of the arc fault. This time is determined by the transformer primary protection fuse. The IEEE 1584 guide recommends IE calculations using the clearing times at the calculated I_{arc} and at 85% of I_{arc}. The calculation that yields the highest energy is used for identifying the magnitude of the hazard. For the two arc fault currents of interest, the total clearing times read from the fuse time current curve in Figure 2 and resultant IE calculations are shown in Table 1.

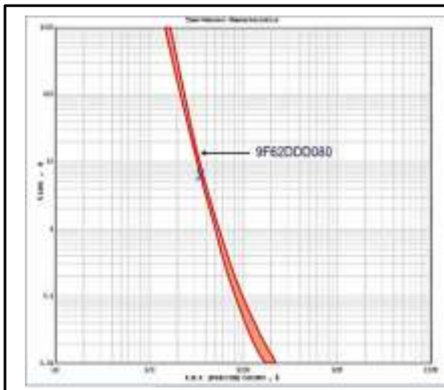

Figure 2: Time current curve for primary fuse.

III. FACTORS AND CONSIDERATION FOR THE SELECTION OF A TRANSFORMER PRIMARY FUSE

To reduce arc flash hazards and maintain reliable operation of the primary fuse, an arc flash energy objective must be added to the protection objectives of the primary fuse. Before changing the fuse to get a faster clearing time for the I_{arc} values, it is essential to review the other factors that affect selection of a transformer primary fuse. These factors include:

- System considerations
- Transformer characteristics
- NEC requirements
- Fuse characteristics

Percent of I_{ARC}	I_{ARC} Secondary	I_{ARC} Primary	Total Clearing Time	Incident Energy*
100%	11,322 A	394 A	6.7 Seconds	73 cal/cm^2
85%	9,624 A	335 A	16 Seconds	61 cal/cm^2

Table 1: Incident energy calculations using the time current curves of the 9F62DDD080.

<u>**System Considerations**</u>

- **Source impedance**. This is often provided by the utility as available MVA or fault current with an estimated X/R ratio. For our example it is the sum of the impedances up to the transformer and helps determine available fault current from the system. Note that this may be a range of values that depend on such things as the amount of generation on-line and the number of transmission lines in service. Calculations of maximum incident energy may require the use of a different value than the calculation for maximum fault current.
- **System Voltage**. This is used to calculate primary available fault current. For a secondary arcing fault, the primary current of a transformer with a rating of 13,800/480V will be 13% lower than that of a transformer rated 12,000/480V. If protected by the same size fuse, the clearing times for a secondary arc fault will be appreciably longer and incident energy can be higher.
- **Cable Type, Size, and Length.** This information is used to determine the impedances used in the short circuit calculations. It is also used to construct cable damage curves. The cables connected to the transformer are subject to short circuit damage if fault currents are not cleared by the primary fuse in times less than that specified on their cable damage curves.
- **Coordination**. It is important that the primary fuse not open on a downstream fault that should be cleared by a feeder or branch overcurrent protective device. To ensure proper coordination, the primary fuse curve should not cross the time current curves of downstream protective devices in the range of available fault currents. Without proper coordination, outages can result in a considerable cost to operations and fuse replacement.

<u>**Transformer Characteristics**</u>

- **Magnetizing Inrush Current.** When a transformer is energized, a transient magnetizing current will flow into the primary winding. The magnitude of this inrush can reach near 25 times the full load amps in the first ½ cycle before decaying to a nominal level. The actual magnitude of this inrush can vary depending on such factors as the residual flux, size of the transformer, source resistance, type of iron, and how the transformer is energized. Not only should the primary protective device be capable of passing 25 times full load amps for 0.01 second, it should be capable of passing 8 to 12 times full load amps for 0.1 seconds without opening as suggested by the IEEE Buff Book[2]
- **Transformer Damage Curve**. ANSI C57.109 specifies a thermal and magnetic force damage curve for power transformers. The protective system must clear transformer secondary overcurrents in times less than that specified on the curve to prevent damage to the transformer.

