

# Optimizing Circuit Breaker Instantaneous Trip Settings for Selectivity and Arc Flash Performance Simultaneously

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# Optimizing Circuit Breaker Instantaneous Trip Settings for Selectivity and Arc Flash Performance Simultaneously

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**Abstract** –This paper and presentation will discuss analytical techniques and new technology that allow switchgear CBs to use sensitive instantaneous settings and maintain selectivity when using traditional electronic trips in switchgear and current limiting molded case circuit breakers, motor circuit protectors or fuses in downstream equipment. New developments in trip technology that allow systems designed with instantaneous protection while maintaining high levels of selectivity and arc flash protection are also discussed.

**Index Terms** — Arc Flash, Incident Energy, Selectivity, Instantaneous protection, Current Limiting Circuit Breakers, Current Limiting Fuses.

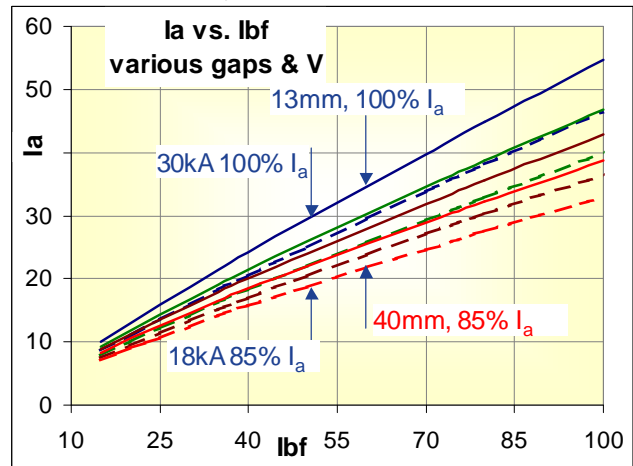
## I. INTRODUCTION

Many power distribution systems in industrial facilities consist of low voltage switchgear, connected to a transformer or a generator. The switchgear feeds motor control centers with various sized motor loads and small distribution loads. In many cases the majority of the protective devices in the motor control centers and small distribution loads are current limiting (CL) circuit breakers, motor circuit protectors or current limiting fuses. Traditional coordination studies ignore the current limiting performance of the overcurrent-protective-devices (OCPD) in the motor control centers. The use of traditional time current curves as the sole basis to assess selectivity, often results in the switchgear feeders being designed omitting instantaneous protection or implementing very high, hence insensitive, instantaneous pickup settings. Furthermore, the main circuit breaker in the switchgear often omits instantaneous protection completely, relying on short time protection to maintain selectivity above the feeder circuit breakers in the switchgear. Even when implementing Zone-Selective-Interlocking (ZSI) this method of designing a low voltage power system can result in relatively high arc flash incident energy at the main bus of major equipment. Understanding how the trip units in the switchgear circuit breakers interpret the current limiting behavior of the downstream protectors allows for more finely tuned instantaneous pickup settings. Furthermore, trip systems may be designed to optimize performance based on the expectation of current limiting behavior in downstream protectors. Modern advances in zone selective interlocking combined with the improved algorithms allows even better performance for multiple layers of large upstream overcurrent protective devices.

## II. ARCING CURRENT, SENSITIVITY AND TIME

A protective device's clearing time at expected arcing current is a key determinant in how much incident energy will result

during an arc flash event. Arc flash analysis using the IEEE 1584 recommended practice (Guide For Performing Arc Flash Incident Energy Calculations) equations shows that interrupting arcing faults in the instantaneous range, even for a large Low-Voltage-Power Circuit Breaker, allow incident energy to remain below Hazard Risk Category 2's maximum of 8 calories per square centimeter for a broad range of conditions that may be found in an industrial system.

