

Performance of Relaying During Wide-area Stressed Conditions



IEEE Power Systems Relaying Committee
C12 Working Group Report
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C12 WG Report Organization

- Description and detailed analysis of causes that lead to wide area disturbance
- Relay behavior under stressed conditions
- Field experience and examples
- **Solutions** to mitigate undesired operations.
- Report available on the PSRC website:

<http://www.pes-psrc.org/>

Blackouts

- Increase in frequency of major, costly, blackouts since '94
- Power system is very complex and man-made
 - General understanding of blackouts caused by natural disasters
 - Human created system-wide outages should be preventable – Blackouts are symptoms (result?) of our decisions
- Analysis of disturbances reveals some common threads:
 - Protection equipment has had major impact on disturbance propagation: Address solutions to prevent propagation!
 - Propagation of the blackout can be arrested
 - Restoration time can be reduced
- It is not possible to avoid multiple contingency initiated blackouts, however:

The probability, size and impact of wide area blackouts can be reduced!

Undesired/ Unexpected Relay Operation During a Disturbance

- Sometimes contributes to the propagation.
Aug. 14, 2003 - Overreaching zone (Z3) operation on one 345 kV line tripped first followed by 14 line trips on over-reaching Zones.
- Sometimes prevents further propagation of a disturbance.
Island created during disturbance survived-
(New England and the Maritime provinces).

Factors Influencing Relay Performance During a Wide Area Disturbance

- Conditions not considered in the relay settings criteria – Multiple contingencies, severe overload condition, system voltage and frequency excursions beyond the normal operating range.
- Hidden failures in the scheme.

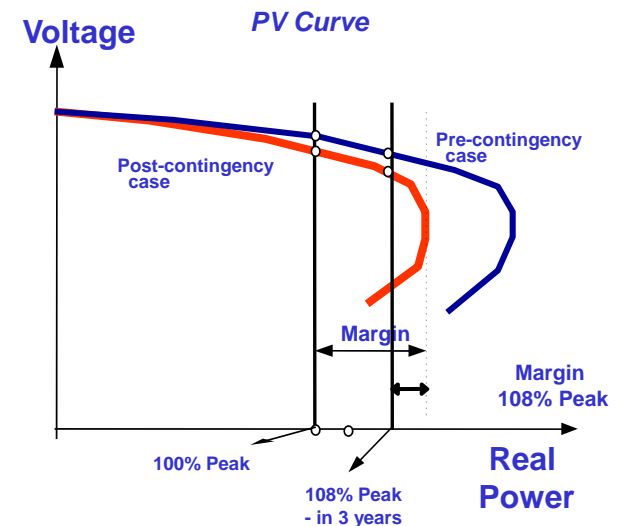
Causes of Wide Area Disturbance

Involves a combination of:

- Voltage instability/ voltage collapse
- Angular instability
- Voltage/ Frequency excursions
- Small Signal Instability
- High equipment loading and high power transfers;
High system unbalance

Voltage Instability

- Inability to maintain voltage so that both power and voltage are controllable
 - Typical scenario: high system loading, followed by a fault, line overload or generators hitting an excitation limit
 - Grid overloads, more reactive power consumed and voltages drop
 - Followed by motors stalling at lower voltages
- How the system gets to the “knee point”
 - Continuous load growth
 - Generator hits the reactive limit and the PV curve shifts
 - Contingency causes the “knee point” to shift to a lower critical load value

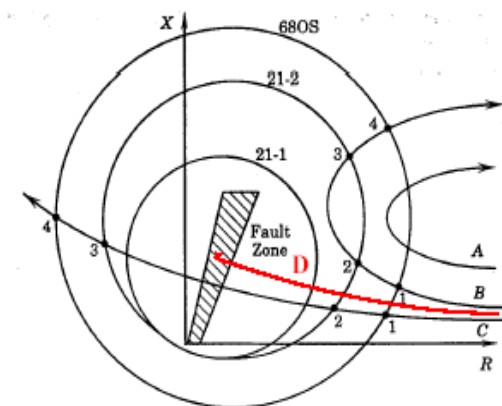
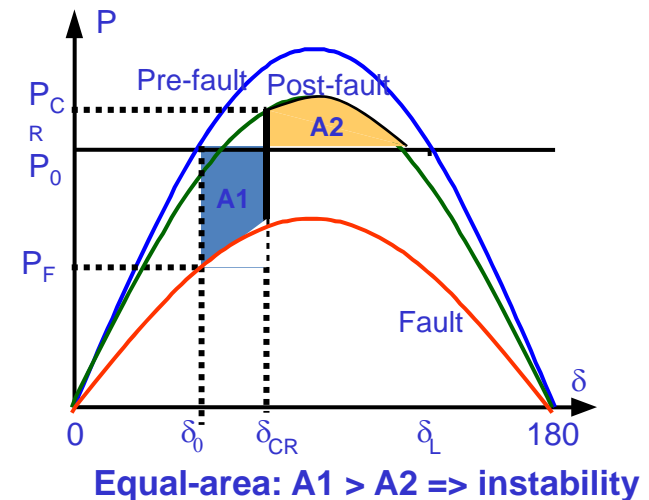