- **Transformer Ratings**. The power rating and voltage rating are used to determine full load current. Transformers may have multiple power ratings if they are equipped with cooling mechanisms such as forced air cooling. Use the highest rating to determine maximum full load amperes. We recommend using the lower rating for estimating magnetizing inrush requirements and the transformer damage curve.
- **Percent Impedance (Z%).** This is typically the major determining factor of available fault current magnitude on the secondary of the transformer. The Z% is the percentage of rated primary voltage required to obtain secondary full load amps. Table 2 shows that for a range of 5:1 for the source impedance, the available fault current changes less than 14%.
- **Turns Ratio**. Used to convert secondary and primary currents to a common basis, this is essential to confirm proper coordination between primary and secondary overcurrent protective devices. The turns ratio is calculated by dividing the primary voltage rating of the transformer by the secondary voltage rating.
- **Connection**. This is important when assessing coordination between primary and secondary protective devices for phase to ground and phase to phase faults. In this example with a Δ-wye connection, a line to line fault on the secondary will yield a line current on one of the primary phase conductors that is 16% higher than the currents on the secondary divided by the turns ratio [4]. For a secondary phase to ground fault, line currents on the primary will be 58% of the line current on the secondary divided by the turns ratio. Since the primary fuse will have longer clearing times than indicated for three phase faults, the transformer damage curve must be shifted accordingly to assess adequacy of transformer protection for secondary ground faults.

Available Fault Current at Transformer Primary	Available Fault Current at Transformer Secondary	Estimated Arc Fault Current at Transformer Secondary
500 MVA	20,224 A	11,322 A
400 MVA	20,058 A	11,244 A
300 MVA	19,786 A	11,117 A
200 MVA	19,264 A	10,872 A
100 MVA	17,850 A	10,203 A

Table 2. Secondary fault current calculations for a Δ-wye transformer rated 13,800/480V, 1000kVA 5.75%

<u>**NEC Considerations**</u>

- **Maximum Allowable Fuse Size**. Article 450.3 covers overcurrent protection of transformers. For the example above, Table 450.3(A) specifies a maximum fuse size of 300% (126A) of the transformer's rated current (42A). Note 1 of the table allows the selection of the next largest standard rating of 150A. Note 2 covers sizing of the 6 feeder breakers used in the example in lieu of a single secondary device. For multiple rated transformers, the fuse size limit is determined using the lower power rating.
- **Ampere Interrupting Rating**. (AIR) Articles 110.9 and 490.21(B)(2) require that the AIR of the fuse be equal to or greater than the maximum available fault current on the primary of the transformer.
- **Voltage Rating**. Article 490.21(B)(3) require that the voltage rating of the fuse be equal to or greater than the maximum system voltage at the transformer primary.

Article 240.100(C) requires adequate short circuit protection of cables feeding the transformer primary.

Fuse Characteristics

There are several types of medium voltage fuses with various ratings. In this Tech Topic we are focusing on E-Rated current-limiting fuses.

