Power System Protective Relays: Principles & Practices

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Abstract:

Protective relays and devices have been developed over 100 years ago to provide "last line" of defense for the electrical systems. They are intended to quickly identify a fault and isolate it so the balance of the system continue to run under normal conditions. The selection and applications of protective relays and their associated schemes shall achieve reliability, security, speed and properly coordinated. Meanwhile, protective devices have also gone through significant advancements from the electromechanical devices to the multifunctional, numerical devices of present day. As the protected components of the electrical systems have changed in size, configuration and their critical roles in the power system supply, some protection aspects need to be revisited (i.e. the use of protection systems to reduce arc flash energy in distribution systems).

This presentation reviews the established principles and the advanced aspects of the selection and application of protective relays in the overall protection system, multifunctional numerical devices application for power distribution and industrial systems, and addresses some key concerns in selecting, coordinating, setting and testing of smart relays and systems.

References (Books)

- Protective Relaying Principles and Applications (Blackburn)
- Industrial Power Systems Handbook (Beeman)
- Industrial Power Systems: (Shoab Khan)
- Power System Protection: (Paul Anderson)
- The art and Science of Protective Relaying (Mason)
- Protective Relaying for Power Generation Systems (Reimert)
- Protective Relays; Their Theory and Practices (Warington)
- Protective Relaying Theory and Applications (Elmore)
- Digital Protection for Power Systems (Johns & Salman)
- Digital Protective Relays; Problems and Solutions (Gurevich)
- Protective Relays Application Guide (GEC Alsthom -3rd ed)
- Protective Relaying for Power Systems Vol 1&2 (Horowitz)
- Applied Protective Relaying (Westinghouse)
- Modern Solutions for Protection, Control and Monitoring of Electric Power Systems (Hector, Ferrer, Schweitzer)
- Analyzing and Applying Current Transformers (Zocholl)

IEEE Protection Standards & Guides

IEEE Std 242 - 2001	*IEEE Buff Book – IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems*
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 C37.106-2003	*IEEE Guide for Abnormal Frequency Protection for Power Generating Plants*
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 Standards & Guides (Continued)

IEEE Std C37.110-2007	***IEEE Guide for the Application of Current Transformers Used for Protective Relaying Purposes***
IEEE Std C37.111-1999	***IEEE Standard IEEE Standard Common Format for Transient Data Exchange (COMRADE) for Power Systems***
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***
IEEE Std C37.2 - 2008	***IEEE Standard for Electrical Power System Device Function Numbers, Acronyms, and Contact Designations***

IEEE Protection Recommended Practices [Replacing Mainly the Buff Book]

STD 3004.1	Recommended Practice for the Application of Instrument Transformers in Industrial and Commercial Power Systems	Published
P3004.2	Recommended Practice for the Application of Protective Relays	
P3004.3	Recommended Practice for the Application of Low -Voltage Fuses in Industrial and Commercial Power Systems	Ballot s
P3004.4	Recommended Practice for the Application of Medium Voltage Fuses in Industrial and Commercial Power Systems	Progress
STD 3004.5	Recommended Practice for the Application of Low -Voltage Circuit Breakers in Industrial and Commercial Power Systems	Published
P3004.6	Recommended Practice for the Application of Ground Fault Protection (First Draft)	Progress
P3004.7	Recommended Practice for the Protection of Power Cables and Busway Used in Industrial and Commercial Power Systems	Started
P3004.8	Recommended Practice for Motor Protection in Industrial and Commercial Power Systems	Balloted
P3004.9	Recommended Practice for the Protection of Power Transformers Used in Industrial and Commercial Power Systems	Progress
P3004.10	Recommended Practice for Generator Protection in Industrial and Commercial Power Systems	progress
P3004.11	Recommended Practice for Bus and Switchgear Protection in Industrial and Commercial Power Systems	circulated
P3004.12	Recommended Practice Service Line Protection	
P3004.13	Recommended Practice for Overcurrent Coordination in Industrial and Commercial Power Systems	Progress

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

Standards for Equipment Selection & Sizing

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.

Function Description in Multifunction Relays

- Use of IEEE Standards 37.2 -2008
- For Multifunction Device C37.2 selected the number 11 and used the following description:" A device that performs three or more comparatively important functions that could only be designated by combining several device function numbers. All of the functions performed by device 11 shall be defined in the drawing legend, device function definition list, or relay-setting record. See Annex A for further discussion and examples.
- On a side note the Standards stated: If only two relatively important functions are performed by the device, it is preferred that both function numbers be used, as described in 3.7
- Appendix A describes 3 methods to combine the multifunction numbering and the key single functions within the relay

Selected Definitions from IEEE Standards and Definition Book

relay computer interface equipment
(1) (surge withstand capability) A device that interconnects a protective relay system to an independent computer, for example, an analog to digital converter, a scanner, a buffer amplifier.
(2) A device that interconnects a protective relay system to an independent computer, for example, a scanner or a buffer amplifier

correct relaying-system performance
The satisfactory operation of all equipment associated with the protective-relaying function in a protective-relaying system. it includes the satisfactory presentation of system input quantities to the relaying equipment, the correct operation of the relays in response to these input quantities, and the successful operation of the assigned switching device or devices.

Cross polarization: (protective relaying)
The polarization of a relay for directionality using some proportion of the voltage from a healthy (unfaulted) phase(s). One example of this is quadrature polarization. In this case, the polarizing voltage is in quadrature to the faulted phase voltage.

differential protective relay (power system device function numbers)
A protective relay that functions on a percentage or phase angle or other quantitative difference of two currents or of some other electrical quantities

directional control (as applied to a protective relay or relay scheme)
A qualifying term that indicates a means of controlling the operating force in a nondirectional relay so that it will not operate until the two or more phasor quantities used to actuate the controlling means (directional relay) are in a predetermined band of phase relations with a reference input.

Selected Definitions from IEEE Standards and Definition Book (Cont'd)

distance relay
(1) A generic term covering those forms of protective relays in which the response to the input quantities is primarily a function of the electrical circuit distance between the relay location and the point of fault.
(2) (power system device function numbers) A relay that functions when the circuit admittance, impedance, or reactance increases or decreases beyond a predetermined value.
(3) A generic term covering those forms of measuring relays in which the response to the input quantities is a function of the electric circuit distance (impedance) between the point of measurement and the point of fault. Note: A distance relay response characteristic, when presented on an R-X impedance diagram, will have an operating area dependent on the manner in which the input quantities are processed and compared.
(4) A protective relay in which the response to the input quantities is primarily a function of the electrical circuit distance between the relay location and the point of fault.

distance relay characteristic
The defined threshold between the operate and nonoperate response of a distance relay, generally referred to as reach and presented on an R-X impedance diagram

Selected Definitions from IEEE Standards and Definition Book (Cont'd)

Drop out protective relaying of utility-consumer interconnections)
Contact operation (opening or closing) as a relay just departs from pickup. The value at which dropout occurs is usually stated as a percentage of pickup. For example, dropout ratio of a typical instantaneous overvoltage relay is 90 percent. (of a relay) A term for contact operation (opening or closing) as a relay just departs from pickup. Also identifies the maximum value of an input quantity that will allow the relay to depart from pickup.
(3) A loss of equipment operation (discrete data signals) due to noise, voltage sags, or interruption.

fault-detector relay
A monitoring relay whose function is to limit the operation of associated protective relays to specific

field protective relay
A relay that functions to prevent overheating of the field excitation winding by reducing or interrupting the excitation of the shunt field. See also: relay.
(IA/ICTL/IAC) [60]

field relay (power system device function numbers)
A relay that functions on a given or abnormally low value or failure of machine field current, or on an excessive value of the reactive component of armature current in an alternating-current (ac) machine indicating abnormally low field excitation.

local backup A form of backup protection
in which the backup protective relays are at the same station as the primary protective relay

Selected Definitions from IEEE Standards and Definition Book (Cont’d)

output circuit (i) (protective relay system)
(1) An output from a relay system which exercises direct or indirect control of a power circuit breaker, such as trip or close.
(2) (protective relay system) A circuit from a relay system that exercises direct or indirect control of power apparatus such as tripping or closing of a power circuit breaker.
power-line carrier (1) (overhead-power-line corona and radio noise) The use of RF energy, generally below 600 kHz, to

transmit information, using power lines to guide the information transmission.
(2) (protective relaying of utility-consumer interconnections)

A high-frequency signal superimposed on the normal voltage on a power circuit.
It is customarily coupled to the power line by means of a coupling capacitor. A tuning device provides series resonance at the carrier frequency. Prevention of shorting of the carrier signal by a fault external to the protected line is ordinarily provided by a line trap.
*(3) The use of radio frequency energy to transmit information over transmission lines whose primary purpose is the trans*mission of power.

reach
(1) (protective relaying) The maximum distance from the relay location to a fault for which a particular relay will operate. The reach may be stated in terms of miles, primary
(2) (of a relay) The extent of the protection afforded by a relay in terms of the impedance or circuit length as measured from the relay location. Note: The measurement is usually to a point of fault, but excessive loading or system swings may also come within reach or operating range of the relay.

Selected Definitions from IEEE Standards and Definition Book (Cont'd)

Reach
(1) (protective relaying) The maximum distance from the relay location to a fault for which a particular relay will operate. The reach may be stated in terms of miles, primary
(2) (of a relay) The extent of the protection afforded by a relay in terms of the impedance or circuit length as measured from the relay location. Note: The measurement is usually to a point of fault, but excessive loading or system swings may also come within reach or operating range of the relay.

reclosing device (power operations)
A control device which initiates the reclosing of a circuit after it has been opened by a protective relay

reliability
(1) (relay or relay system) A measure of the degree of certainty that the relay, or relay system, will perform correctly. Note: Reliability denotes certainty of correct operation together with assurance against incorrect operation from all extraneous causes. See also: security; dependability.
(2) (power system protective relaying) A combination of dependability and security

remote trip (remote release)
A general term applied to a relay installation to indicate that the switching device is located physically at a point remote from the initiating protective relay, device, or source of release power or all these. Note: This installation is commonly called transfer trip when a communication channel is used to transmit the signal for remote hipping. Synonym: remote release

Selected Definitions from IEEE Standards and Definition Book (Cont'd)

Residual current (protective relaying)
The sum of the three phase currents on a three-phase circuit. The current that flows in the neutral return circuit of three wye-connected current transformers is residual current

Residual Voltage: (protective relaying)
The sum of the three line-to-neutral voltages on a three-phase circuit

R-X plot (protective relaying)
A graphical method of showing the characteristics of a relay element in terms of the ratio of voltage to current and the angle between them. For example, if a relay barely operates with 10 V and 10 A in phase, one point on the operating curve of the relay would be plotted as 1 Ohm on the R axis (that is, R = 1, X = O).

selective pole switching
The practice of tripping and reclosing one or more poles of a multipole circuit breaker without changing the state of the remaining pole(s), with tripping being initiated by protective relays that respond selectively to the faulted phases. Note: Circuit breakers applied for selective pole switching must inherently be capable of individual pole opening

single-pole switching
The practice of tripping and reclosing one pole of a multiple circuit breaker without changing the state of the remaining poles, with tripping being initiated by protective relays that respond selectively to the faulted phase. Notes: 1. Circuit breakers used for single-pole switching must inherently be capable of individual pole opening. 2. In most single-pole switching schemes, it is the practice to trip all poles for any fault involving more than one phase.

