Short-circuit, Protective Device Coordination & Arc Flash Analysis

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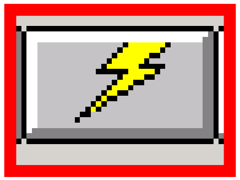
Agenda

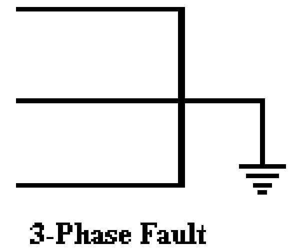
- Short-circuit Calculations for Arc Flash Analysis
- Protection and Coordination Principles
- Arc Flash Analysis and Mitigation
- Upcoming Arc Flash Analysis Standards/Guidelines Changes
- DC Arc Flash Analysis
- Transient Arc Flash Analysis for Generators

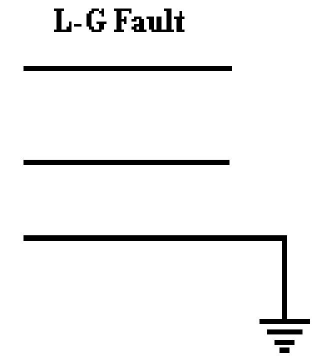
Short-Circuit Analysis

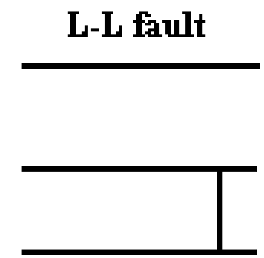


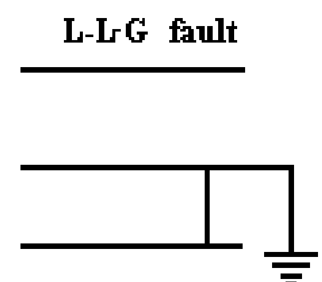
Types of SC Faults

- Three-Phase Ungrounded Fau
- Three-Phase Grounded Fault
- Phase to Phase Ungrounded F
- Phase to Phase Grounded Fault
- Phase to Ground Fault









Fault Current

- $I_{L\text{-}G}$ can range in utility systems from a few percent to possibly 115 % (if $X_o < X_1$) of $I_{3\text{-phase}}$ (85% of all faults).
- In industrial systems the situation $I_{L\text{-}G} > I_{3\text{-phase}}$ is rare. Typically $I_{L\text{-}G} \cong .87 * I_{3\text{-phase}}$
- In an industrial system, the three-phase fault condition is frequently the only one considered, since this type of fault generally results in Maximum current.

Purpose of Short-Circuit Studies

- A Short-Circuit Study can be used to determine any or all of the following:
  - Verify protective device close and latch capability
  - Verify protective device Interrupting capability
  - Protect equipment from large mechanical forces (maximum fault kA)
  - I^2t protection for equipment (thermal stress)
  - Selecting ratings or settings for relay coordination

System Components Involved in SC Calculations

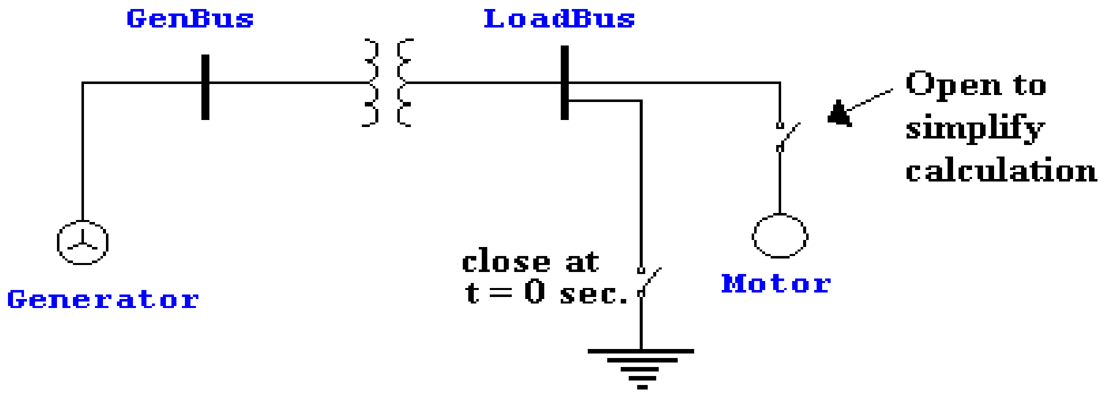
- Power Company Supply
- In-Plant Generators
- Transformers
- Reactors
- Feeder Cables / Cable Trays and Bus Duct Systems

System Components Involved in SC Calculations

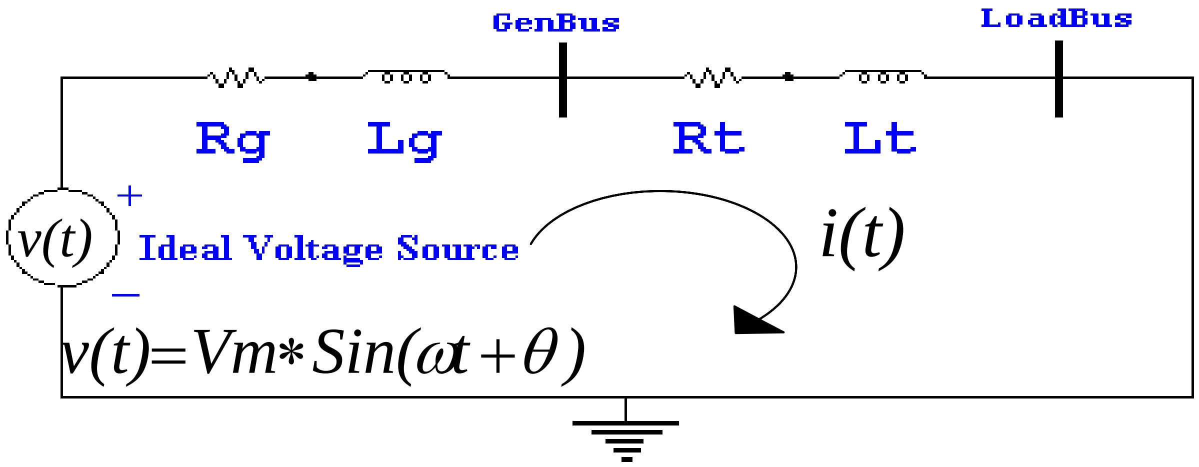
- Overhead Lines
- Synchronous Motors
- Induction Motors
- Protective Devices
- Y_0 from Static Load and Line Cable

Short-Circuit Phenomenon

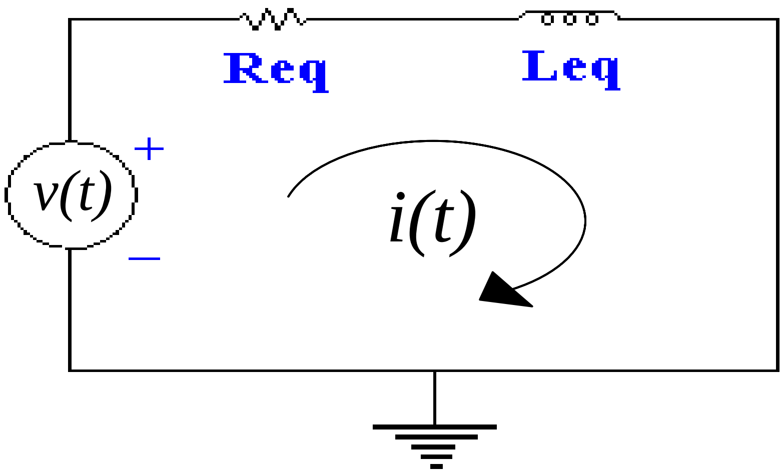
One-Line Diagram in PowerStation



Equivalent Impedance Diagram



Thevenin Equivalent

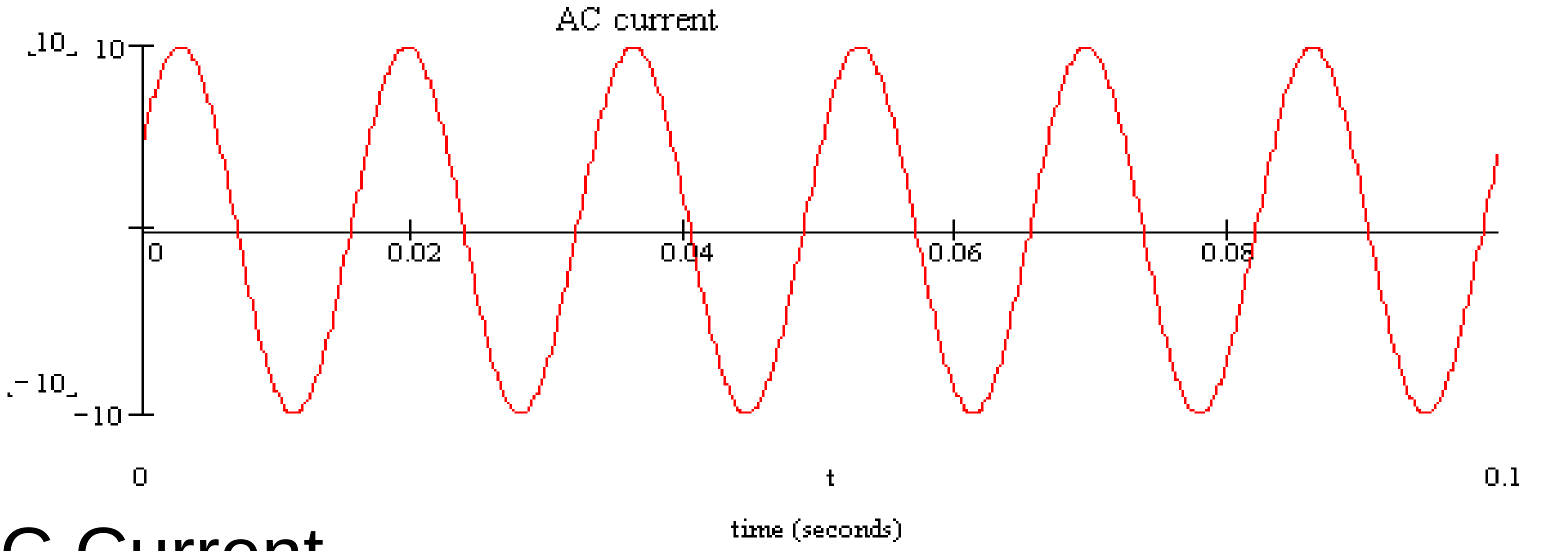


$$\mathbf{v(t) = Ri + L\frac{di}{dt} = Vm \times Sin(\omega t + \theta)} \qquad \mathbf{(1)}$$

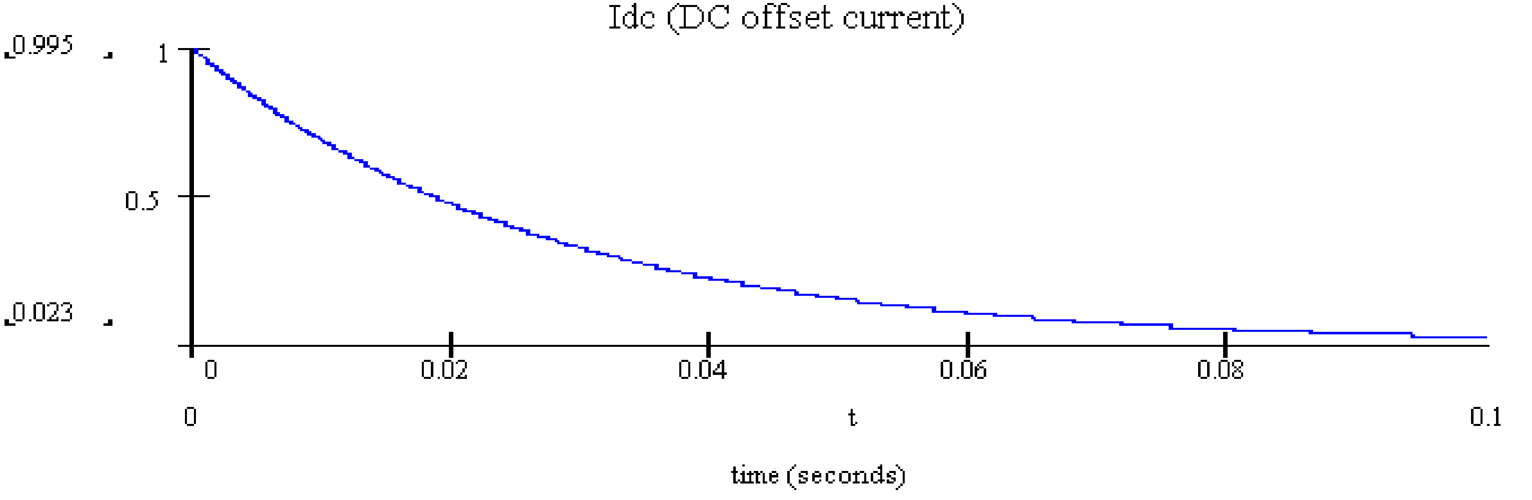
Solving equation 1 yields the following expression

$$\mathbf{i(t) = \underbrace{\frac{Vm}{|Z|} \times sin(\omega t + \theta - \phi)}_{\text{Steady State}} + \underbrace{\frac{Vm}{|Z|} \times sin(\theta - \phi) \times e^{-\frac{R}{L}t}}_{\text{Transient (DC Offset)}}}$$

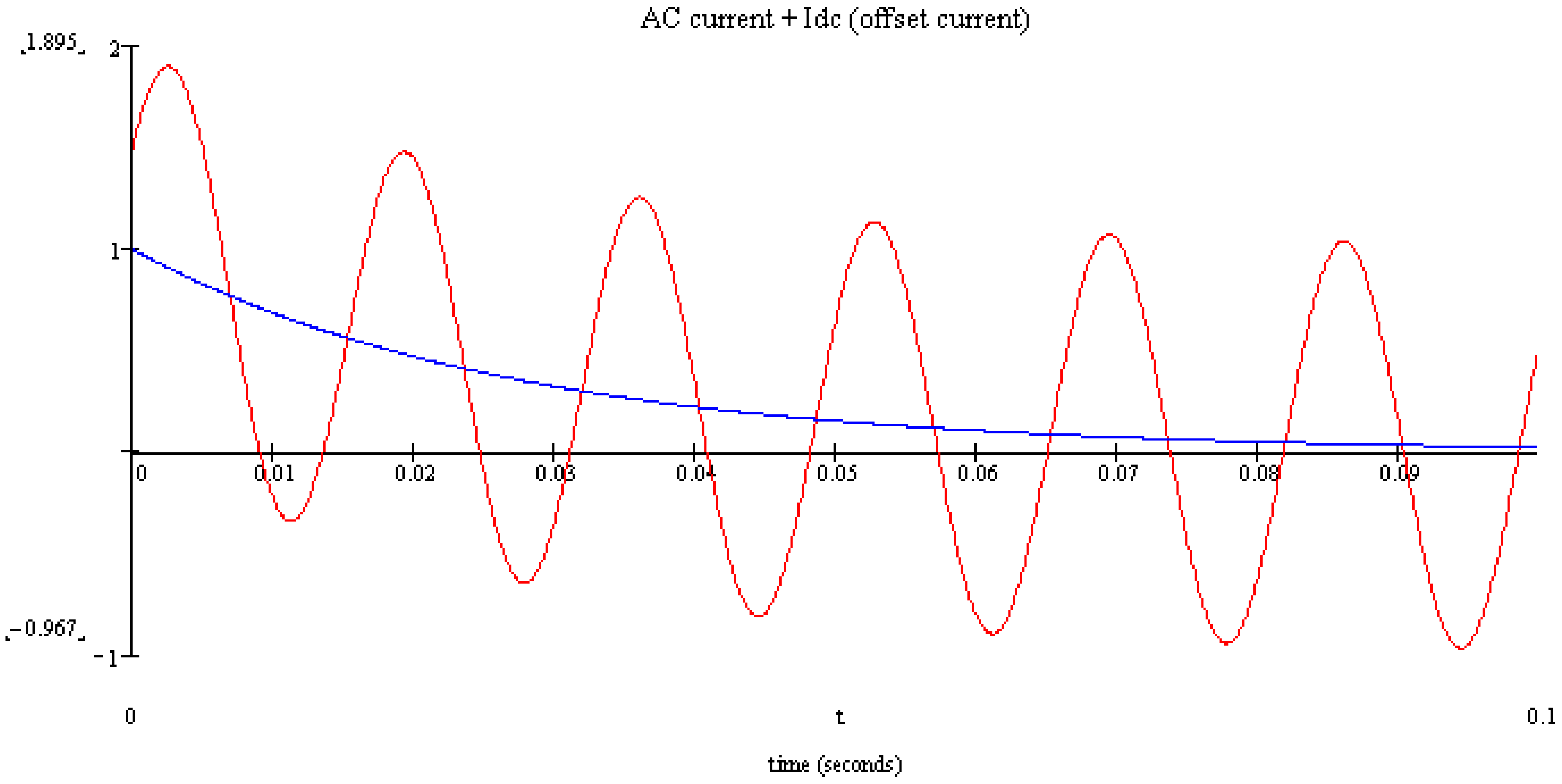
AC Current (Symmetrical) with No AC Decay



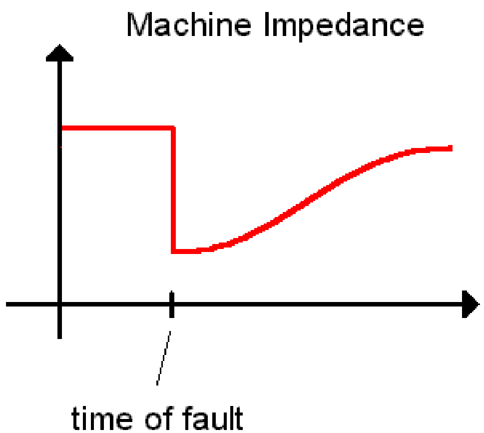
DC Current



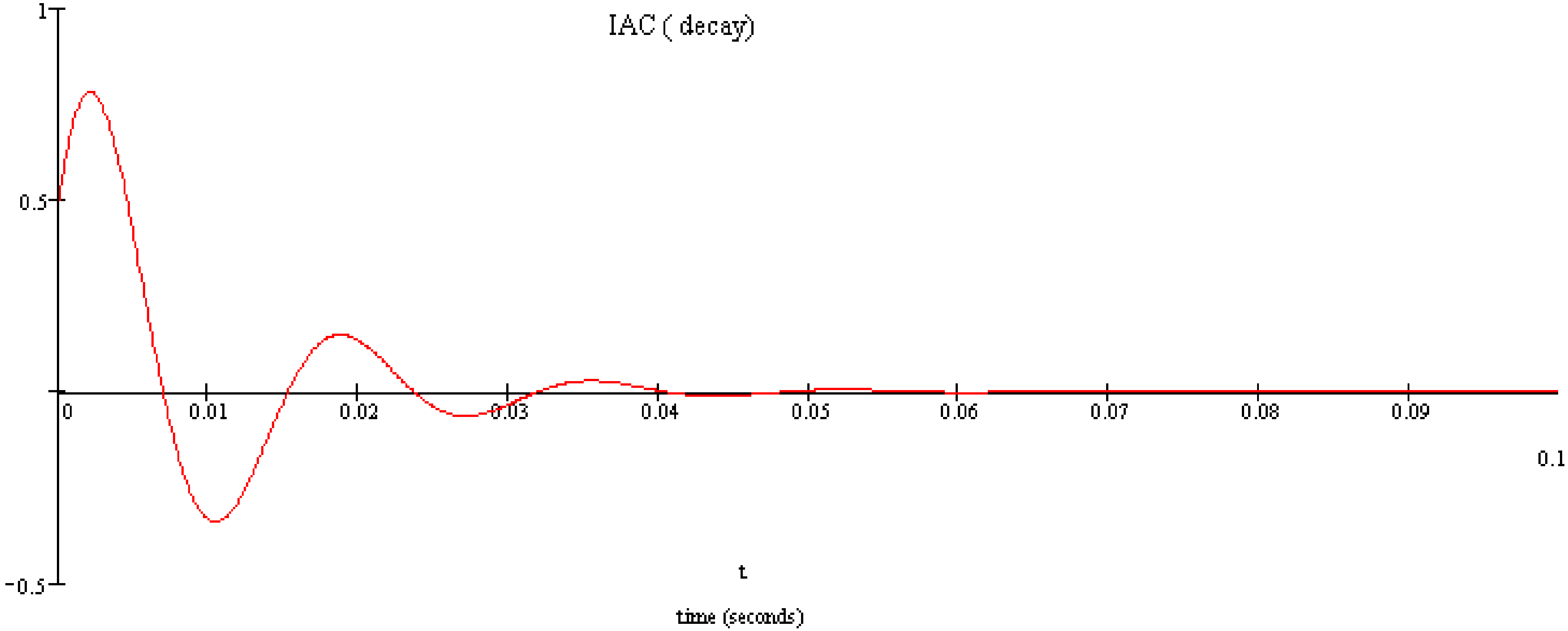
AC Fault Current Including the DC Offset (No AC Decay)



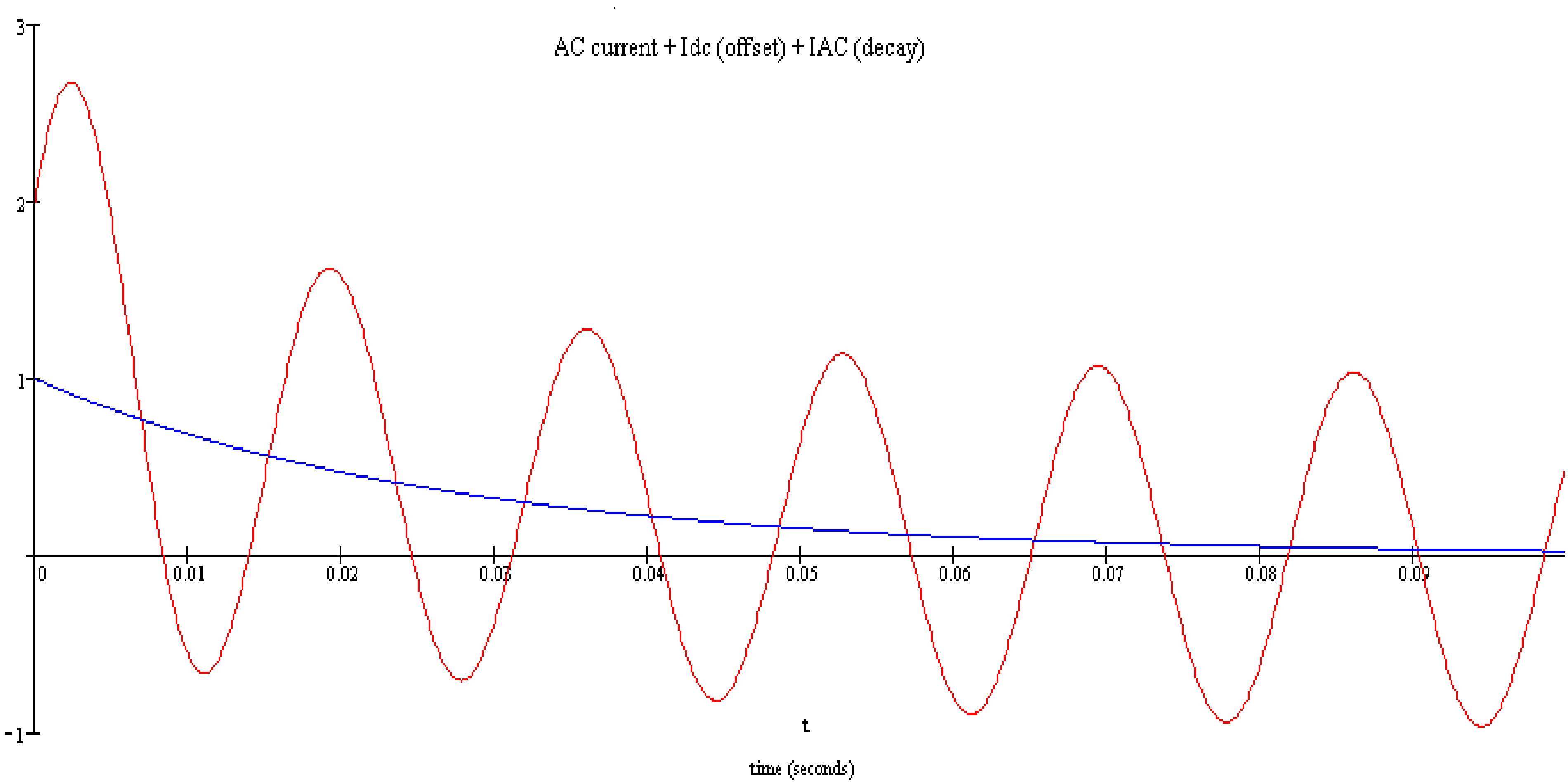
Machine Reactance (λ = L I)



AC Decay Current



Fault Current Including AC & DC Decay



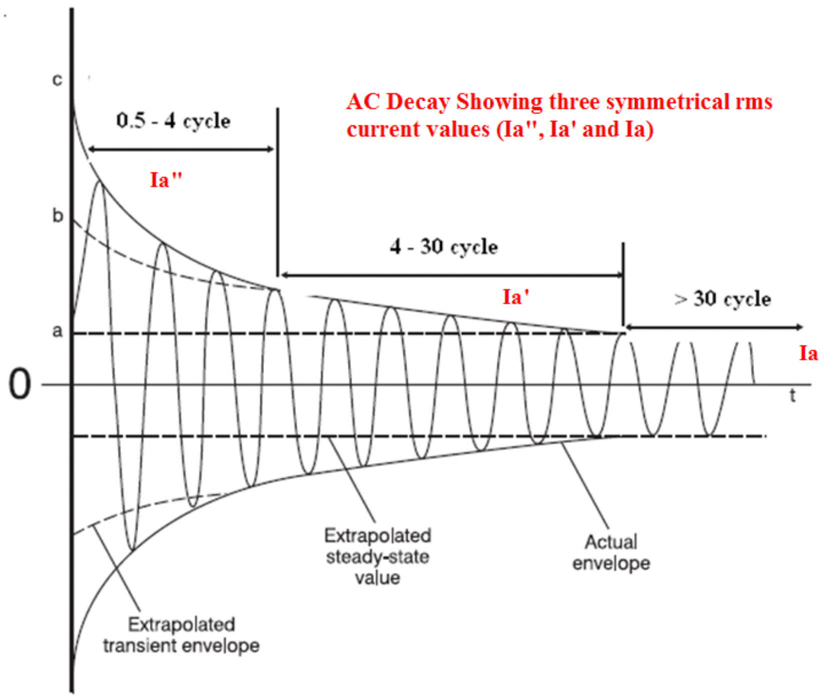
Short-Circuit Study for Arc Flash

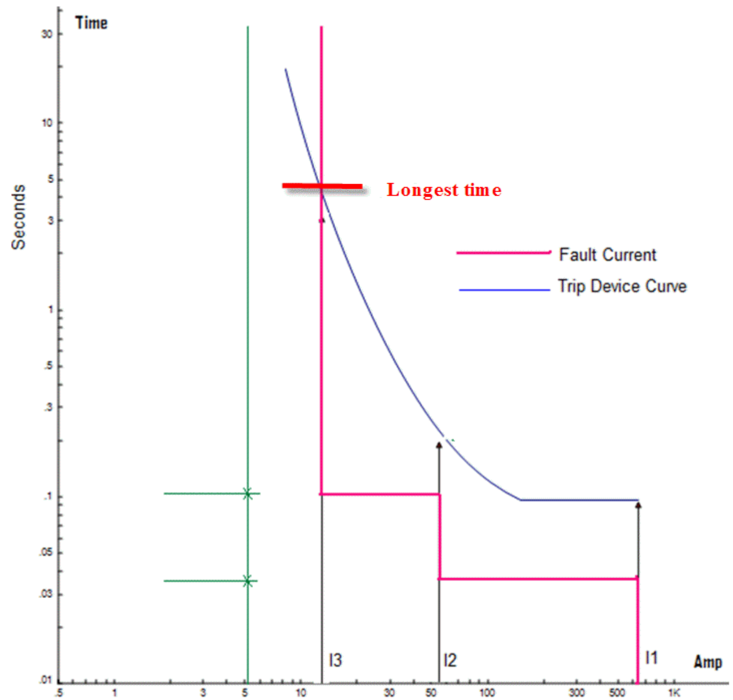
- A Short-Circuit Study can be used to determine any or all of the following:
  - Maximum and Minimum Short-circuit current levels
  - Prefault voltage values should be considered
  - Positive and Negative Impedance Tolerance Adjustments
  - Actual fault current values should be used including decaying contributions for medium voltage systems
  - Operating Conditions and System Configurations which may not be otherwise observed for regular SC studies

Reactance Representation for Utility and Synchronous Machine for AF

	½ Cycle	1 ½ to 4 Cycle	30 Cycle
Utility	X"d	X"d	X"d
Turbo Generator	X"d	X'd	Xd
Hydro-Gen with Amortisseur winding	X"d	X'd	Xd
Condenser	X"d	X'd	α
Synchronous Motor	X"d	X'd	α

Fault Current Decay

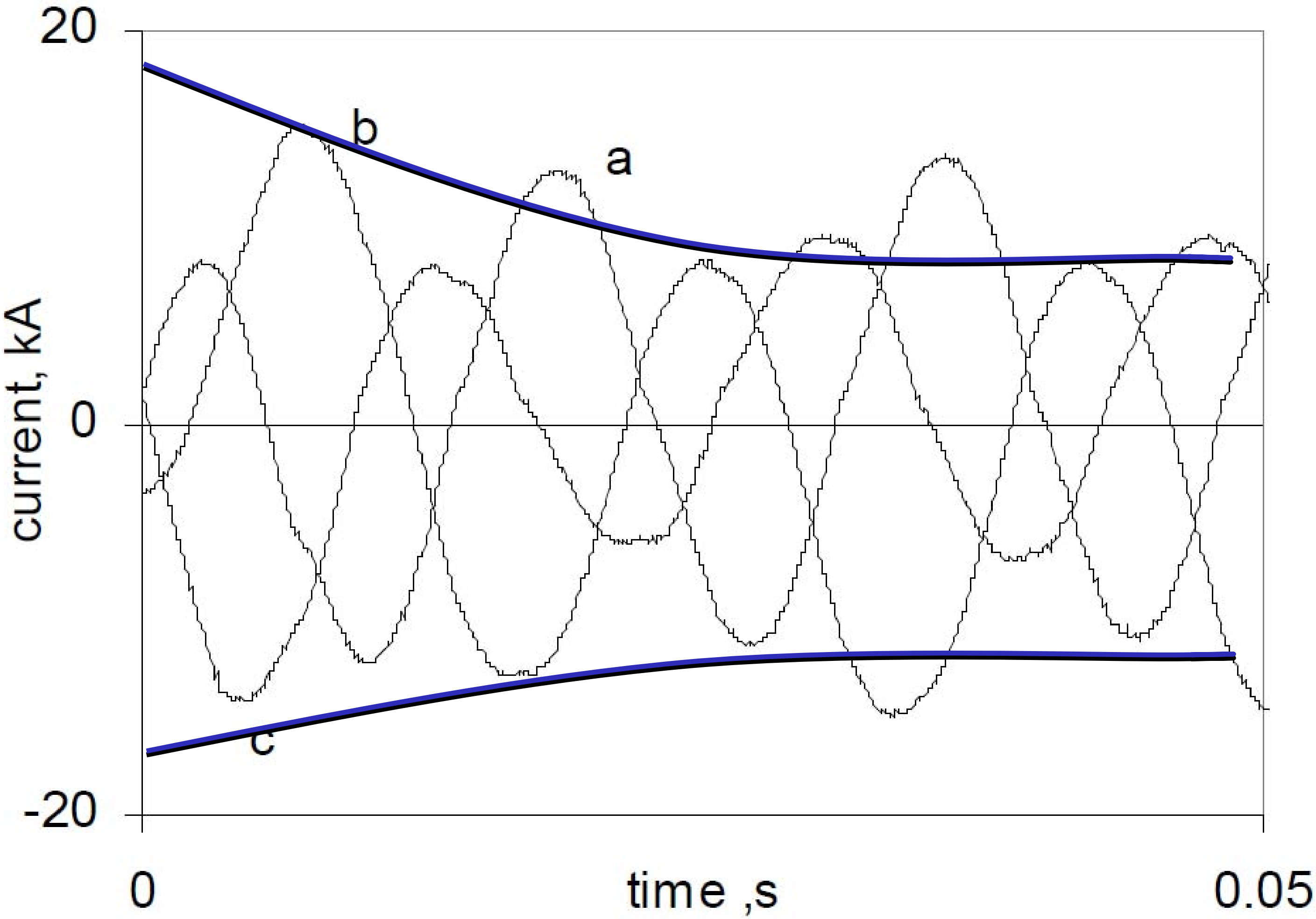




$$\int_{0}^{T_0} \frac{1}{t(I)} dt = 1$$

IEEE Std C37.112-1196 equation (3)

Fault Current Recording



Arcing Currents at 208V, 9.9kA

Overcurrent Protection and Coordination Principles

Definition

- Overcurrent Coordination
  - A systematic study of current responsive devices in an electrical power system.