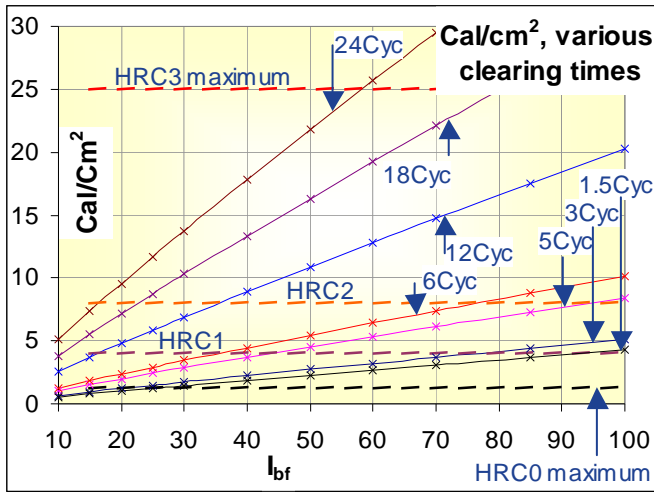


**Fig. 1** 100% and 85 Arcing Current versus time for 480V, Solidly grounded system per IEEE 1585.

Figure one (Fig. 1) demonstrates the variance that IEEE 1584 calculations define for a 480V solidly grounded system for various arcing gap assumptions. The 100% and 85% range defined in the standard predicts the variance observed by the IEEE 1584 working group for the test protocol used to derive arcing current data. This suggested variance does not take into account other variance that may be in the system due to incorrect estimates or fluctuations in system impedance, short circuit calculation errors, estimated data, the difference in the arcing gap from the IEEE 1584 recommendations or any other sources of variance. Arcing current may differ from IEEE 1584 predictions due to many factors. Fig. 1 shows that, without taking into account bolted fault current variance, the IEEE predicted variance and arc gap variance might cause almost 2:1 variation in arcing current. And variance could be in the direction of lower arcing current than predicted.

Fig. 2 demonstrates the effect of clearing time on incident energy for a fixed working distance and for a specific set of system assumptions. This demonstrates that circuit breakers may provide reasonable levels of incident energy protection as

long as they operate with clearing times of 6 cycles or less. Six cycles is a very fast short time band or instantaneous clearing.



**Fig. 2** Incident energy for a 480V, solidly grounded systems with a 32mm arcing gap and 24" working distance.

The two figures combined illustrate the importance of fast clearing and sensitive settings for overcurrent devices relied upon to provide optimal incident energy protection. Generally, to achieve protection at 4cal/cm<sup>2</sup> (HRC1 maximum) 3 cycles or faster clearing is required. However, in many power systems selectivity needs often drive circuit breaker trips toward greater insensitivity and slower operation in the circuits where faster and more sensitive protection is most needed.

### III. CURRENT LIMITING OCPD

Current limiting (CL) overcurrent protective devices (OCPD), either circuit breakers or fuses, once operating beyond their current-limiting-threshold, can have their let-through-current described in instantaneous peak current ( $I_{pk}$ ). Manufacturers publish Peak-Let-Through graphs. Either derived from the graph, or furnished directly from the manufacturer, a mathematical transfer function can be created that describes the peak let-through current in terms of the available prospective fault current. Equations 1 and 2 are examples of such functions for a molded case circuit breaker and a current limiting fuse.

$$y = a + bl + c \ln(I) + d \frac{\ln(I)}{I} \quad \text{Eq. 1}$$

Peak Let-Through current for Current Limiting Circuit Breaker

Where:

- $y$  = let-through peak current
- $a, b, c$  &  $d$  = coefficients for a particular circuit breaker.
- $I$  = prospective bolted fault current

$$y = I_{PT} \left( \frac{I_{AS}}{I_{AT}} \right)^{1/3} \quad \text{Eq. 2}$$

Peak Let-Through current for Current Limiting Fuse

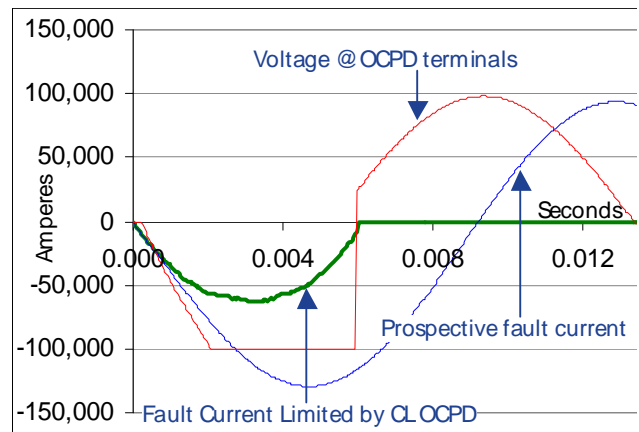
Where:

- $y$  = Peak Let-Through current at prospective bolted fault current
- $I_{PT}$  = Peak let-through current at test prospective fault current ( $I_{AT}$ )

$I_{AS}$  = Prospective current for which Peak-let-through current is desired.

$I_{AT}$  = Test prospective fault current that defines fuse let-through characteristic determined from published curve or provided by manufacturer.

The peak let-through current of an OCPD operating in its current and energy limiting range has a characteristic waveform shape typically described as a portion of a half cycle sine wave as shown in Fig 3. The wave shape has a lower peak current than the prospective and a shorter period than the full prospective half cycle fault current. Regardless of type of OCPD the limited fault current will have limited energy and limited peak current even if the wave shape is not exactly as the traditional model predicts. It is this limited characteristic waveform that can be used by an upstream trip system to differentiate a fault current being interrupted by a current limiting OCPD from an arcing or bolted fault that is not being interrupted by a fast current limiting OCPD.



**Fig. 3** Modeled peak let-through waveform for a single pole of a CL circuit breaker operating in its current limiting range.

### IV. ELECTRONIC TRIP SYSTEMS

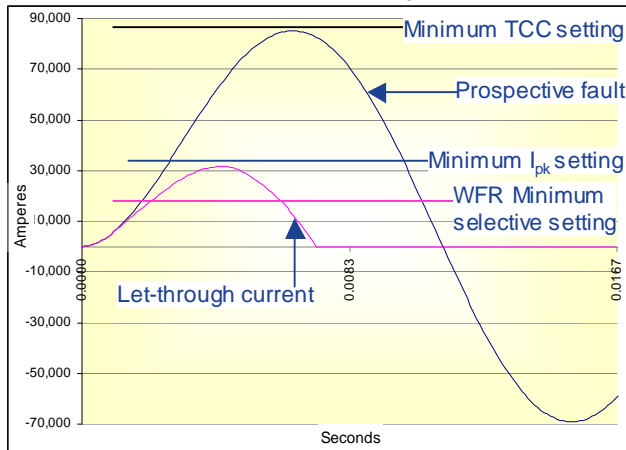
#### A. Peak Let-through selectivity method

The instantaneous algorithm in electronic trips often is a peak sensing algorithm or circuit. Though the trip is calibrated in rms amperes and the associated Trip Time Curve is drawn in rms amperes the trip operates based on instantaneous peak amperes. The conservative assumption is that the trip is calibrated to operate at 1.41 times the rms value shown on the time current curve. Hence a trip nominally set at 10,000A rms is sensitive to 14,100A peak. Allowing for a 10% tolerance the 10,000A rms setting means the trip will not actuate if the peak current is below 12,690A (10,000X1.41X0.9). Using the knowledge that the that an upstream electronic trip is sensitive to peak current will allow the circuit breaker to have its instantaneous algorithm on and set below prospective bolted fault current. The circuit breaker may achieve a significant level of selectivity due to the current-limiting action of the downstream CL OCPD, if the setting is chosen correctly based on the current limiting effect of the downstream OCPD.

