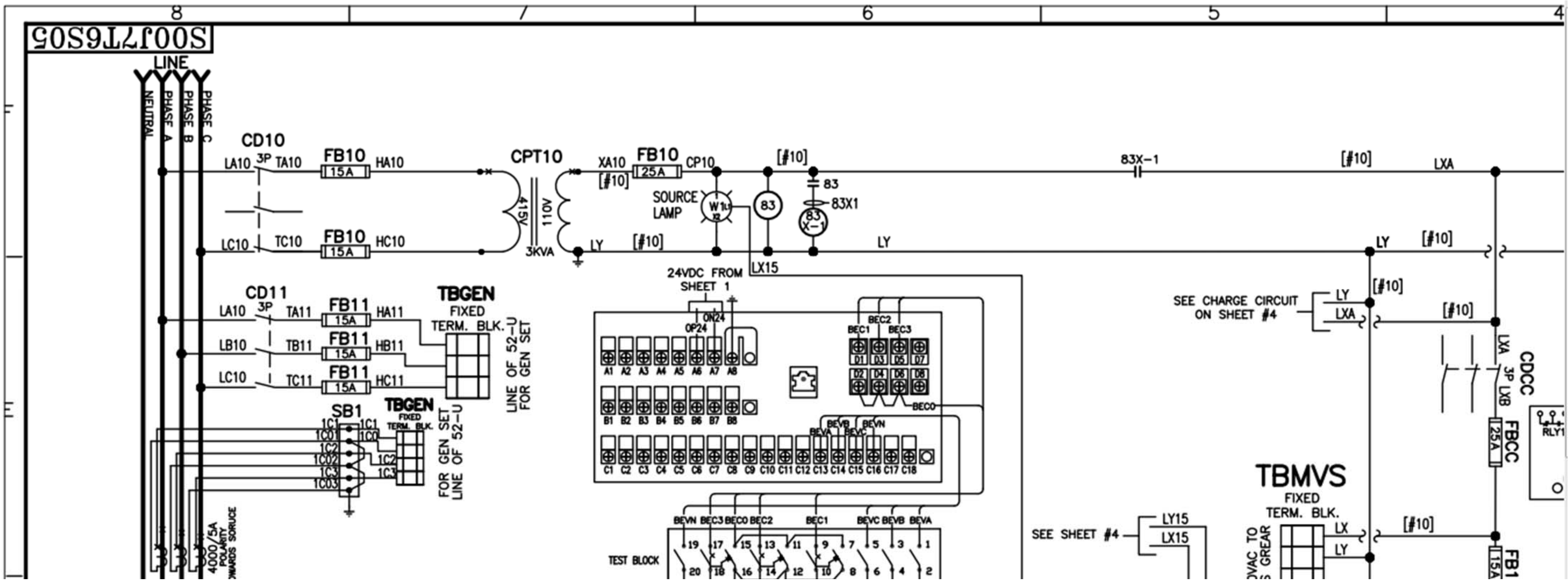

Power System Analysis:

Protection / Coordination Analysis

Dave Loucks, PE, CEM

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Definitions

- **Selective Coordination**: device closest to fault clears the fault
- **Series Rating**: for currents above the interrupting rating of the device, an upstream device (with a higher interrupting rating) clears the fault *before* the device closest to the fault
- **Time Current Curve**: Curve that describes how fast an overcurrent device clears a fault for different values of current.

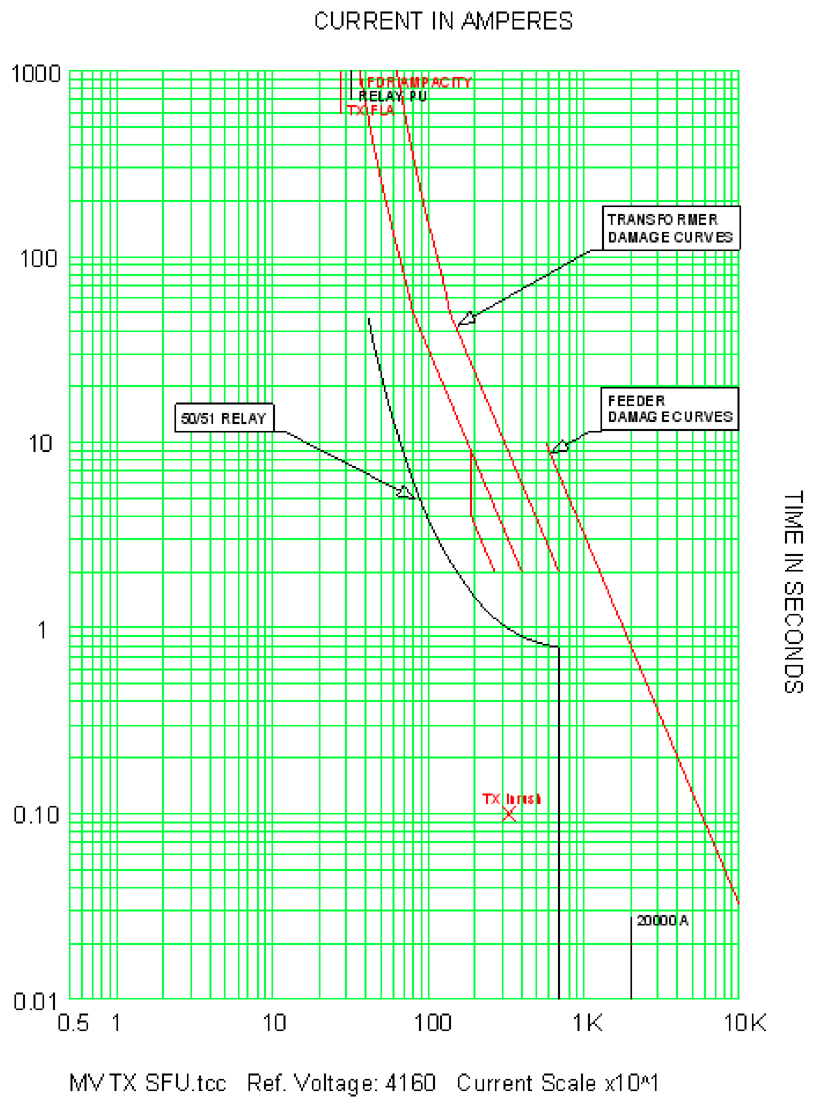
Protective Function (IEEE Device Number)

- Over/undervoltage (59, 27)
- Phase loss/unbalance (46,47)
- Directional current/power (67, 32)
- Over/underfrequency (81)
- Synchronization (25)
- **Overcurrent (50, 51)**

