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Power Plant and Transmission System Protection Coordination

Power Plant and Transmission System Protection Fundamentals

System Protection and Control Subcommittee

Protection Coordination Workshop
Phoenix, AZ
March 17-18, 2010

to ensure the reliability of the bulk power system

Agenda

- Objective
- Introduction to Protection
- Generator and Power Plant Protection
  - Generator Basics
    - Unique Dynamic Characteristics of Generators
    - Generator and Auxiliary System Protection Requirements
  - Generator Step-Up Transformer Basics
    - Protection Requirements
  - Breaker Failure Basics
    - Protection Requirements

Agenda

- Transmission System Protection Basics
  - Step Distance Principles
  - Types of Relaying and Schemes Used
  - Pilot and Communications
  - Infeed
  - Benefit of Using Pilot Schemes and Effect on Coordination Issues
- Pertinent IEEE Guides for Equipment and System Protection and References

Agenda

- Summary of What is Important to Coordination
- Questions and Answers

Objective

- Increase knowledge of recommended protection for power plant and transmission system.
  - Provide transmission protection engineers with insight into power plant protection issues.
  - Provide power plant protection engineers with insight into transmission protection issues.
  - Provide planning engineers with insight into how power plant and transmission protection respond to system conditions.
- Facilitate improved coordination between power plant and transmission system protection.

Introduction to Protection

- Reliability
- Security
- Dependability
- Coordination

Electrical Protection Definitions can be found in IEEE Dictionary Standard 100.

Generator and Power Plant Basics

Typical Steam Turbine Generator found in a Power Plant

The Role of the Generator in the Power System

- Production of Electrical Energy to Meet Load Demand and System Losses
- Balance of Energy and Stability
- Dynamic Behavior
- Voltage Support
- System Frequency

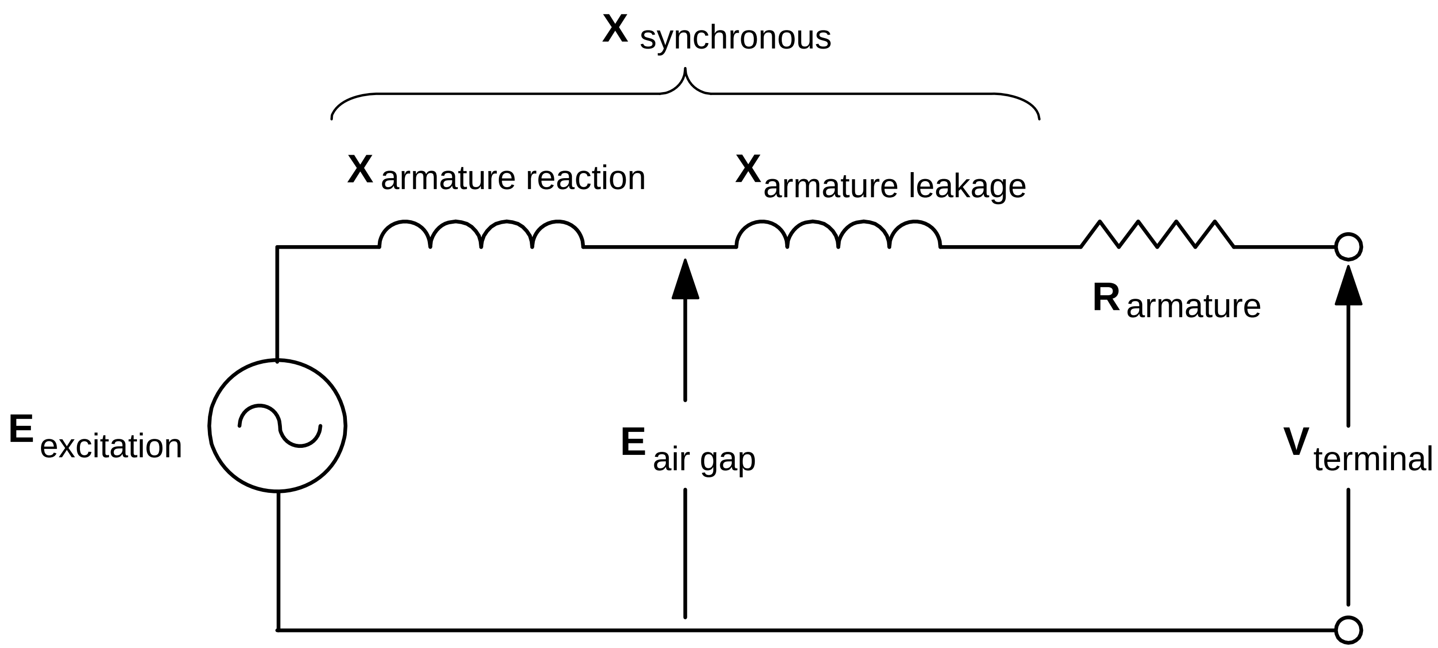
Balance of Energy and Stability

- Power System Stability - “If the oscillatory response of a power system during the transient period following a disturbance is damped and the system settles in a finite time to a new steady operating condition we say the system is stable. If the system is not stable, it is considered unstable.”

