Presenting IEEE 37.48.1 - 2002

Panel Members:
Frank J. Muench, Cooper Power Systems, Member IEEE
John S. Schaffer, G&W Electric, Senior Member IEEE
Mark W. Stavnes, S & C Electric Co., Member IEEE
John G. Leach, Hi-Tech Fuses, Inc., Senior Member IEEE

Introduction & Background

Frank J. Muench, Cooper Power Systems

- This portion of the presentation covers:
  - The need for the standard
  - How the standard differs from others covering these products
  - The key areas of the standard

Need for the Standard

- CL Fuse do things no other device can
  - Limit damage to the system (I^2t control)
  - Limit magnetic damage (Reduce Peak I)
    - Upstream transformers/breakers
    - Cables & connections
  - Improve reliability
    - Support voltage through peak arc voltage
    - Minimize system area affected (I^2t coordination)

Need for the Standard

- To take advantage of CL Fuses one must understand
  - How the fuses work
  - The conventions used in rating fuses
  - Application Guidelines
  - Coordination Guidelines

Survey showed that users do not have this understanding

Need for the Standard

- Need found during a survey of need for changes to add full range fuse criteria to definition, testing & application standards
- Survey submitted through EEI targeting CL fuse specifiers
- Multiple choice questions, describe users and then check understanding
- All user types - typically less than 50% could answer questions correctly

Typical Question

For a back-up Current Limiting Fuse, what is your understanding of the minimum current the fuse is capable of interrupting:

( ) Equal to the rated continuous current

( ) 2 to 3 the rated continuous current

( ) Current which melts the fuse in 1 hr. - room temperature

( ) Current which melts the fuse in 1 hr. - any temperature

( ) Any current that melts the element

(X) Current specified by the manufacturer & marked on the fuse

( ) Other

96 Answered question - 15 correctly

Need for the Standard

- Cause for concern: Failure of the fuse can result if it is exposed to currents less then its minimum interrupting current
- The HV Fuse Subcommittee felt the best way to deal with was to create a teaching document. If one knows how the fuse works & how its rated, the reasons for the application and coordination rules can be understood, and followed.

How Standard Differs

- Part of a family
  - C37.40 - Definitions
  - C37.41 - Testing
  - C37.42-47 - Ratings
  - C37.48 Application guide
- None of these documents teach
- This standard teaches & provides insight into how, why the fuses work and how to use them

Key Areas of Standard

- Follows IEEE guidelines
  - Scope
  - References
  - Fuse Operation and Theory
  - C-L Fuse Type, classes & definitions
  - Application considerations
  - Fuse Coordination
  - Bibliography on C-L fuse design and use

Summary of Need

As new engineers become responsible for using CL fuses, presenting knowledge developed in the past is critical.

This document captures this information and presents it in an organized and readable manner (for an engineer), keeping it accessible.

The bibliography adds references for anyone wishing to delve into CL fuses.

CL Fuse Operation & Theory

John S. Schaffer, G&W Electric Co.

- This portion of the presentation covers:
  - Time and Current Relationships
  - Current Limitation or Not – what it means
  - Circuit Interruption & Recovery
    - CL Fuses
    - Non-CL Fuses
  - Fuse Construction & Operation

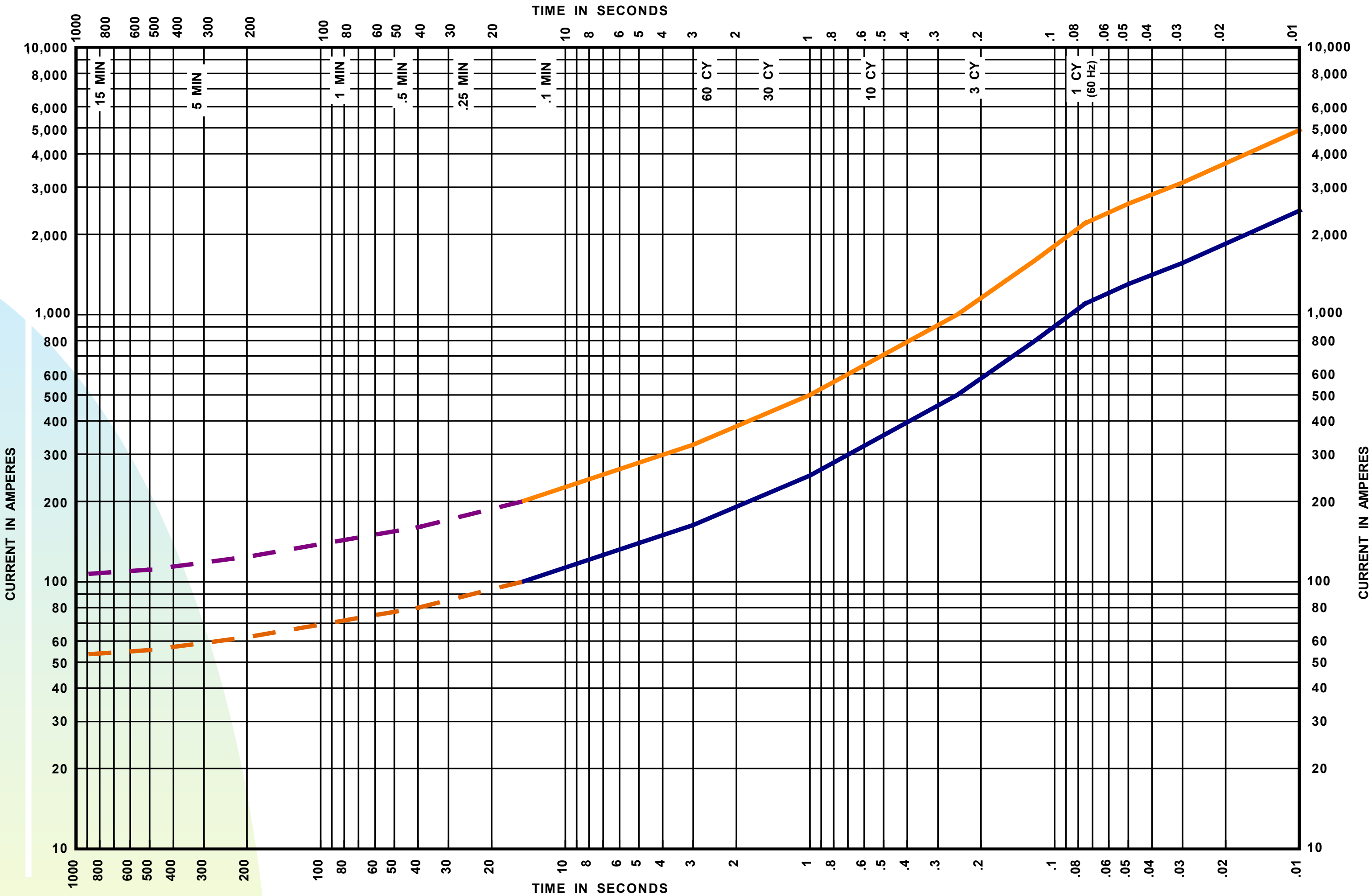
Time & Current Relationships
- Fuse Operation is a Thermal Process

- STEADY STATE - Energy input due to heating of the element equals heat dissipation through the fuse body and connection points. Thermal equilibrium is reached.
- INTERRUPT DUTY – Energy input exceeds the fuse's ability to dissipate heat. This results in melting of the fuse element.

Time & Current Relationships

- Longer times defined by Time Current Characteristic (TCC) Curves.
  - Minimum Melting
  - Total Clearing
- Curves typically start at .01S (10mS) and end at 1000S.
  - 8.3mS is ½ cycle @ 60hZ,
  - 10mS is ½ cycle @ 50hZ.

