Challenges in Application of Distance Relays under Power Swing Conditions

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69th Annual Conference for Protective Relay Engineers, April 4 - 7, 2016

Outline

- Introduction
- Theoretical Analysis of Voltage and Current Signals under Power Swing
- Impact to Distance Relay Performance
- Proposed Solutions
- PSCAD and RTDS Simulation Testing
- Conclusions

Introduction

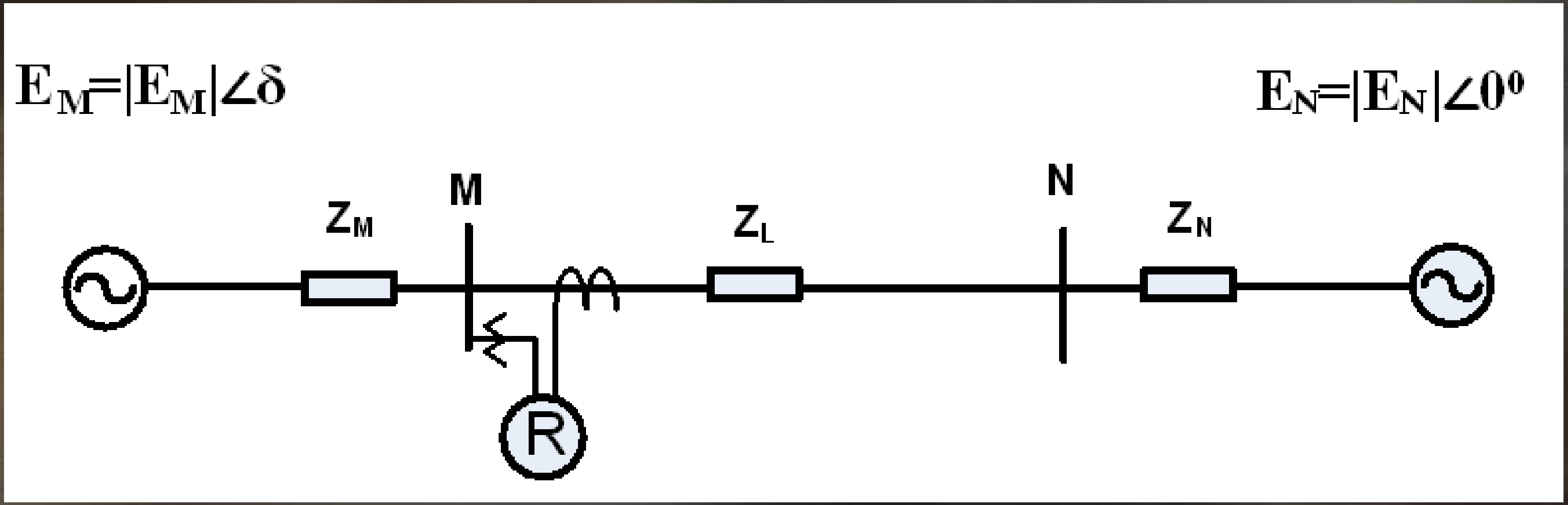
- Power system disturbances may cause stable or unstable power swings in the system
- Apparent impedance trajectories could enter into distance characteristics during a power swing and cause distance relay mis-operations
- A power swing blocking (PSB) function is typically included in modern distance relays to block distance elements during power swing to avoid mis-operations

Introduction

- The PSB signal to the distance elements needs to be removed when a line fault occurs at any time during the swing so that the distance elements can clear the legitimate line fault
- After the removal of the PSB signal from the distance elements, dependability, security and selectivity of the distance elements should be maintained