CAG 1.5-1 to 1.5-5

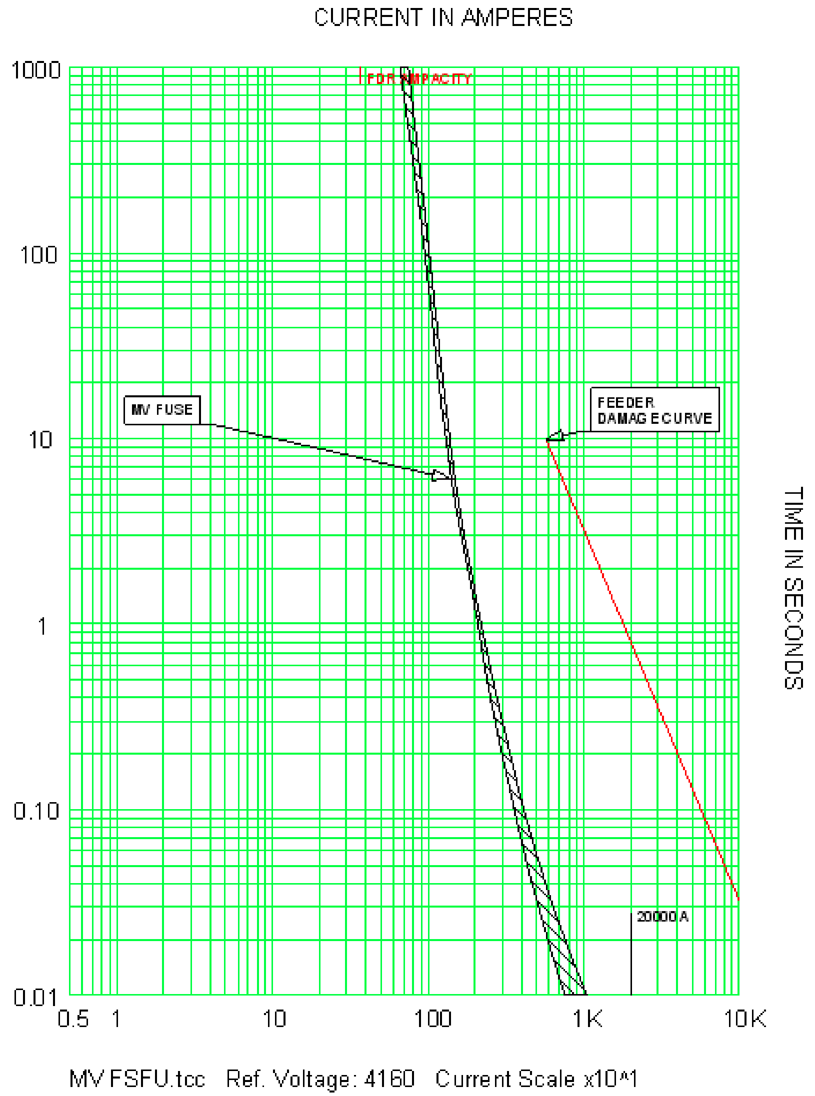
Time Current Curve – Protective Relay

Medium Voltage Switchgear



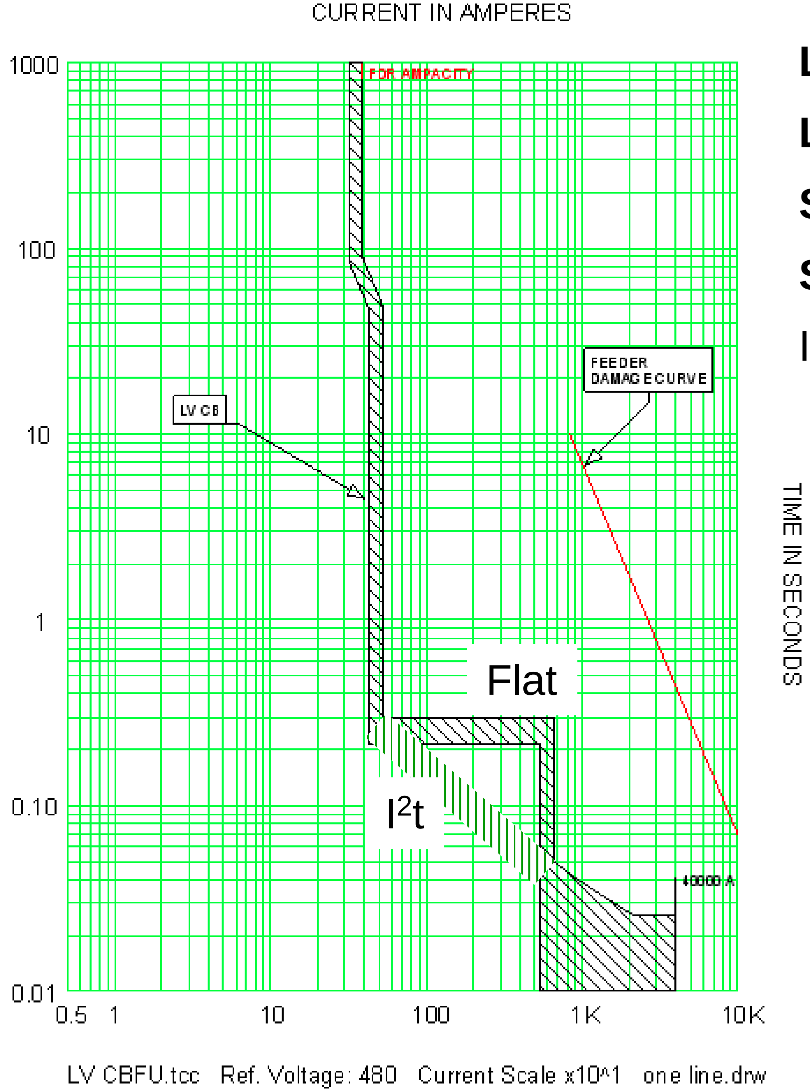
Time Current Curve – MV Fuse

Medium Voltage Load Interrupter Switchgear



Time Current Curve – LV Power Breaker

Low Voltage Switchgear (UL-1558)



