Introduction to Bus Protection

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Purpose & Learning Objectives

Presentation Outline
1. *Physical Bus Types*
2. *Typical Bus Configurations*
3. *Bus Protection Methods & Schemes*
4. *High Z Bus Differential Protection*

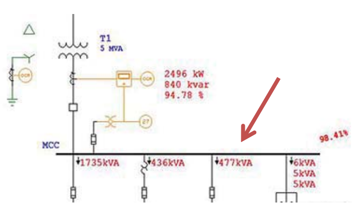
After this presentation you will be able to:
- *Identify common bus arrangements*
- *Identify and understand the operation of common bus protection schemes*
- *Understand high impedance bus differential operating principles (SEL-587Z)*

Electrical Buses

Physical and Electrical Junction

"A bus is a critical element of a power system, as it is the point of convergence of many circuits."

From IEEE Std. C37.97 *A Guide for Protective Relay Applications to Power System Buses*



Open Air Rigid Bus

- Main Components
  - Copper or aluminum conductor
  - Supporting structures
  - Post Insulators
  - Solid and/or flexible connectors
- Advantages
  - Relatively Economical
  - Simple
  - Easy to trouble shoot
  - Short repair time
  - Longer Free Spans

- Disadvantages
  - Exposure
  - Larger footprint required

Strain Bus

- Main Components
  - Flexible Conductors
  - Supporting Structures
  - Strain insulators
- Advantages
  - Small footprint
  - Simplicity
  - Very Economical
  - Short repair time

- Disadvantages
  - Lower reliability
  - Exposure
  - Conductor spacing and capacity

Isolated-Phase Bus

- Main components:
  - Ridged center conductor
  - Supporting insulators
  - Air dielectric
  - Bushings at termination points
  - External supporting structures
- Advantages
  - Higher reliability
  - Protected
  - Smaller conductor spacing
  - Forced air cooling possible

- Disadvantages
  - High cost
  - Long repair time
  - Expensive

Gas Insulated Bus

- Main components:
  - Ridged center conductor
  - Supporting insulators
  - Insulating gas
  - Bushings at termination points
  - External supporting structures
- Advantages
  - Higher reliability
  - Protected
  - Very small corridor

- Disadvantages
  - High cost
  - Difficult troubleshooting
  - Long repair time

Indoor Switchgear Bus

- Main Components
  - Aluminum or copper conductor
  - Solid Connectors
  - Supporting Insulators
- Advantages
  - Versatile
  - Small footprint
  - Protected
- Disadvantages
  - Confined space

Importance of Bus Protection

Bus Fault Characteristics

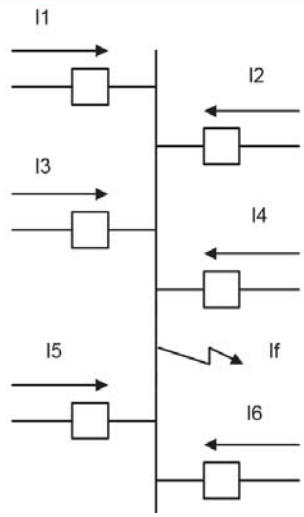
- Not very common

When they do occur:

- Usually bolted faults
- Higher fault magnitudes

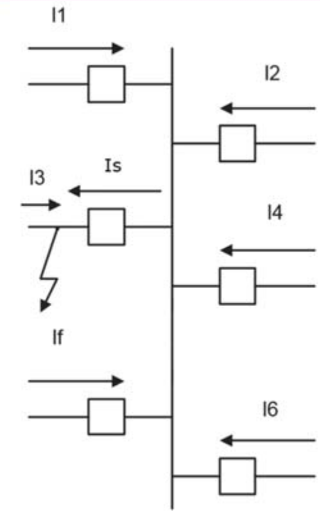
Bus Fault Impact:

- All bus circuits must be interrupted
- Can result in severe system disturbances



Bus Protection Philosophy

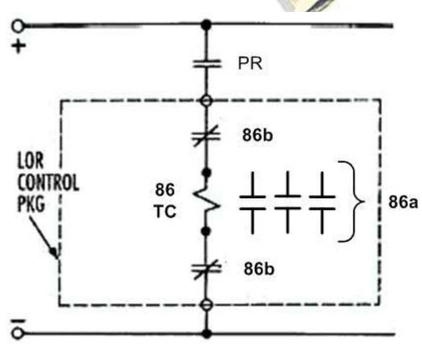
- Dedicated protection
- High speed operation for internal faults
- Two-out-of-two trip criteria
- Optional redundant protection scheme
- Remote backup protection
- Time overcurrent protection
- Security for out-of-zone faults
- Sensitivity for minimum internal faults



Bus Lockout Relays

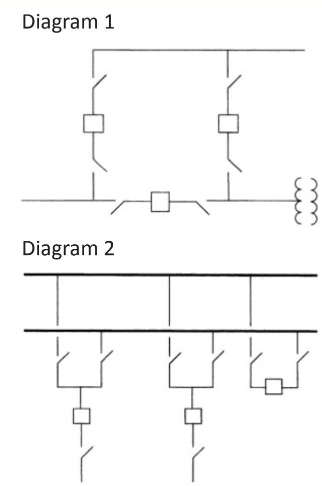
Principle and Operation

- Trips and lockouts the bus breakers
- Many output contacts
- Operation isolates its trip coil
- Very fast operation
- Hardwired to breaker trip circuits
- Can be used to protect relay contacts



Bus Sectionalizing

- Improves system reliability
- Minimizes Impact of Outages
- Utilizes Various Arrangements
  - Combined Arrangements
  - Operating Flexibility
  - Selectivity
  - Bus protection must adapt



