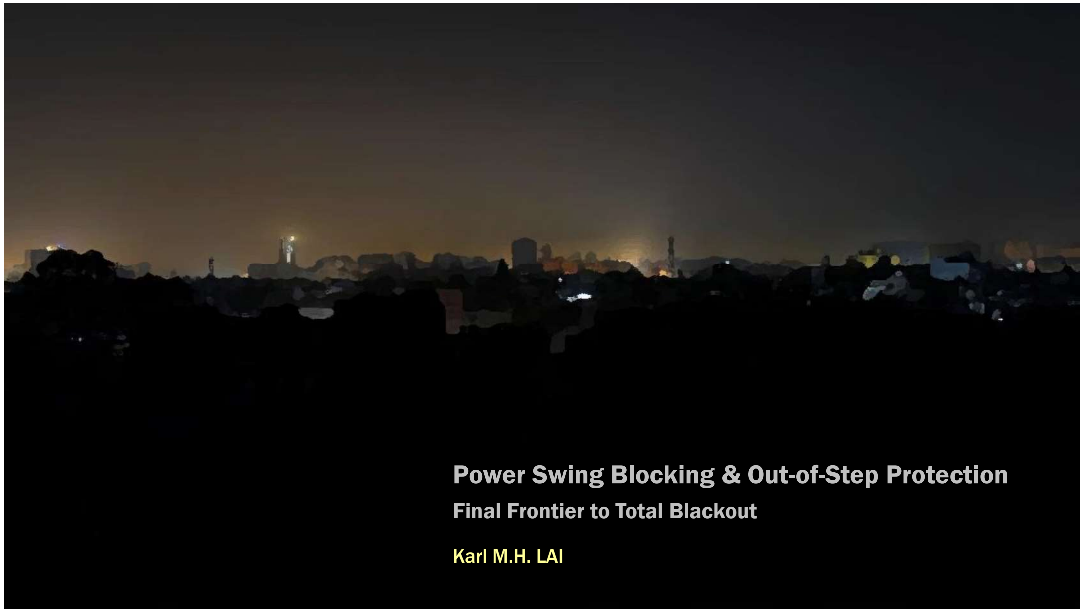


Power Swing Blocking & Out-of-Step Protection

Final Frontier to Total Blackout

Karl M.H. LAI

Power Swing, Out-of-Step and Pole Slipping

Power Swing

Sudden events (e.g. large jump in load, fault occurrence and fault clearance) that disturb the balance of energy and causes oscillation in a power system.

Pole Slipping

Power swing becomes more severe and non-recoverable.

Synchronism is lost between generators.

Excitation of the machines are still intact.

Strong oscillations of real & imaginary power.

Out-of-Step

Loss of synchronism between 2 or several parts of a power system.

Can also be caused by the excitation failure of one machine.

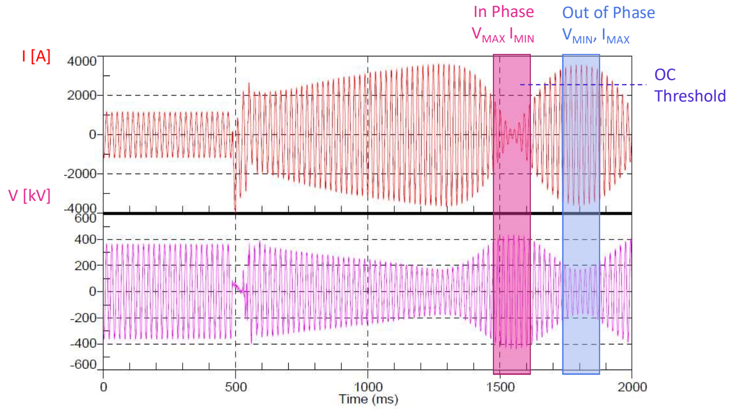
Out-of-Step (OSS) Protection

- Power system should survive under (and after) large disturbances, i.e. fault, loss of largest generator, DC pole block, line switching etc.
- Power Swing may occur after large disturbance (esp. for high-load long-line condition). It is possible that such disturbance may lead to loss of synchronism, i.e. generators operates asynchronously with interconnected systems, a.k.a out-of-step. Once when the power angle δ swings larger than 180º, pole slipping occurs.
- It is important that unwanted tripping of line protections (inc. OC, DOC, UV, DIST and DIR component) should be avoided. Power Swing Blocking (PSB) is to differentiate power swing with fault and block tripping when power swing occurs.
- Out-of-step tripping (OST) is provided at lines with electrical centre, i.e. point with zero voltage (similar to case with bolted three-phase fault). As location of electrical centre varies with source impedance and excitation voltage, it is possible that line intercepts with electrical centre is NOT provided with OST facilities. The goal of optimal OST is to result in generation-load balance, possible after operation of UFLS.
- Detailed stability analysis is needed for ALL operating condition to identity the parts prone to angular instability and locate optimally OST and OSB relay.

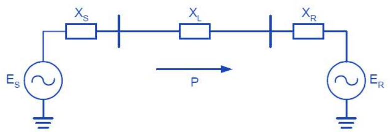
Power Swing after Fault

V_{MAX} = Dielectric Failure

I_{MAX} = Thermal Overload, Mechanical Stress



Power Transfer between Equivalent Sources



Load transfers from slow machine to faster machine during swing. It tends to reduce angular separation. Beyond a limit, an increase in angular separation leads to decrease in power transfer and hence larger power discrepancy and instability.

$$X = X_S + X_L + X_R$$

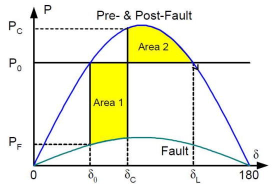
$$\boxed{P = \frac{E_S E_R}{X}\sin\delta}$$

Given sending end voltage $E_s\angle\delta$ and receiving end voltage $E_R\angle 0^o$.

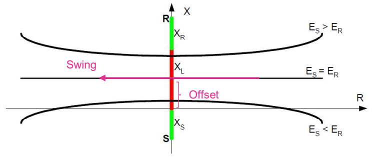
$$I = \frac{E_s\angle\delta - E_R}{X} \quad V = E_s\angle\delta - X_S I \quad \rightarrow \boxed{Z_1 = \frac{V}{I} = -X_s + X\frac{E_s\angle\delta}{E_s\angle\delta - E_R}}$$

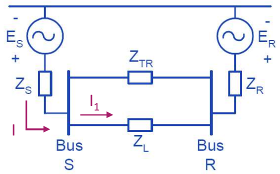
Assume $E_S = E_R$,

$$Z_1 = -X_s + X\frac{1}{1-\angle-\delta} = \underbrace{\left(\frac{X}{2} - X_S\right)}_{\text{Offset}} - j\underbrace{\left(\frac{X}{2}\cot\frac{\delta}{2}\right)}_{\text{Swing}}$$



Power Transfer between Equivalent Sources





Consider a two-source system equivalent with total impedance

$$Z_T = Z_S + Z_{TR} \parallel Z_L + Z_R$$

The swing locus will bisect Z_T, given equal source voltage magnitudes as reasonable initial assumption.

Given $|E_S| = |E_R| = 1$ pu,

$$I = \frac{1\angle\delta - 1}{Z_T}, \qquad I_1 = \frac{Z_{TR}}{Z_L + Z_{TR}} I \rightarrow Z_{seen} = \frac{1\angle\delta - Z_{th1} I}{I_1}$$

Given that

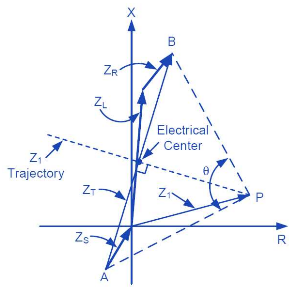
$$m = \frac{Z_{TR}}{Z_L + Z_{TR}} \rightarrow Z_{seen} = \frac{1}{m}\left(-Z_{th1} + \frac{Z_T}{2} - j\frac{Z_T}{2}\cot\frac{\delta}{2}\right)$$

It is to check if

$$\boxed{\frac{1}{m}\left(-Z_{th1} + \frac{Z_T}{2}\right) < Z_L}$$

to see if electrical centre lines in line L.

Power Transfer between Equivalent Sources



Consider the positive impedance seen

$$Z_1 = \frac{V_{1S}}{I_1} = Z_T\left(\frac{E_s\angle\delta}{E_s\angle\delta - E_R}\right) - Z_S$$

The rate of change of positive impedance can be represented by

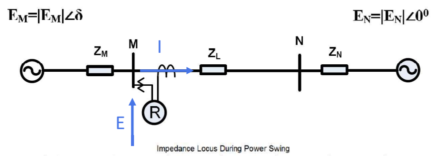
$$\frac{dZ_1}{dt} = -jZ_T\frac{e^{-j\delta}}{(1-e^{-j\delta})^2}\frac{d\delta}{dt}$$

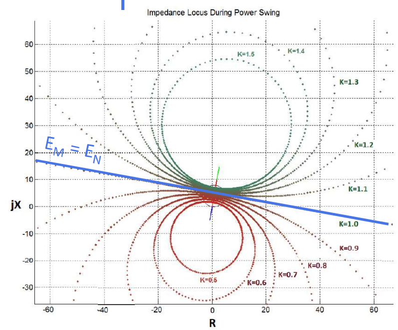
With the identity:

$$\frac{d\delta}{dt} = \omega, \qquad \left|1 - e^{-j\delta}\right| = 2\sin\frac{\delta}{2} \rightarrow \boxed{\left|\frac{dZ_1}{dt}\right| = \frac{|Z_T|}{4\sin^2\frac{\delta}{2}}|\omega|}$$

dZ_1/dt depends upon source impedance, line impedance, and slip frequency (system inertia and dynamic response), which, in turn, depends upon the severity of the perturbation.

Theoretical Analysis for Power Swing





Consider a SMIB system with a generator with constant excitation voltage E_M connected to an infinite bus with large enough system inertia through a line Z_L such that only the generator angle δ swing.

$$E = (E_M - E_N)\frac{Z_L + Z_N}{Z_M + Z_N + Z_L} + E_N$$

$$I = \frac{(E_M - E_N)}{Z_M + Z_N + Z_L}$$

$$Z_{seen} = \frac{E}{I} = \frac{E_M(Z_L + Z_N) + E_N(Z_M)}{E_M - E_N} = \frac{\left(\frac{E_M}{E_N}\right)(Z_L + Z_N) + Z_M}{\frac{E_M}{E_N} - 1}$$

$$\boxed{Z_{seen} = \frac{k(Z_L + Z_N) + Z_M}{k - 1}}$$

Theoretical Analysis for Power Swing

Assumption:
1. Two-source equivalent
2. $E_M = E_N$
3. Homogeneous ($\angle Z_M = \angle Z_L = \angle Z_N$)

<u>Voltage Signal</u>

$$e_N = \sqrt{2}E\sin(\omega_0 t)$$

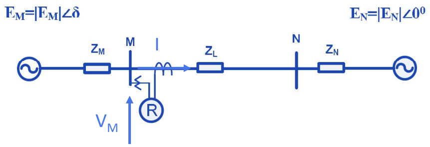
$$e_M = \begin{cases}\sqrt{2}E\sin(\omega_0 t + \beta), & t < t_0 \\ \sqrt{2}E\sin(\omega_1 t + \beta), & t \geq t_0\end{cases}$$

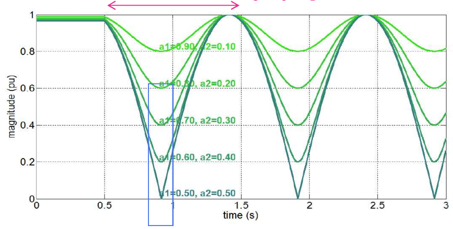
$$v_M = e_M - \left(\frac{e_M - e_N}{Z_\Sigma}\right)Z_M = \left(1 - \frac{Z_M}{Z_\Sigma}\right)e_M + \frac{Z_M}{Z_\Sigma}e_N$$

$$= \underbrace{\left(1 - \frac{Z_M}{Z_\Sigma}\right)}_{a_1}\sqrt{2}E\sin(\omega_1 t + \beta) + \underbrace{\frac{Z_M}{Z_\Sigma}}_{a_2}\sqrt{2}E\sin(\omega_0 t)$$

$$= \sqrt{2}E\underbrace{\sqrt{a_1^2 + a_2^2 - 2a_1 a_2\cos((\omega_0 - \omega_1)t + \beta)}}_{\text{envelope}}\ \underbrace{\boxed{\sin(\omega_1 t + \psi)}}_{\text{carrier}}$$

If $a_1 = a_2 = 0.5$, i.e. $Z_M = Z_N + Z_L$, bus M is the electrical centre, where $v_M = 0$ when $\delta = 180^o$.