Dynamic Behavior of Generators

- Synchronous generators can adjust to changing load conditions fairly readily.
- For small load changes a generator easily can adjust as long as there is a reserve capability.
- Machine characteristics, excitation performance, and the severity of the disturbance will dictate a generator's stability during large transient events.

Synchronous Generator Equivalent Circuit



Synchronous Generator Equivalent Circuit identifying armature reaction and armature leakage reactance and air-gap voltage

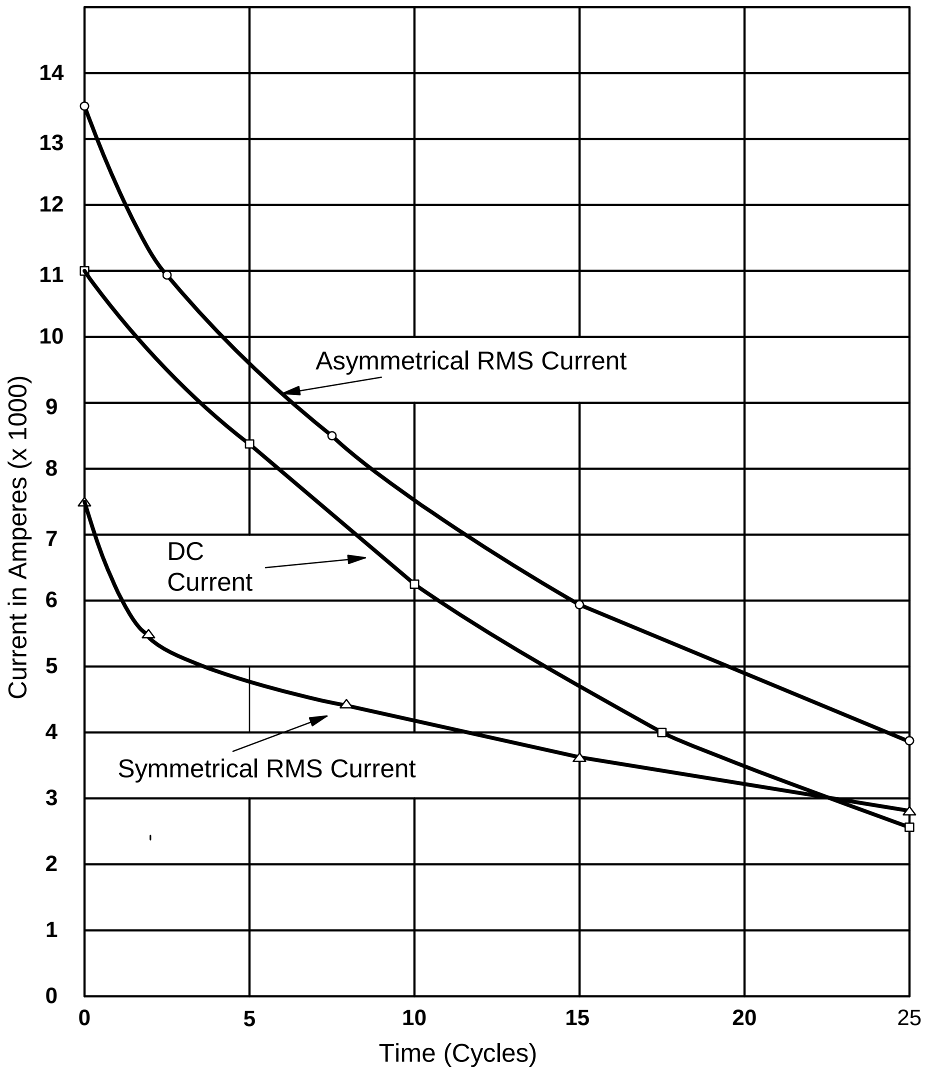
Voltage Support

- Generators on the system are used to maintain voltage.
- Automatic Voltage Regulators are set to meet a scheduled system voltage and provide reactive power support.
- Generators provide system control by maintaining terminal voltage during real and reactive power load changes.