#### B. Waveform recognition (WFR) selectivity method

In more advanced electronic trips an algorithm can consider a combination of peak current and time to determine if the fault

current shows the characteristic wave shape of a current and energy limiting fault current interruption. Since peak currents and time are being considered the trip may be described as capable of waveform recognition (WFR) or energy sensing. A trip able to detect that the waveform is truly energy limiting can be set more sensitively (lower pickup) than one that only considers peak current. Fig. 4 illustrates the difference between the different trip sensing methods. In Fig. 4 the line identified as "Minimum TCC setting", is the setting in peak amperes (ignoring trip sensing and processing tolerance) that a line side CB would need to be selective at the prospective fault current in peak amperes, if determined from a normal Time Current Curve (TCC) coordination study and considering DC offset. The Minimum  $I_{pk}$  setting is the setting the same trip could employ if the peak let-through of the downstream current limiting OCPD is considered. The "WFR setting" is what the trip setting at the same upstream device could be if the trip employs an advanced waveform recognition, or energy, sensing algorithm. Actual setting would vary based on the "quality" of the algorithm and the CL performance of the current limiting device.



**Fig. 4** Comparison of different selective circuit breaker settings for a specific prospective fault condition depending on trip algorithm type and coordination study assessment method

### V. DETERMINING RANGE OF FAULT CURRENTS, MINIMUM SETTING & MAXIMUM POSSIBLE SELECTIVITY

The  $I_{pk}$  based and waveform recognition based analysis requires that the fault current range over which the analysis is valid for a particular downstream OCPD be identified. The start (lower end) of the range is where the OCPD is sufficiently current limiting regardless of fault power factor or number of phases involved. For the peak method the valid threshold is where the peak let-through current will not exceed manufacturer published curves regardless if the fault is single, or 3 phase and regardless fault current asymmetry. For the waveform recognition method the valid starting point is where neither the peak let-through current exceeds published values and where at least two of the phases interrupt current in less than  $\frac{1}{2}$  cycle regardless of phases involved or fault power factor. For fuses, the published current limiting characteristic is derived from a single-phase test. For circuit breakers the curve represents the worst single phase let-through during a three-phase test. For both devices the tests are performed at low power factors in the 15-50% range. Hence, for each type of device, circuit breakers

and fuses, one of two thresholds must be derived. One threshold is used for the peak let-through method and the other for the waveform recognition method. The peak method's related threshold defines the beginning of a range. For the waveform recognition method the related threshold defines the required setting for the upstream trip.

#### A. Threshold for $I_{pk}$ based selectivity determination

The lower current limiting threshold (CLT) used for the  $I_{pk}$  method is derived the same way for both types of devices. The CLT can be derived from the published let-through curve by drawing a diagonal line on the  $I_{pk}$  let-through curve representing  $\sqrt{2}$  times the prospective fault current. The intersection of the  $\sqrt{2}$ -line and the  $I_{pk}$  let-through line is the CLT used for the  $I_{pk}$  analysis for both current limiting fuses and circuit breakers. The CLT may also be derived by setting Eq. 1 and Eq. 2 equal to  $\sqrt{2}$  times prospective rms fault current and solving for the prospective fault current. Eq. 3a-3c shows the mathematical calculation of a fuse's current limiting threshold used for the peak selectivity method, derived from Eq. 2.

$$I_{CLTpeak1} = \sqrt{\frac{I_{PT}^3}{I_{AT}^3} \frac{1}{\sqrt{2}^3}} \quad \text{Eq. 3a}$$

$$I_{CLTpeak1} = \frac{I_{PT}^{3/2}}{I_{AT}^{1/2} (\sqrt{2}^3)^{1/2}} \quad \text{Eq. 3b}$$

$$I_{CLTpeak1} = .595 \times \frac{I_{PT}^{3/2}}{I_{AT}^{1/2}} \quad \text{Eq. 3c}$$

Where:

$I_{CLTpeak1}$  = Lowest prospective rms fault current for which the peak let-through selectivity analysis is applicable for the specific downstream fuse.

$I_{AT}$  = Test prospective fault current that defines fuse let-through characteristic determined from published curve or provided by manufacturer.