Long **T**ime **P**ickup

Long **T**ime **D**elay

Short **T**ime **P**ickup

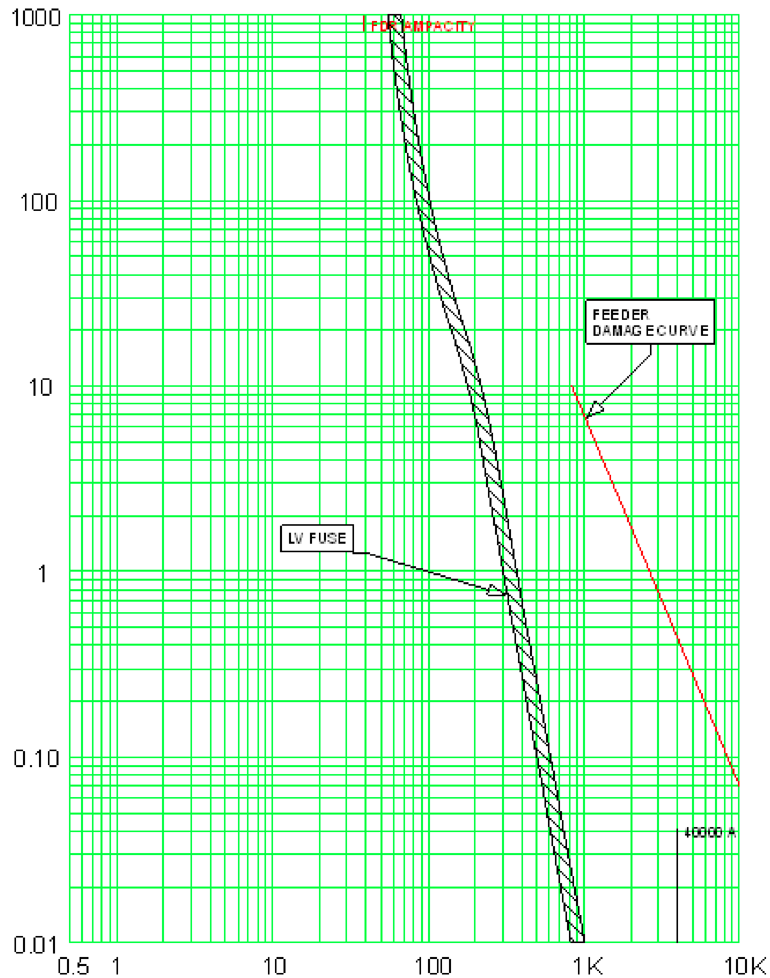
Short **T**ime **D**elay

Instantaneous Pickup

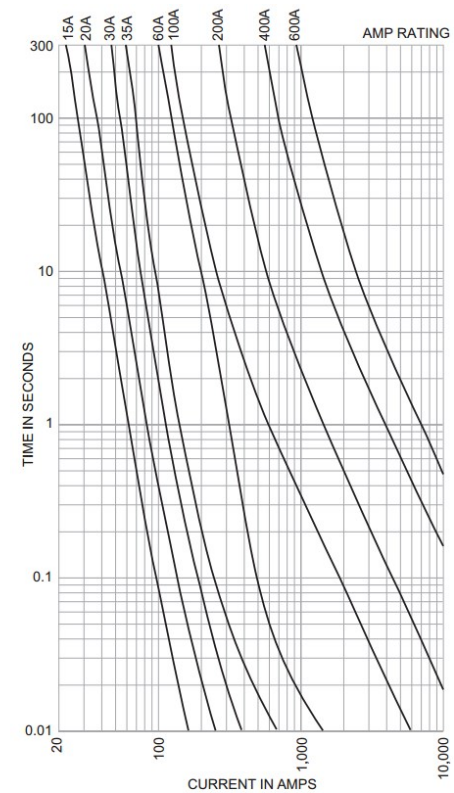
Time Current Curve – LV Fuses

Safety Switch

Current Limiting

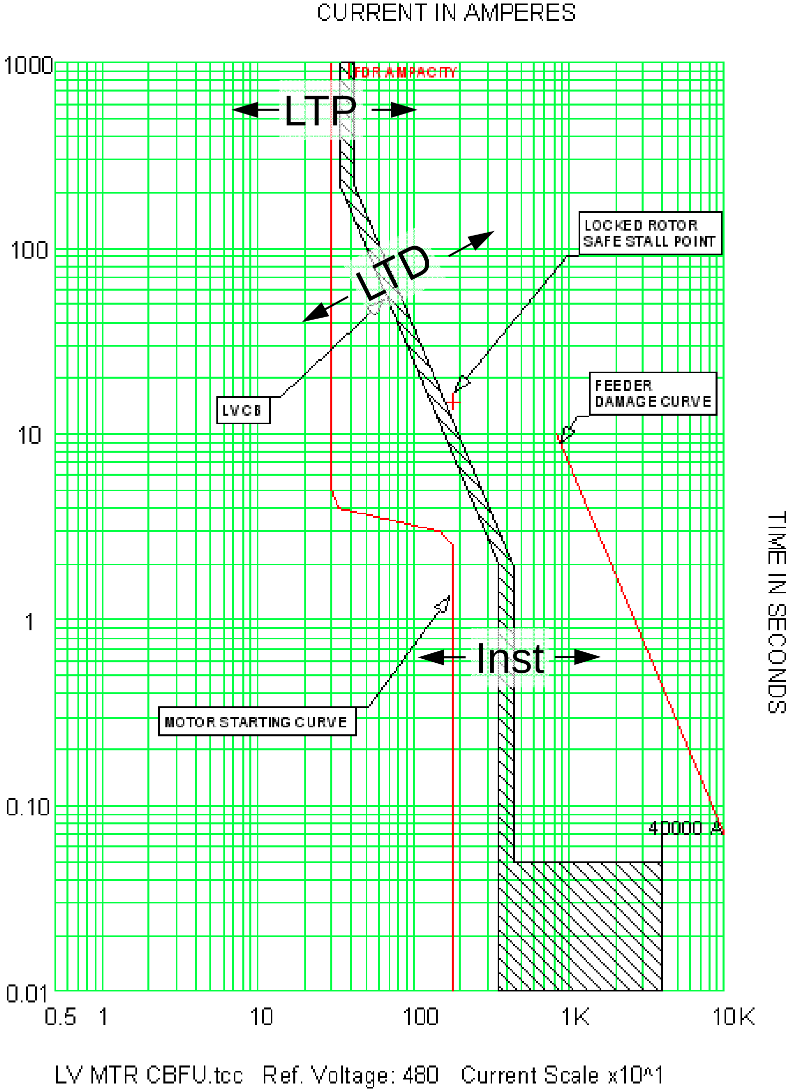


Non-Current Limiting



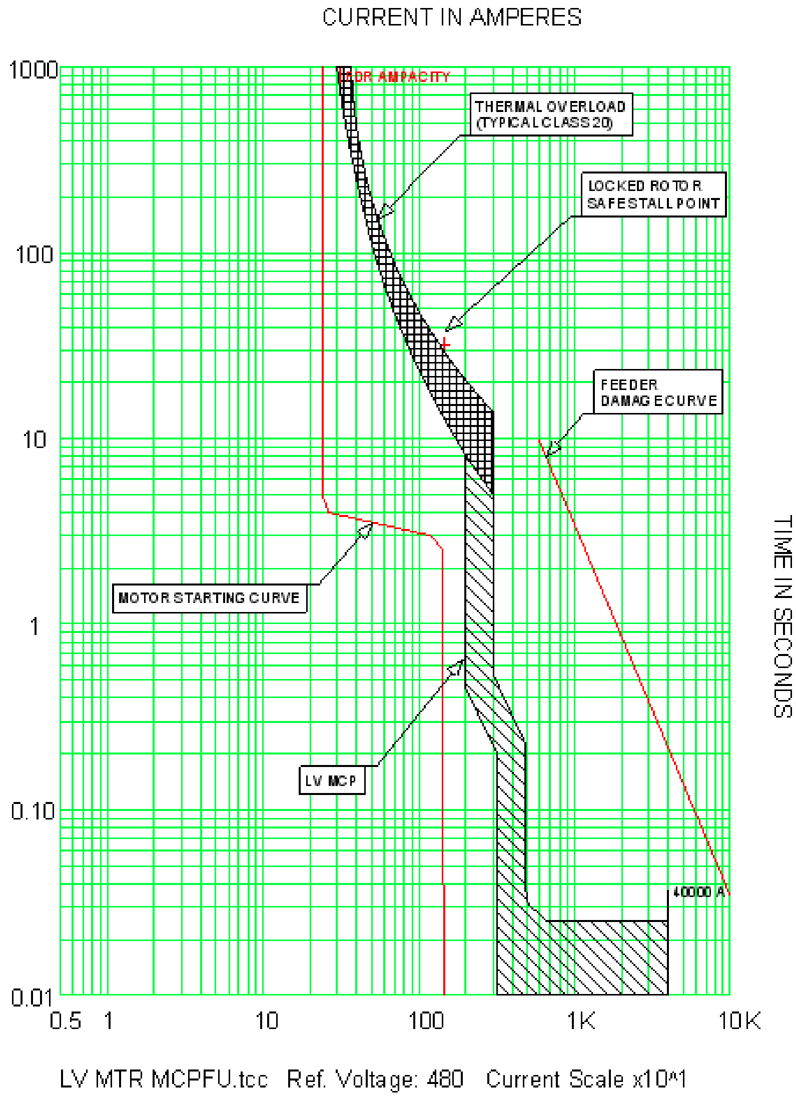
Time Current Curve – LV MCC

Low Voltage
Motor Control Center



Time Current Curve – LV MCC w/ MCP

Low Voltage
Motor Control Center



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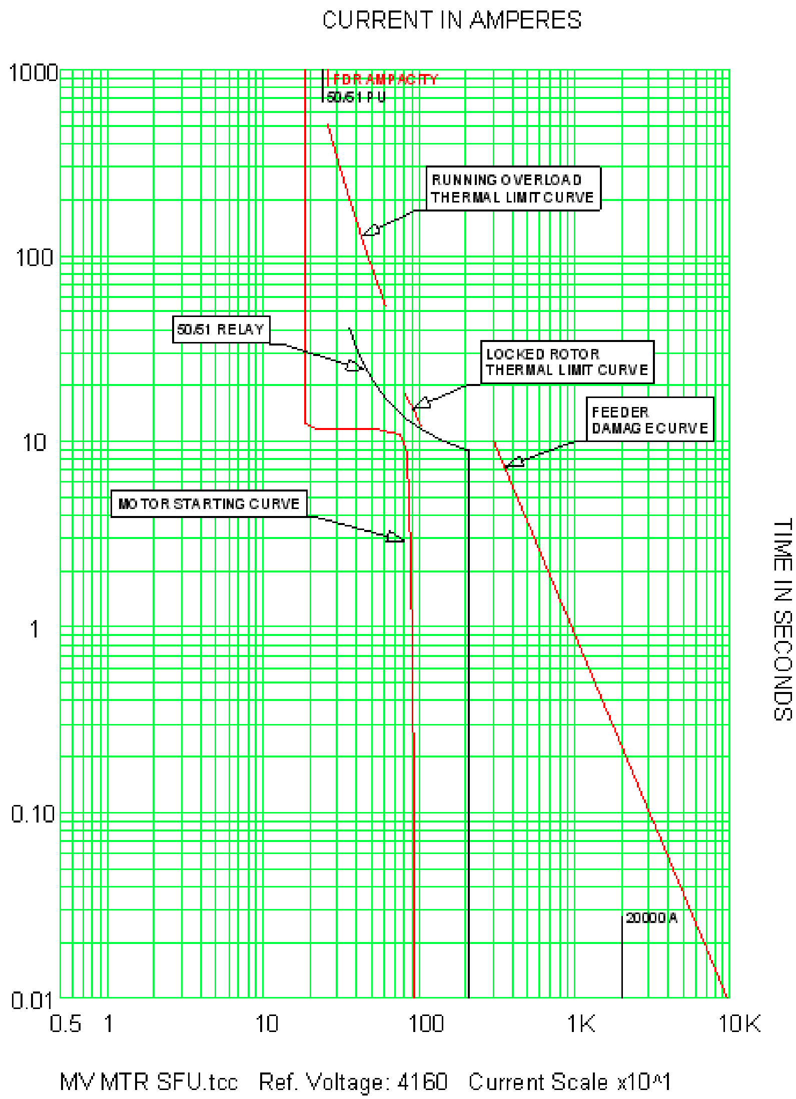
Time Current Curve – MV MCC

Medium Voltage
Motor Control Center



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Bolt-On MCCB (P&S) – UL891

Low Voltage Switchboard – Bolt-On MCCB (P&S) – UL891

- **Electrical Ratings**
  - Voltage: 600A
  - Insulation Rating: 600V
  - Bus Rating: 6000A Main bus & 4000A distribution
  - Short Time / Withstand Rating: 3-Cycle
  - Short Circuit Rating: up to 200kAIC
  - Front or Rear Access
- **Design Standards**
  - UL 891
  - NEMA PB-2

- **Applicable Breakers & Devices:**
  - Power Circuit Breaker (UL1066), 800-5000A (Main and Tie Devices), fixed or drawout
  - Insulated Case Circuit Breakers (UL489), 800–4000A
  - Molded Case Circuit Breakers (UL489), 15–2500A, fixed group mounted
  - Bolted pressure switches, 800–5000A
  - FDPW fusible switches, 400–1200A

Drawout MCCB (P&S) – UL891

Low Voltage Switchboard – Drawout MCCB (P&S) – UL891

- **Electrical Ratings**
  - Voltage: 600A
  - Insulation Rating: 600V
  - Bus Rating: 6000A Main bus & 4000A distribution
  - Short Time / Withstand Rating: 3-Cycle
  - Short Circuit Rating: up to 100kAIC
  - Front or Rear Access
- **Design Standards**
  - UL 891
  - NEMA PB-2
- **Applicable Breakers & Devices:**
  - Power Circuit Breaker (UL1066), 800-5000A (Main and Tie Devices), fixed or drawout
  - Insulated Case Circuit Breakers (UL489), 800–4000A
  - Molded Case Circuit Breakers (UL489), 15–1200A, drawout
  - Molded Case Circuit Breakers (UL489), 15–2500A, fixed or group mounted
  - Bolted pressure switches, 800–5000A
  - FDPW fusible switches, 400–1200A