Single Bus – Single Breaker

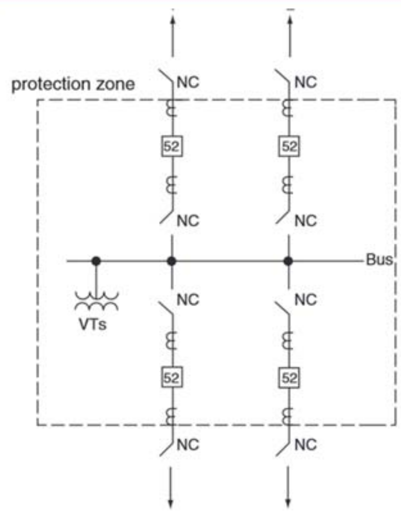
One of the most basic and economical designs

No operating flexibility

No selectivity

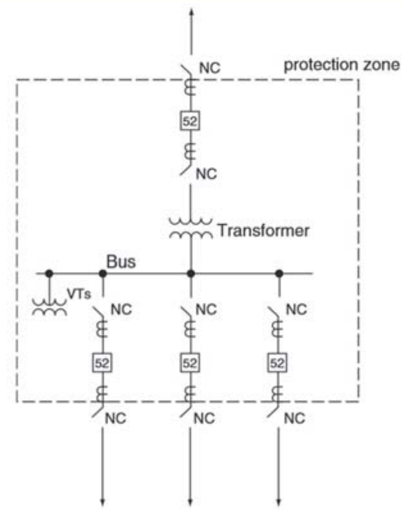
Zone of Protection
- Encompasses the whole bus

Bus fault will interrupt all associated services



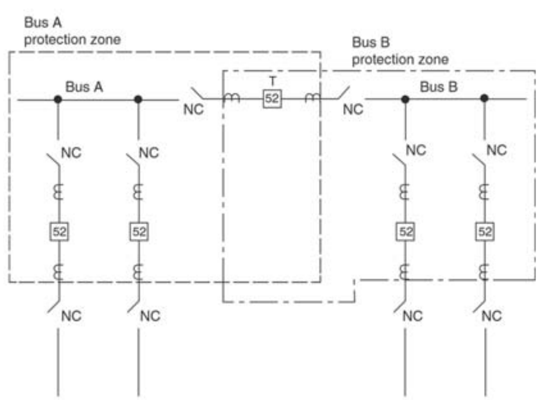
Bus & Transformer – Single Breaker

- Zone of Protection:
  – Bus and Transformer protection is combined
- Usually used in distribution substations
- No selectivity
- No flexibility
- Fault location difficulty
- Very economical



Double Bus w/Bus Tie – Single Breaker

- Zone of Protection:
  - Bus A and Bus B have independent and dedicated protection
- Little Flexibility
- Some Selectivity



Main & Transfer Bus – Single Breaker

Breaker substitution

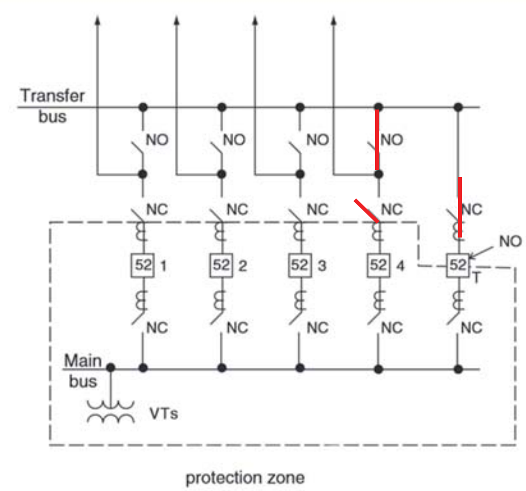
Zone of Protection
Encompasses main bus only

Transfer bus protection provided by transfer breaker

No selectivity

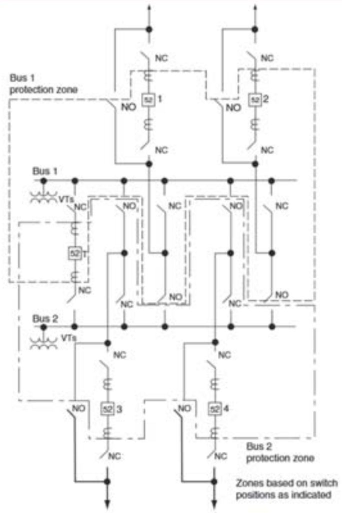
Flexibility increases

Often Combined



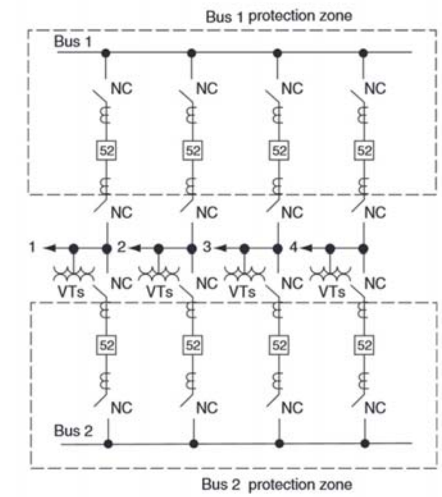
Double Bus – Single Breaker

- Zone of Protection:
  - Bus 1 and Bus 2 have independent protection assigned based on switching condition
- Lots of operating flexibility
- Some selectivity
- Complex switching
- CT winding assignments change
- Not commonly used in the U.S.