$I_{PT}$  = Peak let-through current at test prospective fault current ( $I_{AT}$ )

#### B. Threshold for Waveform recognition (WFR) based selectivity determination

For the waveform recognition analysis a more conservative higher threshold is required to ensure that the current interruption is fully current and energy limiting on all phases regardless of fault asymmetry or number of phases involved. For fuses the threshold may be derived by multiplying the lower threshold determined for the peak method by 140%. Eq. 4 shows the calculation of the higher current limiting threshold required for the waveform recognition algorithm.

$$I_{CLTpeak2} = 1.4 \times .595 \times \frac{I_{PT}^{3/2}}{I_{AT}^{1/2}} \quad \text{Eq. 4}$$

Where:

$I_{CLTpeak2}$  = Lowest prospective rms fault current for which the waveform recognition selectivity analysis is applicable for the specific downstream fuse.

For current limiting circuit breakers the manufacturer must provide the higher threshold required for valid analysis. The manufacturer may provide threshold values based on testing, inspection of fault interruption oscillographic data, or both, as needed to match the trip algorithm used in the upstream circuit breaker trip. These values would be manufacturer and line side circuit breaker algorithm specific.

C. Maximum selectivity and setting variation

Fig. 5 graphically demonstrates the current limiting thresholds used for fuses. Note that the higher threshold for fuses may be calculated but for circuit breakers must be provided by the manufacturer. The three current limiting thresholds can be seen more easily on the fuse let-through curve. The left most (of the graph on Fig 5) is the published single-phase low power factor threshold, the middle threshold is used for the peak analysis and the one further to the right is used for the waveform recognition based analysis.

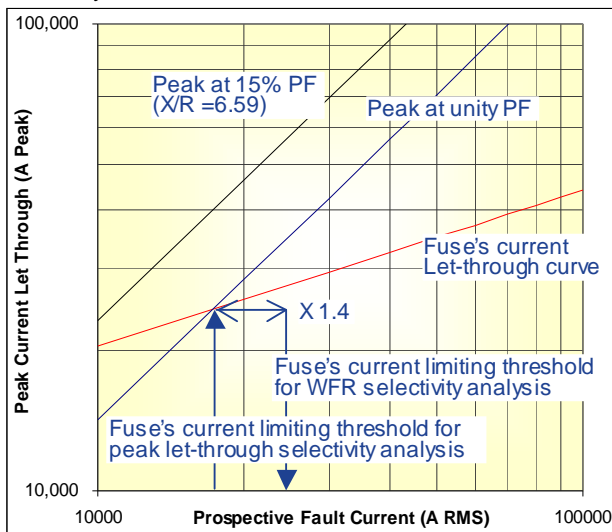


Fig. 5 Fuse I peak let-through functions and derivations of current limiting threshold used for selectivity analysis

The setting for the upstream trip derived via the peak method must be increased as determined by the  $I_{pk}$  let-through transfer function as the available fault current increases. Unfortunately, this reduces protection sensitivity as prospective fault current increases. The setting derived for the waveform recognition method will be selective for the range of fault current up to the upstream circuit breaker's withstand or short circuit rating, depending on circuit breaker capabilities.

Fig. 6 shows the optimized selective settings for a 480V switchgear feeder feeding a motor control center (MCC) with Motor Circuit Protectors (MCP) no larger than 30 amperes. The vertical line is the nominal setting, the band at the bottom of the vertical line accounts for trip tolerance. Bolted fault current at the MCC available from the switchgear is 55kA. Motor contribution at the MCC is 4kA. The plot shows the current limiting Peak Let-Through curve for the MCP. The 100 and 85% arcing currents, based on IEEE 1584 calculations for a 25mm gap, are shown. As can be seen from Fig. 6 both methods yield switchgear settings that should allow the feeder to trip instantaneously for the expected arcing current at the MCC main bus, while maintaining selectivity with a fault below the 30A MCP.