Selected Definitions from IEEE Standards and Definition Book (Cont'd)

thermal limit curves for large squirrel-cage motors
Plots of maximum permissible time versus percent of rated current flowing in the motor winding under specified emergency conditions.
These curves can be used in conjunction with the motor time-current curve for a normal start to set protective relays and breakers for motor thermal protection during starting and running conditions.

time-delay starting or closing relay (power system device function numbers)
A device that functions to give a desired amount of time delay before or after any point of operation in a switching sequence or protective relay system, except as specifically provided by incomplete sequence relay, time-delay stopping or opening relay, and alternating current (ac) reclosing relay, device functions 48, 62, and 79.

time-delay stopping or opening relay (power system device function numbers)
A time-delay relay that serves in conjunction with the device that initiates the shutdown, stopping, or opening operating in an automatic sequence or protective

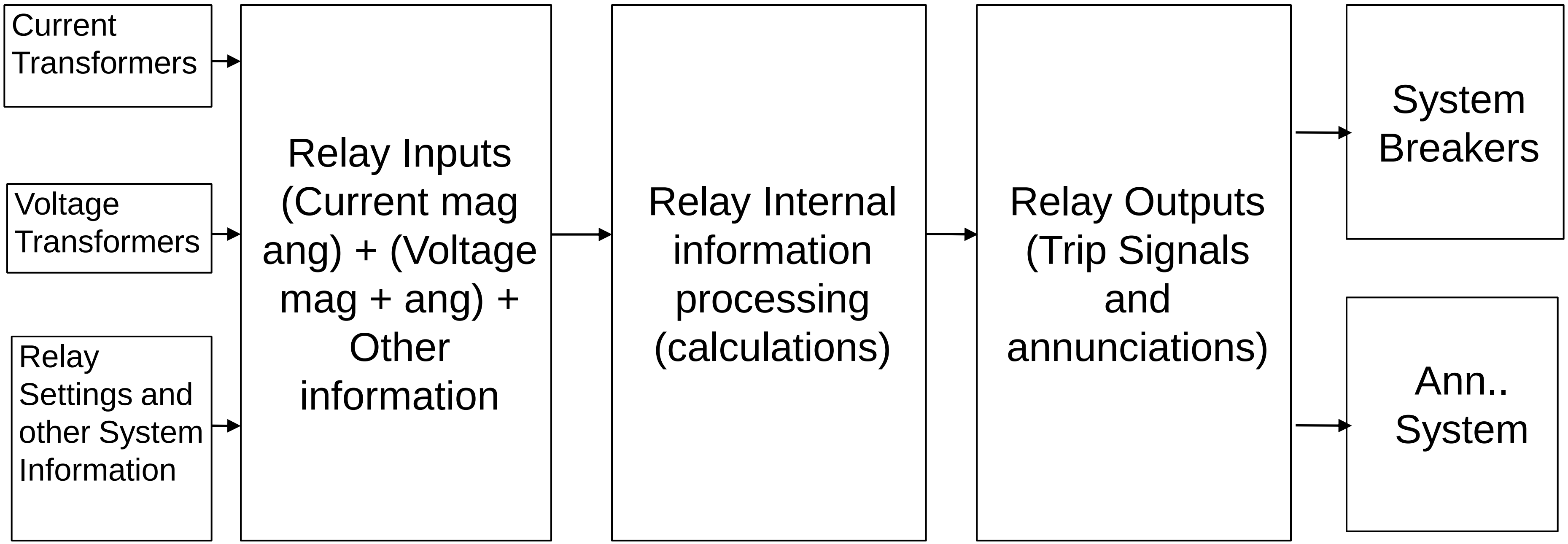
torque control
(1) (protective relaying of utility-consumer interconnections) A means of supervising the operation of one relay element with another. For example, an overcurrent relay cannot operate unless the lag coil circuit is closed. It may be closed by the contact of an undervoltage element.
(2) (of a relay) A method of constraining the pickup of a relay by preventing the torque-producing element from developing operating torque until another associated relay unit

Selected Definitions from IEEE Standards and Definition Book (Cont'd)

transverse-mode voltage (2) (protective relays and relay systems)
The voltage between two conductors of a circuit at a given location

zone of protection
(1) The adjacent space provided by a grounded air terminal, mast, or overhead ground wire that is protected against most direct lightning strikes.
(2) (for relays) That segment of a power system in which the occurrence of assigned abnormal conditions should cause the protective relay system to operate.

Simplified Protective Relays Basic Components

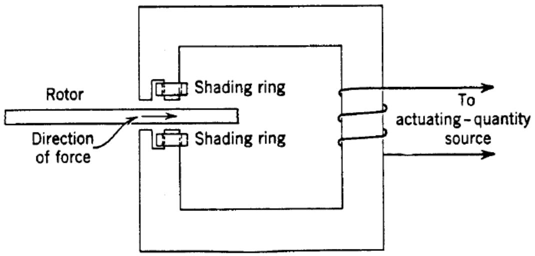


A Little History

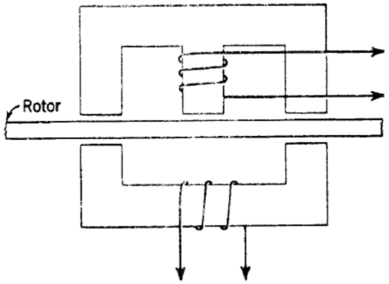
General History of Protective Relays

- 1905 Overcurrent trip devices, built-in HV breakers and First time-overcurrent relay
- 1930 First plug-in relay modular system type
- 1940 mho Distance relay
- 1940 Harmonic restraint transformer differential
- 1950 Compensator poly-phase distance relay
- 1960 Analogue electronics was introduced1964 First solid-state relays
- 1968 Microprocessors introduced
- 1981 Microprocessor-based line protection

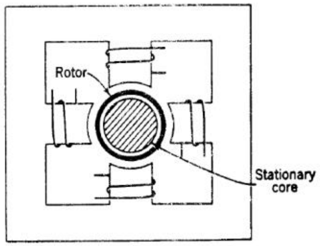
From Mason: Inverse TC Relays



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
- T_s = Initial Spring torque
- T_F = Maximum Travel Spring torque

Reference PAC World:

IEEE's Relays Committee published a "Supplement to recent practices and trends in protective relaying" in 1964. In this paper we find a chapter "use of digital computers" and the following statement: "Because of the complexity of power systems, it is imperative that relay engineers use every available tool to analyze the quantities which affect relaying. Analog computers have been used extensively for many years to determine currents and voltages which occur during short circuit or other abnormal conditions. However, because of <u>the time required</u> to make and analyze such studies, only a limited number of conditions could be investigated. The advent of the high speed digital computer has made it possible to increase the amount of data available for the relaying engineer under essentially all types of system operation. Load flow, short circuit, and stability studies can usually made more rapidly and accurately and the result printed out in much more detail. As an example, at least one utility has expanded a short-circuit computer program to calculate and print out the impedances seen by relays located near the assumed fault. Such information greatly assists the engineer in selection, application, and setting of system relays."

PAC World Some early References:

Early papers describing how to realize protection utilizing computers were published at the end of 1960s

A paper by George, D. Rockefeller's, Westinghouse, paper "Fault Protection with a Digital Computer“ was published in (1968)

A digital computer was subsequently applied to protect the Tesla -Ballot 230 kV line of the Pacific Gas and Electric Company

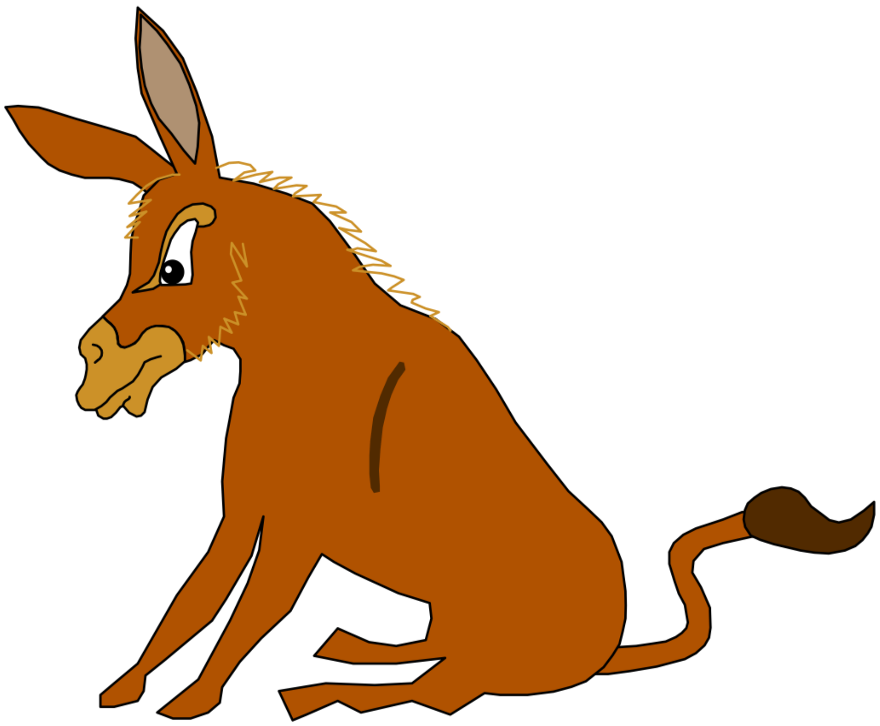
A few paper on line protection

The paper "Generator differential protection using a hybrid computer" (Mohindar S. Sachdev and D.W. Wind, was published in 1972

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 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

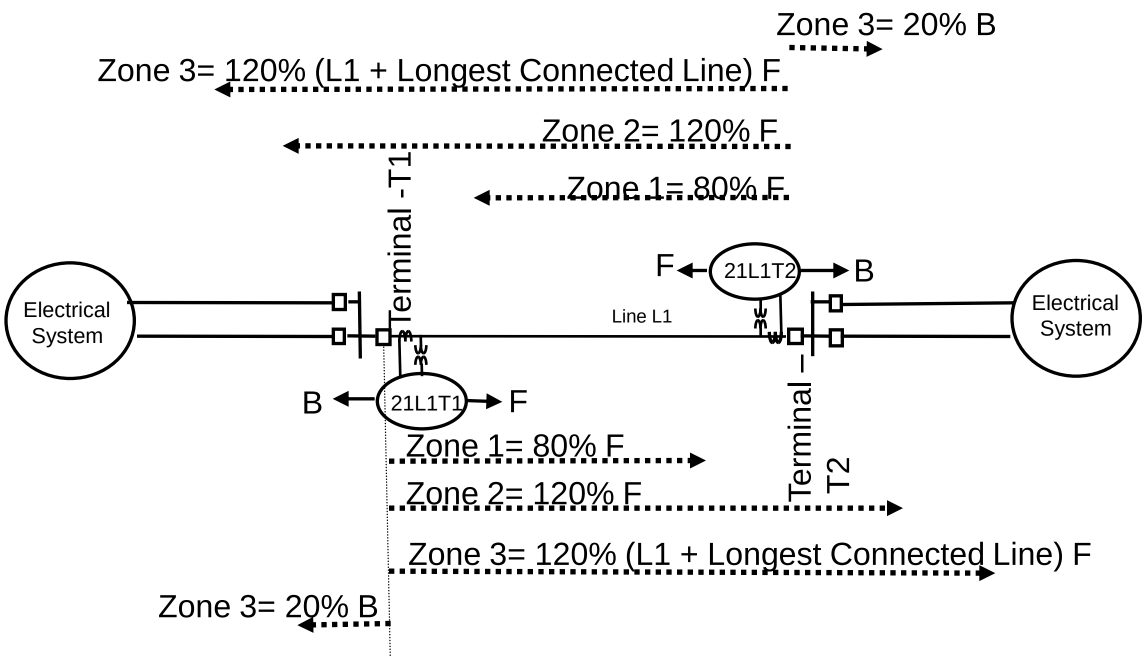
- ***Word of wisdom from an (old) experienced man:***
- ***"Avoid unnecessary complications to the system: The more guts you have the more belly aches"***