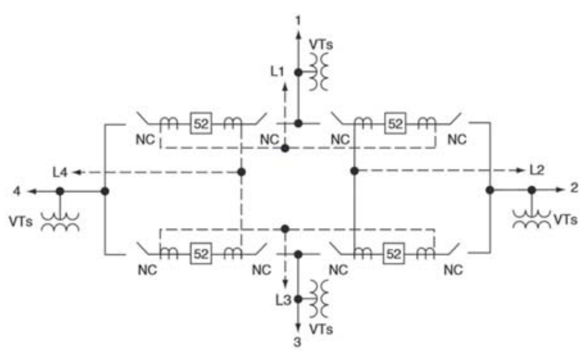
Double Bus – Double Breaker

- Zone of Protection:
  - Bus 1 and Bus 2 have independent protection
- Full operating flexibility
- Improved Selectivity
- Increased cost
- Very common



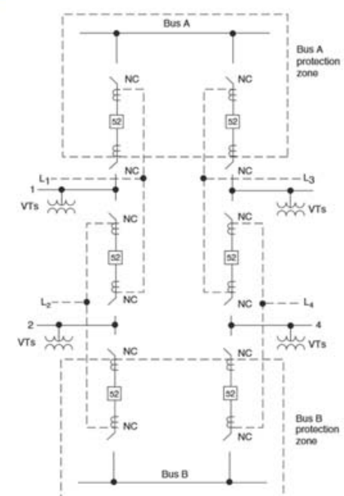
Ring Bus

- No dedicated bus protection
- Full operating flexibility
- Good selectivity
- Shared breakers
- Economical



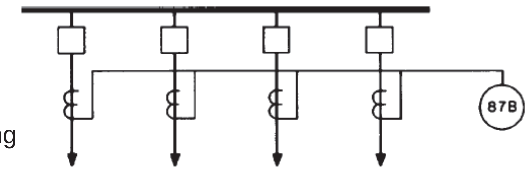
Breaker-And-A-Half Bus

- Full operating flexibility
- Excellent selectivity
- Widely used
- Zone of Protection:
  - Bus A and Bus B have independent and dedicated protection zones.
- Line position protection provided by branch circuits
- Economical



Differential Overcurrent

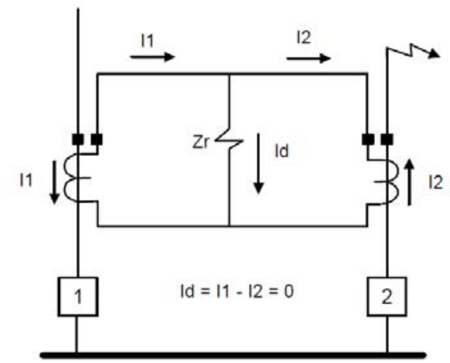
- CT secondary leads summed out side the relay
- Identical Tap ratios
- CT matching
- Difference Current using 51/50 elements
- Time delayed
  - Avoid misoperation due to transient saturation



Differential Overcurrent (continued)

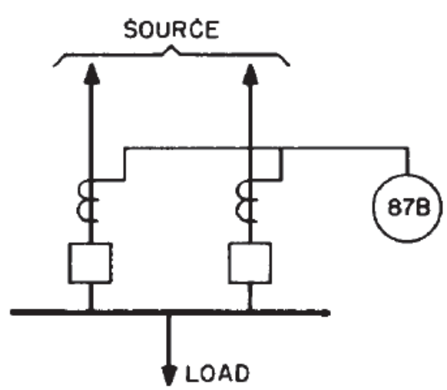
Advantages
- Economical

Disadvantages
- Security
- Strong sources
- Time-delayed clearing
- Difficult to set properly
- Not suitable in areas of system with high X/R ratio



Partial Bus Differential

Operating Principles:
- Source CT leads summed outside relay
- Tie breaker CTs included
- Overcurrent element
- Pickup set above load
- Selectivity required
- Optional: Distance elements

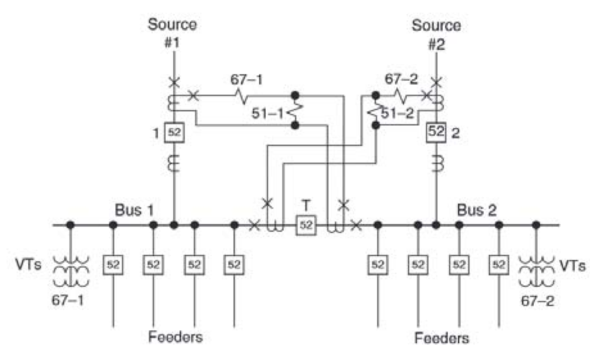


Partial Bus Differential (Continued)

Partial Bus Differential (Continued)

Advantages:
- Very economical

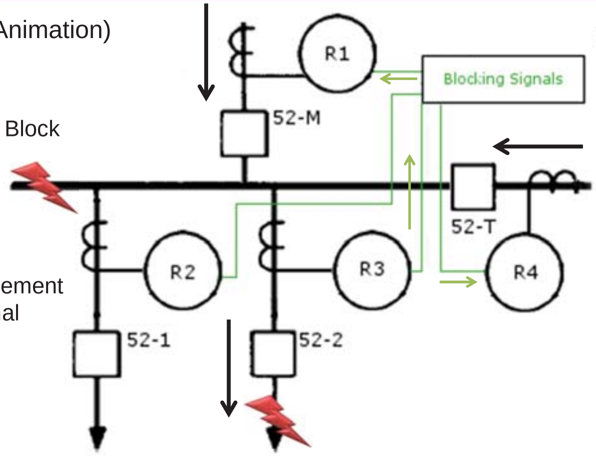
Disadvantages:
- Fault Current/FLA
- Required selectivity
- Reduced sensitivity
- Used with radial circuits

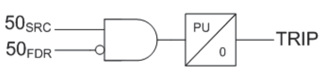


Zone Interlock Scheme (Fast Bus Tripping)