*Table 3 -Rated Symmetrical Interrupting Currents**

- **Fuse Type and Ratings.** E-Rated fuses are typically used to protect medium voltage transformers. E-Rated current-limiting fuses are covered by three of the standards in the ANSI/IEEE C37.40 series:
    - C37-40 Covers service conditions
    - C37.41 Specifies tests that prove the compliance to the standard
    - C37.46 Specifies fuse characteristic and ratings
- **E-Rating (Ampere Rating).** The E-rating defines the continuous current rating and a melting time criteria. Fuses with ratings of 100E and below must melt in 300 seconds or less for currents 200-240% of their E-ratings. Above 100E, the fuses must melt in 600 seconds or less for currents 220-264% of their E-rating.
- **Interrupting Capabilities.** There are three interrupting tests specified in C37.41 that E-Rated fuses must pass without evidence of venting or case rupture.
    - *The Series 1 Test* (Maximum interrupting rating) verifies that the fuse can interrupt fault currents at its marked AIR and Voltage Rating. Ratings commonly used are shown in Table 3.
    - *The Series 2 Tests* (Maximum Energy) subject the fuse design to conditions (Current, X/R and closing angle) that will create maximum internal arc energy during the fuse's interruption.
    - *The Series 3 Tests* (One Hour Opening) ensure that the fuse can safely clear a current that would cause opening in not less than one hour. Note that currents below this level (and above E-rating) may cause overheating damage to the fuse. Low level overload protection for transformers must be provided by overload relays or thermal sensing devices.
- **Current Limitation**. For E-Rated current-limiting fuses, the fuse must clear short circuits greater than its threshold current in less than ½ cycle while preventing the current from rising to its prospective maximum as shown in Figure 3. There are no let through standards for medium voltage fuses as there are for low voltage fuses [5]. Individual let through charts [6] need to be consulted for fuse performance. The threshold is typically less than 50% of the primary available fault current in industrial distribution systems, ensuring minimal destructive energy during primary faults

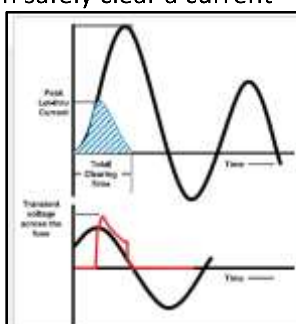

Figure 3.Current-limiting performance.

- **Voltage Rating**. For medium voltage primary fuse protection, the voltage rating of the fuse should be the next highest voltage rating above the system voltage. Care must be exercised to ensure that the fuse's transient arc voltage does not create conditions that could damage surge arrestors connected to the supply side of the fuse [7]. When a fuse interrupts a circuit in its current-limiting mode, it breaks current before a natural zero-crossing. This di/dt develops the transient voltage across the fuse shown in Figure 3. This voltage, larger than the system voltage, will be imposed upon other equipment upstream from the fuse as indicated in the equivalent diagram of Figure 4. The magnitude of the transient voltage is related to the system voltage and is covered by C37.46 as shown in Table 4.

Maximum Rated Voltage	Maximum Peak Voltage for Fuses through 12A	Maximum Peak Voltage for Fuses above 12A
2.8kV	13kV	9kV
5.5kV	25kV	18kV
15.5kV – 17.2kV	70kV	49kV
27.0kV	123kV	84kV
38kV	173kV	119kV

Table 4. Maximum transient voltage permitted by ANSI C37.40

- **Time Current Curve Characteristic**. Time current curves are presented as a band between two curves: Minimum Melting and Total Clearing. The curve on the left of the band is the minimum melting curve indicating the minimum amount of time needed for a range of current to melt the element and initiate internal arcing. The total clearing time (curve on the right of the band) is the total amount of time required for the fuse to clear an overcurrent. Clearing includes melting time, arcing time, and manufacturing tolerances.

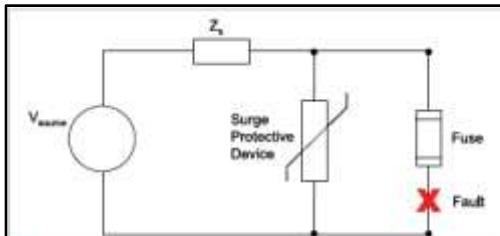

Figure 4. Circuit for transient voltage.

Figure 5 shows these curves for two 80E fuses manufactured by Mersen. Note that they both meet the single clearing time requirement for E-Rated fuses as described above.