Not necessary reaching zero

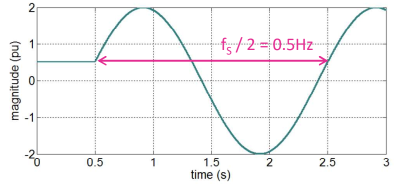
Theoretical Analysis for Power Swing

<u>Current Signal</u>

$$i = \frac{e_M - e_N}{Z_\Sigma}$$

$$i = \frac{\sqrt{2}E\sin(\omega_1 t + \beta) - \sqrt{2}E\sin(\omega_0 t)}{Z_\Sigma}$$

$$= \frac{\sqrt{2}E}{Z_\Sigma}\underbrace{2\sin\left(\frac{\omega_1 - \omega_0}{2}t + \frac{\beta}{2}\right)}_{\text{envelope}}\underbrace{\boxed{\cos\left(\frac{\omega_1 + \omega_0}{2}t + \frac{\beta}{2}\right)}}_{\text{carrier}}$$



Independent of a_1 and a_2

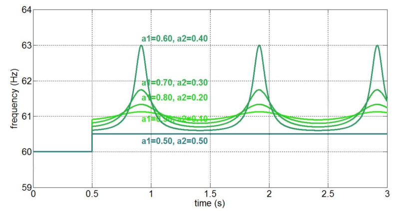
<u>Signal Frequency</u>

We decide to obtain signal frequency from voltage (more reliable than current, which may be affected by fault DC, loading condition, open circuits and harmonics.

$$f = \frac{1}{2\pi}\frac{d(\omega_1 t + \psi)}{dt}$$

$$\psi = \tan^{-1}\left(\frac{a_1\sin\beta - a_2\sin(\omega_0 - \omega_1)t}{a_1\cos\beta + a_2\cos(\omega_0 - \omega_1)t}\right)$$

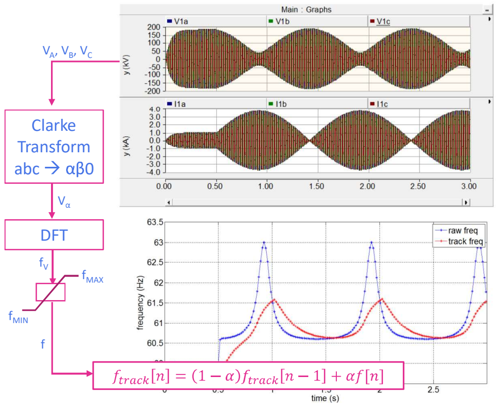
$$= \tan^{-1}\left(\tan\left(\frac{(\beta - 2\pi f_s t)}{2}\right)\right) = \frac{\beta}{2} - \pi f_s t\ (a_1 = a_2)$$



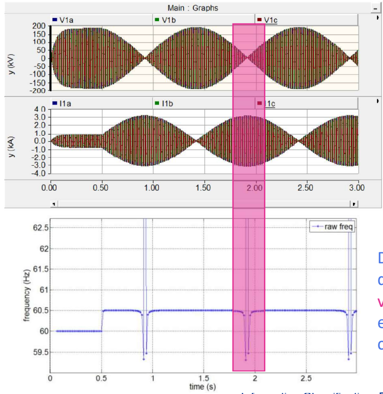
Theoretical Analysis for Power Swing

Frequency Tracking:
Variable Sampling Rate –
always 64 points / cycle (Δt changing)

Simulation ($a_1 = 0.6, a_2 = 0.4$)



Simulation ($a_1 = 0.5, a_2 = 0.5$)

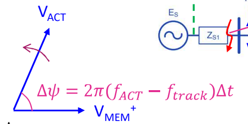


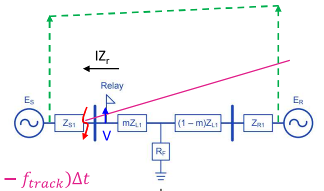
Discontinuity due to zero voltage at electrical centre

Theoretical Analysis for Power Swing

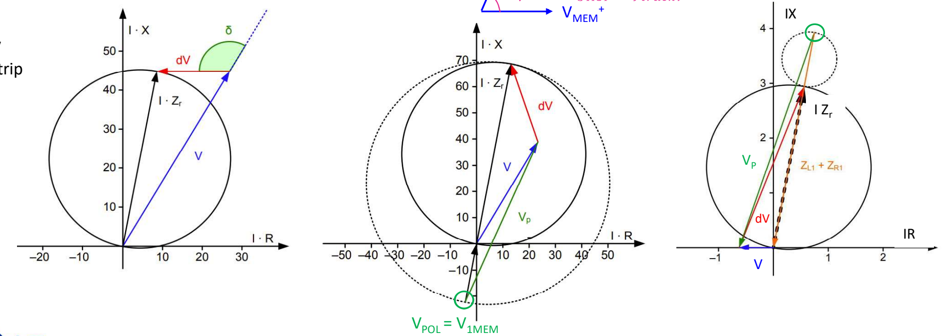
<u>Memory Polarization and Voltage Angle Compensation</u>

Expansion occurs with sequence memory polarization. V_{MEM}^+





$V_{POL} = V$
$V_{OP} = dV$
$= IZ - V$
$\delta < 90^o$ → trip



$V_{POL} = V_{1MEM}$
Larger than the actual measured.

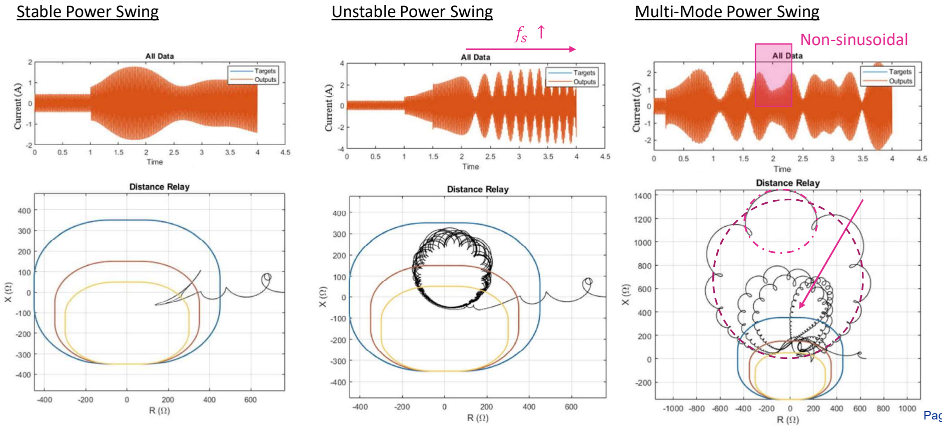
CLP 中電

Types of Power Swing

Predictive Model –
Estimate future power swing signal and calculate the **RMSE difference** to detect fault under swing.

Swing: $f(t) = A\cos(2\pi f_2 t)\cos(2\pi f_1 t + \theta), \quad f_1 \gg f_2$

Fault: $f(t) = Be^{f_s t\, e^{-1/\tau f_s}}\cos(2\pi f_1 t + \theta)$



Highlight

- It is noted that distance relay SHOULD have frequency tracking algorithm, or else voltage polarization memory rotation w.r.t. measured voltage and current may experience, hence triggering DIR and DIST element.
- Uncontrolled tripping during OOS condition can lead to equipment damage due to out-of-phase breaking with large transient recovery voltage (i.e. voltage across CB) and large restrike. Hence, trip-on-way-out (TOWO), i.e. trip when Z_1 slides out of zone, is more preferred than trip-on-way-in (TOWI), in which may be preferred to avoid thermal overload with large system (high current – I^2R) and severe voltage dip and potential load loss.
- During system fault, dZ_1/dt depends also on the amount of signal filtering in the relay. During a system swing, the measured impedance moves slowly on the impedance plane and slip frequency of equivalent two source system.

Difficulties in Out-of-Step Protection

- Detect Evolving Fault after issuing OSB:

  Power Swing results in in-phase (V_{MAX}, I_{MIN}) and out-of-phase (V_{MIN}, I_{MAX}) condition in which may lead to dielectric failure or thermal overload and hence 3 phase fault. OSB can be reset by I_2 – DOC or residual current I_0 - OC component. Actual 3 phase fault can be reset with increase in rate-of-change of impedance (dZ_1/dt).

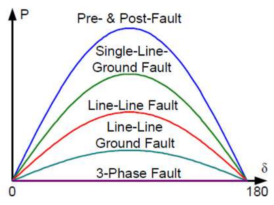
  Note: dZ_1/dt depends on dynamic response of generation (AVR, PSS), dynamic response of load (sheddable load, responsive load, reactive load, IM) and power system devices (FACTS).

- Faulted Phase Selection to issue single pole / three pole tripping:

  It is to retain single-pole tripping capability (under OOS condition) to avoid angular instability.

- Others:

  Detect power swing during pole open conditions, detect fault during pole open (SPO) power-swing blocking.

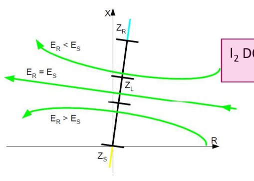


Distance Protection Requirement during OOS

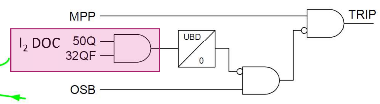
- **Speed**: Distance may trip with time delay during OOS
  Distance asserts an OSB word bit to block trip operation. These elements are operative again in case of unbalanced fault where I_2 – DOC element resets OSB word bit.
- **Selectivity**: Distance may trip three poles for internal SLG fault during OOS.
  Although I_2 – DOC resets OSB, distance element overreaches when OOS falls on the protected line and fault occurs with large δ. It may lead to three pole trip under SLG fault.
- **Dependability:** It is difficult to pick up I_2 – DOC element when fault occurs at V_{MAX} – I_{MIN} condition, i.e. dielectric failure. For evolving 3 phase fault without I_2, it also requires a dZ/dt unblock element.
- **Security:** Distance element must be secure to external faults during system OOS.
  Distance element trips on external fault under SPO condition. Security against external fault is traditionally gained by using a coordinating delay (UBD) of I_2 – DOC element that is used to reset OSB. It is impossible to use coordinating delay on a parallel line transmission system.

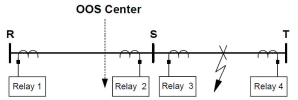
Timer Delay (UBD) and POTT based Tripping

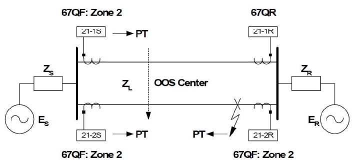
- With OOS occurs between R-S, Distance at Relay 1 overreaches to see the fault at S – T. With forward fault, I_2 – DOC resets OSB. A UBD timer is added to ensure Relay 3 can clear the fault first.
- If OOS centre lies on a parallel line, to provide coordination for fault at line 2, UBD timer can be set in line 1. Yet, the opposite case can occur, and it makes UBD setting scheme useless.
- To achieve security in parallel line, POTT scheme (Z2 at 21-1S + Rev. Z3 at 21-1R for fault at line 2) can secure the healthy line.