Operating Principle: (Animation)

- Source circuit(s)
  - Time delayed
  - Receives/Sends Block Signal
  - Directionality
- Radial circuit(s)
  - Instantaneous element sends block signal
- Communication





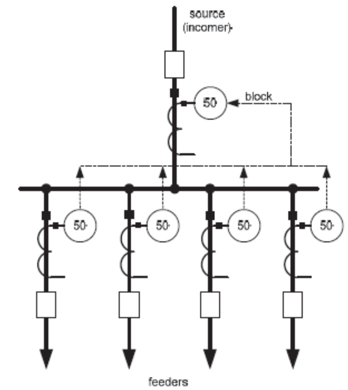
Zone Interlock Scheme (Continued)

Advantages:

- Fast compared to inverse-time OC elements
- Relatively economical

Disadvantages:

- Requires Communication Scheme
- Security against CT Saturation
- Slower than high-Z or percentage-restraint schemes



Directional Comparison

Operating Principle:

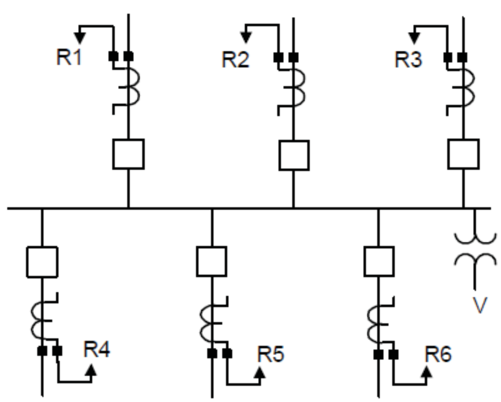
- Distance Elements

Advantages

- Relatively Economical
- Few CT constraints

Disadvantages

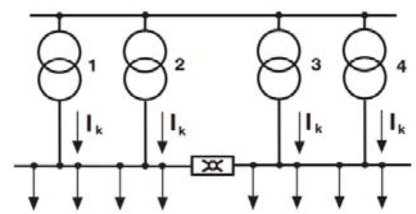
- Voltage Reference
- Multiple Failure Points

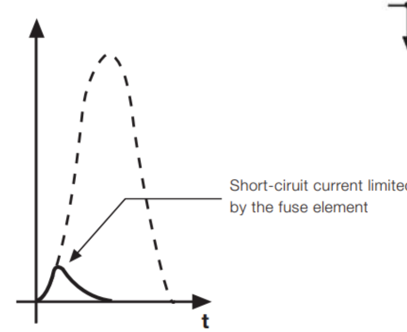


High Current Interruption & Limiting

Fuses & Short Circuit Limiters

- High Interrupt rating
- IS limiter operates in less than 1ms





Advantages

- Extremely High Speed

Disadvantages

- Replacements needed with fusible interrupters

Arc Flash Protection

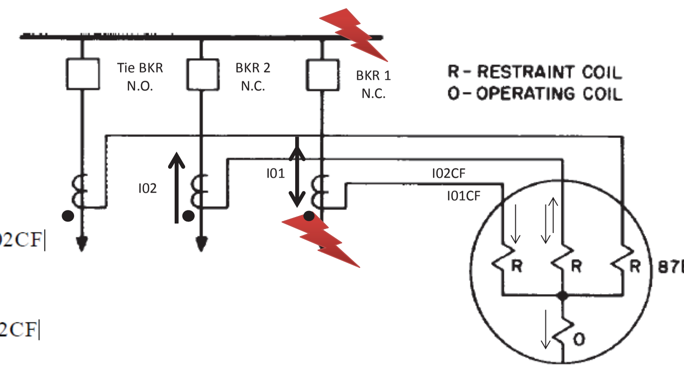
Optical Sensors
- Fiber optic sensors or loops
- Indoor Switchgear

Advantages
- Relatively Economical
- Extremely High Speed

Disadvantages
- Supervision with optical

Percentage Restrained Differential

Operating Principle: (Animation)
- Relay measures difference and restraint quantities
- Trip if difference current exceeds a set percentage of the restraining quantity

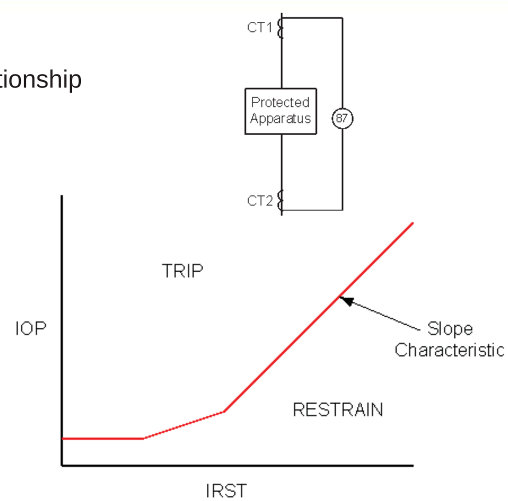


$$IRT1 = |I01CF| + |I02CF|$$

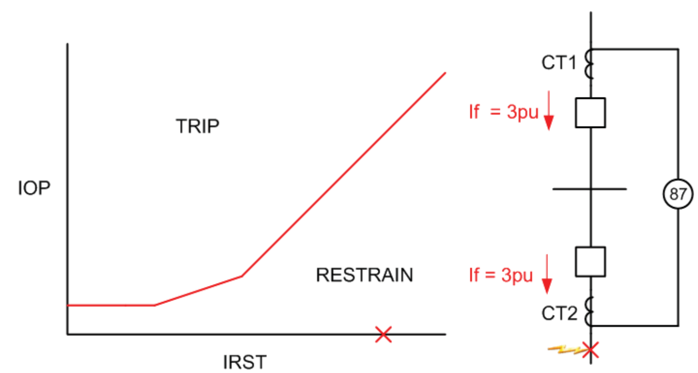
$$IOP1 = |I01CF + I02CF|$$

Percentage Restrained Differential (Continued)