Objective

- To determine the ratings and settings of fuses, breakers, relay, etc.

- To isolate the fault or overloads.

Coordination

- Limit the extent and duration of service interruption
- Selective fault isolation
- Provide alternate circuits

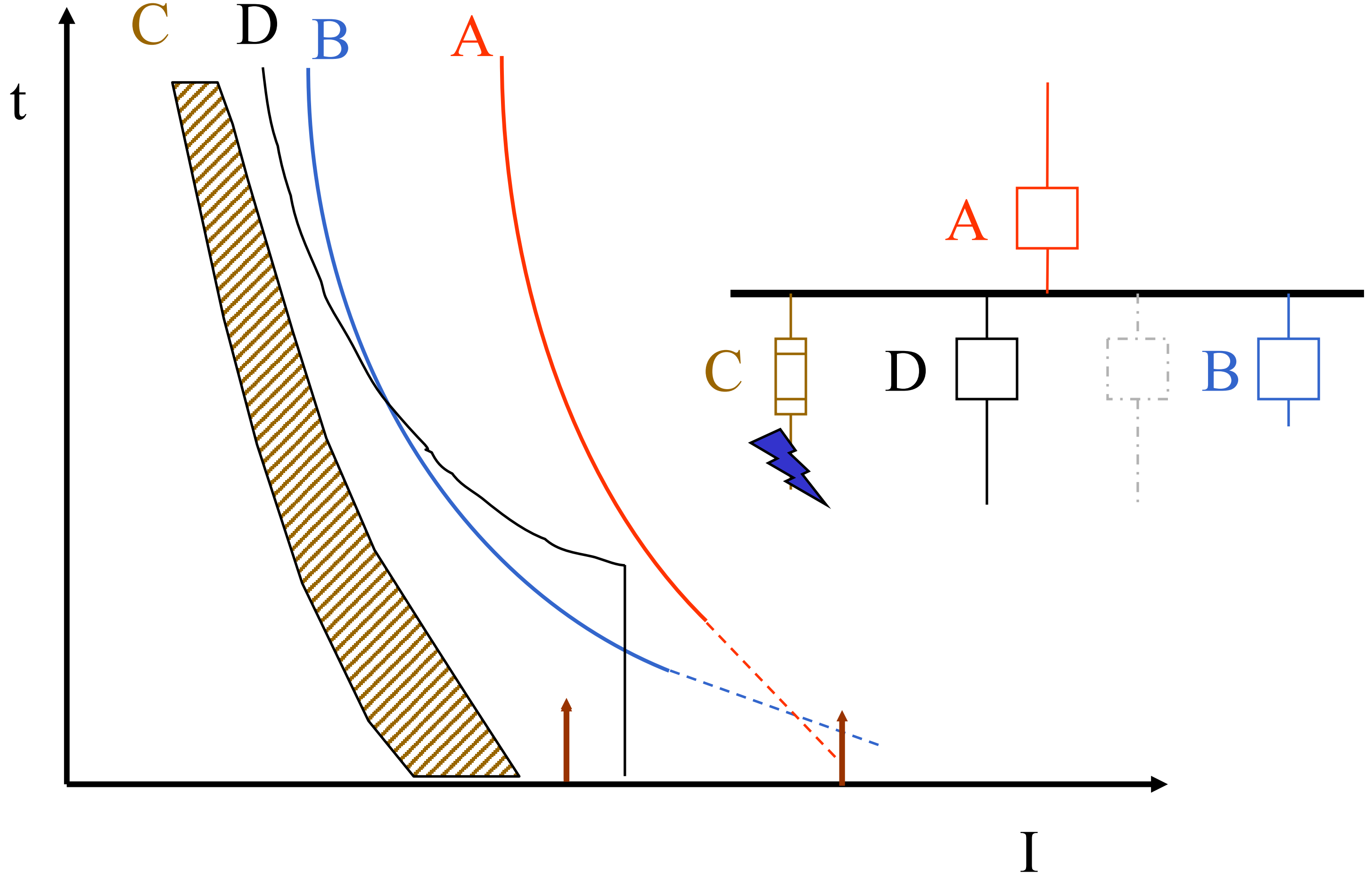
Protection

- Prevent injury to personnel
- Minimize damage to components
  - Quickly isolate the affected portion of the system
  - Minimize the magnitude of available short-circuit

Spectrum Of Currents

- Load Current
  - Up to 100% of full-load
  - 115-125% (mild overload)
- Overcurrent
  - Abnormal loading condition (Locked-Rotor)
- Fault Current
  - Fault condition
  - Ten times the full-load current and higher
- Arc Fault Currents
  - Between 95 to 38% of bolted fault currents

Coordination



Protection vs. Coordination

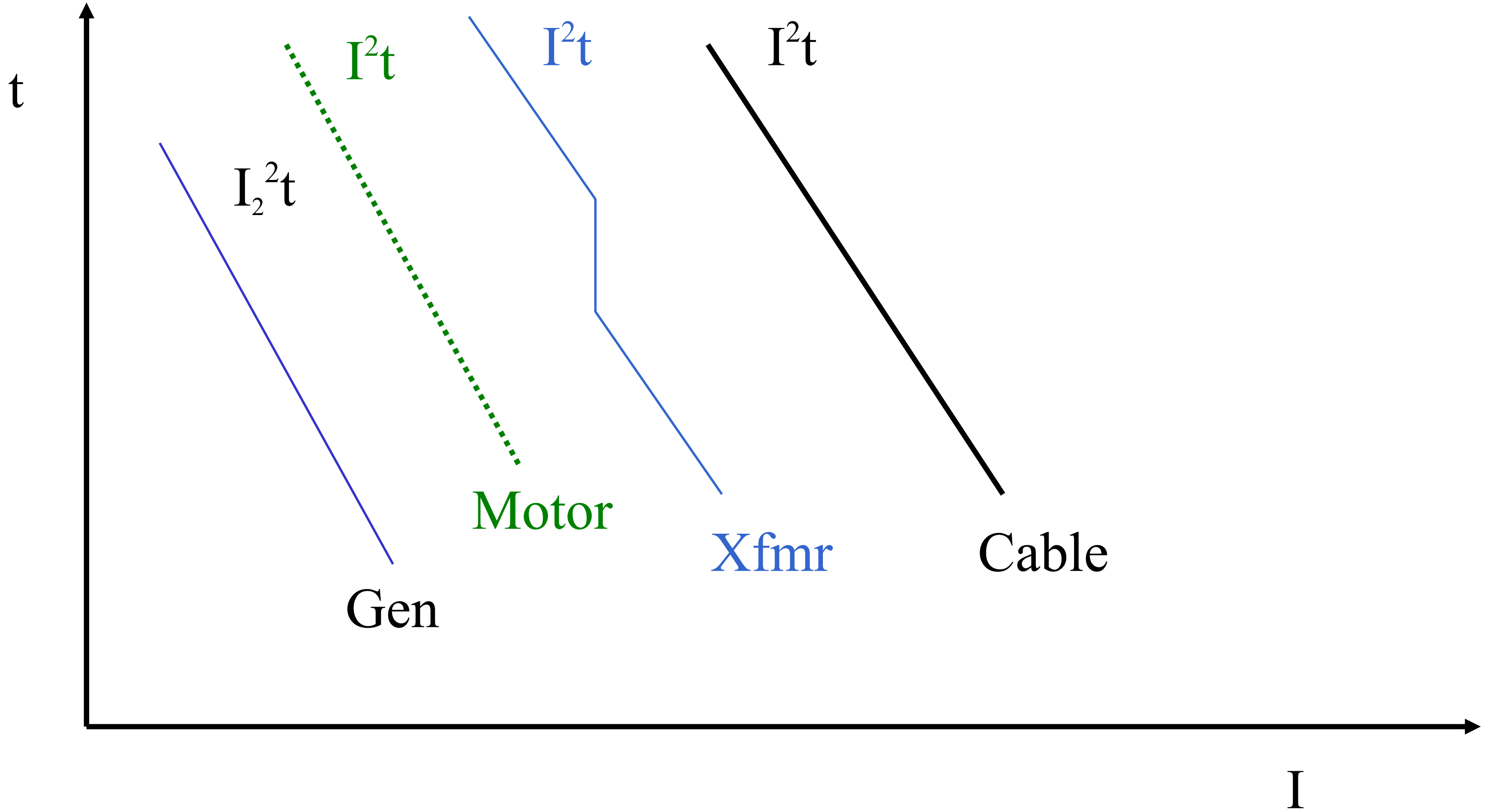
- Coordination is not an exact science
- Compromise between protection and coordination
  - Reliability
  - Speed
  - Performance
  - Economics
  - Simplicity

Fixed Points

Points or curves which do not change regardless of protective device settings:

- Cable damage curves
- Cable ampacities
- Transformer damage curves & inrush points
- Motor starting curves
- Generator damage curve / Decrement curve
- SC maximum and minimum fault points

Capability / Damage Curves



Cable Protection

The actual temperature rise of a cable when exposed to a short circuit current for a known time is calculated by:

$$A = \sqrt{\frac{I^2 t}{0.0297 \log\left[\frac{T_2 + 234}{T_1 + 234}\right]}}$$

Where:

A= Conductor area in circular-mils

I = Short circuit current in amps

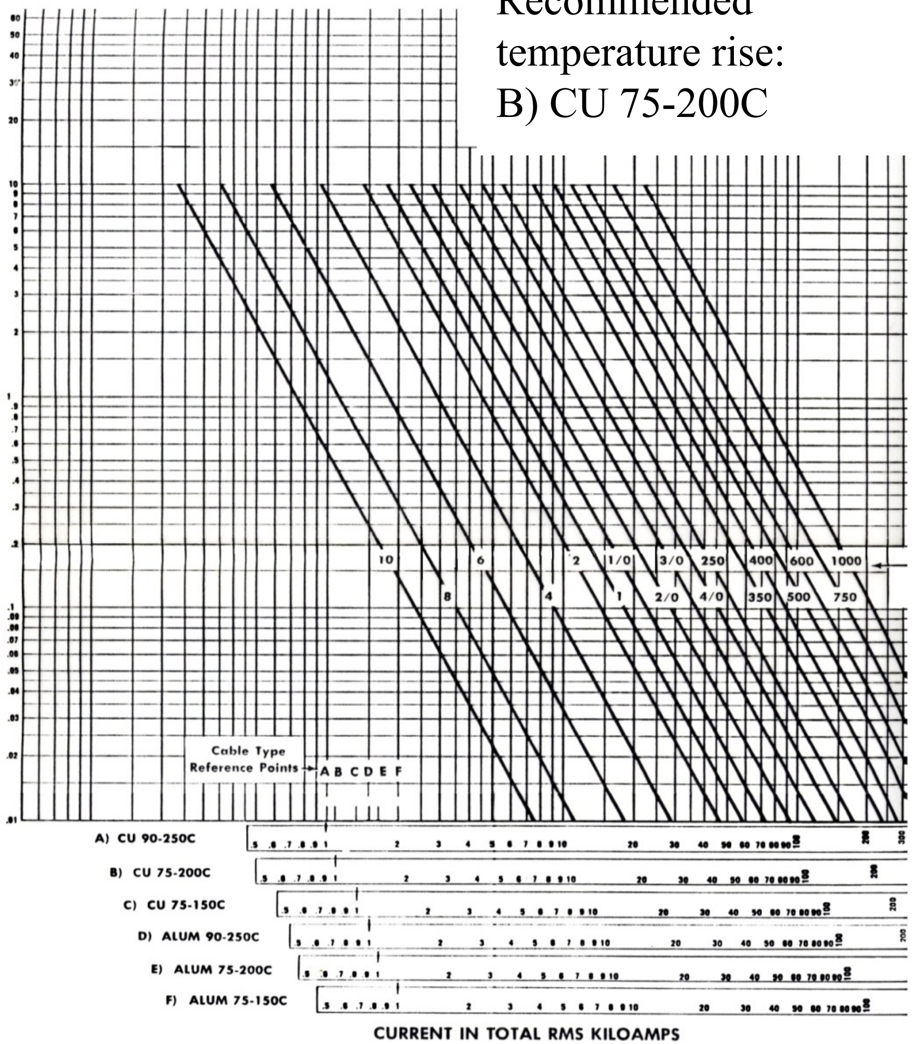
t = Time of short circuit in seconds

T_1= Initial operation temperature (75^0C)

T_2=Maximum short circuit temperature (150^0C)

Cable Short-Circuit Heating Limits

Recommended
temperature rise:
B) CU 75-200C



INSULATED CABLE
SHORT CIRCUIT HEATING LIMITS

Transformer Categories I, II

Fig 1
Category I Transformers

NOTE: The maximum short-circuit withstand capability of Category I Transformers is defined in ANSI/IEEE C57.12.00-1980 [2]

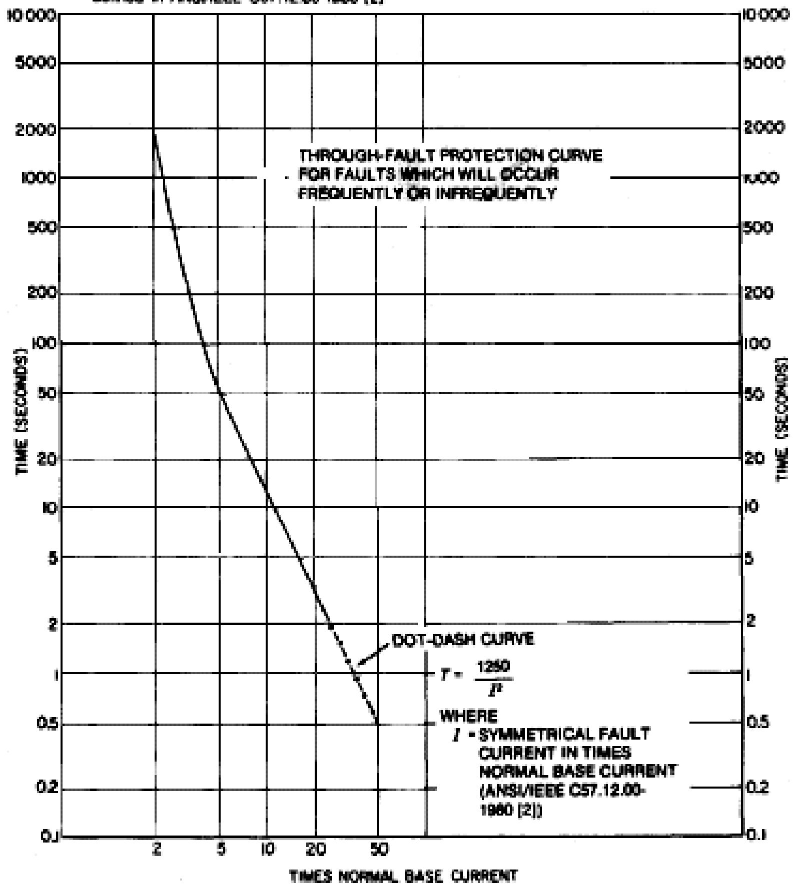
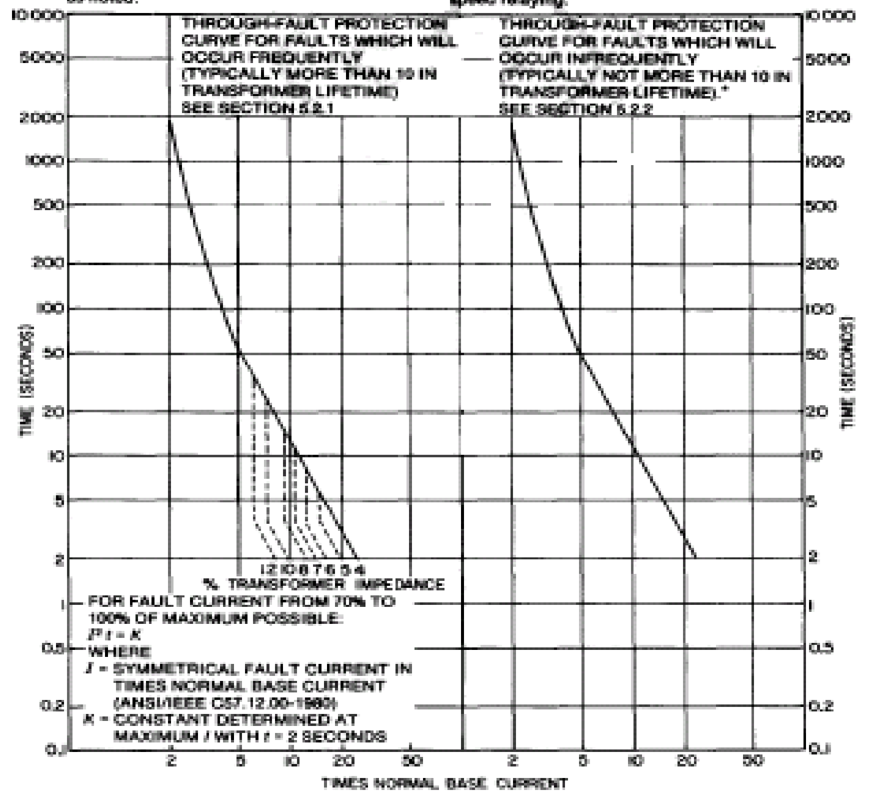
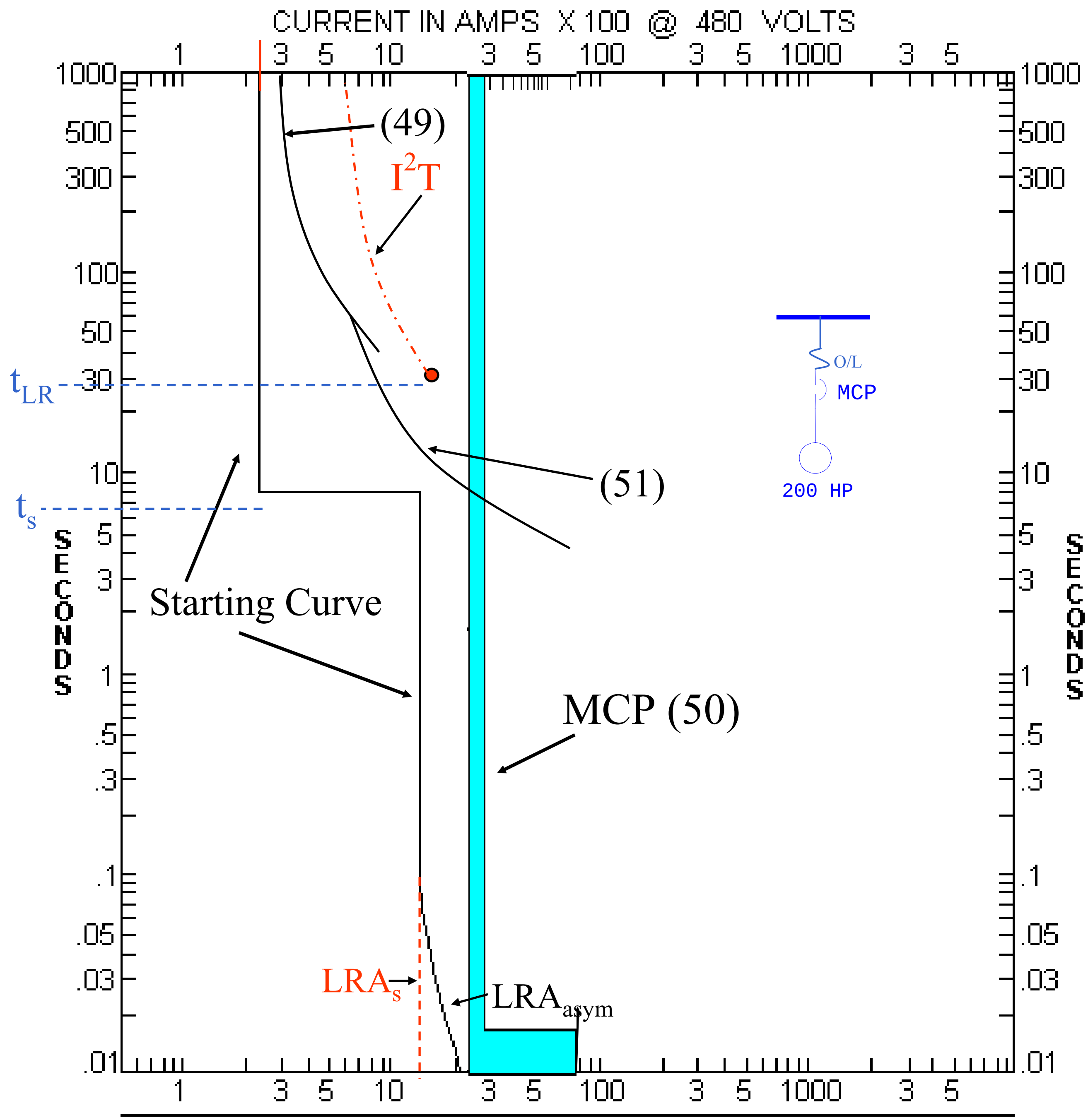


Fig 2
Category II Transformers

NOTE: Sample $I^2 t = K$ curves have been plotted for selected transformer impedances as noted.

* This curve may also be used for backup protection where the transformer is exposed to frequent faults normally cleared by high-speed relaying.





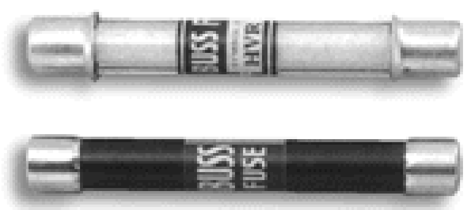
CURRENT IN AMPS X 100 @ 480 VOLTS
SECONDS
(49)
I²T
(51)
Starting Curve
MCP (50)
LRA_s
LRA_asym
t_LR
t_s
O/L
MCP
200 HP

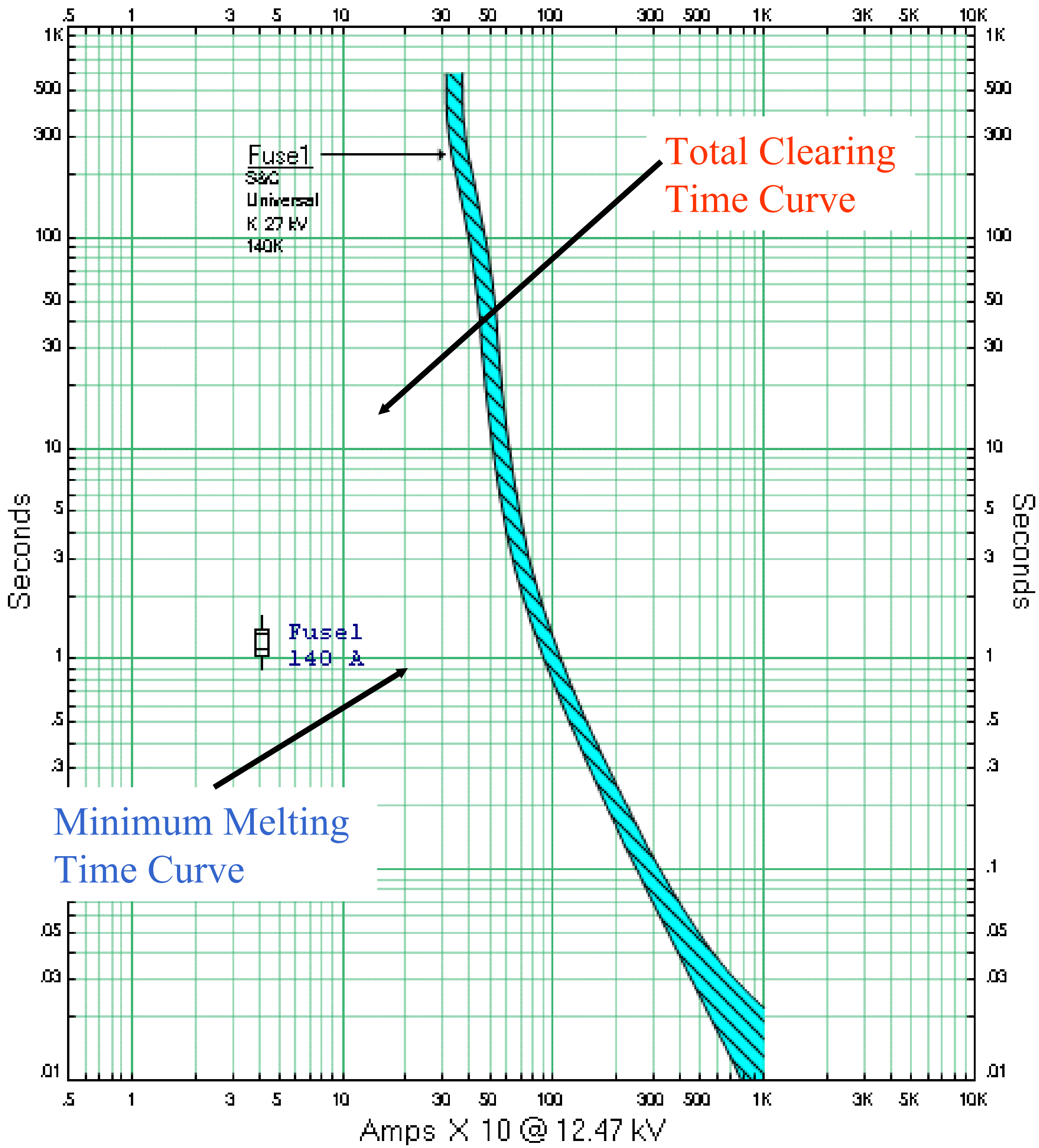
Protective Devices

- Fuse
- Overload Heater
- Thermal Magnetic
- Low Voltage Solid State Trip
- Electro-Mechanical
- Motor Circuit Protector (MCP)
- Relay (50/51 P, N, G, SG, 51V, 67, 49, 46, 79, 21, ...)

Fuse Types

- Expulsion Fuse (Non-CLF)
- Current Limiting Fuse (CLF)
- Electronic Fuse *(S&C Fault Fiter)*



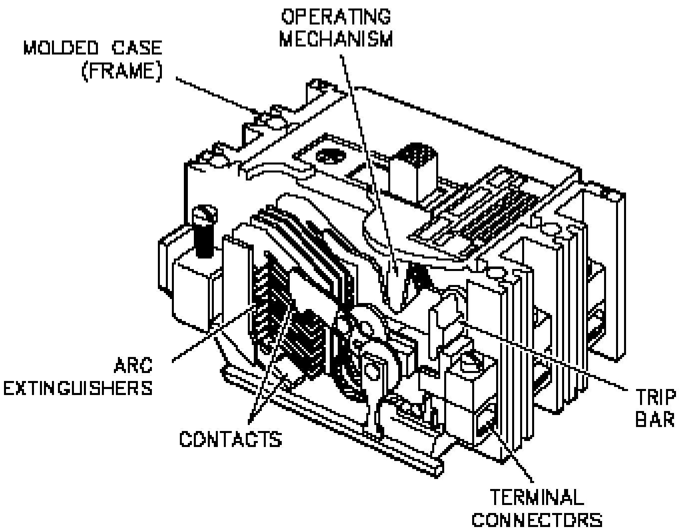

Total Clearing Time Curve
Minimum Melting Time Curve
Fuse1
S&C
Universal
K 27 kV
140K
Fuse1
140 A
Seconds
Amps X 10 @ 12.47 kV

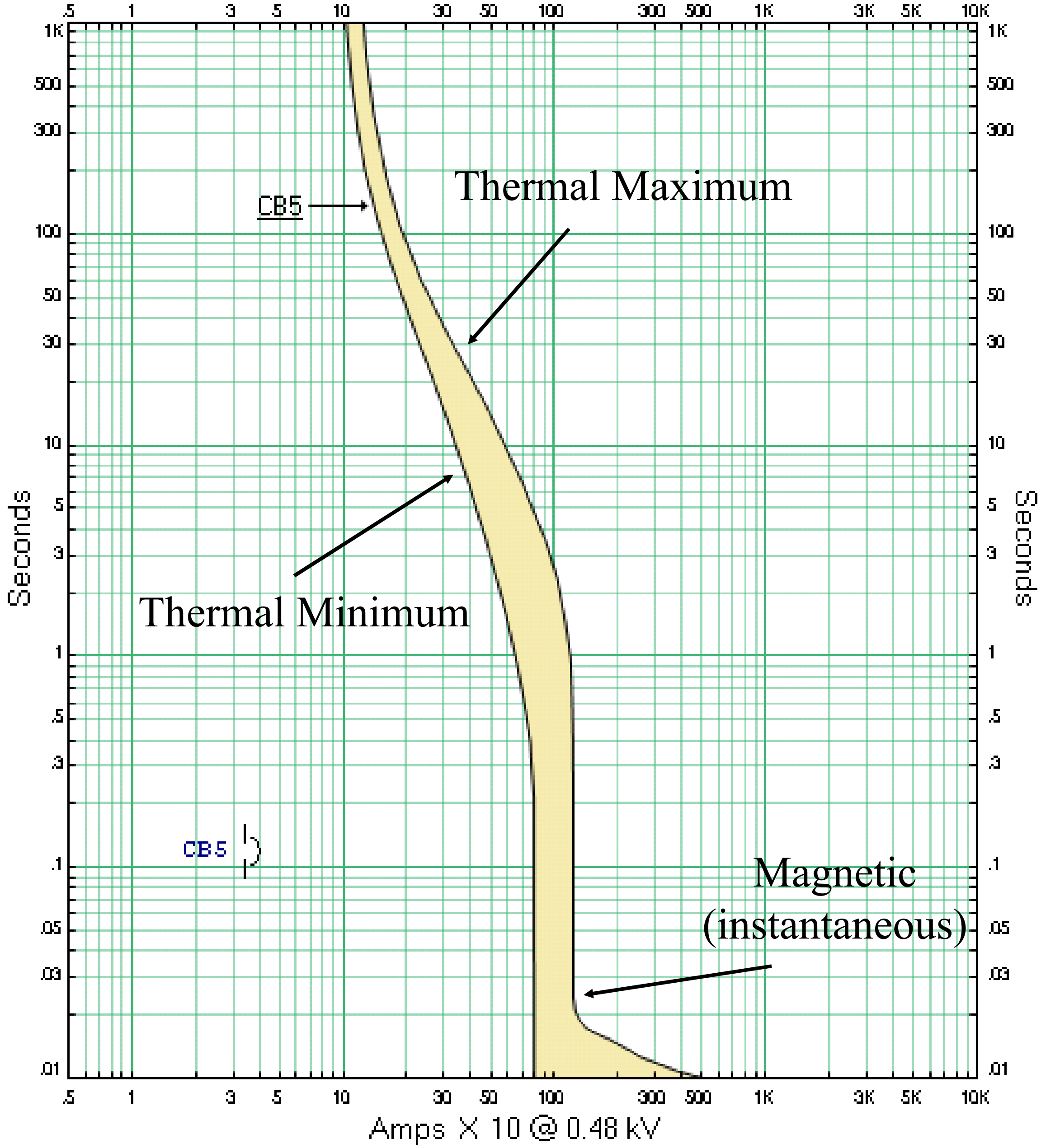
Molded Case CB

- Thermal-Magnetic
- Magnetic Only
- Motor Circuit Protector (MCP)
- Integrally Fused (Limiters)
- Current Limiting
- High Interrupting Capacity
- Non-Interchangeable Parts
- Insulated Case (Interchange Parts)