Voltage Excursions

- Fluctuations beyond the accepted operating range.
- Can occur due to heavy loads, sudden loss of load, Motor Starting, Switching operations capacitor/ reactors.
- More controllable than Voltage instability/collapse.
- Long term variations – several minutes.
- Short term – 10-20 ms or few cycles; Excursions are typically larger than long term variations such as those during faults.

Transient Angular Instability

- Caused by the rotor dynamics of generators when they accelerate at different speeds
- Out-of-Step Relaying
 - Do not trip on recoverable swings
 - Separate the out of step segments
 - Separate to match generation and load
- Detailed stability studies required
- Detecting the multi-area out-of-step may be required



Small Signal Instability

- Inability of power system to restore a state of equilibrium following a small disturbance.
- Primarily due to Generator rotors swinging relative to one another.
 - 0.1-1 HZ between inter-area.
 - 1-2 HZ - local plant mode.
- Undamped oscillations can reach control limits or result in protective relay operation.
- Power System Stabilizers (PSS) offset negative damping and supplement excitation control.

High Equipment Loading and High Power Transfers

- Stressed conditions often occur at or near the system peak load.
- This could be poor power factor loads generating high current flow through equipment.
- High temperatures may result in conductor sag and insulation failures propagating the disturbance.

Cold Load Pickup

- Loss of load diversity after a long outage.
- Cold load pick up is the inrush current during restoration of load.
- Inrush current could be several times the normal load.
- Can cause overcurrent relay operation.

Frequency Excursion

- Occurs due to imbalance of generation and load.
- Caused by variation in load or generation; system faults or line switching.
- Excessive load causes decline in frequency.
- Excessive generation causes increase in frequency.

High System Unbalance

- Current Unbalance due to asymmetry of transmission line configurations – Ex.- untransposed lines.
- Heavy loading generates neg. seq. current as high as 15% and zero seq. current as high as 10% of the pos. seq. current.
- During single pole tripping conditions.

Protection Behavior During Stressed Conditions

The report addresses issues with the following:

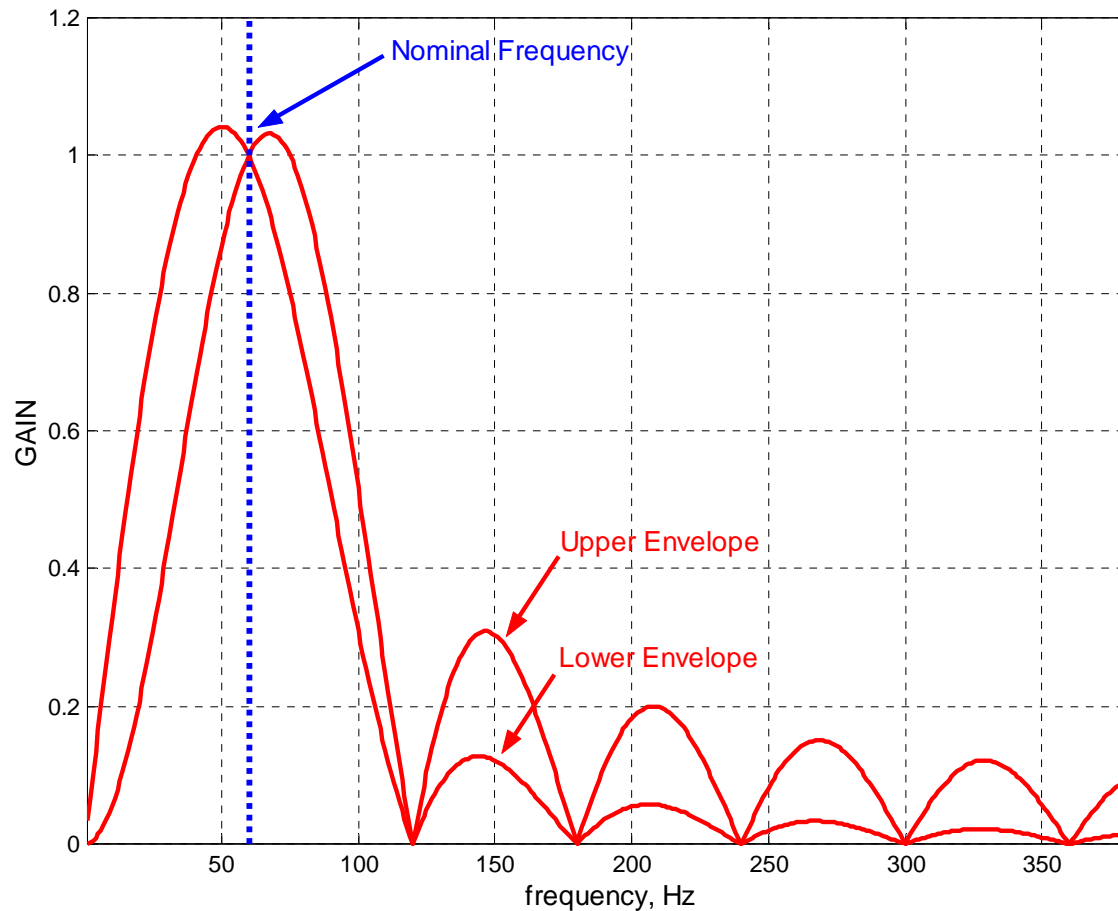
- Transmission line protection
- Transformer protection
- Generator Protection
- Bus Protection
- Shunt Reactor/ Capacitor Protection
- Feeder Protection
- Motor Protection