Swing loci depends on source voltage.

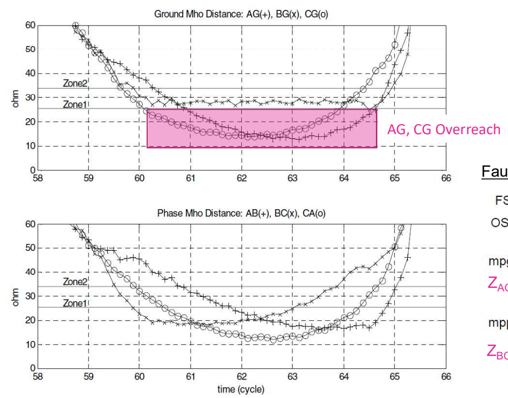




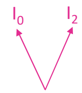


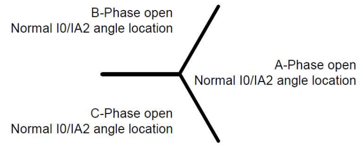
Faulted Phase Selection

BG Fault during System OOS:

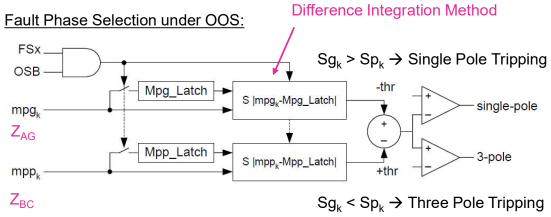


Normal Fault Phase Selection:





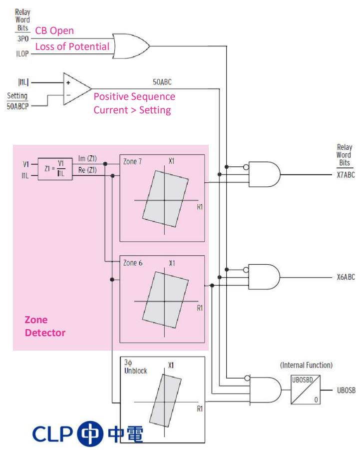
Fault Phase Selection under OOS:

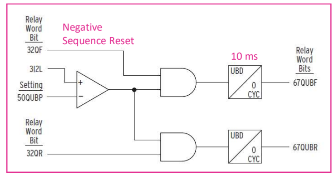


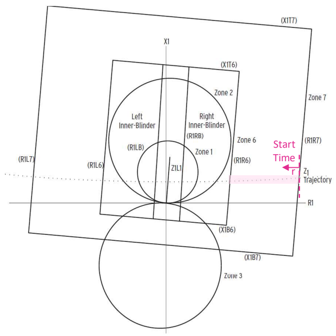
SEL421: Out-of-Step Blocking Logic

- OOS logic determines if a power swing is stable.
- OOS **blocks** distance protection when the measured positive-sequence impedance (Z_1) remains between inner zone Z6 and outer zone Z7 longer than the OOS blocking delay (OSBD).
- If either negative sequence directional element (I_2 Dir) 67QUBF picks up during a power swing, the logic **overrides** OOS blocking (i.e. an unbalanced fault occurred.) The negative sequence current level detector (I_2 OC) 50QUB determines the sensitivity of 67QUBF elements, for all zones **except Zone 1**.

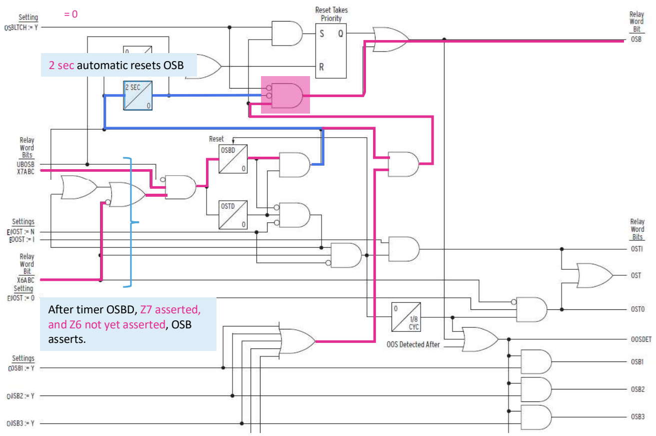
SEL421: Out-of-Step Blocking Logic



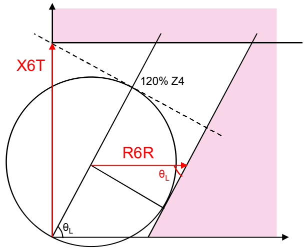


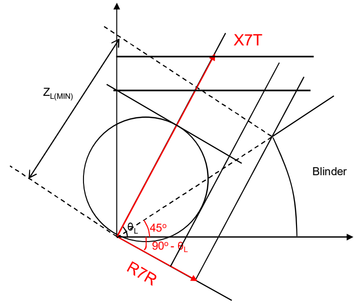


SEL421: Out-of-Step Blocking Logic



Setting Criteria





Zone 6 Inner Blinder:

$$R6R = \frac{120\%Z4}{2}\frac{1}{\sin\theta_L}$$

$$X6T = 120\%Z4$$

Goal: Block before reaching outer tripping zone

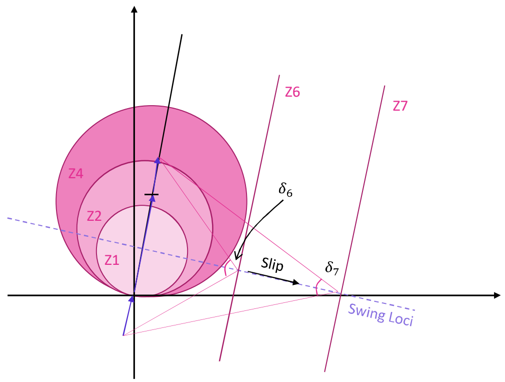
Zone 7 Outer Blinder:

$$R7R = 0.9\, Z_{L,min}\cos(45^o + 90^o - \theta_L), \qquad Z_{L,min} = \frac{V_n^2}{3S_{max}}$$

$$X7T = X6T + (R7R - R6R)$$

Goal: Remain stable at load blinder (Loadability).

Setting Criteria



Given $Z_T = Z_S + Z_L + Z_R$,
i.e. Z_S and Z_R are source impedance at local and remote,
Z_L is line impedance.

$$\delta_6 = 2\tan^{-1}\left(\frac{\frac{|Z_T|}{2}}{R6R}\right)$$

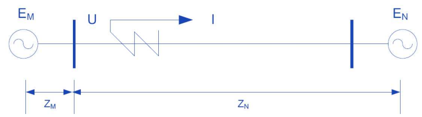
$$\delta_7 = 2\tan^{-1}\left(\frac{\frac{|Z_T|}{2}}{R7R}\right)$$

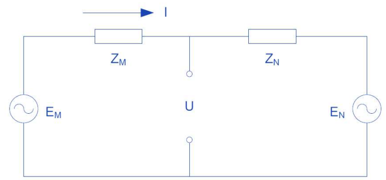
Given that minimum slip time resulted from maximum slip frequency (5 Hz – CLP) from system analysis:

$$\boxed{T_{67} = \frac{\delta_6 - \delta_7}{360^o}\frac{1}{f_{swing}}\ [s]}$$

Note:
Difficulties lies in time and system-config varying nature of slip speed and source impedance.

Pole Slip (Out-of-Step) Relay – NR RCS993





Take E_N as the reference phasor, and then it has

$$\frac{E_N}{E_M} = \rho e^{-j\delta} \qquad \delta = t\Delta\omega + \alpha$$

$$I = \frac{E_M - E_N}{Z_M + Z_N} = \frac{E_M}{Z_M + Z_N}(1 - \rho e^{-j\delta})$$

$$U = E_M - IZ_M$$

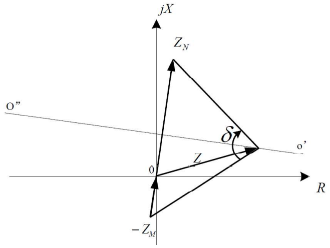
$$\boxed{Z_{seen} = \frac{U}{I} = \frac{Z_M + Z_N}{(1 - \rho e^{-j\delta})} - Z_M}$$

Hence,

$$\boxed{\rho e^{-j\delta} = \frac{Z - Z_N}{Z - (-Z_M)}}$$

Pole Slip (Out-of-Step) Relay – NR RCS993

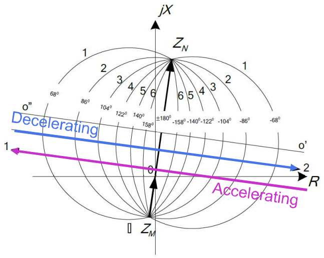
Oscillation Detector:

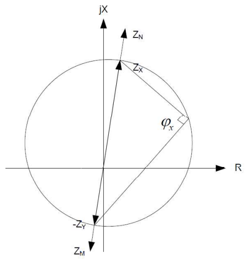


$$Z = \frac{U_{BC}}{I_B - I_C} \qquad \begin{cases} U_I = U_{BC} - (I_B - I_C)Z_N \\ U_{II} = U_{BC} + (I_B - I_C)Z_M \end{cases}$$

$$\boxed{\left|\arg\frac{U_I}{U_{II}}\right| = \left|\arg\frac{Z - Z_N}{Z - (-Z_M)}\right| \geq 140^o}$$

Out-of-Step Detector:





$$\begin{cases} U_I = U_{AB} - (I_A - I_B)Z_N \\ U_{II} = U_{AB} + (I_A - I_B)Z_M \end{cases} \qquad \begin{cases} U_{III} = U_{CA} - (I_C - I_A)Z_X \\ U_{IV} = U_{CA} + (I_C - I_A)Z_Y \end{cases}$$

$$\left|\arg\frac{U_I}{U_{II}}\right| = \left|\arg\frac{Z - Z_N}{Z - (-Z_M)}\right| \geq \varphi_x \qquad \left|\arg\frac{U_{III}}{U_{IV}}\right| = \left|\arg\frac{Z - Z_N}{Z - (-Z_M)}\right| \geq 90^o$$

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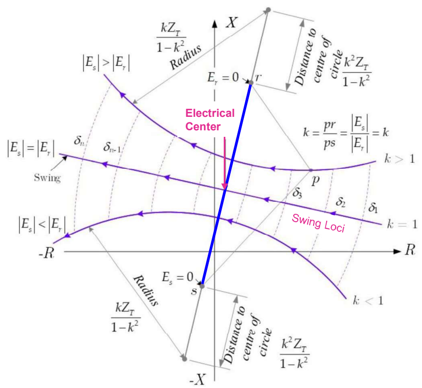
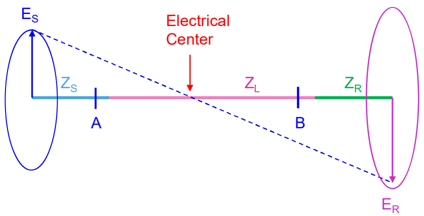
Electrical Center



At the electrical center, the voltage is exactly zero. It means that relays at both ends of the line perceive it as a bolted 3 phase fault and immediately trip the line. Hence, the existence of electrical centre in line implies:

1. System Instability
2. Likelihood of Nuisance Tripping in Distance Relay



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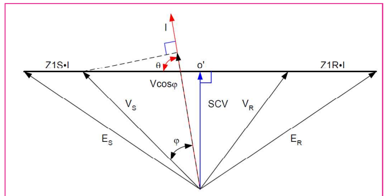
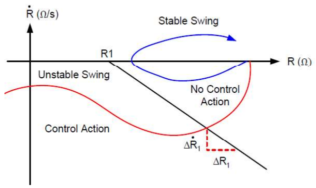
Other OOS Detector

Note:
dZ_1/dt can be executed by 1) $Z7 + \text{timer} + \overline{Z6}$ or
2) continuous monitoring of dZ_1/dt