Drawout ICCB (LVA) – UL891

Low Voltage Switchboard – Drawout ICCB (LVA) – UL891

- **Electrical Ratings**
  - Voltage: 600Vac
  - Insulation Rating: 2200Vac
  - Bus Rating: 10,000A Main bus & 6,000A Vertical Section bus
  - Short Circuit Rating: Up to 200Kaic(Current Limiting), 150kA **4 cycle**
  - Short Time Rating: Up to 100kA (double wide), 85kA (single wide)
- **Design Standards**
  - UL 891
  - CSA
- **Applicable Breakers**
  - Power Circuit Breaker (UL1066), 800-4000A
  - Insulated Case Circuit Breakers (UL489), 800–6000A Insulated Case Circuit Breakers (UL1066), 800-4000A
  - Molded Case Circuit Breakers (UL489), 15–2500A, fixed group mounted

Low Voltage Switchgear (LVA) – UL1558

Low Voltage Switchgear (LVA) – UL1558

- **Electrical Ratings**
  - Voltage: 600Vac
  - Insulation Rating: 2200Vac
  - Bus Rating: 10,000A Main bus & 6,000A Vertical Section bus
  - Short Circuit Rating: Up to 200Kaic(Current Limiting), 150kA 4 cycle
  - Short Time Rating: Up to 100kA (double wide), 85kA (single wide)
- **Design Standards**
  - ANSI C37.20.1
  - ANSI C37.51
  - UL 1558
  - CSA C22.2 No. 31-10
- **Applicable Breakers**
  - Power Circuit Breaker (UL1066), 800-6000A

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2014: 240.87

240.87 **Arc Energy Reduction**. Where the highest continuous current trip setting for which the actual overcurrent device installed in a circuit breaker is rated or can be adjusted is 1200 A or higher, 240.87(A) and (B) shall apply.

(A) Documentation. Documentation shall be available to those authorized to design, install, operate, or inspect the installation as to the location of the circuit breaker(s).

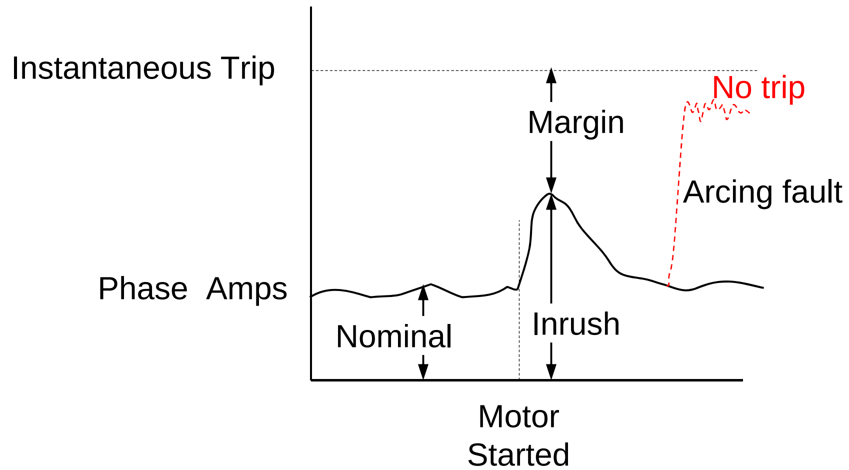
(B) Method to Reduce Time. One of the following or approved equivalent means shall be provided:

1) Zone-selective interlocking
2) Differential relaying
3) Energy-reducing maintenance switching with local status indicator
4) Energy-reducing active arc flash mitigation system
5) An approved equivalent means

2014: 240.87 Informational Notes

1. An energy-reducing maintenance switch allows a worker to set a circuit breaker trip unit to "no intentional delay" to reduce the clearing time while the worker is working within an arc-flash boundary as defined in NFPA 70E-2012, Standard for Electrical Safety in the Workplace, and then to set the trip unit back to a normal setting after the potentially hazardous work is complete.
2. An energy-reducing active arc flash mitigation system helps in reducing arcing duration in the electrical distribution system. No change in the circuit breaker or the settings of other devices is required during maintenance when a worker is working within an arc flash boundary as defined in NFPA 70E-2012, Standard for Electrical Safety in the Workplace.

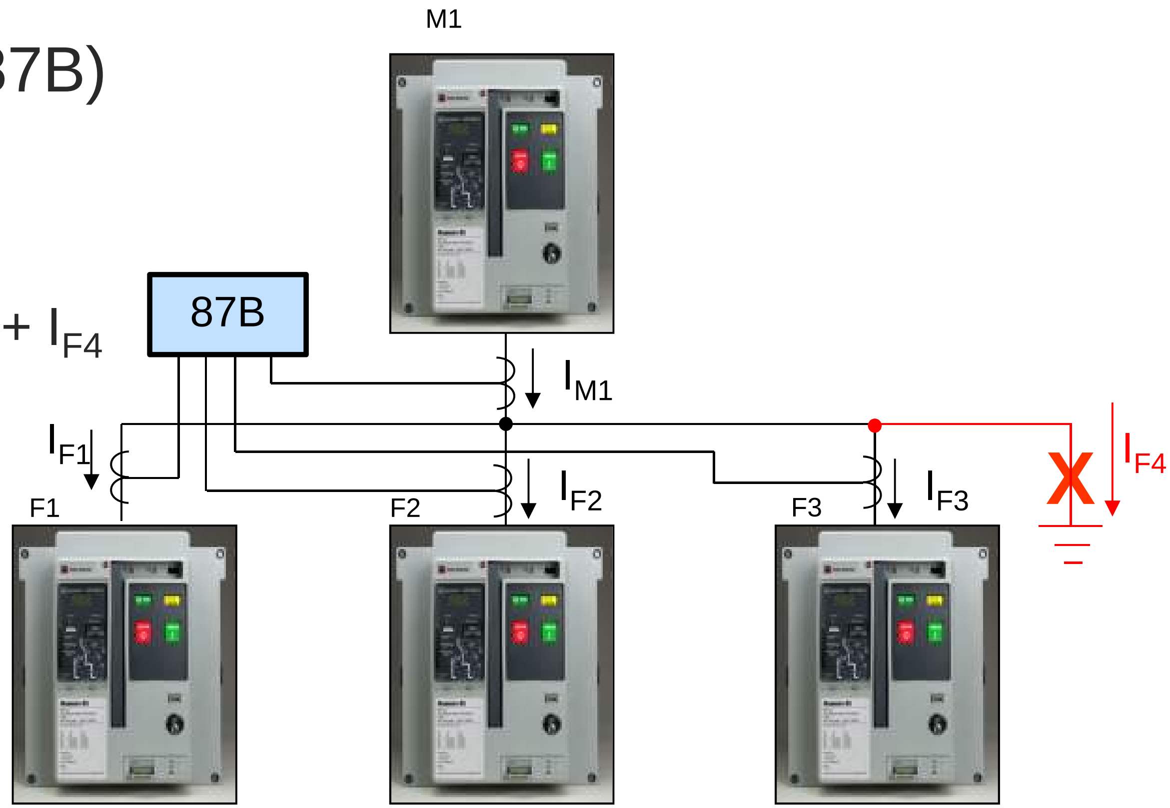
Why Isn't Instantaneous Good Enough?



- Even with instantaneous tripping, fault current (typically due to GF) might be too low