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:-ive sequence, harmonics

Distance Protection as Examples for Protective Relaying Systems

Some Basic Aspect of Distance Protection



$$Z_{fault} = \frac{V}{I}$$

Distance protection is directional Relay is capable of multiple setting (Zones)

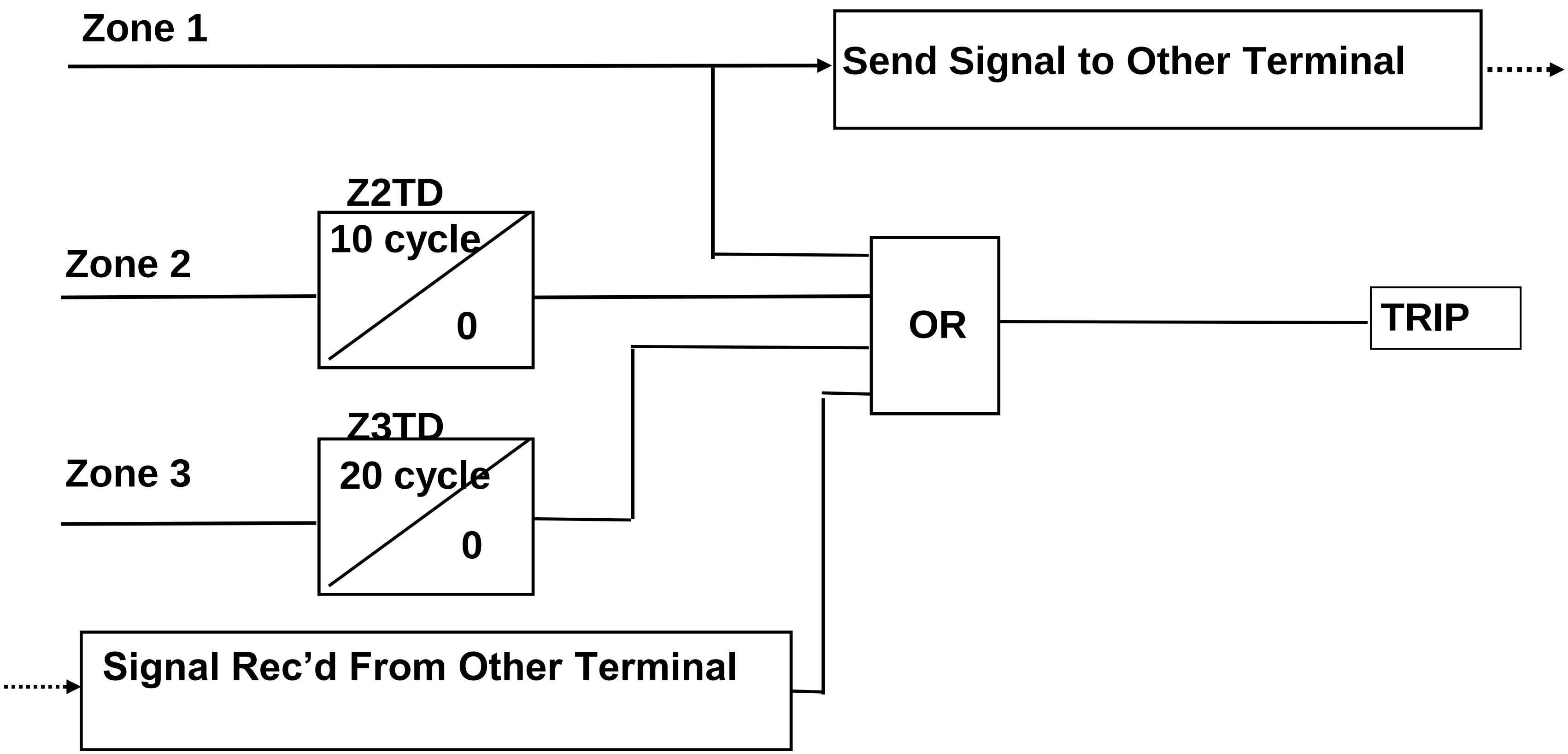
Some Basic Aspect of Distance Protection (Typical Settings)

Zone	Setting Reach	Time Delay
Zone 1	80% of Line Healthy Impedance	Instantaneous
Zone 2	120% of Line Healthy Impedance	8 – 10 cycles
Zone 3 (Forward)	120% of Line Healthy Impedance + Longest Adjacent Line	> Adjacent Line Primary Protection
Zone 3 (Back)	20% Looking Back	> Any adjacent protection in the Back Zone

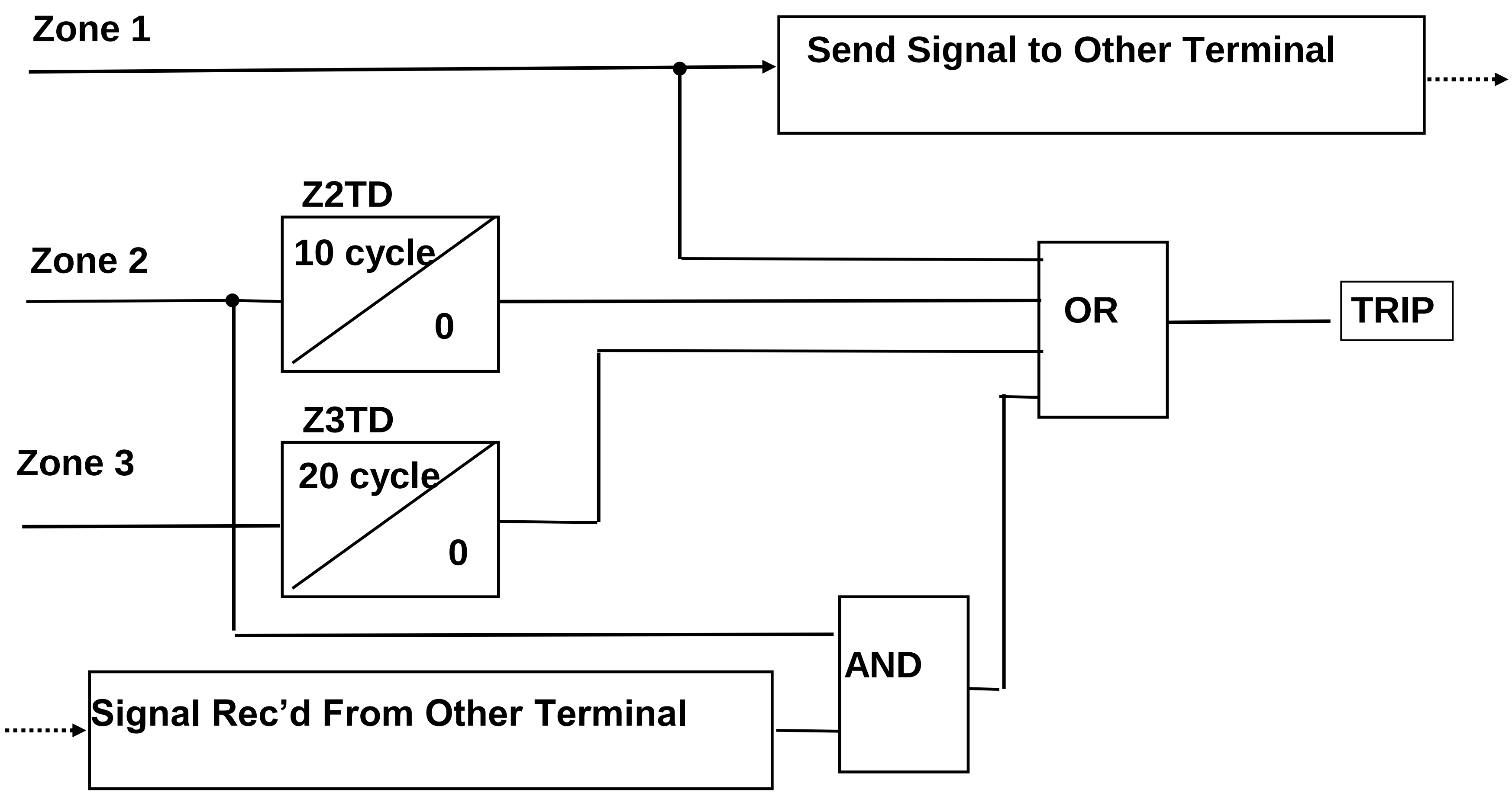
Some Basic Aspect of Distance Protection (Communication Aided)

Scheme	Abbreviation	Remote Signal Zone	Logic Block	Local Zone
Direct under-reach Transfer Trip	DUTT	Z1	N/A	N/A
Permissive Under-reach Transfer Trip	PUTT	Z1	Permissive (AND)	Z2
Permissive Over-reach Transfer Trip	POTT	Z2	Permissive (AND)	Z2
Blocking Transfer Trip	BTT	Z3	Blocking (NOT)	Z2