Impact of Frequency Excursion

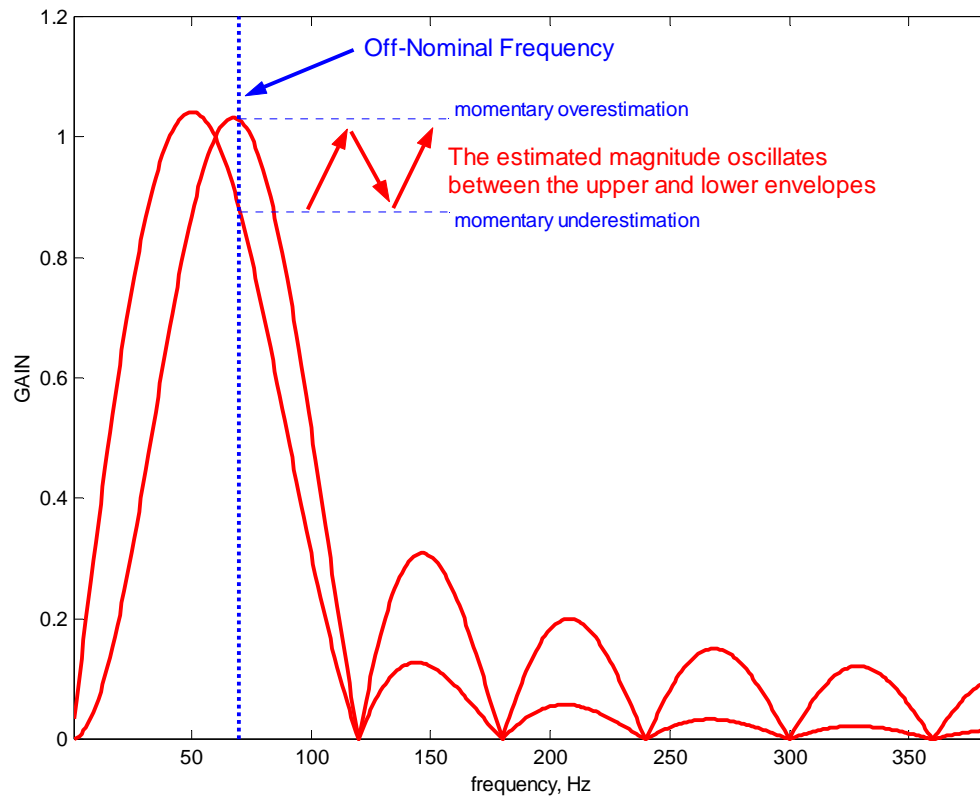
Off –nominal frequency operation affects most of the microprocessor-based relays.

- Relays make use of fundamental frequency components for their protection function.
- Phasor estimation techniques in Microprocessor-based relays work well at nominal frequency.

Frequency Response of the Full-cycle Fourier Phasor Estimator



Phasor Estimation- Off-nominal Frequency Response



- Frequency Tracking algorithms are slow/ may stop tracking during a disturbance.
- Effect on Current differential schemes are inconsequential.