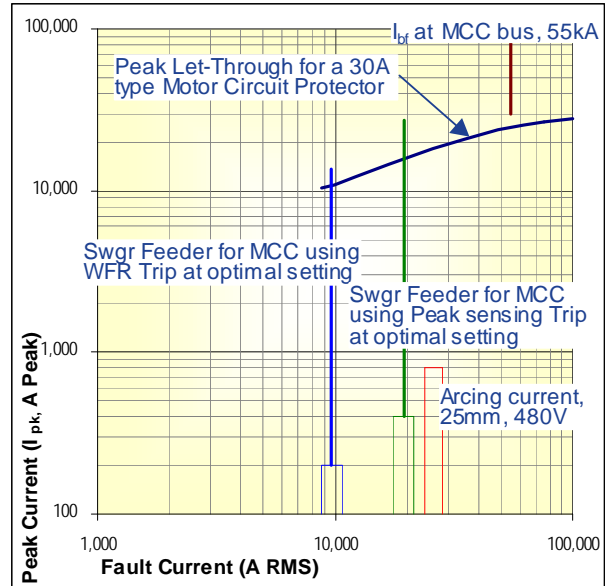


Fig. 6 Peak and WFR settings above a 30A MCP with 55kA available, showing arcing current for 25mm gap at 55kA  $I_{bf}$

Fig. 7 shows the same analysis for a 250A MCP or current limiting molded case circuit breaker. To be selective with the larger device the switchgear feeder setting must be raised such that it overlaps the expected arcing current. If this setting is used arc fault protection timing must be determined from the short time delay band, not the instantaneous clearing. However, in both cases the WFR setting is selective and allows protection at settings significantly lower than the arcing fault level thereby clearing instantaneously for expected arcing currents. In this case the incident energy at 18" operating distance from the MCC bus is expected to be 5.4 cal/cm<sup>2</sup> on this 480/277V system.

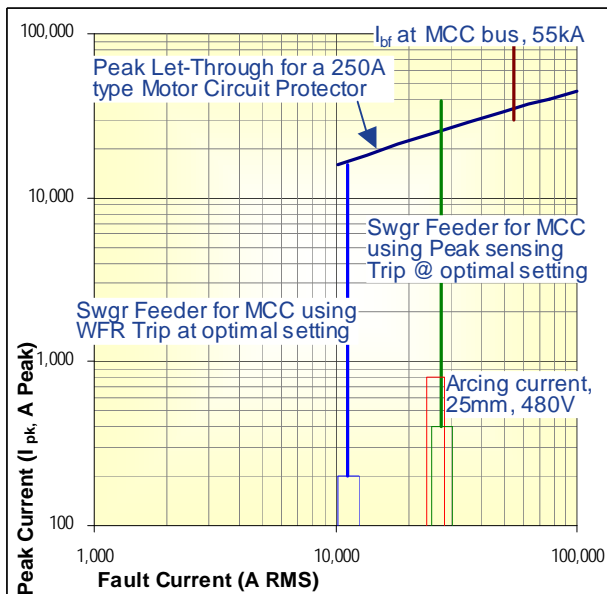
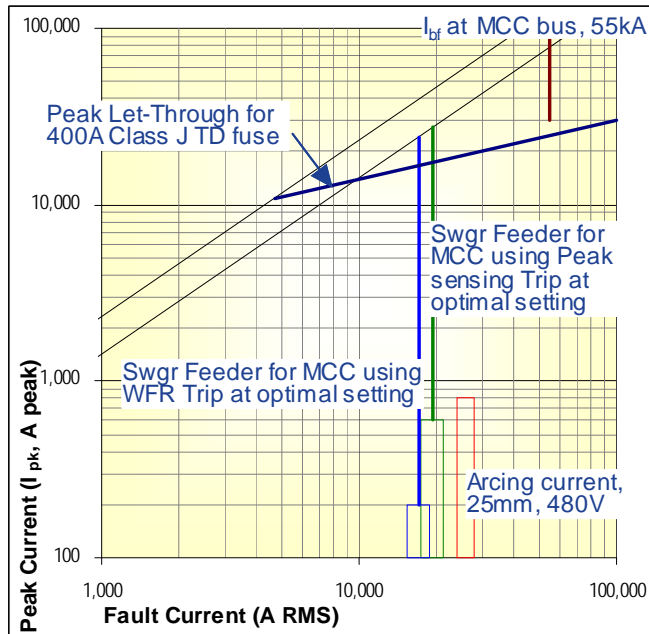


Fig. 7 Peak and WFR settings above a 250A MCP with 55kA available, showing arcing current for 25mm gap at 55kA  $I_{bf}$



Fig. 8 demonstrates similar analysis for a 400A Class J time delay fuse at 480V. The fuse's low current limiting threshold allows selective settings while maintaining the upstream MCC feeder sensitive enough to trip on expected arcing fault current on the MCC bus. It should be noted that the settings are suitable for application at 600V when derived for fuses as all published current limiting data for fuses is typically at 600V.