System Frequency

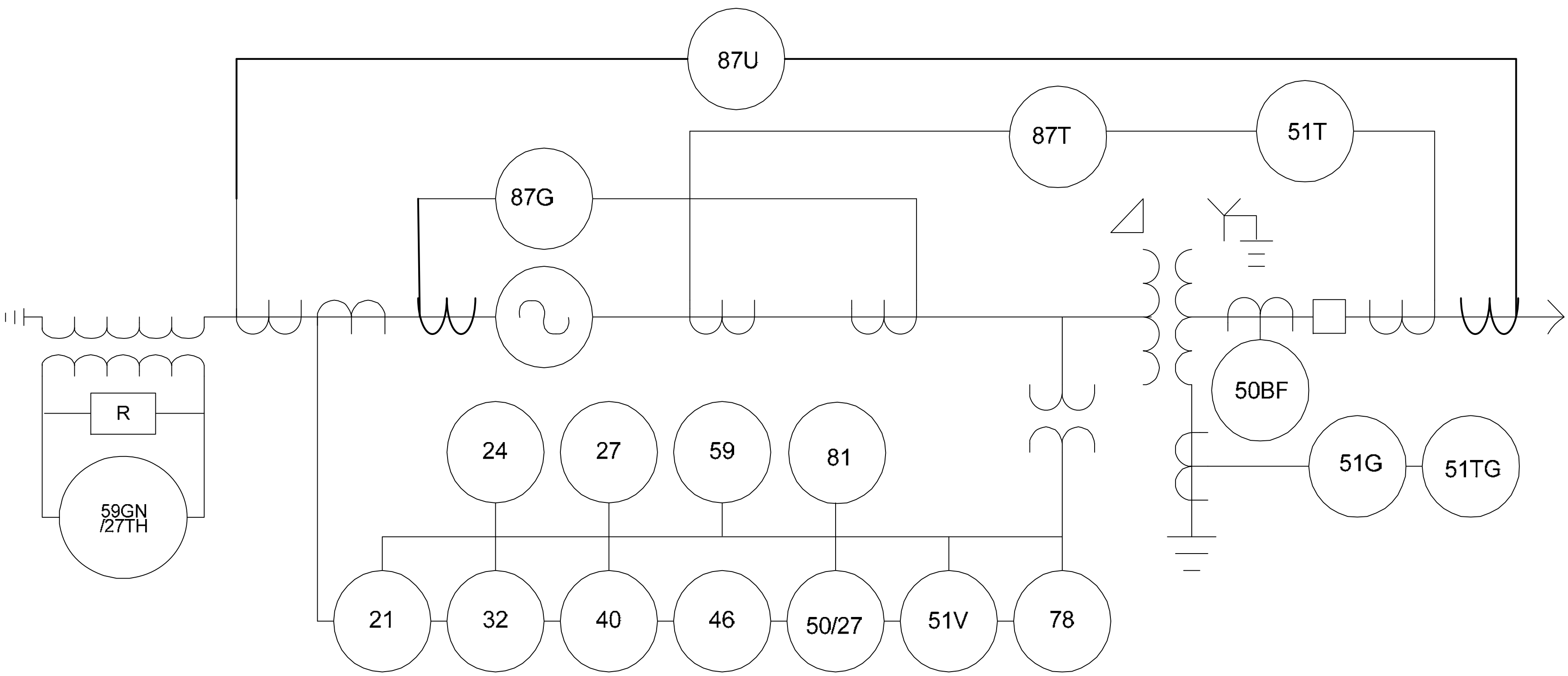
- Balance between generators and system loads.
- System frequency is maintained through turbine speed control.
- Excessive load will bog down the system frequency.
- Light load conditions will increase system frequency.

Unique Dynamic Characteristics of Generators - Short Circuit Current Decrements



Reference: Fitzgerald, A. E. , Kingsley, Charles, and Umans, Stephen, **Electric Machinery**, fourth edition, McGraw-Hill Book Company, New York, 1983.

Power Plant Equipment Protection Requirements



Generator Fault and Abnormal Operating Conditions

- Generator Faults
  - Stator Phase
  - Stator and Field Ground
- Generator Step-up Transformer Faults
  - Phase and Ground
- System Back Up for Faults
  - Phase and Ground
- Abnormal Operating Conditions
  - Over/undervoltage
  - Overexcitation
  - Load Unbalance
  - Loss-of-Field
  - Loss-of-Synchronism (Out-of-Step)
  - Over/underfrequency
  - Loss of Prime mover (Motoring)
  - Inadvertent Energizing
  - Breaker Failure

Pertinent Power Plant Protection for Coordination Considerations

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- Phase Distance Protection (Function 21)
- Overexcitation or V/Hz (Function 24)
- Undervoltage Protection (Function 27)
  - Generator Unit Protection
  - High Side Protection Applied at Point of Common Coupling
  - Generating Plant Auxiliary Power Supply Systems
- Reverse Power Protection (Function 32)
- Loss-of-Field Protection (LOF) (Function 40)
- Negative Phase Sequence or Unbalanced Overcurrent Protection (Function 46)
- Inadvertent Energizing Protection (Function 50/27)
- Breaker Failure Protection (Function 50BF)

Pertinent Power Plant Protection for Coordination Considerations

- Backup Phase (Function 51T) and Backup Ground Overcurrent Relay (Function 51TG)
- Voltage-Controlled or -Restrained Overcurrent Relay (Function 51V)
- Overvoltage Protection (Function 59)
- Stator Ground Relay (Function 59GN/64G)
- Out-of-Step or Loss-of-Synchronism Relay (Function 78)
- Over and Underfrequency Relay (Function 81)
- Transformer Differential Relay (Function 87T), Generator Differential Relay (Function 87G) Protection and Overall Differential Protection (Function 87U)

Phase Distance Protection (Function 21)

- Distance Protection to provide back-up protection for system faults that have not been cleared by transmission system circuit breakers via their relays.
- Impedance measurement derived from the quotient of generator terminal voltage divided by generator stator current.
  - Machine Coverage
  - System Relay Failure Coverage
- Coordination Concerns – Undesired operation for system conditions; especially stressed voltage situations and power swings.