Fuse Mounting, Sizes, and Options. Medium voltage fuses come in a wide variety of shapes and sizes as shown in Figure 6. In the United States, the most common mounting method is the ferrule style used on barrel diameters of 0.8125", 1.562", 2.00", 3.00" and 4.00". These fuses are mounted into steel reinforced clips and are available in a variety of lengths. Other common mounting methods are the clip-lock style that mounts into cam locking clips and a variety of bolt-on fuse types. For larger ampere ratings, fuses may have more than one fuse barrel connected together to form a single fuse. Options include indicators that can be used to signal fuse openings and 'hook-eye' options for fuse removal with a switching stick.

Figure 6. Common Fuse Mounting Types: Ferrule, Clip Lock, Bolt On

Other Considerations when Changing Fuses for a Transformer Application

If changing fuse type and/or downsizing the ampere rating, check with the switch manufacturer to ensure that the watts loss of the replacement fuse is acceptable. Also, determine if the desired fuse characteristics come in a fuse mounting that can physically fit into the primary switch enclosure.

IV. REDUCING ARC FLASH ENERGIES

Lowering the arc flash incident energy at the switchgear in the example of section 2 requires a clearing time at the expected 85% I_{arc} much faster than the existing fuse. When selecting a new primary fuse, care must be taken to ensure that the replacement fuse does not compromise any of the selection criteria of section 3. To accomplish this, a 9F60HMH080 fuse with a more 'inverse' time current characteristic is evaluated (See Figure 5).

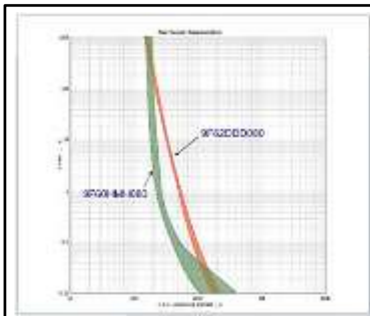

Figure 5. Time current curves for two different 15.5kV 80E fuses.

To completely assess acceptability of this fuse it is necessary to evaluate its 1) compliance with the requirements of the NEC, 2) current carrying capability under expected conditions, 3) time current characteristic of the fuse relative to relevant factors, and 4) physical compatibility with the existing primary switch and enclosure.

Must meet requirements of NEC. The 80E ampere rating of the replacement fuse (9F60HMH080) meets the 300% maximum sizing (126A) requirements of Table 450.3(A). The interrupting rating of 50kA at 15.5kV ensure that the AIR is greater than available fault current (NEC 110.9) and the voltage rating is greater than system voltage (NEC 490.21(B)(3)). Since the 15.5kV rating is the next highest rating, the transient arc voltage from the fuse should not interfere with upstream surge arrestor operation.

Must have adequate current carrying capability. The transformer full load amps (FLA) is less than 45% of the capability of either fuse and will not pose a problem.

Must have acceptable time current characteristic. The clearing times at expected secondary arc fault currents are read from the time current curve of the replacement fuse (shown as T1 and T2 in Figure 7) The resultant incident energy calculations are shown in Table 5. The calculations for the 9F60HMH080 yields an acceptable incident energy calculation of 11 cal/cm^2. Calculations are compared with the existing 9F62DDD080 fuse in the table.

> The 9F60HMH080 fuse will pass the magnetizing inrush currents without opening. Both inrush time/current requirements (shown as A and B) are to the left of the fuse curve on the plot of Figure 7.
>
> The 9F60HMH080 fuse shows better protection against transformer through faults as compared to the original fuse since its curve is to the left of the ANSI transformer damage curve shifted for ground faults (C on Figure 7) on the Δ-wye transformer. The new fuse also shows better protection for the cable feeding the primary as compared to the original fuse (D on Figure 7).
>
> The 9F60HMH080 fuse will coordinate with the feeder breakers for secondary fault currents up to 16,800A as indicated by the intersection of the fuse time current curve with the feeder breaker curve (E and G on Figure 7). Because the fuse is on the primary side of the Δ-wye transformer and the circuit breaker is on the secondary, we must adjust the intersection point

from Figure 7 by the turns ratio and an additional 16% [4]. See [8] for more information on coordination of fuses and circuit breakers.

