November 2013 Technical Seminar

Power System Protection Coordination

Part 1: Principles & Practices: By Mr. Rasheek Rifaat, P.Eng, SMIEEE
Part 2: Selectivity : By Dr. Peter Sutherland, Fellow IEEE

Power System Protection Coordination

Part 1: Principles & Practices

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Abstract:

Since the inception of industrial electrical systems, coordination tasks were performed to ensure that protection systems would operate with the necessary reliability and security. The tools to perform such tasks have evolved from the use of a glass table with light and log-log curve sheets into computer base programs with GUI. Meanwhile, protective devices have also gone through advancements from the electromechanical devices to the multifunctional, numerical devices. Throughout the changes in coordination tools and protective device configurations, a good number of protection coordination principles remain with us. In addition, new techniques are developed to assist us with the use of protection systems to reduce arc flash energy in addition to basic protection functions. Part 1 will discuss the principles and basics of protection system coordination, the developments in the coordination programs and present day multifunctional numerical devices used in distribution and industrial systems.

References (Standards & Books)

- IEEE Buff Book™ IEEE Std 242, 2001
- IEEE Brown Book™ IEEE Std 399, 1997
- Protective Relaying Principles and Applications
- Industrial Power Systems Handbook: Beeman
- Industrial Power Systems: Shoab Khan
- Power System Protection: Paul Anderson
- A complete list will be available in a hard copy format
- IEEE Std 1015-1993, IEEE Recommended Practice for Applying Low-Voltage Circuit Breakers Used in Industrial and Commercial Power Systems (IEEE Blue Book)
- NFPA 70, *National Electrical Code,* National Fire Protection Association, Quincy, Massachusetts, 2005
- CEC (Canadian Electrical Code),

IEEE Protection Guides

IEEE Std C37.91-2008	***IEEE Guide for Protective Relay Applications to Power Transformers***
***IEEE* Std C37.95-2002 (R2007)**	***IEEE Guide for Protective Relaying of Utility-Customer Interconnections***
***IEEE* Std C37.96-2012**	***IEEE Guide for AC Motor Protection***
IEEE Std C37.99-2012	***IEEE Guide for the Protection of Shunt Capacitor Banks***
IEEE Std C37.101-2006	***IEEE Guide for Generator Ground Protection***
IEEE Std C37.102-2006	***IEEE Guide for AC Generator Protection***
IEEE Std C37.108-2002 (R2007)	***IEEE Guide for the Protection of Network Transformers***
IEEE Std C37.109-2006	***IEEE Guide for the Protection of Shunt Reactors***

IEEE Protection Guides (Continued)

IEEE Std C37.110-2007	***IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes***
IEEE Std C37.112-1996 (R2007)	***IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays***
IEEE Std C37.113-1999 (R2004)	***IEEE Guide for Protective Relay Applications to Transmission Lines***
IEEE **Std C37.114-2004**	***IEEE Guide for Determining Fault Location in AC Transmission and Distribution Lines***
IEEE **Std C37.117-2007**	***IEEE Guide for the Applications of Protective Relays used for Abnormal Frequency Load Shedding and Restoration***
IEEE Std C37.119-2005	***IEEE Guide for Breaker Failure Protection of Power Circuit Breaker***
IEEE Std C37.234-2009	***IEEE Guide for Protective Relay Applications to Power System Buses***

Recommended for Equipment Damage Curves

IEEE Std C57.12.59-2001 (R2006)	IEEE Guide for Dry-Type Transformer Through-Fault Current Duration & Errata 2006
IEEE Std C57.109-1993 (R2008)	IEEE Guide for Liquid-Immersed Transformer Through-Fault Current Duration
IEEE Std 620-1996 (R2008)	IEEE Guide for the Presentation of Thermal Limit Curves for Squirrel Cage Induction Machines

Recommended for Equipment Selection

IEEE Std C37.06-2009	AC High Voltage Circuit Breakers Rated on Symmetrical Current Basis Preferred Rating and Related Required Capabilities for Voltages Above 1000V
IEEE Std C37.010-1999 (R2005)	IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis
UL 67 – 2009	UL Standard for Safety- *Panelboards*
UL 489 – 2013	UL Standard for Safety- Molded-Case Circuit Breakers, Molded-Case Switches, and Circuit Breaker Enclosures
UL 845– 2005	UL Standard for Safety- M*otor Control Centers*
UL 891 – 2005	UL Standard for Safety- *Dead-Front Switchboards*
UL 1066 – 2012	UL Standard for Safety- Low-Voltage AC and DC Power Circuit Breakers used in Enclosures
UL 1558 – 1999	UL Standard for Safety- Metal-Enclosed Low-Voltage Power Circuit Breaker Switchgear

Excerpts from Mason's Book "The Art and Science of Protective Relays:

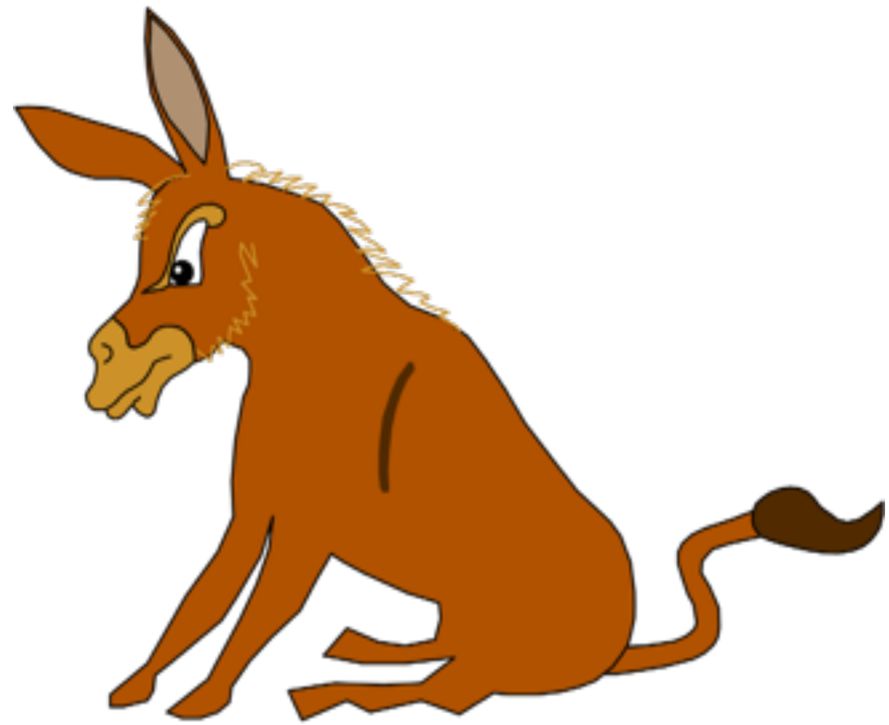
- The function of protective relaying is to cause the prompt removal from service of an element of a power system when it suffers a short circuit or when it starts to operate in any abnormal manner that might cause damage or otherwise interfere with the effective operation of the rest of the system.

- As we advanced in making and applying protective devices Overcurrent Protection and Coordination shall be:
  - More Science
  - Less Art!!

What are the Important Aspects of Protection Systems?

Protection Characteristics

- Reliability:
  - Dependability: correct device/relay operation: (must operate when required)
  - Security: against incorrect device/relay operation (should not operate unnecessarily)
- Speed
- Selectivity
- Economics



What about Consistency?