TCC Curve



Presented at the 2003 IEEE/PES T&D Conference and Exposition, Dallas,TX

IEEE Switchgear Committee WG on Full Range Fuses

Time & Current Relationships

- Higher magnitude fault currents result in a faster melt, and permit little cooling of the element.
- Characteristics are related more closely to the fuse melting I^2t.
- These shorter term relationships [below .01 seconds] result in the Let-Through Curve for Current-Limiting Fuses.

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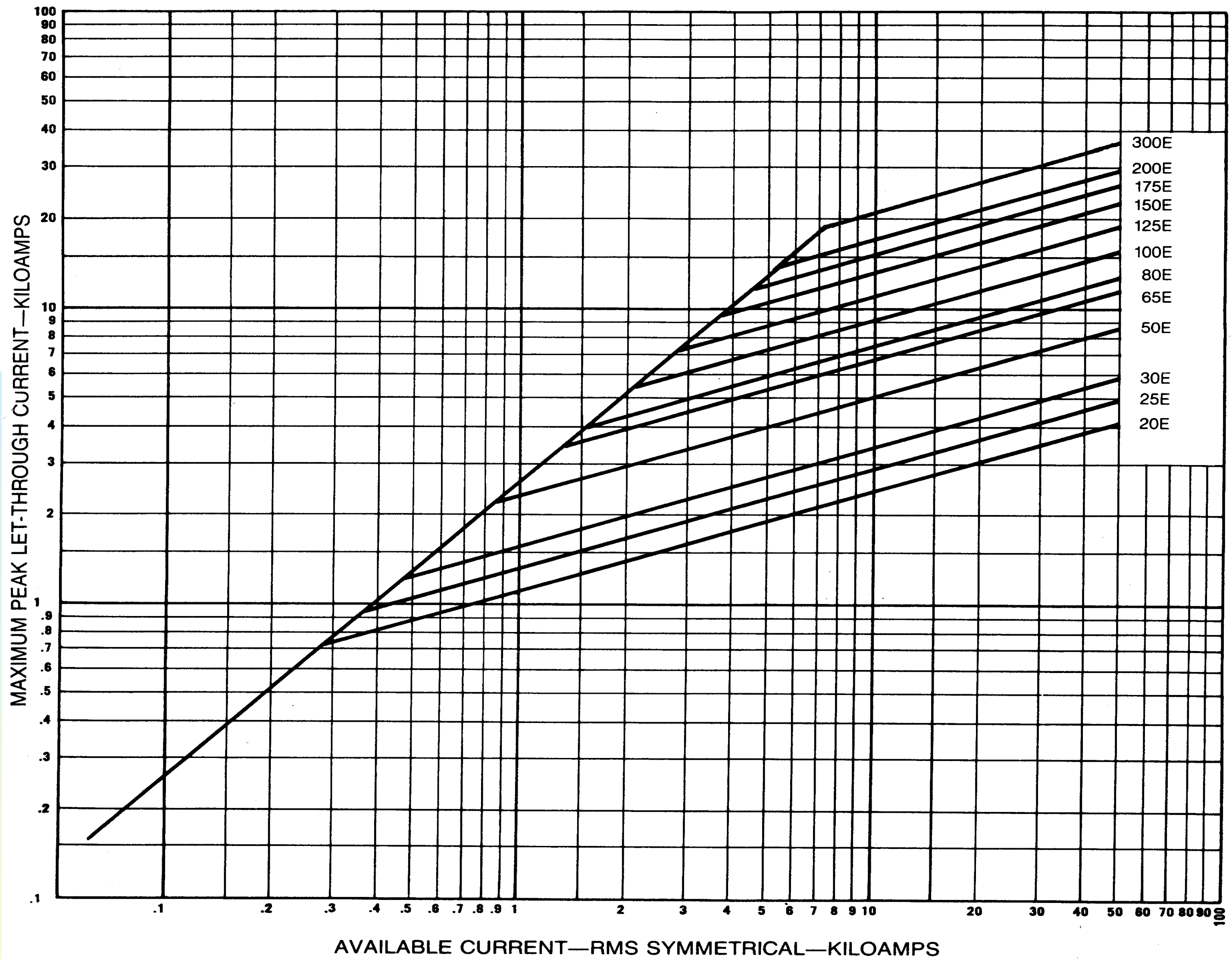
Current Limiting Fuse Let-through Characteristics



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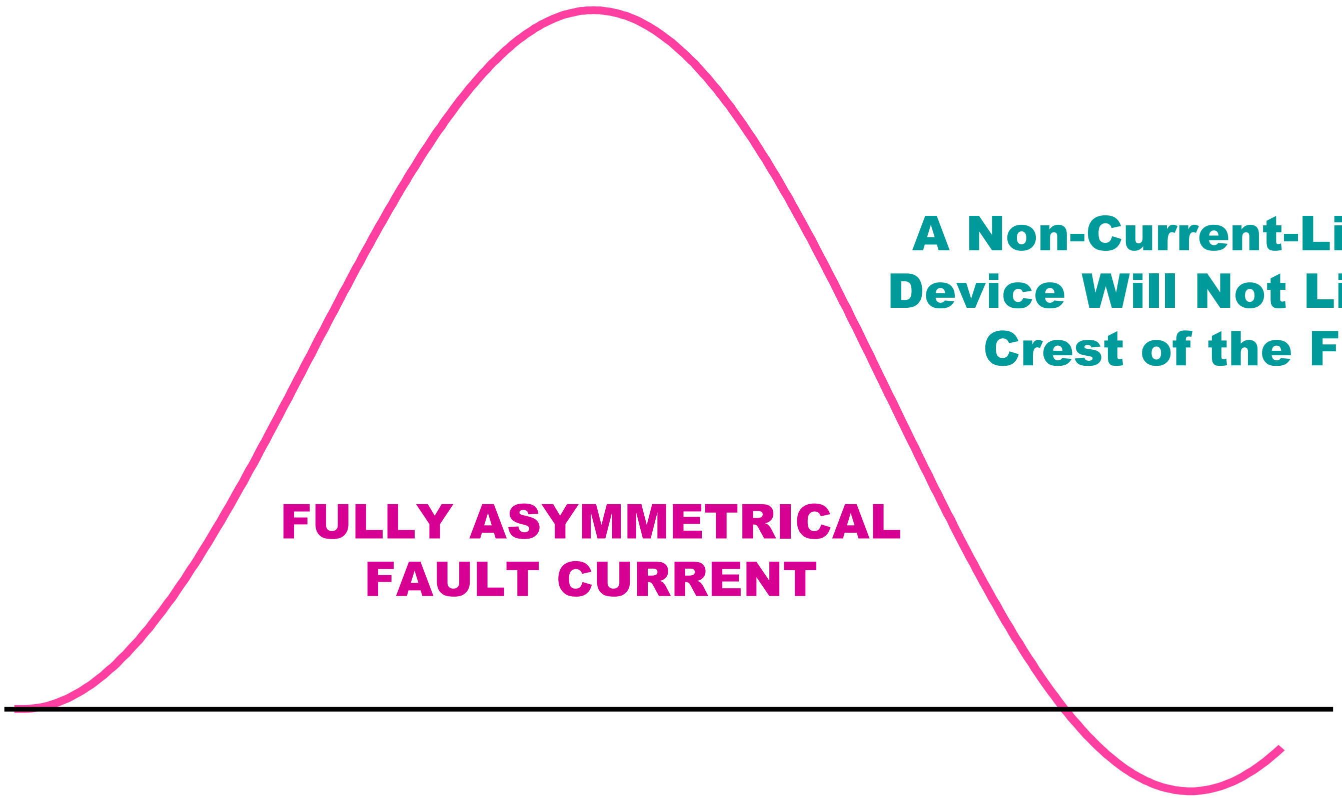
OPERATING CHARACTERISTICS