Power Swing Analysis

- Simple Power System

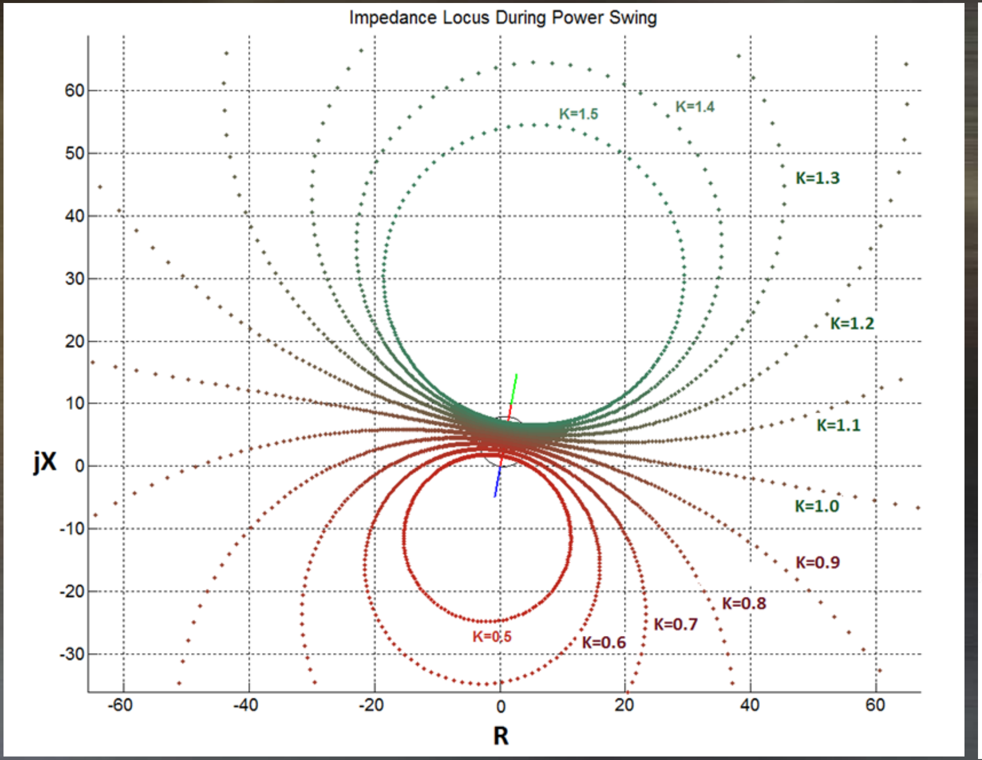


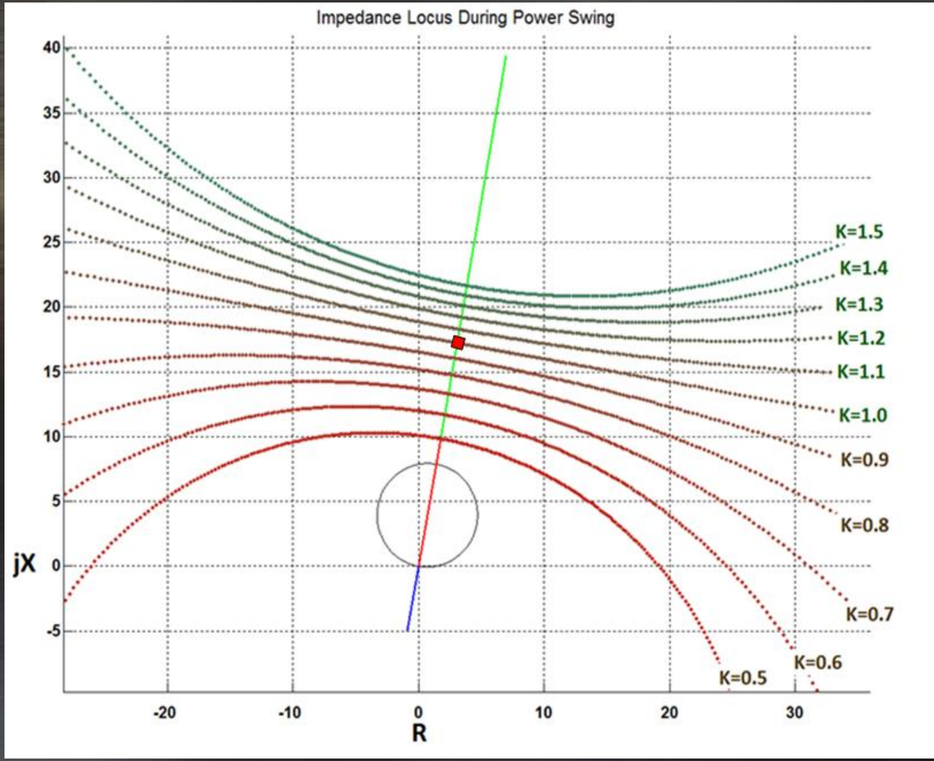
$$Z = \frac{E_M \cdot (Z_L + Z_N) + E_N \cdot Z_M}{E_M - E_N}$$