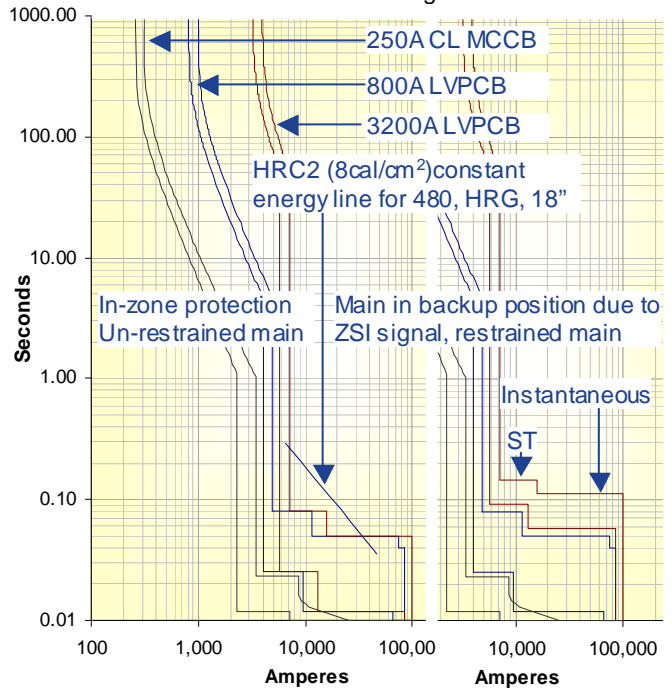
**Fig. 8** Peak and WFR settings above a 400A Class J Time Delay fuse with 55kA available, showing arcing current for 25mm gap at 55kA  $I_{br}$

A comment on motor contribution currents: When analyzing a system for selectivity and arc flash hazard it is important to properly account for motor contribution current. For selectivity analysis only the current that flows through the upstream circuit breaker should be considered. For arc flash hazard analysis on a bus all possible currents should be considered. During a fault downstream of the feeder the feeder will see the motor contribution from its own bus that its line side main will not. That current will help to accelerate the operation of the downstream overcurrent device and, hence, it makes the selectivity analysis conservative.

## VI. ADVANCED TRIP ALGORITHMS AND ZONE SELECTIVE INTERLOCKING (ZSI)

An advanced instantaneous trip algorithm may provide sufficient time for ZSI to function in the instantaneous range. This capability allows the benefits of a feeder's sensitive instantaneous pickup to extend to a tie and main circuit breaker. The combination of the capabilities can allow main circuit breakers to provide main bus protection at sensitive instantaneous pickup settings while providing selectivity up to high fault currents such as 100kA. Fig. 9 shows a pair of circuit breakers such as a main and a feeder above a CL molded case circuit breaker (MCCB) that are set to be selective up to 65kA at feeder, and 85kA at the main circuit breaker, while providing instantaneous protection at a nominal 10,400A at the feeder and 14,400A at the main circuit breaker. Arcing current for a 32mm gap at 480V is estimated at 24-20.5kA per IEEE 1584

recommended practice. The diagonal constant energy line in Fig. 9 demonstrates that both the feeder and the main are able to protect allowing less than 8cal/cm<sup>2</sup> for a broad available bolted fault range, while maintaining selectivity via the Instantaneous Zone Selective Interlocking scheme.



**Fig. 9** Three circuit breakers (250A MCCB, 800A LVPCB & 3200A LVPCB) set selectively up to 65kA & 85kA - Instantaneous clearing for low in-zone fault currents.