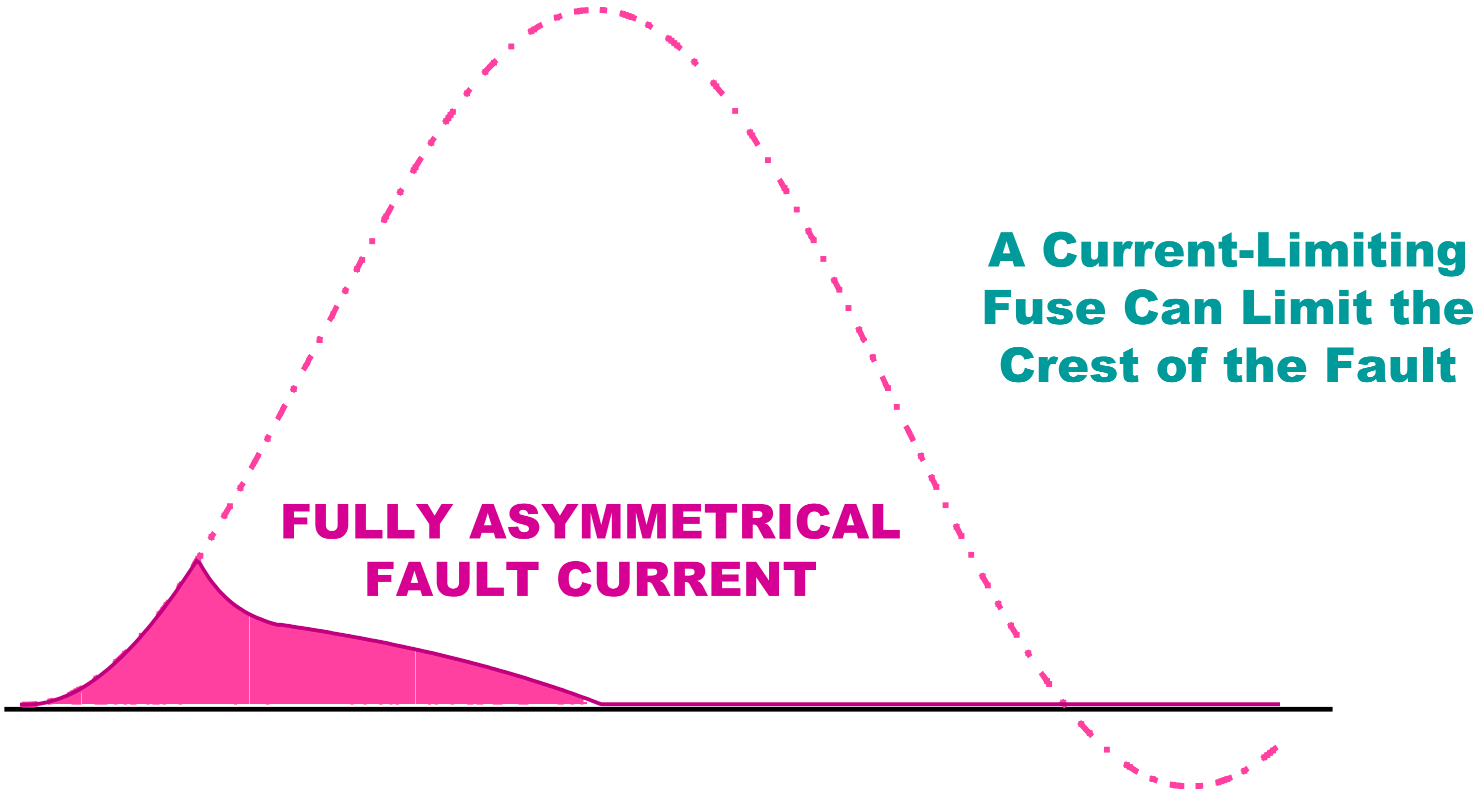
- All fuses carry continuous currents.
- They melt to initiate interruption of a fault.
- There are substantial differences in the arcing and interrupting characteristics of CL Fuses and Non-CL types.

Current Limitation or Not
- What Current Limitation Means



A Non-Current-Limiting Device Will Not Limit the Crest of the Fault

Current Limitation or Not
- What Current Limitation Means



Current Limitation or Not

Non-Current-Limiting Fuses:

- Expulsion (Power & Distribution Cutouts)
- Vacuum
- SF_6
- Oil Fuse Cutout
- Liquid Fuses

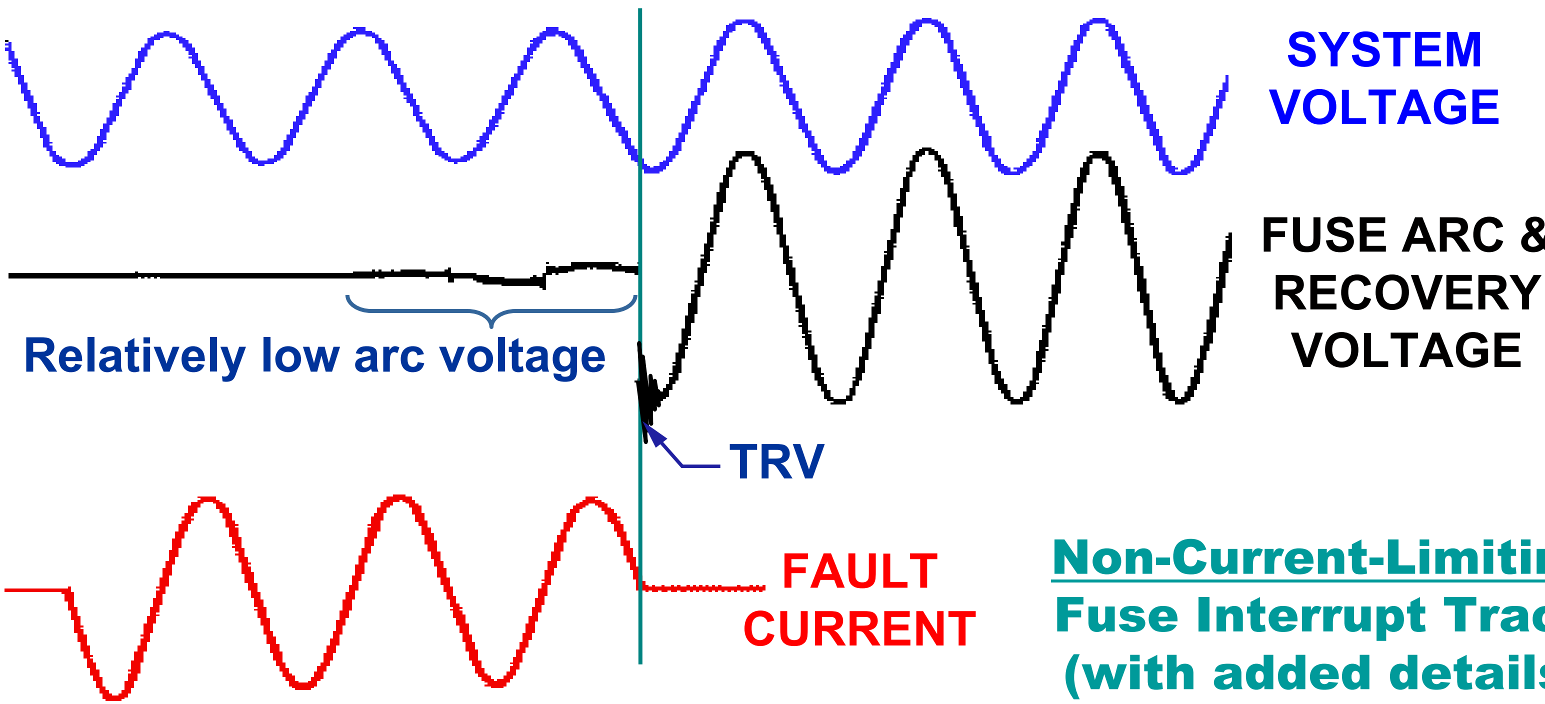
Current-Limiting Fuses:

- Traditional CL Fuse Types (Power & Distribution)
- Commutating or Triggered Current Limiters

Operating Characteristics

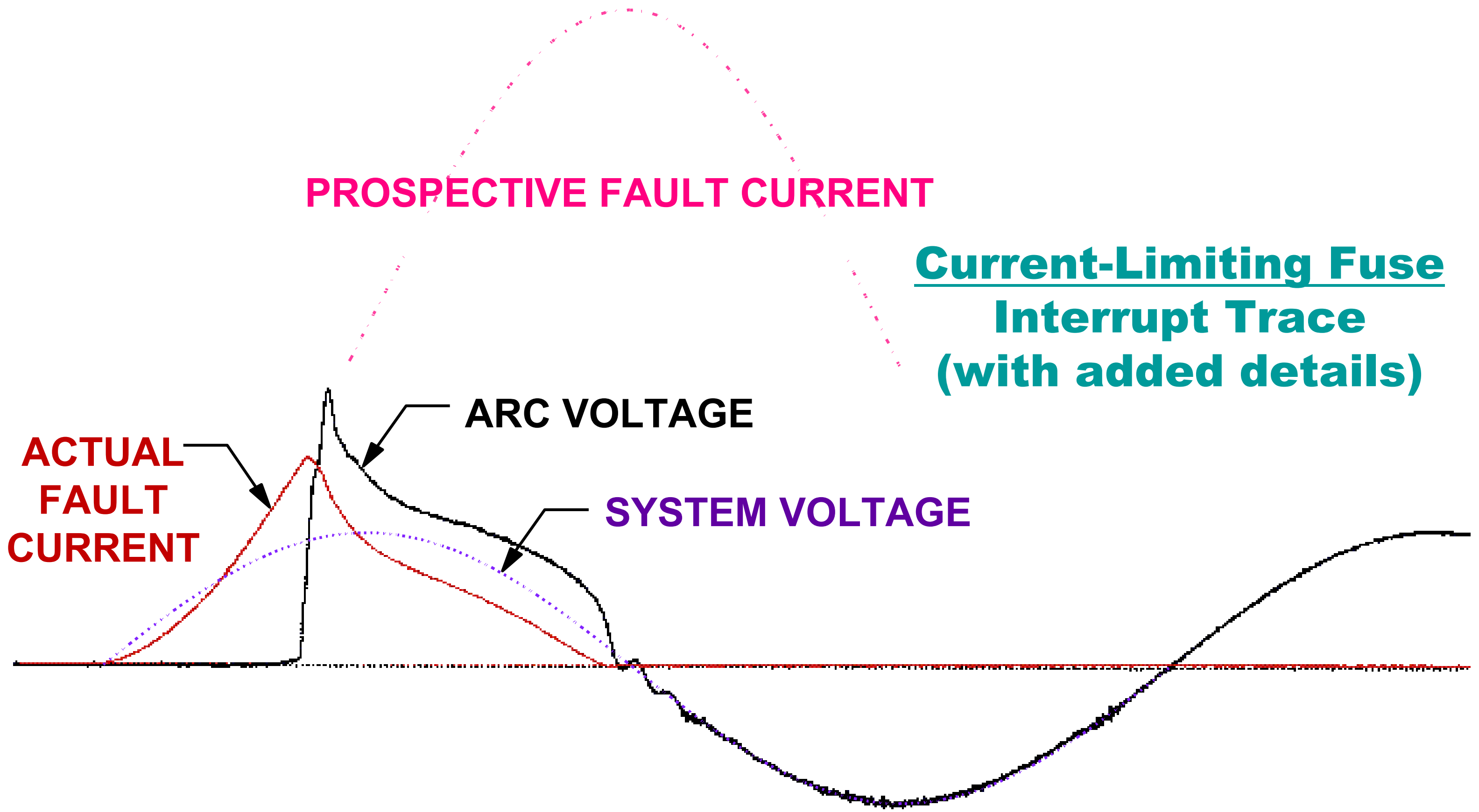
FUSE CHARACTERISTIC	NON-CURRENT-LIMITING	CURRENT-LIMITING
Arc Voltage	Lower	Higher
Circuit Modifying	No	Yes – adds resistance in the clearing process
Current Zero Shifting	No	Yes
Max. Interrupting Current	Lower	Higher
Let-through Current	Full Available Crest	Peak is Limited
Recovery Voltage	Transient – up to 2 times power frequency crest	Equal to the power frequency crest
Operating Losses	Low	Higher
Continuous Current Ratings	Higher	Lower for std. CL Types Higher for Commutating Current Limiters & Triggered Fuses.

Current Limitation or Not
- How the interrupt traces appear



Non-Current-Limiting Fuse Interrupt Trace (with added details)

Current Limitation or Not
- How the interrupt traces appear



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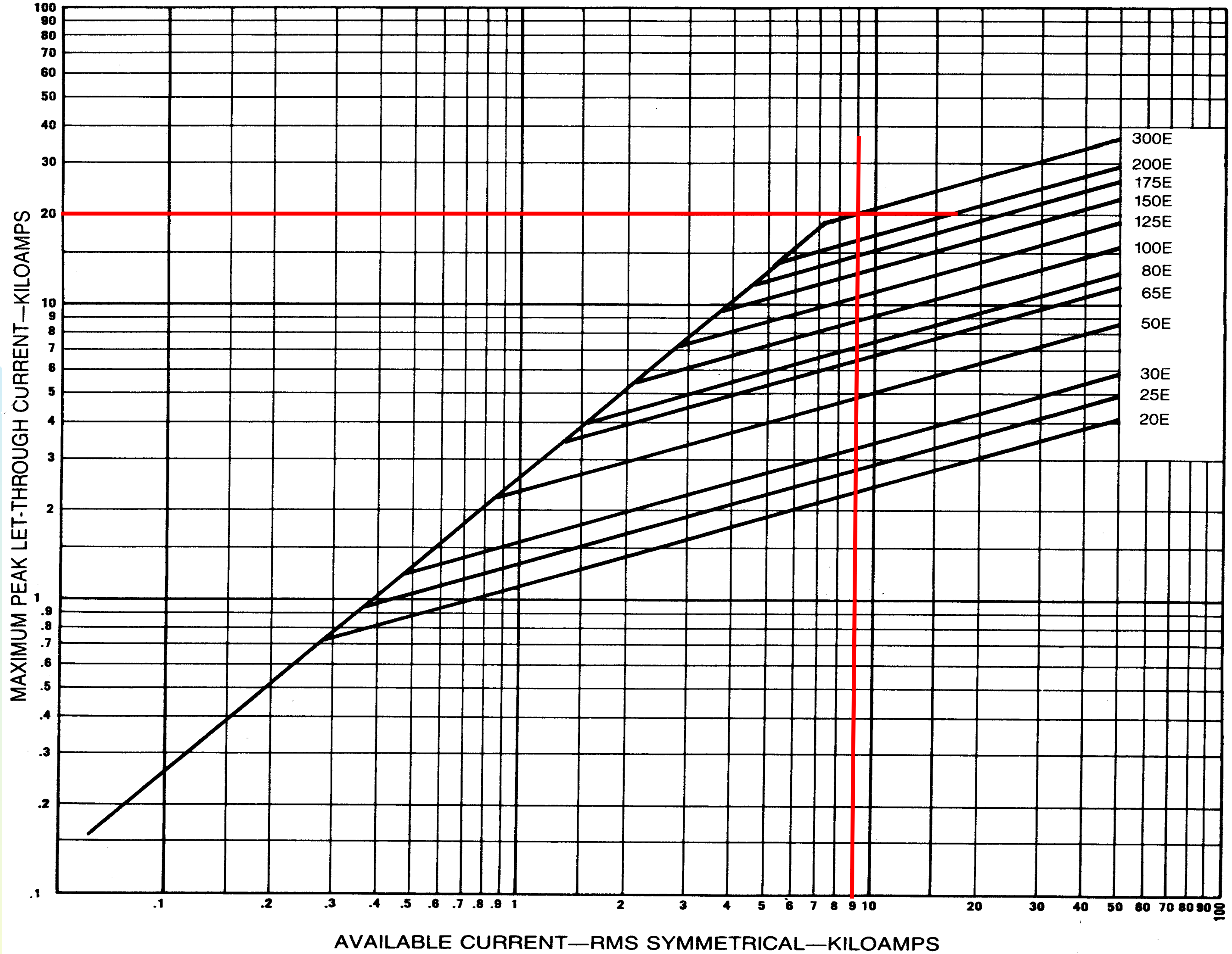
Current Limiting Fuse Let-through Characteristics