- Operate vs. Restraint Relationship
- Slope Setting
- Controlling Factors
  - CT Performance
  - X/R Ratio
  - Fault Magnitude
- Duel Slop Characteristic



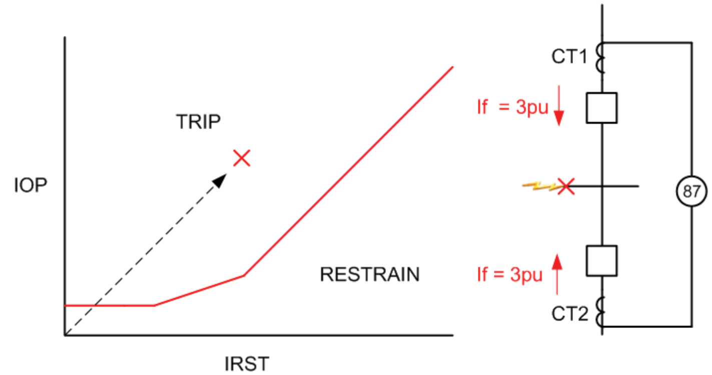
Percentage Restrained Differential (Continued)



IRST = |3| + |3| = 6

IOP = |3 + (-3)| = 0

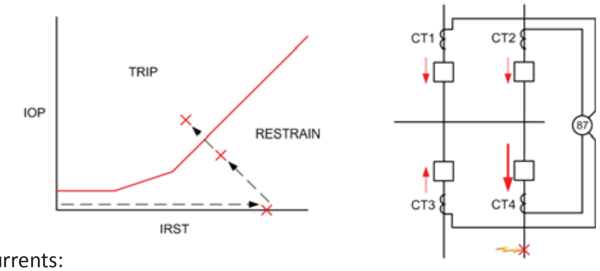
Percentage Restrained Differential (Continued)



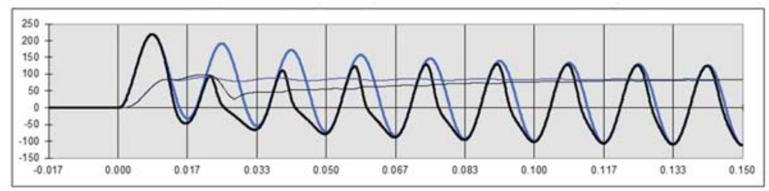
IRST = |3| + |3| = 6

IOP = |3 + 3| = 6

Percentage Restrained Differential (Continued)

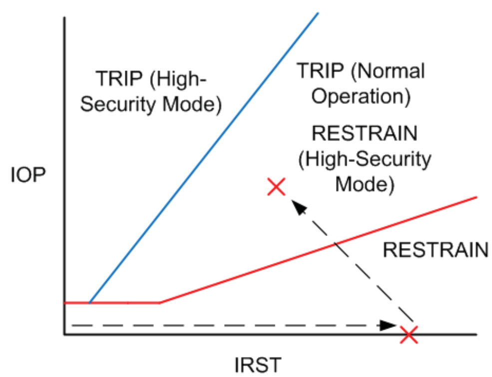


CT4 Currents:



Percentage Restrained Differential (Continued)

- Relay constantly monitors changes in operate and restraint currents
- Increase in restraint without an increase in operate current indicates external fault
  - Relay enters high-security mode
- Only requires short period (~2-4ms) of unsaturated operation



Percentage Restrained Differential (Continued)

Settings Considerations

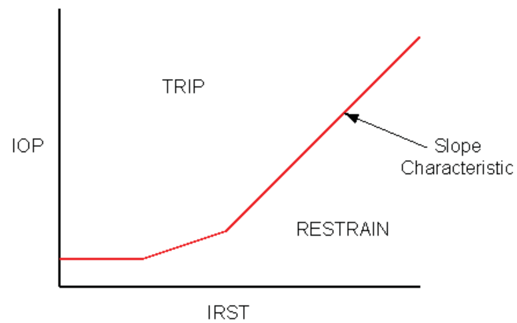
- Minimum pickup must be greater than error difference current, but less than minimum available fault current
  - Typically set to 1pu of bus continuous rating on solid-grounded systems
  - Lower pickups used on impedance-grounded systems
- Slope settings
  - Withstand measurement errors at low currents
  - Withstand saturation-induced errors at high currents
- Modern relays with adaptive an slope characteristic provide enhanced security and sensitivity

Percentage Restrained Differential (Continued)

Advantages:
- Fast Operation
- Good security

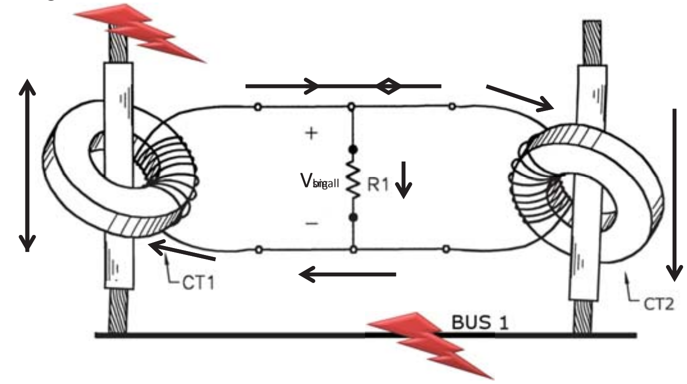
Disadvantages:
- CT criteria and performance critical
- May require many relay current inputs
- Sensitivity—High Z Grounded Systems