Reduce Arcing Time – Bus Differential

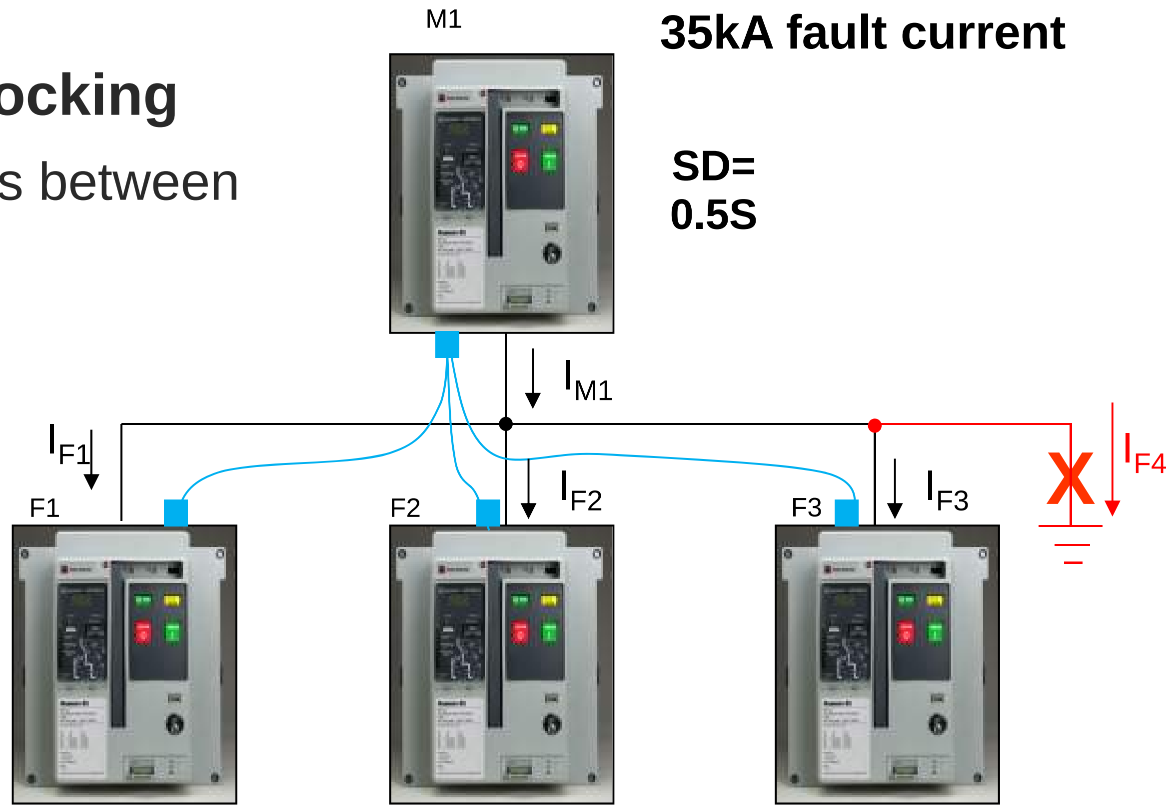
- Bus Differential (87B)
  - MV or HV
  - $I_{M1} = I_{F1} + I_{F2} + I_{F3}$
  - $I_{M1} = I_{F1} + I_{F2} + I_{F3} + I_{F4}$
  - $I_{M1} \neq I_{F1} + I_{F2} + I_{F3}$
  - Instantaneous trip!
- CT issues
  - CT balancing
  - CT accuracy / linearity
  - CT “burden” capacity
    - Load impedance - saturation



Reduce Arcing Time – ZSI

- **Zone Selective Interlocking**
  - Uses communications between devices
  - Tells each other if a fault is seen
- M1 “asks” if any other breaker sees fault
  - No 5 Vdc restraint sent
  - M1 clears instantaneously!

35kA fault current



<u>Without</u> ZSI = 0.5 S:

43.7 Cal/cm²

Greater than Cat. 4 PPE

DANGER!

<u>With</u> ZSI = 0.08 S:

7.0 Cal/cm²

Cat. 2 PPE

FR Shirt & Pants

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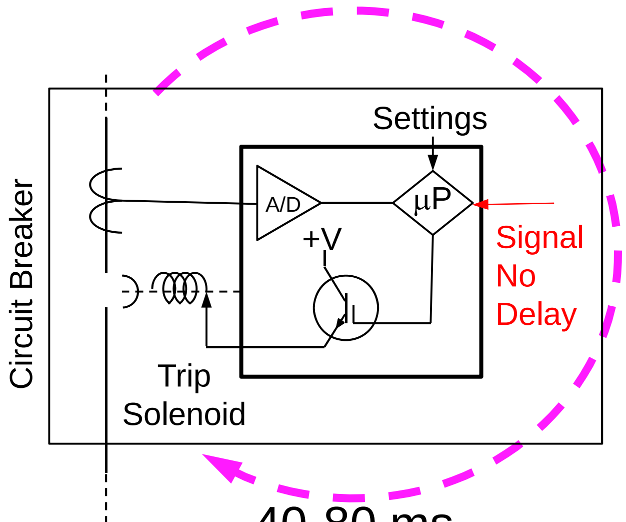
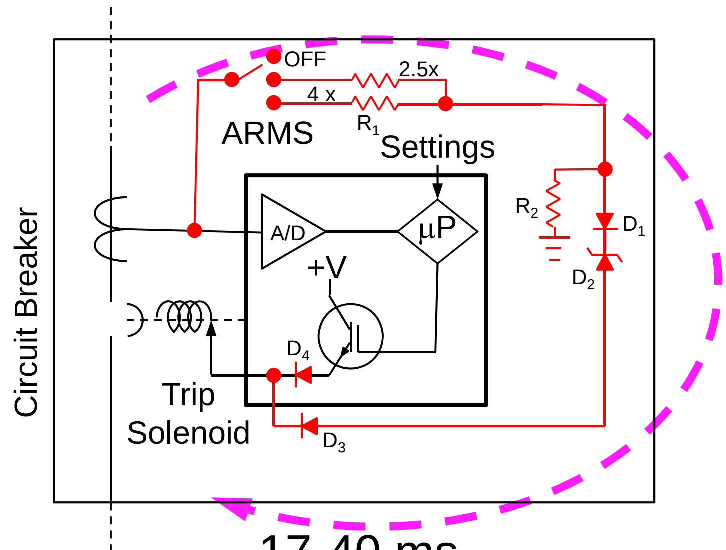
Reduce Arcing Time – ARMS

- Not all "ARMS" are the same
- Some simply bypass ZSI
- "Faster than instantaneous"

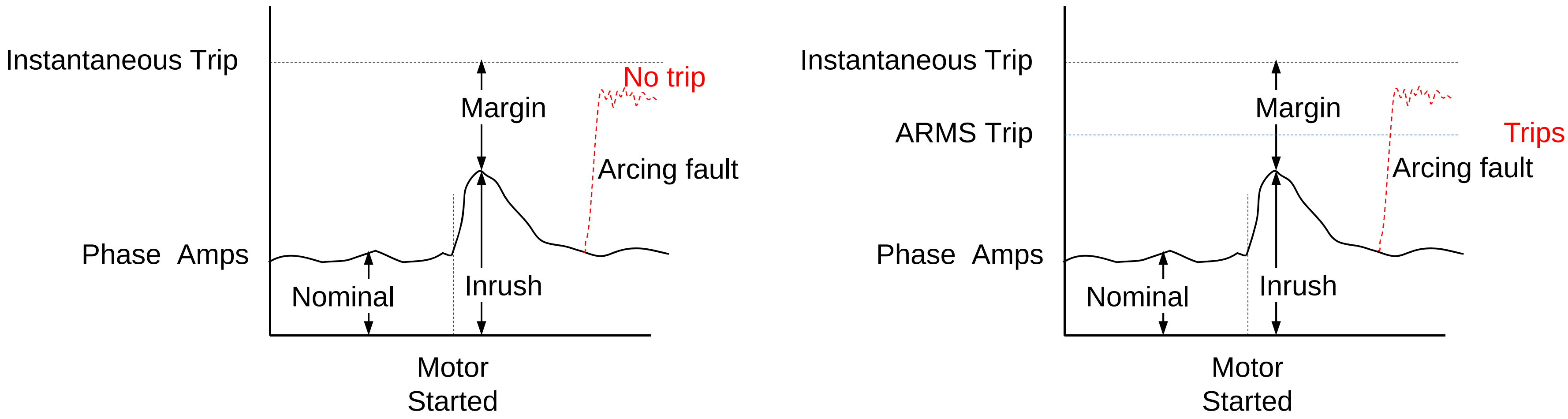


40-80 ms
Fault occurs until breaker trips

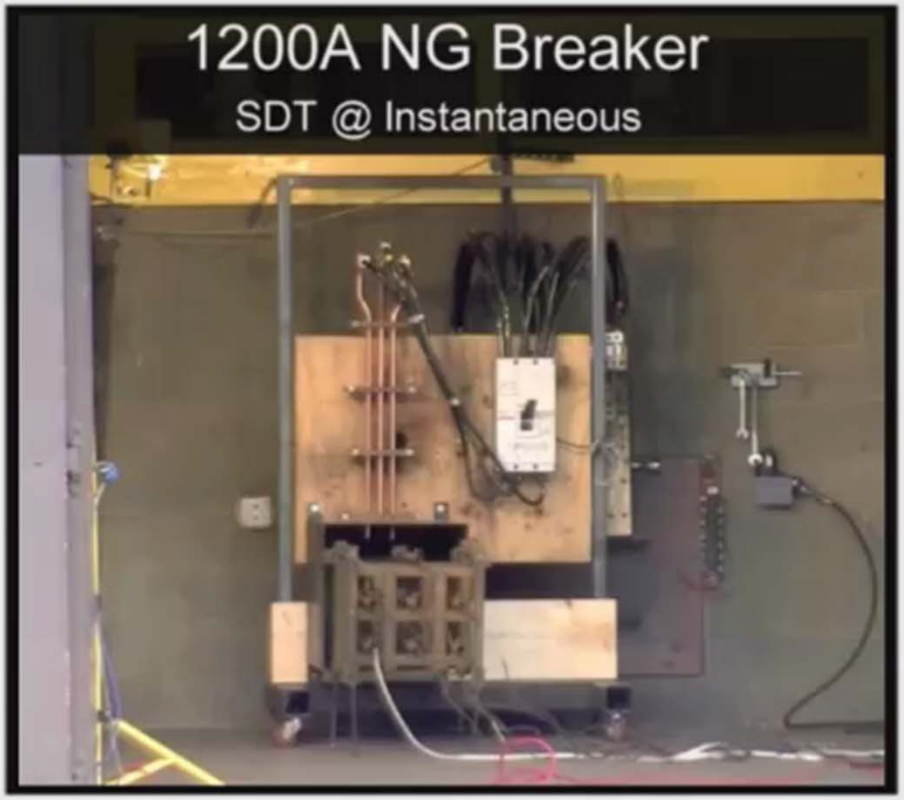


17-40 ms
2-3 times faster clearing

Also ARMS Provides a Lower Pickup



- Picks up to clear at lower current– reduces incident energy
- Clears faster than instantaneous – further reduces incident energy