Overexcitation or V/Hz Protection (Function 24)

- Protection measures a ratio of voltage to frequency at the generator terminals.
- Provides overexcitation protection for the generator and any terminal connected transformers, i.e. GSU and auxiliaries.
- Overexcited magnetic cores can lead to severe overheating and breakdown in insulation.
- Coordination Concerns – Coordinate with Underfrequency Load Shedding (UFLS) programs in the system.

Undervoltage Protection (Function 27) Generator Unit Protection

- Typically provides alarm and supervision for other protection using generator terminal voltage. Rarely used to trip the generator directly.
- Provides detection of low voltage that may result in reduction in stability limit, excessive reactive power drawn from the system, and malfunction of voltage sensitive devices and equipment.
- Coordination Concerns – Coordinate with any system undervoltage protection, system fault conditions, and stressed system voltage situations for which the system is designed to survive.

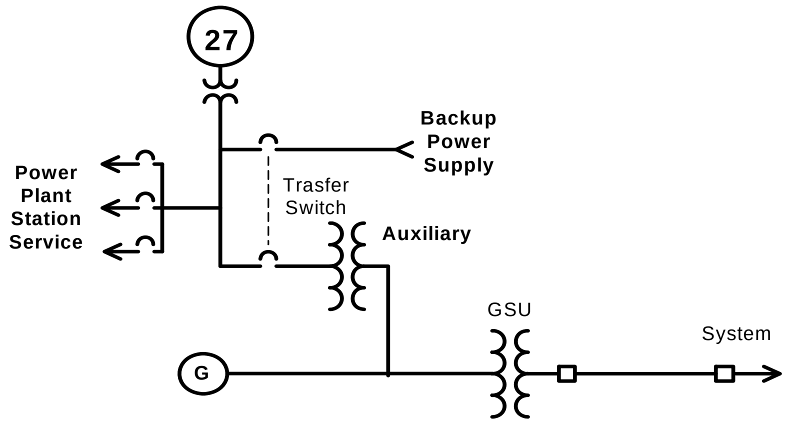
Undervoltage Protection (Function 27) High Side Protection at Point of Common Coupling

- Protection measures system voltage at the point of common coupling.
- Provides a trip of the distributed resource on undervoltage if it is islanded with local load or is subjected to a prolonged system fault.
- Coordination Concerns – Coordinate with any system undervoltage protection, system fault conditions and stressed system voltage conditions for which the system is designed to survive.

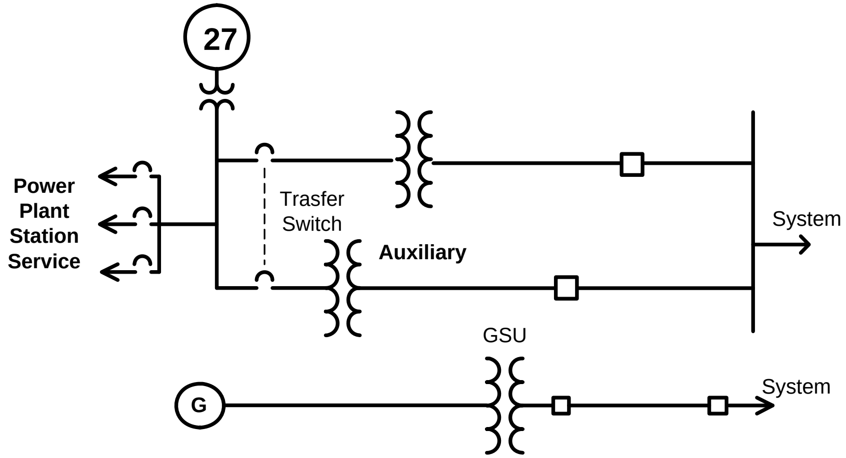
Undervoltage Protection (Function 27) Generating Plant Auxiliary Power Systems

- Protection measures auxiliary system voltage.
- Provides alarming or tripping, automatic transfer to backup supply, starting emergency generation.
- Coordination Concerns – Coordinate with any system undervoltage protection, system fault conditions and stressed system voltage situations for which the system is designed to survive.

