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
- 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
- CEC (Canadian Electrical Code),
## IEEE Protection Guides

<table>
<thead>
<tr>
<th>IEEE Std Number</th>
<th>Title</th>
</tr>
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<tbody>
<tr>
<td>C37.91-2008</td>
<td>IEEE Guide for Protective Relay Applications to Power Transformers</td>
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<tr>
<td>C37.96-2012</td>
<td>IEEE Guide for AC Motor Protection</td>
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<tr>
<td>C37.99-2012</td>
<td>IEEE Guide for the Protection of Shunt Capacitor Banks</td>
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<tr>
<td>C37.101-2006</td>
<td>IEEE Guide for Generator Ground Protection</td>
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<tr>
<td>C37.102-2006</td>
<td>IEEE Guide for AC Generator Protection</td>
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# IEEE Protection Guides (Continued)

<table>
<thead>
<tr>
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<tr>
<td>IEEE Std C37.112-1996 (R2007)</td>
<td>IEEE Standard Inverse-Time Characteristic Equations for Overcurrent Relays</td>
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<tr>
<td>IEEE Std C37.117-2007</td>
<td>IEEE Guide for the Applications of Protective Relays used for Abnormal Frequency Load Shedding and Restoration</td>
</tr>
<tr>
<td>IEEE Std C37.234-2009</td>
<td>IEEE Guide for Protective Relay Applications to Power System Buses</td>
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</table>
## Recommended for Equipment Damage Curves

|--------------------------------|----------------------------------------------------------------------------------|
# Recommended for Equipment Selection

<table>
<thead>
<tr>
<th>Standard</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>IEEE Std C37.06-2009</td>
<td>AC High Voltage Circuit Breakers Rated on Symmetrical Current Basis Preferred Rating and Related Required Capabilities for Voltages Above 1000V</td>
</tr>
<tr>
<td>UL 67 – 2009</td>
<td>UL Standard for Safety- Panelboards</td>
</tr>
<tr>
<td>UL 845– 2005</td>
<td>UL Standard for Safety- Motor Control Centers</td>
</tr>
<tr>
<td>UL 891 – 2005</td>
<td>UL Standard for Safety- Dead-Front Switchboards</td>
</tr>
<tr>
<td>UL 1066 – 2012</td>
<td>UL Standard for Safety- Low-Voltage AC and DC Power Circuit Breakers used in Enclosures</td>
</tr>
<tr>
<td>UL 1558 – 1999</td>
<td>UL Standard for Safety- Metal-Enclosed Low-Voltage Power Circuit Breaker Switchgear</td>
</tr>
</tbody>
</table>
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 respond 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:

- Protective Devices Settings
- Equipment Operating Range
- Equipment Damage Range
- Protective Devices Settings Area
- Protective Devices Settings Area
- Protective Devices Settings Area
- Protective Devices Settings Area
From Mason: Inverse TC Relays

Three Types:
- Shaded Pole (A)
- Wattmeter Structure (B)
- Induction Cup Structure (C)
Time Current Equation Per WG 7

\[ K_I I^2 = m \frac{d^2 \theta}{dt^2} + K_d \frac{d\theta}{dt} + \frac{\tau_f - \tau_s}{\theta_{\text{max}}} \theta + \tau_s \]

- Where as:
  - \( \theta \) = Desk travel
  - \( \theta_{\text{max}} \) = Travel to contact close
  - \( K_I \) = Torque constant related to current
  - \( m \) = Moment of inertia
  - \( I \) = Current
  - \( K_d \) = Damping factor
  - \( \tau_s \) = Initial Spring torque
  - \( \tau_f \) = 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 Conductor
Rated For 90°C Maximum Continuous Operation

Curves Based on the Formula

\[ I = 0.0297 \log_{10} \left( \frac{T_s + 224}{T - 234} \right) \]

- \( I \) = Short Circuit Current - Amperes
- \( A \) = Conductor Area - Circular Mils
- \( t \) = Time of Short Circuit - Seconds
- \( T_s \) = Maximum Operating Temperature - 90°C
- \( T \) = Maximum Short Circuit Temperature - 90°C

Conductor Size (AWG/kcmil)
Overcurrent Protection for Transformers

- Thermal Damage
- Mechanical Damage
- 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

- Design A

![Graph showing NEMA Design Letter with Design A line.](image-url)
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)
  - $I_a$
  - $I_b$
  - $I_c$

- **Multiple (i.e., 3) Balanced Systems** (Positive, Negative & Zero Sequence)
  - $I_{a1}$: +ive
  - $I_{b1}$
  - $I_{c1}$
  - $I_{a2}$: -ive
  - $I_{b2}$
  - $I_{c2}$
  - $I_{zero}$
Symmetrical Components:

Positive Sequence

R1

Zero Sequence

B0

Negative Sequence

R0
Symmetrical Components:

\[ a = 1^{\angle}120^\circ = -0.5 + j0.866 \]
\[ a^2 = 1^{\angle}240^\circ = -0.5 - j0.866 \]
\[ a^3 = 1^{\angle}360^\circ = 1^{\angle}0^\circ = 1 + j0 \]

\[ I_a = I_1 + I_2 + I_0 \]
\[ I_B = a^2 I_1 + aI_2 + I_0 \]
\[ I_c = aI_1 + a^2 I_2 + I_0 \]
\[ I_0 = \frac{1}{3}(I_1 + I_2 + I_0) \]
\[ I_1 = \frac{1}{3}(I_a + aI_b + a^2I_c) \]
\[ I_2 = \frac{1}{3}(I_a + a^2I_b + aI_c) \]
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:

\[
Z_1 = Z_2 = Z_0 \gg Z_G
\]

\[
I_{G-F} = \frac{V_{L-N}}{Z_1}
\]
Ground Fault Currents (Continued)

• For High Resistance Grounded System:

\[
Z_1 = Z_2 = Z_0 \ll Z_G
\]

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

Arc Flash Requirements

BKR info (LV)

Relay info

Fuse info

SLD

Motor Starting

Min SC Levels

Protection Coordination Report

Relay Setting programs

Client

Relay
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>
<thead>
<tr>
<th>Figure 8-7a points</th>
<th>Fault (A, rms)</th>
<th>Main device</th>
<th>Clearing time (s)</th>
<th>Arc energy (kWs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1500</td>
<td>Relay</td>
<td>0.33</td>
<td>50</td>
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<tr>
<td></td>
<td></td>
<td>Circuit breaker</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fuse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>4000</td>
<td>Relay</td>
<td>0.25</td>
<td>100</td>
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<td></td>
<td></td>
<td>Circuit breaker</td>
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<td>13200</td>
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<tr>
<td></td>
<td></td>
<td>Fuse</td>
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<td>120000</td>
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<tr>
<td>III</td>
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<td>Circuit breaker</td>
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<tr>
<td></td>
<td></td>
<td>Fuse</td>
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<td>Circuit breaker</td>
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<td>400</td>
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<tr>
<td></td>
<td></td>
<td>Fuse</td>
<td>0.01</td>
<td>20</td>
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</table>
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