IOP = |I1 + I2|
IRST = |I1| + |I2|



High Impedance Bus (Voltage) Differential

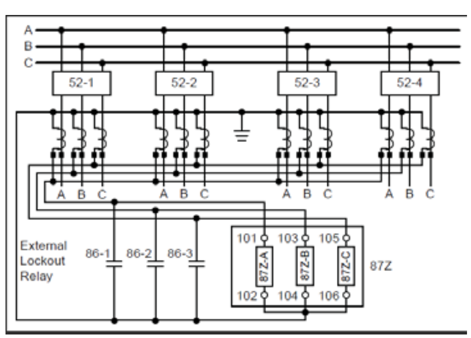
Introduction and Basic Concept (Animation)
- Popular Bus Protection Scheme
- Arc Flash Mitigation



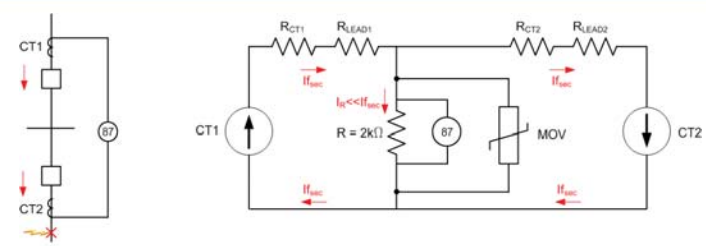
High Impedance Bus Differential (Continued)

Characteristics and Typical Application Layout

- CTs connected in parallel with high-impedance relay input
- Relay operates on voltage across high-impedance inputs
- Can accommodate a large number of terminals
- Excellent sensitivity and speed
- Simple element to configure



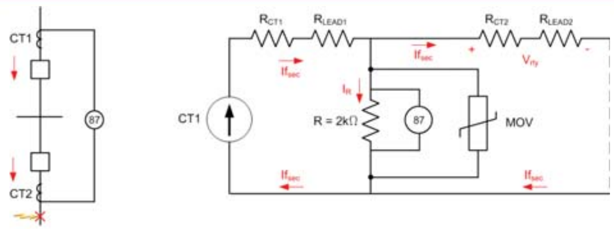
High Impedance Bus Differential (Continued)



External Fault (or typical loading) Case:

- Current circulates between CTs
- Negligible current flow through high-impedance relay input (high resistance/burden path)

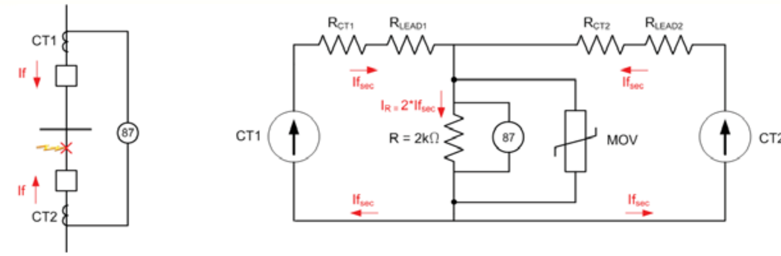
High Impedance Bus Differential (Continued)



Worst-Case External Fault:

- CT2 completely saturates (does not supply any representative secondary current waveform)
- High impedance input sees voltage developed by secondary current flowing through CT winding resistance and lead resistance
- Element pickup must be set greater than this voltage (typically by a factor of 1.5 to 2) for security

High Impedance Bus Differential (Continued)

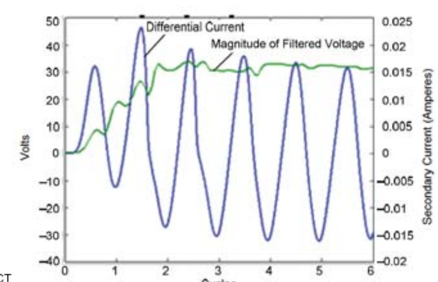


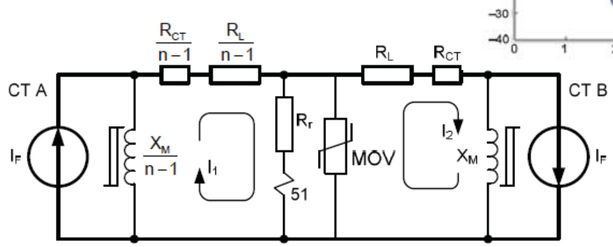
Internal Fault Case:

- Current flows through stabilizing resistor and produces high secondary voltages
- Voltage magnitude limited by MOV
  - LOR ‘a’ contacts required across high-impedance input
- CTs produce current and secondary voltage until they saturate

High Impedance Bus Differential (Continued)

- Stabilizing resistor
- MOV protects element
- Bus LOR required

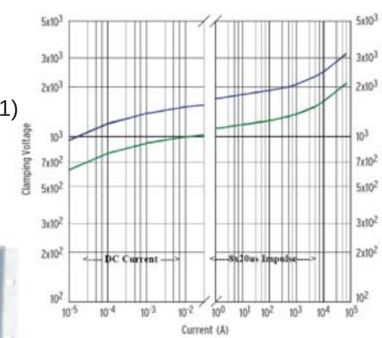




High Impedance Bus Differential (Continued)

- SEL 587Z Relay
- Uses a 2000Ω resistor
- MOV size options
- SEL Recommended Settings (Per AN2008-01)
  - Vs setting of 200V
  - Optional Time Delayed Setting

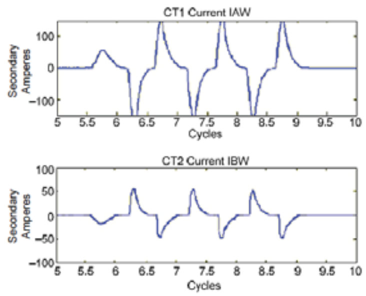
Cutaway view showing stabilizing resistors and MOVs.