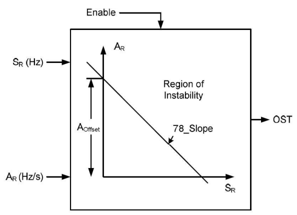
- dZ_1/dt is difficult to set 1) as extensive stability studies are required to determine fastest slip rate. 2) with varying source impedance. 3) detect evolving 3 phase fault during OOS.
- Other methods:



Swing Centre Voltage based
+ Clarke Transformation



R dot Plane based



Synchrophasor Based
(Slip Frequency – Acceleration)

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Other OOS Detector: TKEO

Teager-Kaiser Energy Operator (Fault Detection during Power Swing)

Type of Oscillation

- Stable Swing
- Unstable Swing
- Multi-mode Oscillation

Type of Fault

- Series Compensated Line (Series Cap + MOV)
  - Conduction of MOV (non-linear element)
  - Voltage and Current Inversion of Series Cap
  - Sub-synchronous Oscillation of Series Cap Line
- Measurement Unit prone of Noise
  - CCVT transient
  - CT saturation
- Fault difficult to detect
  - High R_F Fault (with low DC component)
  - Fault Location – Close in / Far End fault
  - Under Power Swing (δ = 180°, V_{MIN} I_{MAX} condition) with 3φ fault
- Fault Type
  - SLG fault, DLG fault, L-L fault, 3φ fault
  - Open Pole (Single Pole Auto-Reclose Condition)
  - Evolving Fault

System Interaction

- RE Penetration (Mismatch of Penetration %, inertia and slip frequency)
- AVR + PSS (raising terminal voltage with damping)
- UPFC (fast control of line voltage & effective line impedance to maintain real power flow)
- Auto Reclose (too fast or too slow)
- Series Compensation (Se cap – voltage inversion, MOV – nonlinear spike)

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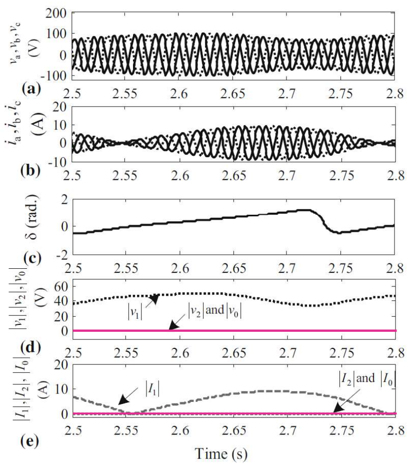
Other OOS Detector: TKEO

Measured Signal during Power Swing



Teager-Kaiser Energy Operator (Fault Detection during Power Swing)

- TKEO originally is used for AM-FM demodulation to estimate envelope.
- It is defined as

$$\psi[x(t)] = \dot{x}(t) - x(t)\ddot{x}(t)$$

- Common signals –

$$x(t) = A\cos(\omega t) \rightarrow \psi[x(t)] = A^2\omega^2$$

No filter needed for decaying DC

$$x(t) = A \rightarrow \psi[x(t)] = 0$$

$$x(t) = \underbrace{a(t)}_{\text{Swing Envelope}}\cos(\omega t) \rightarrow \psi[x(t)] = \underbrace{a^2(t)\omega^2}_{\text{Low Freq Signal}} + \underbrace{\cos^2(\omega t)\psi[a(t)]}_{\text{Fundamental Freq Signal}}$$

- Discrete form:

$$\psi[x[n]] = x[n]^2 - x[n-1]x[n+1]$$

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Other OOS Detector: TKEO

Teager-Kaiser Energy Operator

- Consider $3U_0$ and I_2 as input
  - $3U_0$ – no CT saturation (difficulties – ungrounded system)
  - I_2 – no CCVT transient, reliable for line-to-line

$$U_0 = \frac{U_a + U_b + U_c}{3} \rightarrow |\psi[U_0]| > 0$$

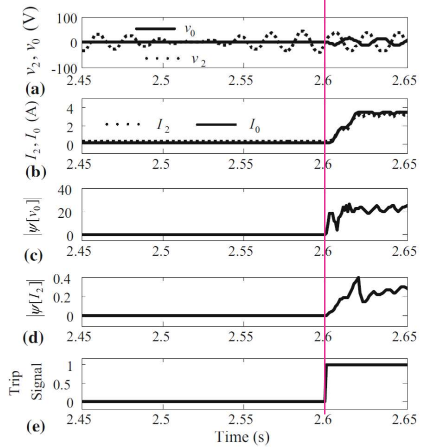
OR

$$I_2 = \frac{I_a + \alpha^2 I_b + \alpha I_c}{3} \rightarrow |\psi[I_2]| > 0$$

Trip

Fault - 150km, 200Ω (A-G fault)
Swing - f_s = 2.5Hz, δ=170°

Fault inception



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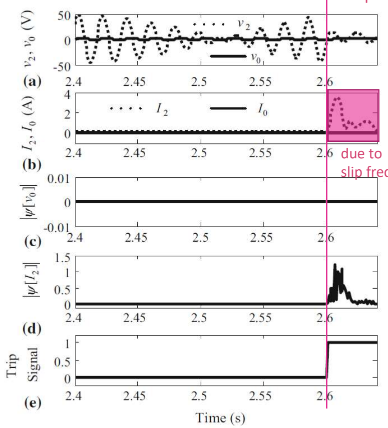
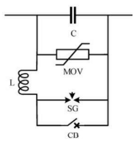
Other OOS Detector: TKEO

Fault – 200km, 5Ω (3 phase fault)
Swing - f_s = 2.5Hz, δ=170°

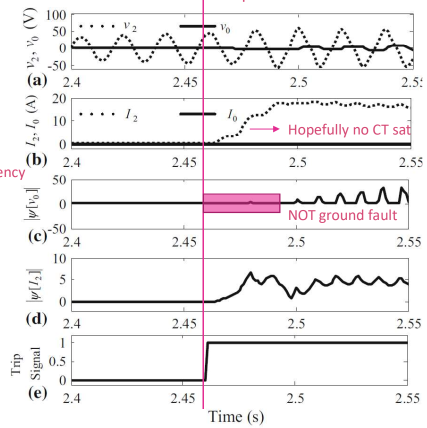
Fault inception



40% compensation (MOV + se cap)
Fault - 100km, 50Ω (B-C fault)
Swing - f_s = 2.5Hz, δ=165°



Fault inception



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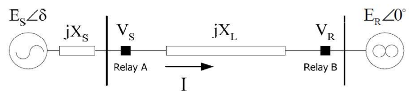
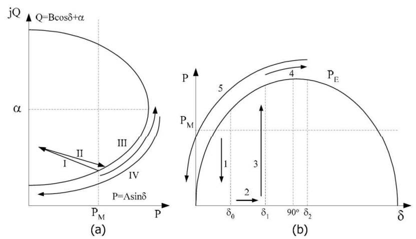
Other OOS Detector: Complex Power

Time Variation of Complex Power

- Machine δ_M are often not measurable.
- P – Q can reflect the condition of P - δ





$$V_S = \frac{E_R\angle 0\, jX_S + E_S\angle\delta\, jX_L}{j(X_S + X_L)} = \frac{E_R X_S\angle 0 + E_S X_L\angle\delta}{X_S + X_L}$$

$$I = \frac{E_S\angle\delta - E_R\angle 0}{j(X_S + X_R)}$$

$$S = VI^*$$

$$S = \left(\frac{E_R X_S\angle 0 + E_S X_L\angle\delta}{X_S + X_L}\right)\left(\frac{j(E_S\angle -\delta - E_R\angle 0)}{(X_S + X_R)}\right)$$

$$S = P + jQ$$

$$= \underbrace{\frac{E_R E_S}{X_S + X_L}}_{A}\sin\delta + j\left[\underbrace{\frac{X_S - X_L}{(X_S + X_L)^2}E_R E_S}_{B}\cos\delta + \underbrace{\frac{X_L E_S^2 - X_S E_R^2}{(X_S + X_L)^2}}_{\alpha}\right]$$

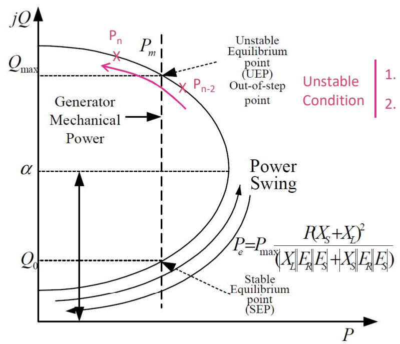
$$P + jQ = A\sin\delta + j[B\cos\delta + \alpha]$$

$$\rightarrow \boxed{\left(\frac{P}{A}\right)^2 + \left(\frac{Q - \alpha}{B}\right)^2 = 1}$$

Note: B > 0 ← $X_S > X_L$
B < 0 ← $X_S < X_L$

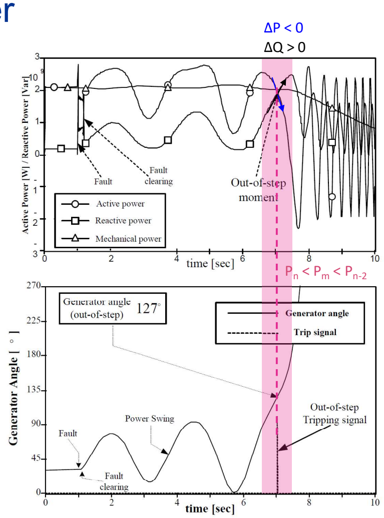
Other OOS Detector: Complex Power

Time Variation of Complex Power

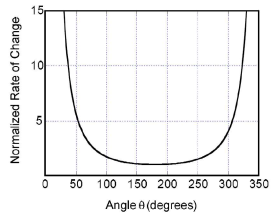


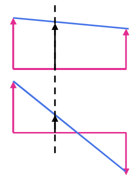
Unstable Condition

1. $P_n < P_m < P_{n-2}$ (trigger)
2. $\Delta P < 0$ and $\Delta Q > 0$ (trip)



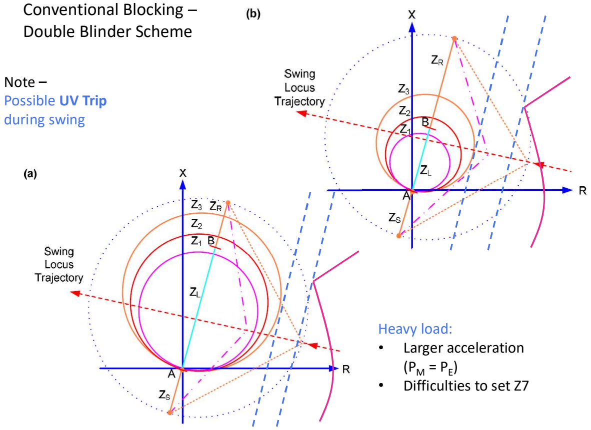
Other OOS Detector: Rate of Change of Impedance





Conventional Blocking – Double Blinder Scheme

Note – Possible **UV Trip** during swing



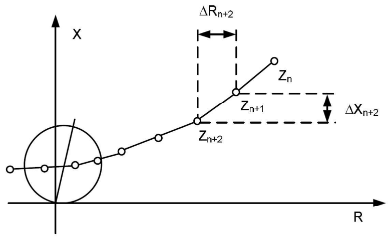
Rate of Change of Impedance:
$$\left|\frac{dZ_1}{dt}\right| = \frac{|Z_T|}{4\sin^2\frac{\delta}{2}}|\omega|$$

Detect pole slip at minimum dZ/dt:
$$\left|\frac{dZ_1}{dt}\right|_{min} = \frac{|Z_T|}{4}|\omega| \qquad \delta = 180^o$$

Depends on - Source & Line Impedance
Slip Frequency (System Inertia + Acc. Energy)

Heavy load:
- Larger acceleration ($P_M = P_E$)
- Difficulties to set Z7

Other OOS Detector: Continuous Impedance Calculation



Parameter $|\Delta R| = R[n] - R[n-k], \qquad |\Delta X| = X[n] - X[n-k]$

Detection Requirement

Continuity - $|\Delta R| > \varepsilon_R$ and $|\Delta X| > \varepsilon_X$

Monotony - $\mathrm{sgn}|\Delta R|_n = \mathrm{sgn}|\Delta R|_{n+1}$ and $\mathrm{sgn}|\Delta X|_n = \mathrm{sgn}|\Delta X|_{n+1}$

Smoothness - $\left|\frac{\Delta R}{\Delta X}\right| < \left|\frac{\Delta R}{\Delta X}\right|_{set}$

Advantage

- It does not require any setting.
- It can handle slip frequency up to 7Hz.
- It can be supplemented by concentric characteristics to detect very slow-moving trajectory.