Impedance Locus during Power Swing

$Z_M=5\Omega\angle 80^0$, $Z_N=5\Omega\angle 80^0$
$Z_L=10\Omega\angle 80^0$

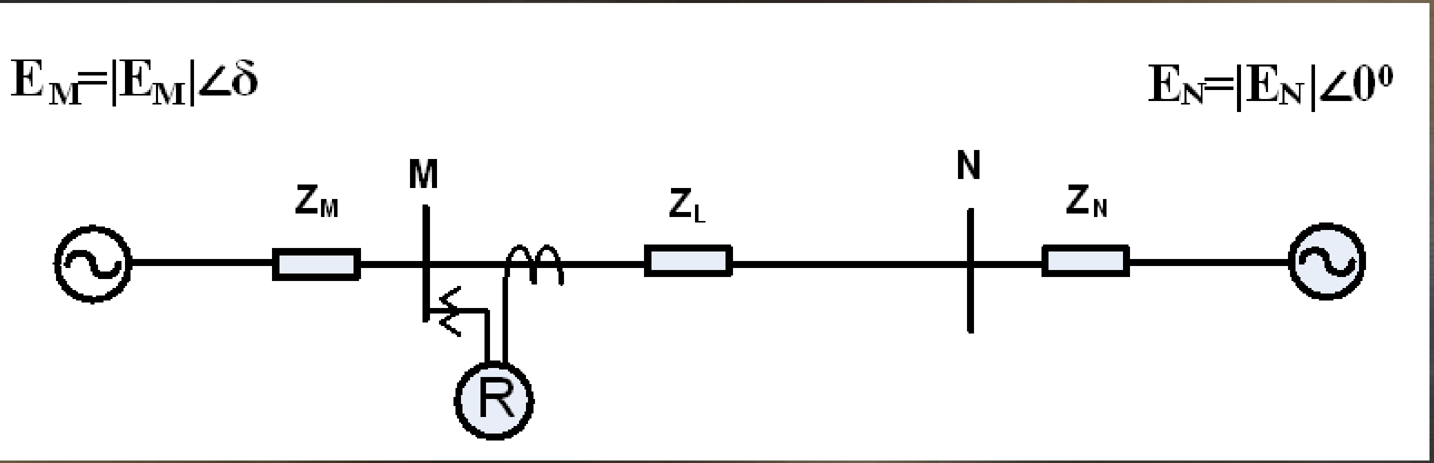
$Z_M=5\Omega\angle 80^0$, $Z_N=30\Omega\angle 80^0$
$Z_L=10\Omega\angle 80^0$