Types

- Frame Size
- Poles
- Trip Rating
- Interrupting Capability
- Voltage

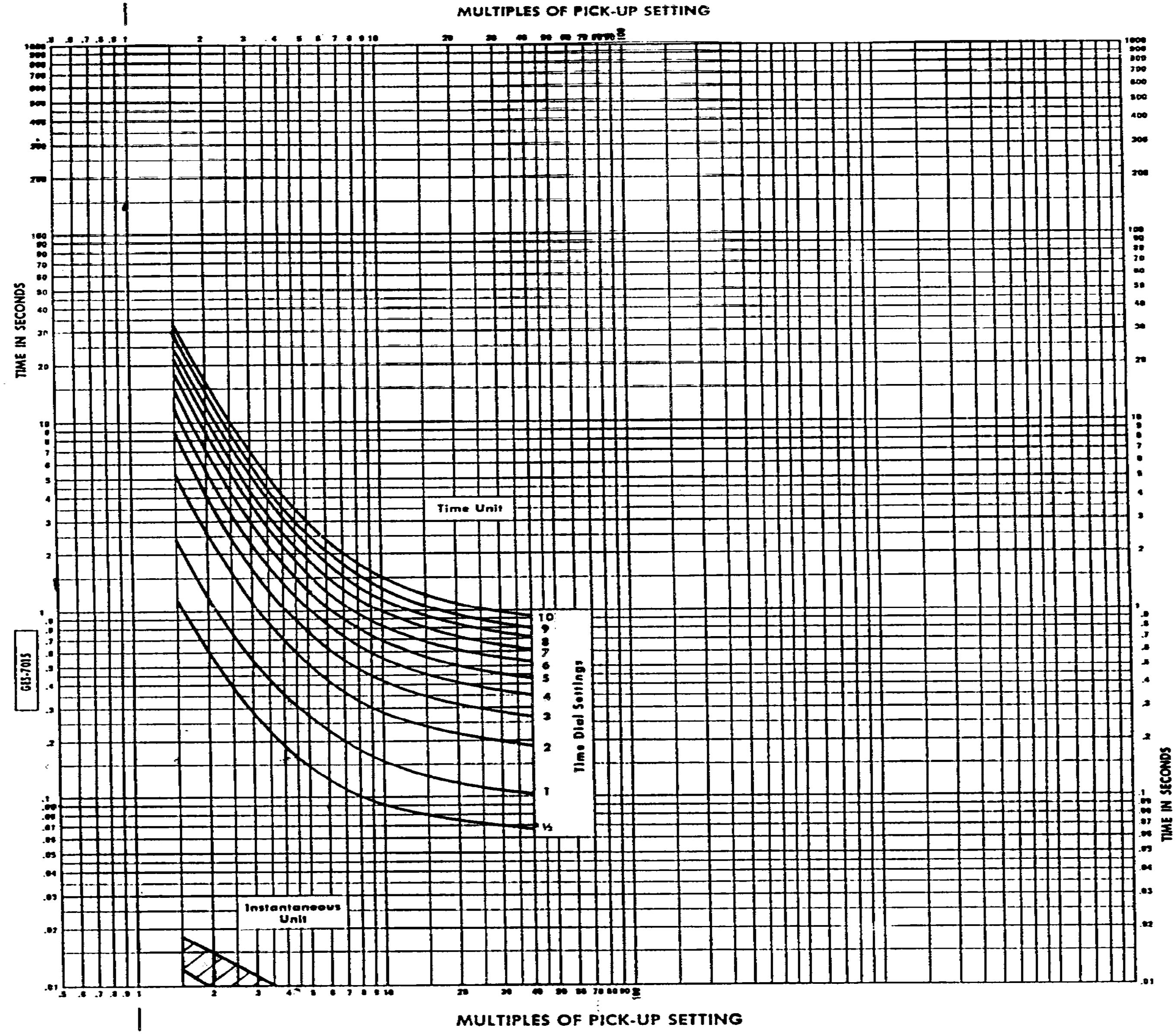




Thermal Maximum
Thermal Minimum
Magnetic (instantaneous)
CB5
CB5
Seconds
Seconds
Amps X 10 @ 0.48 kV
.5
1
3
5
10
30
50
100
300
500
1K
3K
5K
10K
.01
.03
.05
.1
.3
.5
1
3
5
10
30
50
100
300
500
1K

Overcurrent Relay

- Time-Delay (51 – I>)
- Short-Time Instantaneous (I>>)
- Instantaneous (50 – I>>>)
- Electromagnetic (induction Disc)
- Solid State (Multi Function / Multi Level)
- Application



GENERAL ELECTRIC	TIME OVERCURRENT RELAY **IFC 53 RELAY** Very Inverse Standard Time Time-current Curves	GES-7015

Ratings (Amperes)
Time Unit: 0.5-4, 1.0-12
Instantaneous Unit: 2-50, 6-150

Frequency Rating
60 Hertz

Settings

Time Unit (Taps)	Inst. Unit
0.5, 0.6, 0.7, 0.8, 1.0, 1.2, 1.5, 2.0, 2.5, 3.0, 4.0	Continuously Adjustable
1.0, 1.2, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 10.0, 12.0	

GENERAL ELECTRIC CO., POWER SYSTEMS MANAGEMENT, PHILADELPHIA, PA. 19142

Relay Coordination

- Time margins should be maintained between T/C curves
- Adjustment should be made for CB opening time
- Shorter time intervals may be used for solid state relays
- Upstream relay should have the same inverse T/C characteristic as the downstream relay (CO-8 to CO-8) or be less inverse (CO-8 upstream to CO-6 downstream)
- Extremely inverse relays coordinates very well with CLFs

Arc Flash Analysis Methods and Mitigation

Analysis Methods for Arc Flash Hazards

NFPA 70E 2009 “Standard for Electrical Safety in the Workplace”

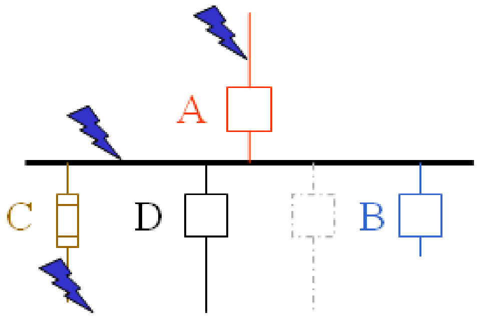
IEEE 1584 2004a “Guide for Performing Arc Flash Hazard Calculations”

Arc Flash Incident Video

Arc Flash Incident Video

Arc Flash Incident Video

AF Analysis Considerations



- Possible Arc Fault Locations
  - Line side arc faults
  - Load side arc faults
- Arc Flash Analysis Worst Case Scenarios
  - Maximum bolted short-circuit fault current
  - Minimum bolted short-circuit fault current
- Arcing Current Variation
  - Incident Energy at 100% of arcing current
  - Incident Energy at 85% of arcing current

Analysis of AF Results

- Arc Flash Analysis Scope
  - 100s or 1000s of Buses
  - High/Medium/Low Voltage Systems
  - Multiple Operating Configurations
  - Dozens of Multiple Scenarios to be considered

Analysis of AF Results

- Determine Which Protective Device Clears the Arc Fault
  - Is it the first upstream device in all cases?
- Determine the Locations with Special Analysis Conditions
  - Ibf is less than 700 or higher than 106,000 Amps
  - The bus nominal kV less than 0.208 kV
  - The feeder source has capacity less than 125 kVA (may not have enough energy to generate the arc)

Methods to Mitigate the Incident Energy

- Methods to Reduce the Fault Clearing Time
  - Improving coordination settings of OC PDs.
  - Type 50 protective devices (Instantaneous)
  - Arc Flash light sensors
  - Maintenance mode (switch)
  - Differential protection
  - Zone selective interlocking protection (ZSIP)
- Methods to Increase the Working Distance
  - Remote racking of breakers/Remote switching
  - Use of Hot Sticks

Methods to Mitigate the Incident Energy

- Methods to Reduce the Short-Circuit Current
  - Current limiting fuses and circuit breakers
  - Current limiting reactors, Isolating Transformers
  - High resistance grounding
- Methods to Reduce the Energy Exposure
  - Arc resistant switchgear
  - Arc shields
  - Infrared scanning, Partial Discharge and or Corona Cameras

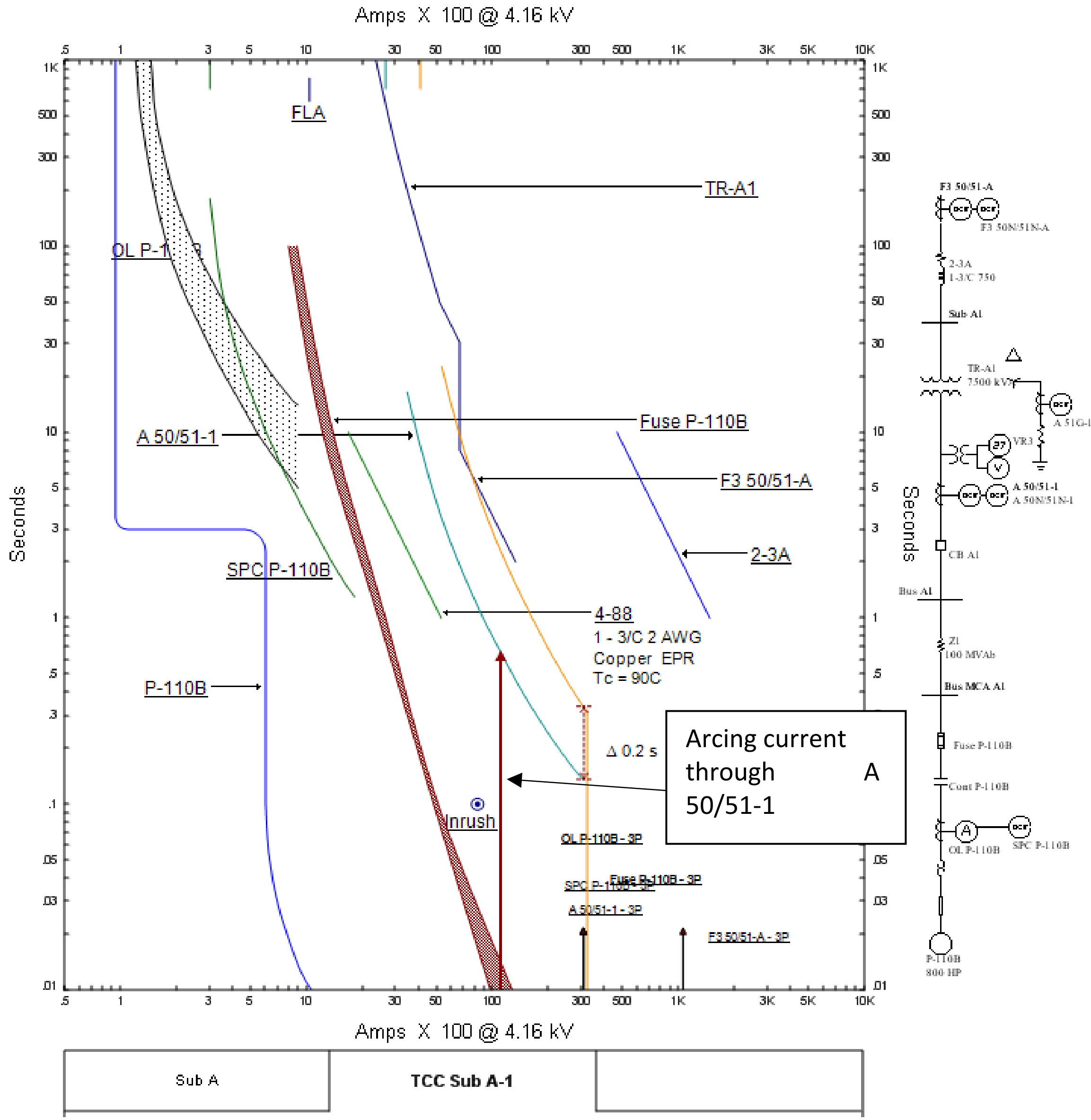
Improving Over-Current Device Coordination Settings

- Purpose is to isolate the fault with the nearest upstream over-current protective device
- Arc flash results are extremely dependent on coordination settings
- Unnecessarily high time dial settings for type 51 over-current devices
- Selection of fuses with faster total clearing time characteristic curves can reduce the energy significantly

Fault Clearing Time is 37 cycles with current time dial settings

Incident Energy released is greater than 27 cal/cm²

Category 4

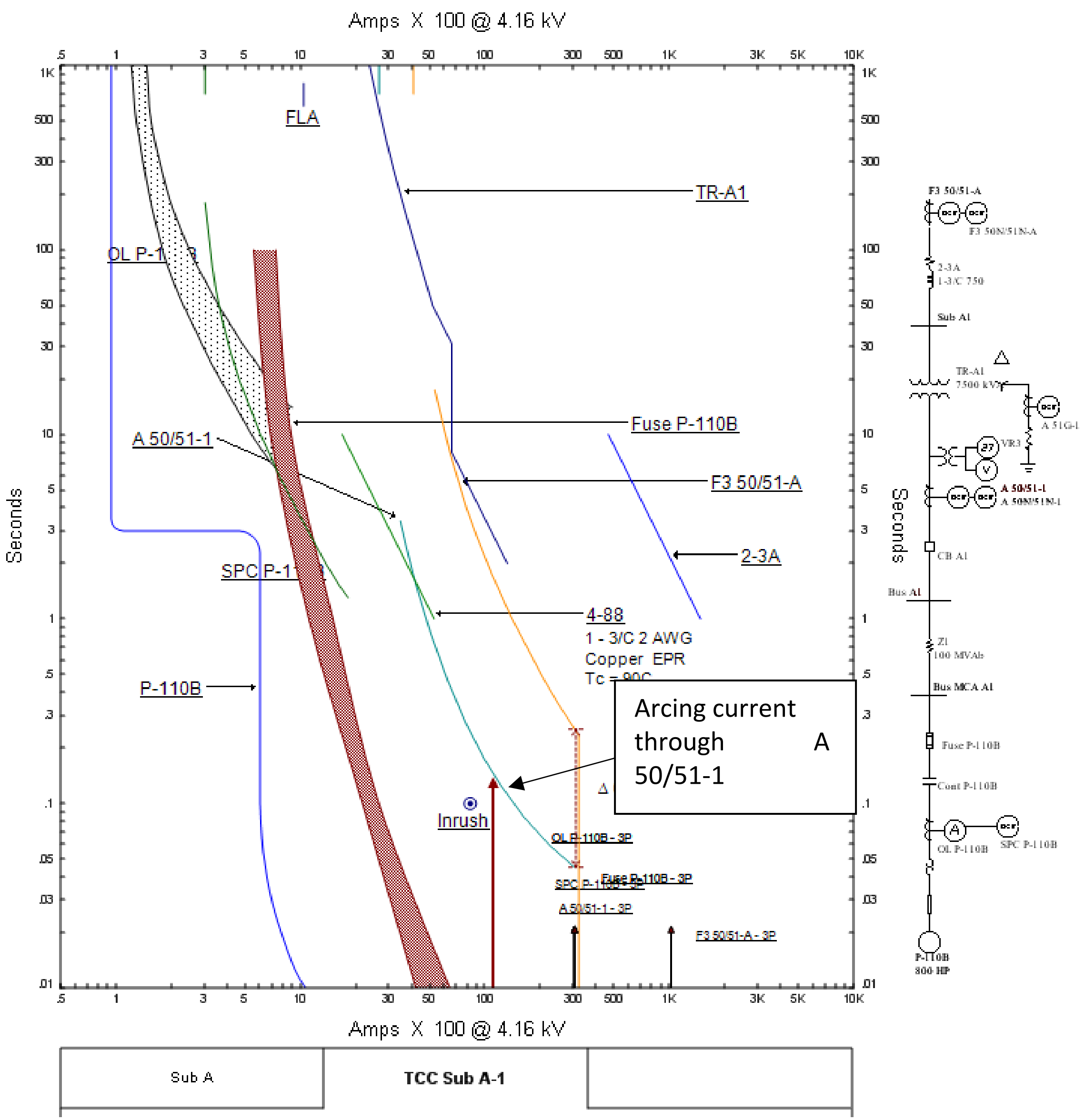


Fault Clearing Time = 10 cycles

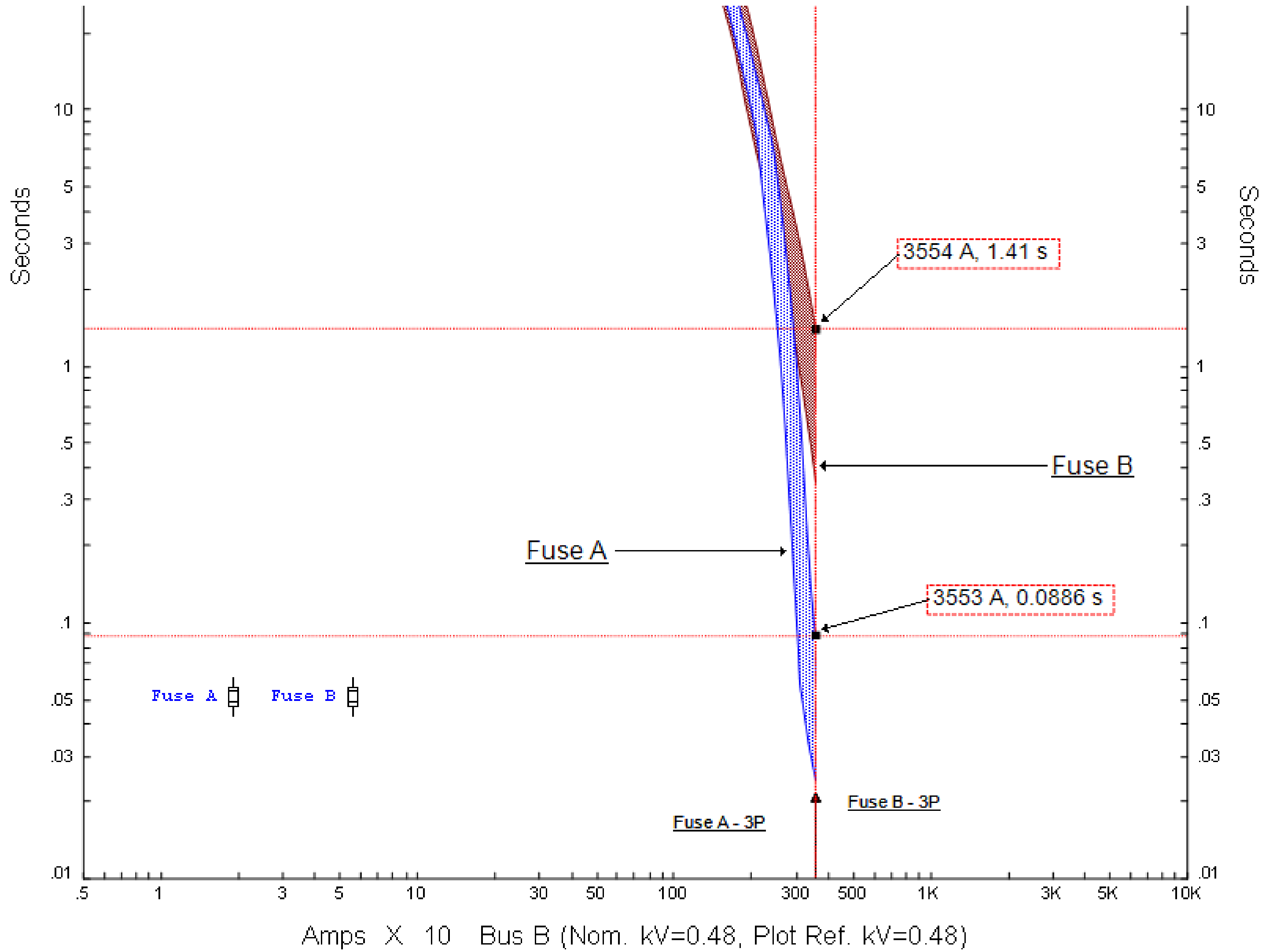
with lower time dial settings

Incident Energy released is less than 8 cal/cm²

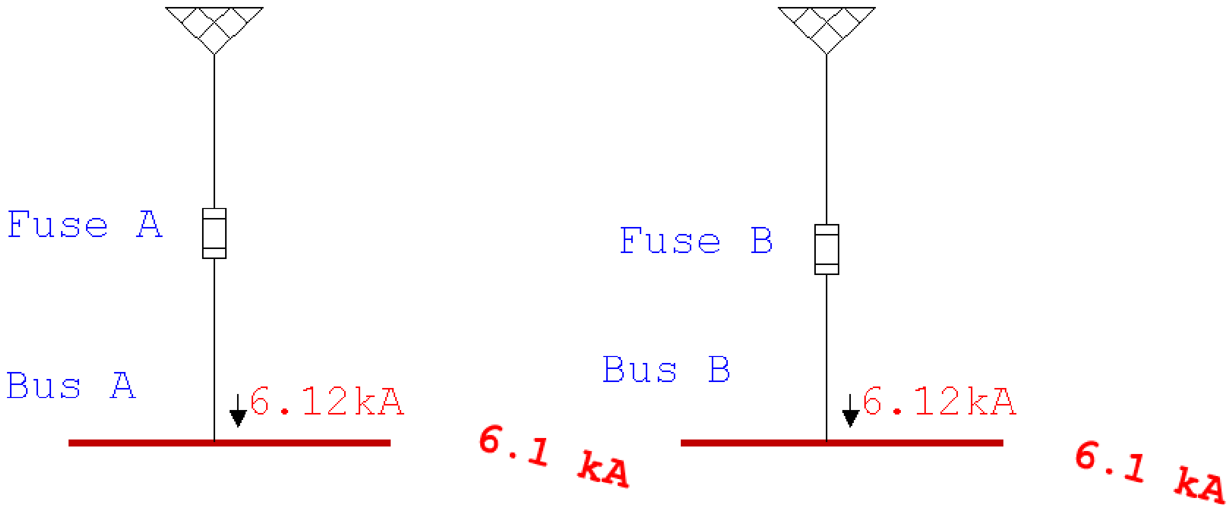
Category 2



Fuse Total Clearing Time based on 3.5 kA Arc Fault



Incident Energy Released for Each Fuse



85% Ia = 3.56 kA
Category 0
1.27 ft
0.94 cal/cm² @18"

FCT = 0.09 sec.

85% Ia = 3.56 kA
Category 3
8.26 ft
14.80 cal/cm² @18"

FCT = 1.41 sec.

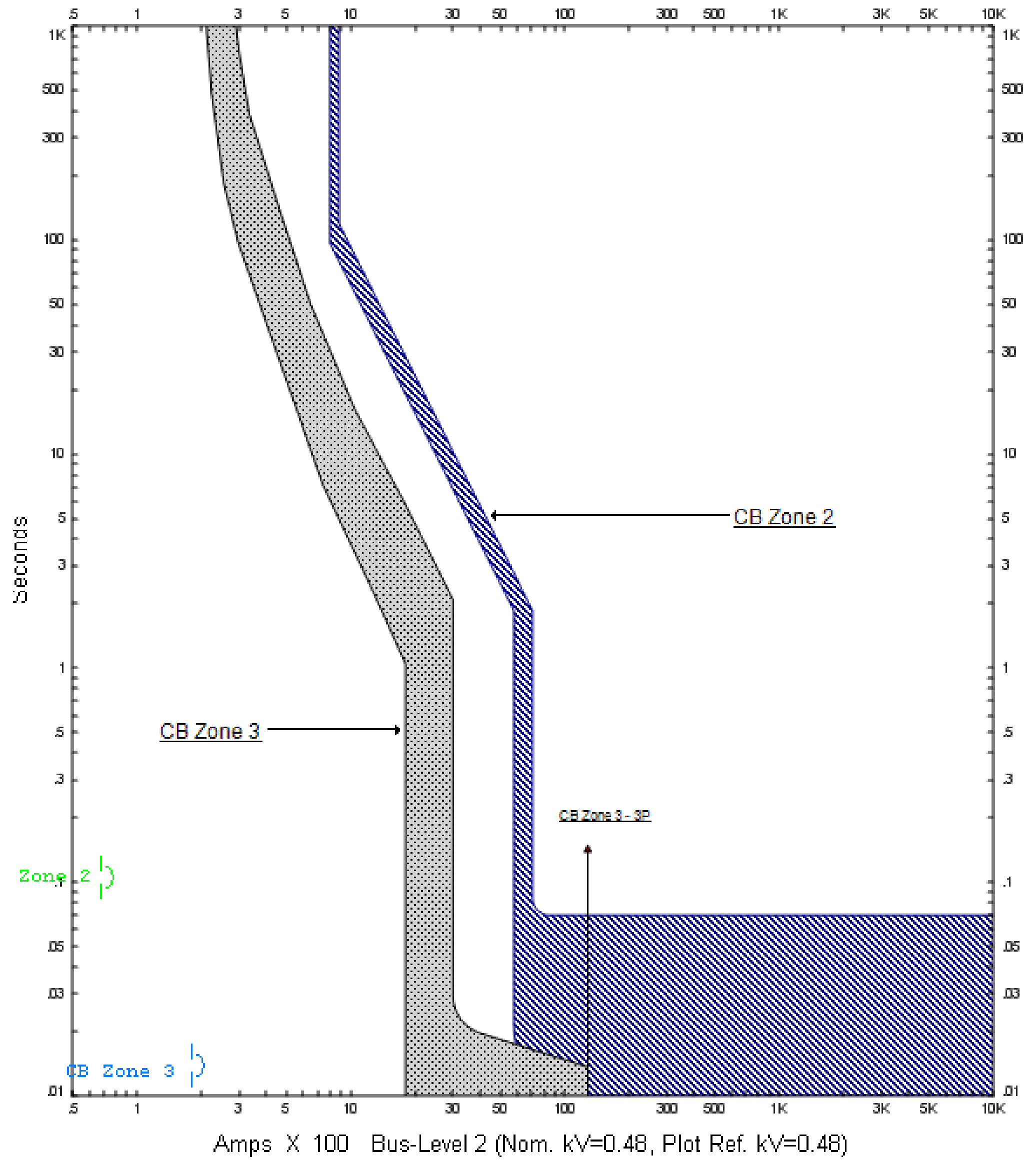
Type 50 Protective Device

- Relays with instantaneous settings
- Molded case circuit breakers
- Insulated case breakers
- Power circuit breakers with instantaneous direct acting trip elements

Type 50 PD Advantages

- Fast acting to reduce the fault clearing time since it can operate within 3 to 6 cycles
- Commonly available for most MV and LV applications
- Cost effective and do not require special installations
- Already installed in electrical system and may only require adjustments to reduce the incident energy

Type 50 Protective Devices



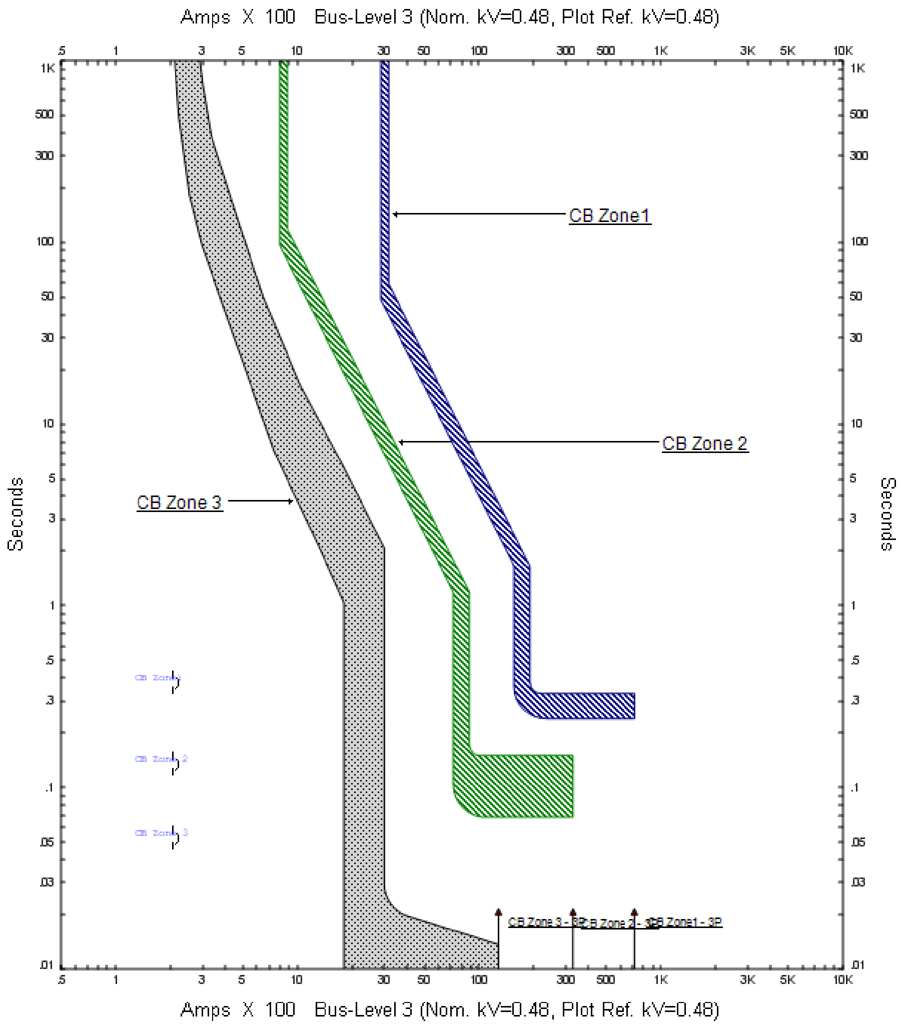
Type 50 PD Drawbacks

- To achieve coordination with downstream elements, upstream source Protective Devices have longer time delays (do not have instantaneous protection)

- The arcing current magnitude passing through the Type 50 protective device must be higher than the device’s instantaneous pickup setting

Type 50 PD Drawbacks

Selective Coordination introduces time delays



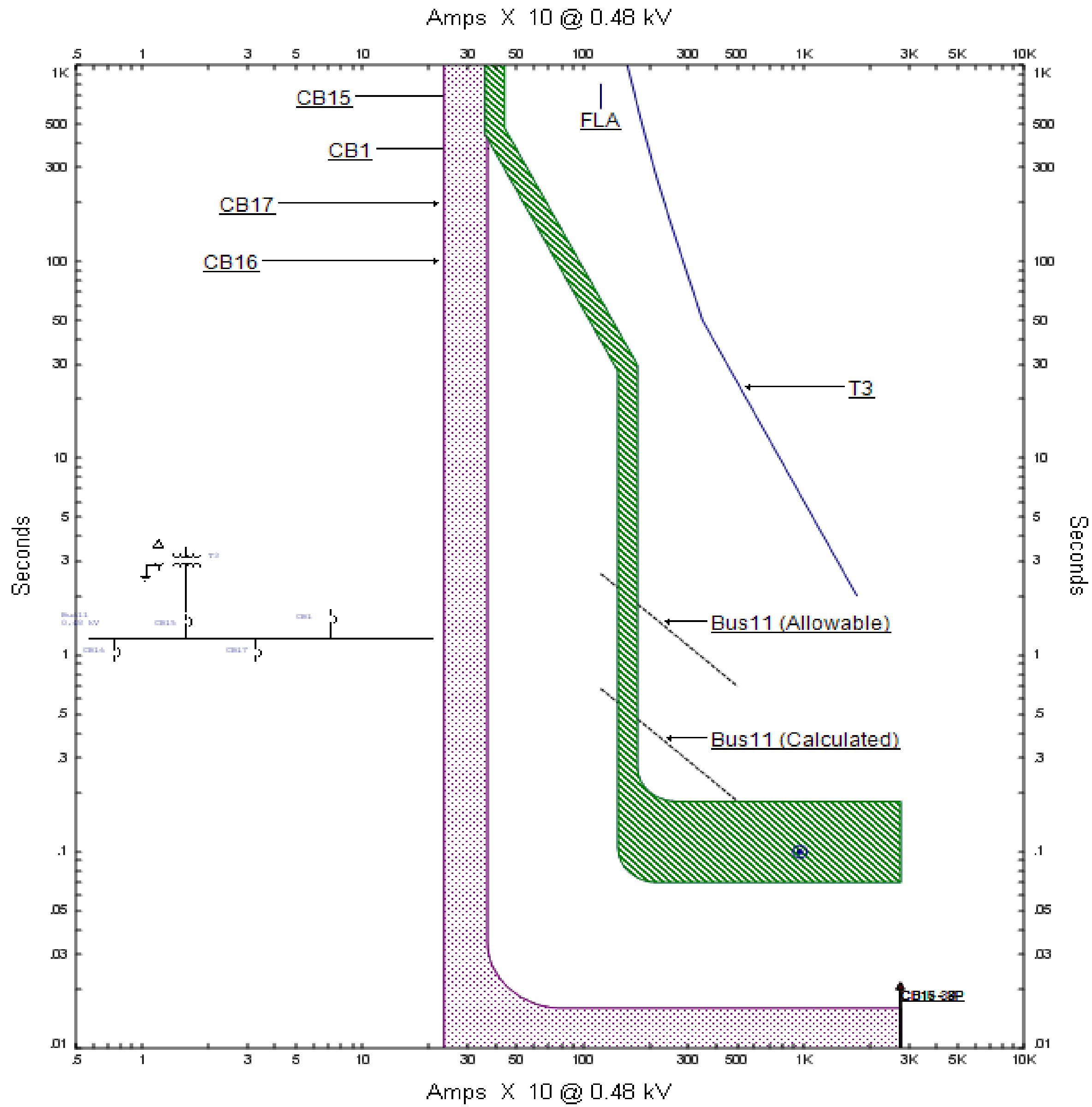
Maintenance Mode

- Very fast acting trip device reduces the Fault Clearing Time (FCT)
- Are designed to pickup under very low arcing current values (instantaneous pickup setting is very low)
- Does not require complicated installation and will effectively protect locations downstream from the trip unit with maintenance mode