Protection Reliability

- Dependability: Must Operate When Required
  - Proper system design
  - Backup
    - To operate when main system fails
    - To cover any parts that may fall in-between protected zones (fall in between the cracks)
  - Reliability of hardware. Testing and in-service proven history (How you can get that in a fast changing world?)
  - Reliability of software (software testing and checking)
  - High quality protection system design
  - Appropriate settings

Protection Reliability (Continued)

- Security: against incorrect relay/device operation (must NOT operate unnecessarily)
- Unit Protection System: able to detect and response to faults within the Protection Zone
- Non-unit Protection System: depends on correlated and coordinated responses to establish selectivity (i.e. Time-Overcurrent)

Some Modes of Failures in Protection Systems

- Failure of current or voltage signal to the relays.
- DC supply failure
- Failure of relay itself:
    - Relay Hardware Components
    - Software Failure
    - Power Supply Failure
- Failure of a Fuse
- Failure of Circuit Breaker (tripping circuit or mechanism, or signal to trip the breaker)
- Miscoordination

Simplicity as an additional Important Characteristic of Protection Systems

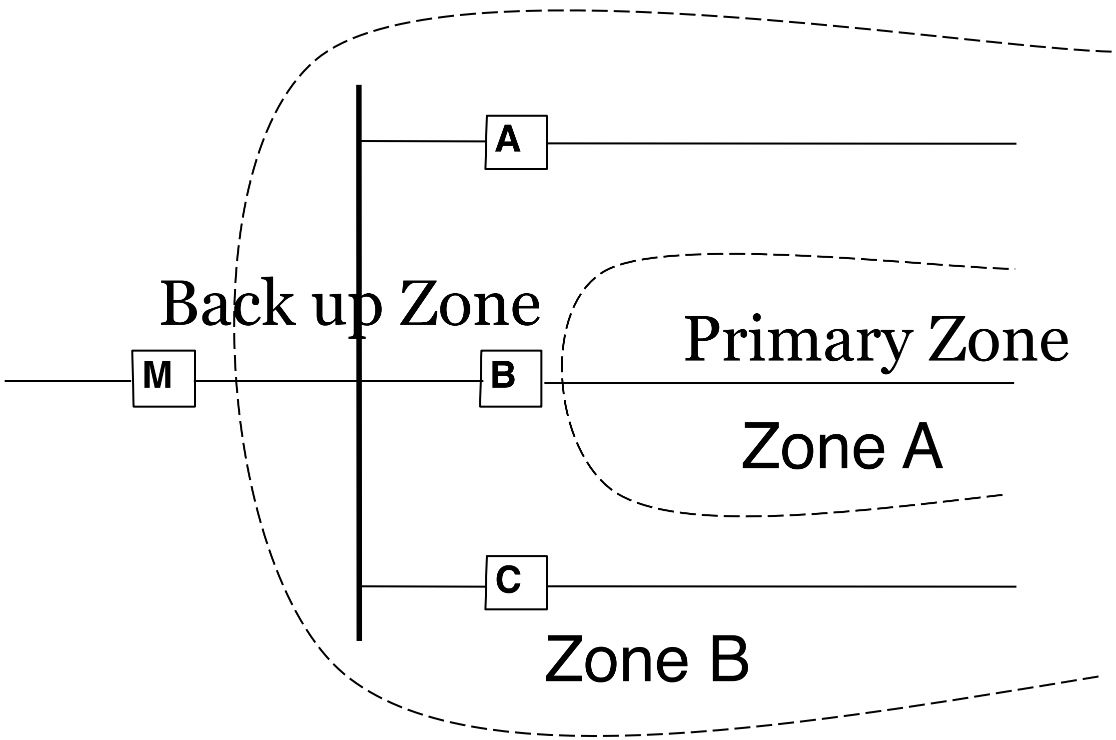
- ***Word of wisdom from an*** (OLD) ***experienced man:***
- ***"Avoid unnecessary complications to the system: The more guts you have the more belly aches"***

Some Aspects of Relay Selectivity:

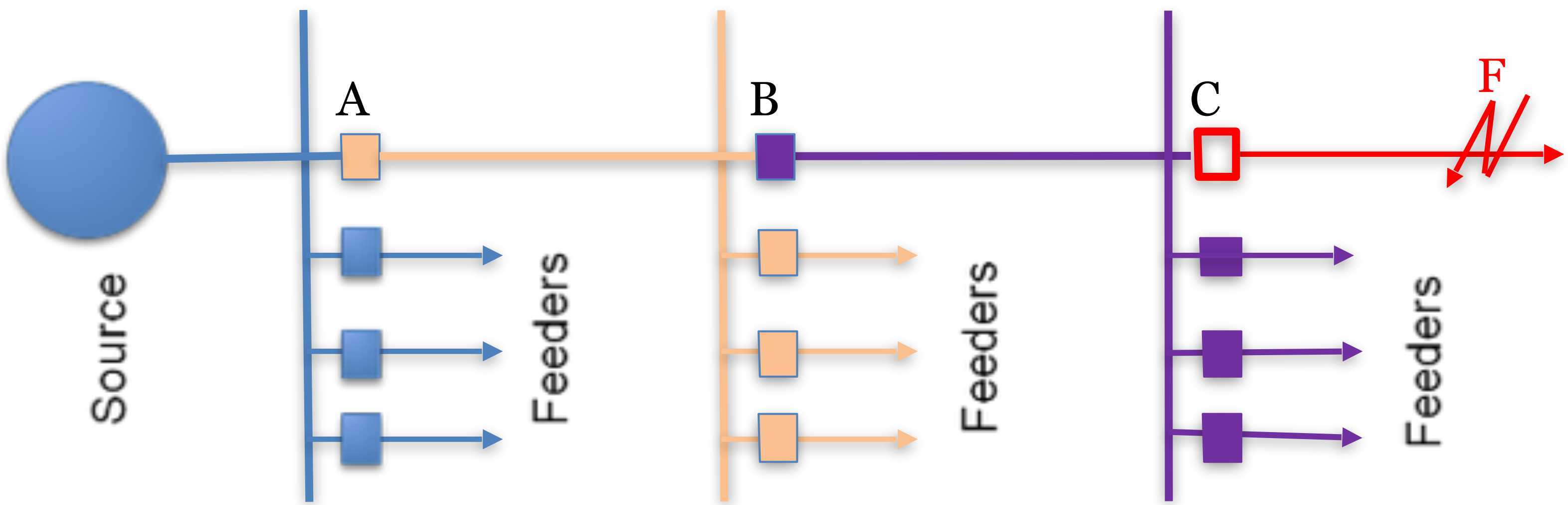
- Discrimination (location of fault, type of fault) by different methods (Examples):
  - Time
  - Current Magnitude
  - Distance (V/I)
  - Time + Current Magnitude
  - Time + Distance
  - Time + Direction of Current
  - Use of Communication
  - Use of other quantities:negative sequence, harmonics

Overlapping in Overcurrent Protection

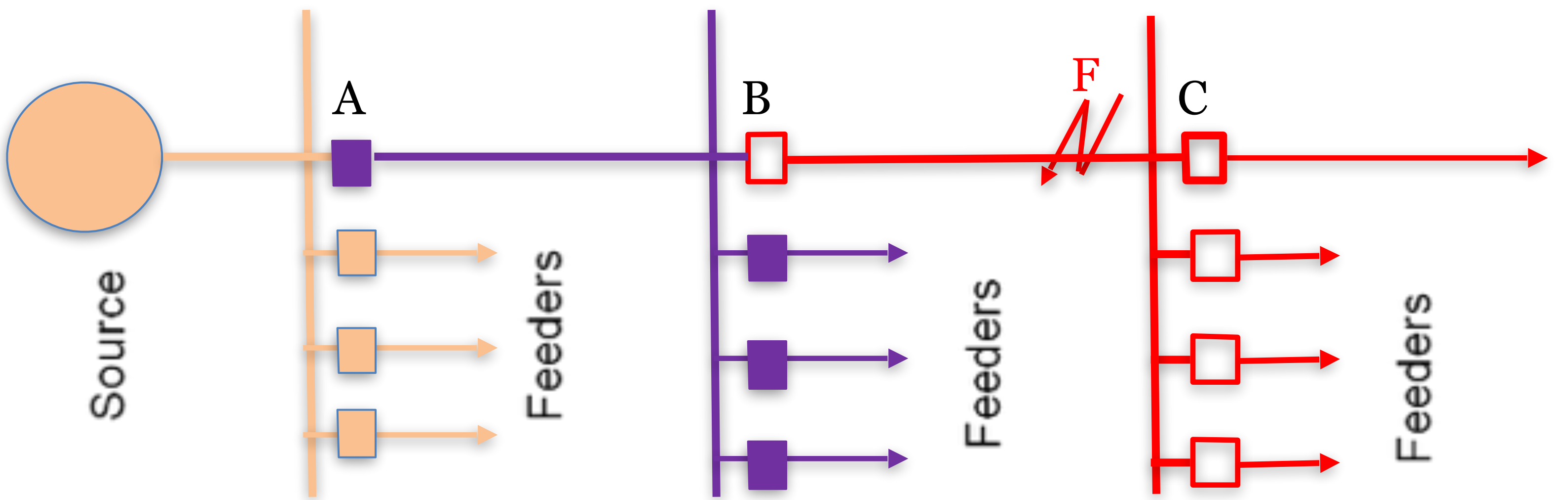
- Overcurrent Protection: simple, it will overlap
- Coordination to ensure selectivity