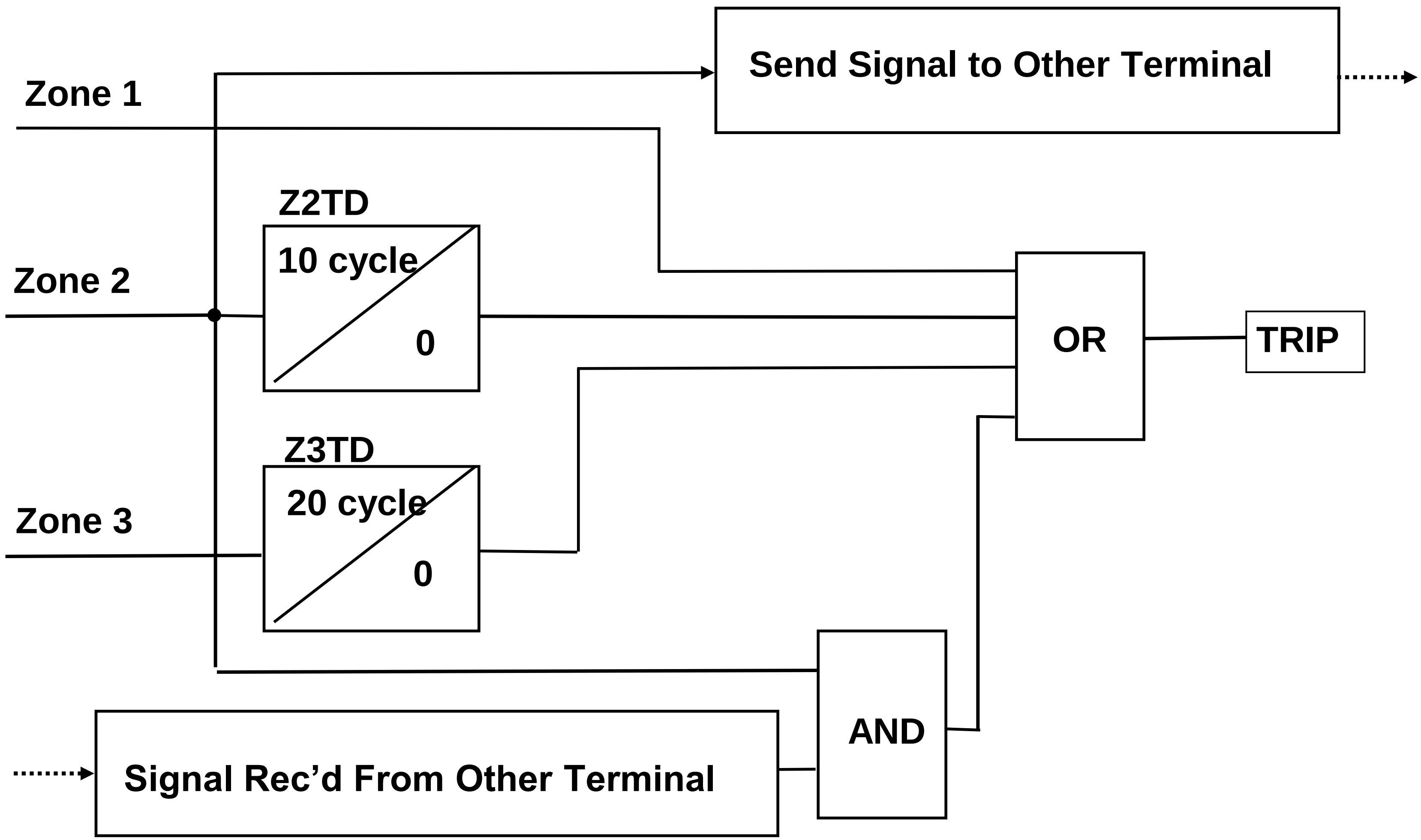
Block Diagram for Direct Under-Reach Transfer Trip DUTT



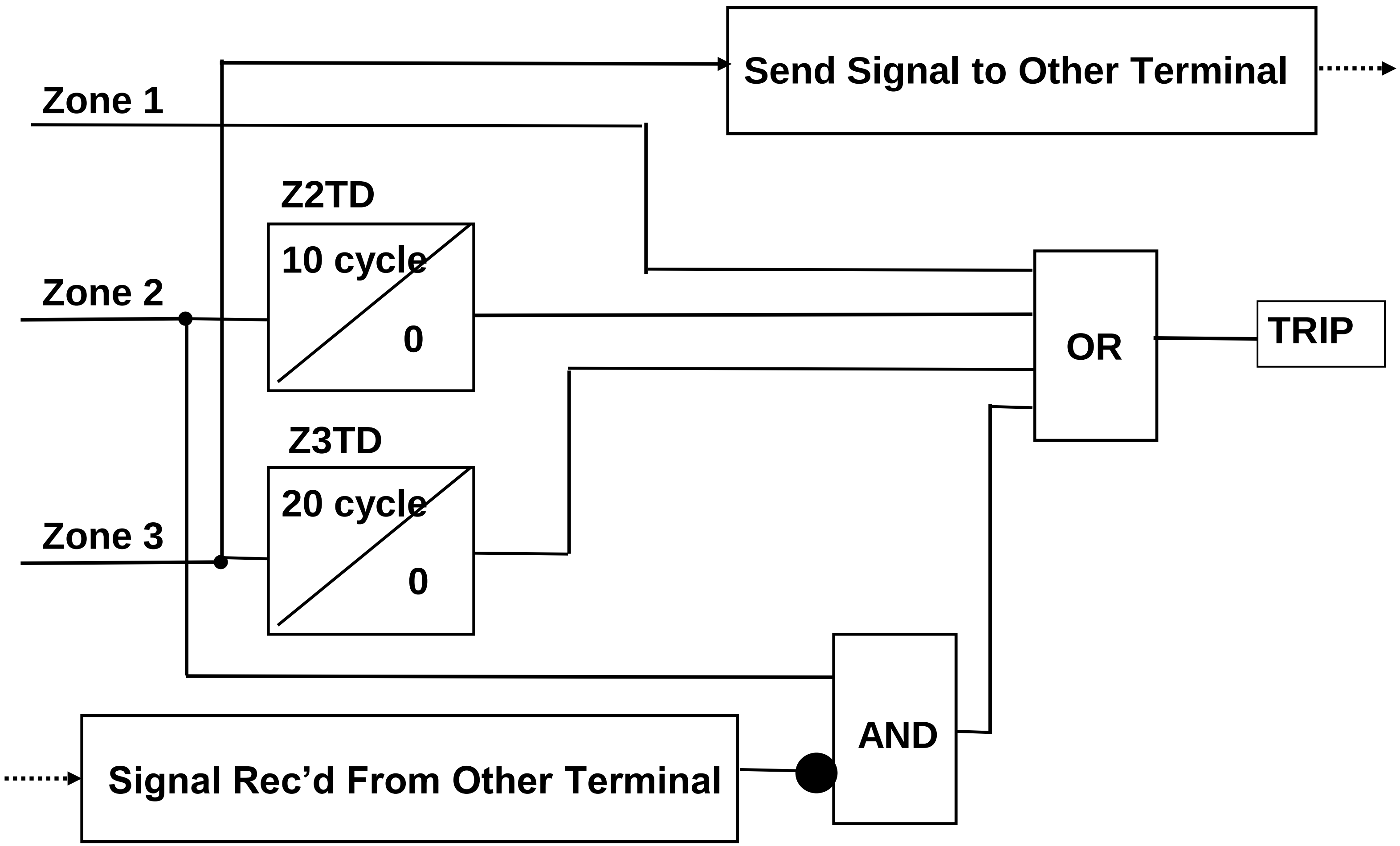
Block Diagram for Permissive Under-Reach Transfer Trip PUTT