The 9F60HMH080 fuse is capable of interrupting currents down to 240A, compared to 180A for the existing fuse.

Must be compatible with existing equipment. The physical dimensions of this fuse must also be taken into account to ensure that they fit the existing equipment. Both of these fuses have the same length and clip spacing; however, the suggested 9F60HMH080 is a double barrel fuse and most likely the equipment is setup for a single barrel. 9F61BNW402 (two per fuse) is an adaptor to convert a single barrel support or disconnector to a double barrel.

			9F62DDD080		9F62HMH080	
Percent of I_{bf}	I_{arc} Secondary	I_{arc} Primary	Total Clearing Time	Incident Energy	Total Clearing Time	Incident Energy
100%	11,322 A	394 A	6.7 Seconds	73 cal/cm²	0.2 Seconds	7.8 cal/cm²
85%	9,624 A	335 A	16 Seconds	61 cal/cm²	0.3 Seconds	11 cal/cm²

Table 5. Incident energy calculations using the time current curves of the replacement fuse.

The watts loss of the new fuse at transformer full load amps is compared with the original fuse and deemed to be within acceptable limits.

V. SUMMARY

Arc flash incident energies on the secondary of power transformers are frequently above many companies' limit for energized work (40 cal/cm^2). This forces them to require outages to perform routine task in the main switchgear. As discussed in this Tech Topic, it may be possible to reduce the incident energy by simply changing the fuse type. A detailed analysis of the system and fuses should be preformed when changing fuse rating or type [9]. Contact Mersen Electrical Services at Electricalservices.nby@mersen.com to discuss your requirements for an arc flash hazard analysis.

Calculations provided by EasyPower® software from ESA.

VI. TIME CURRENT CURVE EVALUATION FOR REPLACEMENT FUSE (FIGURE 7)

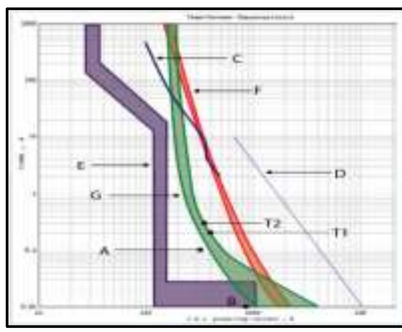

Figure 7 Time Current Curve evaluation for replacement fuse.

A. Magnetizing Inrush Current at 0.1 sec

   (8 x Transformer primary FLA)

B. Magnetizing Inrush Current at 0.01 sec

   (25 x Transformer primary FLA)

C. ANSI C57 Transformer Damage Curve shifted for phase to ground through faults
D. Cable Damage Curve
E. Largest feeder breaker time current curve
F. Original fuse curve (see section 2)
G. 9F60HMH080 (80E) time current curve.

T1.Clearing time for 100% Iarc (11,322A;0.2 seconds)

T2.Clearing time for 85% Iarc (9,624A;0.3 seconds)

VII. REFERNCES

1. Buff Book Section 10.2
2. Buff Book Section 10.8.3.3
3. IEEE Std 1584TM – 2002 IEEE Guide for Performing Arc-Flash Hazard Calculations Annex B Section 1.2
4. Mersen Advisor 111, Section P Application Info., page P17
5. UL Standard 248 Low Voltage Fuses - Part 1: General Requirements
6. Mersen Advisor 111, Section L Application Info., page P33
7. Daz J. "Coordination of Surge Arresters with Medium Voltage Current Limiting Fuses" IEEE Transaction on Industry Applications, vol 38, issue 3, 2002, pp 744-751
8. Tech Topic Selective Coordination Note 1 , Issue 1
9. Tech Topic Arc Flash Note 3: Arc Flash Hazard Analysis is Required