Transmission Line Protection

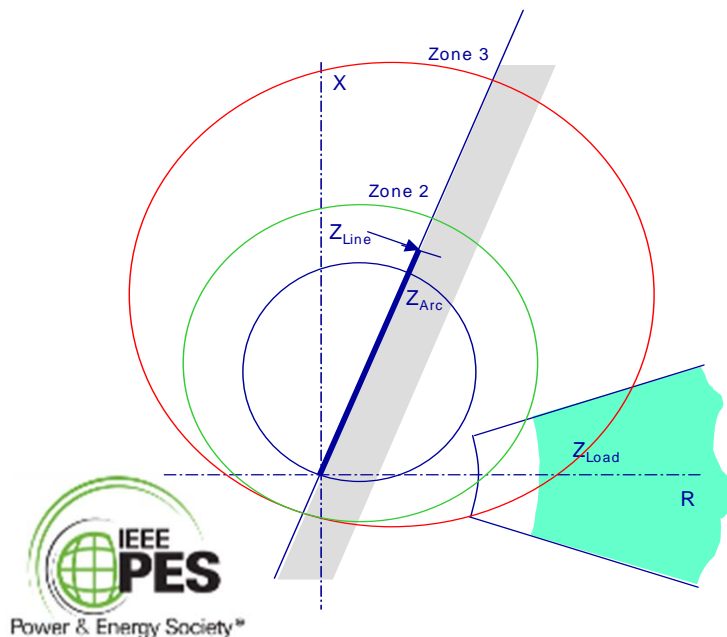
Distance or Current differential/comparison scheme.

Relay may operate for faults outside the protected zone or its intended application

- Power swings
- Heavy loads.
- Frequency excursion
- Voltage instability
- Combination of the above

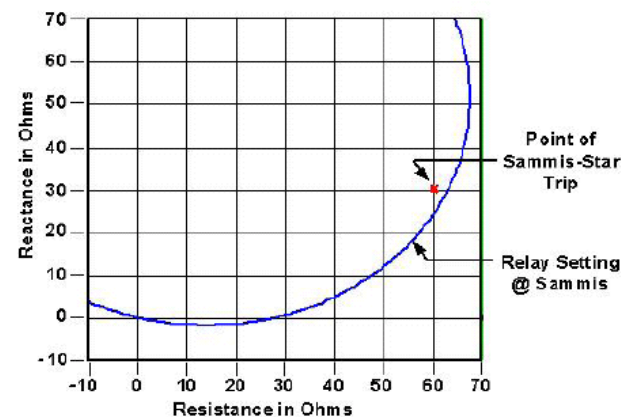
Heavy Overloads

- May result in faults lines sagging into trees or equipment damage
- Distance relays pick up if overloads not relieved - Zone 3 tripping as Relay detects this as three phase fault
- Thermal line protection, usually not widely used in the US

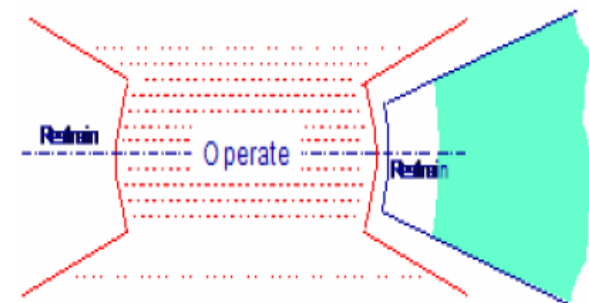
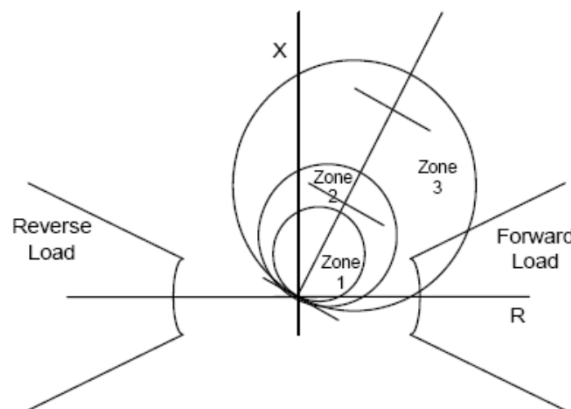
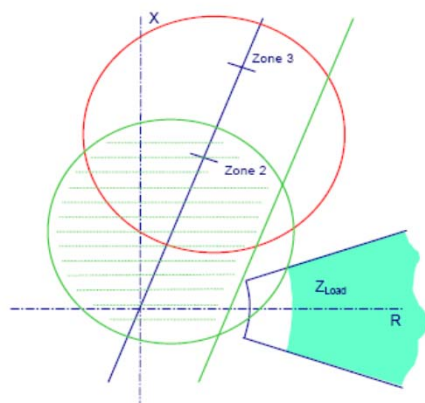