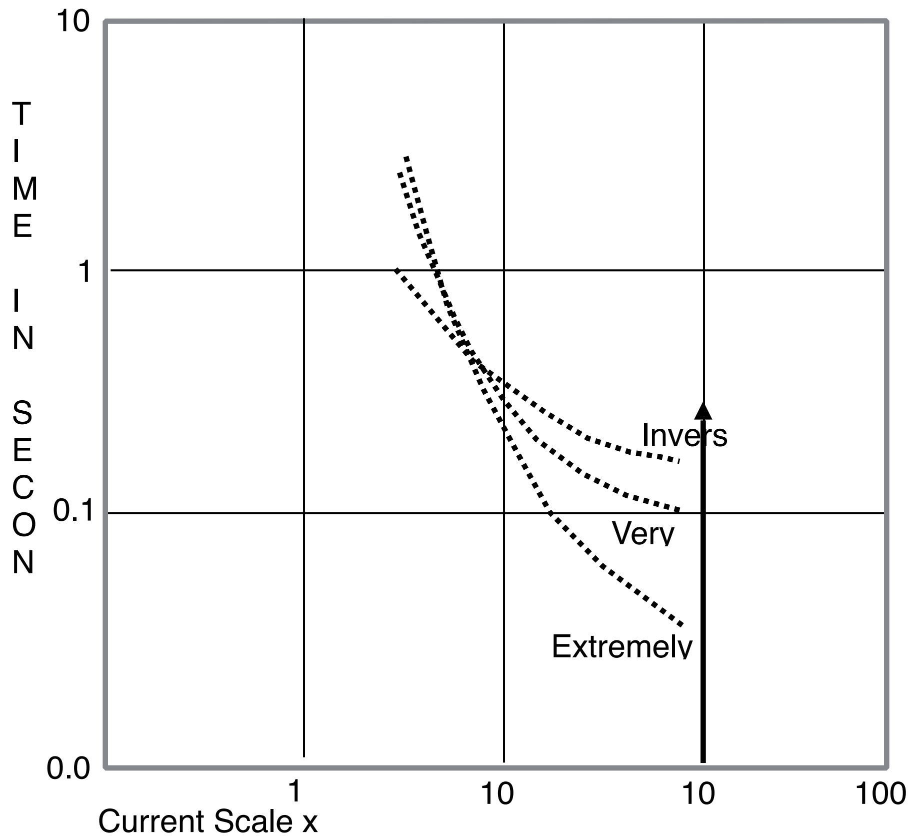
Coordination for Radial Feeders



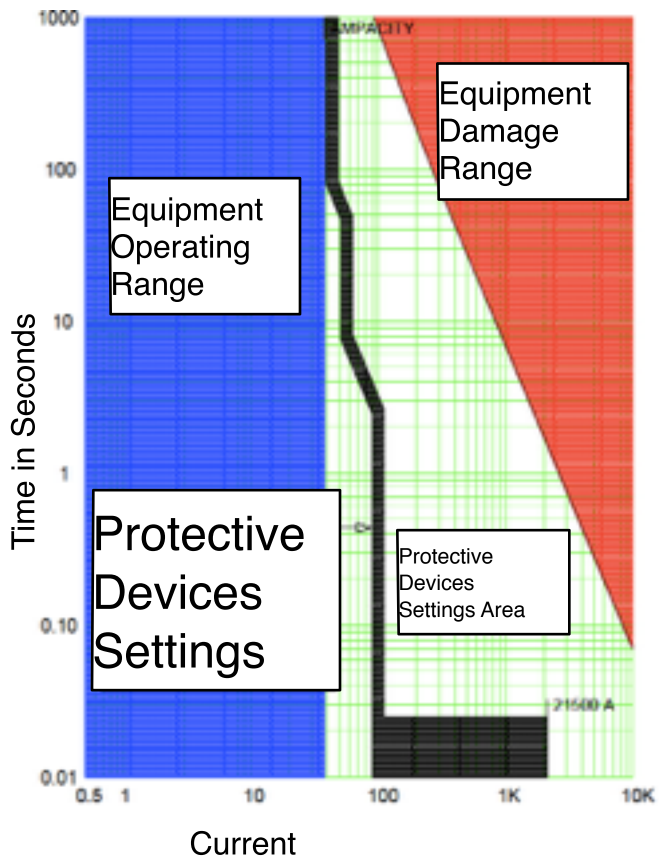
Coordination for Radial Feeders

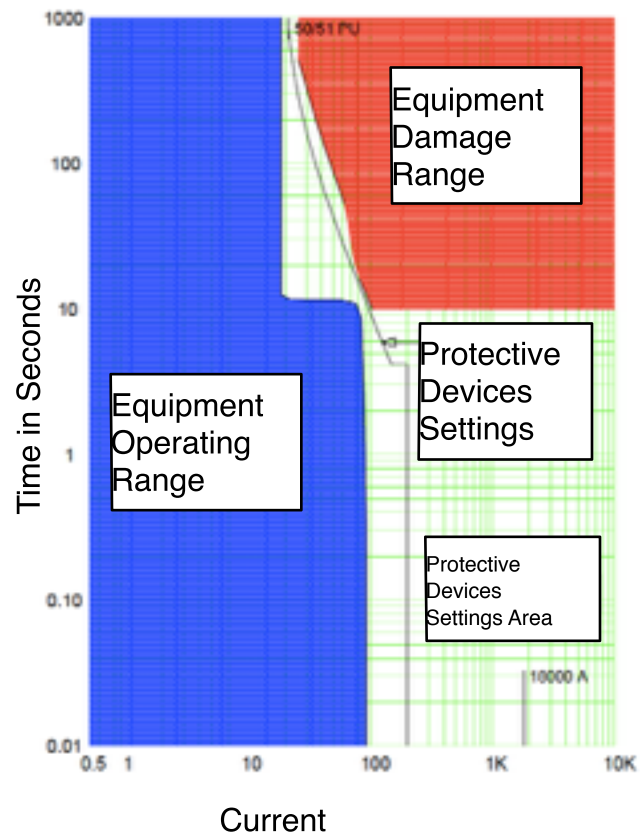


Inverse Current Time Characteristics

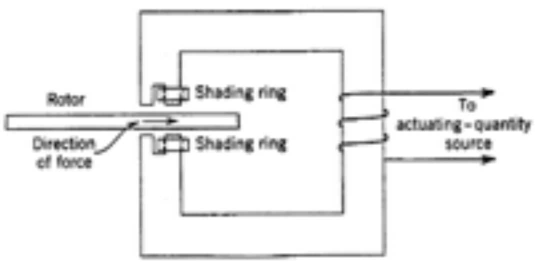


Log-Log Graph Areas:

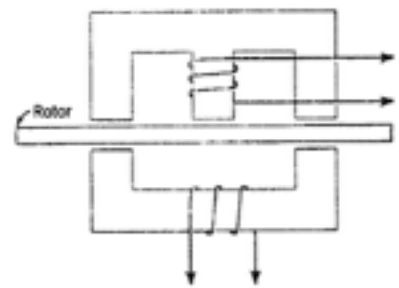




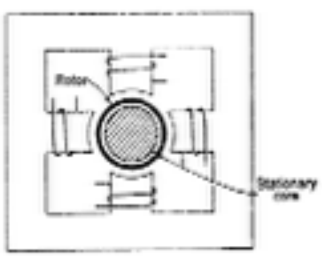
From Mason: Inverse TC Relays



A



B



C

Three Types:

- Shaded Pole (A)
- Wattmeter Structure (B)
- Induction Cup Structure (C)