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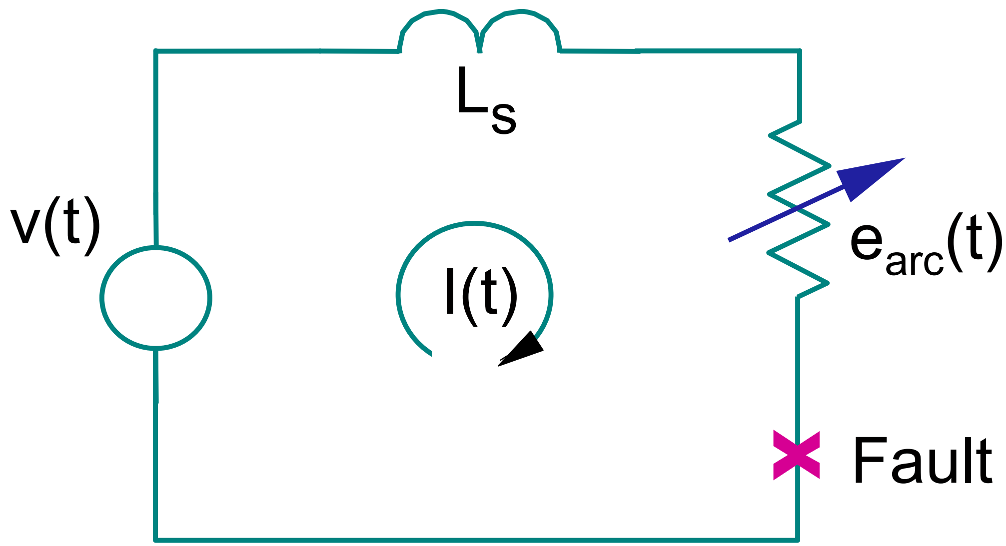
CIRCUIT INTERRUPTION & RECOVERY

- Note, for this example, a 9kA rms, sym. prospective fault yields a peak of 20kA instantaneous amperes.
- The instantaneous crest of a symmetrical fault is 1.414 times the rms, symmetrical value.
- The instantaneous crest of a fully asymmetrical fault may be double that, or 2.8 times the rms, sym. value, depending on circuit X/R relationships.

CIRCUIT INTERRUPTION & RECOVERY



$$v(t) - e_{arc}(t) = L\, di/dt$$

$$i(t) = 1/L \int [v(t) - e_{arc}(t)]\, dt$$

CIRCUIT INTERRUPTION & RECOVERY

$$v(t) - e_{arc}(t) = L\, di/dt$$

$$i(t) = 1/L \int [v(t) - e_{arc}(t)]\, dt$$

- Current is Proportional to the difference in areas under the voltage traces.
- A higher source voltage yields a higher fault.
- A higher arc voltage sustained over time will result in greater limitation of that fault.
- Current is inversely proportional to the inductance.

CIRCUIT INTERRUPTION & RECOVERY

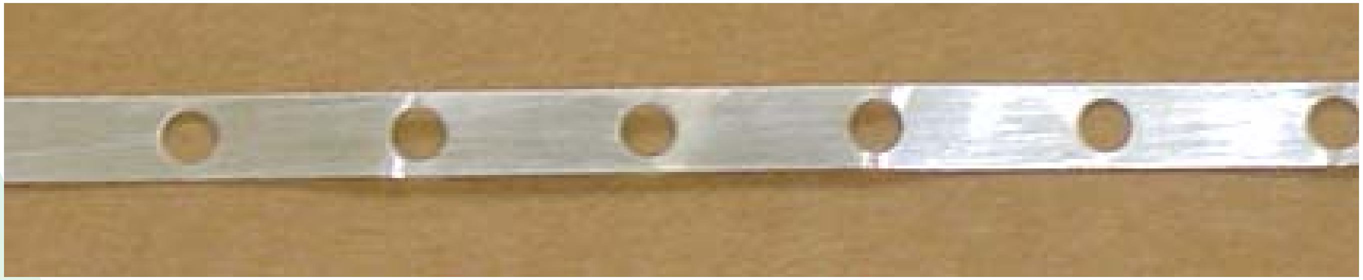
- Fuse arc voltage must exceed the system voltage for current limitation to occur.
- Non-CL Fuses yield low arc voltages. Arc energy is therefore also low. This yields a more rapid deionization of the arc zone during clearing, at a natural current-zero.
- The low arc voltage of Non-CL Fuses does not appreciably affect the circuit characteristics.
- The point of extinction is commonly near a voltage maximum, resulting in a substantial TRV.

CIRCUIT INTERRUPTION & RECOVERY

- CL Fuses yield high arc voltages. Arc energy is substantial.
- System inductances force this higher arc voltage and sustain the arc.
- The fuse absorbs much of the energy stored in these inductances.
- The fuse adds a high resistance to the circuit causing a shift of the current-zero.
- Clearing is near the voltage-zero, which now has also become the modified current-zero.

FUSE CONSTRUCTION & OPERATION

- CURRENT-LIMITING FUSES
  - High arc voltages are produced by melting and arcing at multiple locations.



  - Constriction & cooling of the arc raises the arc voltage.
  - Silica Sand is the typical arc & energy absorption media during interruption.

FUSE CONSTRUCTION & OPERATION

- CURRENT-LIMITING FUSES
  - Overvoltages are limited by standards and controlled by design.
  - Fuse Voltage Rating must be coordinated with system voltage.
  - Never use an underrated fuse.
  - Also, don’t use a 15kV fuse on a 5kV circuit.