NORTH AMERICAN ELECTRIC RELIABILITY COUNCIL

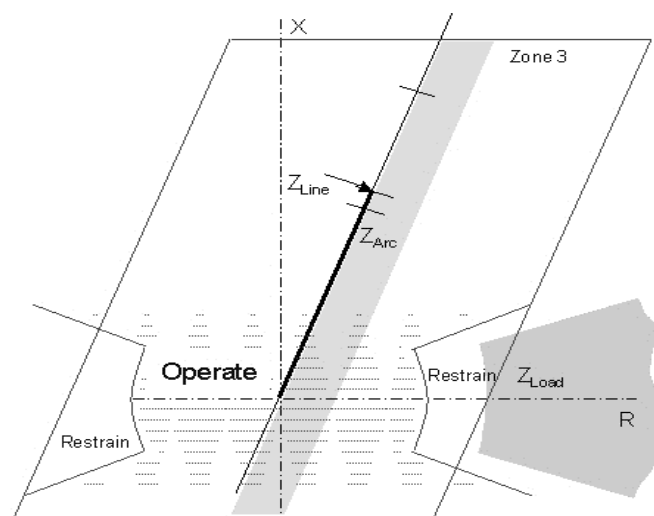
Sammis-Star Zone 3 Relay Operates on Steady State Overload



Load Encroachment Logic



Methods Available
to prevent relay
operation for loads



Zone 3 Summary

- Zone 3 cannot be arbitrarily removed without reviewing concrete protection applications and alternatives
- Protection Applications and Settings Should not interfere with Operation
 - Conductor Thermal Ratings, Sagging, and Re-rating
- New installations or upgrades using microprocessor relays can minimize effects of load encroachment
- Where conflict between impedance set points and load encroachment use alternative protection methods
 - Direct Transfer Trip
 - Line differential relays
- Use of adaptive protection or multi-setting groups

Power Swing Detection and Application of Relays

- Slow Variation of Voltage and current instead of a step change during faults.
- Three phase balanced phenomenon.
- Power swings may cause unwanted Relay operations at locations that can lead to cascading outages.
- Relay applications on transmission lines for power swing blocking and out of step conditions are covered in depth in the report produced by IEEE PSRC after August 14, 2003 event. Available on line at <http://www.pes-psrc.org/>

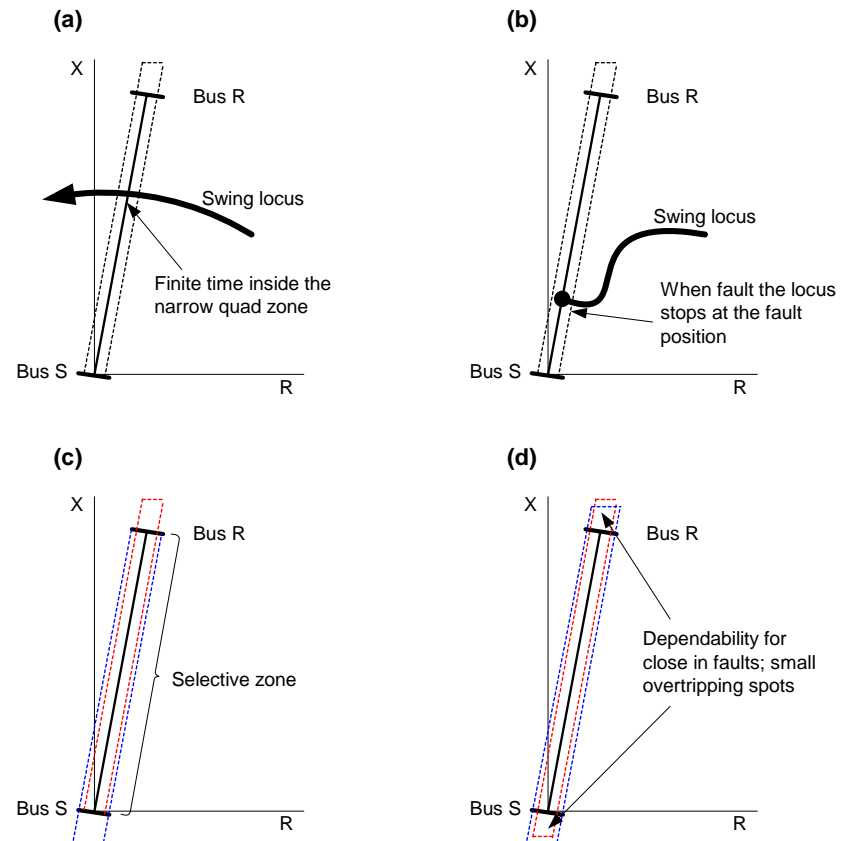
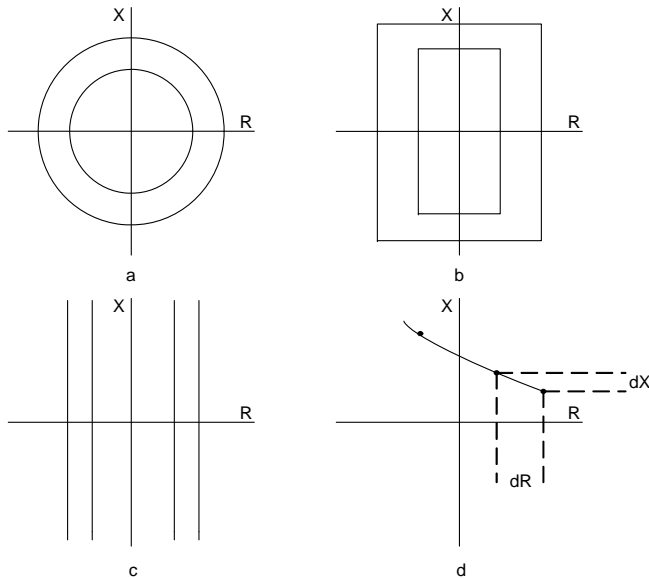
Power Swing Blocking Relay (PSB)