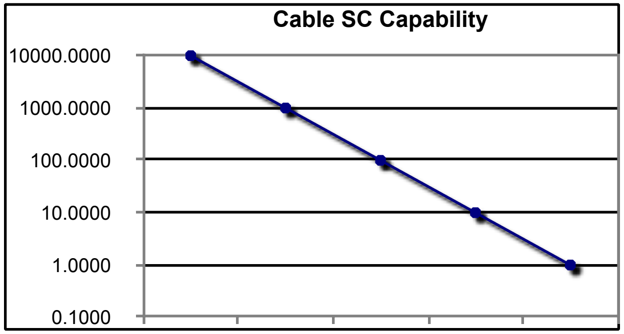
Time Current Equation Per WG 7

$$K_I I^2 = m\frac{d^2\theta}{dt^2} + K_d\frac{d\theta}{dt} + \frac{\tau_F - \tau_S}{\theta_{max}}\theta + \tau_S$$

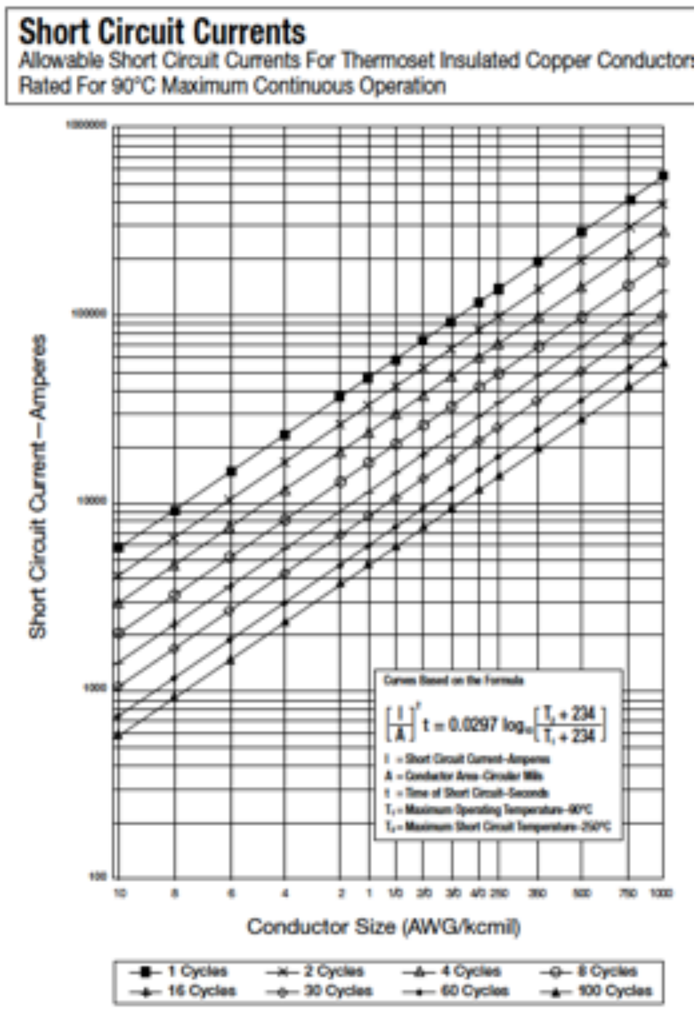
- Where as:
- Θ = Desk travel
- Θ_{max} = Travel to contact close
- K_I =Torque constant related to current
- m = Moment of inertia
- I = Current
- K_d = Damping factor
- τ_s = Initial Spring torque
- τ_F = Maximum Travel Spring torque

Overcurrent Protection for Conductors

- Continued O/C Causes Heat Damage
- Through Fault Currents (High Short Circuit Currents)
- Cable Damage Curves
- Where:
  - A: Conductor area in cmil
  - T: SC duration
  - T1: Max Operating Time (in this case: 105 °C)
  - T2: Max SC Temperature rating of conductor (in this case: 205°C)



$$\left[\frac{I_{SC}}{A}\right]^2 t = 0.0297 \log_{10}\left[\frac{T_2+234}{T_1+234}\right]$$


Short Circuit Currents
Allowable Short Circuit Currents For Thermoset Insulated Copper Conductors
Rated For 90°C Maximum Continuous Operation
Short Circuit Current—Amperes
1000000
100000
10000
1000
100
10
8
6
4
2
1
1/0
2/0
3/0
4/0
250
350
500
750
1000
Conductor Size (AWG/kcmil)
Curves Based on the Formula
$\left[\frac{I}{A}\right]^2 t = 0.0297 \log_{10}\left[\frac{T_2 + 234}{T_1 + 234}\right]$
I = Short Circuit Current–Amperes
A = Conductor Area–Circular Mils
t = Time of Short Circuit–Seconds
T_1 = Maximum Operating Temperature–90°C
T_2 = Maximum Short Circuit Temperature–250°C
1 Cycles
2 Cycles
4 Cycles
8 Cycles
16 Cycles
30 Cycles
60 Cycles
100 Cycles

Overcurrent Protection for Transformers

- Thermal Damage
- Mechanical Damage
- IEEE Standards C57-109™(1993) IEEE Guide for Liquid-Immersed Transformer Through-Fault-Current Duration
- IEEE Standards C37-91™ IEEE Guide for Protective Relay Applications to Power Transformers
- Challenges:
  - Low current when number of shorted turns is small
  - High Inrush (if not provided by supplier, typical used 12 Times – 0.1 s)
- Protection using relays or fuses

Code (NEC/CEC) Requirements

- protection on primary, secondary or both
- Factors:
  - Transformer voltage, kVA, and Z
  - Primary and secondary connections
  - Loads
  - Magnetizing inrush (0.1 second, 12 times)
  - Thermal and mechanical protection
  - Available SC currents on primary and secondary

Overcurrent Protection for Generators

- Low Fault current (decrement curve)
- Two time of overcurrent:
  - Voltage Controlled
  - Voltage Restrained
- Coordination with downstream
- Generator Connection and High Resistance Grounding

Protection for Generators

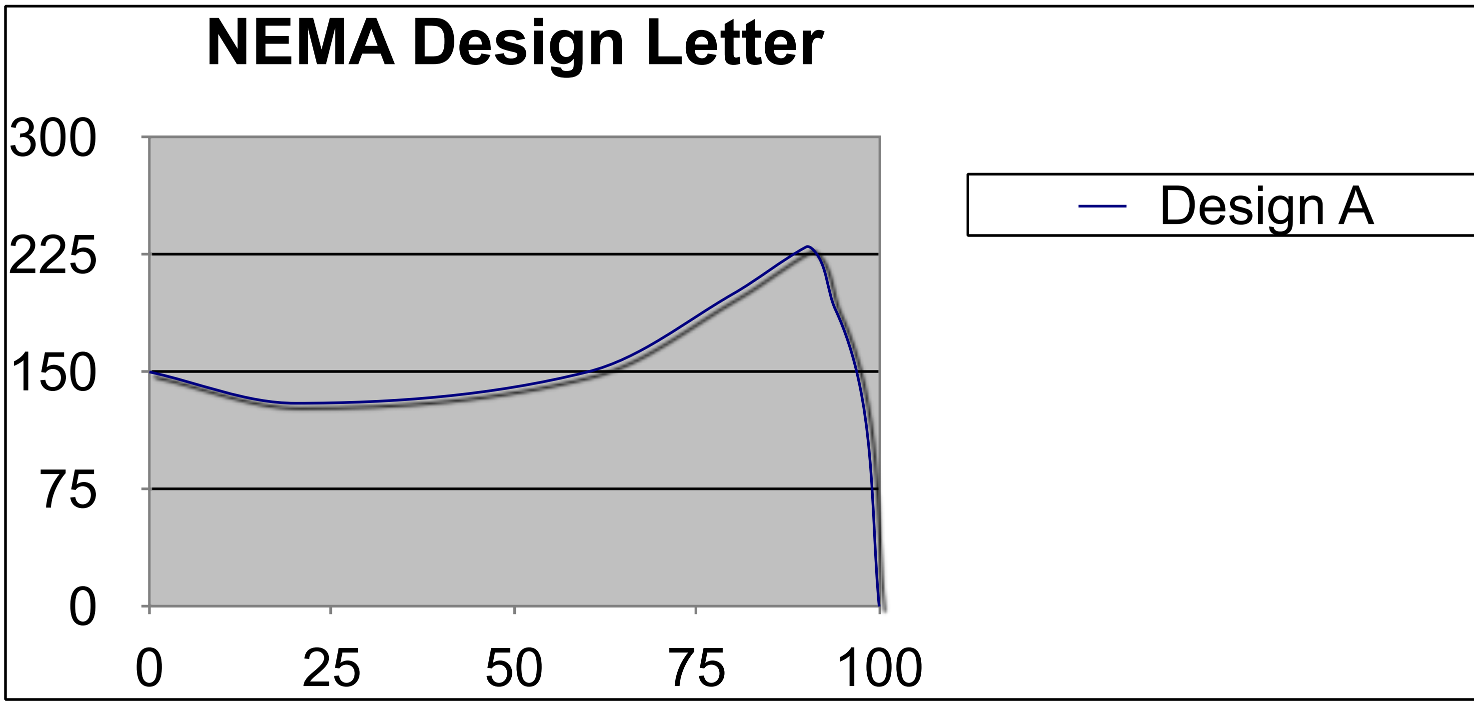
- See the IEEE Guide for AC Generator Protection IEEE Std C37.102™ 2006)
- Generator is composed of many sub-systems: stator, rotor, exciter, mechanical drive
- Using multiple functions such as:
  - Differential
  - Stator Ground Fault
  - Negative Sequence
  - Failure of cooling system
  - Field winding protection
  - Loss of field
  - Unbalanced current
  - Overexcitation
  - Reverse power
  - Volt to frequency
  - Backup protection (Z, 51V)