$K=|E_M|/|E_N|$

Theoretical Analysis of Signals Supplied to Relay

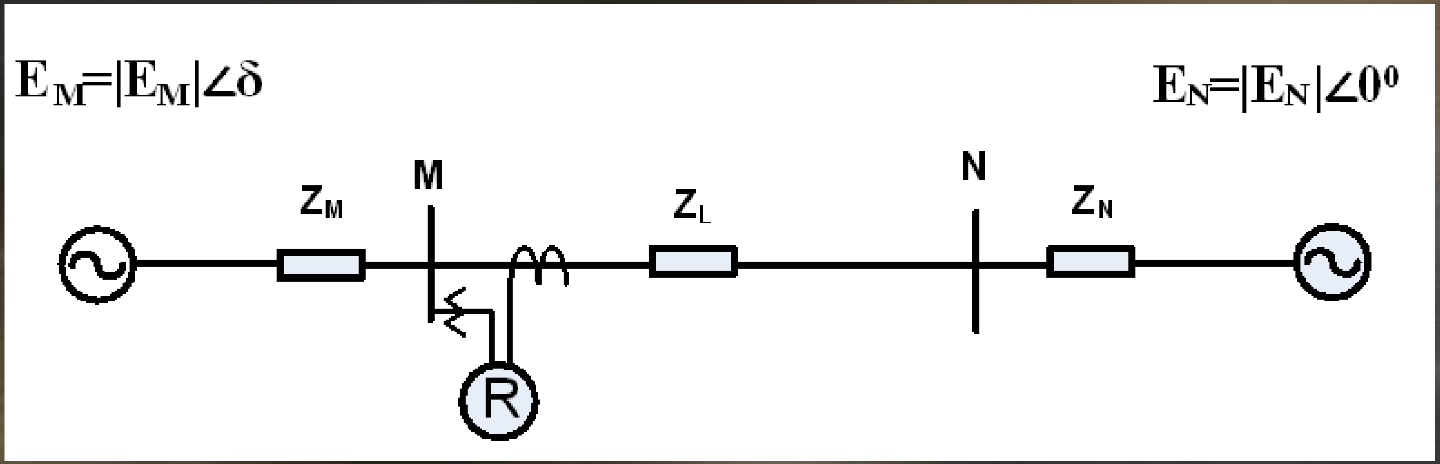


$$e_N = \sqrt{2} \cdot E \cdot sin(\omega_0 t)$$

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

- E_M and E_N are assumed to have the same amplitude
- Power swing is simulated with a frequency change at source M

Theoretical Analysis of Voltage Signals



$$v_M = e_M - \frac{e_M - e_N}{Z_\Sigma} * Z_M$$

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

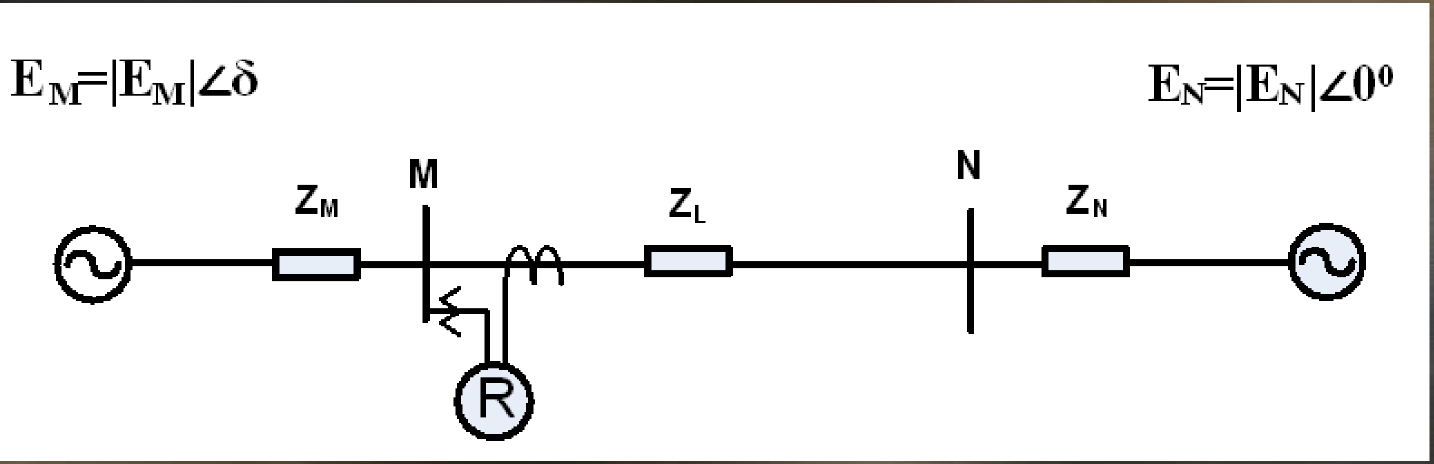
$$= \left(1 - \frac{Z_M}{Z_\Sigma}\right) \cdot \sqrt{2} \cdot E \cdot \sin(\omega_1 t + \beta) + \frac{Z_M}{Z_\Sigma} \cdot \sqrt{2} \cdot E \cdot \sin(\omega_0 t)$$