Concerns with Auxiliary System Power Supply Source



Unit Auxiliary Transformer Supplied Scheme



Transmission System Transformer Supplied Scheme

Reverse Power Protection (Function 32)

- Protection measures reverse power derived from the real component of generator voltage times generator stator current times the square root of three.
- Provides protection of the prime mover from damage due to motoring.
- Coordination Concerns - None

Loss-of-Field (LOF) Protection (Function 40)

- Protection measures impedance derived from the quotient of generator terminal voltage divided by generator stator current.
- Provides detection and protection for complete or partial loss of the field excitation due to field winding open or shorts, tripping of the field breaker, loss of supply, or voltage regulation failure.
- Coordination Concerns – Undesired operation during system disturbances and system power swings that are recoverable.

Negative Phase Sequence or Unbalanced Overcurrent Protection (Function 46)

- Protection measures stator negative sequence current produced by the unbalanced conditions of the system to which the generator is connected.
- Provides protection from excessive negative sequence currents due to asymmetries, unbalanced loads, unbalanced system faults, and open phases. This can cause rotor component heating damage.
- Coordination Concerns – Coordinate with system protection for unbalanced conditions. Awareness of continuous negative sequence level due to system conditions and coordinate the continuous negative sequence current protection or alarm such that it does not exceed the generator capability.

Inadvertent Energizing Protection (Function 50/27)

- Protection measures both generator terminal voltage and generator stator current to detect inadvertent energizing of the generator.
- Provides detection of accidental energizing of an off-line unit causing it to start-up as an induction motor. Significant damage can occur in a few seconds of machine motoring through the GSU transformer.
- Coordination Concerns – Set point of the undervoltage supervision should be below 50 percent nominal voltage with at least a two second time delay. Undesired tripping due to a higher set point should be avoided during stressed system conditions and disturbances that can be survived.

Voltage-Controlled or -Restrained Overcurrent Protection (Function 51V)

- Protection measures generator terminal voltage and generator stator current. The current sensitivity varies as a function of the terminal voltage.
- Provides back-up protection for system faults when the power system that the generator is connected to is protected by time-current coordinated protection.
- Coordination Concerns – Should coordinate with system elements for faults and is not recommended when system protection is distance type protection.

Overvoltage Protection (Function 59)

- Protection measures generator terminal voltage.
- Provides protection against generator overvoltage. This prevents generator insulation breakdown for sustained overvoltage.
- Coordination Concerns – Coordinate with any system overvoltage protection.

Stator Ground Protection (Function 59GN/64G, 27TH)

- Protection measures the generator neutral zero sequence voltage.
- Provides protection for generator system ground faults.
- Coordination Concerns – Proper time delay is required so that the protection does not trip due to inter-winding capacitance issues for faults on the system or instrument secondary grounds.

Out-of-Step or Loss-of-Synchronism Protection (Function 78)

- Protection uses a measurement of apparent impedance derived from the quotient of generator terminal voltage divided by generator stator current.
- Provides loss-of-synchronism (out-of-step) protection for generators that have electrical centers located near the generator and its step-up transformer for swing conditions.
- Coordination Concerns – Undesired operation during system disturbances and system power swings that are recoverable. Stability studies need to be performed.

Over and Underfrequency Protection (Function 81)

- Protection measures voltage frequency to detect over and underfrequency conditions.
- Provides protection against sustained abnormal frequency operation for the prime mover and generator.
- Coordination Concerns – Coordination is required with the system underfrequency load shedding (UFLS) program and stressed system frequency conditions for which the system is designed to survive. The UFLS needs to take action first to arrest the abnormal frequency condition.

Generator Differential Protection (Function 87G) and Overall Differential Protection (Function 87U)

- Protection measures difference current in its associated zone.
- Provides high-speed phase fault protection for the generator zone (87G) and unit overall zone (87U)
- Coordination Concerns – None except to insure overlaps are done correctly.

Generator Step-Up Transformer Basics

GSU Transformer, Auxiliary Transformer and Isolated Phase Bus

Backup Phase (Function 51T) and Backup Ground Overcurrent Protection (Function 51TG)

- Protection measures GSU phase and neutral ground current.
- Provides back-up protection for faults in both the GSU and generator, and for system faults.
- Coordination Issues – Coordinate with generator protection and the slowest system protection. Use of the backup phase protection (Function 51T) is not recommended due to the difficulty of coordinating with system protection functions and the detection of faults due to the generator fault current decrement.

Backup Phase Overcurrent Protection (Function 51T)

- If function 51T is applied, it must be set to the following requirements:
  - The 51T must have a minimum pickup of twice the generator MVA rating at rated power factor.
  - The 51T must operate slower with margin than the slowest transmission protection system that it must coordinate with based on protection design including breaker failure time.
  - The 51T must sense the required fault based on the transmission protection design with the fault current available from the generator in the time frame that it is set to operate.
  - The Generator Owner must determine that the setting for the 51T that coordinates with the transmission protection will also coordinate with the generator protection systems for the fault current available from the transmission system.