Block Diagram for Permissive Over-Reach Transfer Trip POTT

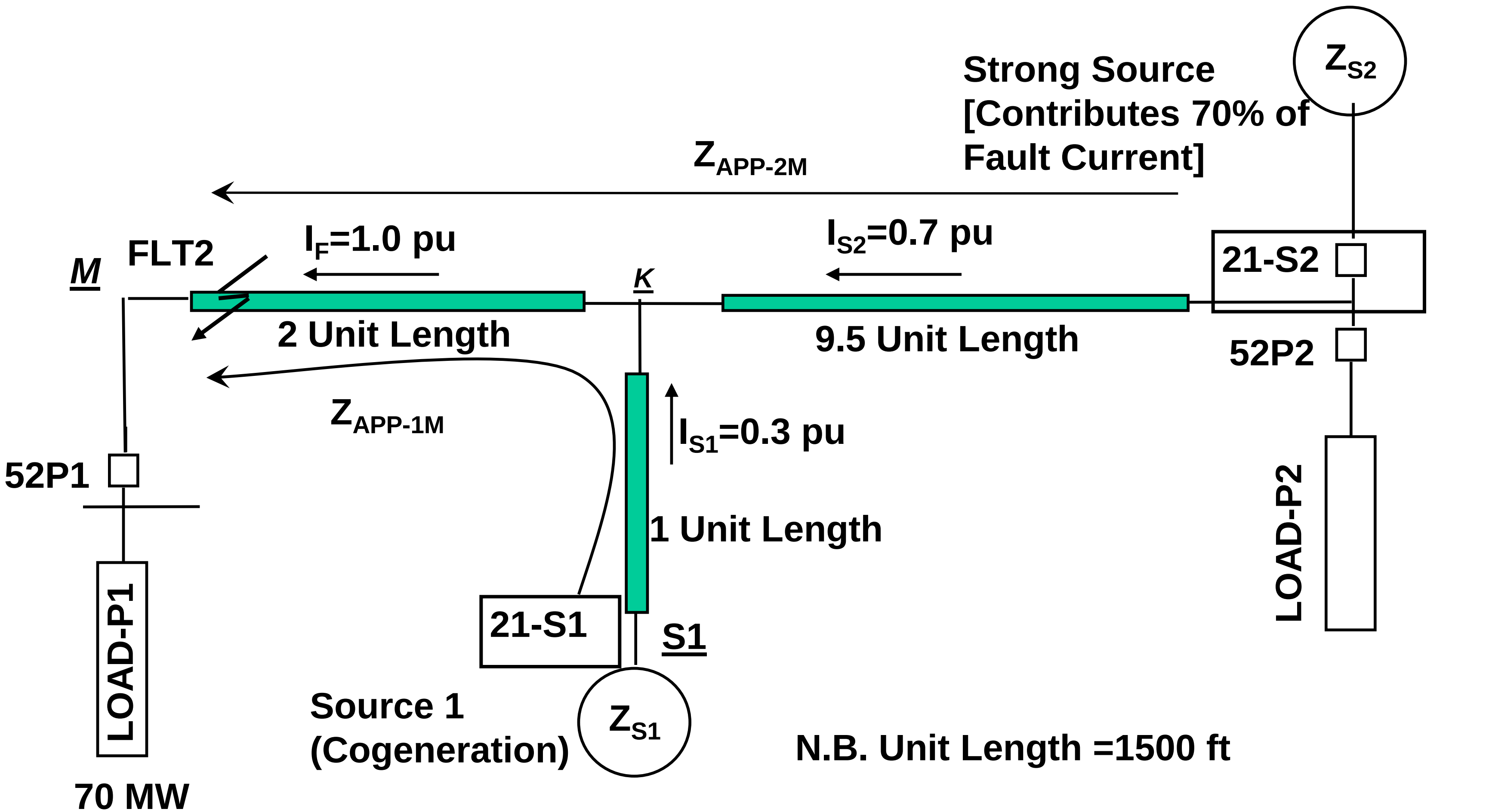


Block Diagram for Blocking Transfer Trip BTT



Multiple Sources and Fault Current In-feed: Concerns and Calculations

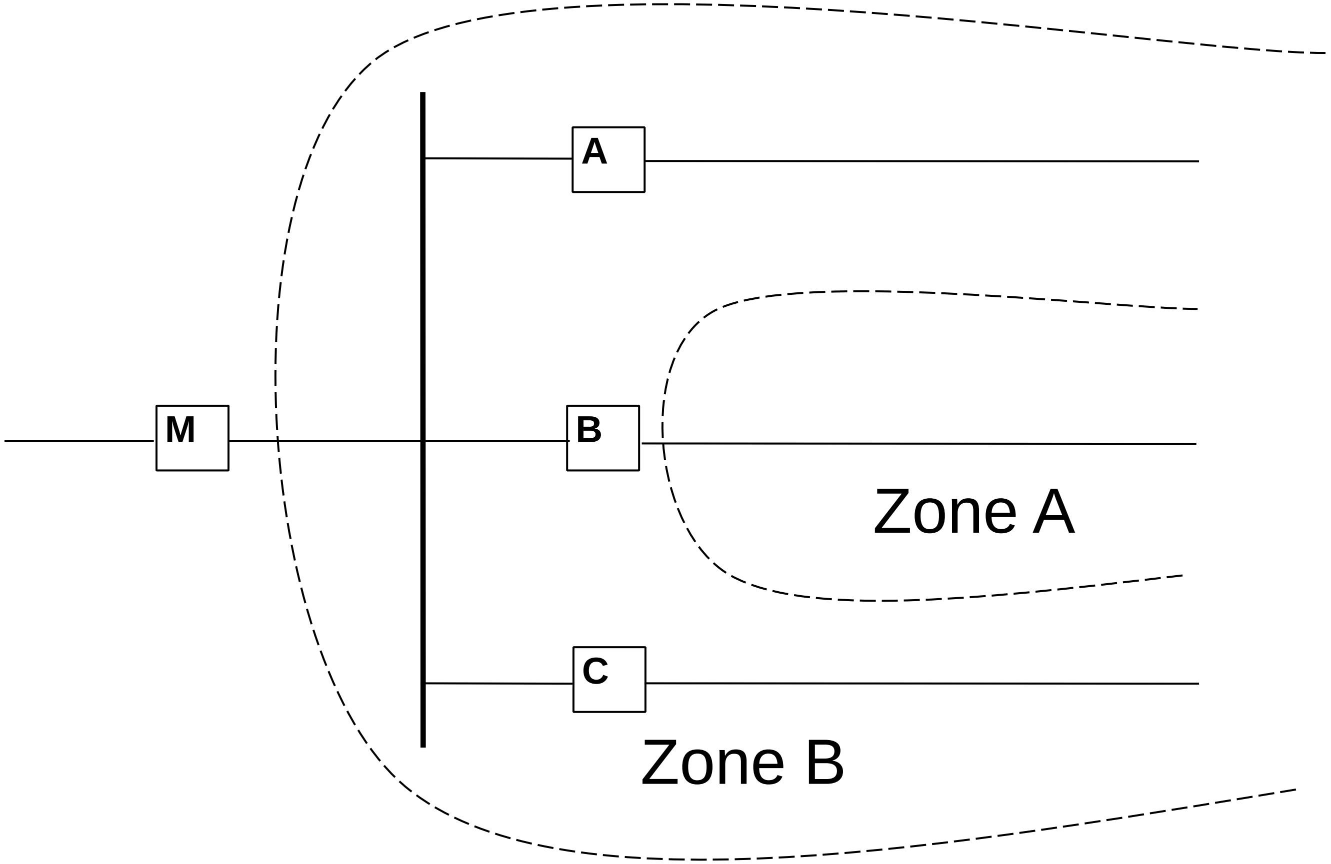
$$Z_{App\_S1-M} = \frac{(I_{S1} x Z_{S1-K}) + (I_F x Z_{KM})}{I_{S1}} = \frac{(0.3x1) + (1x2)}{0.3} = 7.55 Unit.length$$



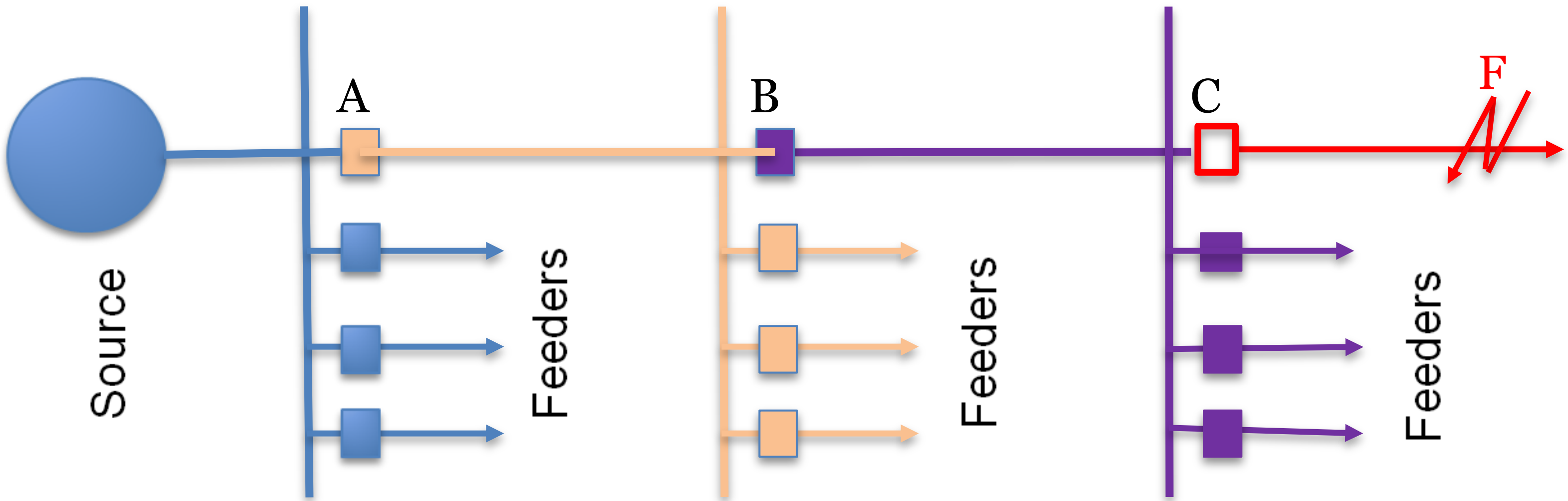
Other Important Protection Schemes

Overlapping in Overcurrent Protection

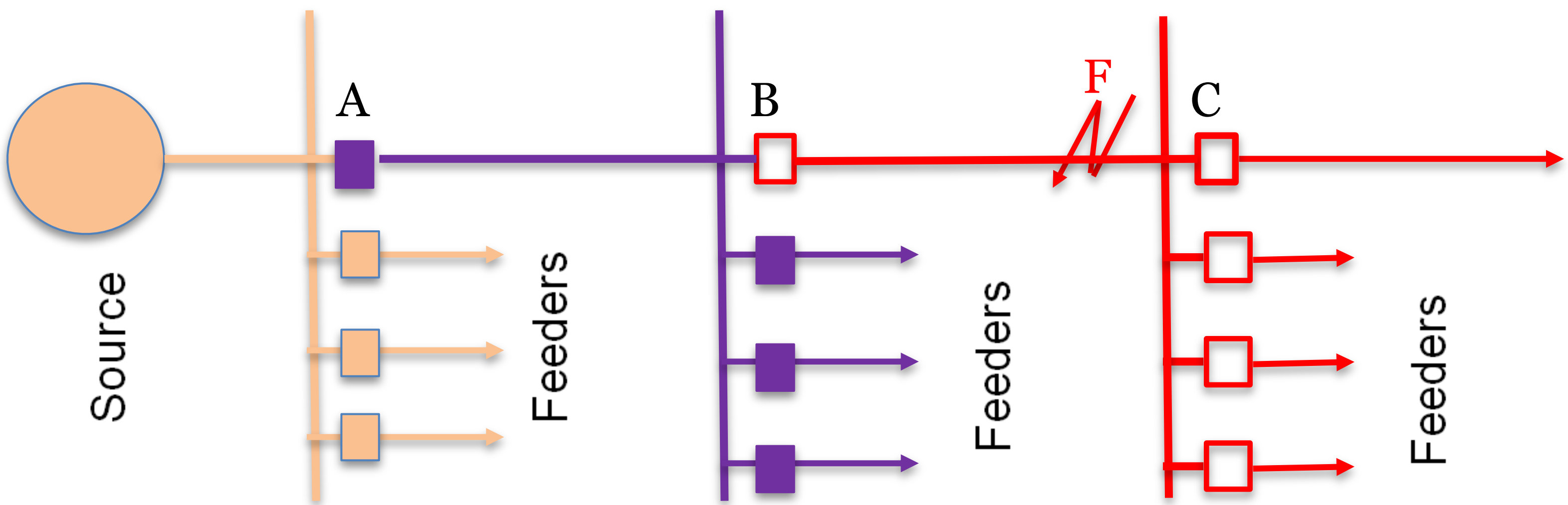
- Overcurrent Protection: simple, it will overlap
- Coordination to ensure selectivity