- PSB – discriminates between faults and power swings (Stable and unstable).
- Blocks relay elements prone to operate during stable and unstable power swings.
- Allows relay elements to operate during faults or for faults that evolve during Out of step conditions.

Out of Step Tripping Relay (OST)

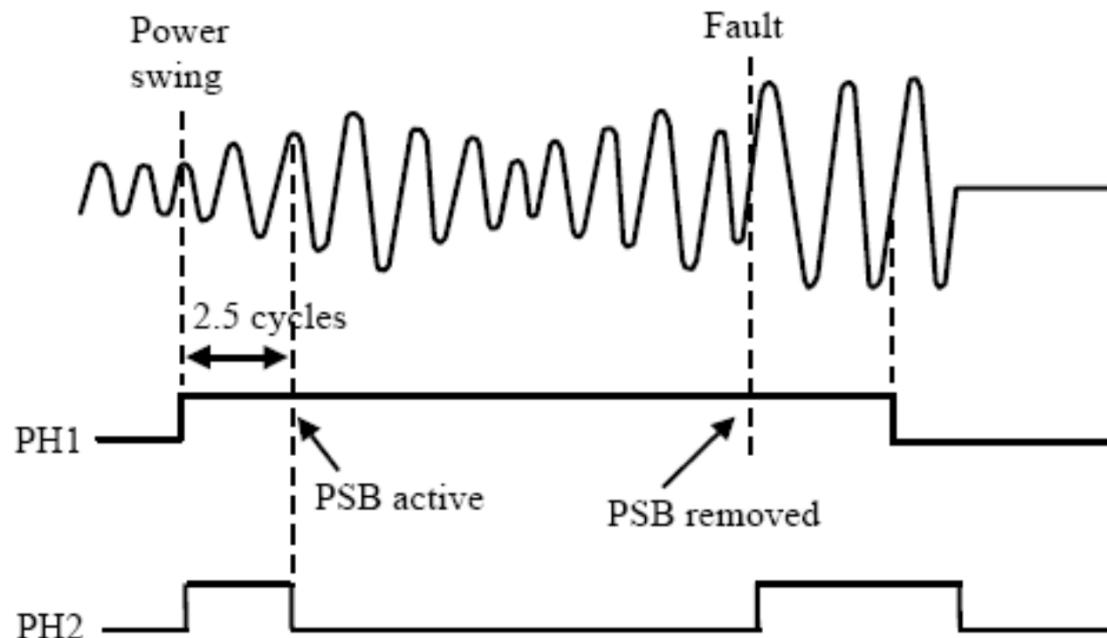
- Discriminates between stable and unstable power swings.
- Initiates system area separation at pre-determined points to maintain stability.
- Protection philosophy is simple but, proper implementation requires transient stability studies.