Backup Ground Overcurrent Protection (Function 51TG)

- Function 51TG must be set to the following requirements:
  - The 51TG must have a pickup with margin greater than the largest non-fault system unbalance anticipated based on system design.
  - The 51TG must operate slower with margin than the slowest transmission protection system that it must coordinate with based on protection design including breaker failure time.

Transformer Differential Protection (Function 87T)

- Protection measures difference current in its associated transformer zone.
- Provides high speed phase fault protection for the transformer zone (87T).
- Coordination Concerns – None except to insure overlaps are done correctly.

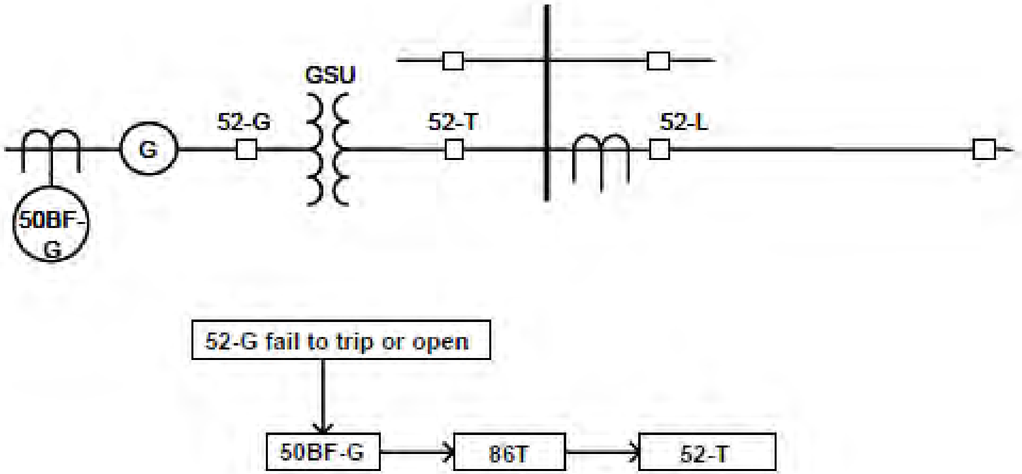
Breaker Failure Basics

HV Substation Breaker

Breaker Failure Protection (Function 50BF)

- Protection measures breaker current and monitors the breaker “a” switch.
- If the generator breaker does not clear the fault or abnormal condition in a specified time, the timer will trip the necessary breakers to remove the generator from the system.
- Coordination Issues - All upstream (next level) protection settings and systems must be considered when evaluating the performance of breaker failure functions associated with generators. Total clearing time, which includes breaker failure time, of each breaker in the generation station substation should coordinate with the critical clearing times associated with unit stability.

Breaker Failure Protection (Function 50BF)