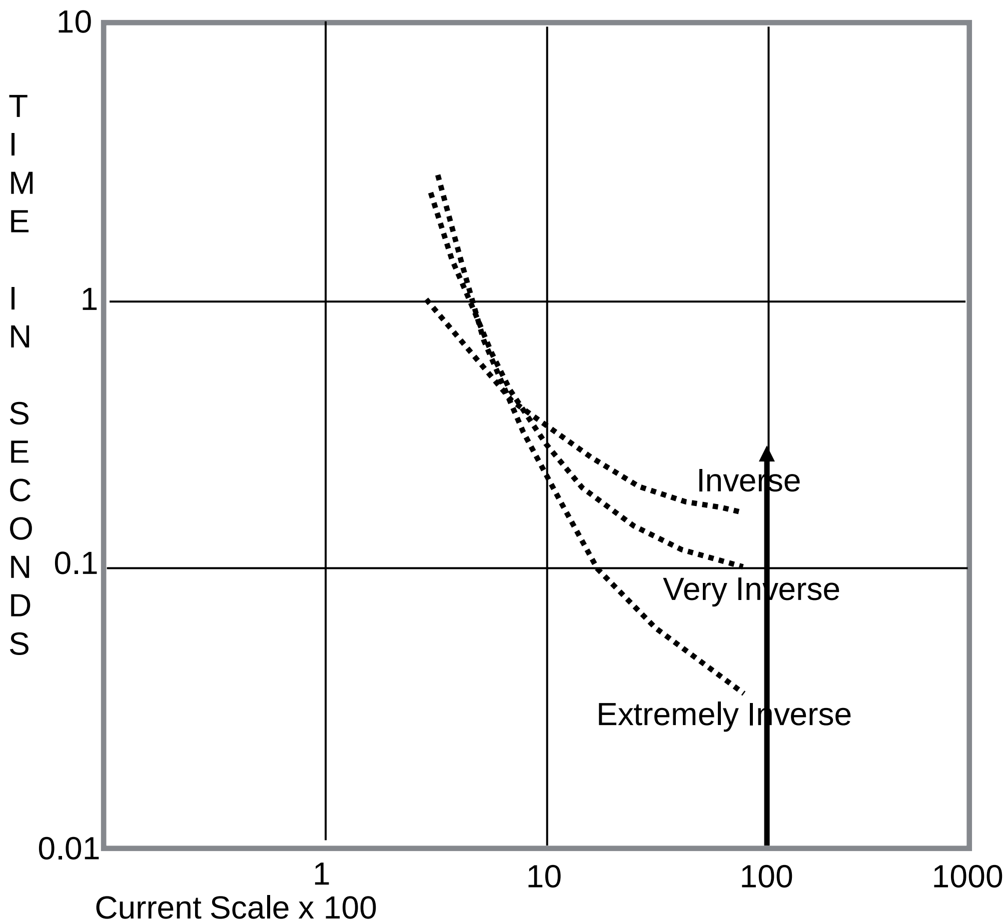
Coordination for Radial Feeders

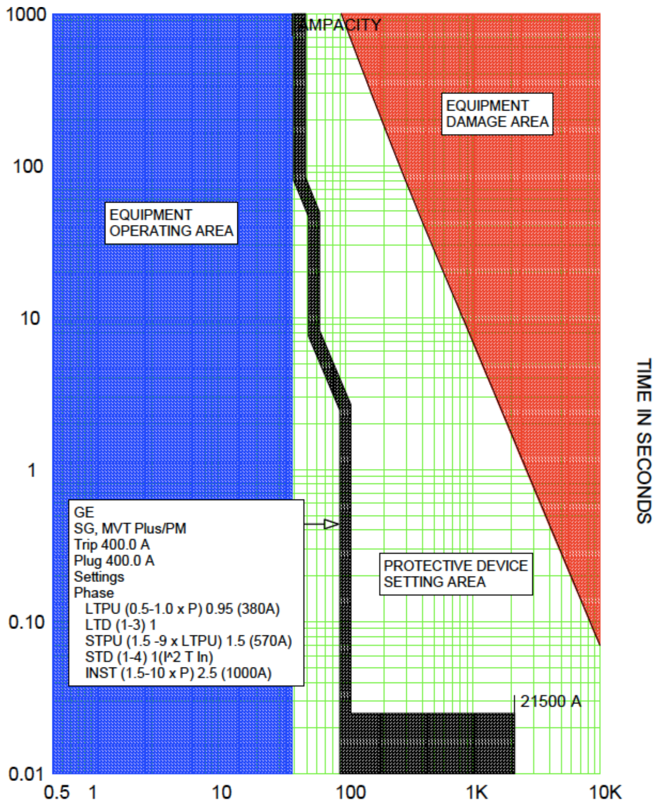


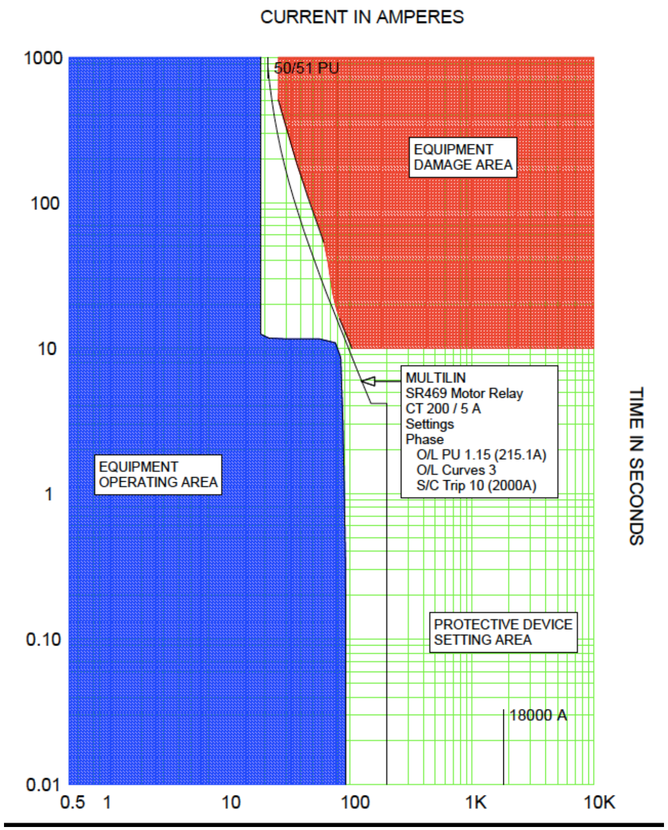
Coordination for Radial Feeders



Inverse Current Time Characteristics

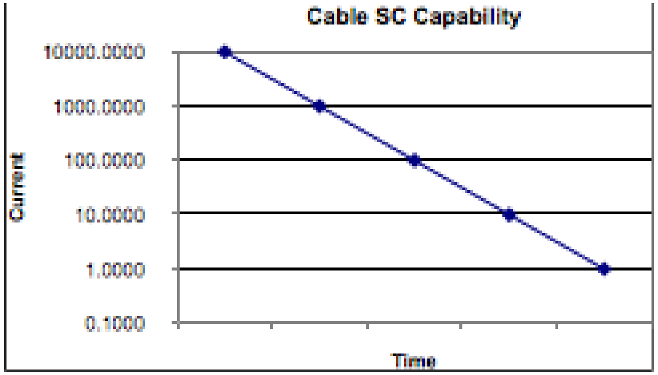



1000
100
10
1
0.10
0.01
0.5 1 10 100 1K 10K
AMPACITY
EQUIPMENT DAMAGE AREA
EQUIPMENT OPERATING AREA
GE
SG, MVT Plus/PM
Trip 400.0 A
Plug 400.0 A
Settings
Phase
LTPU (0.5-1.0 x P) 0.95 (380A)
LTD (1-3) 1
STPU (1.5 -9 x LTPU) 1.5 (570A)
STD (1-4) 1(I^2 T In)
INST (1.5-10 x P) 2.5 (1000A)
PROTECTIVE DEVICE SETTING AREA
21500 A
TIME IN SECONDS


CURRENT IN AMPERES
1000
100
10
1
0.10
0.01
0.5 1 10 100 1K 10K
50/51 PU
EQUIPMENT DAMAGE AREA
MULTILIN
SR469 Motor Relay
CT 200 / 5 A
Settings
Phase
O/L PU 1.15 (215.1A)
O/L Curves 3
S/C Trip 10 (2000A)
EQUIPMENT OPERATING AREA
PROTECTIVE DEVICE SETTING AREA
18000 A
TIME IN SECONDS

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)



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

Overcurrent Protection for Conductors

- Example on using an MCCB for protection of a conductor :

  - See Figure 15-2 of the IEEE Buff Color Book IEEE Std 242-2001 (Copyright 20© IEEE) (http://ieee.org)

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 Transformers

- Example on using a relay for protection of a transformer :
  - See Figure 15-4a of the IEEE Buff Color Book IEEE Std 242-2001 (Copyright 20© IEEE) (http://ieee.org)

Overcurrent Protection for Transformers

- Example on using a fuse for protection of a transformer :
  - See Figure 15-4b of the IEEE Buff Color Book IEEE Std 242-2001 (Copyright 20© IEEE) (http://ieee.org)

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

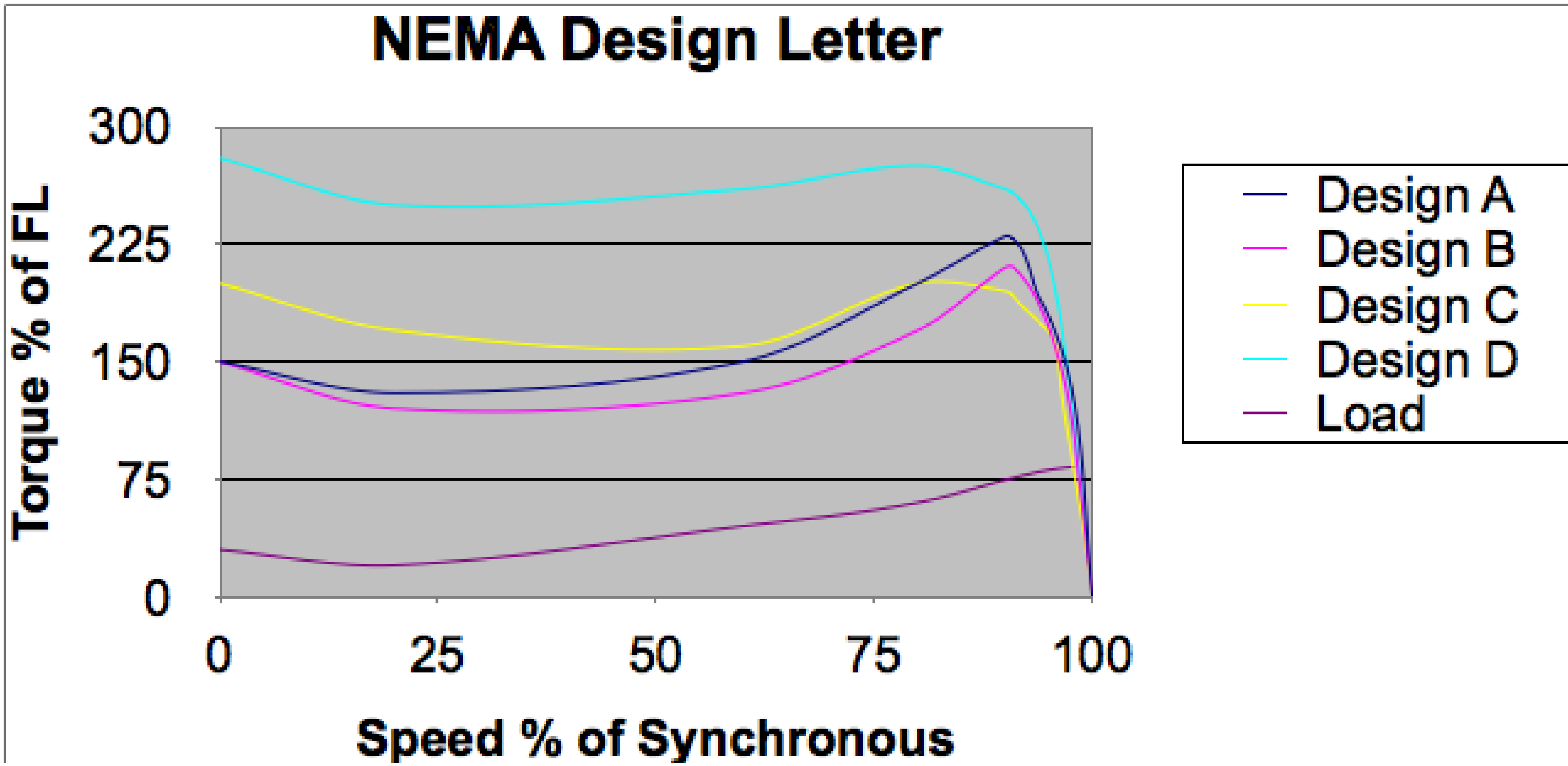
- See the IEEE Guide for AC Generator Protection IEEE Std C37.102™ 2006)
- Generator is composed of many sub-systems: stator, rotor, exciter, mechanical drive
- Using multiple functions such as:
  - Differential
  - Stator Ground Fault
  - Negative Sequence
  - Failure of cooling system
  - Field winding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