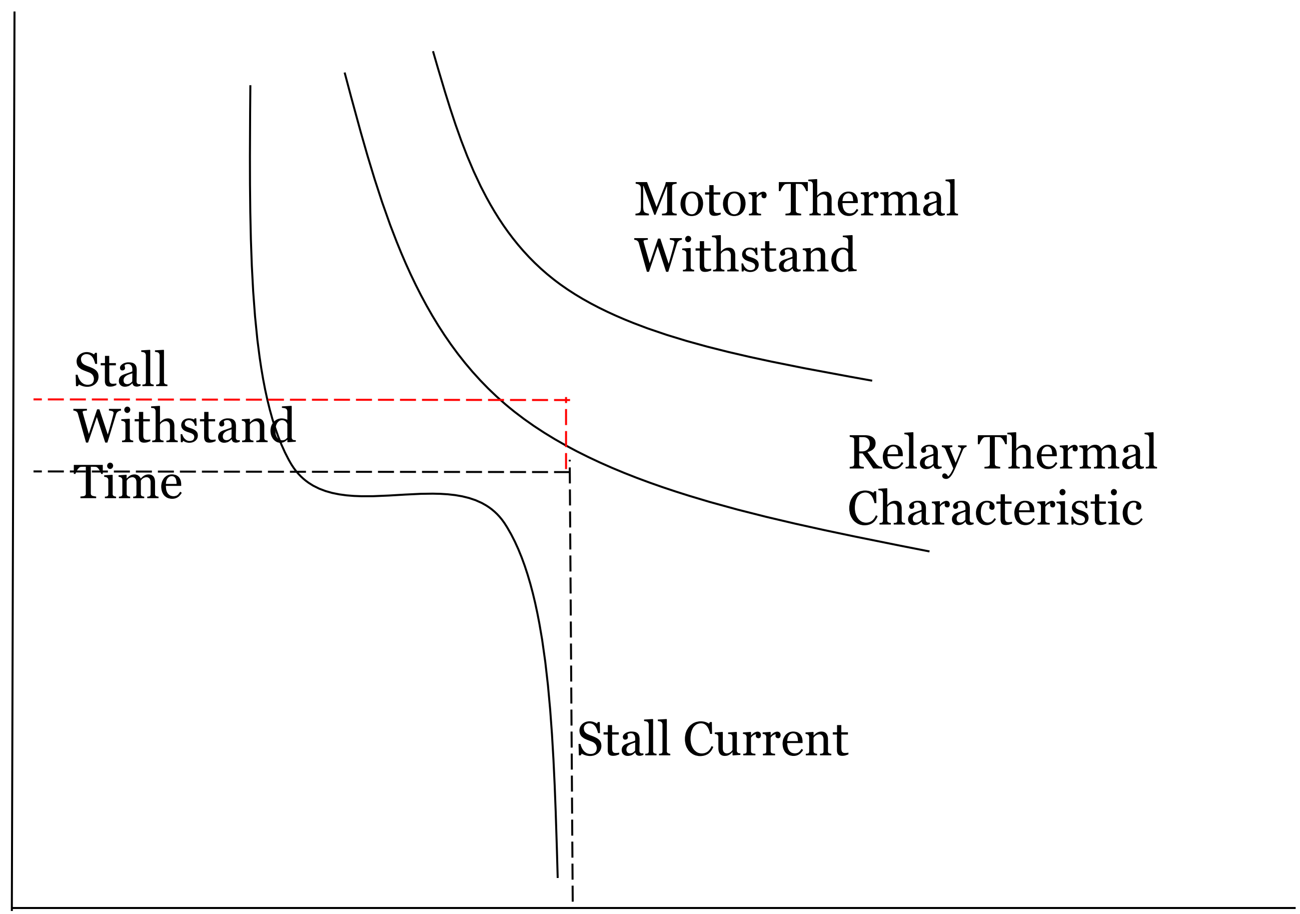
Review of Motor Basics (Motor)

- Motor power is calculated as
- Where:
  - N: running speed in rpm
  - Ns: synchronous speed in rpm

$$P_r(hp) = \frac{N \times T}{5252}$$

$$P_r(kw) = \frac{N \times T}{974}$$


NEMA Design Letter
300
225
150
75
0
0
25
50
75
100
Design A


Motor Thermal Withstand
Stall Withstand Time
Relay Thermal Characteristic
Stall Current

Notes on Coordination Studies

(Excerpts from the IEEE Brown Book™ (IEEE Std 399)
Section 15.2

a. Note motor horsepower, full load current, acceleration time and locked rotor current
b. For each protective device: note short circuit current, full load current, and voltage level at each device. List device manufacturer and type, and program file name for device
c. For each low-voltage breaker, indicate long time, short time, instantaneous. Note settings if existing device
d. For each fuse, note rating
e. For each relay, note tap range, CT ratio, tap and time dial, if known, and whether relay has instantaneous setup
f. For each transformer, note kVA, fan cooled rating, impedance, and transformer connection.
g. For cable damage curves: note cable size, conductor material and cable insulation.

Equipment & Systems GF Protection Considerations

Concerns about Ground Fault Protection

- Statistically ground faults are the most probable type of faults to occur
- Not related to normal feeder current
- Could have severe effect
- Could quickly evolve to a L-L or 3-phase faults
- Not transferred between different parts of a system when transformers with delta connections are used

Safety Concerns:

- Why Grounding is important?
  - 90% of faults are line to ground
  - Safety of workers
    - Electrical shocks
    - Arc flash
    - Transfer potential
  - Safety of equipment
  - Operation of protective devices (detecting and isolating of faulted circuits)

Asymmetrical Faults

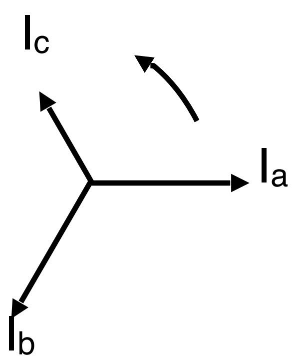
Symmetrical Components:

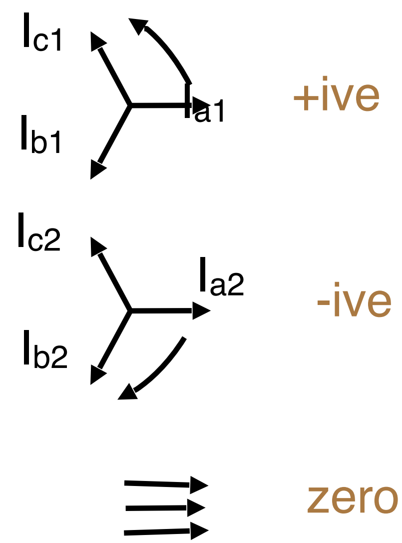
A Little Bit of Math (Fortisco, 1917)