FUSE CONSTRUCTION & OPERATION

- CURRENT-LIMITING FUSES
  - Low Current Interrupting Duty
    - This is an area of difficulty for CL Fuses
    - Many have minimum interrupt ratings above their continuous current ratings.
    - Classifications discussed later
  - Low Current Design Considerations
    - Low current series elements
    - Parallel elements
    - Other techniques

FUSE CONSTRUCTION & OPERATION

- CURRENT-LIMITING FUSES
  - Other CL Fuse Types
    - Commutating, Triggered or Electronically actuated current limiters
      - Some capable of very high continuous currents
      - Use alternate main current path
  - Indicating Fuses
    - Various techniques
      - Visual Indication
      - Some provide a striker for alternate tripping capabilities.

FUSE CONSTRUCTION & OPERATION

- NON-CURRENT-LIMITING FUSES
  - Wide variety of fuse types and interruption techniques.
  - Specifics of these are covered in the tutorial and will not be reviewed here.

CL Fuse Types, Classes & Definitions

Mark W. Stavnes, S & C Electric Co.

- When using CL Fuses, it is critical to apply the fuses properly and consider the following:
  - The fuse class
  - The fuse type
  - The fuse ratings

Fuse Class (4.2)

- Determined by where fuse is to be used on the utility system
- Different duty according to its use in relation to the substation
- There are two classes – Power Class and Distribution Class
- Each class has different test requirements to reflect the different duty

Power Class CL Fuses

- Designed and tested to allow use on feeders and locations in or close to the substation.
  - Locations provide little impedance in event of a fault.
  - Impedance is mainly from inductance of transformer, thus low resistance
  - Low power factor, high X/R ratio

Distribution Class CL Fuses

- Designed and tested to allow use in locations which are some distance from the substation
  - Cable resistance results in a reduced X/R ratio
  - Less stress on the fuse when it interrupts the circuit

Interrupting the Circuit

- High inductive reactance to resistance ratio (X/R) circuit is difficult for fuse to interrupt
  - Current and voltage are out of phase
  - Current zero occurs close to the voltage peak
- CL fuse inserts a dynamically increasing resistance which lowers the X/R

Testing Requirements

- Power class fuses are tested on circuits with higher X/R ratio to reflect the more severe duty from application in or near the substation.

Fuse Type (4.3)

- There are three basic types of CL fuses
  - Back-Up fuses
  - General-purpose fuses
  - Full-range fuses

Back-up CL Fuses

- Can interrupt any current between its rated minimum interrupting current and its rated maximum interrupting current
  - Lower currents can lead to the fuse not successfully interrupting the circuit
  - Limited in application
  - Often used in series with another interrupting device

General Purpose Fuses

- Can interrupt any fault current between a current that will cause the fuse to melt in not less than 1 hour and its rated maximum interrupting current
  - Typically applied for transformer through-fault protection
  - Must assure current between rated continuous and 1 hour are not seen
  - Ambient temperature must be considered

Full-Range Fuses

- Can interrupt any continuous current between the minimum current that can cause melting of the ribbon, at the maximum application temperature, and its rated maximum interrupting current
  - Does not require another device to protect against overloads or high-impedance faults
  - Does require the maximum application temperature to be maintained

Current Rating Conventions (4.4)

- Rated Continuous Current
  - Based on the fuse operating at an ambient temperature of 40°C without reaching temperatures that would cause damage
- "C", "E", and "R" Rating Designations
  - Link melting time-current-characteristics to the Rated Continuous Current rating
  - Were intended to provide some measure of fuse interchangeability

Current Rating Conventions (4.4)

- Rating fuses in enclosures
  - Internal elevated temperatures can reduce its melting current
  - Temperature surrounding the fuse becomes the reference ambient
- Outdoor back-up fuses
  - Given same continuous current rating as the largest fuse link that can be used in the series connected fuse

CL Fuse Applications

Frank J. Muench, Cooper Power Systems

- CL Fuses must do the following
  - Carry load currents (steady state)
  - Withstand normal transients (temporary)
  - Melt on excessive currents (faults)
  - Interrupt the circuit when they melt
- In doing this they
  - Allow normal loading of equipment/systems
  - Protect equipment & system
  - Improve power quality

Equipment CL Fuses Protect

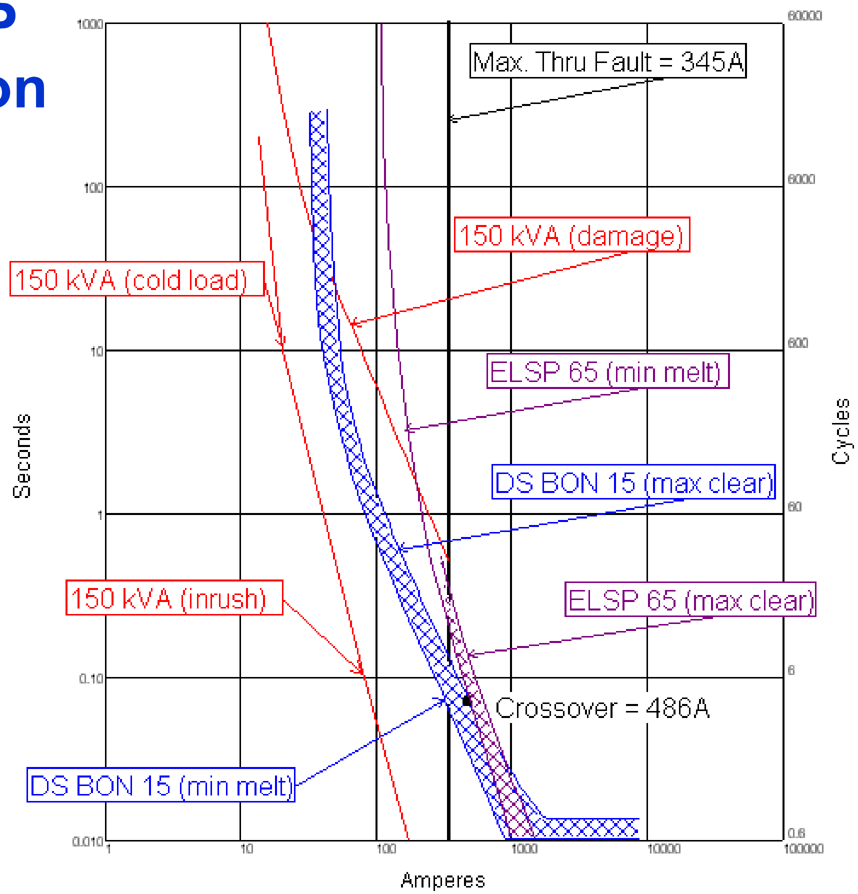
- Transformers
- Feeders and sections of the system
- Capacitors
- Potential Transformers
- Motors and Circuits with Motors

Transformer Applications

- Inrush conditions - avoid damage with fuse selection .01 s melt I vs 25*Load I
- Pick-up Situations - avoid damage with fuse selection 6*I@1s, 3*I@10s, 2*I@15m
- Normal Loads/Overloads compare TCC vs XFMR life/damage curves (C57.91 & .93)
- Through faults
  - Damage curve (C57.109) vs TCC of fuse)
  - Crossover at Max I_{sc} for Transformer

Transformer Protection

BON - ELSP Coordination



Feeder & Section Protection

- Continuous Current (less than fuse rated continuous current at temp around fuse)
- Inrush (Conservative = 25 * $I_{kVA\ connected}$)
- Pick-up Situations - avoid damage with fuse selection 6*I@1s, 3*I@10s, 2*I@15m
- Fault I vs rated interrupting current of fuse

Capacitor Protection

- Inrush levels (again use fuse size selection to prevent damage to fuse)
- Steady State conditions - allowances vs ratings
- Let through energy vs case rupture

Potential Transformers

- Fuse voltage ratings: 1 to 1.4 times max line to line voltage or as manufacturer suggests
- Current rating: smallest that will not result in chance fuse operation; a multiple of fuse minimum melting I^2t compared to measured values for the PT, may need to add in discharges from system capacitance.