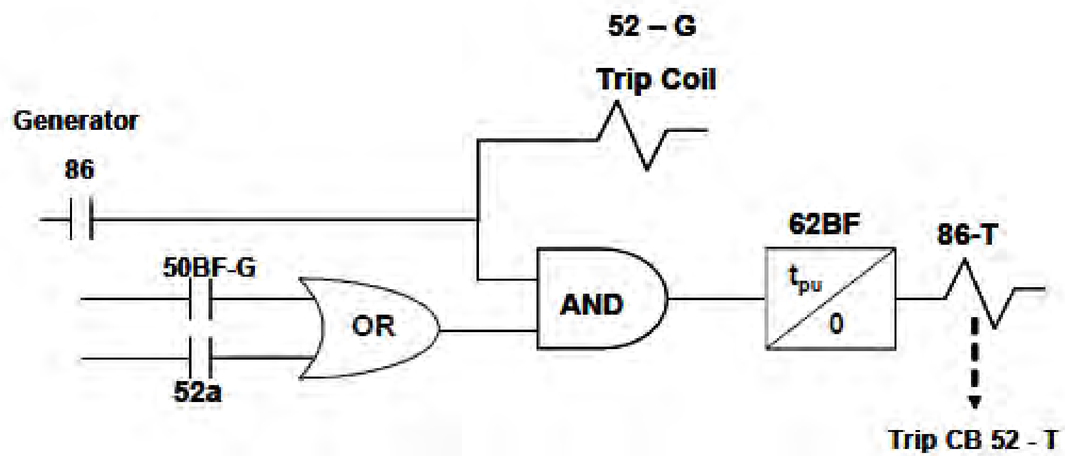


Figure 3.8.1 — Unit Breaker Failure Logic Diagram

Transmission System Basics

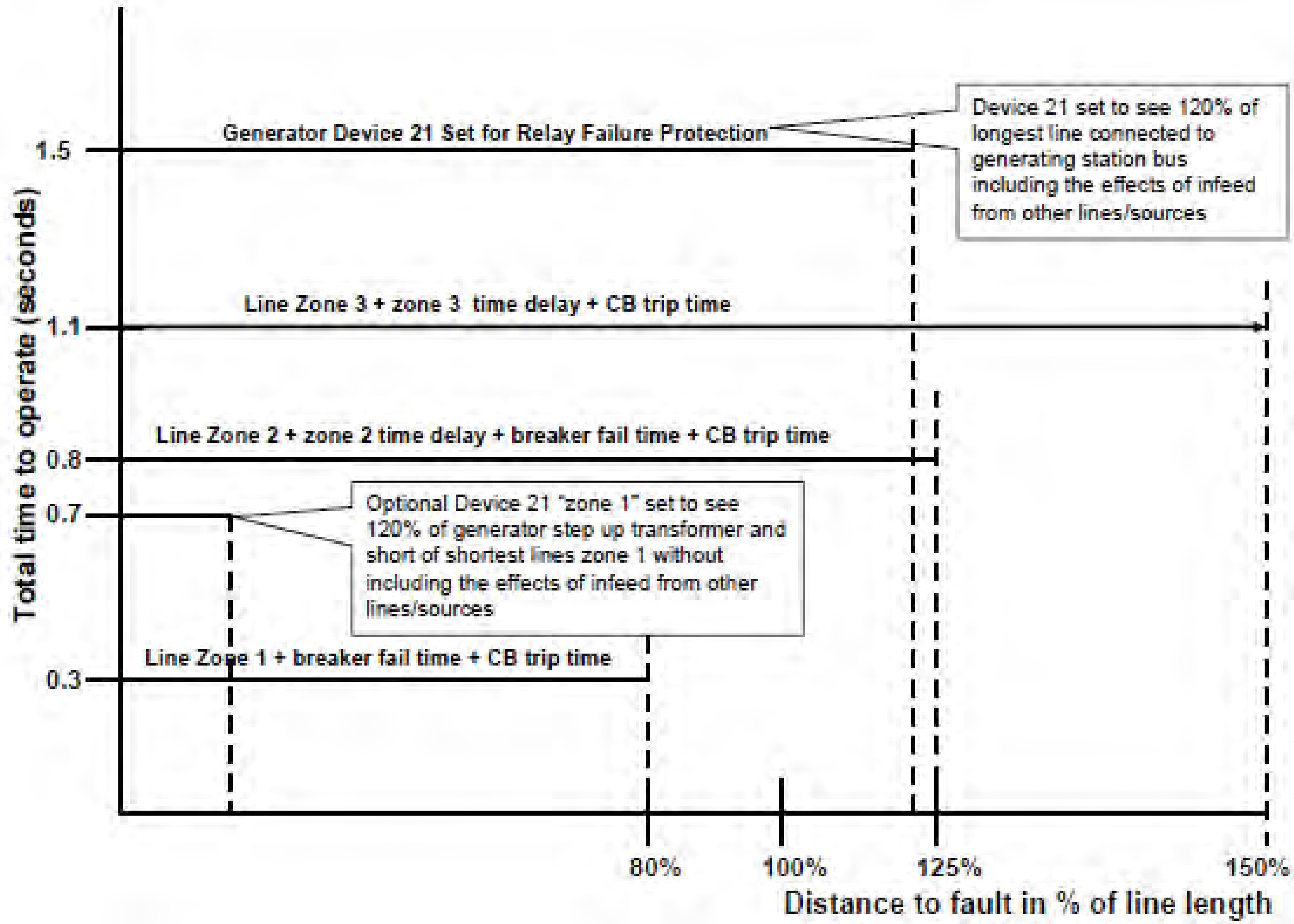
- Types of Relaying and Schemes Used
- Step Distance Principles
- Pilot and Communications
- Infeed
- Benefits of Using Pilot Schemes and Effect on Coordination Issues

Types of Relaying and Schemes Used

- Overcurrent (50, 51, 50N, 51N, 50G, 51G)
- Directional Overcurrent (67, 67N)
- Distance (21, 21N)
- Differential (87)
- Step Distance
- Pilot (Communication-Aided) Schemes