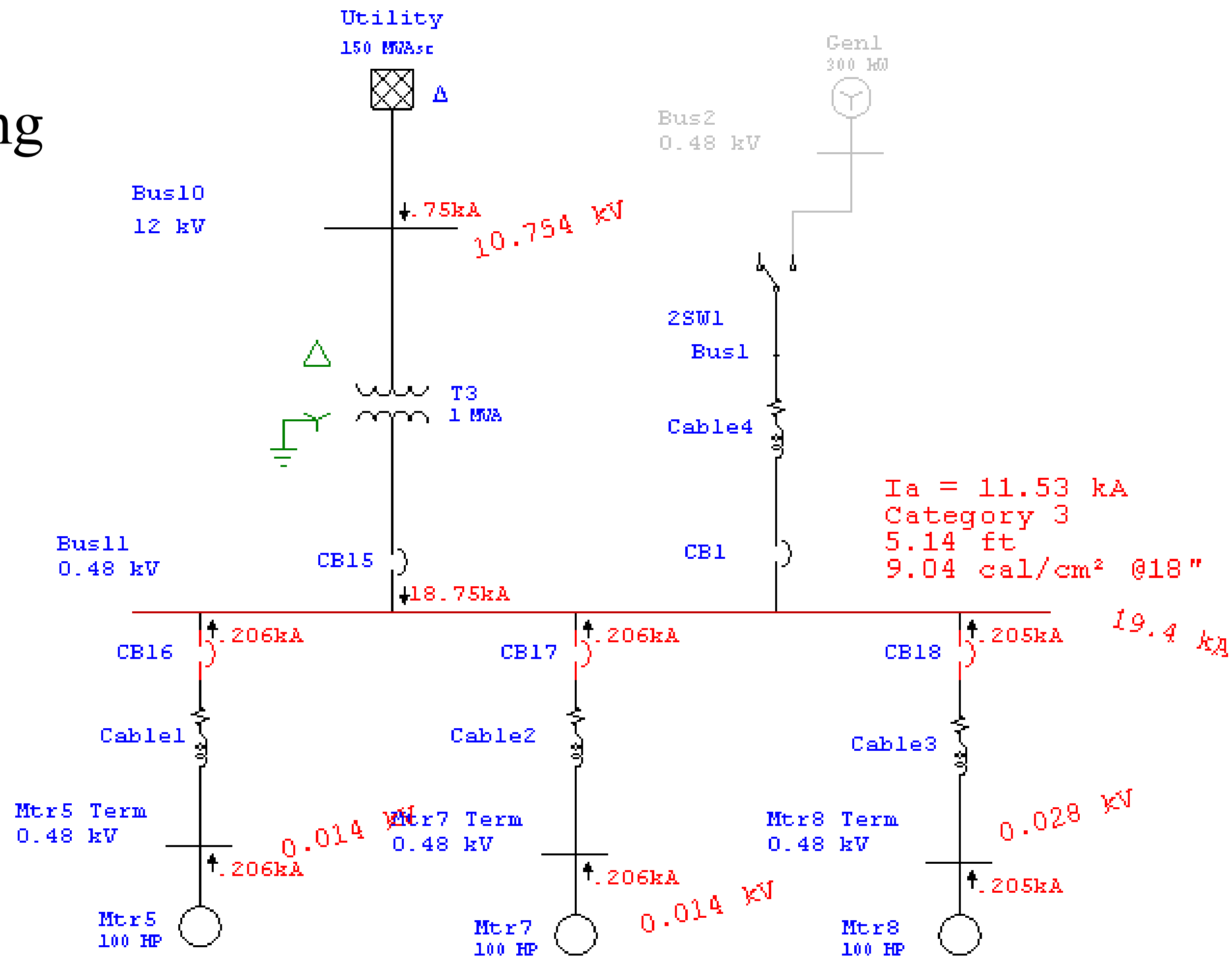
Maintenance Mode

Normal Operating Mode

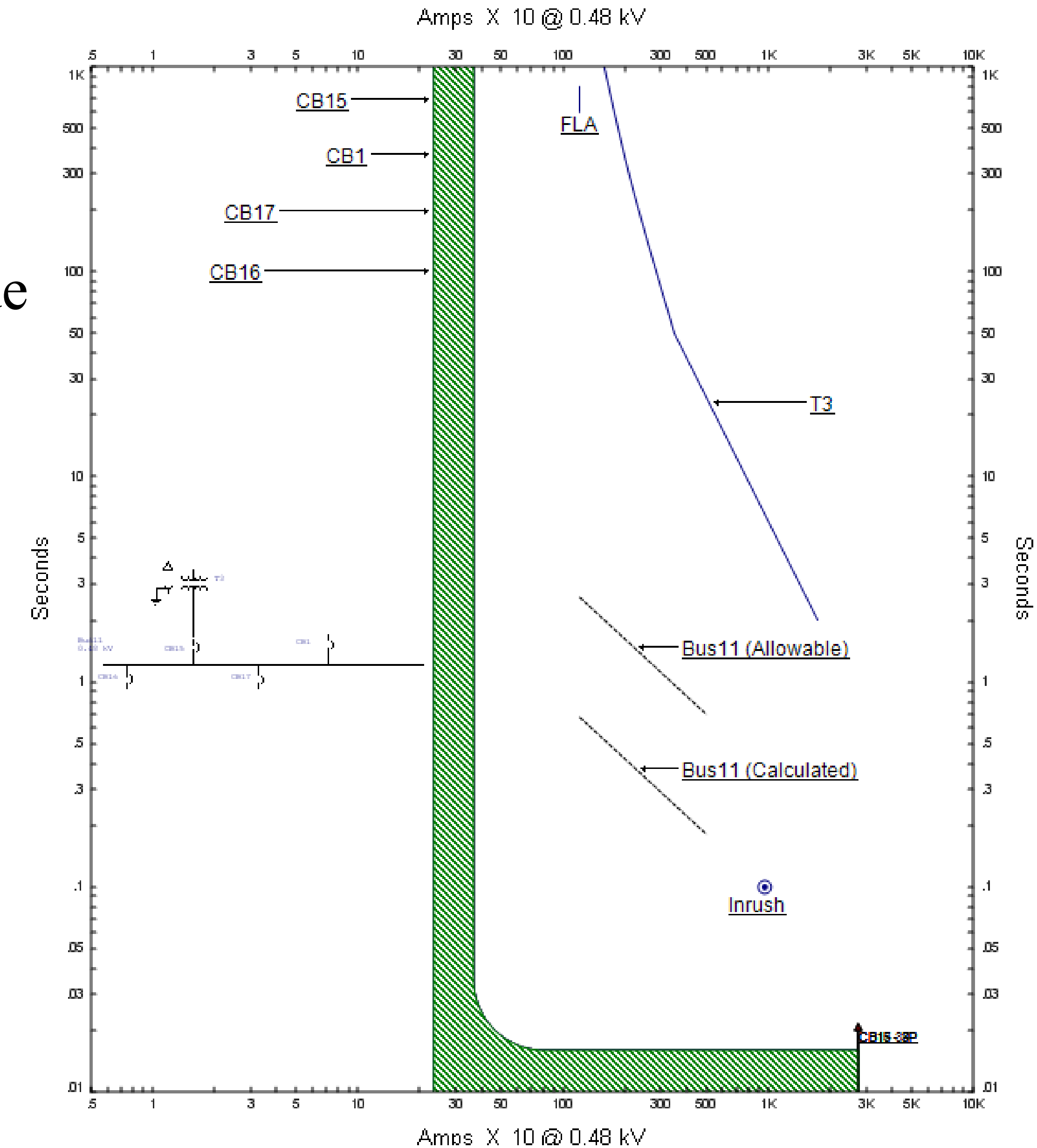
Normal Operating Mode



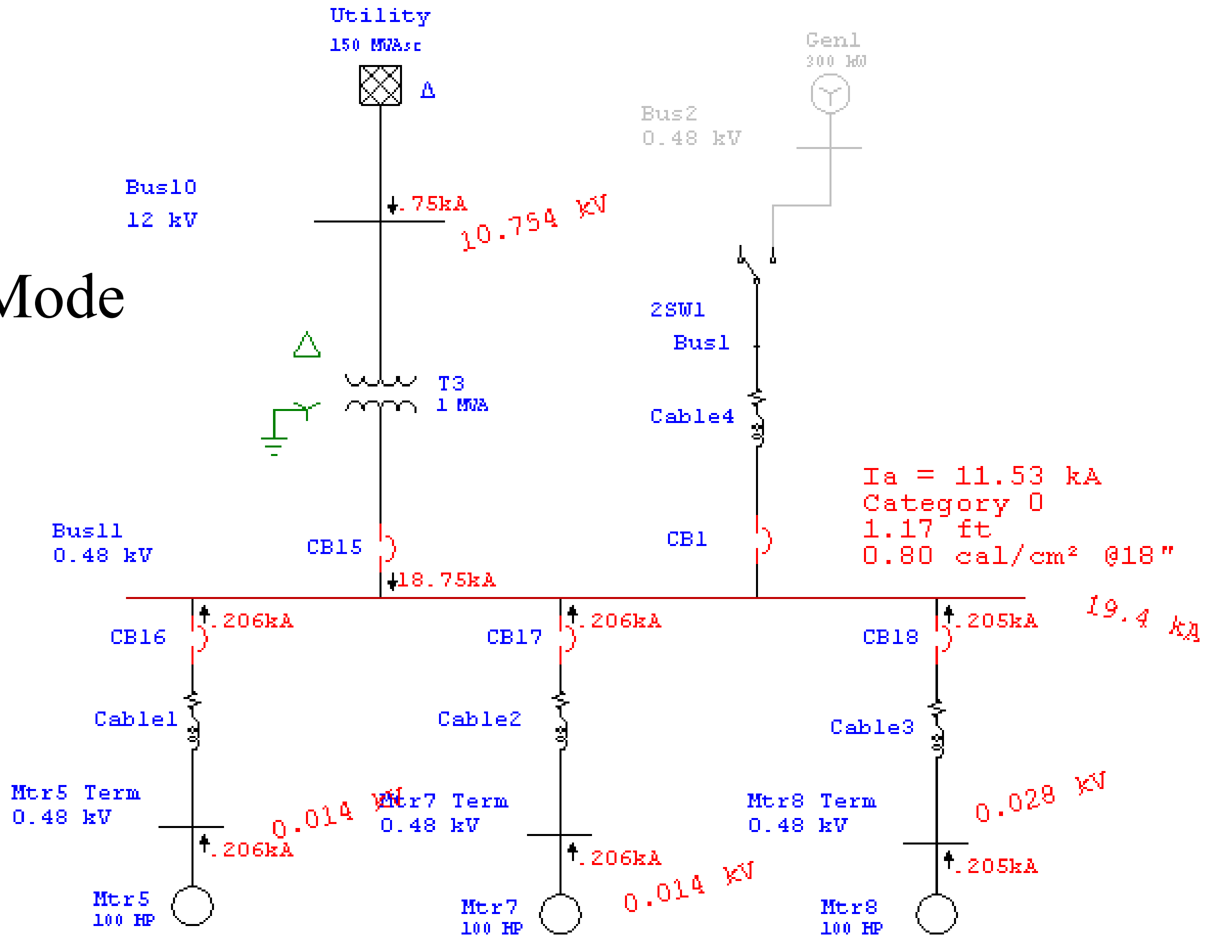
Normal Operating Mode



Maintenance Mode



Maintenance Mode
ON



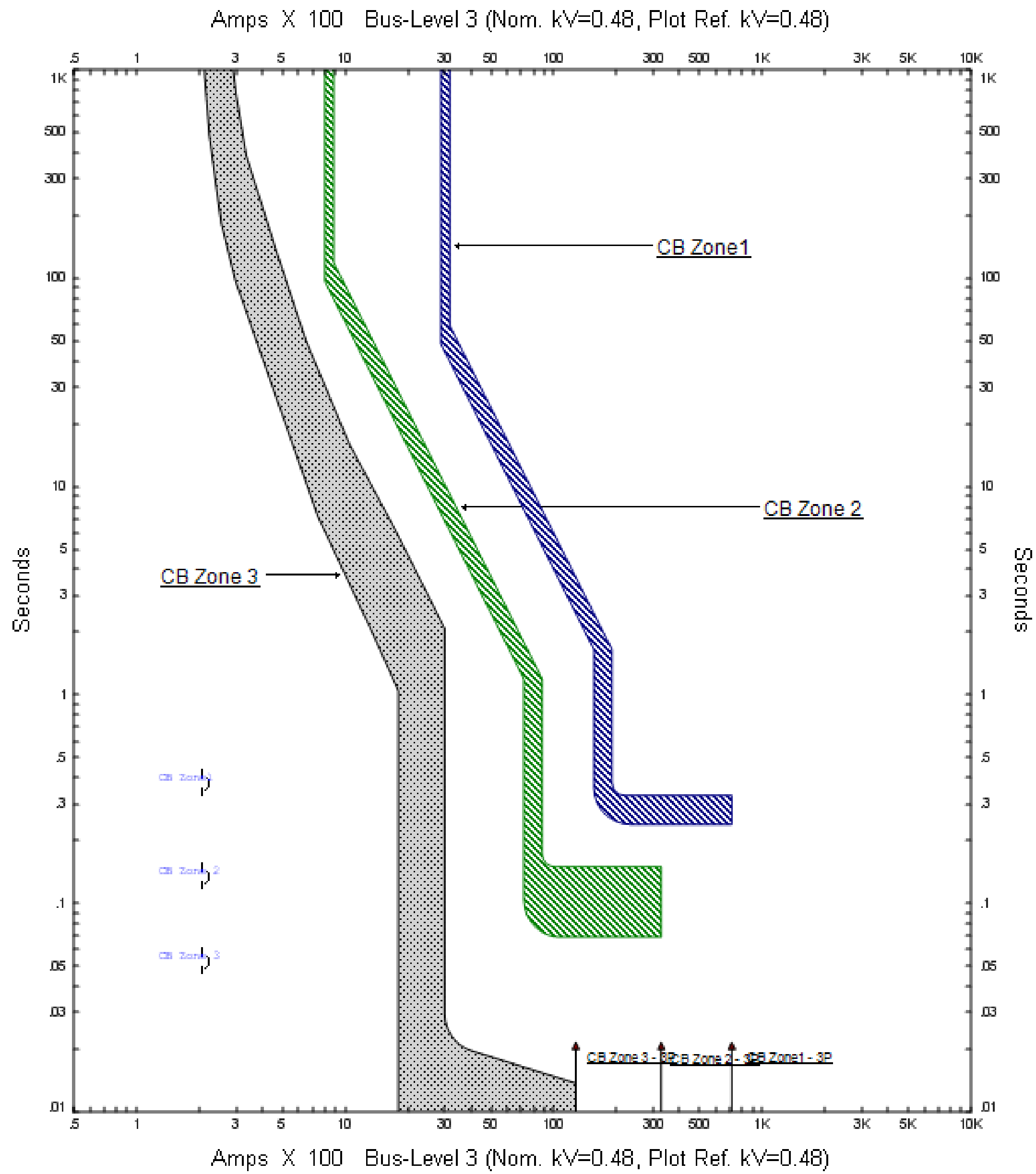
Maintenance Mode Drawbacks

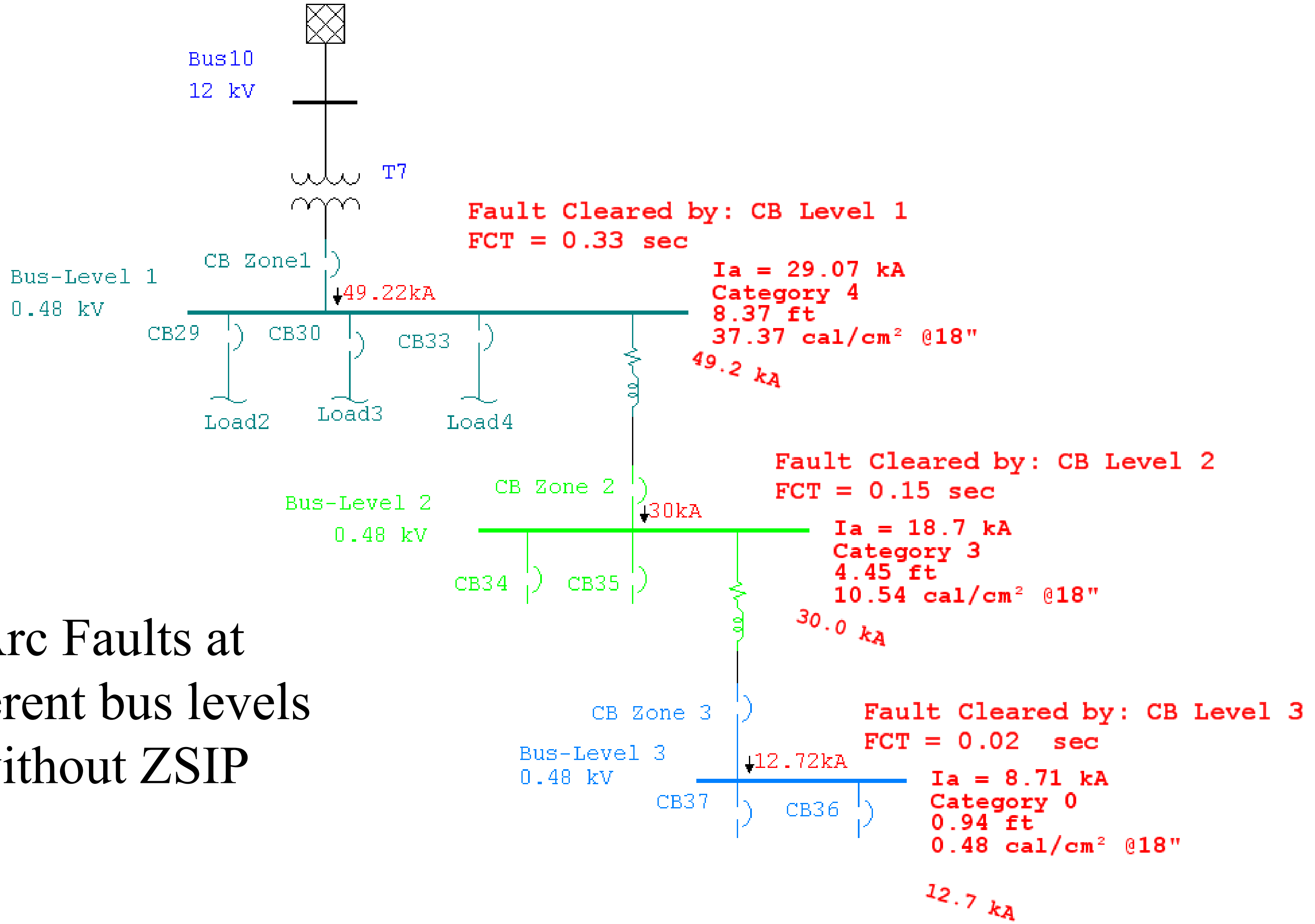
- System will not have coordination during the maintenance period because of reduced instantaneous pickup settings
- Does not increase equipment protection unless the maintenance mode is ON
- May not protect certain zones where energized equipment tasks may be performed

Zone Selective Interlocking Protection (ZSIP)

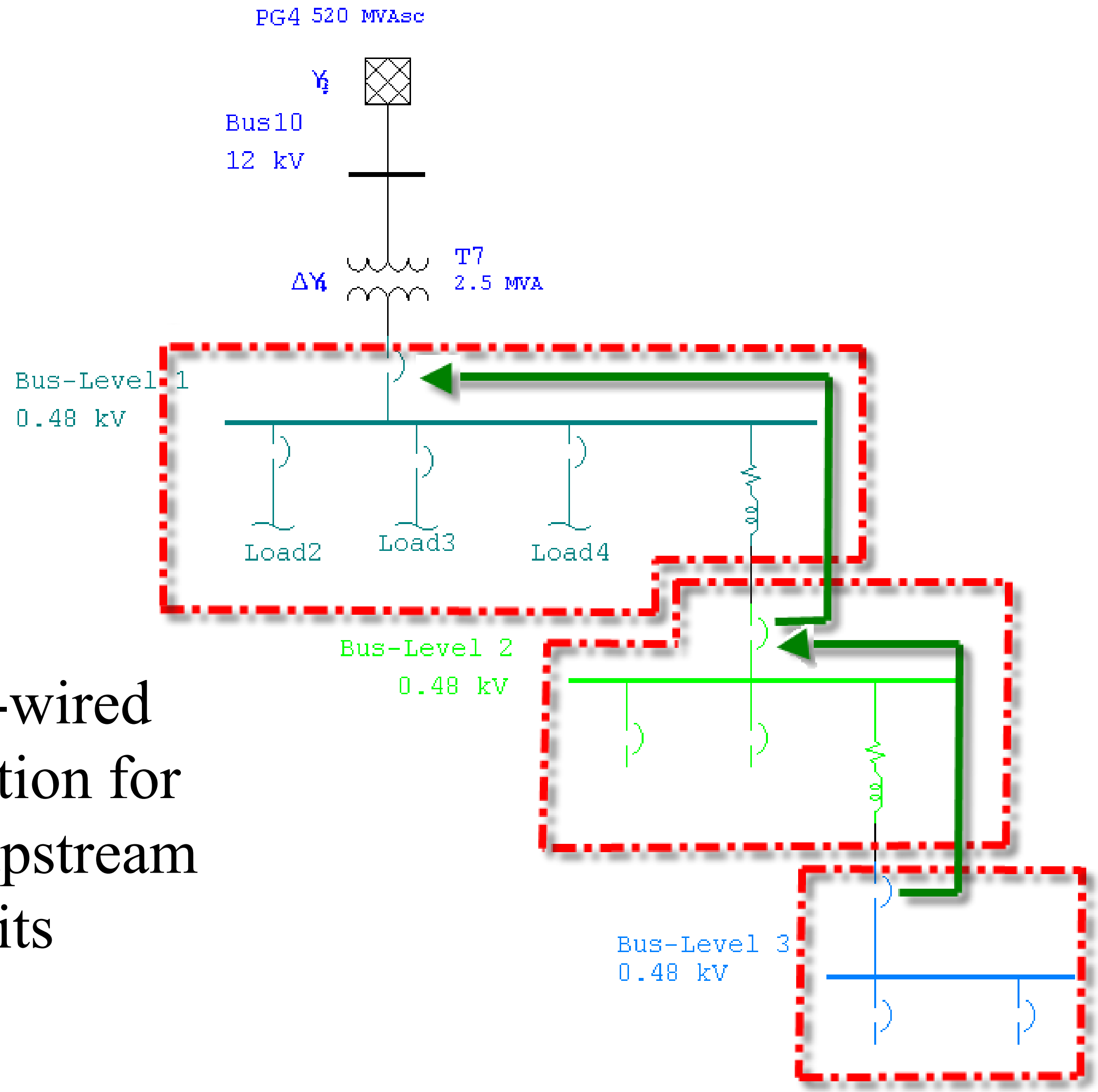
- Reduced arc fault clearing times
- Zone selection is accomplished by means of hard wired communication between trip units
- Only the trip unit closest to the fault will operate within instantaneous since upstream units are restrained by the unit closest to the fault
- Equipment and personnel arc fault protection

Normal Coordination Settings

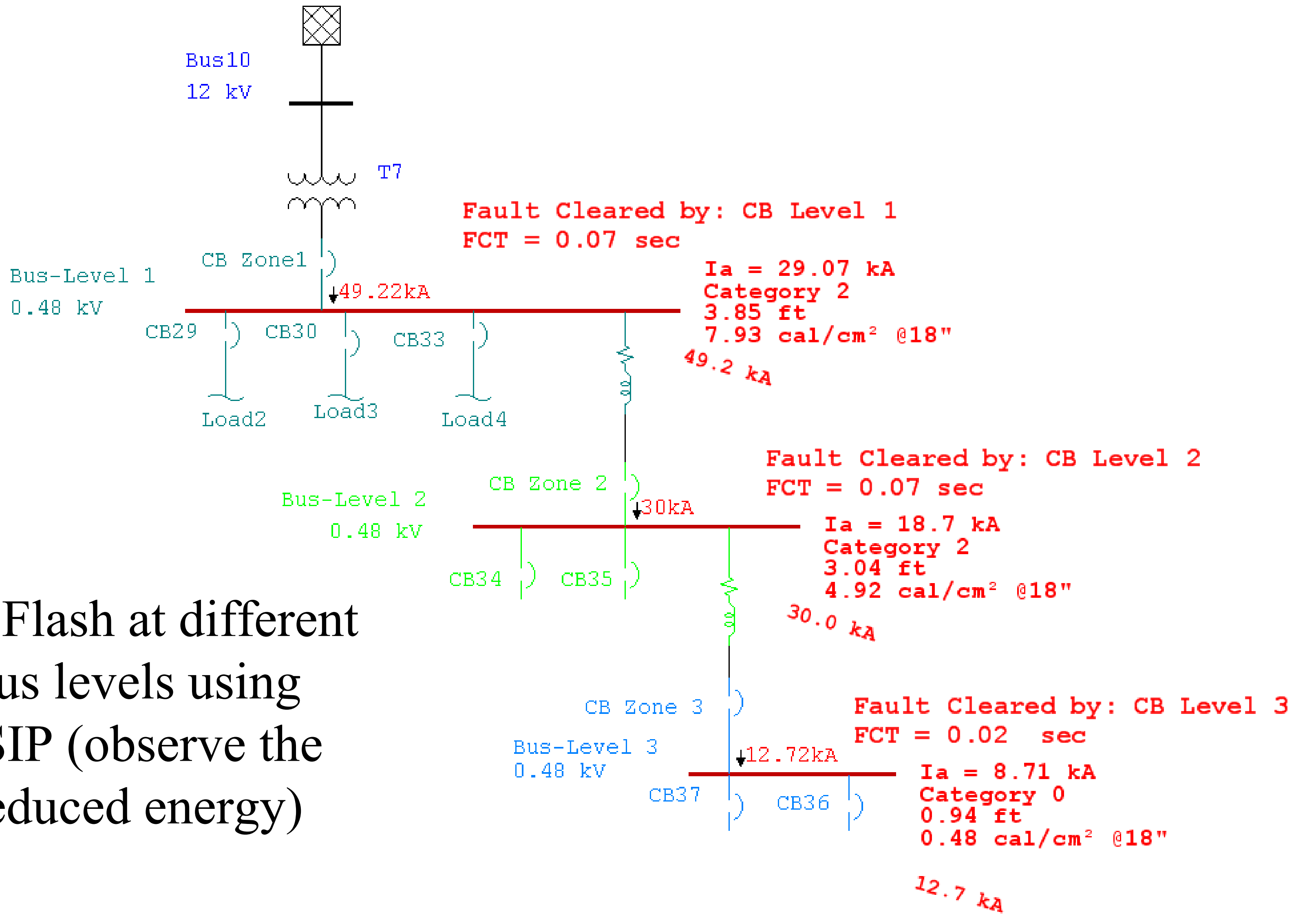




Arc Faults at different bus levels without ZSIP



ZSIP hard-wired communication for restraining upstream trip units



Arc Flash at different bus levels using ZSIP (observe the reduced energy)

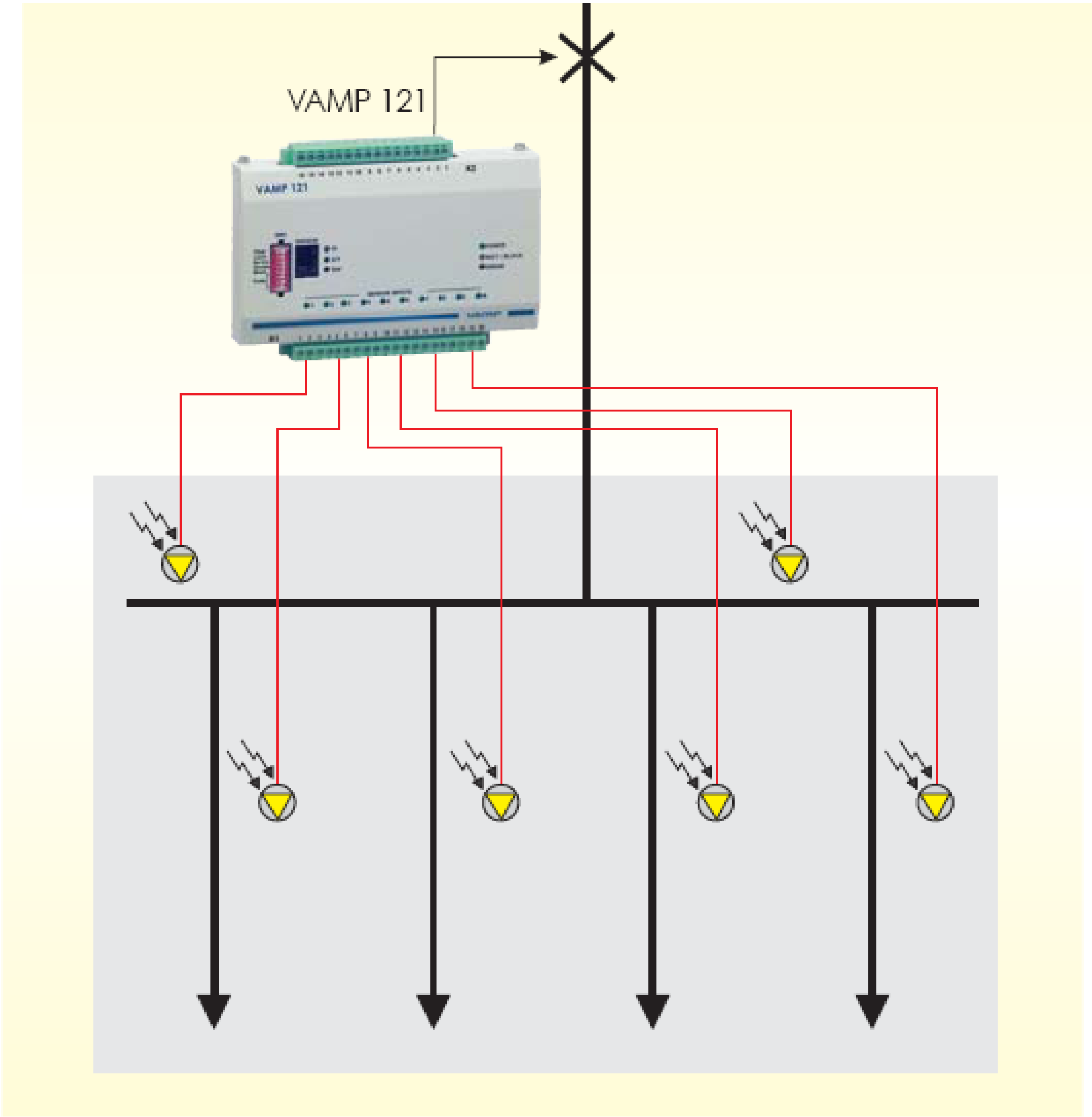
ZSIP Drawbacks

- May take a bit longer to operate than type 50 devices because of the inherent time delay required for the ZSI logic operation
- If system is not coordinated, ZSIP does not necessarily force coordination and other upstream devices may operate before the device closest to the fault
- Arcing current must still be above short time pickup