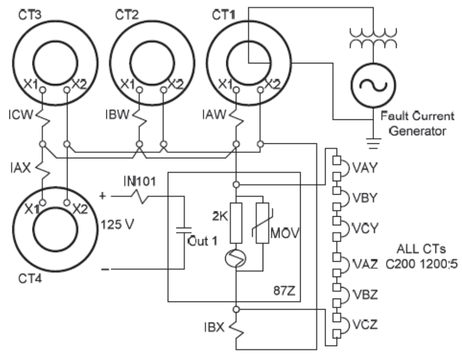


High Impedance Bus Differential (Continued)

Manufacturer Internal Fault Testing

- Test currents of 20 kA, 40 kA and 60 kA applied.
- Heavy CT saturation observed

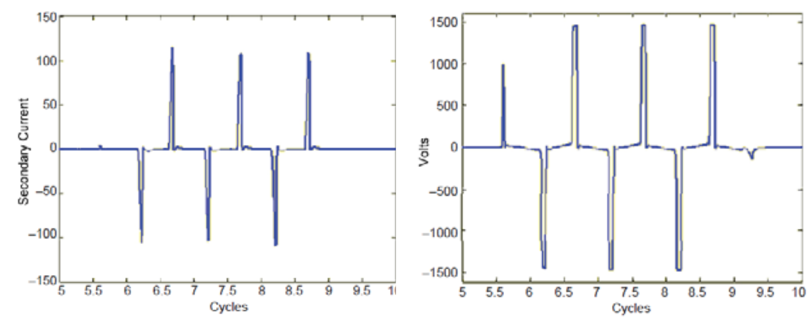




High Impedance Bus Differential (Continued)

Waveforms obtained from manufacturer testing

- Differential current and voltage waveforms
- Note the voltage is limited to 1500V by the internal MOV
- C200 1200:5 CTs, 60 kA internal fault

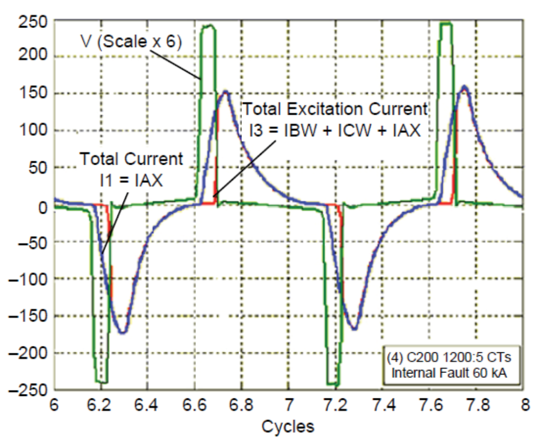


High Impedance Bus Differential (Continued)

60 kA Internal Fault Test

1. CT Voltage (Green)
2. Total Current (Blue)
3. Excitation Current (Red)

- Resistor vs. Magnetizing Current
- The volt-time area

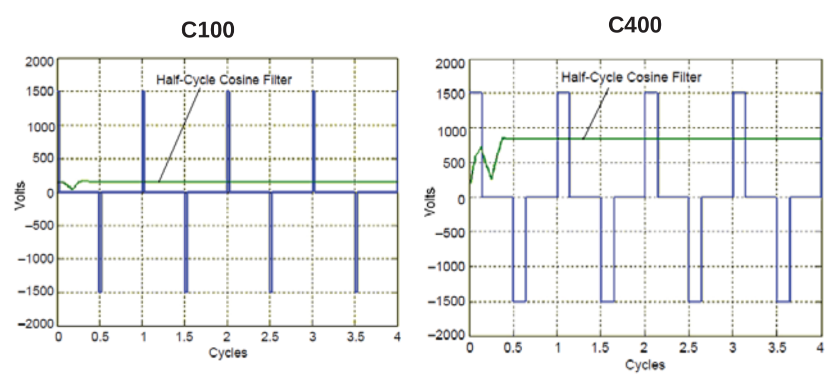


High Impedance Bus Differential (Continued)

Volt-time area proportional to C-rating

Dictated by lowest-rated CT in differential circuit

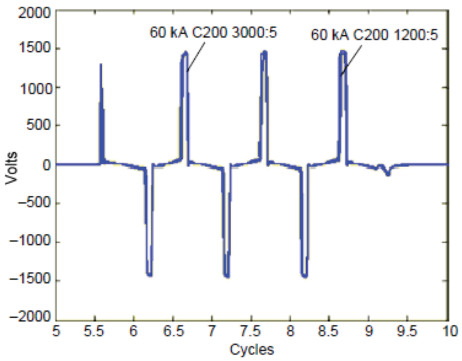
SEL recommends at least a C200 CT



High Impedance Bus Differential (Continued)

Volt-time area is similar for CTs with equivalent C-rating, even if ratios are different

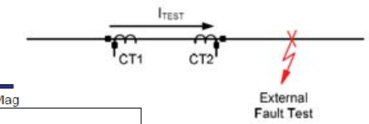
Maximum voltage limited by MOV

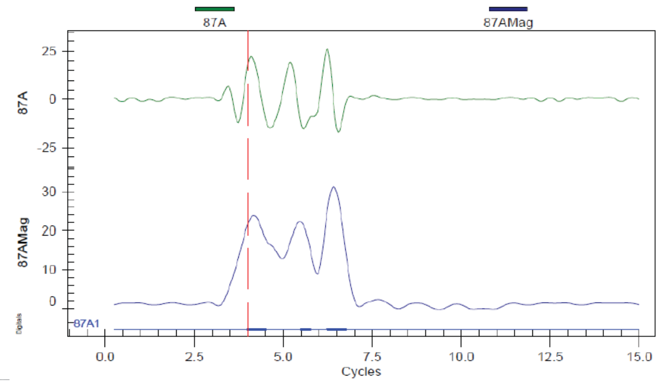


High Impedance Bus Differential (Continued)

Manufacturer External Fault Testing Results

- Fault currents of 20 kA, 40 kA and 60 kA.