1200A NG Breaker
SDT @ Instantaneous

Documented Example of ARMS

- Olin Chemical
- Energized 480V work (21 kAIC)
- Come-along used to pull cable
- Chain drifted to bus
- Faulted bus

Implementation of an Arc Flash Reduction Maintenance Switch – A Case Study

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Paper No. ESW-2012-08

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Abstract - This paper presents a case study of an event that occurred in an industrial facility that resulted in an outage without extensive damage and no harm to employees due to proper use of arc flash reduction products and a safety program. The case in point will illustrate a design of a power distribution system that was approached with safety in mind as well as the safety program that complimented the design resulting in a much less severe event. Arc flash reduction solutions and techniques will be discussed, especially those that were used in this example. The safety program implemented at this facility will also be reviewed to illustrate the proper recipe for safety. This case illustrates how even working de-energized can present opportunities for accidents to occur that should be addressed through proper use of installed safety equipment coupled with the successful implementation of a safety program..

Index Terms — Arc Flash, ARMS, Maintenance

I. INTRODUCTION

Arc flash events can be devistating to all involved on many different levels. With tthe proper safety plan and proper use of various technologies, arc flash events can be a thing of the past. There are many technologies on the market today that can help reduce the energy in a power distribtuion system in the case that a problem arises. This is a documented event that demonstrates the power of utilizing not only technologies but also the safety procedures that help ensure everyone's safety on the job.

An arc flash requires time and current. The various technologies on the market seek to reduce one or the other or both of these components in the effort to reduce the energy released – hence mitigating the arc flash event.

II. SAFETY PLANS AND PROCEDURES

A. Project Preparation / Background

This project involved a major rework of a 480 volt distribution system which was supplied from a 1000kVA transformer. One of the first steps in this project, as per NFPA 70E Section 130.4(A) and 130.5(B), a shock and arc flash work hazard analysis was performed. This analysis found that a complex lockout and safe work permit was required for the last portion of the project which included the removal of a three conductor cable from the back of the 480 volt switchgear. This cable was removed from cable tray exiting the switchgear before work in the switchgear began. An Arc Flash Maintenance switch was identified to exist up stream of the 480 volt switchgear and was planned to be utilized for this project. The available energy without the maintenance switch and with the maintenance switch was 17.7 Cal/cm sq and 2.9 Cal/cm sq respectively. The PPE that was specified for this project included level 2 as the energy level was 2.9Cal/cmsq per the arc flash calculations. The available fault current at the 480 volt switchgear was 21,000 amps.

B. Energized Work

The electrical contractor for this portion of the project, obtained the complex lockout and safe work permit and as per NFPA 70E section 120.2(D)(2), performed a project review to determine the necessary PPE that was required. The contractor also reviewed the switchgear installation to understand all aspects of the project and equipment that would be interfaced with. The energized cubicles and the maintenance switch were located. To proceed, the maintenance bypass switch, located on the switchgear, was placed in the on position and appropriate locks were put in place.

C. Event

During the actual work of removing the 3 conductors, a rope was used as is typical with this type of project. The rope could not grab the conductors and would slip off of the cable which showed no signs of moving. The electrical contractor then employed a come along to assist in the removal as the come along could apply more force. The first conductor was successfully removed with this new tool. Upon removing the second conductor a small flash was observed below him. At this same instant the lights to the plant went out. The electrical contractor stopped his work and waited for the plant electricians to arrive not knowing what had just occurred.

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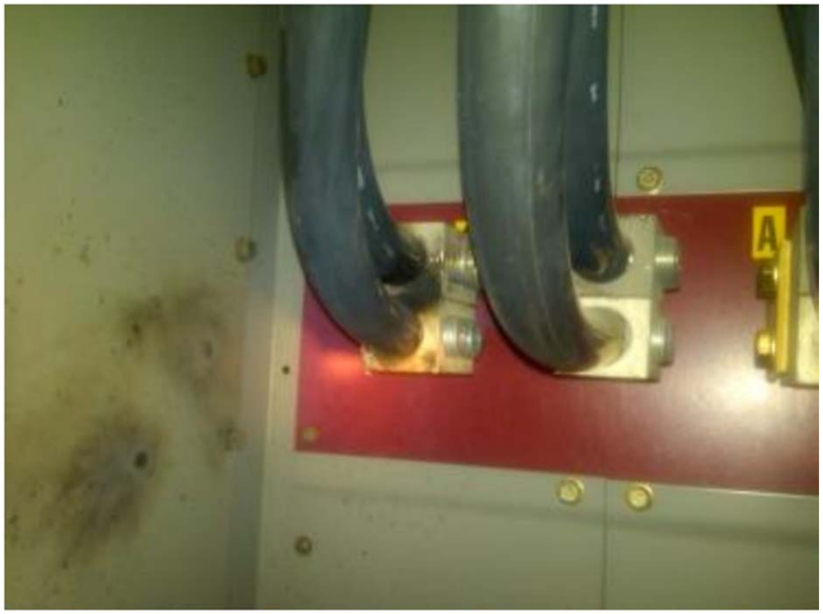
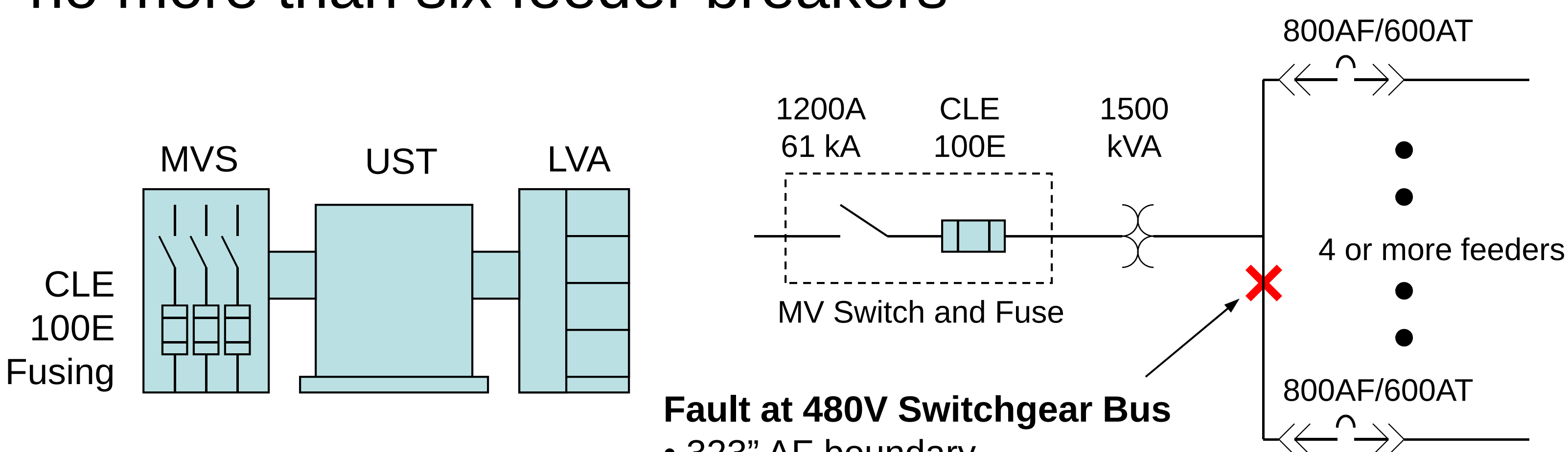
Olin Chemical ARMS Case Study

- No injury to electrician, no loss of equipment
- Completed project and re-energized the switchgear.
- Total down time for the plant due to this event was minimal



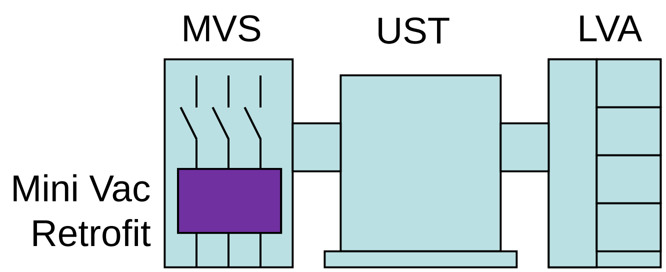
Unit Substation – Excessive Fault Energy