## VII. CONCLUSIONS & SUMMARY

The combination of current limiting branch circuit protectors, fuses or circuit breakers, and line side circuit breakers with adjustable electronic trips may yield instantaneous trip pickup settings that provide both the required selectivity and desirable arc flash hazard mitigation if the proper coordination analysis techniques are used. Significant improvement may be achieved using traditional electronic trips and even greater improvements may be possible using more modern advanced waveform recognition or energy sensing algorithms.

Either trip sensing technology requires that traditional time current curve analysis be supplanted with more sophisticated methods that recognize the downstream device's current limiting characteristics and the upstream device's exact trip algorithm operating characteristics. Some of the analysis may be performed with published information and other may require cooperation with the upstream trip device manufacturer to optimize settings.

Advances in Zone Selective Interlocking, in conjunction with the newer advanced sophisticated instantaneous algorithms can extend the benefits of the sensitive instantaneous pickup to system source circuit breakers, increasing the probability that large main circuit breakers will also provide instantaneous protection for their main buses and lowering arc flash hazard to more acceptable levels where high arc flash hazard is traditionally expected.

Table 1 lists typical trip setting settings for two types of trips above various current limiting over-current devices that may be found in a motor control center. One column identifies the settings that a trip with waveform capture capability would use, the 2<sup>nd</sup> column identifies the setting that a peak sensing trip would need above the same devices to achieve selectivity up to 55kA. Exact settings would vary based on the exact manufacturer and model of the downstream device, and, possibly, the upstream device as well.

**Table 1**  
**Typical "Minimum Instantaneous Thresholds" for**  
**upstream feeders above CL OCPDs (3)**

CL OCPD Device Type	CL OCPD Device Size	WFR Trip	Peak Sensing
		Min. Setting @ Feeder Trip (1) (2)	Min setting for 55kA Selectivity
MCP with current limiters	3A	310 A	1,820 A
MCP with current limiters	7A	310 A	1,820 A
MCP with current limiters	15A	840 A	3,570 A
MCP with current limiters	30A	1,770 A	5,800 A
MCP with current limiters	50A	3,800 A	9,740 A
MCP with current limiters	100A	7,210 A	14,770 A
MCP with current limiters	150A	10,750 A	19,200 A
Molded Case MCP	150AF	9,600 A	27,610 A
Molded Case MCP	250AF	11,200 A	27,640 A
Lighting CL MCCB	100AF	6,540 A	16,000 A
Molded Case MCB	150AF	9,600 A	27,610 A
Molded Case MCB	250AF	9,900 A	22,407 A
Molded Case MCB	600AF	20,350 A	33,810 A
Class J, time delay	30A	970 A	3,090 A
Class J, time delay	100A	3,810 A	7,730 A
Class J, time delay	200A	7,590 A	12,240 A
Class J, time delay	400A	15,050 A	19,320 A
Class J, time delay	600A	26,730 A	28,330 A
Class RK1, time delay	30A	1,030 A	3,220 A
Class RK1, time delay	100A	4,300 A	8,370 A
Class RK1, time delay	200A	9,450 A	14,170 A
Class RK1, time delay	400A	18,970 A	22,540 A
Class RK1, time delay	600A	32,380 A	32,190 A
Class RK5, time delay	30A	2,900 A	6,440 A
Class RK5, time delay	100A	8,820 A	13,520 A
Class RK5, time delay	200A	15,050 A	19,320 A
Class RK5, time delay	400A	34,340 A	33,480 A
Class RK5, time delay	600A	57,120 A	47,000 A

**Notes:** (1) Selectivity will range up to the short circuit rating of the lowest rated device in pair, or the withstand of the line side device, whichever is lowest. (2) Minimum setting assumes 10% tolerance. Not all trips will be able to provide exact setting, next higher setting should be used. (3) Settings above circuit breakers applicable at 480V & below, settings above fused devices applicable at 600V & below.

**VIII. ACKNOWLEDGEMENT**

The authors wish to thank Miss Cindy Cline from Ferraz Shawmut for her generous assistance with fuse application.

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**X. VITAE**

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