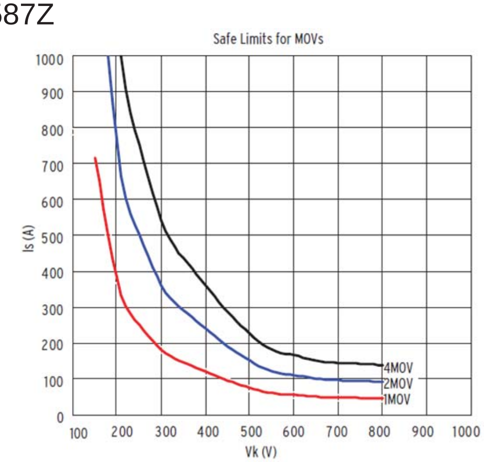




High Impedance Bus Differential (Continued)

MOV Sizing for SEL-587Z

- MOV requirements based on energy dissipation limits for 4-cycle duration
    - Requires 86 “a” contacts wired across relay inputs!
- Energy rating is a functior of knee-point voltage and maximum secondary current



High Impedance Bus Differential (Continued)

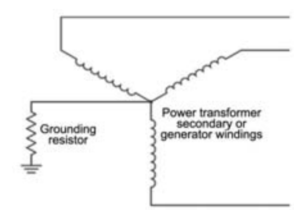
Manufacturer Testing Results for SEL-587Z

Recommended High-Value Setting:

- 200V with no time delay
- Sensitive and Secure

Optional Recommendations For Low-Value Setting:

- Only needed in some applications (e.g. HRG/LRG)
- Minimum sensitivity calculations
- Implement a time delay (min 1 cycle).



High Impedance Bus Differential (Continued)

Secure Voltage Setting Calculation

- Sensitivity impacted by wiring design
- Worst-case out-of-zone fault condition
- Relay pickup set to a multiple of V_r

$$V_r = (R_{CT} + P \bullet R_{LEAD}) \bullet \frac{I_F}{N}$$

V_r = voltage across the high-impedance element
I_F = maximum external fault current
N = CT ratio
R_{CT} = the CT secondary winding and lead resistance up to the CT terminals
R_{LEAD} = the one-way resistance of lead from junction points to the most distant CT
P = 1 for three-phase faults and 2 for single-phase-to-ground faults

High Impedance Bus Differential (Continued)

Minimum Sensitivity Calculation

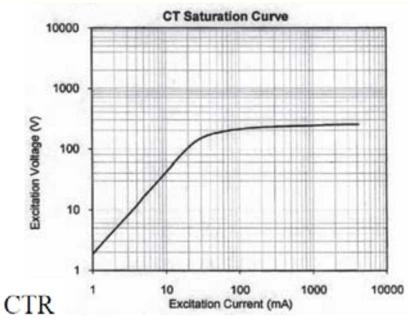
- Verify for Internal Fault
- Ignore MOV leakage current
- Use CT Excitation Characteristic
  - When Vs < knee point voltage:

$$I_{min} = (n \bullet I_e + I_r + I_m) \bullet N$$

  - When Vs > knee point voltage:

$$I_{MIN} = \left[n \bullet \left(I_e @ \tfrac{V_S}{2} \right) \bullet 2 + I_R @ V_S \right] \bullet CTR$$

I_{min} = minimum current
n = number of current transformers in parallel with the relay, per single phase
I_e = current transformer exciting current at relay setting voltage = V_s
I_r = current through the relay at relay setting voltage = V_s
I_m = current through the MOV at relay setting voltage = V_s



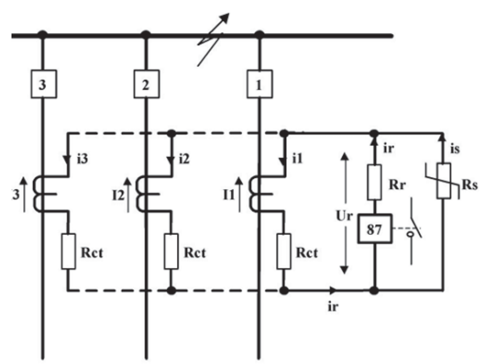
High Impedance Bus Differential (Conclusion)

Advantages:

- Very fast operation
- High security
- Incorporates large number of terminals

Disadvantages:

- Sensitivity decreases as number of CTs and/or lead lengths increases
- Must use CTs with C200 rating or greater
- Complexities associated with mixed-ratio CTs



Summary

- Bus protection is critical
- Bus Sectionalizing
  – Operating flexibility
  – Selectivity
- Bus Protection Schemes
  – Wide variety of schemes available based on application
    - Criticality
    - Available fault current & X/R ratio
    - Sensitivity/Speed Requirements
    - CT availability

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- *Basler Electric Company, Bus Protective Relaying, Methods and Application, Revision Date: 6-8-2005*
- *General Electric Company, Bus Differential Protection, WPRC 1995, GER-3961*
- *Zocholl, E. Stanley and Costello, David, Schweitzer Engineering Laboratories, Inc., Application Guidelines for Microprocessor-Based, High-Impedance Bus Differential Relays*
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Thank you for your time!

This concludes the educational content of this activity.

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QUESTIONS?

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