Other OOS Detector: Synchrophasor Based OOS Relay

Assumption:
- $Z_S << Z_L$
- $E_S / E_R \approx 1$

Given that

$$\frac{V_S}{V_R} = \frac{\left(\frac{Z_S}{Z_T}\right) + \left(1 - \frac{Z_S}{Z_T}\right)\frac{|E_S|}{|E_R|}\angle\delta}{\frac{Z_S + Z_L}{Z_T} + \left(1 - \frac{Z_S + Z_T}{Z_T}\right)\frac{|E_S|}{|E_R|}\angle\delta} \boxed{\approx 1\angle\delta}$$

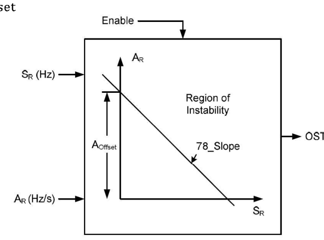
It is difficult to obtain mechanical angles differences δ_M between two (or more) sources.

However, the power angle δ can be approximated by V_S / V_R.

$$S_R = \frac{d\delta}{dt} \quad A_R = \frac{dS_R}{dt}$$

Detection Requirement

1. $S_R \neq 0,\ A_R > 0$ (Power Swing Detection)
2. $A_R > 78\mathrm{Slope}\ S_R + A_{\mathrm{offset}}$ (Predictive OST)



3. $|\delta| > |\delta|_{SET}$

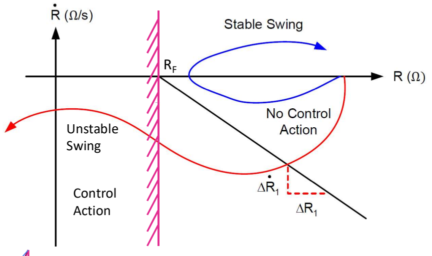
Other OOS Detector: Phase Plane Detection

Control Variable: $U_1 = (Z - Z_1) + T_1\boxed{\frac{dZ}{dt}}$ Effect of Impedance Derivative – Tripping will be faster at a higher impedance changing rate.

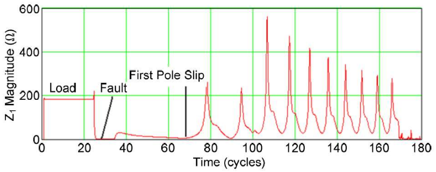
If $Z < Z_1$ or U_1 = negative, OST is issued.

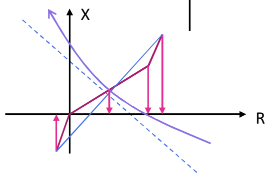
Replace Z with R – Relay is less sensitive to the location of swing centre with respect to the relay location.

Control Variable: $\boxed{U_1 = (R - R_1) + T_1\frac{dR}{dt}}$

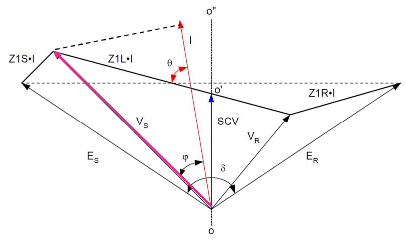


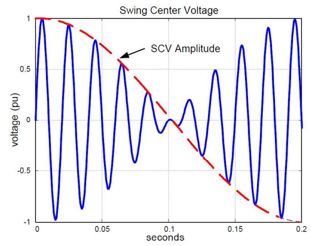
Unstable Swing





Swing Centre Voltage (SCV)





1. SCV independent of Z_S and Z_L. → "no-setting" power swing blocking function
2. Bounded with lower limit of 0 pu and upper limit of 1 pu.
3. SCV = SCV(δ), directly relates to angular difference of two sources.

SCV(t) is the instantaneous SCV with average frequency of $\omega + 1/2\,(d\delta/dt)$

$$SCV(t) = \underbrace{\sqrt{2}E\sin\left(\omega t + \frac{\delta(t)}{2}\right)}_{\text{Carrier}}\underbrace{\cos\left(\frac{\delta(t)}{2}\right)}_{\text{Amplitude Modulated}} \rightarrow \boxed{SCV \approx |V_S|\cos\varphi}$$

Local Estimate

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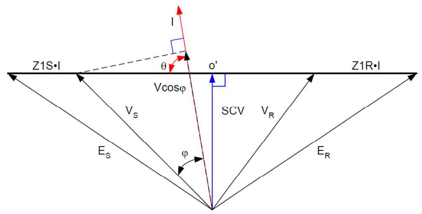
Swing Centre Voltage (SCV)

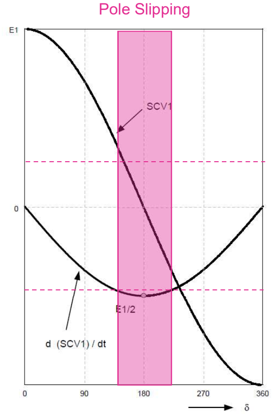


It is given that SCV_1 and $dSCV_1$

$$\boxed{SCV_1 = E_1\cos\frac{\delta}{2} \qquad \frac{d(SCV_1)}{dt} = -\frac{E_1}{2}\sin\frac{\delta}{2}\frac{d\delta}{dt}}$$

- SCV_1 = 0 when δ = 180º (< $SCV_{1,\,SET}$ for pole slipping).
- $dSCV_1$ = 0 when δ = 0,

Pole Slipping



$SCV_1 > SCV_{1,\,SET}$

$dSCV_1 < dSCV_{1,\,SET}$

Map V_S onto I → SCV

1. During no-load condition, line-charging current leads local voltage by 90º and hence SCV = 0
→ NOT representing true SCV.

2. Sign changes in SCV when δ = 0 is resulted from reversal of line current, i.e. φ changes 180º when δ goes through 0º point. → discontinuity.

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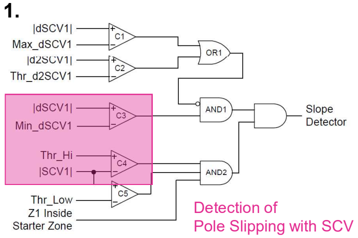
Power Swing Detector based on $d(SCV_1)/dt$

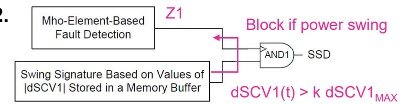
1.



Detection of Pole Slipping with SCV

Problem: NOT possible to mathematically compute slip frequency with dSCV1.

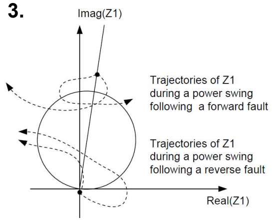
2.

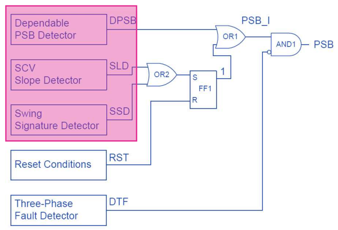


$dSCV1(t) > k\,dSCV1_{MAX}$

Z1 + no discontinuity (δ = 0º) presented on SCV1 signal before Z1 = OOS

3.





Tackle swing after long lasting fault.

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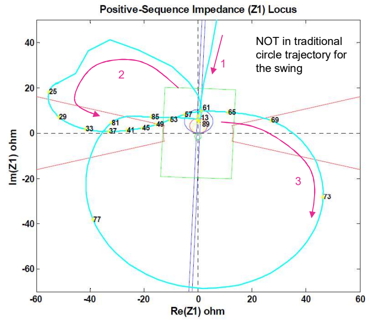
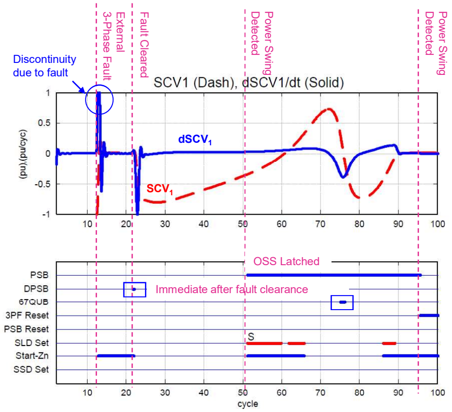
Example 1: OOS after External 3ϕ Fault

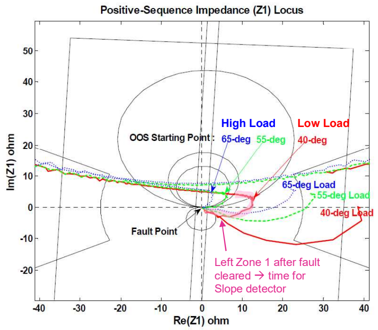
Given a 500kV 3-machine network with AVR and PSS control.

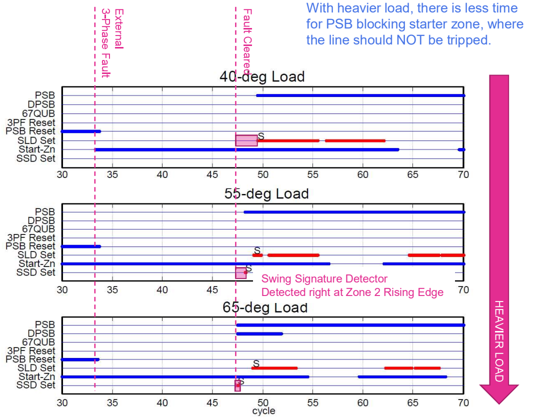




Example 2: OOS with Different Pre-Fault Loads

Bolted Close-in Reverse Fault cleared within zone. OOS occurs immediately within zone. PSB does not have time to react.



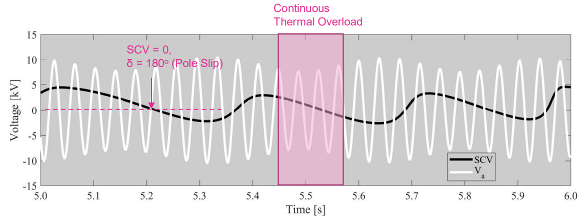


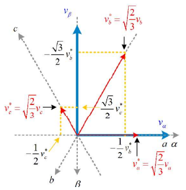
Clarke's Transformation based SCV

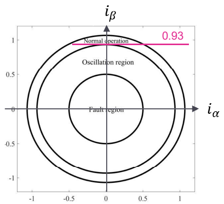
Given Clarke Transformation:

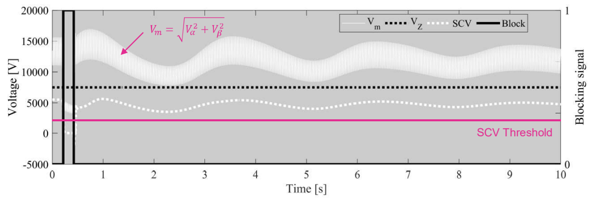
$$\sqrt{\frac{2}{3}}\begin{pmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ \sqrt{2}/2 & \sqrt{2}/2 & \sqrt{2}/2 \end{pmatrix} V_{abc} = V_{\alpha\beta 0}$$

It is known that behaviour of these components provides information about phase involved, and values of them are related with fault distance and fault location.