Out of Step Relay Characteristics



Narrow Quadrilateral function

Application of Super-imposed Component

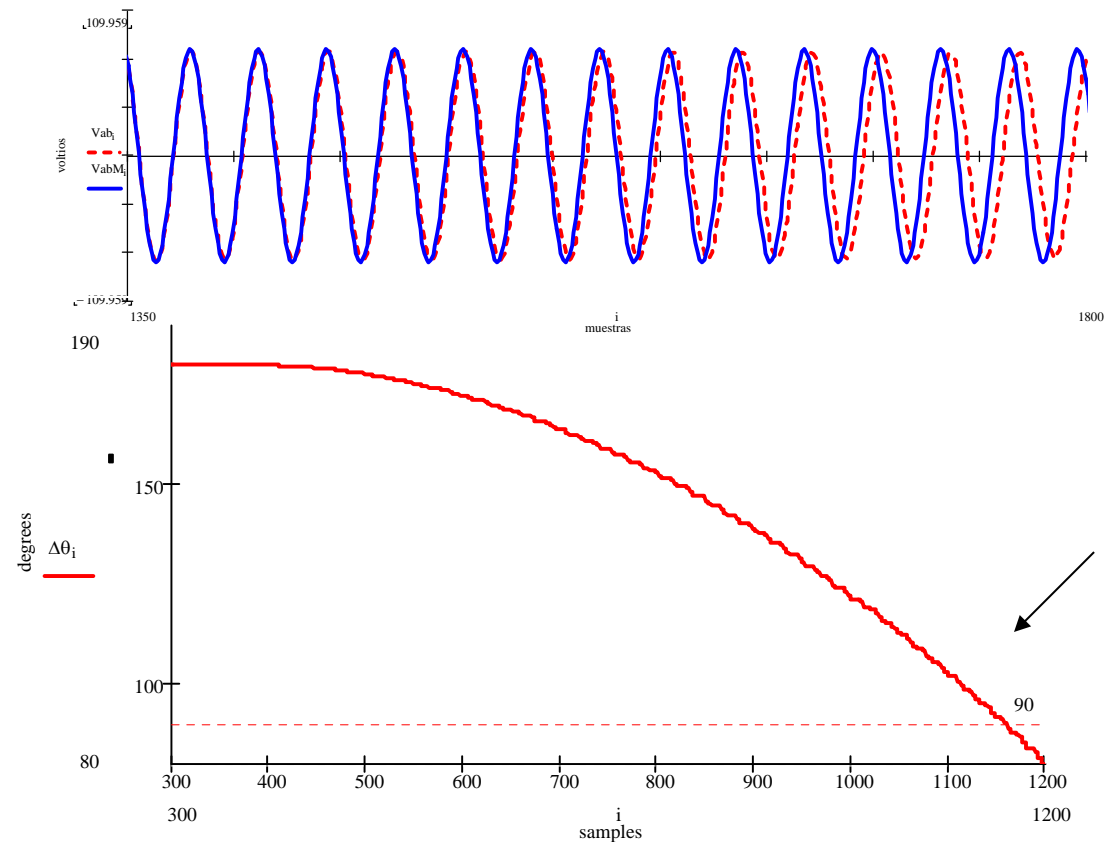
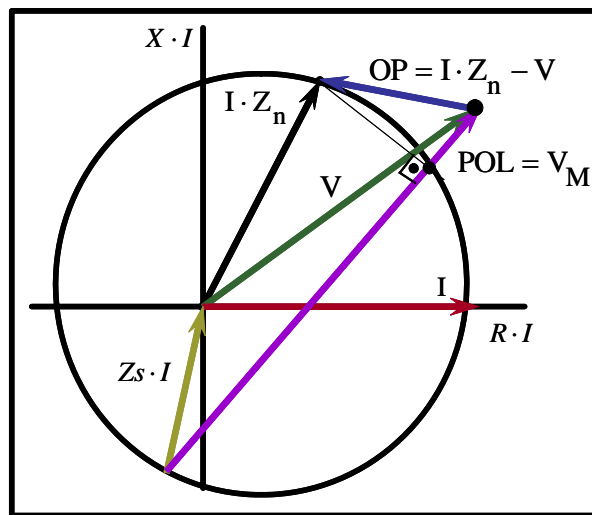


Superimposed component elements operation during power swing

Effect of Frequency Excursion on Distance Protection

- Misoperations due to errors in impedance calculations are minimal.
- Memory polarization is the main cause of undesired tripping.
 - Operating quantity – $I \cdot Z - V$
 - Polarizing quantity – $K \cdot V_{\text{Memory}}$
 - Operating Criterion – $\text{Angle}(V_{\text{OP}} - V_{\text{POL}}) \leq 90^\circ$

Distance Relay Operation During Off-nominal Frequency



Change in Phase Angle between V_{OP} and V_{POL}

Solutions- Frequency Tracking and Compensation

- Numerical relays adapt estimation algorithms to maintain accuracy during slow changes in frequency.