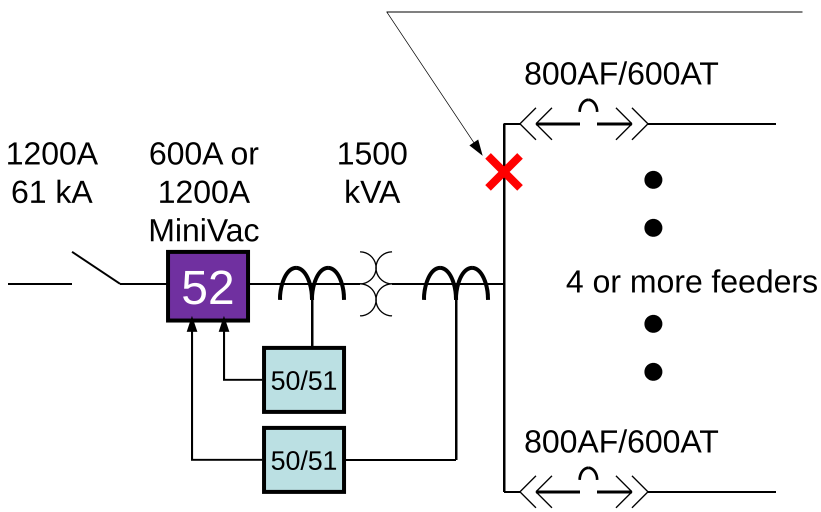
- Unit substations without secondary overcurrent protection present some significant challenges
- Unit subs without secondary main breakers are very common
- Design can be NEC-compliant as long as there are no more than six feeder breakers



Fault at 480V Switchgear Bus
- 323” AF boundary
- 105.4 cal/cm^2
- NFPA 70E-2004 Category - Extreme Danger!

Reduce Arcing Time – Unit Substation

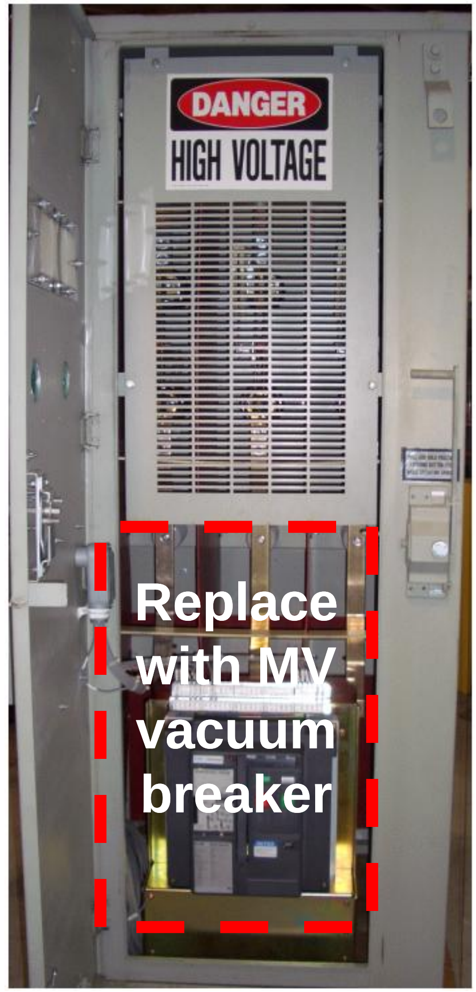




Fault at 480V Switchgear Bus
- 323” AF boundary
- 105.4 cal/cm^2
- NFPA 70E-2004 Category - Extreme Danger

Versus
- 40.7” AF boundary
- 4 cal/cm^2
- NFPA 70E-2004 Category **2**

ARMS MV Retrofit Photos



Light Sensing Relays

- Able to “see” flash of light
  - When correlated with current (reduce nuisance trips), can trip quickly
- Issues
  - Mechanical clearing time of power breaker ≈ 80 ms
  - If light relay could detect in 2 ms (vs 4 ms for current sensing, worst case):
    - 80 + 2 = 82 ms (light sensing alone)
    - 80 + 4 = 84 ms (current sensing alone)
    - (82-84)/84 = 2.3% faster
    - 40 cal/cm^2 → 39 cal/cm^2 (no real savings)

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Selective Coordination

- A 208Y/120 volt branch panelboard consisting of main lugs only and 40 - 20A trip single-pole breakers and 1 - 35A trip 2-pole breaker is located 113 feet away from the 225A trip feeder breaker supplying the panelboard through 1-4/0 copper conductor in metallic conduit per phase and neutral. There is 67,000 amperes rms available at the 225A trip breaker.

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Selective Coordination

- Step 1: Utilize Eaton Web site calculator or other means to determine the short circuit current at the branch panelboard. When using the Eaton calculator. select system voltage of 208Y/120 volts; enter 67,000 starting amperes into the RED box of the calculator. Select copper conductors in metallic raceway. conductor size of 4/0 and length of 113 feet and 1 conductor per phase. The calculator yields 10,968 amperes rms symmetrical of available fault current at the load side breakers in the branch panelboard.

Selective Coordination

- Step 2: First determine the model of the load side breaker from Tables 6, 7 and 8, which has an interrupting capacity greater than or equal to the available fault current of 10,968 amperes and of a bolt-on type because they are used in a panelboard.

  The first breaker model meeting this criteria is a ‘OBHW.’

Selective Coordination

- Step 3: Utilizing Table 9, find the row for the QBHW breaker having a trip rating of 35 amperes. Since this is NOT shown in the table, go to the next larger trip of 40 amperes. Move horizontally to find the minimum value that exceeds 10,968 amperes. Proceeding horizontally across page 20, stop at the value of 14.4 kA (14,400 amperes). Proceeding up the column, find the heading of LG Family of breakers having ETU with an available trip unit range of 160 to 400 amperes. Since the required trip unit of 225 falls within this range, the LG Family of breakers is suitable to provide selective coordination with the QBHW breaker.

Selective Coordination

Load Side Breaker – Indicates the frame family and amperage range of the load side molded case circuit breaker

Breaker Family – Indicates line side molded case breaker frame family to selectively coordinate with the load side breaker

Type Trip Unit – Indicates the type of the trip unit. T/M = Thermal Magnetic Trip, ETU = Electronic Trip Unit

Minimum Trip – Indicates the minimum available amperage rating for a specific breaker family on the line side

Maximum Trip – Indicates the maximum available amperage rating for a specific breaker family on the line side

Table 2.

Load Side Breaker	Breaker Family Type Trip Unit Minimum Trip Maximum Trip	Line Side Breaker											
		LG ETU 100 A 250 A	LG ETU 160 A 400 A	LG ETU 250 A 600 A	LG T/M 630A	N ETU 150 A	N ETU 400 A 400 A	N ETU 400 A 600 A	N ETU 400 A 800 A	N ETU 600 A 1200 A	R ETU 800 A 800 A	R ETU 800 A 1000 A	R ETU 800 A 1200 A
BRH, QPHW, QBHW & QCHW (120 Vac for 1-Pole, 120/240 Vac for 2-Pole and 240 Vac for Delta Rate 2-Pole and All 3-Pole													
15		10	14.4	22	22	22	22	22	22	22	22	22	22
20		9.0	14.4	22	22	22	22	22	22	22	22	22	22
30		9.0	14.4	22	22	22	22	22	22	22	22	22	22
40		7.5	14.4	22	22	22	22	22	22	22	22	22	22
50		7.5	14.4	22	22	22	22	22	22	22	22	22	22

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Tools

- Selective Coordination Calculator: http://www.eaton.com/ecm/idcplg?IdcService=GET_FILE&allowInterrupt=1&RevisionSelectionMethod=LatestReleased&noSaveAs=0&Rendition=Primary&dDocName=AP01200003E
- Short Circuit Calculator: http://www.eaton.com/ecm/idcplg?IdcService=GET_FILE&allowInterrupt=1&RevisionSelectionMethod=LatestReleased&noSaveAs=0&Rendition=Primary&dDocName=PCT_459616

More Tools

- Selective Coordination Guide

EATON | Cutler-Hammer

Selective Coordination Breaker Application by Short Circuit Current Ratings in Panelboards

Industry Application IA01400001E

Introduction

This guide is designed to facilitate the selection of Eaton lighting and power panelboards, Types PRL1a, PRL2a, PRL3a and PRL4B using molded case circuit breakers which attain full selective coordination. This document utilizes information contained in IA01200002E for selectively coordinated circuit breakers. The selective coordination values shown are based on Eaton test data.

The ratings indicate the load side fault current at which two breakers will selectively coordinate. The manufacturer's tested data typically are significantly higher than would be indicated by circuit breaker time-current curves. This is attributed to utilization of state-of-the-art load side high-speed performance molded case circuit breakers, which may be current limiting. Although some molded case circuit breakers may not be formally marked as current limiting, these breakers still begin to open before the first ½ cycle peak, inserting arc impedance into the circuit, thus reducing the peak let-through current with resulting lower I^2t. This reduction by the load side breaker reduces the current to a level below the instantaneous override of the line side breaker resulting in selective coordination.