Motor Protection

- Voltage (fuse voltage rating>system)
- Current (fuse I compared to max overload)
- Frequency (50 vs 60 Hz)
- Interrupting rating(greater than system I available)
- Pulse withstand(starting current)
- Location

General Considerations

- Peak arc voltage/system voltage support
- Physical location factors
  - Under-oil
  - Dry-well
  - Indoor
  - Outdoor
  - In areas of restricted cooling
  - Areas near heat sources
  - In vaults/enclosures
  - Hazardous/explosive areas

CL Fuse Coordination

John G. Leach, Hi-Tech Fuses, Inc.
Dan Gardner, Hi-Tech Fuses, Inc.

This section focuses on how to properly coordinate current-limiting fuses with other series connected protective devices.

Importance of proper coordination

- Improper coordination leads to
  - Nuisance Operations
  - Possible fuse failure

Coordination concerns

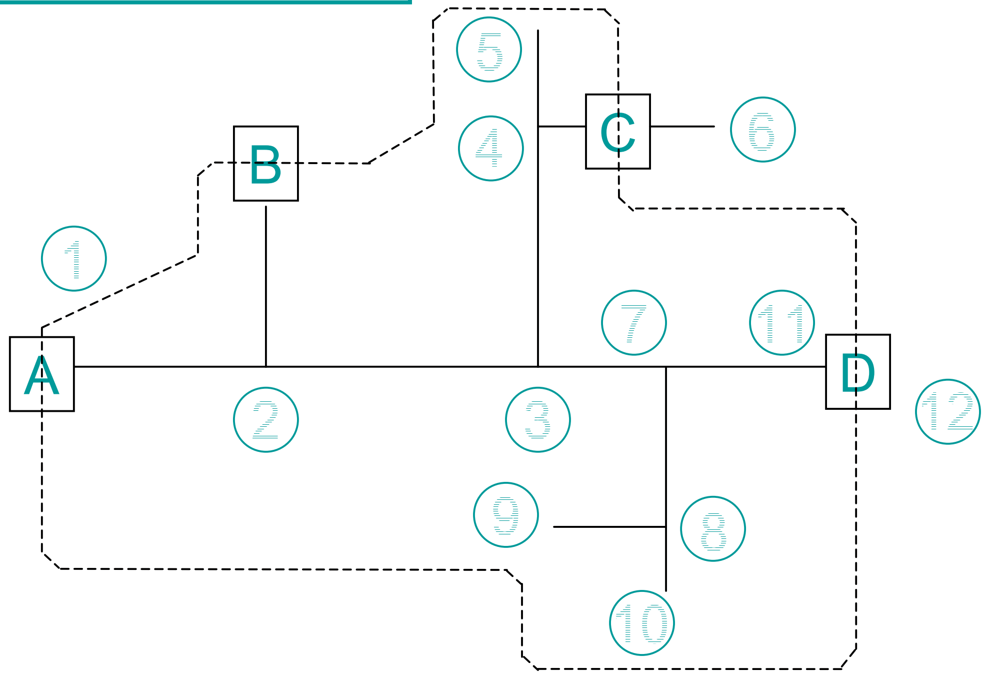
- Limit outages to smallest number of customers possible
- Protect the fuse from currents which could damage the fuse

Determining Zone of Protection

Definition: Reach is the measure of the ability of the fuse to sense a fault condition within its zone of protection.

$$\text{Reach} = \frac{\text{Min. fault current through device within zone of protection}}{\text{Min. current to operate fuse}}$$

Example:

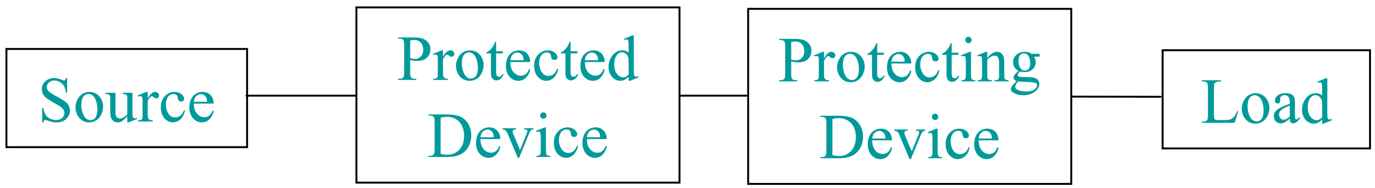


Min. Fault Current at 10: 450A

Min. Operating Current of Fuse: 100A

$$\text{Reach} = \frac{450\text{A}}{100\text{A}} = 4.5$$

Time Margin between TCC's



Applies to:

- Current-limiting fuse / Current-limiting fuse coordination
- Current-limiting fuse / Expulsion fuse coordination
- Expulsion fuse / Current-limiting fuse coordination
- Recloser / Current-limiting fuse coordination
- Current-limiting fuse / Recloser coordination

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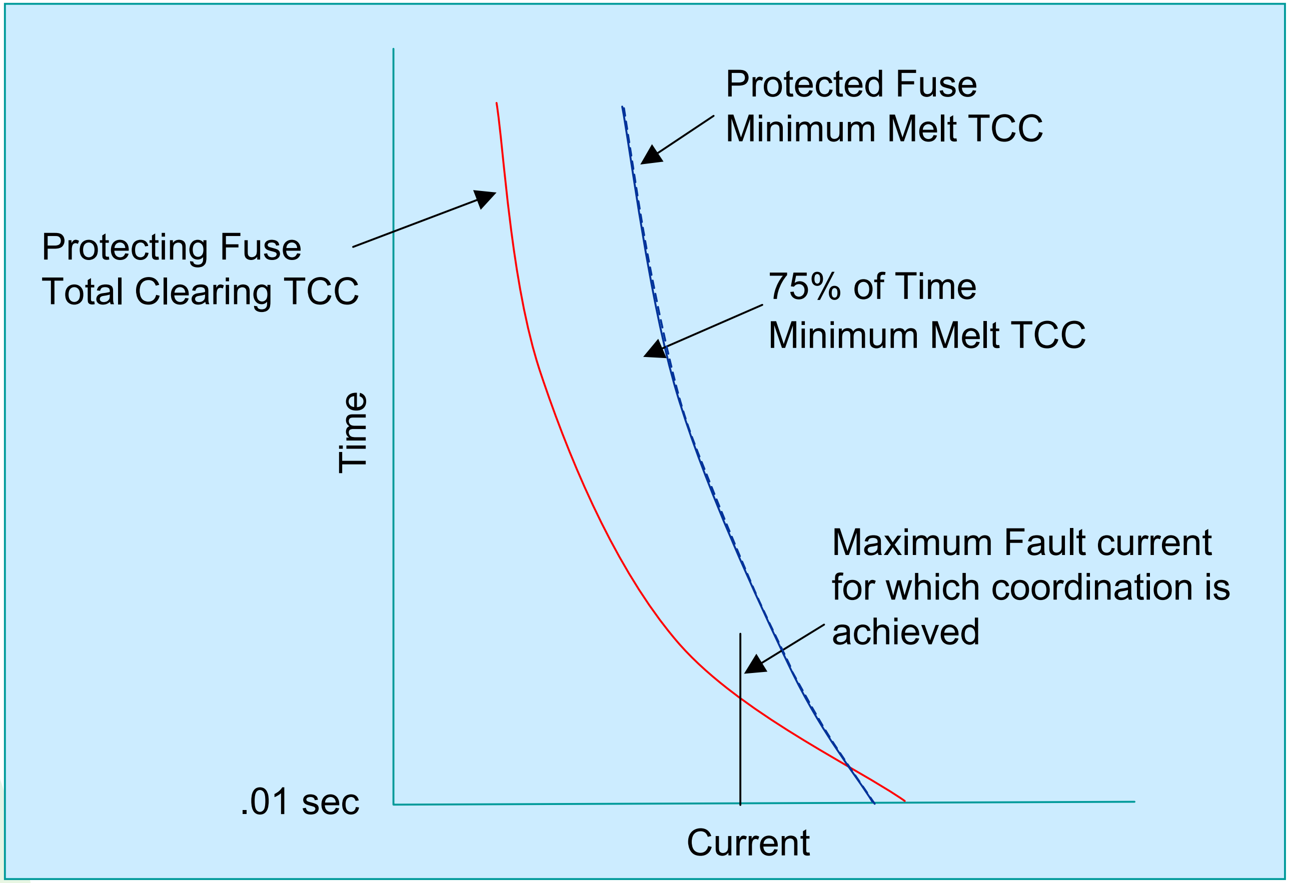
Example:



For High Currents: Total I^2t of Protecting Fuse = 75% of Min. Melt I^2t of Protected Fuse

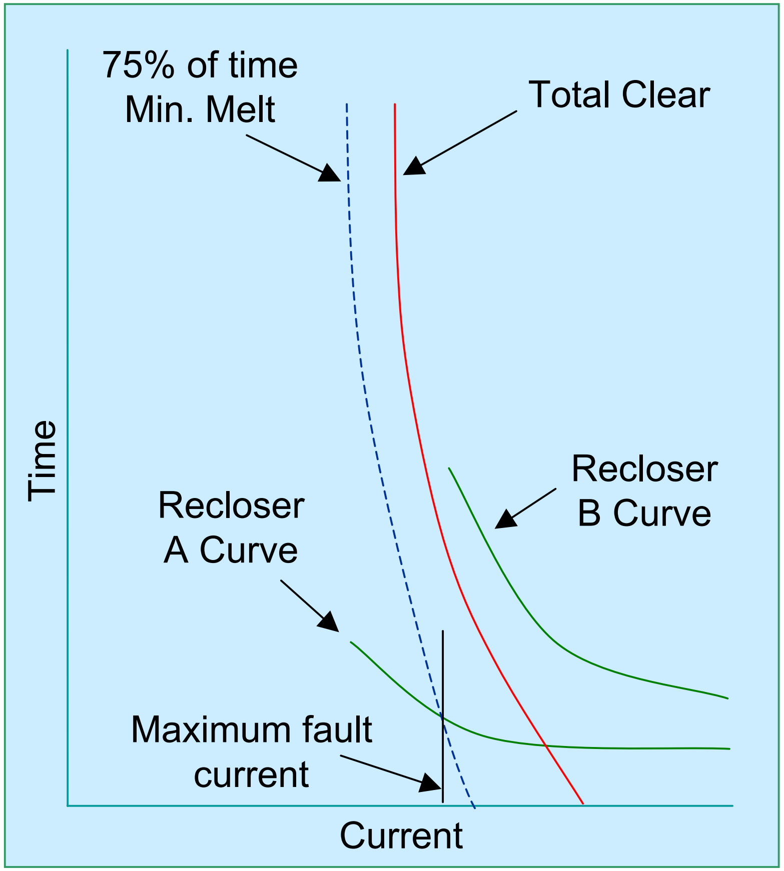
Recloser / CL Fuse Coordination

- Two Scenarios
  - Both protect overhead circuits
  - Recloser protects overhead circuit / CL fuses protect underground dips

Overhead Circuits

- Transient Faults Common
- Recloser removes temporary faults
- CL fuse removes permanent faults

Example:



Overhead with Underground Dips

- Underground faults are usually permanent
- Fuse should immediately remove fault
- Two ways to assure this
  - Available fault current at fuse greater than .01 sec current on Total Clearing Curve
  - Defeat instantaneous trip

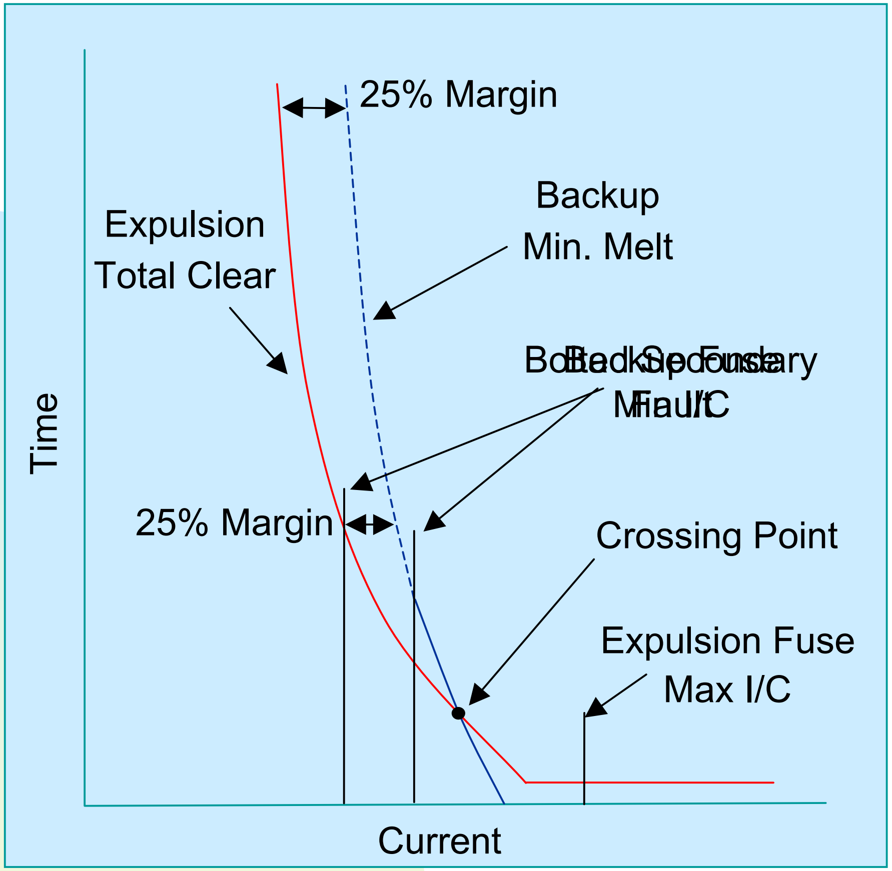
Motor Starter Fuse Coordination

- Assure protective devices do not operate during starting or under overload
- Thermal overload relay protects against low fault currents
- Fuse protects against short circuit currents

Backup Fuse Coordination

- Backup fuse must be used with another series device (i.e. expulsion fuse)
- Assure backup fuse cannot be damaged
  - During expulsion fuse operation
  - Under overload conditions
  - By inrush or cold-load pickup

Two methods of Coordination



Time Current Curve Crossover

- Current at crossover point greater than Min. I/C of backup fuse and less than Max. I/C of expulsion fuse
- 25% margin in current at long times
- For transformers, 25% margin in current at point corresponding to the bolted secondary fault current of the transformer

Matched-Melt

- Min. I^2t let through by backup must be greater than the maximum melt I^2t of the expulsion fuse

Crossover vs. Matched-Melt

Time Current Curve Crossover

- Often use smaller backup fuse
- Fuse larger transformers

Matched-Melt

- Expulsion fuse always melts
  - Removes voltage stress from backup fuse
  - Provides visual indication
  - For three phase applications, allows use of L-N rated backup fuse if expulsion fuse is L-L rated