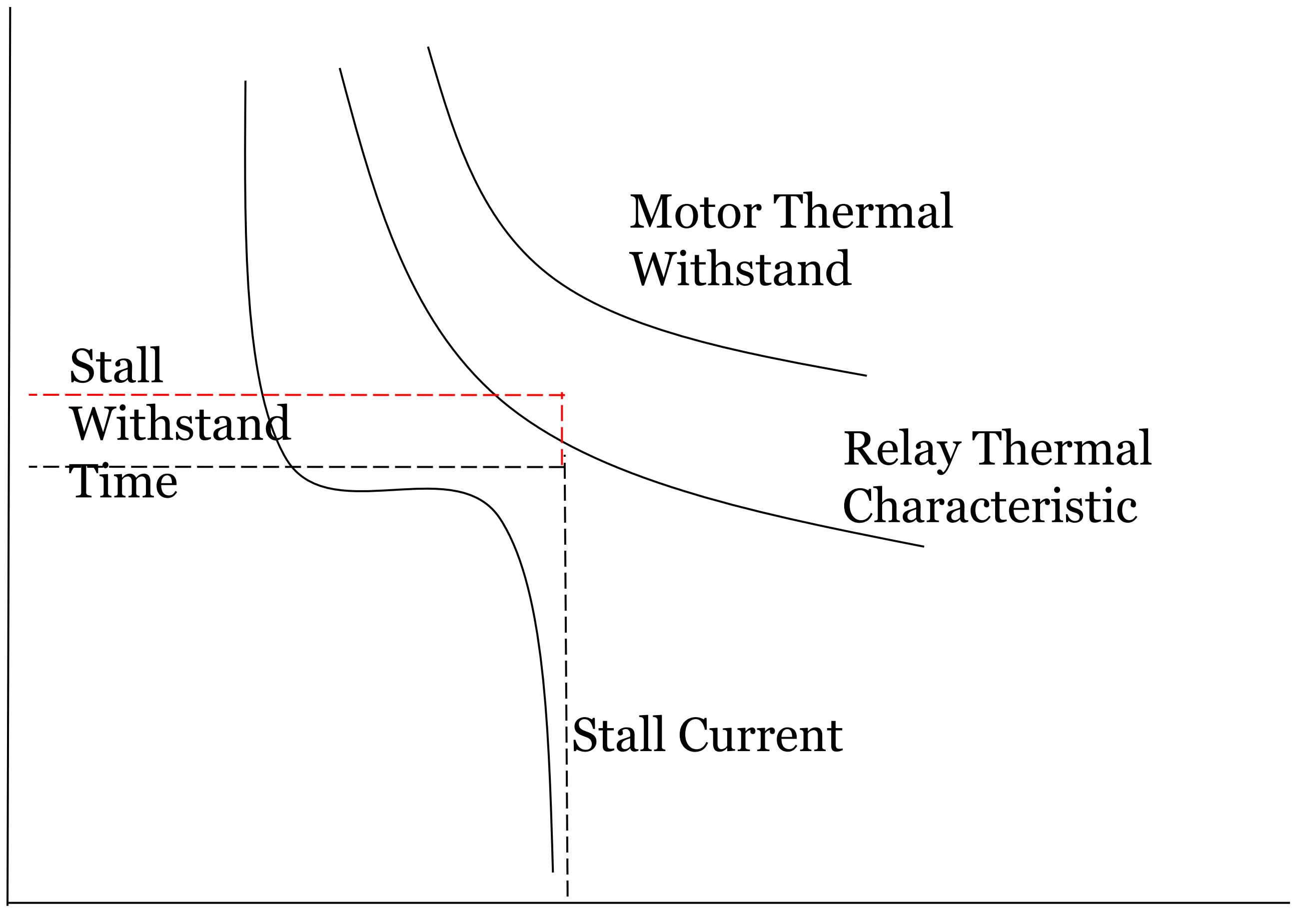
Review of Motor Basics (Motor)

- 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
Torque % of FL
300
225
150
75
0
0
25
50
75
100
Speed % of Synchronous
Design A
Design B
Design C
Design D
Load


Motor Thermal
Withstand
Stall
Withstand
Time
Relay Thermal
Characteristic
Stall Current

The General Philosophy of Protection System Design & Protection System Coordination

Identify Modes of Failures in Protection Systems, and how to reduce Frequency of Failures?

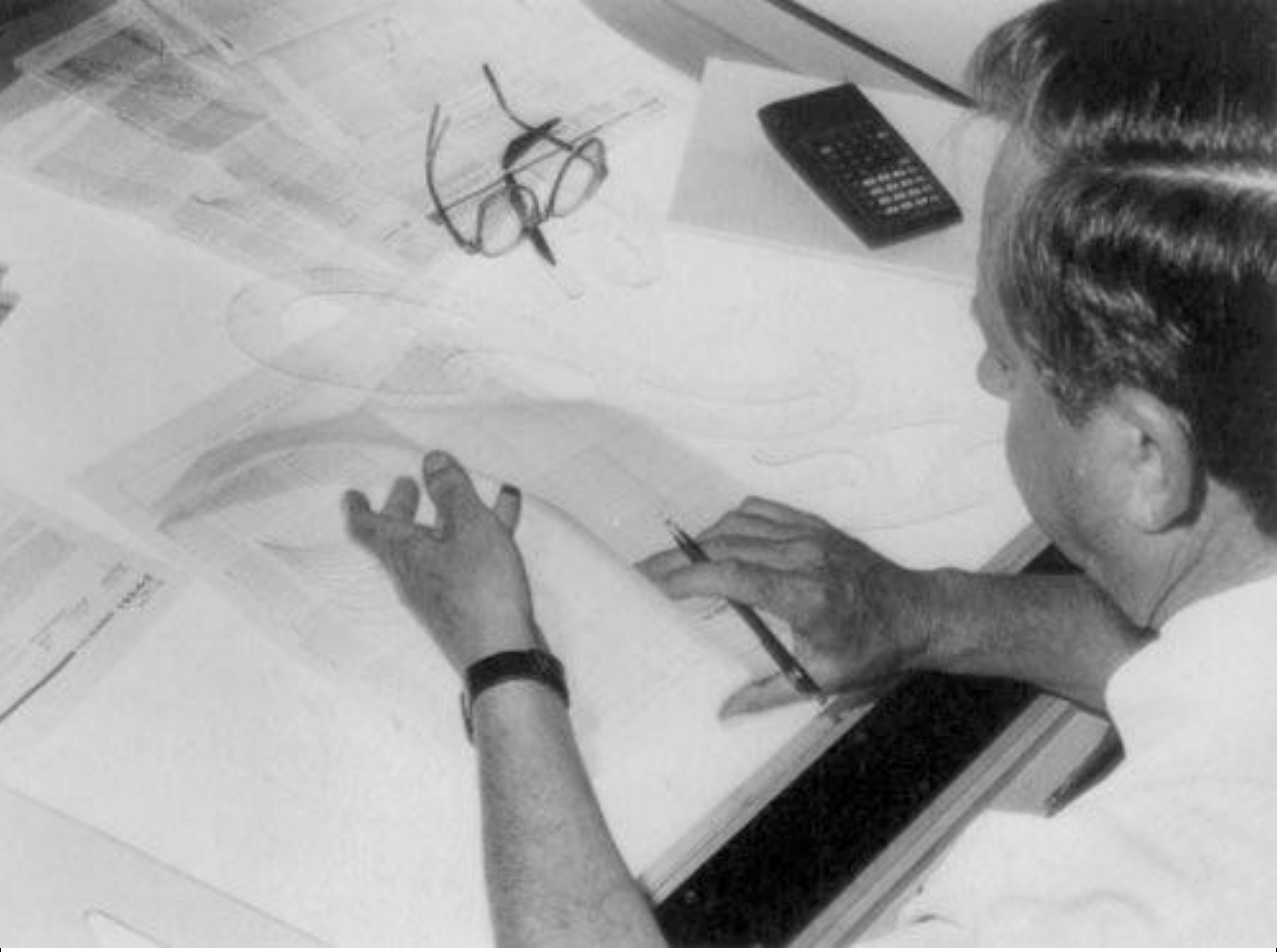
- Failure of current or voltage signal to the relays.
- DC supply failure
- Failure of relay itself:
  - Relay Hardware Components
  - Software Failure
  - Power Supply Failure
  - Redundancy using different platforms
- Failure of a Fuse
- Failure of Circuit Breaker (tripping circuit or mechanism, or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

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 (X Axis)-Log (Y-Axis) Green Graph Paper was superimposed on manufacturer's supplied curves and the Subject O/C Graphs were Obtained

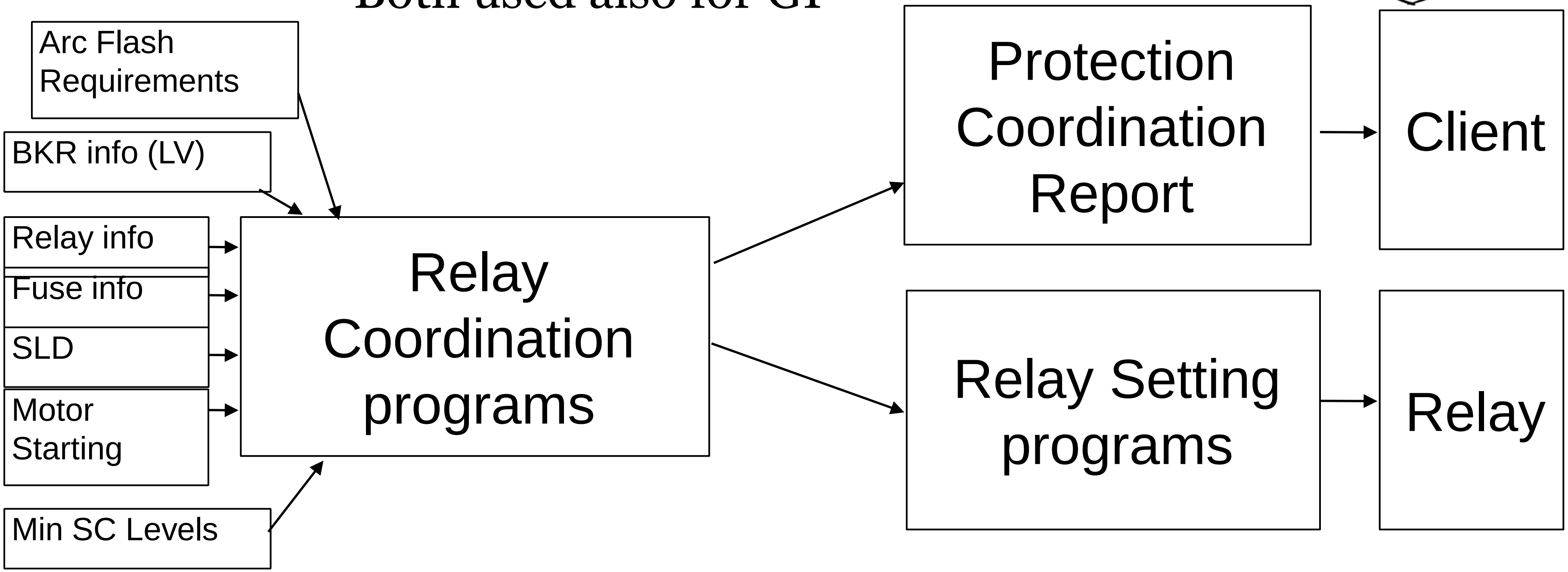


Relay Setting in the Past:

- 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

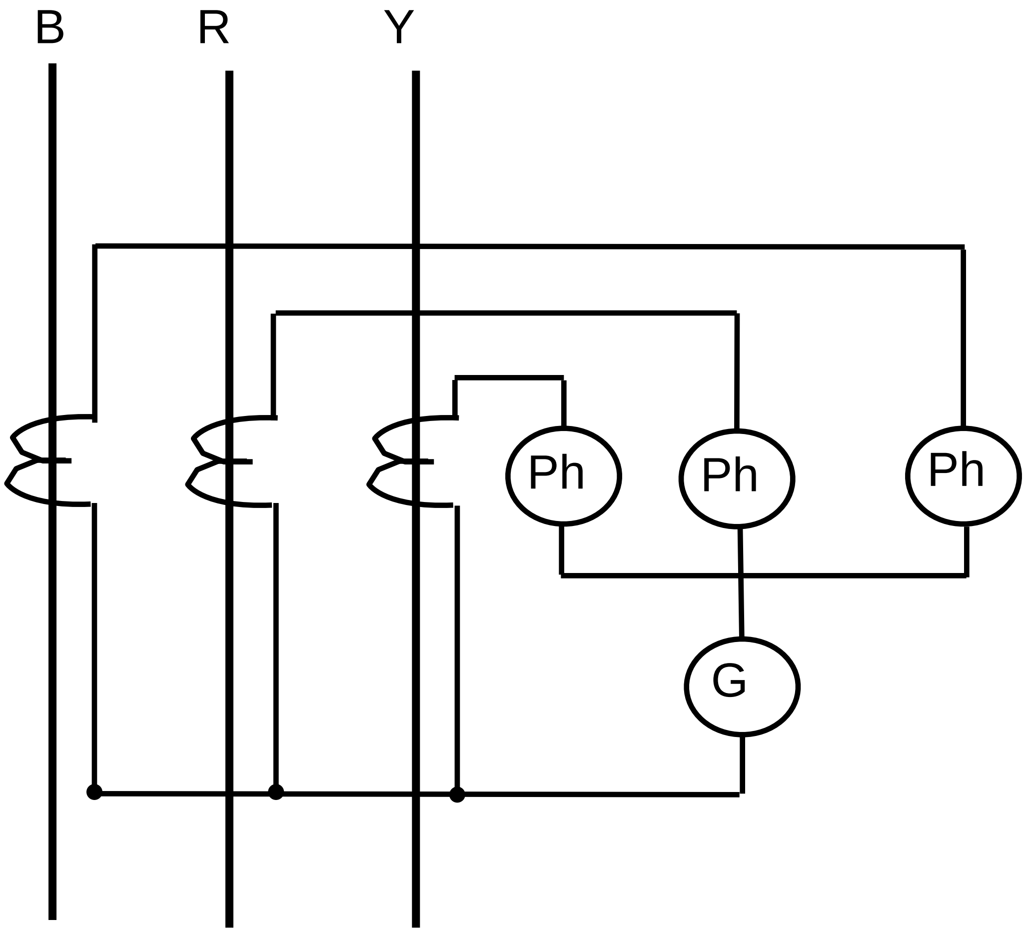
- Two types of programs:
  - Relay Coordination programs
  - Relay setting programs
  - Both used also for GF



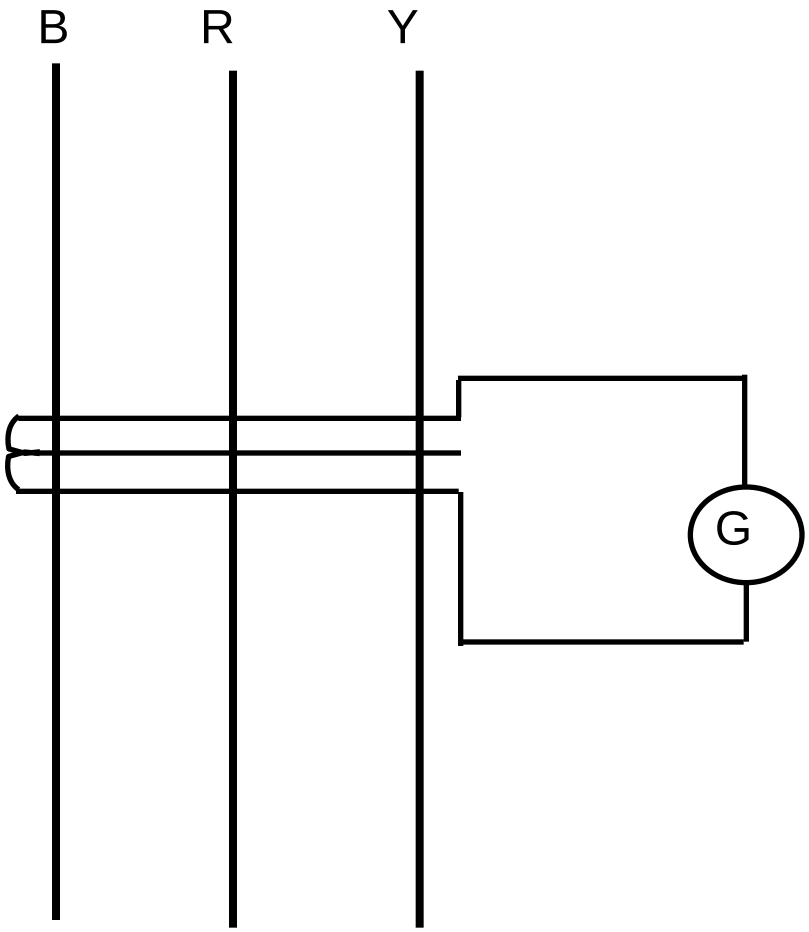
Information Required for Coordination Studies

- 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 current 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

Residual Connection



Core Balance Connection



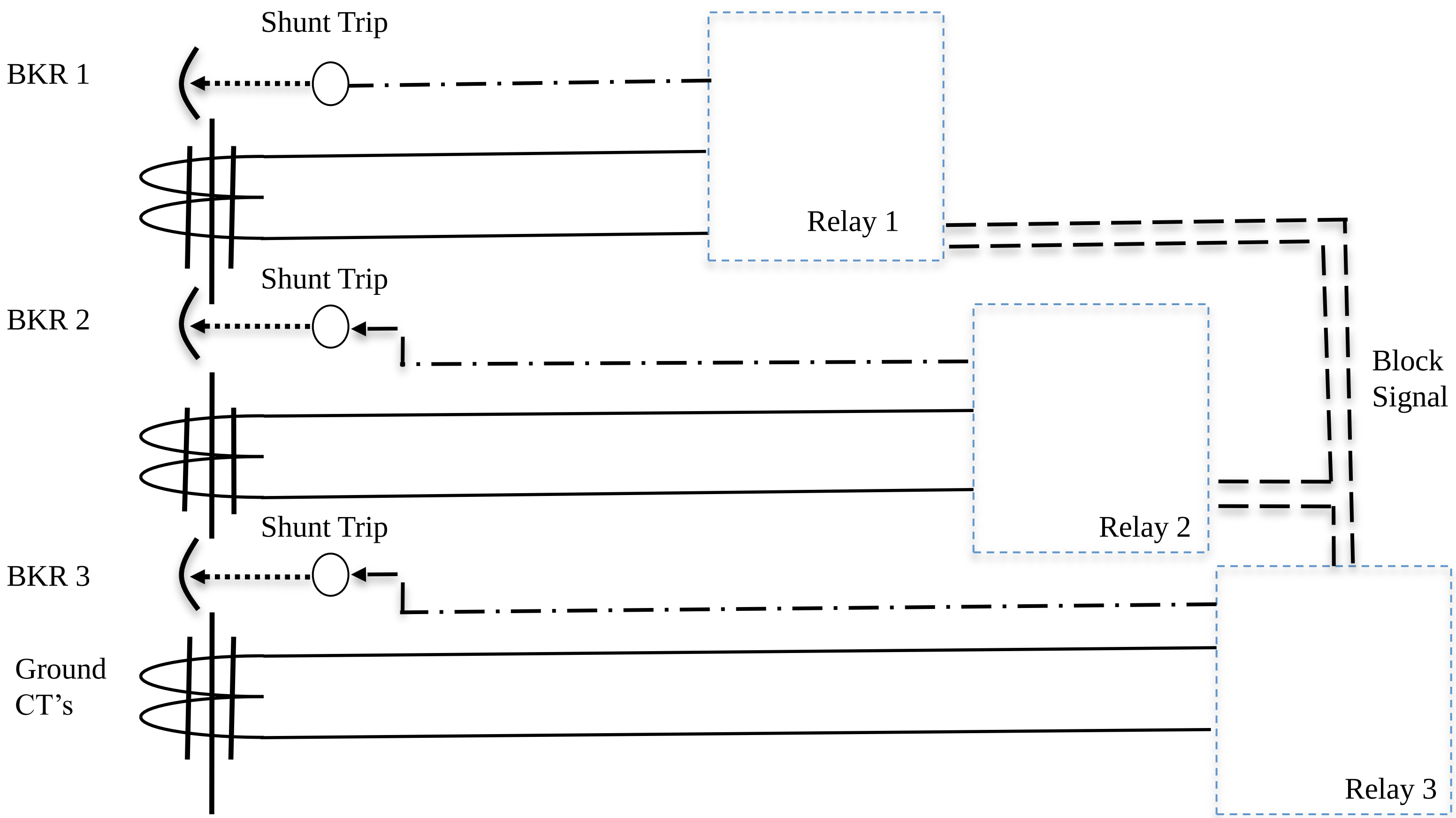
Transformer Zero Sequence Impedance:

- Construction of transformer magnetic circuit
  - 3 limbs, 5 limbs core, shell
  - Ratio of yoke cross section to limb cross section
  - Overlapping of joints
  - Thickness of core lamination
  - Saturation flux density
  - Winding connection

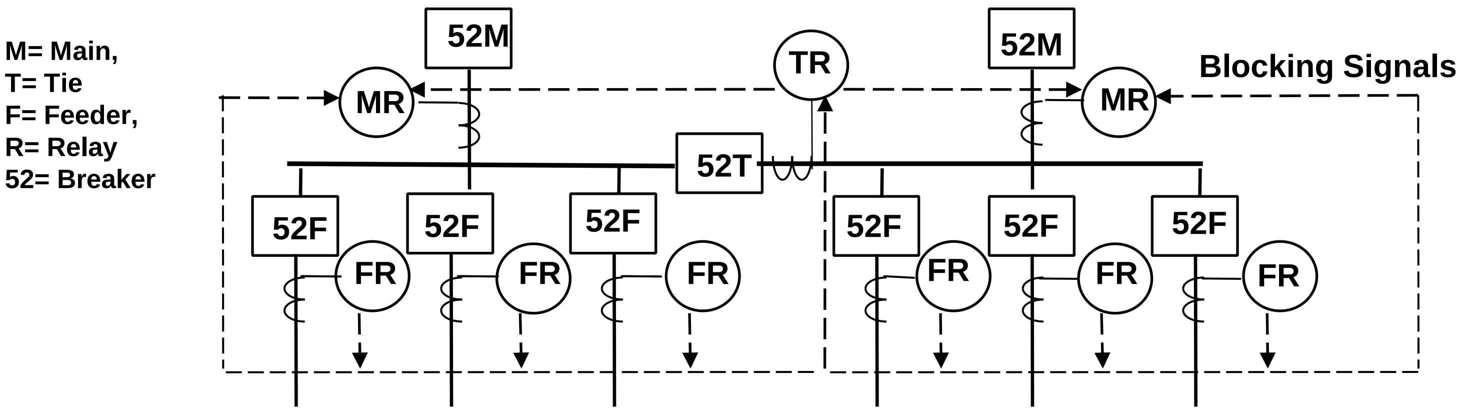
Case Study for Transformer Ground Fault Protection:

- Inrush current was considered a transformer protection issue
- Accordingly it was discussed in IEEE Series C37
- Inrush types:
  - Energization
  - Recovery (after a nearby fault)
  - Sympathetic (two transformers operating in //le or in series)

Zone Selective Interlocking; Some Practical Concerns



Blocking Protection



- Scheme uses digital signals from down-stream relays on the feeder breakers to block relays on main and tie breakers if the fault is outside the bus zone
- Modern communications between relays allow a short delay (50 milliseconds) to be sufficient for a stable system operation.

Factors affecting the selection of bus protection:

- Maximum Three Phase Fault Current
- Maximum and Minimum Phase to Ground Fault Current
- Impact of System and Bus Configurations
- Probability of Bus Failure
- Current Transformers (CTs)
- Arc Flash Studies Requirements

Applications of Communications for LV Bus Protection and Switchgear Arc Flash Incident Energy Reduction

- Direct communications: Blocking scheme
- Use of IEC 61850 and GOOSE in LV Bus Protection, and Smart Grids

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

What Did We Capture from the Tutorial Today?

- Summary
- Discussion
- Questions