Arc Flash Light Sensors

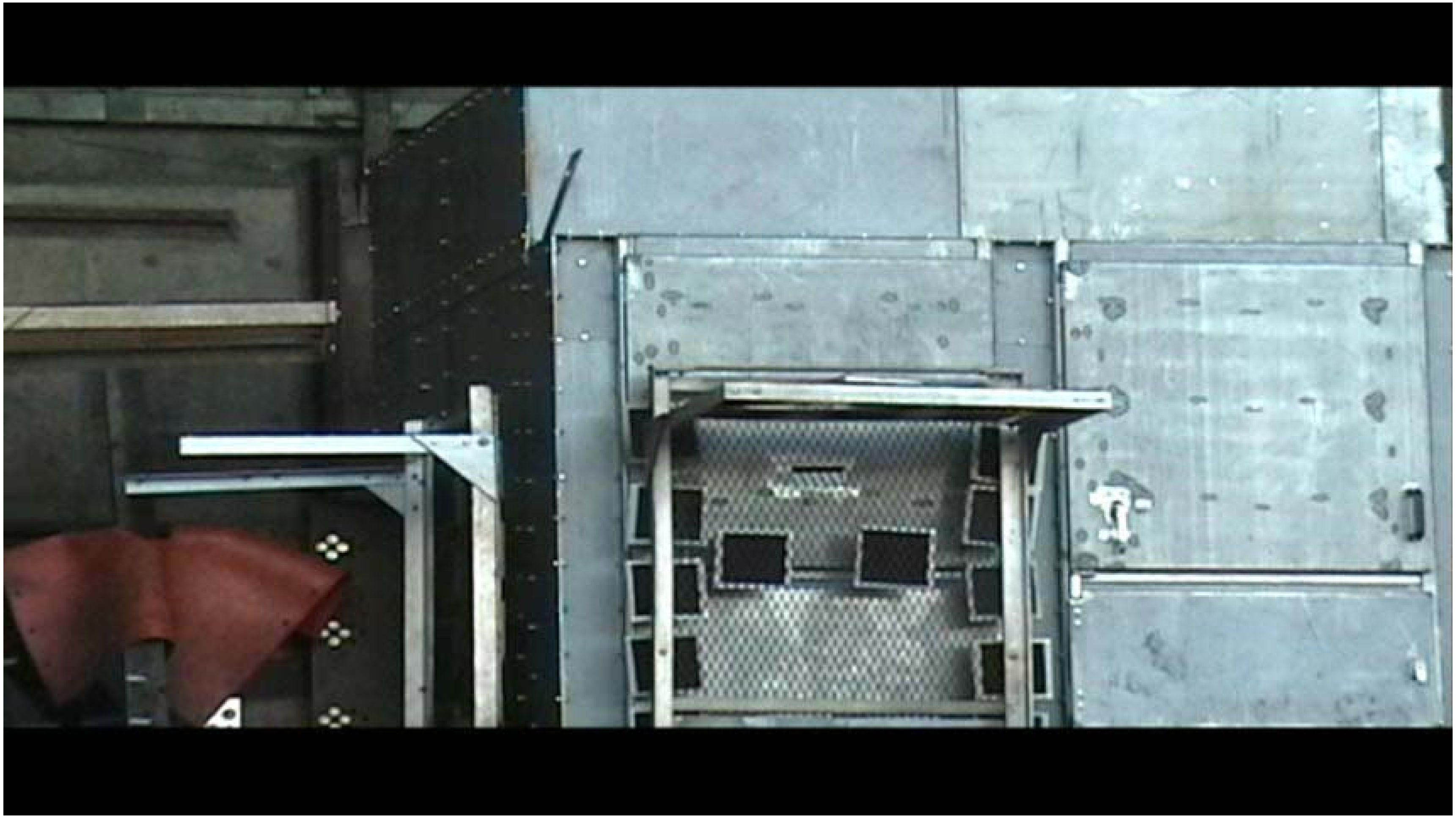
- Detect the light emitted by the arc
- Very fast operation (5 to 10 ms) after the light is detected
- Provide comprehensive zone or individual cubicle arc flash protection (doors open or closed) when correctly applied
- Light sensor protection can be worn at time of task being performed for additional safety

Light Sensors



Kema-Laboratory Tests
50 kA - 500 ms Arc Fault Clearing Time

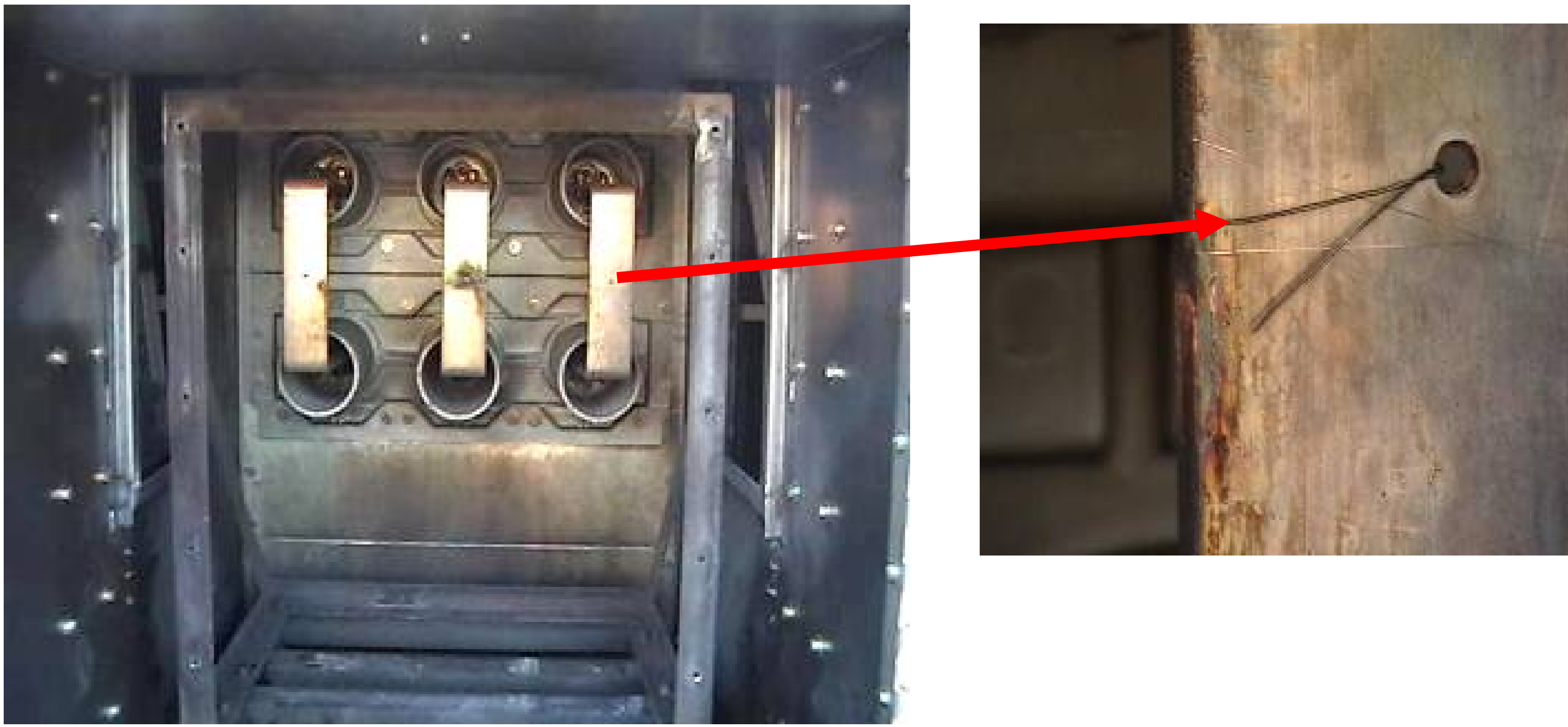
Arc Flash without Light Sensors



Kema-Laboratory Tests
50 kA - 500 ms Arc Fault

Kema-Laboratory Tests
50 kA Arc Fault with 50ms Fault Clearing Time

Kema-Laboratory Tests
50 kA Arc Fault with 50ms Fault Clearing Time

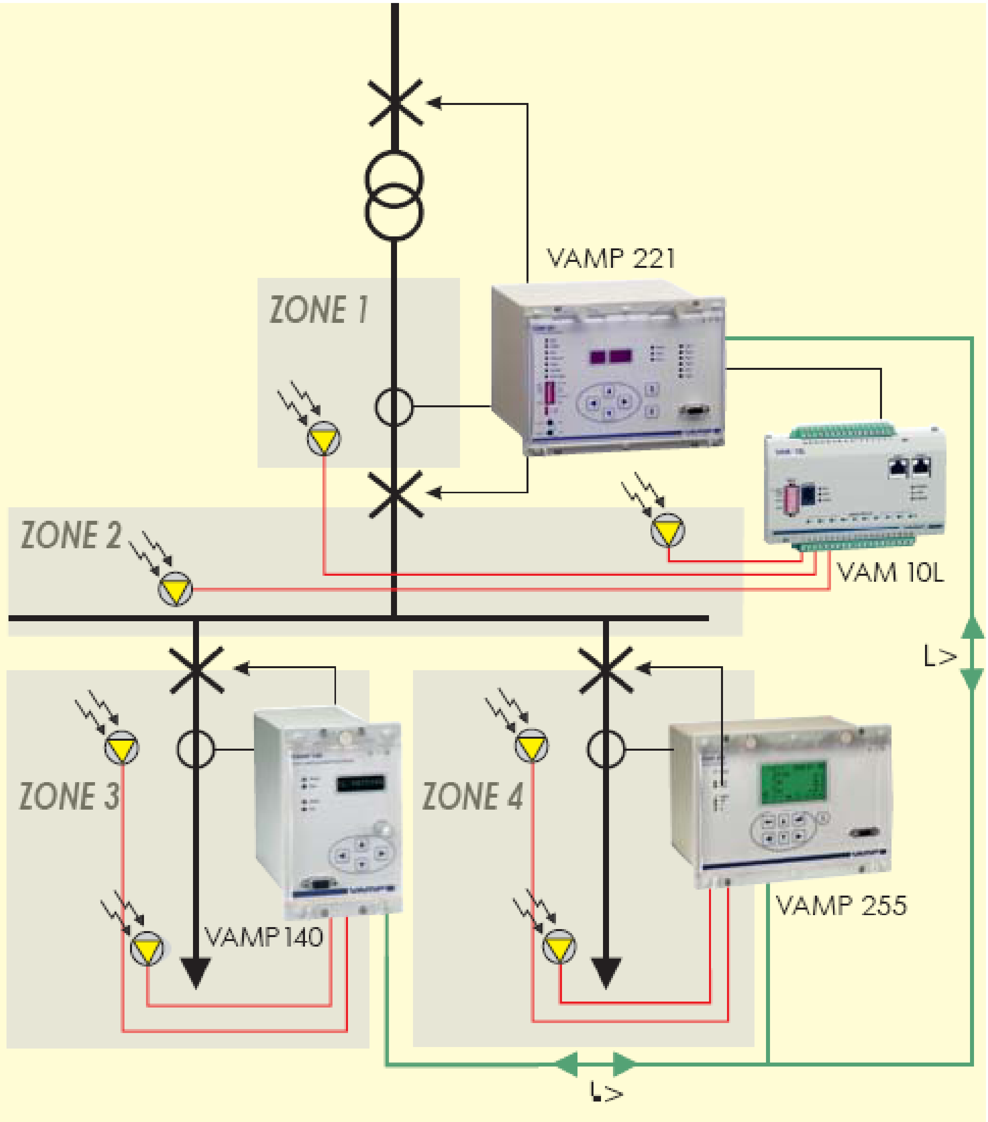


Arc Flash Light Sensor Drawbacks

- Nuisance trips caused by light emitted from sources other than electrical arcs (can be remedied by using a more robust approach by combining over-current and light sensors)

- Positioning of the light sensors poses a possible problem if they are obstructed or blocked and cannot see the light emitted by the arc

Light Sensor and Over-Current Relay Combination

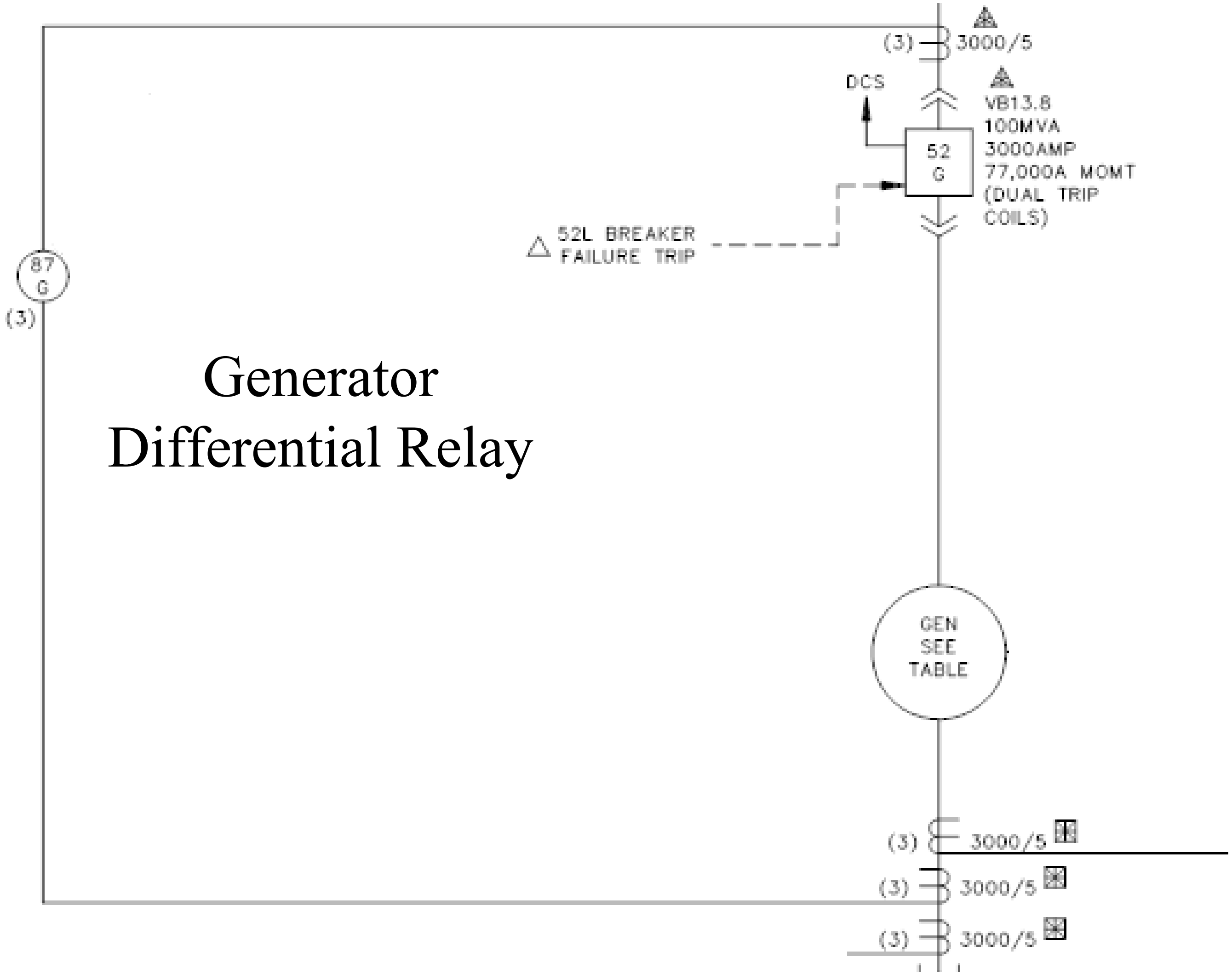


Re-VAMPed protection system of MV/LV switchgear

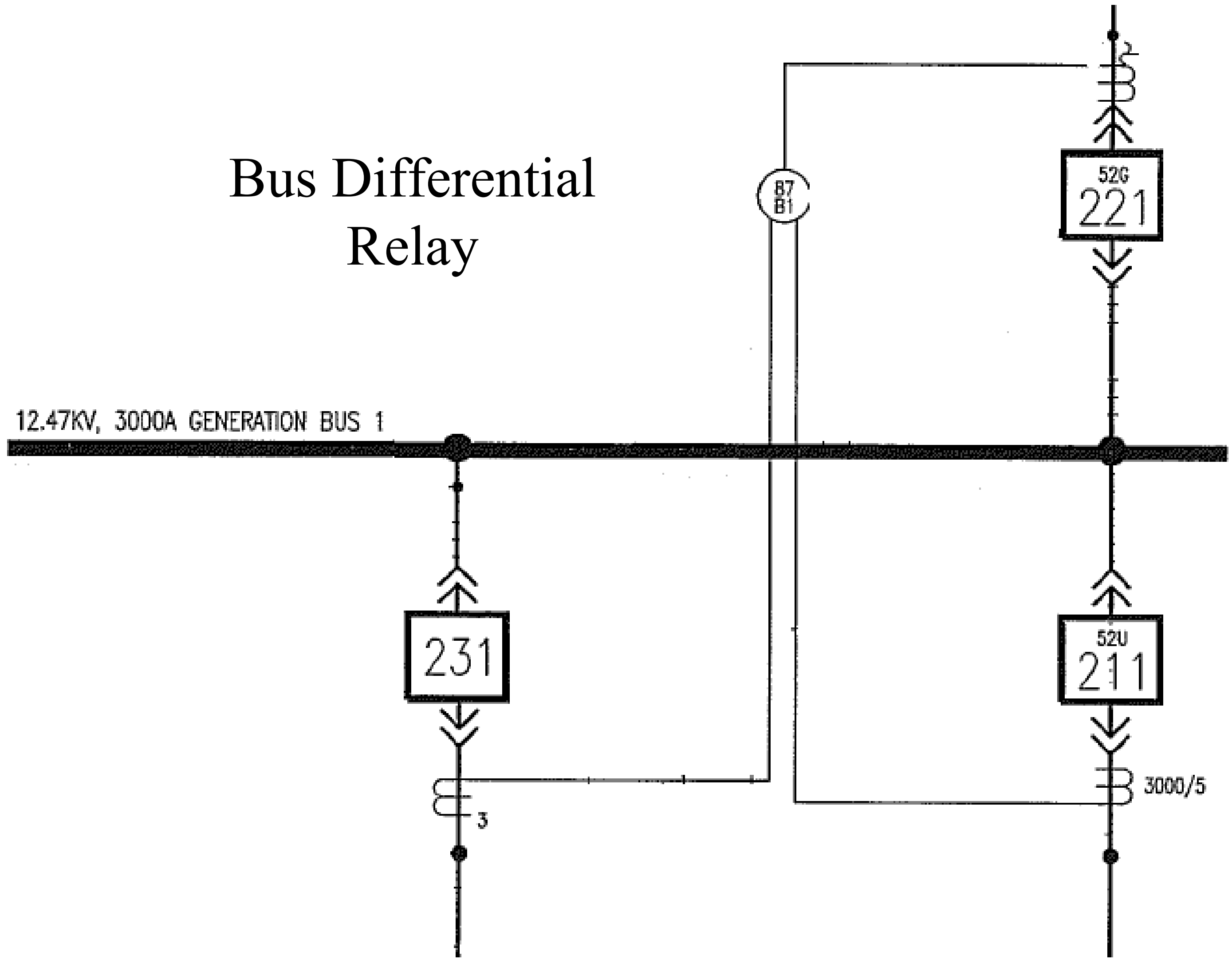
Differential Protection

- Short Arc Fault Clearing Times
  - Differential protection can operate (relay plus breaker) within 4 to 6 cycles
  - Relay can operate within ½ to 3 cycles
- Maintain coordination between protective devices upstream and downstream from the Differential Protection Zone
- Differential protection provides continuous equipment arc flash protection

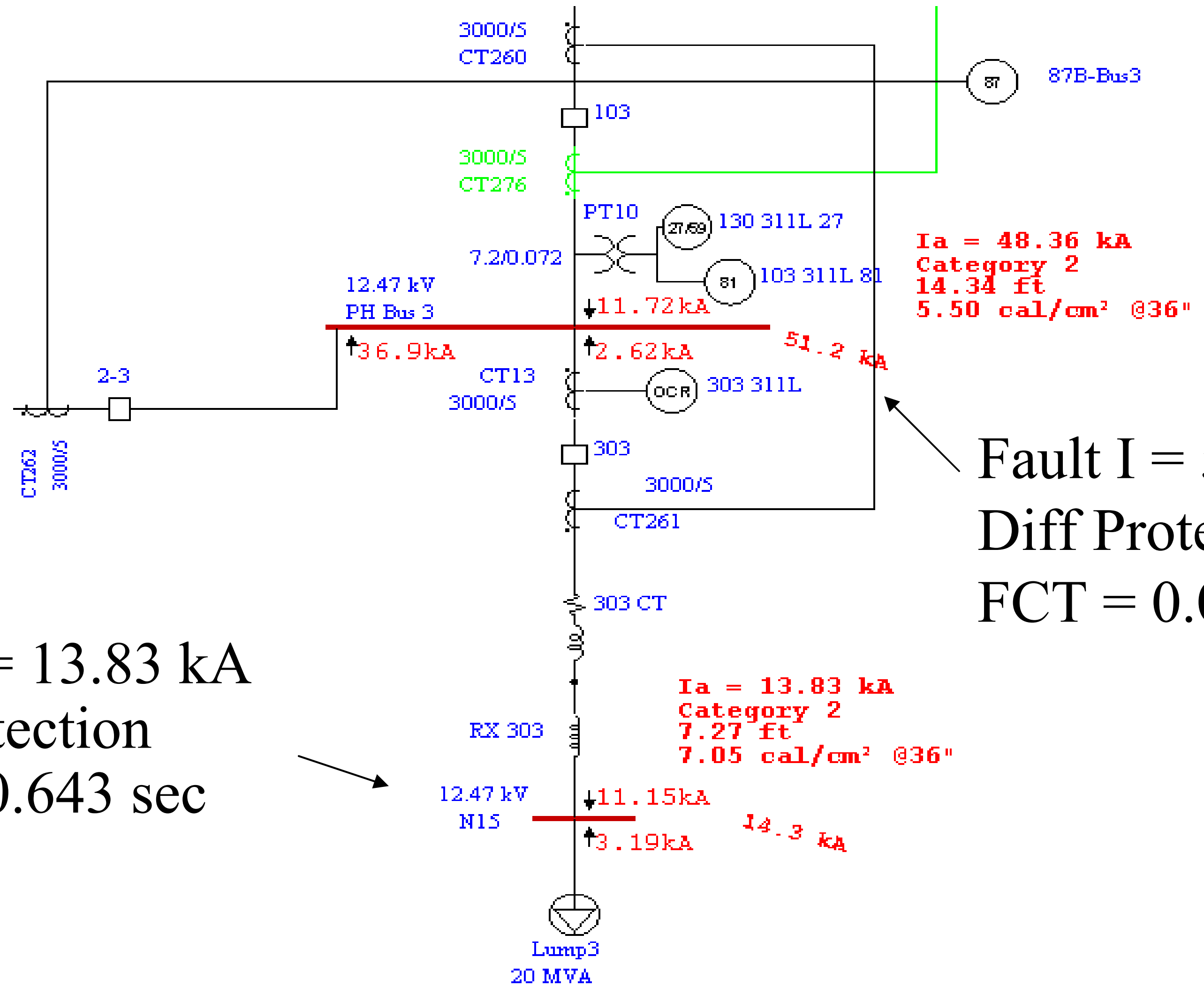
Generator Differential Relay



Bus Differential Relay



Bus Diff Protection vs. OC Relay



Fault I = 51.2 kA
Diff Protection
FCT = 0.060 sec

Fault I = 13.83 kA
OC Protection
FCT = 0.643 sec

Differential Protection Drawbacks

- Nuisance trips caused by transformer inrush currents which are seen by relay as internal faults - the magnetizing current has particularly high second order harmonic content which can be used to restrain or desensitize the relay during energizing

- Higher equipment and installation costs - relatively higher costs when compared to traditional over-current protective devices
- Limited zone of protection for differential ct nodes

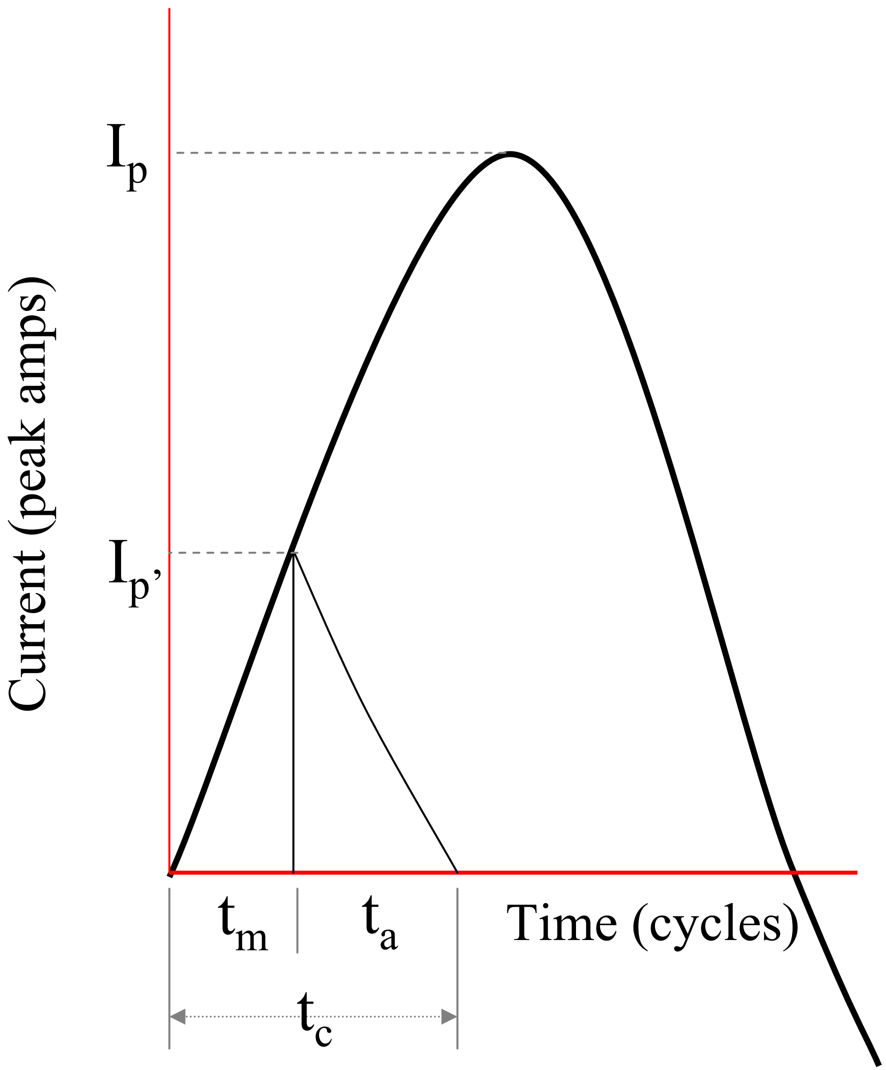
Current Limiting Methods

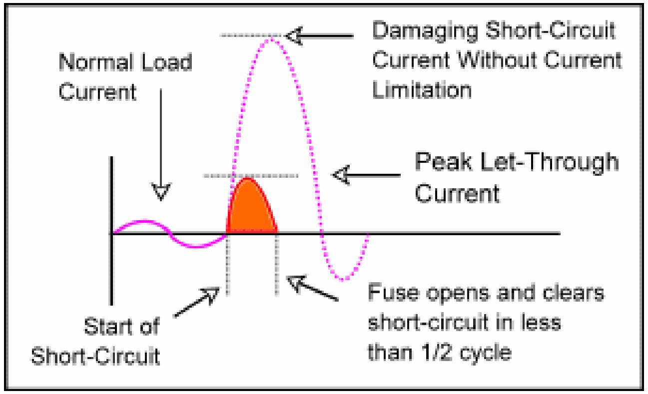
- Current Limiting Fuses
- Current Limiting Circuit Breakers
- Current Limiting Reactors
- Isolating transformers
- High Resistance Grounding

Current Limiting Fuses

- Current limiting fuses can operate in less than ½ cycle
- Current limiting action is achieved as long as the magnitude of the arcing current is within the current limiting range
- Current limitation curves (peak let-through curves) are needed in order to check if the fuse can limit the current
- Can be very effective at reducing the incident energy if properly used

Current Limiting Action





$t_a = t_c - t_m$

t_a = Arcing Time

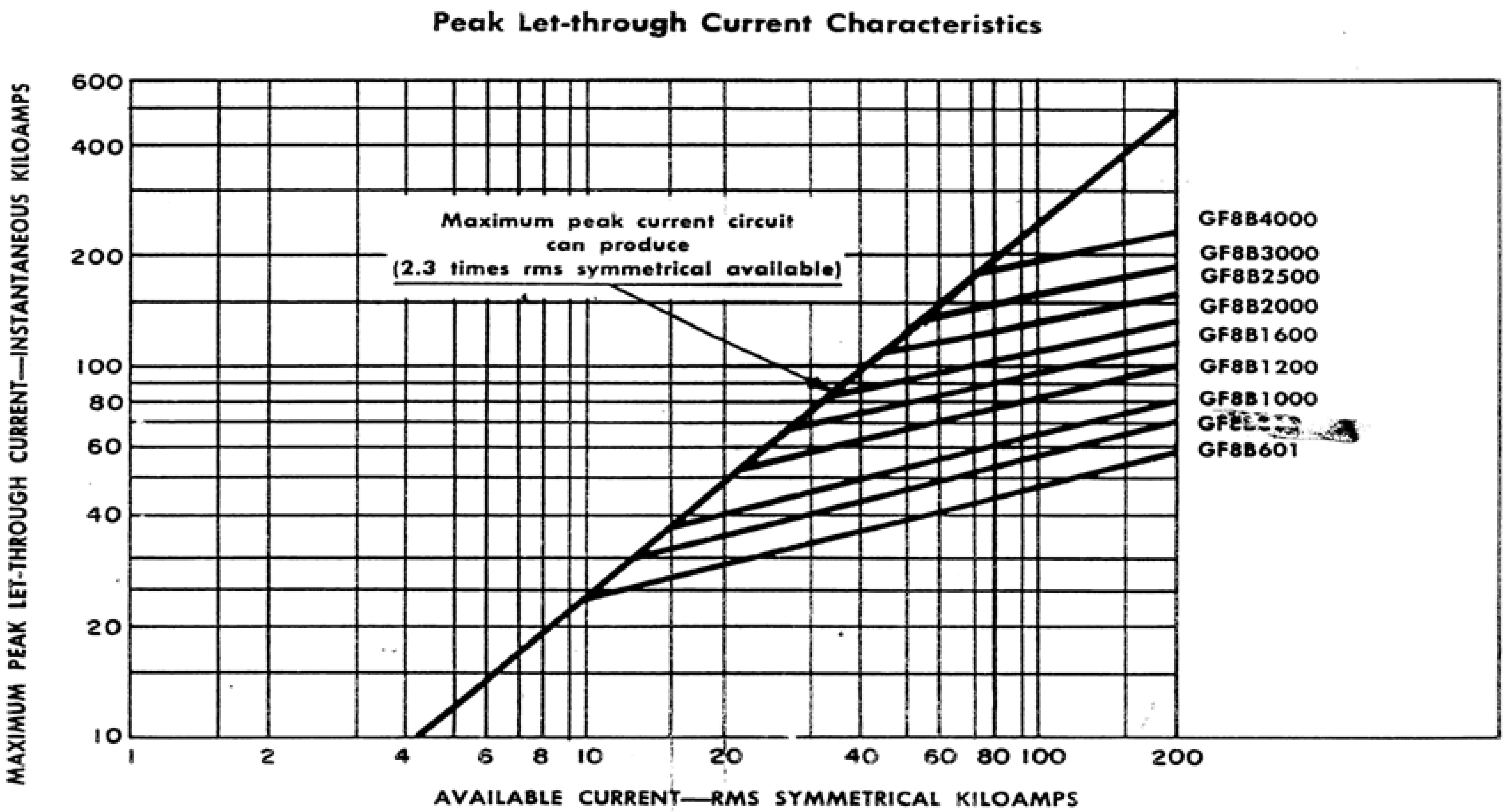
t_m = Melting Time

t_c = Clearing Time

I_p = Peak Current

$I_{p'}$ = Peak Let-thru Current

Current Limiting Action



Current Limiting Fuse Drawbacks

- Current limiting action is achieved as long as the magnitude of the arcing current is within the current limiting range
- Can be thermally damaged and have altered characteristics
- Needs spares (which may be expensive) and there is not indication of the type of fault.
- Energization on pre-existing fault = another blown fuse