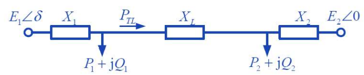
Power Fluctuation in Tie-line

- Under a disturbance (load rejection, generator tripped, DC block, etc.) occurs in power system and before the system recovers to the new steady state, there will be an oscillating transient process (frequency and power oscillation) in the system.

1. Moment of Disturbance – Power Redistribution: Power ΔP_r distributed o generator i: $\Delta P_i = \Delta P_r \frac{K_{ir}}{\sum_{j=1}^{n} K_{jr}}$

   Synchronization Coefficient: $K_{ir} = E_i U_r B_{ir} \cos \delta_{ir}$

2. Before the action of governor – Generator Motion Equation: $\Delta P_i = \frac{T_{ji}}{\sum_{j=1}^{n} T_{jj}\, \Delta P_r}$ T_{ji} = inertia time constant of generator i



Consider a differential-algebraic equation: given that $x = \begin{pmatrix} \dot{\delta} \\ \delta \end{pmatrix}, y = \begin{pmatrix} V \\ I \end{pmatrix}$

$$\begin{cases} \dot{x} = f(x, y, P_0) & \text{— Electromechanical dynamic equation} \\ 0 = g(x, y, P_0) & \text{— Network Constraint} \end{cases}$$

Power Fluctuation in Tie-line

Before Disturbance

$$\begin{cases} 0 = f(x_0, y_0, P_0) \\ 0 = g(x_0, y_0, P_0) \end{cases}$$

Under Disturbance

$$\begin{cases} 0 = f(x_0, y_1, P_1) \\ 0 = g(x_0, y_1, P_1) \end{cases}$$

Aftre Disturbance

$$\begin{cases} \dot{x} = f(x, y, P_1) \\ 0 = g(x, y, P_1) \end{cases} \rightarrow \begin{cases} \dot{x} = f(x_s, y_s, P_1) \\ 0 = g(x_s, y_s, P_1) \end{cases}$$

Tieline Power: $P_{TL0} = P_{G,S} - P_{L,S} = P_{L,R} - P_{G,R}$

$P_{TL1} = h(x_0, y_1)$

$P_{TLs} = h(x_s, y_s)$

Operating Point: $x_0 = x_0$, $y_1 = y_0 + \Delta y$, $P_1 = P_0 + \Delta P$

Given steady state solution: (x_s, y_s)

When impact power is insignificant, distance between initial point x_0 and equilibrium point x_s in state space is very close. Hence, the system can be linearized into

$$\Delta \dot{x} = J\Delta x, \qquad \Delta x(t) = \sum_{i=1}^{n} (\psi_i \Delta x(0)) e^{\lambda_i t} \phi_i$$

where eigenvalues, left eigenvectors and right eigenvectors of state matrix J are λ_i, ψ_i and ϕ_i respectively.

Recall -

$$\Delta P_i = \Delta P_r \frac{K_{ir}}{\sum_{j=1}^{n} K_{jr}} \rightarrow P_{TL1} = P_{TL0} + \Delta P \frac{K_{Sk}}{K_{Sk} + K_{Rk}}$$

$$= P_{TL0} + \Delta P \frac{E_S U_k B_{Sk} \cos\delta_{Sk}}{E_R U_k B_{Rk} \cos\delta_{Rk} + E_S U_k B_{Sk} \cos\delta_{Sk}}$$

$$\approx P_{TL0} + \Delta P \frac{X_S^{-1}}{X_S^{-1} + X_R^{-1}} \approx P_{TL0} + \Delta P \frac{X_R}{X_R + X_S}$$

$$X_S \gg X_R \rightarrow P_{TL1} \approx P_{TL0}$$

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Power Fluctuation in Tie-line

Similarly, the tie-line power can be expressed as a function of state variable with: $P_{TL} = h'(x)$
which can be linearized at the equilibrium point as:

$$\Delta P_{TL} = P_{TL} - P_{TLs} = b\Delta x = \sum_{i=1}^{n} (\psi_i \Delta x(0))(b\phi_i) e^{\lambda_i t}$$

Setting the eigenvalues at the system dominate mode as $\sigma \pm j\omega_d$, the oscillation power at tie-line can be written as:

Under Disturbance (t = 0⁺)

$\Delta P_{TL} = Ae^{\sigma t}\sin(\omega_d t + \theta)$

$\Delta P_{TL}(0) = A\sin(\theta) = P_{TL1} - P_{TLs}$ … (1)

It is given that $\Delta\dot{\delta} = 0$ at the moment of failure, i.e. t = 0⁺

$\Delta \dot{P}_{TL} = b'\Delta\dot{\delta} = 0$

$\Delta \dot{P}_{TL}(0) = A(\sigma\sin\theta + \omega_d\cos\theta) = A\sqrt{\sigma^2 + \omega_d^2}\sin(\beta - \theta) = 0$ … (2)

where $\beta = \cos^{-1}\zeta$, $\zeta = -\frac{\sigma}{\sqrt{\sigma^2 + \omega_d^2}}$ = damping ratio

With (1) and (2), $P_{TL}(t) = P_{TLs} + \Delta P_{TL}(t) = P_{TLs} + \frac{(P_{TL1} - P_{TLs})}{\sin\theta} e^{\sigma t}\sin(\omega_d t + \theta)$

Tie-line Extreme Value Flow: $\boxed{P_{TL,max} = P_{TLs} + (P_{TLs} - P_{TL1})e^{-\pi\zeta/\sqrt{1-\zeta^2}}}$ Error: 5.90%

Under Disturbance (t = 0⁺)

$$\boxed{\Delta P_i = \frac{T_{Ji}}{\sum_{j=1}^{n} T_{Jj}} \Delta P_r}$$

Substitute Power Distribution Equation:

$$\boxed{P_{TL,max} = P_{TLs} + \Delta P \left(\frac{T_{J,S}}{T_{J,S} + T_{J,R}}\right) e^{-\pi\zeta/\sqrt{1-\zeta^2}}}$$ Error: 13.38%

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Note - P_M changes due to governor is represented by

$$\boxed{\Delta P_m = -\frac{1}{1 + sT_g} \frac{\Delta\omega}{R_g} P_N}$$

Angular Frequency

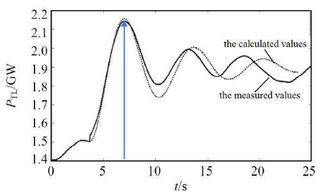
Rated Power

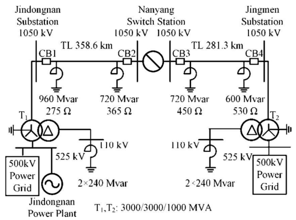
Inertial Time Constant

Power Fluctuation in Tie-line

- The greatest factors that influences the peaks of tie-line power fluctuation includes:
  - Initial Delivery Power of Tie Line (P_{TL0})
  - The ratio of inertia time constant of generators in two-area interconnected power system ($T_{J,S}$ and $T_{J,R}$)
  - Damping Ratio of Oscillation mode between two areas of the system (ζ)
- It is noted that the first swing of tie-line power fluctuation is mainly the expression of electromechanical oscillation mode, which is largely influenced by the generator inertia time constant, and is little influenced by speed control system.
- During the first swing, the governor has NOT yet caused the large change of mechanical power of prime motor. Hence, in calculation of power peak of first swing, the impact of governor is NOT considered. If there is any impact, it would influence the peak value by the damping ratio of oscillation modes.

Simulation Background –
(North China : Central China Power Grid)
Generation Capacity Ratio - 1.5: 1
Inertia Time Constant Ratio – 1.1: 1.5
Damping Ratio – 0.07: 0.20





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Method to Improve Transient Stability

1. Minimize Fault Severity and Duration
2. Increase of Restoring Synchronizing Forces
3. Reduction of Accelerating Torque by:
   a) Control of Prime-Mover Mechanical Power
   b) Application of Artificial Loads

$$\boxed{P = \frac{E_S E_R}{X}\sin\delta}$$

- **High Speed Fault Clearance**: Reduce KE gained by generator due to fault duration (t) and fault point voltage (V_F)
- **Local Breaker Failure Protection**: Reduce time a fault remains in the system. (or else cleared by back-up)
- **Single Pole Operation**: It allows remained power transfer capability and reduces accelerating power in P-δ curve.
- **Dynamic Braking**: It uses artificial load near generators to consume power output from generator.
- **Shunt Compensation**: It maintains voltage at selected network location to increase flow of synchronizing power.
- **Steam Turbine Fast Valving**: It is to reduce generator output without removing the unit from bar.
- **High Speed Excitation System** (with high ceiling voltage): It is to increase internal voltage hence synchronizing power.
- **Control Separation and Load Shedding**: It is to avoid disturbance propagating into neighbor systems and trigger protection.
- **Reduction of Transmission System Reactance**: It is to increase effective post-fault synchronizing power.
- **Power System Stabilizer**: PSS compensates phase lag introduced by generator and its excitation system to satisfy power transfer.

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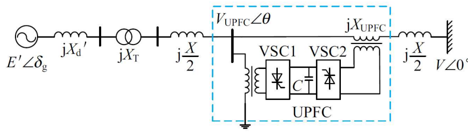
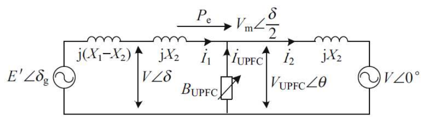
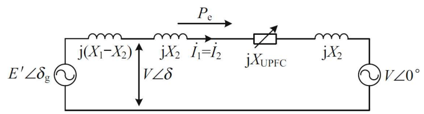
Other Means to Improve Transient Stability – UPFC



Shunt – Voltage Control



Series – Impedance Control



Type of Instability –

1. Low frequency Oscillation due to Negative Damping
2. Forced Oscillation due to Resonance

$$\frac{T_J}{\omega_0}\frac{d^2\Delta\delta}{dt^2}+D_g\frac{d\Delta\delta}{dt}=-\Delta P_e+\Delta P_m$$ (Linearized Swing Equation)

$$\Delta P_e \approx \Delta T_e = K\Delta\delta + D_e\frac{d\Delta\delta}{dt}$$

$$\frac{T_J}{\omega_0}\frac{d^2\Delta\delta}{dt^2}+D\frac{d\Delta\delta}{dt}+K\Delta\delta=\Delta P_m = r\sin\Omega t$$

Governor induced oscillation

$$\Delta\delta = \boxed{B\sin(\Omega t-\varphi)}+B_1(t)\cos(\omega_d t)+B_2\sin(\omega_d t)$$

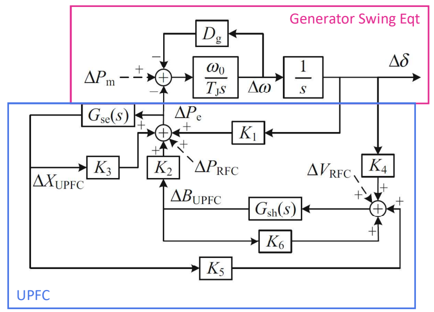
Dominating

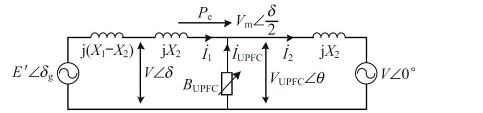
$$\frac{T_J}{\omega_0}\frac{d^2\Delta\delta}{dt^2}+K\Delta\delta=0 \rightarrow \boxed{\omega_n=\sqrt{\frac{\omega_0 K}{T_J}}}$$