Step Distance Principles

- Zones
  - Zone 1
  - Zone 2
  - Zone 3



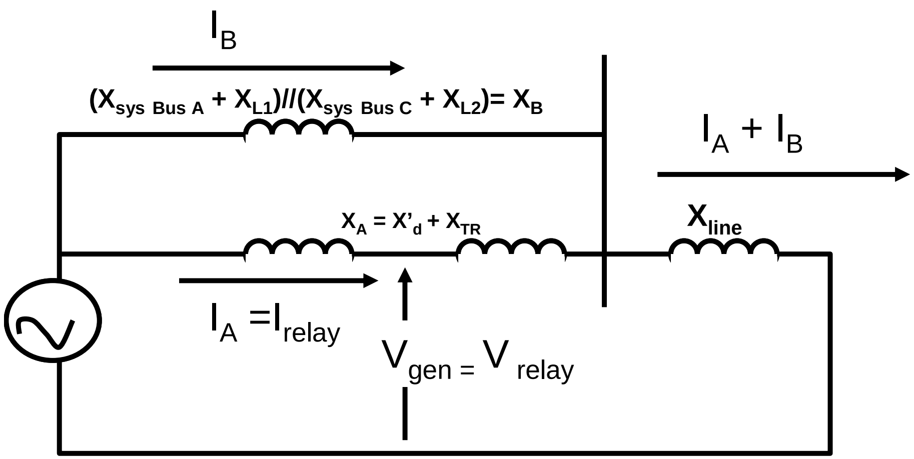
Pilot and Communications

- Pilot schemes use communication channels to send data from the local protection terminal to the remote protection terminal(s).
- This information allows high-speed tripping to occur for faults occurring on 100% of the protected line.
- General Schemes Used:
  - Transfer Trip
  - Directional Comparison
  - Current Differential
  - Phase Comparison

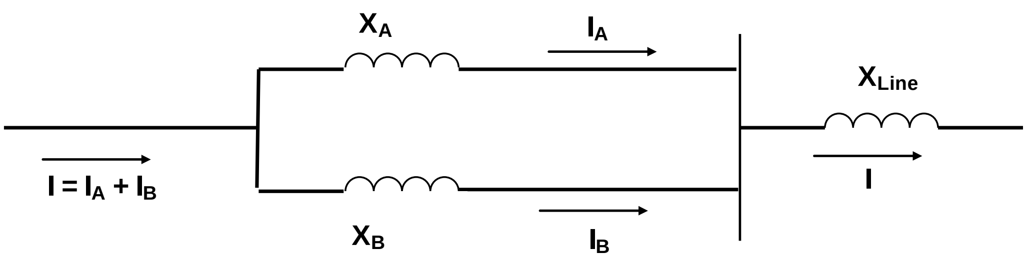
Infeed

- A source of fault current between a relay location and a fault location.
- Infeed has the effect of causing the relay to measure a higher impedance than the actual impedance between the relay and the fault location.
- The method of calculating the effect of infeed (also known as apparent impedance) is akin to a current divider relationship of two circuit paths in parallel.
  - The positive sequence equivalent diagram for the example is shown on the next slide.
  - The model combines impedances behind the faulted line.
  - The generator impedance relay measures the quotient Vgen/Irelay

Current Infeed Example Calculation



Restating I in terms of I_A and recognizing the current divider relationship of the impedance branches:



$$I_A = I\left(\frac{X_B}{X_A + X_B}\right)$$

$$I = I_A\left(\frac{X_B + X_A}{X_B}\right)$$

$$V_{Relay} = I_A X_{TR} + I_A\left(\frac{X_B + X_A}{X_B}\right)X_{Line}$$

$$I_{Relay} = I_A$$

$$Z_{Relay} = \frac{V_{Relay}}{I_{Relay}} = X_{TR} + \left(\frac{X_B + X_A}{X_B}\right)X_{Line}$$

Benefits of Using Pilot Schemes and Effect on Coordination Issues

- Provides high-speed fault clearing.
- Impacts on dependability and security are dependent on the type of Pilot Scheme implemented.
- These factors are related and require a balance.
- Power Plant to Transmission System Protection Coordination could benefit from the use of Pilot Schemes due to higher speed and more selective operation.
- Communication back to the plant system would also benefit the coordination.

Pertinent IEEE Guides for Equipment and System Protection

- IEEE Std. C37.91-2008 – IEEE Guide for Protecting Power Transformers
- IEEE Std. C37.96-2000 – IEEE Guide for AC Motor Protection
- IEEE Std. C37.101-2006 – IEEE Guide for AC Generator Ground Protection
- IEEE Std. C37.102-2006 – IEEE Guide for Generator Protection
- IEEE Std. C37.106-2005 – IEEE Guide for Abnormal Frequency Protection for Power Generating Plants
- IEEE Std C37.113-1999(R2004) – IEEE Guide for Protective Relay Applications to Transmission Lines
- IEEE Std. C37.119-2005 – Guide for Breaker Failure Protection of Power Circuit Breakers
- IEEE Std. 242-2001 – IAS Buff Book – Protection and Coordination

References

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- Patel, S. C., Chau, N. H. and Gardell, J. D., “Upgrading and Enhancing the Generator Protection System By Making Use of Digital Systems,” 24th Annual Western Protective Relay Conference Oct 21 - Oct 23, 1997.
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What is Important to Coordination – Summary

- Distance Protection – Time Coordination and Power Swings
- Overcurrent Protection – Time-Current Coordination
- Voltage Protection – Time-Voltage Coordination and stressed system voltage conditions for which the system is designed to survive
- Volts per Hertz and Frequency Protection – Coordinate with Underfrequency Load Shedding and stressed system frequency conditions for which the system is designed to survive
- Loss of Excitation and Loss of Synchronism – Coordinate with system disturbances and system power swings that are recoverable
- Generator Breaker Failure – Total and Critical Clearing Times

Question & Answer

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