Unbalanced Multiple Phase System

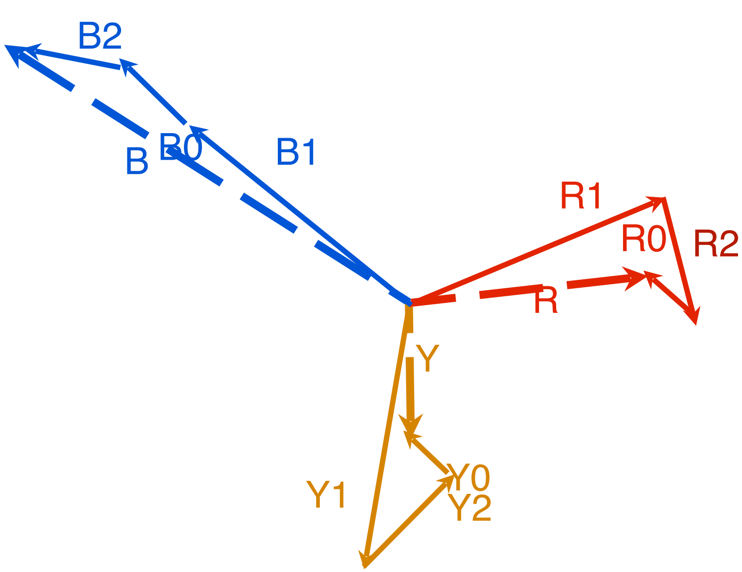
(i.e.. 3 Phase)

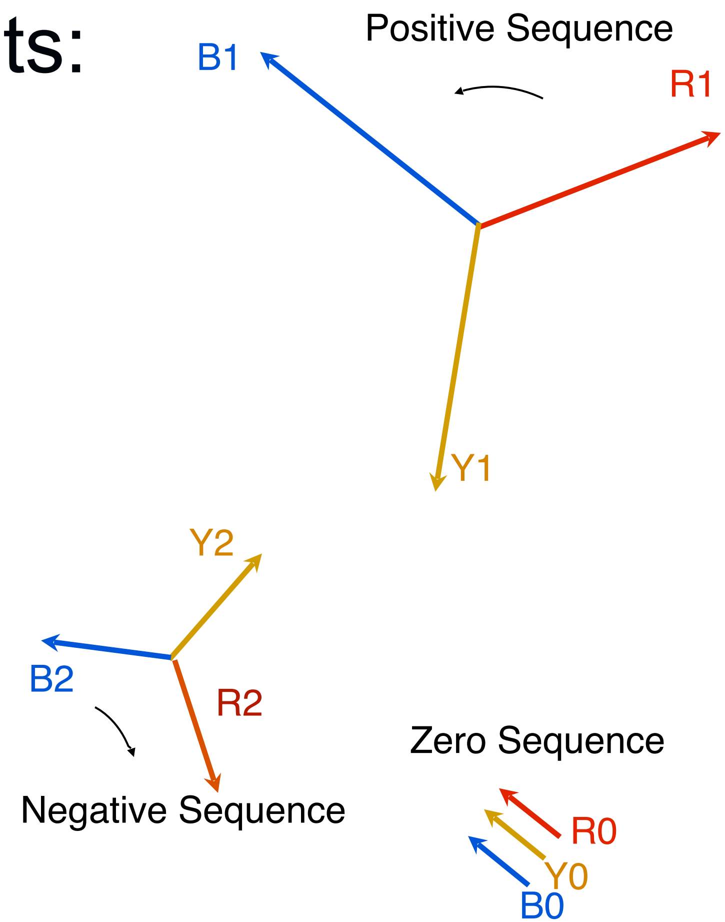
Multiple (i.e. 3) Balanced Systems (Positive, Negative & Zero Sequence)



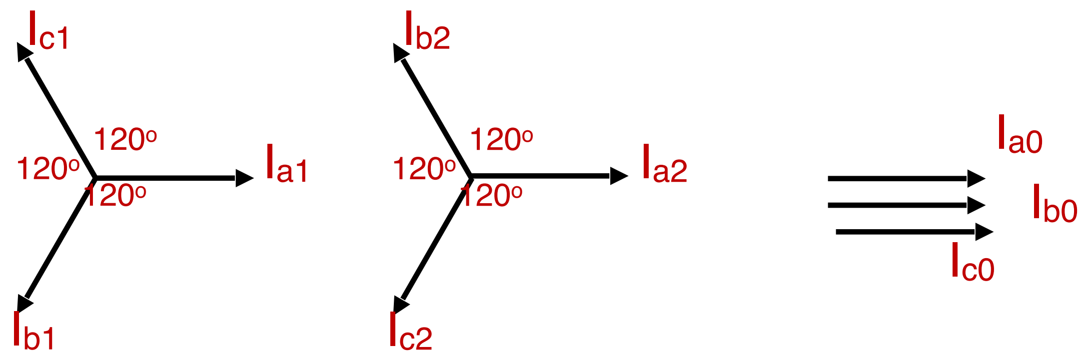


Symmetrical Components:





Symmetrical Components:



$$a = 1\angle 120^o = -0.5 + j0.866$$

$$a^2 = 1\angle 240^o = -0.5 - j0.866$$

$$a^3 = 1\angle 360^o = 1\angle 0^o = 1 + j0$$

$$I_a = I_1 + I_2 + I_0$$

$$I_B = a^2 I_1 + aI_2 + I_0$$

$$I_c = aI_1 + a^2 I_2 + I_0$$

$$I_0 = \tfrac{1}{3}\left(I_1 + I_2 + I_0\right)$$

$$I_1 = \tfrac{1}{3}\left(I_a + aI_b + a^2 I_c\right)$$

$$I_2 = \tfrac{1}{3}\left(I_a + a^2 I_b + aI_c\right)$$

Ground Fault Currents

$$I_{G-F} = \frac{3V_{L-N}}{Z_1 + Z_2 + Z_0 + 3Z_G}$$

- Where:
  - Z_1 : + Sequence Impedance
  - Z_2 : - Sequence Impedance
  - Z_0 : Zero Sequence Impedance
  - Z_G : Fault Ground Return Impedance (combined impedance of ground return circuit (arc impedance + grounding circuit impedance + neutral grounding impedance)

Ground Fault Currents (Continued)

- For Solidly Grounded Systems and Bolted Faults:

$$Z_1 = Z_2 = Z_0 >> Z_G$$

$$I_{G-F} = \frac{V_{L-N}}{Z_1}$$

Ground Fault Currents (Continued)

- For High Resistance Grounded System:

$$Z_1 = Z_2 = Z_0 << Z_G$$

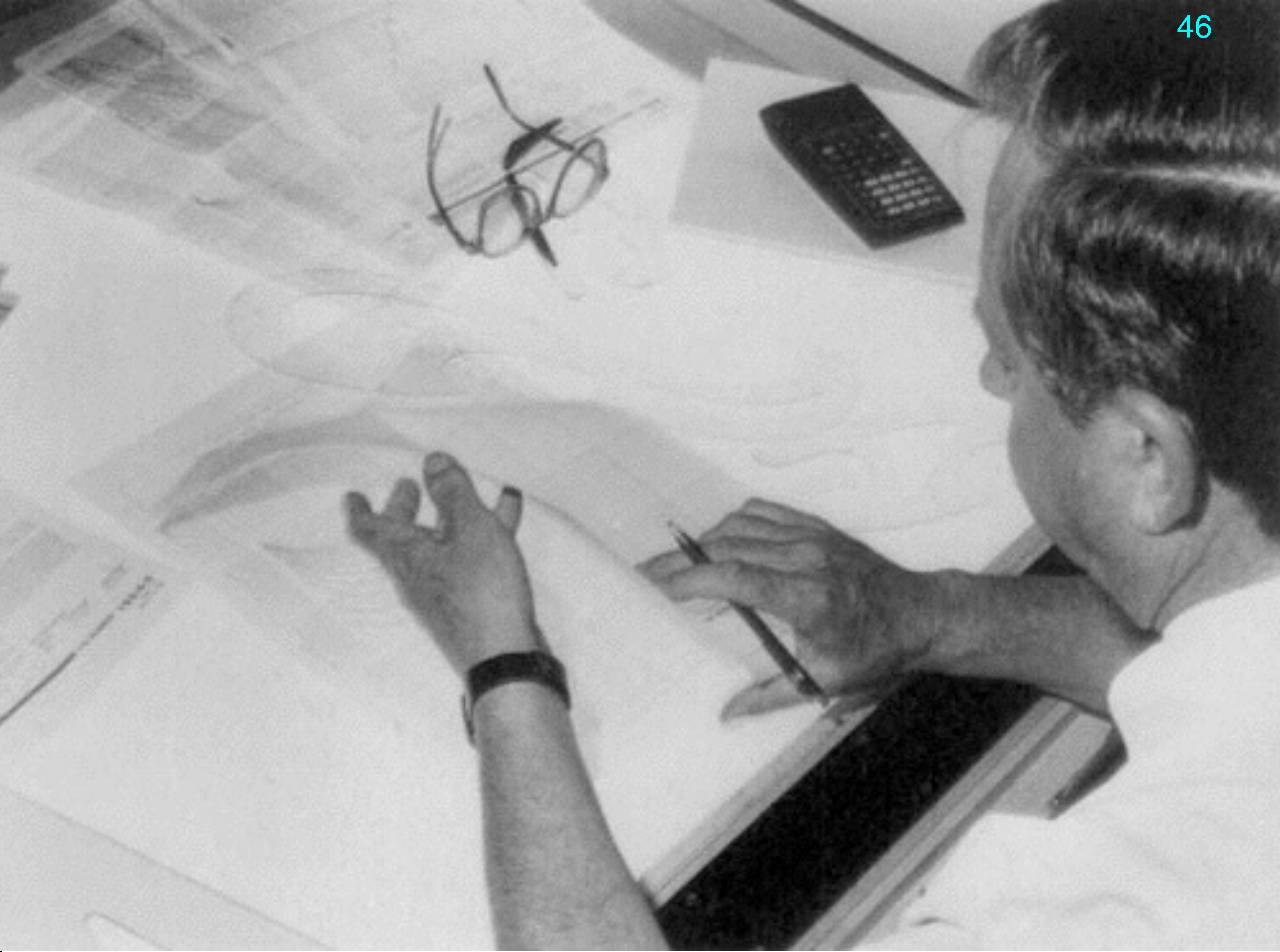
$$I_{G-F} = \frac{V_{L-N}}{Z_G}$$

How have Modern Methods Impacted us?

Protection Coordination Programs & Numerical Relays & Devices

Coordination The Old Way – and Change of Time

- For Many Years, Time Overcurrent Coordination Was Performed Using a Light Table
- A Log-Log (X Axis &Y-Axis) Green Graph Paper was superimposed on manufacturer's supplied curves and the Subject's O/C Graphs were Obtained

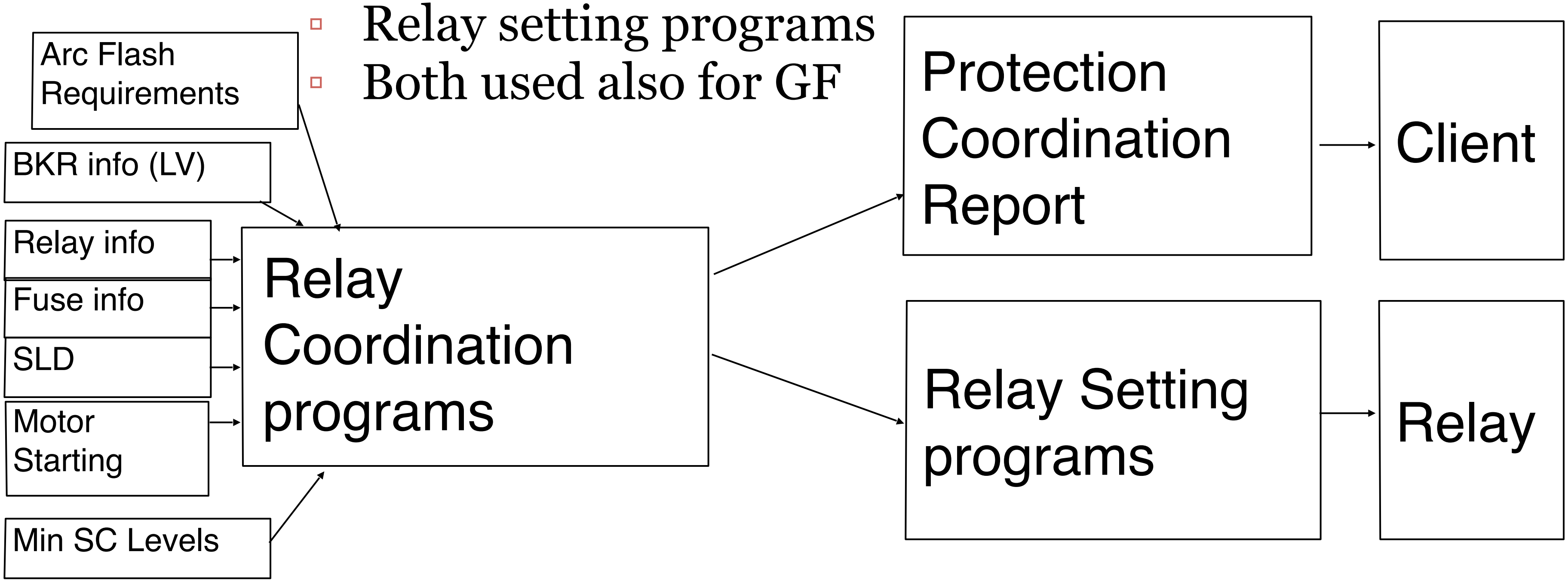


Relay Setting in the Past:

- In the era of electromagnetic relays, settings were done by tap adjustment.
- Repeat relays and hard wired logics were used to provide interlocking and control functionality.
- Every relay covers only one function for only one phase
- In general; more space, more power supply, more burden on current and potential transformers
- Use taps to set a relay, use testing to fine tune it
- Relay needed frequent testing as mechanical parts needed adjustments

Setting Modern Protective Relays

- Two types of programs:
  - Relay Coordination programs
  - Relay setting programs
  - Both used also for GF



Information Required for Coordination Studies

- In Section 15.2 of the IEEE Brown Book™ (IEEE Std 399) it was stated that whether the coordination is done manually or by computer, it is necessary for the engineer to "describe" the system. The information needed to perform a coordination study is a single line diagram showing the following:
  - Protective device manufacture and type
  - Protective device ratings
  - Trip settings and available range
  - Short-circuit current at each system bus (three-phase and line-to-ground)
  - Full load currents of all loads
  - Voltage level at each bus
  - Transformer kVA, impedance and connections (delta-wye, etc.)
  - Current transformer (CT) and potential transformer (PT) ratios
  - Cable size, conductor material, and insulation
  - All sources and ties
- For GF; special attention is given to:
  - Source / transformer neutral connections and resistance ratings
  - CT arrangements, ratio and accuracies

Demonstration of Use of Software Packages

- Use of equipment libraries. The importance of accuracy and completeness
- Connection between the Protection Coordination and other studies (i.e. load flow, short circuit and arc flash). Ensure suitability of the overall model for coordination studies
- Flexibility in settings (ensure simplicity and allow future maintenance and upgrading)
- Use of overcurrent elements in multifunction relays
- Implementation of multiple settings for arc flash

Multi-Function Relay Coordination

- Each MF relay offers a few functions. Coordinate between the different functions. Be aware of which function will operate first and which one will act as a back up
- Many MF relays offer logic building facilities
  - Relay job is protection first
  - Logics that support protection functionalities get higher priorities
  - Logics shall not tax relay to any degree that affect its speed or functionality

Multi-Function Relay Coordination (Cont'd)

- Large additional tasks such as Transfer schemes could justify using additional relays
- Electrical Equipment Differ in their Protection Needs. Use correct Relay for the Subject Equipment
- Communication Facilities allow Relays Communicating among themselves and to other Devices (SCADA etc). Communication priorities shall be Established with Protection Functions having the Highest Priorities

Relay Settings by Supplier's Custom Software:

- Develop settings offline
- View and change settings for enabled elements only
- Automatically check interrelated settings
- Automatically highlight out-of-range settings
- Transfer settings files using a PC communication link
- More than one group setting in some relays
- Building logic
- Actual settings back to computer for records
- Friendliness

Fig 8-7-a of the Buff Book "with permission"

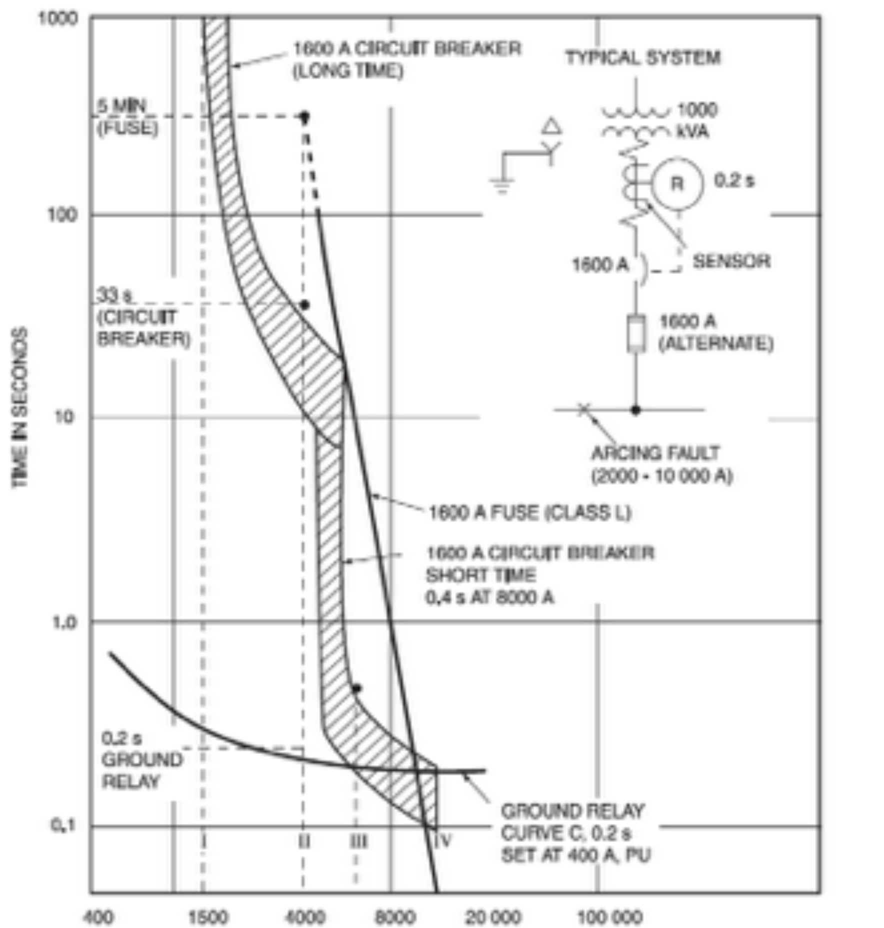


Table 8-1 of the Buff Book "with Permission"

Table 8-1—Arc energies for assumed faults of Figure 8-7a

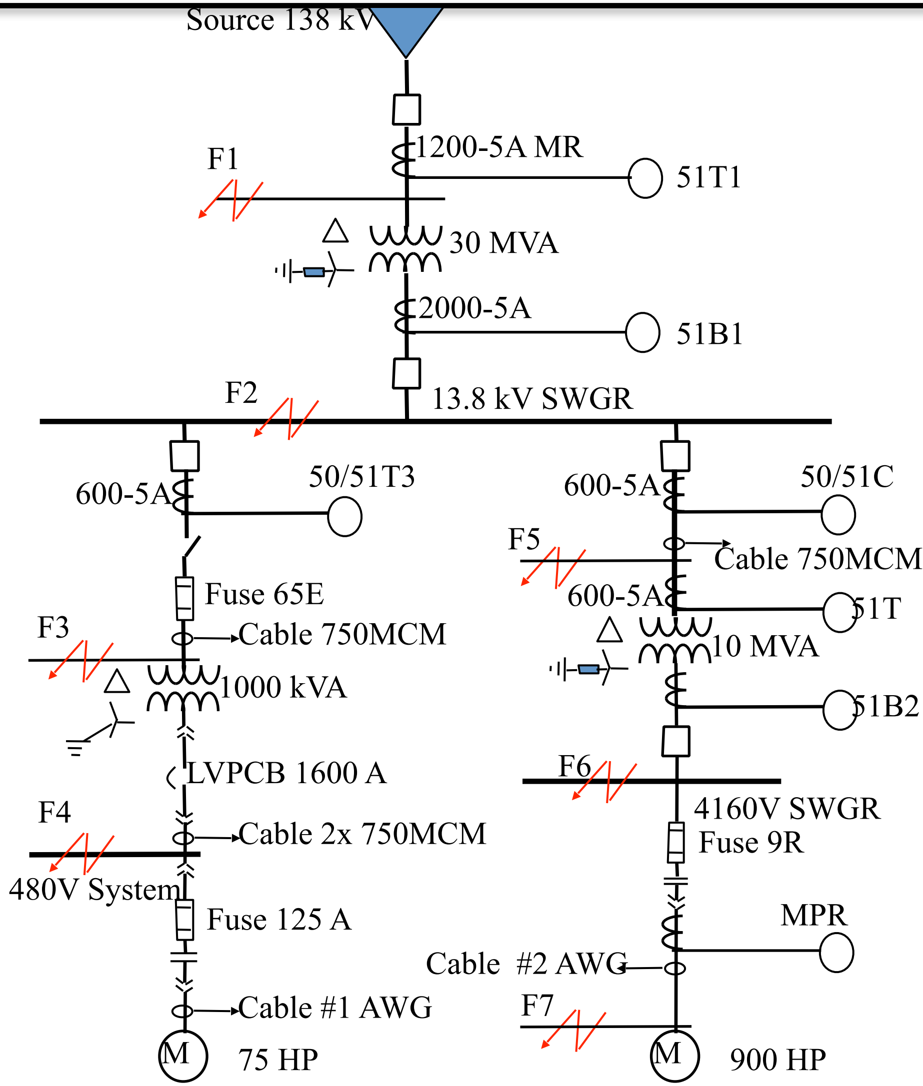
Figure 8-7a points	Fault (A, rms)	Main device	Clearing time (s)	Arc energy (kWs)
I	1500	Relay Circuit breaker Fuse	0.33 ∞ ∞	50 ∞ ∞
II	4000	Relay Circuit breaker Fuse	0.25 33.00 300.00	100 13 200 120 000
III	8000	Relay Circuit breaker Fuse	0.25 0.4 10.00	200 320 8000
IV	20 000	Relay Circuit breaker Fuse	0.25 0.20 0.01	500 400 20

Relay Setting Programs:

- Setting by the use of a lap top computer, setting program and interface
- In numeric relays "all the eggs are in one basket"
  - Multiple functions
  - Multiple phases, and
  - Relay logic
- Errors in relay settings could paralyze the protection scheme of the power system and equipment
- Relay Setting Programs are developed to minimize errors in setting the relays (and lay the blame only on the engineer)

Relay Setting Programs:

- In addition to the comparator functions being numerically performed, the relay does additional calculations such as calculating primary current, and phase angle difference in delta-WYE transformers
  - For these additional functions, we need to input the CT ratio, PT ratio, power transformer phasing etc
- The relay also includes capability to perform logic checks:
  - For this purpose the logic needs to be input



Example C2

A demonstration Example

- ***Similar to example C1 but with a neutral resistance in 13.8 kV and 4160 V systems***
- ***For comparison purposes the example is similar in parts to Figure 15-13 of the IEEE Buff Color Book IEEE Std 242-2001 (Copyright 2001 IEEE) (http://ieee.org)***

Concerns with Arc Flash Energy

Modern Protection Systems Help Reduce Arc Flash with their Fast Acting Responses. How?

See Part 2

Let us See for Ourselves:

What would be the concerns based on our experience in modern days?

What Did We Capture from the Part 1 of Today's Seminar?

Questions?

Now Part 2