Current Limiting Reactors
Isolating Transformers

- Current limiting reactors can help to reduce the available fault current and thus reduce the available energy
- Isolating transformers help to reduce high kA short-circuit levels (down to less than 10 kA).
- Isolating transformers add impedance between the main switchboard and the smaller panels fed from it. The short-circuit available at the switchboard may be considerably higher

Increasing the Working Distance

- Hot Sticks
- Remote Racking
- Remote Switching

Remote Racking/Remote Switching

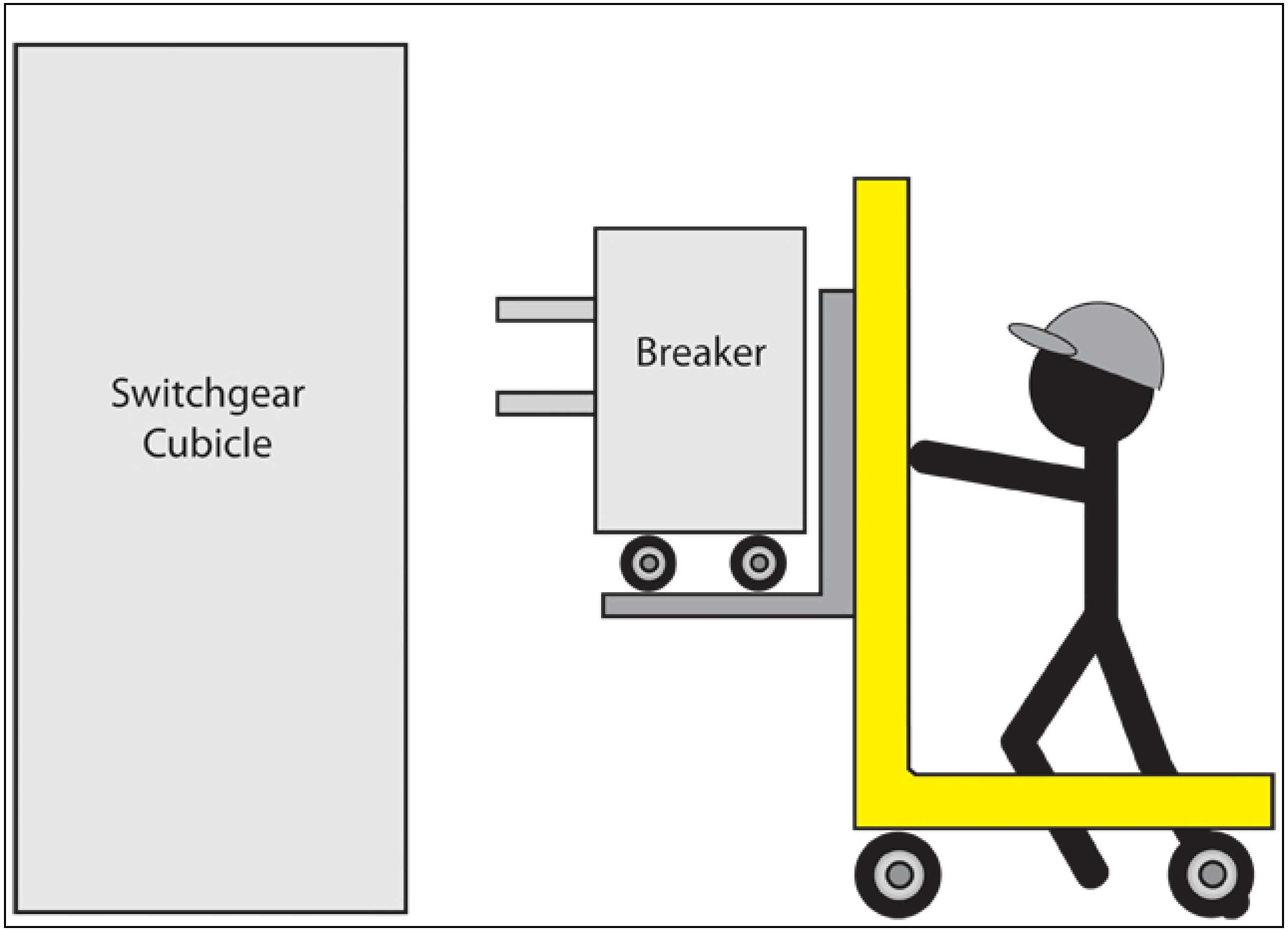
- Are used to increase the personal space between the potential source of the arc and the electrician

- Can be combined with high strength plastic shields to reduce the effects of the arc flash/blast

Remote Racking/Remote Switching

Remote Racking/Remote Switching

Remote Racking / Remote Switching



Remote Racking / Remote Switching

Universal Remote Power Racking System (RPR-2)

Mitigating/Avoiding the Incident Energy

- Arc Resistant Switchgear
- Arc Flash Shields

Arc Resistant Switchgear

- Funneling or re-directing the incident energy away from the personal space
- Special design and construction allows the front of the equipment to experience low levels of energy
- Arc flash may still be very severe and equipment will suffer considerable damage

Arc Resistant Switchgear

Upcoming Arc Flash Analysis Standards/Guidelines Changes

Arc Flash Analysis Standards/Guidelines Changes

- How will these standards affect your AF Analysis Calculations?
  - IEEE 1584b -2010
  - IEEE 1584.1-2010
  - IEEE 1814
  - NFPA 70E -2011
  - NESC- Utility Models / Testing for utility equipment

Arc Flash Analysis Standards/Guidelines Changes

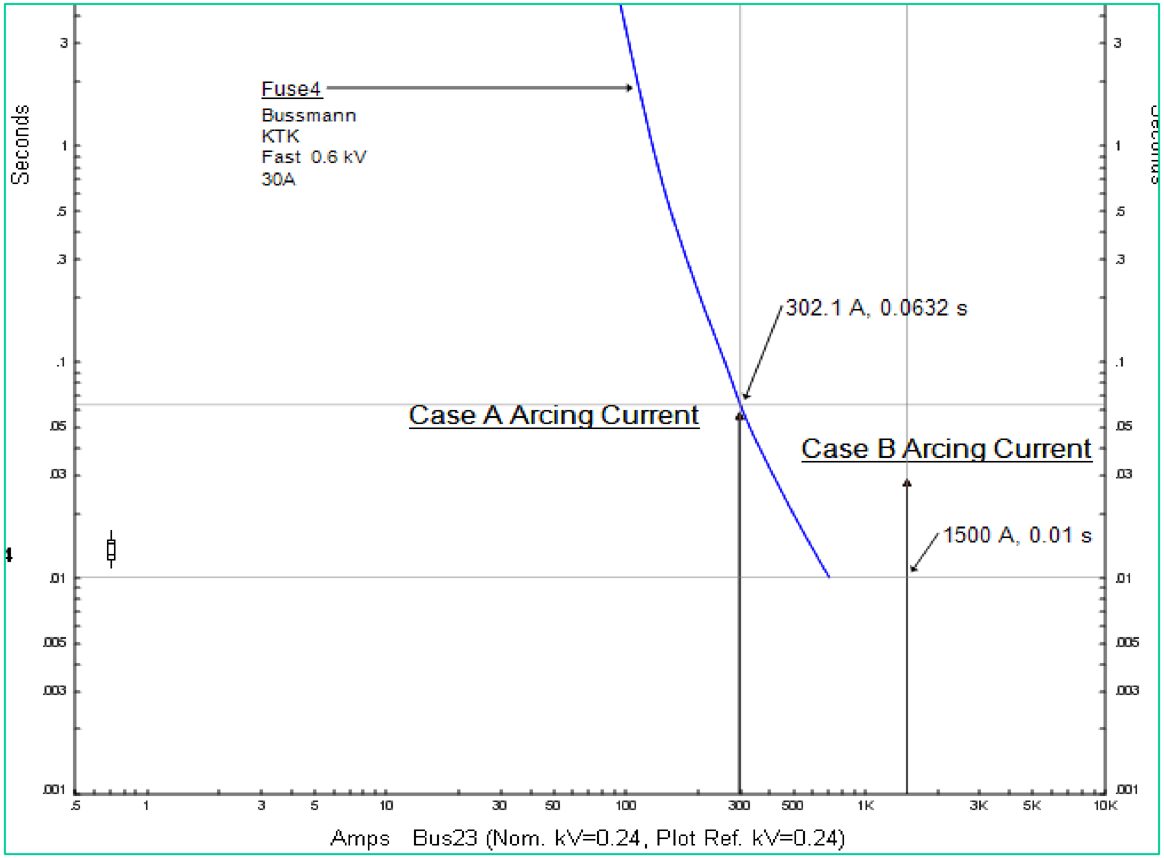
- Recent Papers on arc flash in Low Voltage Equipment
- NFPA 70E and IEEE Collaboration to develop / revise current Models
- DC Arc Flash Calculations

NFPA 70E & IEEE1584 Collaboration Efforts "Phase I" Test Results

- Refined Equations for Incident Energy Calculations ~ Vertical, Horizontal and Vertical with Barrier Conductor arrangements
- Effect of Sound ~ 140 db @ 20 kA fault
- Effect of Light ~ 45,000,000 LUX from Arc Fault – Bright day is about 20,000 LUX
- Arc Blast Pressure Wave Effects ~ 0.9 psi 120 to 200 lbs of force

IEEE 1584b - Amendments

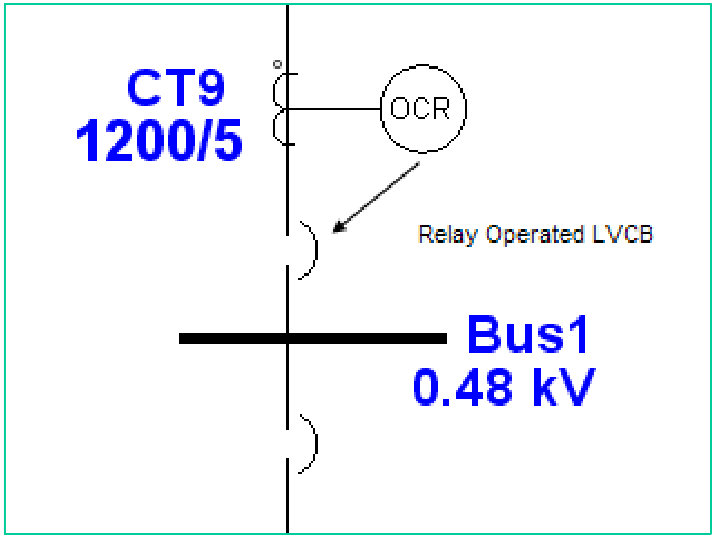
$$A)\ If\ \ Fuse\ has\ Average\ Melt\ Time\ Curve\ ,then$$
$$FCT = Time\ from\ Curve + \ 10\%\ of\ Time\ from\ Curve + 0.004\ seconds$$



IEEE 1584b - Amendments

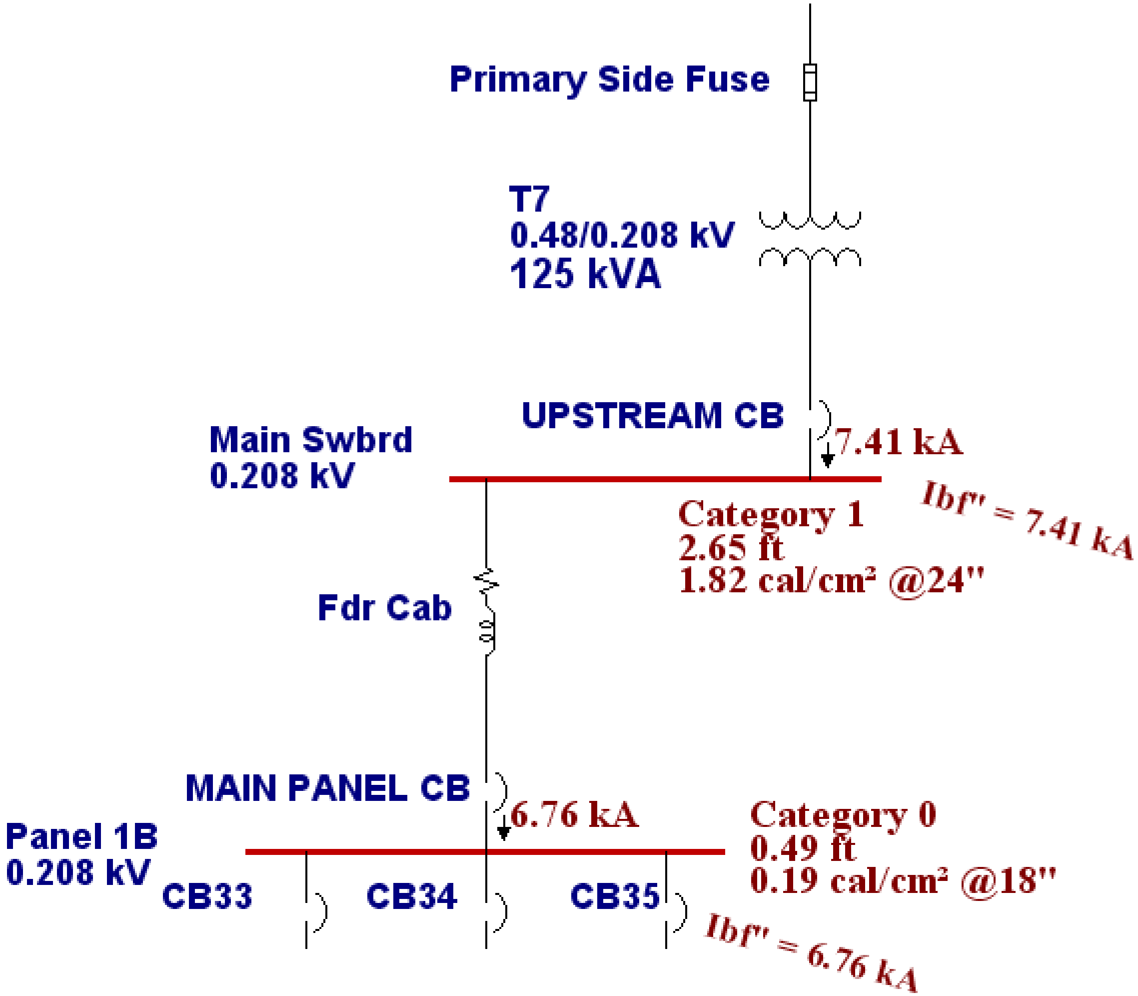
Relay Operated Power Circuit Breaker Interrupting times

Circuit Breaker Rating and Type	*Interrupting Time at 60 Hz (cycles)*	*Interrupting Time at 60 Hz (seconds)*
Low Voltage Molded Case CB	**3.0 (used to be 1.5)**	**0.050 (used to be 0.025)**
Low Voltage Insulated Case CB	**3.0**	**0.050**
Low Voltage Power CB	**3.0**	**0.050**

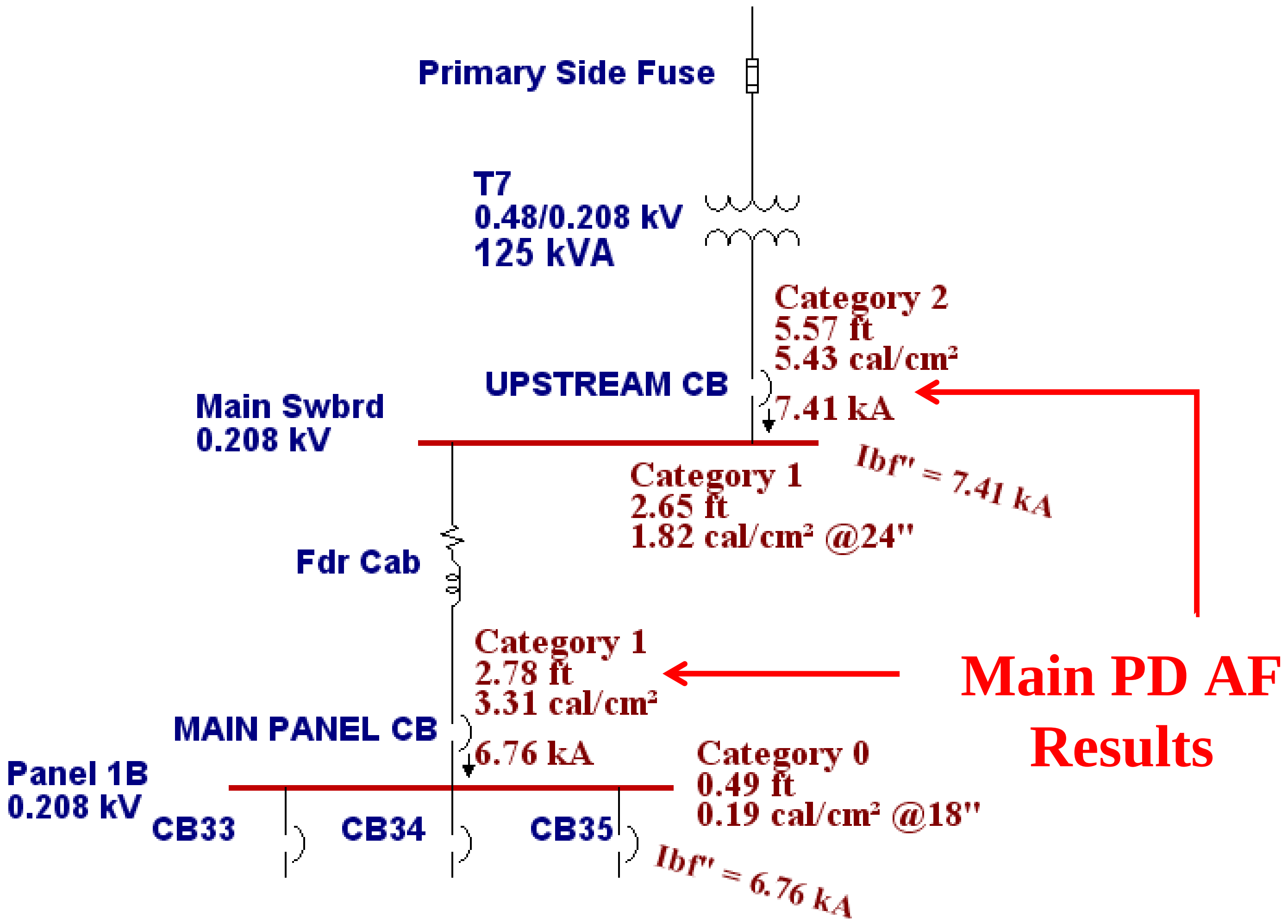


IEEE 1584b - Amendments

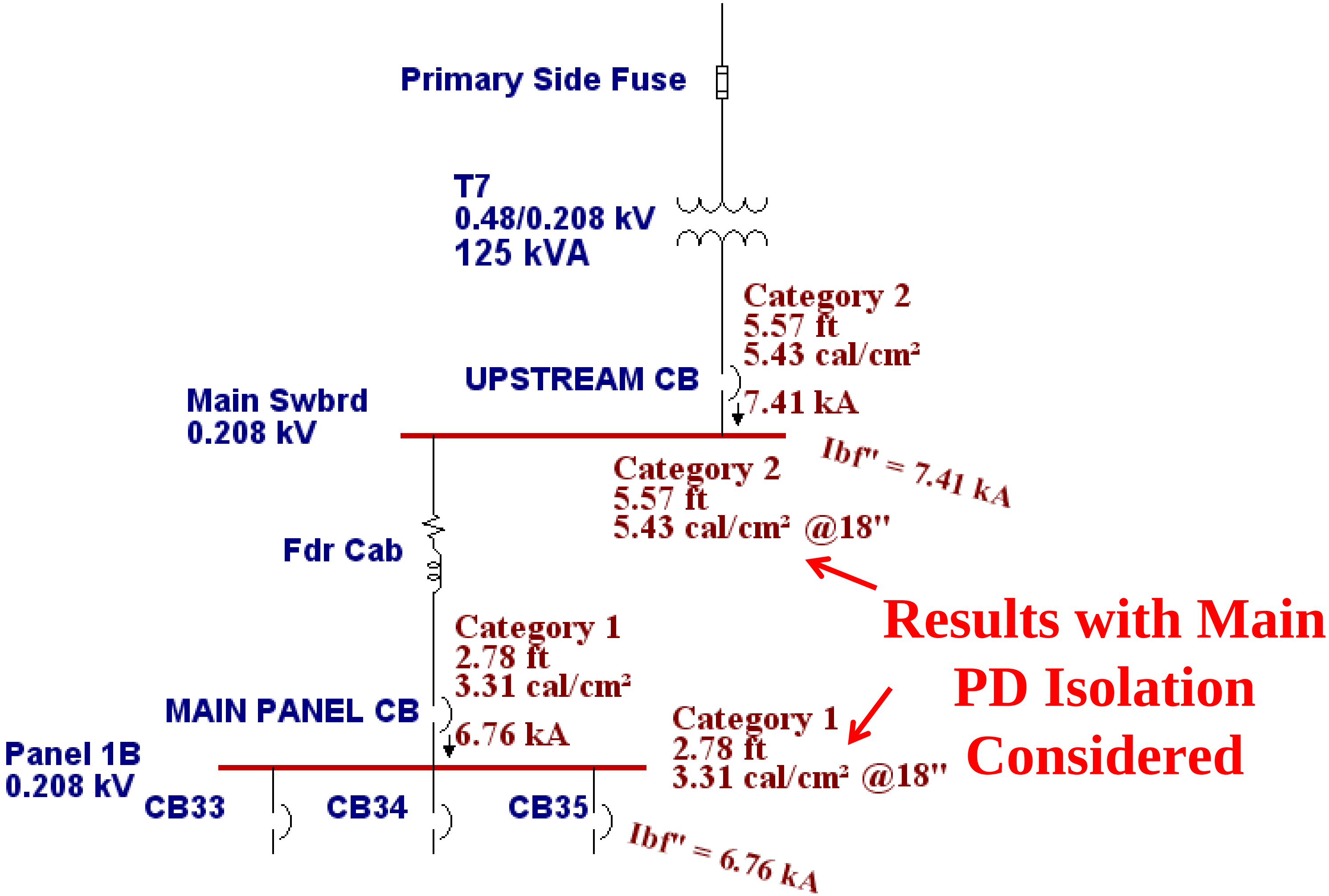
IEEE 1584b - Amendments



IEEE 1584b - Amendments



IEEE 1584b - Amendments



Arc Flash for LV Systems

Impact of Arc Flash Events with Outward Convective Flows on Worker Protection Strategies
ESW2010-11

Mike Lang, Member IEEE   Ken Jones Member IEEE
Thomas Neal, PhD

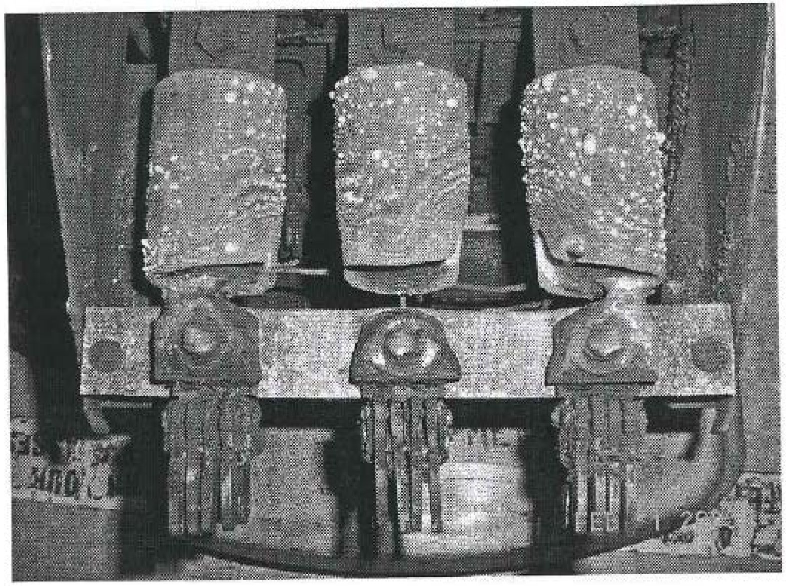


Figure 6. Arc fault damage resembling barrier configuration.

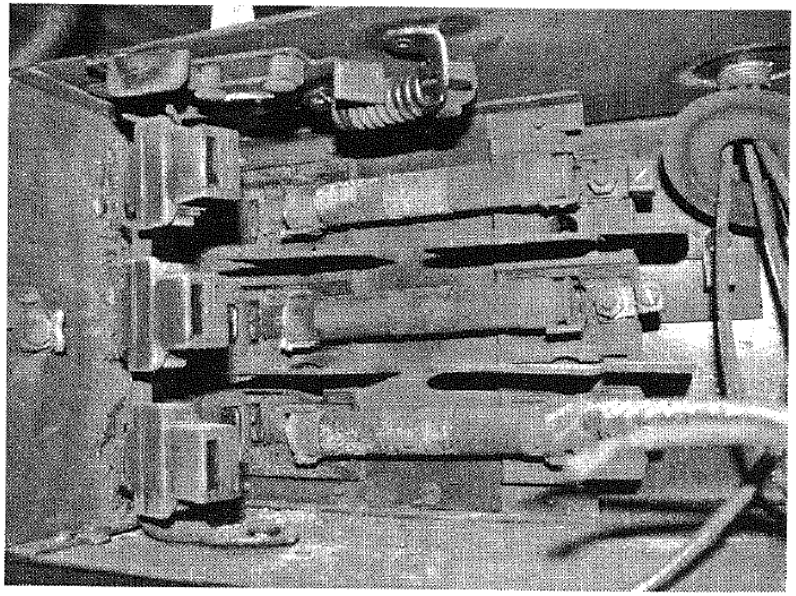


Figure 7. Photo of bus plug switch with burn back of bus bars.

Arc Flash for LV Systems

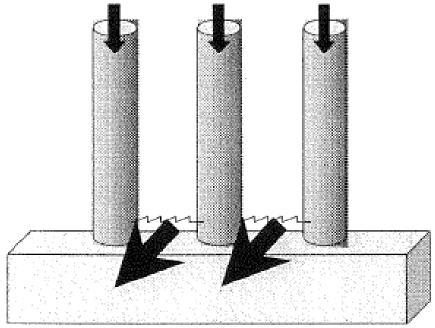


Fig. 5 Outward Deflection of Plasma by Barrier

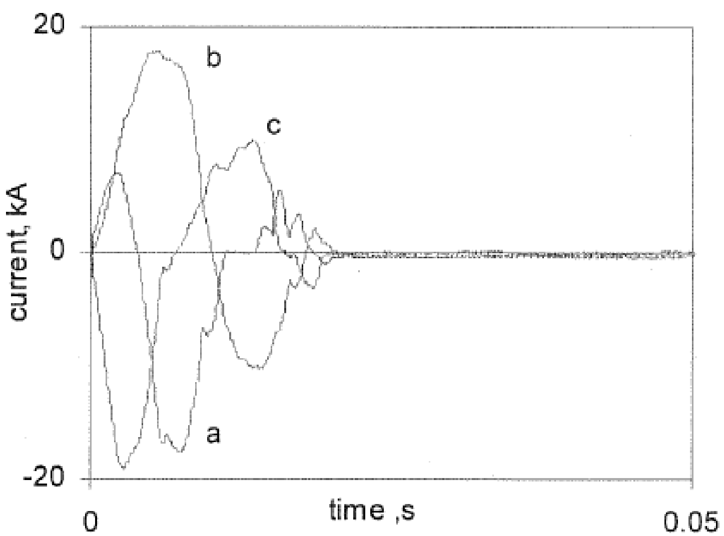


Fig. 6 Arcing Currents at 250V, 13kA - No Barrier .