Resonant Frequency

Other Means to Improve Transient Stability – UPFC

Analysis of UPFC





UPFC shunt side - STATCOM

$$\begin{cases}\dot{E}' = \dot{V}_{UPFC} + jX_1\dot{I}_1\\ \dot{V}_{UPFC} = \dot{V} + jX_2\dot{I}_2\\ \dot{I}_1 = \dot{I}_2 - \dot{I}_{UPFC}\\ \dot{I}_{UPFC} = j\dot{V}_{UPFC}B_{UPFC}\end{cases}$$

$$G_{sh}(s) = \frac{K_{sh}}{1+sT_{sh}}$$

$$\begin{cases}T_{sh}\frac{d\Delta B_{UPFC}}{dt} = -K_{sh}(\Delta V_{UPFC}-\Delta V_{RFC}) - \Delta B_{UPFC}\\ \Delta T_e \approx \Delta P_e = K_1\Delta\delta + K_2\Delta B_{UPFC}\\ \Delta V_{UPFC} = K_4\Delta\delta + K_5\Delta B_{UPFC}\end{cases}$$

Extra control – shift resonant frequency to avoid undamped oscillation

$$\Delta V_{RFC} = G_{RFC}(s)\Delta\delta = (\Gamma + s\Psi)\Delta\delta$$

$$\rightarrow \Delta P_e = \Delta T_e = K_1\Delta\delta - \frac{K_2K_{sh}(K_4-G_{RFC}(s))}{1+K_5K_{sh}+j\Omega T_{sh}}$$

Other Means to Improve Transient Stability – UPFC

$$\Delta T_e = K_1\Delta\delta - \frac{K_2K_{sh}(K_4-G_{RFC}(s))}{1+K_5K_{sh}+j\Omega T_{sh}} \longleftrightarrow \Delta P_e\approx\Delta T_e = K\Delta\delta + D_e\frac{d\Delta\delta}{dt}$$

$$K = K_1 - \frac{K_2K_{sh}((1+K_5K_{sh})(K_4-\Gamma)+\Omega\Psi T_{sh})}{1+K_5K_{sh}+\Omega^2T_{sh}}$$

$$= \underbrace{K_1 - K_4\left(\frac{K_2K_{sh}(1+K_5K_{sh})}{1+K_5K_{sh}+\Omega^2T_{sh}}\right)}_{K_0} - \underbrace{\left(\frac{K_2K_{sh}(1+K_5K_{sh})}{1+K_5K_{sh}+\Omega^2T_{sh}}\right)}_{A_1}\Gamma - \underbrace{\left(\frac{K_2K_{sh}\Omega T_{sh}}{1+K_5K_{sh}+\Omega^2 T_{sh}}\right)}_{A_2}\Psi$$

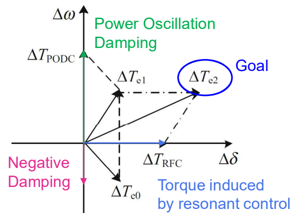
$$K = K_0 + A_1\Gamma + A_2\Psi$$

$$P_e = \frac{VV_m}{X_2}\sin\frac{\delta}{2},$$ V_m = mid point voltage

$$\Delta P_e = \cancel{\frac{\partial P_e}{\partial V}}\Delta V + \frac{\partial P_e}{\partial V_m}\Delta V_m + \frac{\partial P_e}{\partial\delta}\Delta\delta + \cancel{\frac{\partial P_e}{\partial X_2}}\Delta X_2$$

$$\frac{T_J}{\omega_0}\frac{d^2\Delta\delta}{dt^2}+D_g\frac{d\Delta\delta}{dt}=-\Delta P_e+\Delta P_m \longrightarrow \frac{T_J}{\omega_0}\frac{d^2\Delta\delta}{dt^2}+D_g\frac{d\Delta\delta}{dt}+\frac{\partial P_e}{\partial V_m}\Delta V_m+\frac{\partial P_e}{\partial\delta}\Delta\delta=\Delta P_m$$

With $\boxed{\Delta V_m = K_m\Delta\delta}$ $\longrightarrow \frac{T_J}{\omega_0}\frac{d^2\Delta\delta}{dt^2}+D\frac{d\Delta\delta}{dt}+\left(K_M\frac{\partial P_e}{\partial V_m}+\frac{\partial P_e}{\partial\delta}\right)_0\Delta\delta=\Delta P_m$

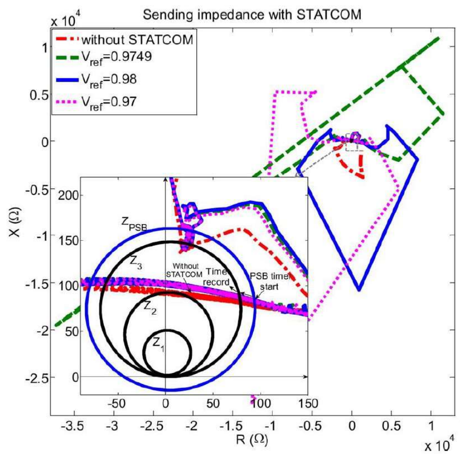


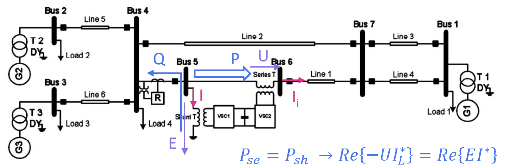
$$\frac{T_J}{\omega_0}\frac{d^2\Delta\delta}{dt^2}+\left(K_M\frac{\partial P_e}{\partial V_m}+\frac{\partial P_e}{\partial\delta}\right)_0\Delta\delta=0$$

$$\boxed{\omega_n=\sqrt{\frac{\omega_0}{T_J}\left(K_M\frac{\partial P_e}{\partial V_m}+\frac{\partial P_e}{\partial\delta}\right)_0}}$$

K to be designed with modulated $\Delta V_m = K_m\Delta\delta$

Other Means to Improve Transient Stability – UPFC





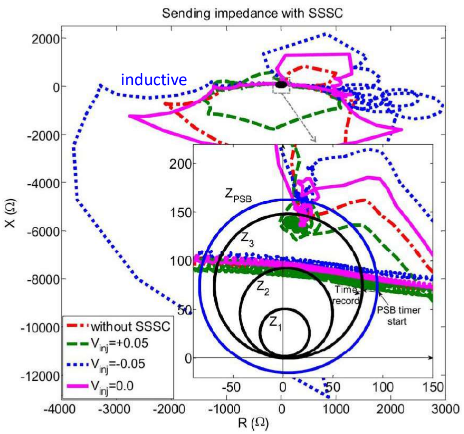
$$P_{se} = P_{sh} \rightarrow Re\{-UI_L^*\} = Re\{EI^*\}$$

During Power Swing condition, bus voltage (Bus 5) changes. The shunt controller attempts to bring it to reference voltage.

STATCOM absorbs or generates reactive power at the installation point. It increases the impedance circle radius during swing due to shunt controller response.

It is noted that the shunt part of UPFC supply reactive power for voltage control, while maintaining the exchange of real power required by the series part.

Other Means to Improve Transient Stability – UPFC



SSSC (series mode of UPFC) can control the effective line impedance.

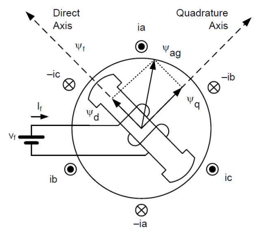
It injects controllable voltage in quadrature of line current to emulate capacitive (U > 0) or inductive (U < 0) compensation mode.

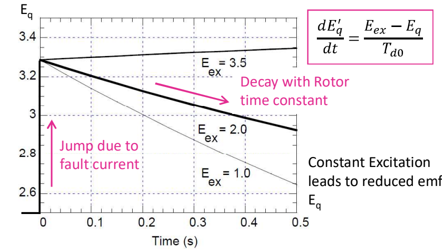
It was found that impedance locus has a greater radius in inductive mode, while smaller radius in capacitive mode.

UPFC causes an increase of the impedance movement. (SSSC mode has the highest speed – more difficult for detection).

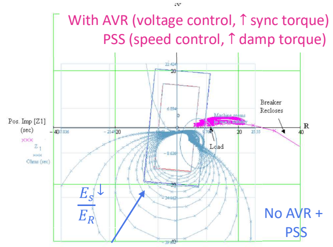
SSSC improves system stability by reducing effective line impedance. Hence, a longer time is required for a fault really reaches power swing.

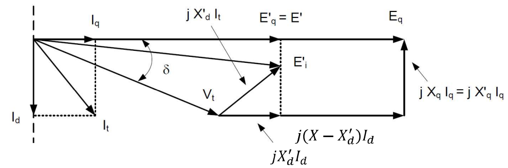
Effect of AVR and PSS to Power Swing and Transient Stability





Constant Excitation leads to reduced emf E_q





Modelling of power swing requires constant voltage source.

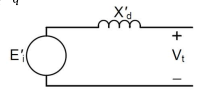
$$E_q = V_t + jX_dI_d + jX_qI_q$$

During transient state,

$$E_q' = V_t + jX_d'I_d + jX_q'I_q$$

Assume cylindrical (i.e. $X_d' = X_q'$),

$$E_i' = V_t + jX_d'I_t$$



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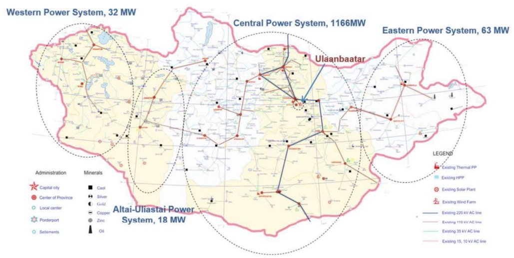
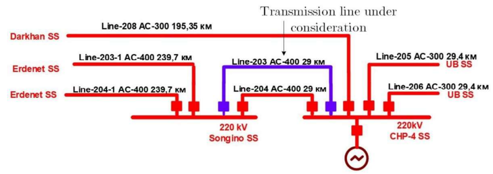
Example

- Mongolian system is connected to Russian' system with a double circuit transmission line at 220kV.
- On 2018/09/15, a power outage occurred at CES of Mongolian with 900MW curtailed during disturbance due to an SLG occurred at CHP-4, the largest thermal power plant in CES.
- The fault is cleared within 90ms with main 220kV line and bus isolated. The voltage reached 0.81pu due to a shortage of reactive power source.
- Increased import power from Russian grid and overload the line with power oscillations. The line is tripped by OOS.
- Generator is tripped by overexcitation and loss of field with delayed OOS tripping in Russian – Mongolian link and without UFLS followed up.





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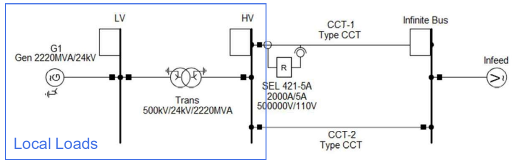
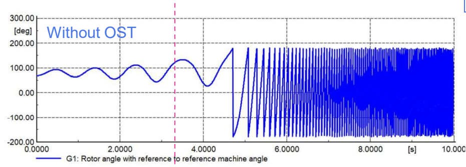
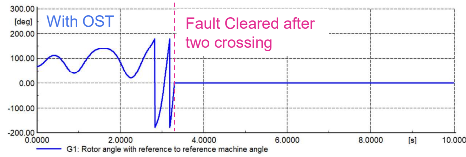
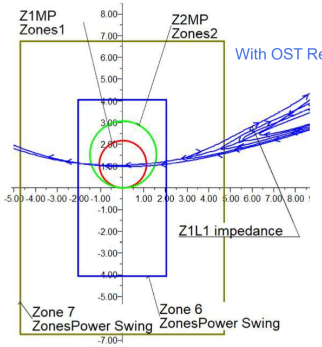
Example



Case 1: OST under Power Swing Caused by Transfer Limit







Case 2: Power Swing after Bolted Fault at CCT-2

Goals: Provide correct setting to interconnectors to enable faster trip. G1 can avoid going to instability with UFLS initiated.