Suggested methods for memory polarized relays:
Memory voltage is used

- Only during fault conditions with the use of fault detectors.
- Only if the available voltage is below a level.

Other Transmission Schemes and Applications

- Current differential
 - Asymmetric Channel delays may cause misoperation
 - Harmonics or frequency deviation may affect depending on the filtering technique used.
 - Generally not affected by other stressed conditions.
- Parallel lines
- Multi-Terminal and Tapped lines
- Series compensated lines
- High speed communication scheme considerations

Transformer Protection

- Thermal
 - Provides protection against loss of life of the transformer
 - Used for tripping if top oil or Winding Temperature exceeds a set point
- Overcurrent
 - Overload protection (Some degree of thermal Protection).
 - Typically set to 130% to 200% of the top rating.
 - May operate during temporary overloads.

Transformer Thermal/ Overcurrent Relay Solutions

- Supervisory control action based on top oil and winding temperature allowing loss of life during stressed conditions will prevent tripping during temporary overloads.
- Second differential scheme provides required redundancy instead of using overcurrent relays.

Transformer Over Excitation Protection

- Transformer differential relays not equipped with fifth harmonic restraint may trip.
- The restraint may block operation resulting in failure of the transformer. –Aug.10, 1996 California disturbance resulted in four 230 kV transformer failures during over voltage /under-frequency conditions.
- Recommended to use V/Hz protection on all transformers.

Transformer Differential Protection

- Uses 2nd , 4th and 5th Harmonic restraint
- At nominal frequency operation, filters remove the fundamental frequency component (Zero Gain).
- At off-nominal frequency operation, multiple reclose operations leading to magnetizing/ sympathetic inrush, prolonged over voltage conditions may lead to relay misoperation due to errors in harmonic frequency detection.
- Frequency Tracking/ compensation Algorithms may help.

Generator Protection Issues

- Under-Voltage Protection – Many units tripped in Aug. 2003
- Back up protection – Voltage restrained or voltage controlled overcurrent protection and Distance protection.
 - Low voltage and swing conditions (not considered during the setting) have contributed to major events
- Load Rejection - 25 units (3826 MW) tripped during 1996 disturbance . Hydro units should not be locked out.

Generator Protection Issues, con.

- Loss of Field Protection - Picked up during stable power swings. Were not coordinated with excitation control and limit settings.
- Under Frequency relays – were not coordinated with manufacturer recommendation on low frequency turbine operation. Not required on Hydro units. No voltage supervision
- Unknown causes due to lack of data recorders.
IEEE PSRC website - “Performance of Generator protection during major system disturbance”

Generator Relay Coordination

- Abnormal Voltage Protection – Must coordinate with control systems allowing operation of generator and excitation system outside their safety limit.
- Backup protection – Limit the reach of these relays to coordinate settings with overload. Should coordinate with bus relays and breaker failure relays.
 - For voltage controlled relays, the voltage setting is set below the lowest system operating voltage.

Generator Relay Coordination

- Loss of Field Protection: Can trip on recoverable power swing. Studies needed to determine the required time delay.
- Over Excitation: V/Hz relay should be coordinated with generator and transformer capabilities and with Minimum Excitation Limit control.
- Out of Step – System studies needed to determine proper setting. Typically set to trip only on unstable swings.
- Under Frequency load shedding relays should be coordinated with generator under frequency relay.

Bus Protection

- Differential protection.
- CT saturation detection may block relay during high current flows.
- Adaptive protection scheme is proposed in the report to use “2 out of 3” voting scheme during system stressed conditions.

Other Protection Schemes

- Feeder Protection – May operate under cold load pick up conditions. Settings are coordinated to prevent operation during this situation.
- Motor Protection – impacted by abnormal voltage or frequency operation. IEEE guide to Motor Protection addresses these issues.

Improving Protection Performance

- Protection coordination studies across regions and within in the region.
- coordination with equipment control and protection
 - Study and review protection designs on a regular basis, as system conditions change
- Avoid hidden failures by adequate testing of not only individual relays, but also overall relay applications
- Increase the security of protection design in the areas vulnerable to blackouts
 - Voting schemes are implemented by some utilities.

Conclusions

- Protective systems are often involved in major wide area disturbances, sometimes preventing further propagation and sometimes contributing to the spread.
- The report identifies key system conditions that affect the protection performance, describes proven methods and recommendations to improve the protection performance.

Questions?