The test circuit utilized by manufacturers to validate selective coordination must be known and reasonable. Eaton tests circuit breakers in a manner similar to the test circuit used in UL® 489 testing to list molded case circuit breakers. This test circuit allows for 4 feet of wire on the line side of the line side breaker and 4 feet of wire length for the combination of wire from the load side of the line breaker through the load breaker to the point of the fault. For each shown combination, the selective coordination test utilizes wire size based on the trip unit rating for the line and load breakers per National Electrical Code® Table 310.16.

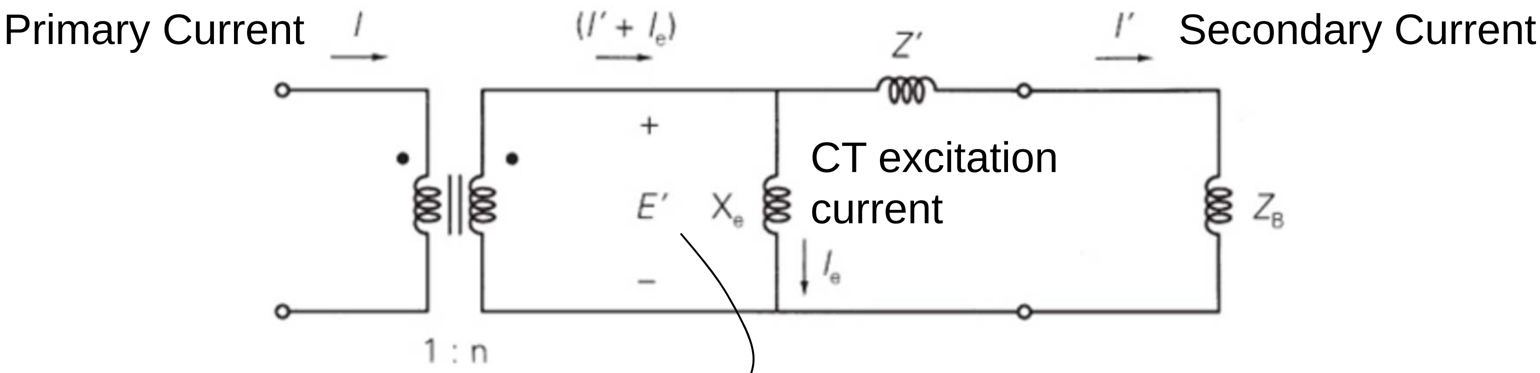
In addition to the panelboard selective coordination data, we have provided secondary fault current data for select, commonly used aluminum and copper wound dry-type distribution transformers. This data can be found in the Appendix.

Organization of Data

The data contained in this publication is arranged in Panelboard Table format, utilizing Eaton tested breaker combinations of selectively coordinated Cutler-Hammer® molded case circuit breakers. The panelboard tables have been divided into two parts: Lighting Panelboards and Power Panelboards.

eaton.com/selectivecoordination

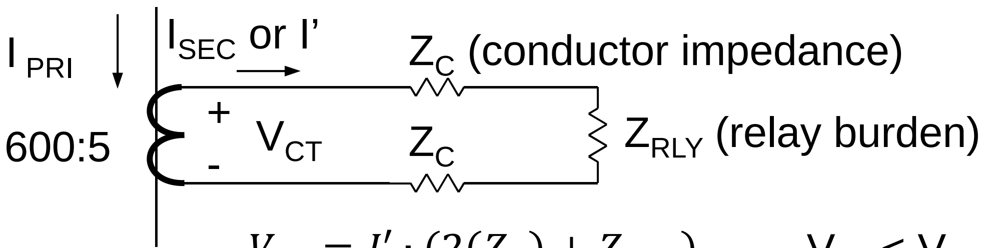
CT Error



$$I_e = \frac{E'}{X_e} \qquad E' = I' \cdot (Z' + Z_e)$$

$$CT_{err} = \frac{I_e}{I' + I_e}$$

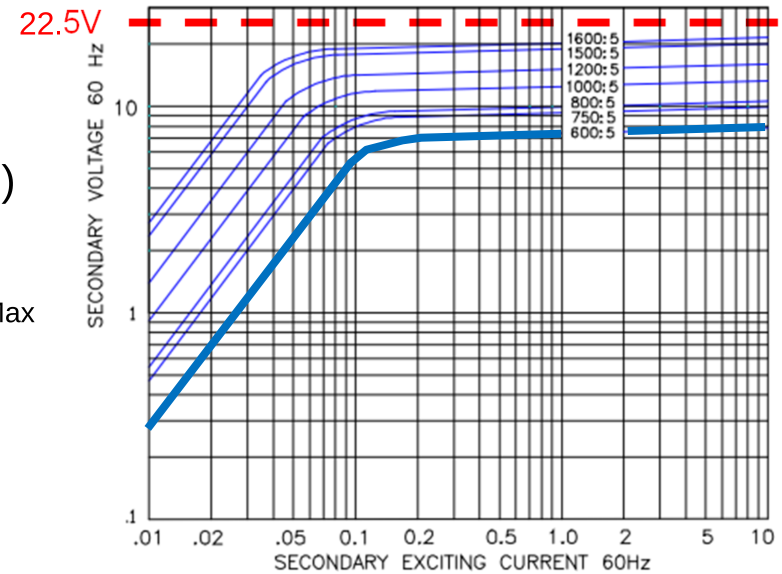
CT Saturation

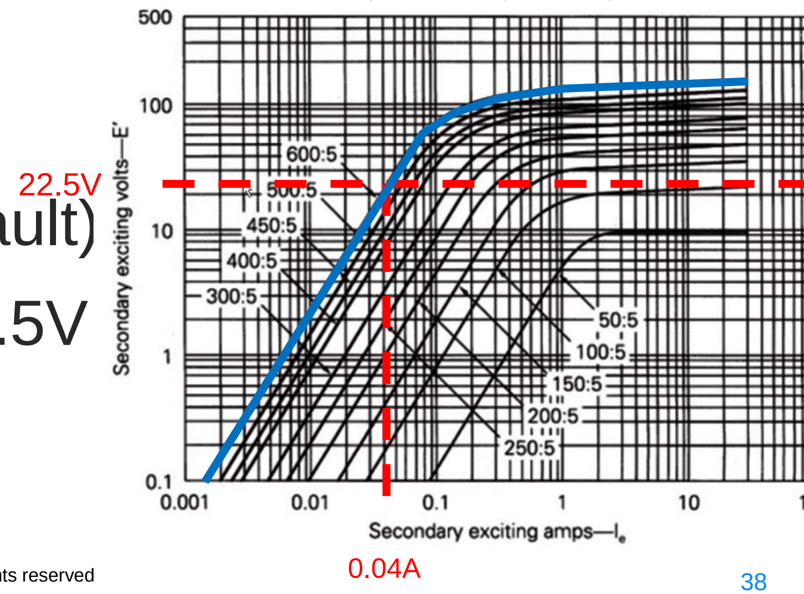


$$V_{CT} = I' \cdot (2(Z_C) + Z_{RLY})$$

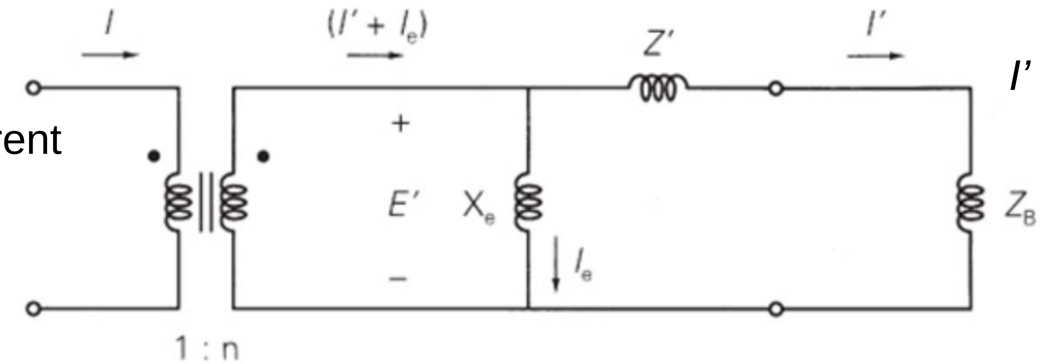
$V_{CT} < V_{Max}$

- #14 AWG (0.002525 Ω/ft)
- 100' total wiring (50' x 2)
- Z_{RLY} = 0.2 Ω load
- Z_C = 100 * 0.002525 = 0.25 Ω
- I_{SEC} = I' = 5A * 10 = 50A (10x fault)
- V_{CT} = I'*Z = 50*(0.25+0.2) = 22.5V
- 0.5% (or better) accuracy?





CT Error



I Primary Current

I' Secondary Current

$$CT_{err} = \frac{I_e}{I' + I_e}$$

- $I' = 50$ A
- $I_e = 0.04$

$$CT_{err} = \frac{0.04}{50 + 0.04} = 0.08\%$$

✓ *Better than 0.5%*

- Why should differential relaying schemes use the same CTs at each bus?