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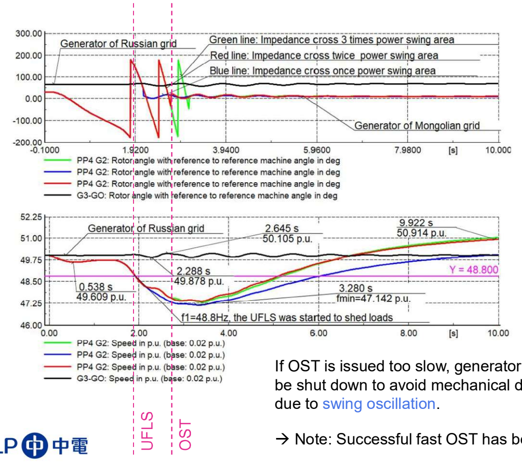
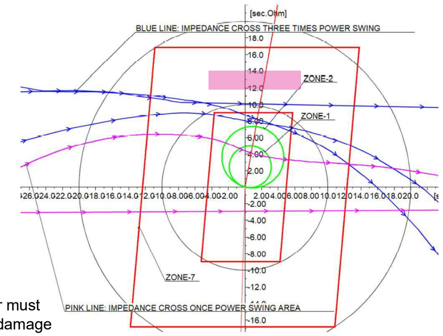
Example

At 2018, it took 4.5s and 5 slip cycles (4 crossings) to trigger OST to clear the unstable power swing. Generator 2 at CHP-4 had its shaft damaged due to the electromechanical oscillation.
After revising the setting, 1.022s and 1.5 slip cycles (the second crossing) has triggered OST, and UFLS is triggered beforehand.





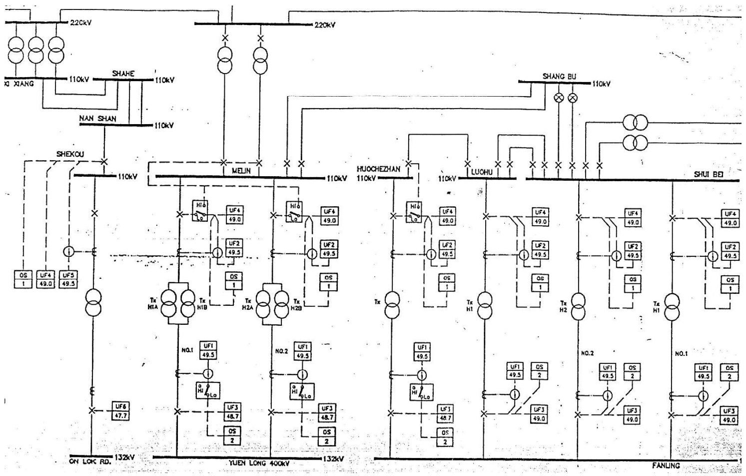
If OST is issued too slow, generator must be shut down to avoid mechanical damage due to swing oscillation.

→ Note: Successful fast OST has been performed in power swing in August 2021.

Conclusion

- Power Swing Blocking (PSB) is to block tripping of distance element during swing.
- It is noted that power swing can lead to prolonged thermal overload at out-of-phase (I_{MAX}, V_{MIN}) condition and dielectric failure at in-phase (I_{MIN}, V_{MAX}) condition, which can lead to cascade tripping or evolving three phase fault. To tackle evolving fault during power swing, I_2 – DOC can reset OSB.
- Typical method is to consider the rate-of-change of positive sequence impedance dZ_1/dt, which could positively reflect the status of power angle δ. Another method is swing center voltage (SCV) based. It gains popularity as it requires no setting, bounded and independent of system condition and source impedance.
- To set the blinders for PSB or OST, inner zone depends on the outermost tripping zone, and outer zone depends on the maximum load, or minimum load impedance.
- OSB includes a UBD coordination delay in single circuit to avoid tripping due to overreached element during SPO condition. Yet, POTT with current reversal blocking is to ensure healthy line security.
- System stability analysis under different operating conditions is needed to determine electrical center and hence optimal location of OST to embrace generation/load balance.
- OST is often enabled with trip-on-way-out (TOWO) as it can avoid out-of-phase breaking with large transient recovery voltage (TRV) and high chance of restrike. Yet, trip-on-way-in may be needed to avoid such delay and hence prolonged voltage dip and load loss. It is noted that delay tripping with several slip cycle can lead to overexcitation tripping of generators and hence total blackout.

Appendix 1: OSS Relay for Weak Interconnection



Appendix 2: Distance Setting Calculation Example

TSA – BKP TEE GWN/BAL CIRCUIT (PSB)

Power Swing Blocking				
Power Swing Blocking (EOOS):	1		(0 = Disable, 1 = Enable)	
Cyclic circuit rating - MW	135	MW		
Slip Frequency in Hz	5	Hz		
Min. Source Impedance (Secondary)	3.872	Ohm	ZT, Min. Transfer Impedance (Secondary) =	11.89389676 Ohm
Max. Source Impedance (Secondary)	23.232	Ohm	ZT, Max. Transfer Impedance (Secondary)=	50.61389676 Ohm
ZLOAD =	172.0888889	Ohm (Min. load impedance that Zone 7 must not entered.)		
% of Zone 6 Resistance =	120	% of Zone 4	% of Zone 6 Reactance =	120 % of Zone 4
Zone 6 Resistance - Right (R1R6) =	5.40	Ohm	Zone 6 Reactance - Top (X1T6) =	9.96 Ohm
The travelling time from Z7 to Z6 under Max. Source impedance condition at the slip frequency.				
Let % of ZLOAD for Zone 7 Calculation =	75	% (< 80% for safety reason)		
Zone 7 Resistance - Right (R1R7) =	49.09	Ohm		
Zone 7 Reactance - Top (X1T7) =	53.66	Ohm		
Ang_R6 (rad) =	2.721	radian		
Ang_R7 (rad) =	0.952	radian		
OSBD (ms) =	56.326	ms (OSBD must be > 10ms)		
OSBD (cyc) =	2.816	cycles		
Remark:				
R1R7/R1R6 =	9.098	(Must be > 1.5)		

$$R1R6 = \frac{120\%Z4}{2}\frac{1}{\sin\theta_L}$$

$$R1R7 = 0.9Z_{load}\cos(45^o + 90^o - \theta_L)$$

$$X1T6 = 120\%Z4$$

Setting Criteria:	Line(%)	100%
Phase	Tx(%)	0%
Zone 1 (sec. Ω)	4.150027953	67.36 deg
Zone 2 (sec. Ω)	6.225041929	67.36 deg
Zone 4 (sec. Ω)	8.300055905	67.36 deg

Appendix 3: Taiwan 303 Blackout Investigation Report

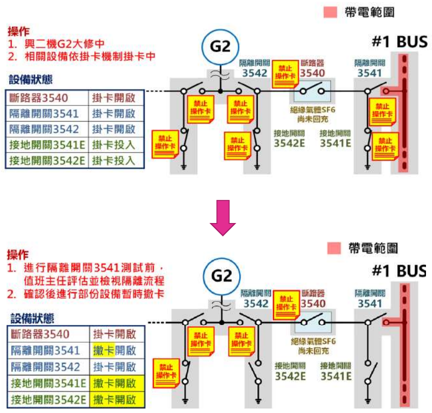
Event Background

- G2 Overhaul
- CB 3540 Degas due to large moisture content
- DS 3541 Work on Control Circuit

Generation staff performed tests on DS 3541 control circuit by **removing notices and unlock** 3542E, 3541E and DS 3541.

Note:

1. CB 3540 has been degas-ed
2. Interlock for DS 3541 only includes opening of 3541E, 3542E, BB Earth & CB 3540 (no gas status on CB 3540)
3. Closing of DS3541 by motor requires **7 sec**.



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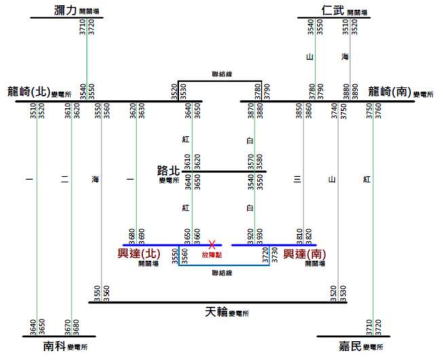
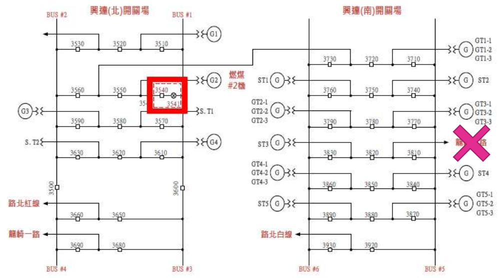
System Background

龍崎三路 was under outage. 興達(北) was coupled with 興達(南) with 興達(南) has only one outgoing feeder, inter-station connector protection rendered inoperative to avoid blackout of 興達(南) .

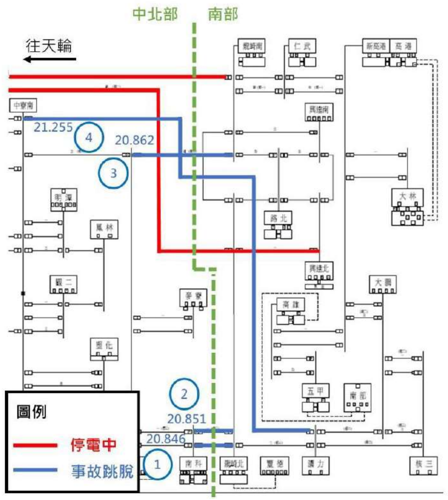




1. During closing of DS3541 [7 sec], (three phase) arcing current at CB3540 exists.
2. $I_{ARC} > I_{CT\ Supervision}$ for 5 sec → **HZBBZ lockout**, OCEF not yet operated → No protection operated for BFP.
3. **Backup protection** – Z2 and Z3 on outgoing feeders operated after 0.3 sec and 1.0 sec. Yet, 龍崎-興達 No.1 distance NOT operated due to **Power Swing Blocking**.

Result

1. Interconnectors between Taiwan South (Generation side) and Taiwan North (Load side) were tripped with **System decoupling protection** (OST).
2. Taiwan South was under **over-frequency** due to generation > load, most of the generators are tripped with **UV, NPS, OF, overexcitation, field current thermal overload**.
3. Taiwan North was under **under-frequency** due to load > generation. 1st **UFLS** 3605MW shed, system frequency goes back to 59.7Hz. Yet, load still increases and 2nd **UFLS** was triggered with 746MW shed.



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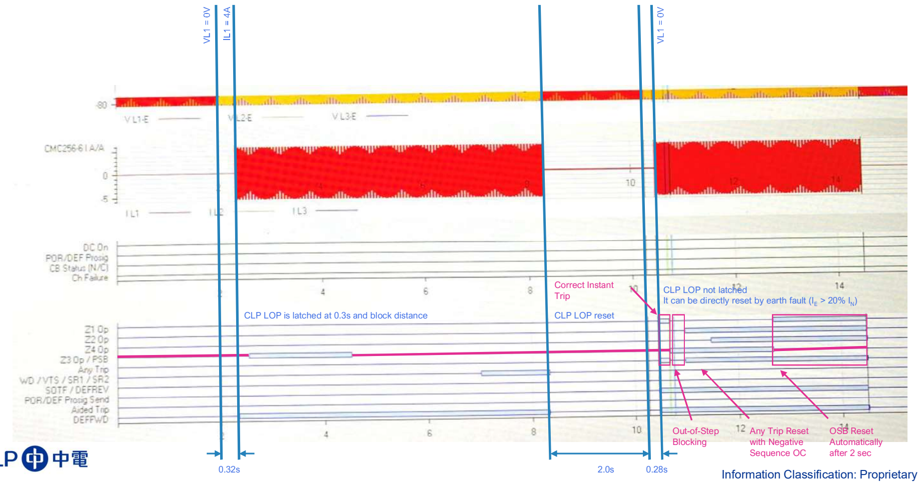
Appendix 4 – CLP LOP Logic Vs OSB Logic



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