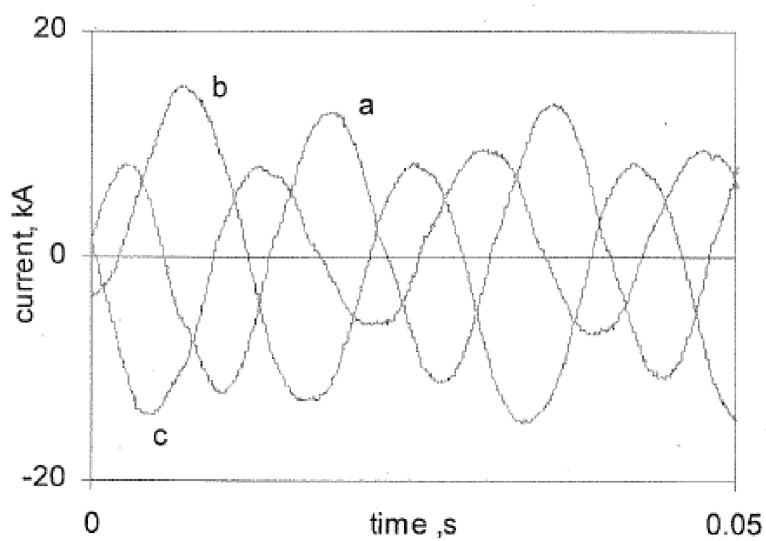
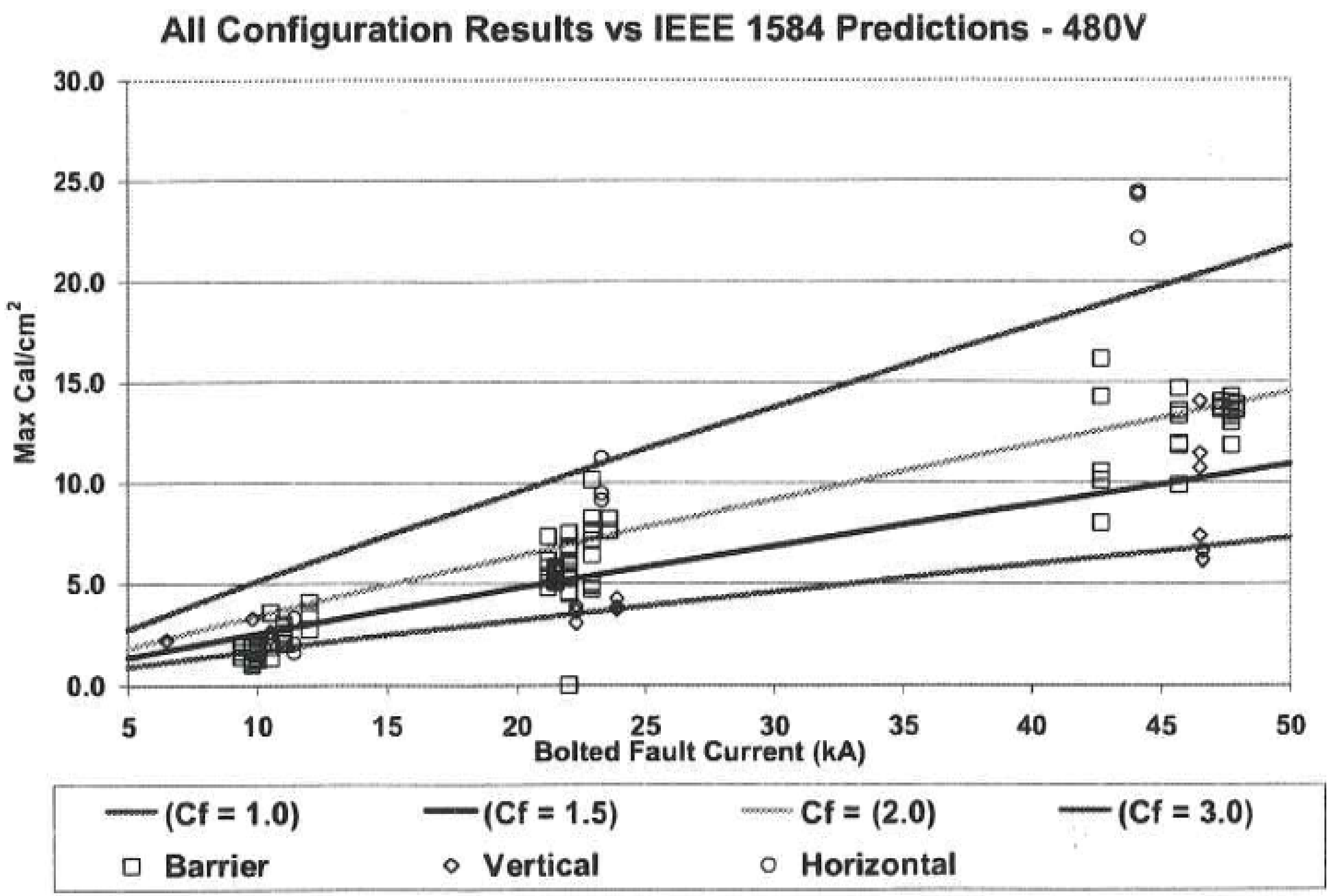
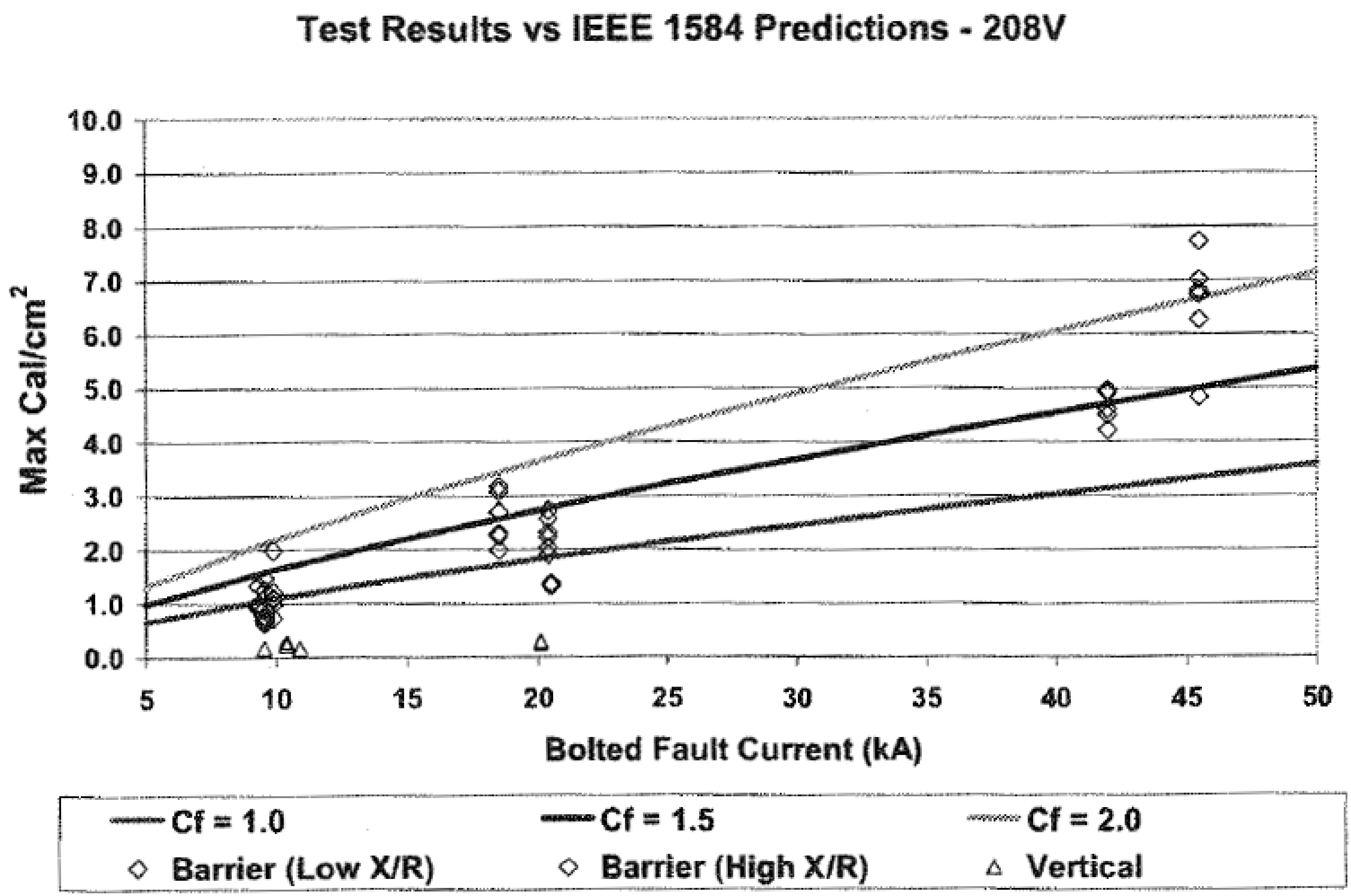


Fig. 8 Arcing Currents at 208V, 9.9kA - With Barrier

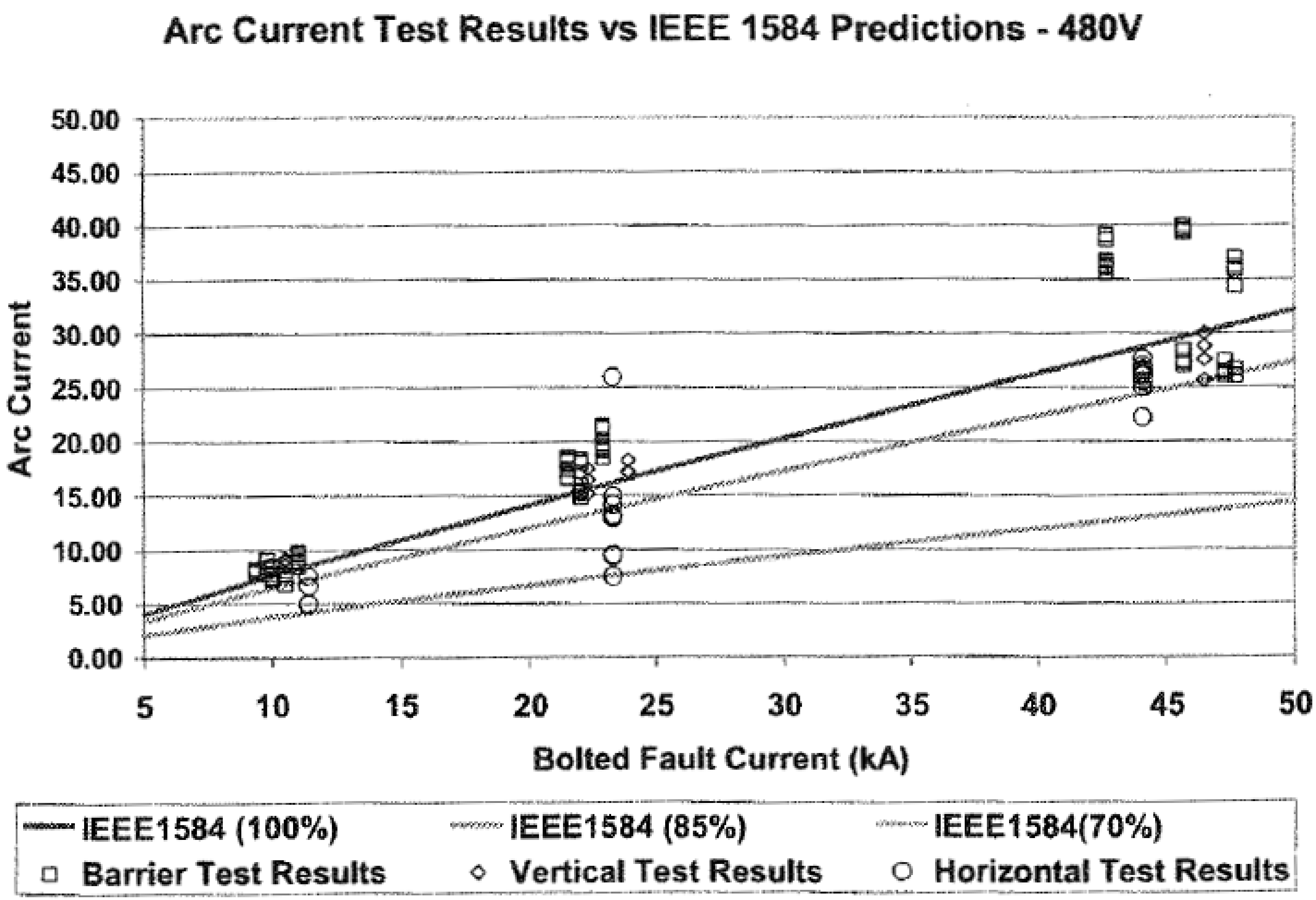
Arc Flash for LV Systems



Arc Flash for LV Systems



Arc Flash for LV Systems



IEEE 1584.1 Analysis Guidelines

- Define what are the requirements for performing AF analysis
- Defines the complexity of Systems and the experience required to perform and AF study
- Educates the Engineering process (how to make conservative assumptions)

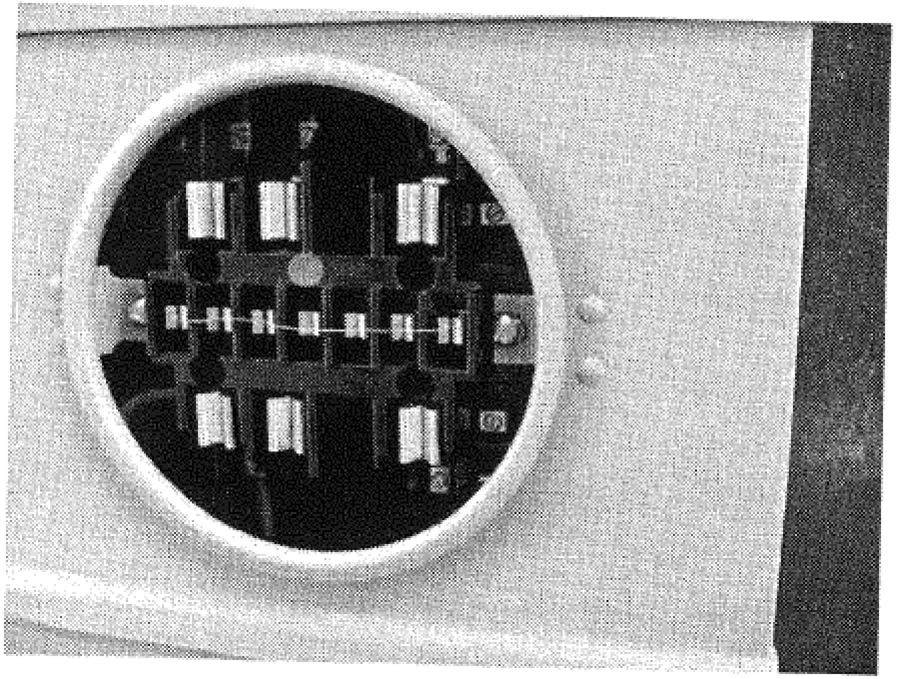
IEEE 1814 Safety by Design

- Reduce the Risk by designing safer equipment
- Samples of better Disconnect Switch Design
- Including Technology like ZSIP into Unit Substation Design

NESC – ROP for 2012

200 Amp Meter Base

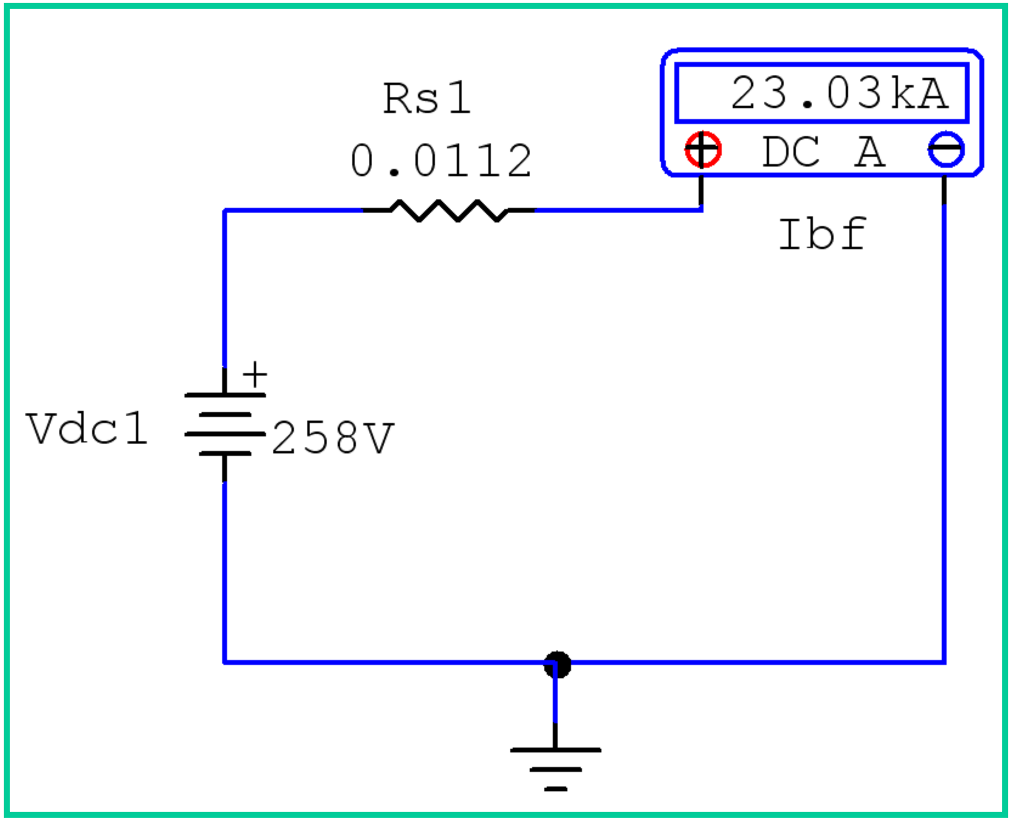
Shorting Wire in Meter Base



DC Arc Flash Analysis

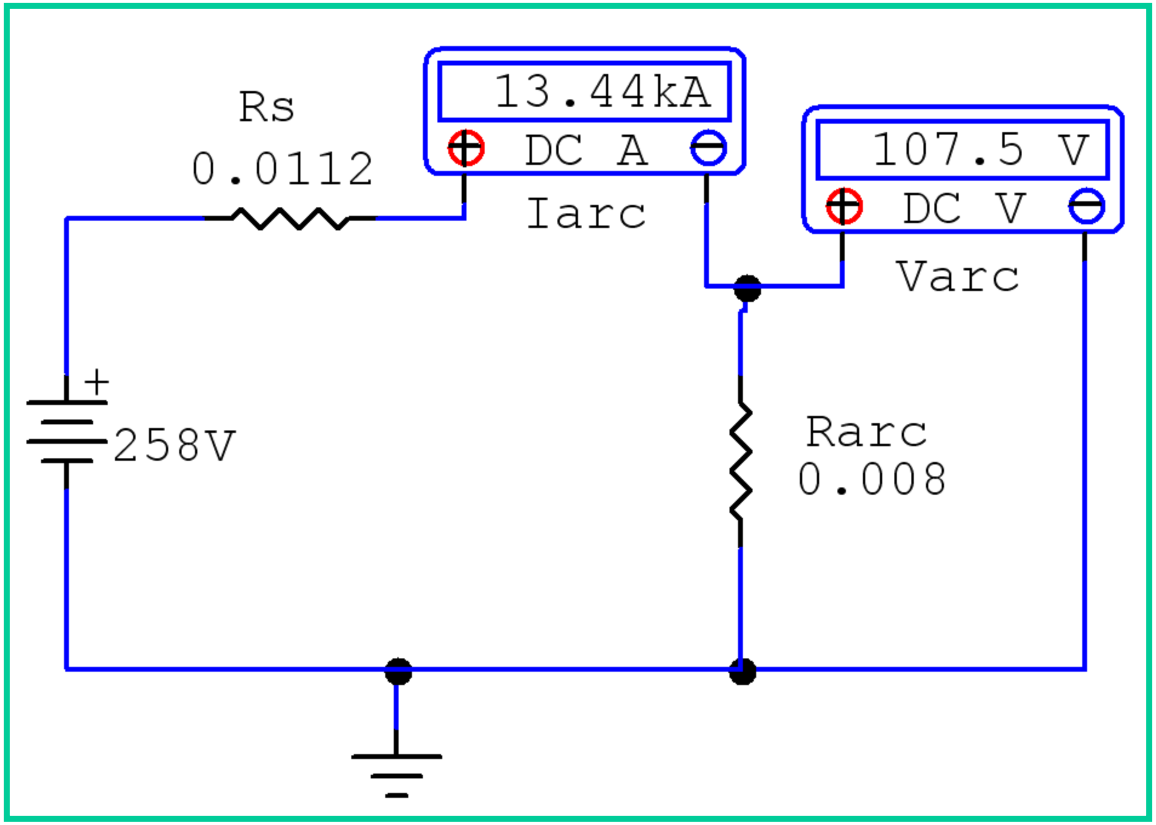
Methodology for DC Arc Flash

- DC SC and Arc Flash



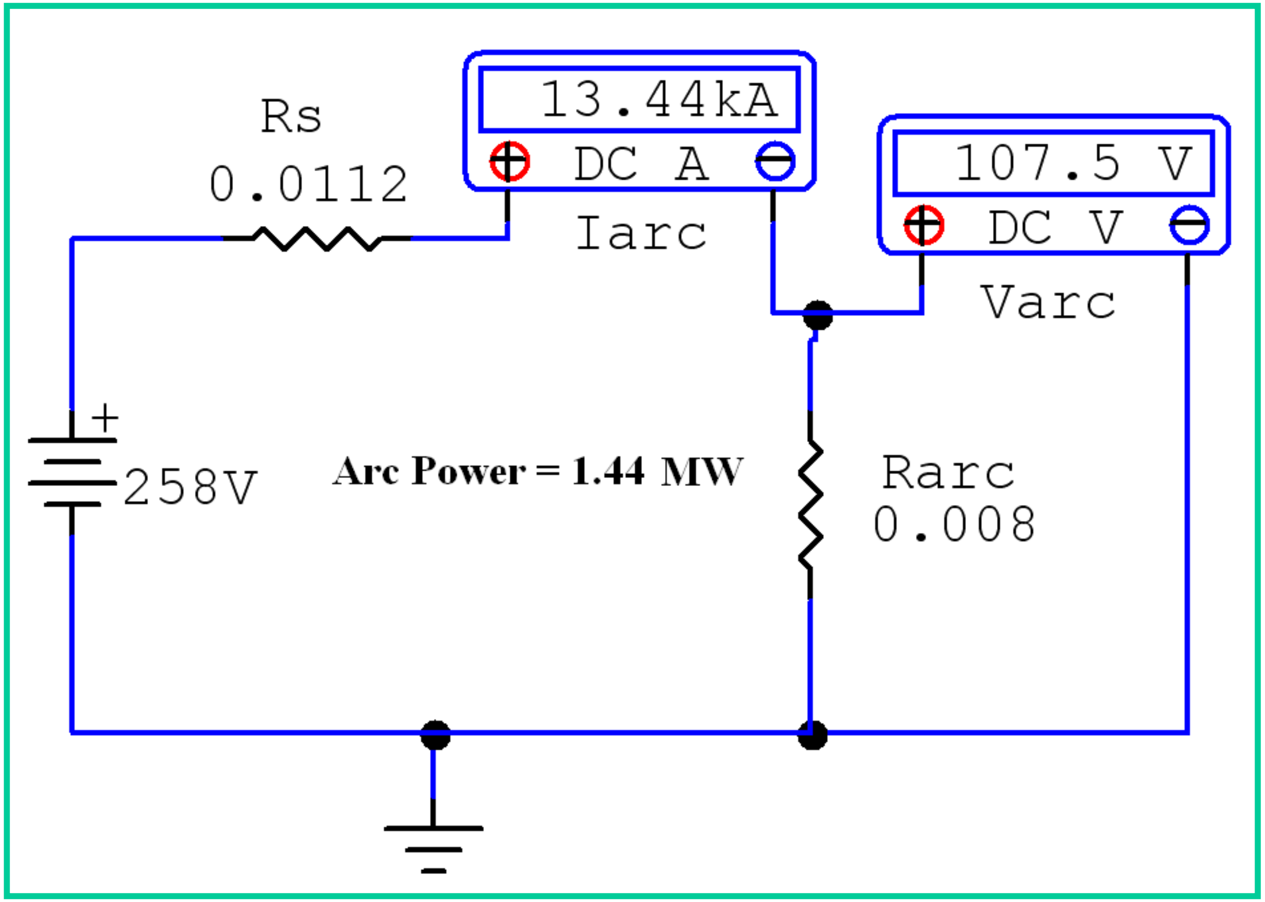
Methodology for DC Arc Flash

- DC Arc Flash Basic Concepts



Methodology for DC Arc Flash

- DC Arc Power



Methodology for DC Arc Flash

- Maximum Power Method (2007 IEEE Electrical Safety Workshop)

$$I_{arc} = 0.5 \times I_{bf}$$

$$IE_{m} = 0.01 \times V_{sys} \times I_{arc} \times \frac{T_{arc}}{D^{2}}$$

Methodology for DC Arc Flash

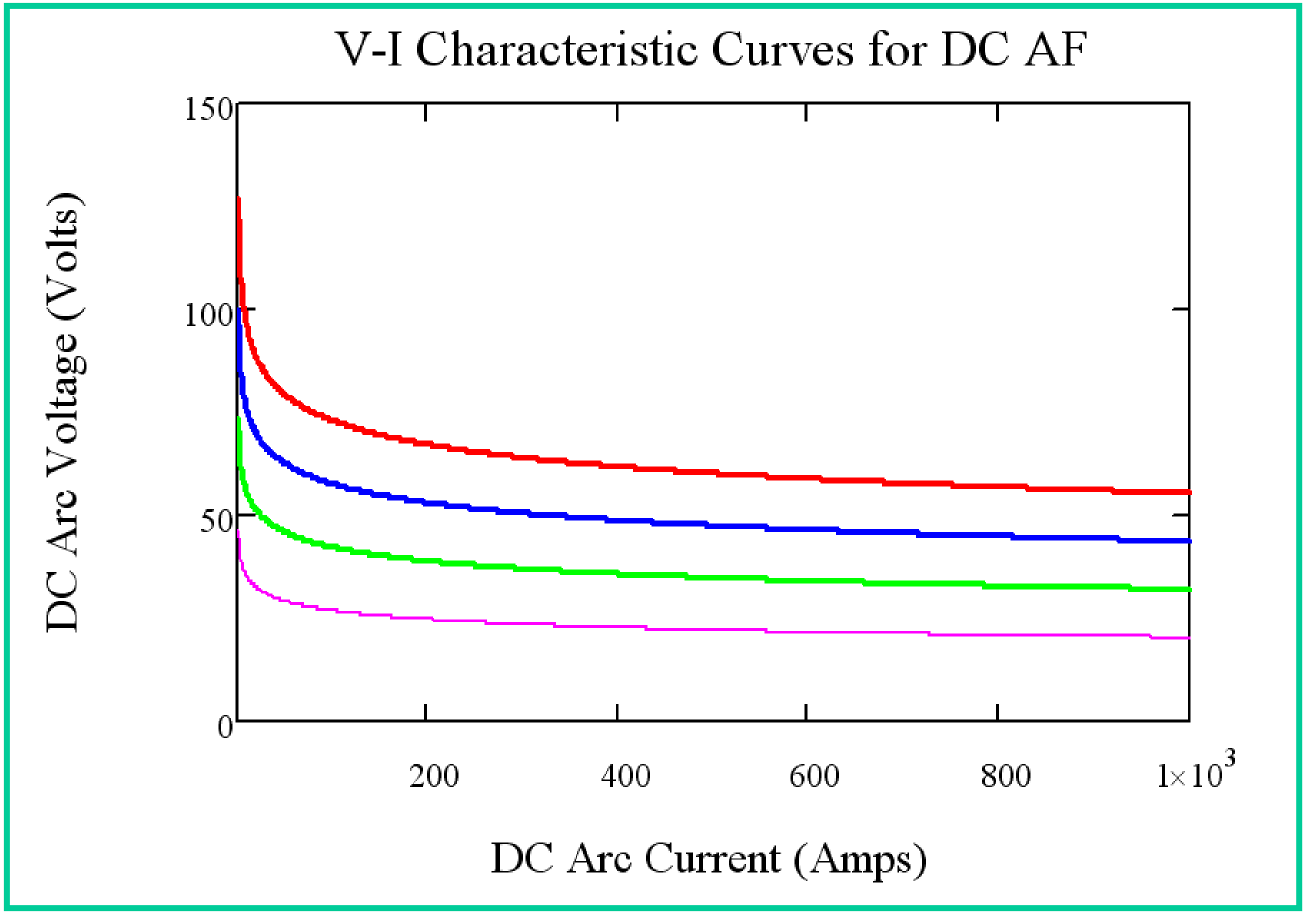
- Detailed Theoretical Calculation Method (2009 IEEE PCIC) (Testing has confirmed the theoretical method)

$$V_{arc} = (20 \times 0.534 \times Z_g) \times I_{arc}^{0.12}$$

$$R_{arc} = \frac{(20 \times 0.534 \times Z_g)}{I_{arc}^{0.88}}$$

Methodology for DC Arc Flash

- V-I Characteristic Curves



Methodology for DC AF

- Arc Energy Equations

$$Power = V_{dc} \times I_{dc}$$

$$P_{arc} = V_{arc} \times I_{arc} = I_{arc}^{2} \times R_{arc}$$

$$E_{arc} \approx I_{arc}^{2} \times R_{arc} \times t_{arc}$$

Methodology for DC AF

- DC Incident Energy Equations for Open Air and Enclosed Configurations

$$E_s = \frac{E_{arc}}{4\pi d^2}$$

$$E_1 = k \times \frac{E_{arc}}{a^2 + d^2}$$

Methodology for DC AF

- Enclosed DC Arc Fault values a and k

Enclosure	Width (mm)	Height (mm)	Depth (mm)	a (mm)	k
Panelboard	305	356	191	100	0.127
LV Switchgear	508	508	508	400	0.312
MV Switchgear	1143	762	762	950	0.416

Test System

- Example using the theoretical method

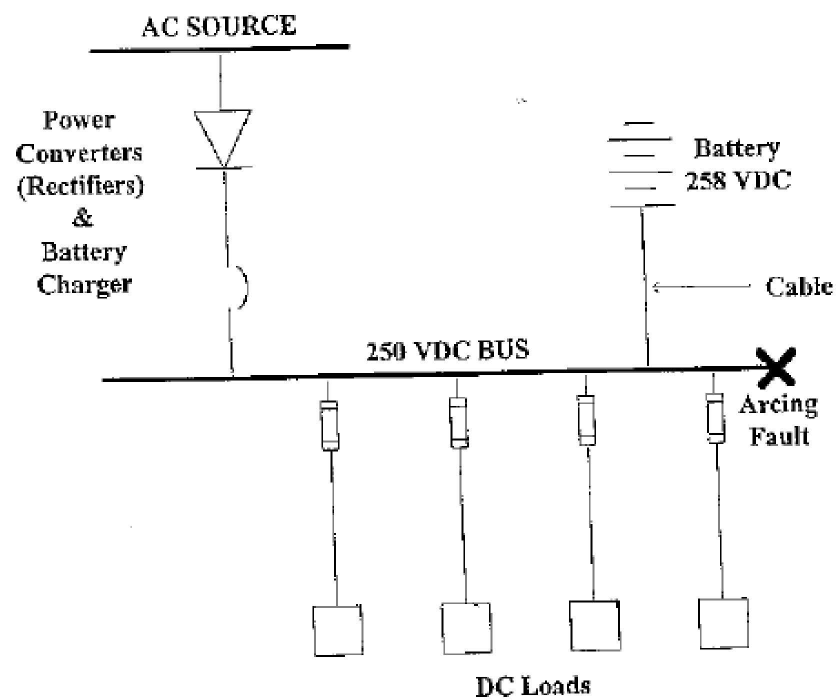


Fig. 18 DC System One-Line Diagram

Diff Method Result Comparison

- Comparison of the Maximum Power Method vs. Theoretical Method

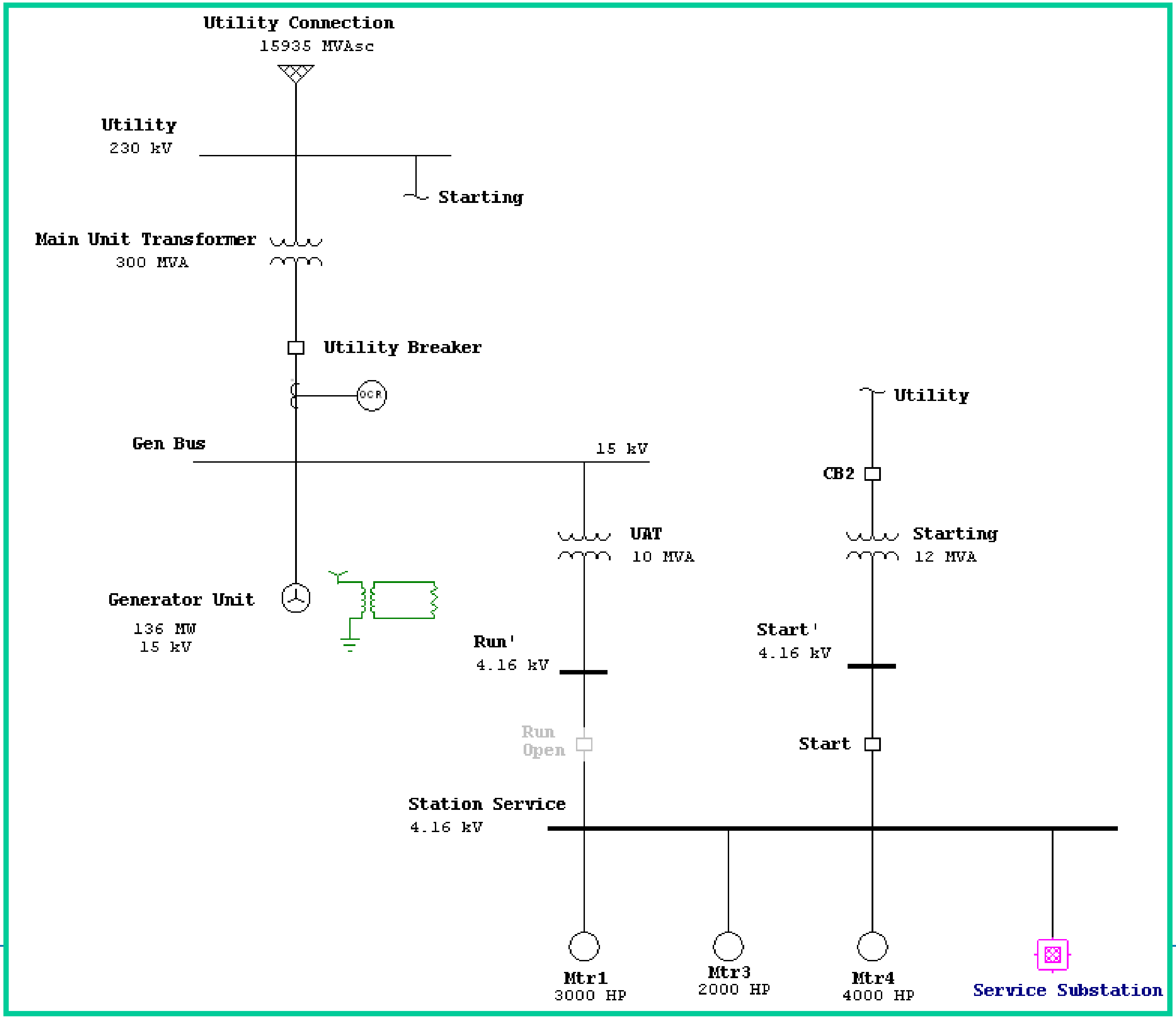
DC Arc Flash Method	I_{bf} dc (kA)	I_{arc} dc (kA)	R_{arc} (ohms)	FCT (sec)	I.E. (cal/cm^2)
Maximum Power	18.63	9.315	N/A	1.2	13.8
Theoretical Method	18.63	11.800	0.008	1.2	12.5

Transient Arc Flash Analysis for Generators

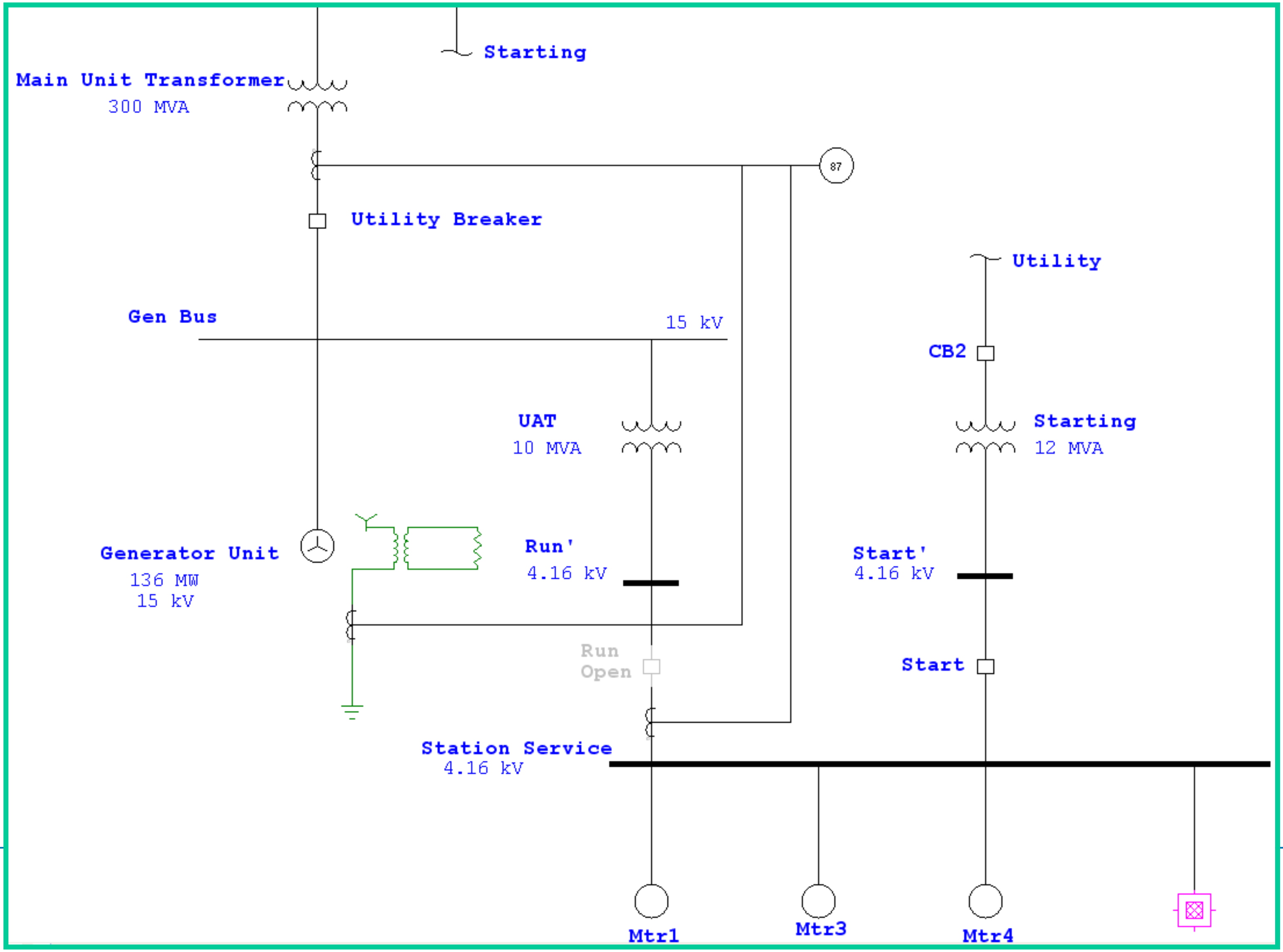
Problem Description

- Arc Flash Incidents near or on Generator Auxiliary Load
- No Generator Circuit Breaker
- Long Fault Clearing Time because of continuous generator short-circuit current contribution
- Trying to determine a practical level of PPE to be used for the task
- To determine a systematic method to determine the incident energy for systems with high fault current decay

System Description



System Description

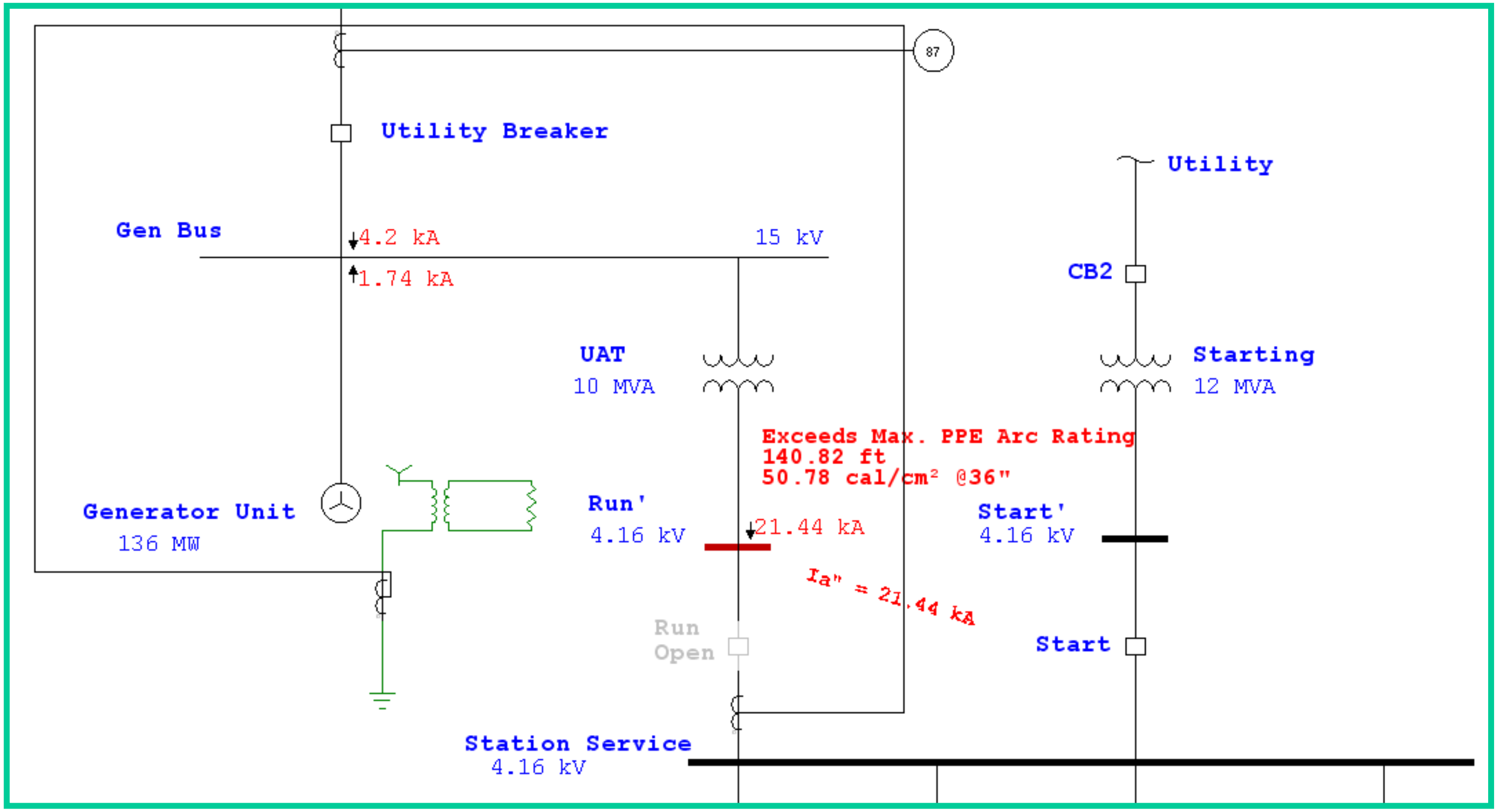


Analysis Techniques and Assumptions

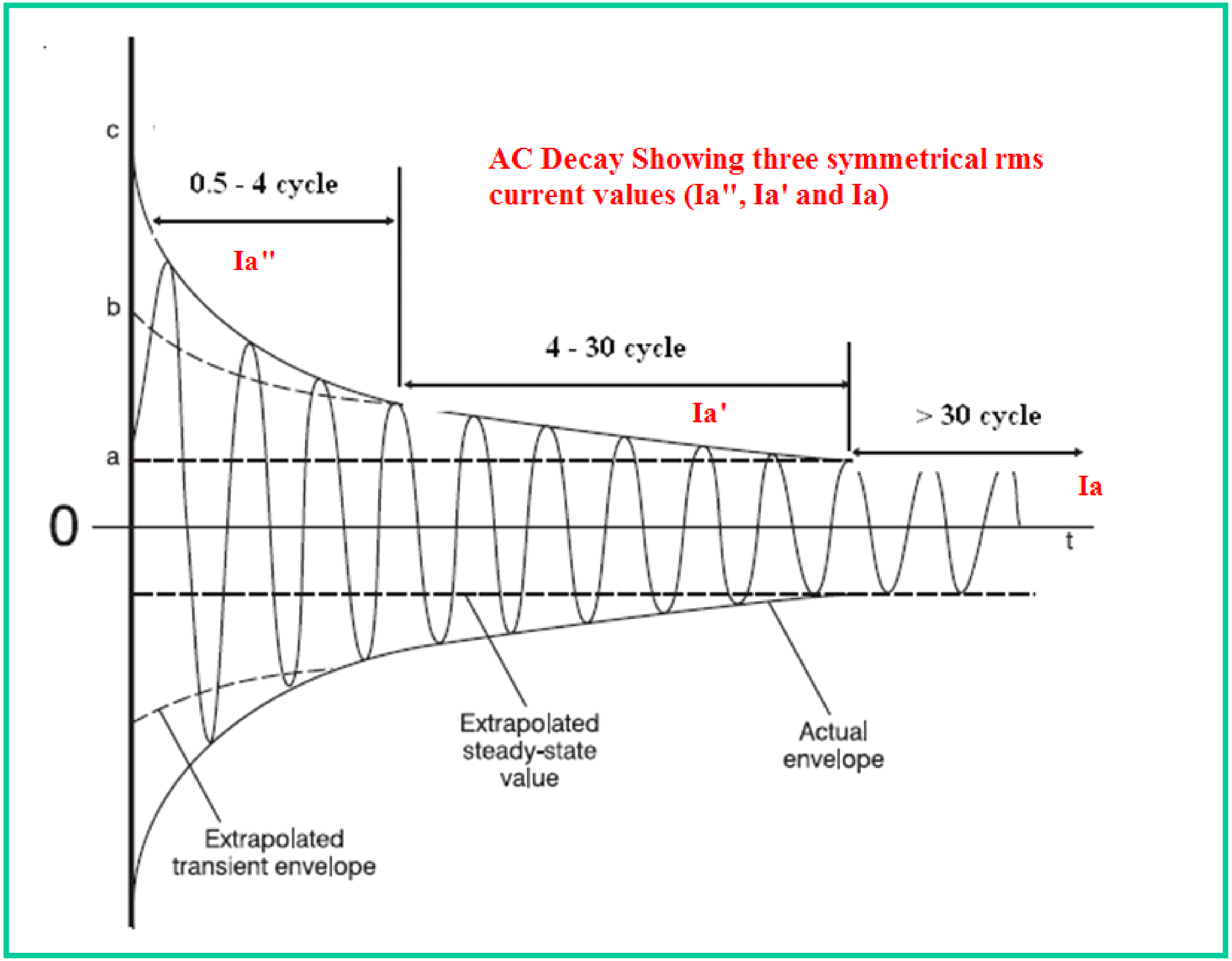
- IEEE 1584 and NFPA 70E do not provide any specific analysis method for such systems
- The classic IEEE 1584 method utilizes the Bolted fault current to determine the arc fault current
- The guidelines do not consider any transients or decay in the fault currents

Arc Flash Analysis

Utility Breaker Operates 6 cycles after Arc Fault is detected



Arc Flash Analysis



Arc Flash Analysis

Scenario ID	Arc Flash Method	Arcing Current (kA)	I.E. (cal/cm^2) for 2.0 sec
Case 1	Half Cycle (Ia”)	21.44	**51.6**
Case 2	Four Cycle (Ia’)	21.33	**51**
Case 3	Decay Method (Ia” ~ Ia)	21.4 ~ 11.5	**35.7**

Problems with Regular Arc Flash Analysis Method

- The calculation results show very high incident energy values
- Results in too much PPE requirements for the task
- Difficult to estimate the actual energy

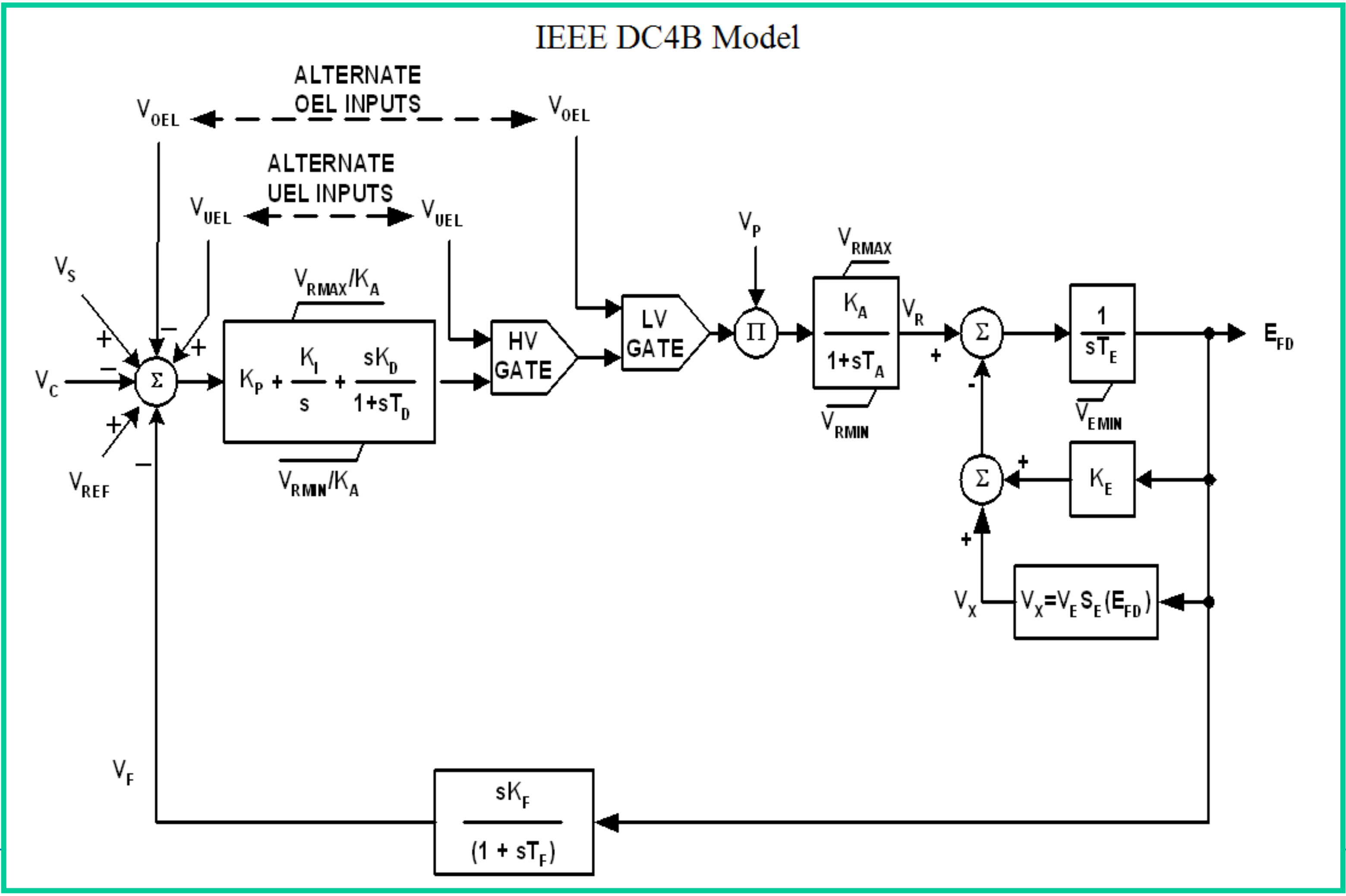
Benefits from Transient Stability Analysis

- Determine actual bolted fault current contributions
- Model actual generator time constants and exciter field discharge strategies
- Accurate recalculation of the bolted fault current levels for system separation
- Actual response of the Excitation and Generator Controls

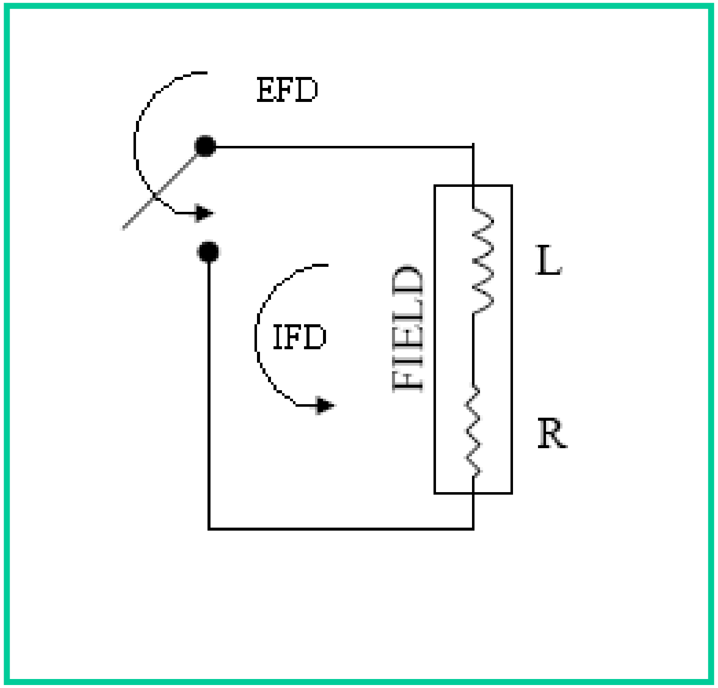
Methods of Reducing Generator Fault Current

- Loss of Excitation
- Field Discharge Resistor / Crowbar bypass system
- Negative Field Forcing

Exciter Model Used for the Simulations

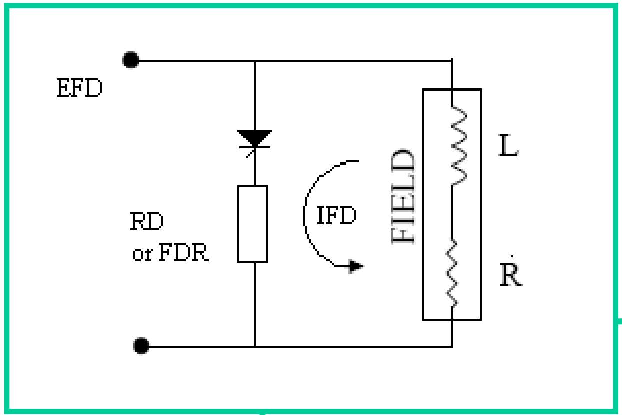


Field Discharge: Short-Circuit

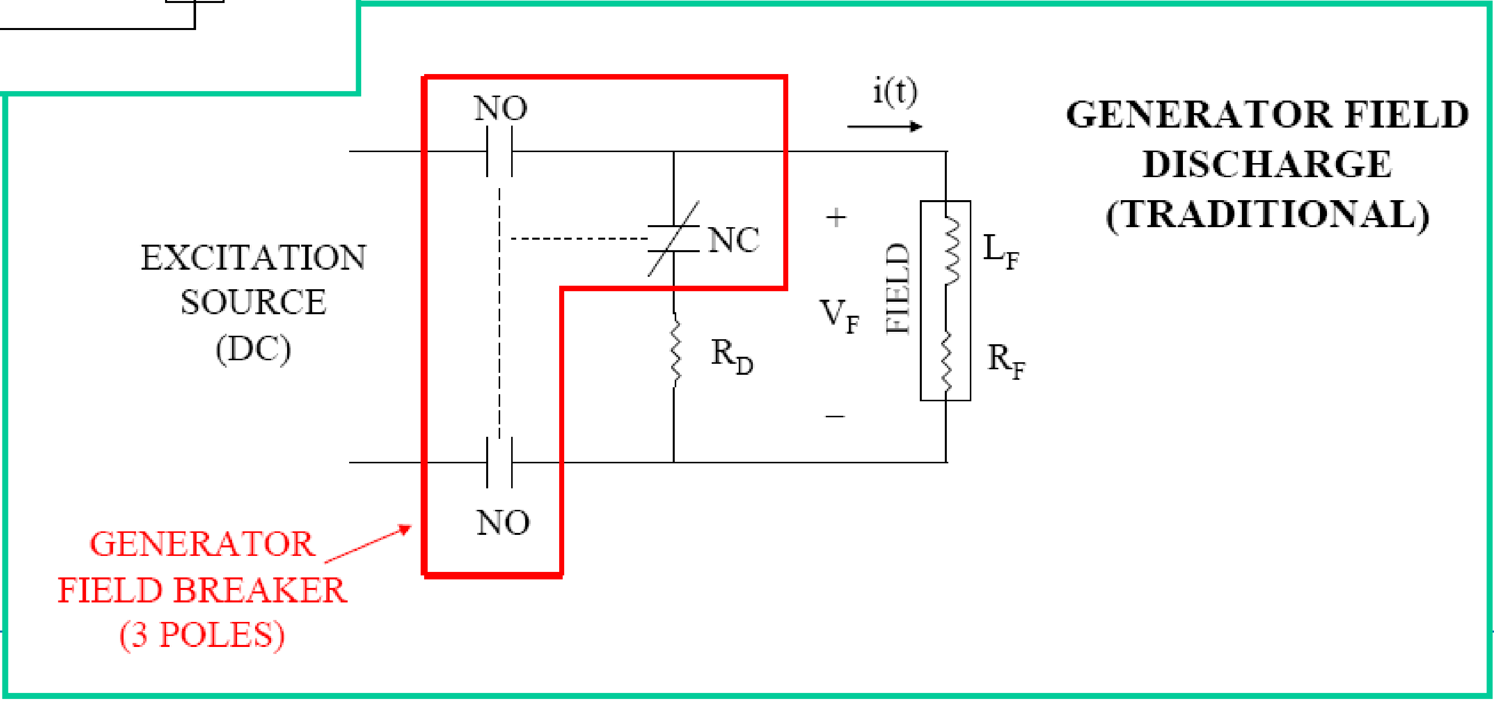


Equivalent Circuit Model for Field Discharge Simulation

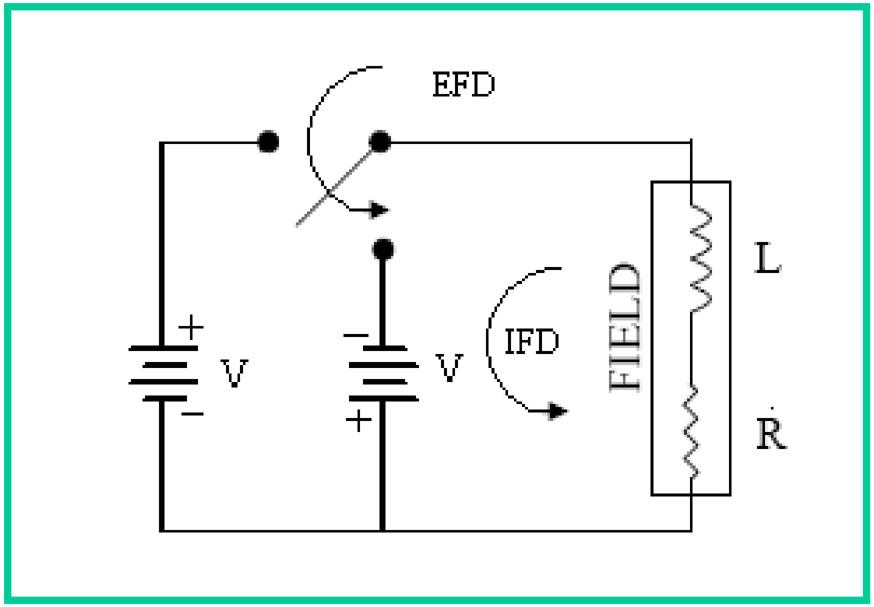
Field Discharge Resistor



A Field Discharge Resistor (FDR) is added along with the generator Time Constant (T'_{do})



Negative Field Forcing

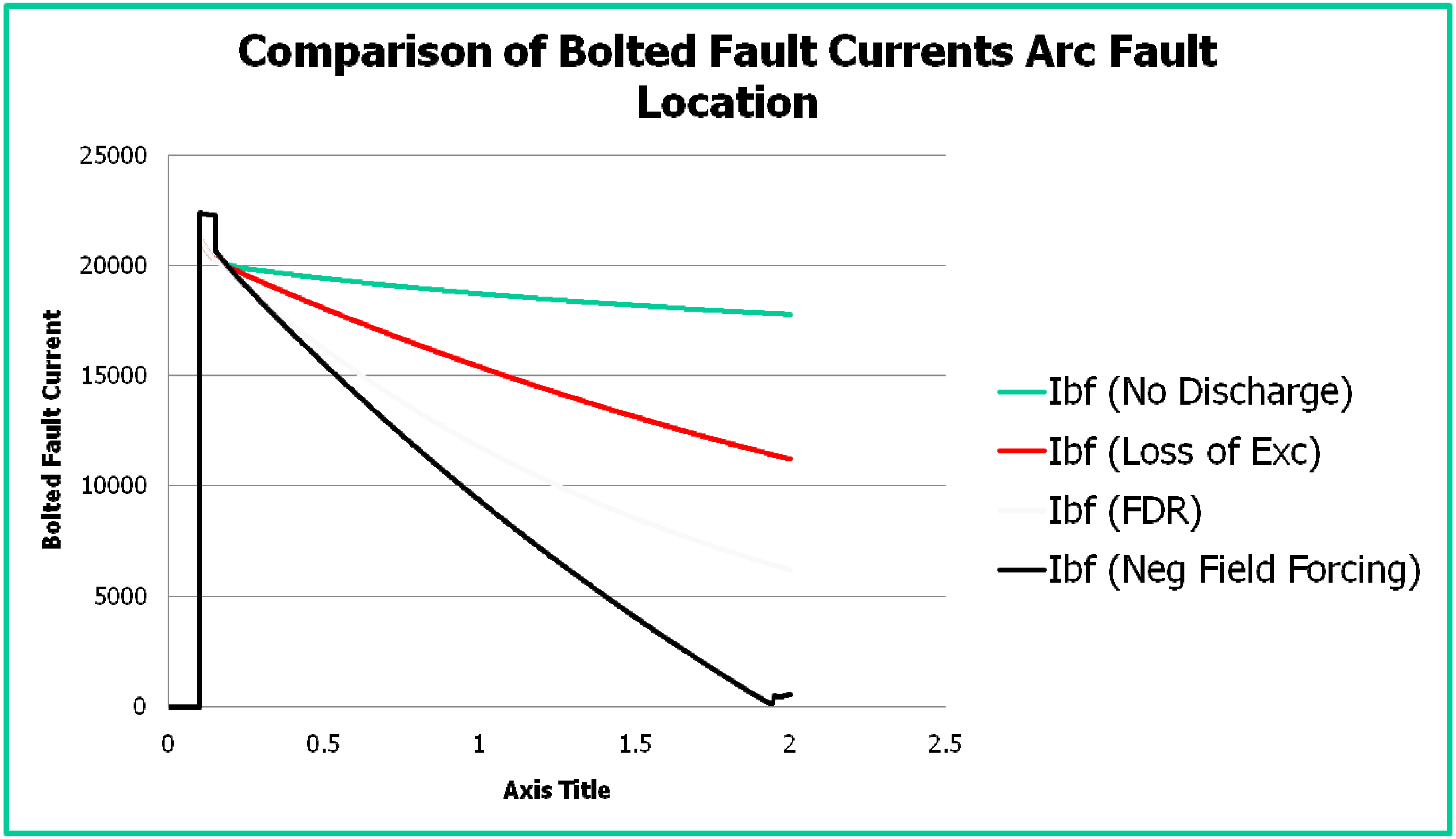


For Negative Field Forcing. The discharge rate is dependent on the value of the negative voltage

Transient Stability Scenarios

Scenario ID	Field Discharge Scheme	Simulation Method	Bolted Fault Current @ 2.0 sec
Case 1	None	TS	17.7 kA
Case 2	Loss of Excitation	TS	11.2 kA
Case 3	FDR to with RD = RF	TS	6.2 kA
Case 4	Negative Field Forcing	TS with UDM	0.54 kA

Fault Current Comparison

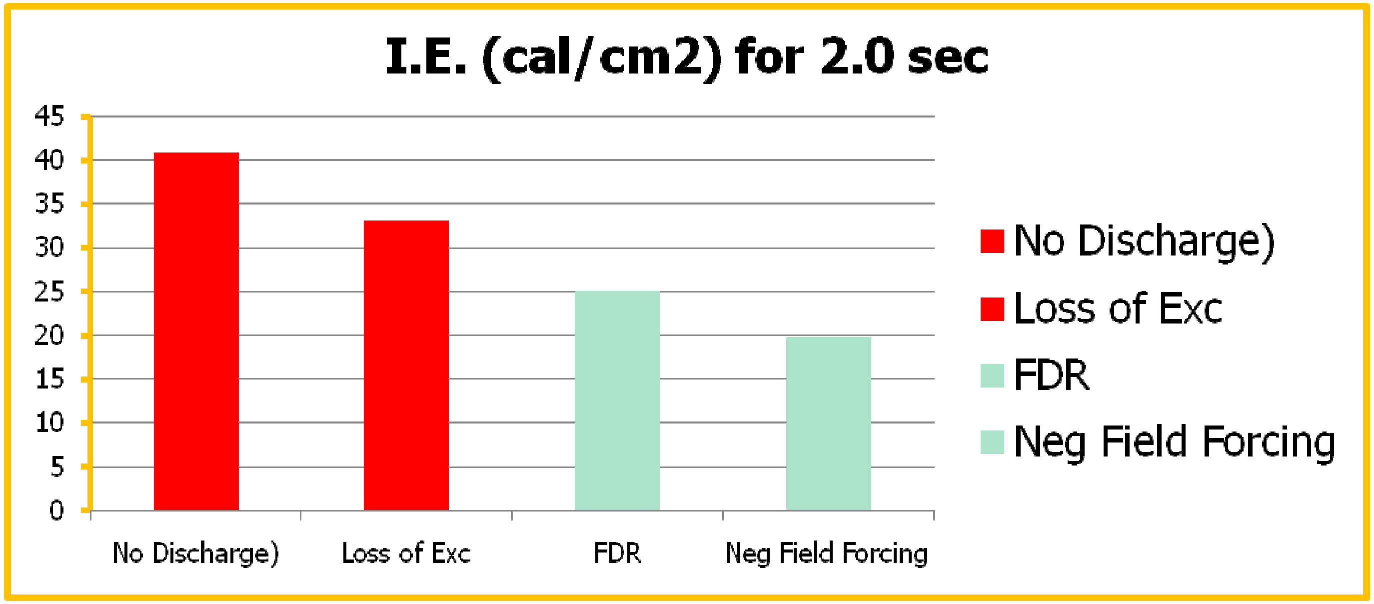


Incident Energy Determination from TS Results

- Using Spreadsheet, MathCAD or Matlab to import the bolted fault current values from the Transient Fault Study
- The IEEE 1584 2002 Empirical Equations are used
- The energy is determined by integrating the incident energy results from each time step up to arbitrary time of exposure (i.e. 2.0 sec)

Incident Energy Comparison

Scenario ID	Field Discharge Scheme	I.E. (cal/cm²) for 2.0 sec
Case 1	None	40.8
Case 2	Loss of Excitation	33.1
Case 3	FDR to with RD = RF	25.7
Case 4	Negative Field Forcing	19.8



Comparison Against Arc Flash

	I.E. (cal/cm²) for 2.0 sec (Arc Flash with TS)	I.E. (cal/cm²) for 2.0 sec (Regular Arc Flash)
Highest Results	40.8	51.6
Lowest Results	**19.8**	35.7

References

- Generator Field Discharge Methods – provided by Wayne Eads of Southern Company Generation
- IEEE Standard 421.5 IEEE Recommended Practice for Excitation System Models for Power System Studies
- IEEE 1584 2002
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Questions?

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