$$= a_1 \cdot \sqrt{2} \cdot E \cdot \sin(\omega_1 t + \beta) + a_2 \cdot \sqrt{2} \cdot E \cdot \sin(\omega_0 t)$$

$$Where:\ a_1 = \left(1 - \frac{Z_M}{Z_\Sigma}\right)$$

$$a_2 = \frac{Z_M}{Z_\Sigma}$$

Theoretical Analysis of Voltage Signals



$$v_M = \sqrt{2}\cdot E\cdot\sqrt{a_1^2 + a_2^2 + 2a_1a_2\cos((\omega_1-\omega_0)\,t+\beta)}\cdot\sin(\omega_1 t + ph)$$

$$=\sqrt{2}\cdot E\cdot Mag\cdot\sin(\omega_1 t + ph)$$

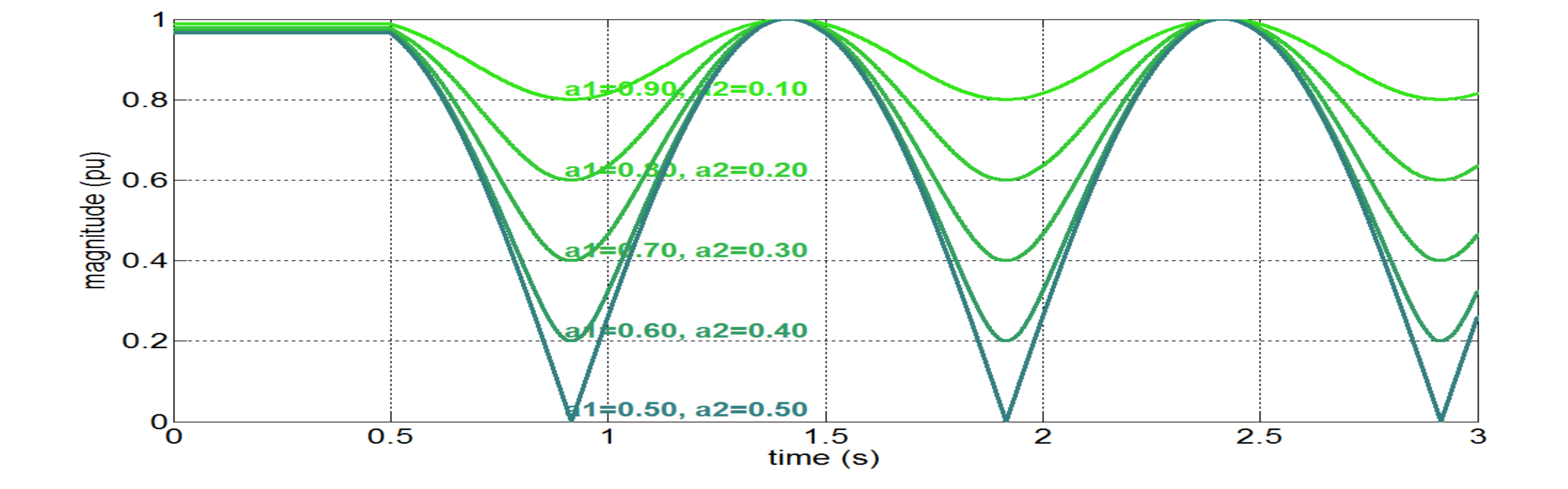
$$Mag = \sqrt{a_1^2 + a_2^2 + 2a_1a_2\,cos((\omega_1-\omega_0)\,t+\beta)}$$

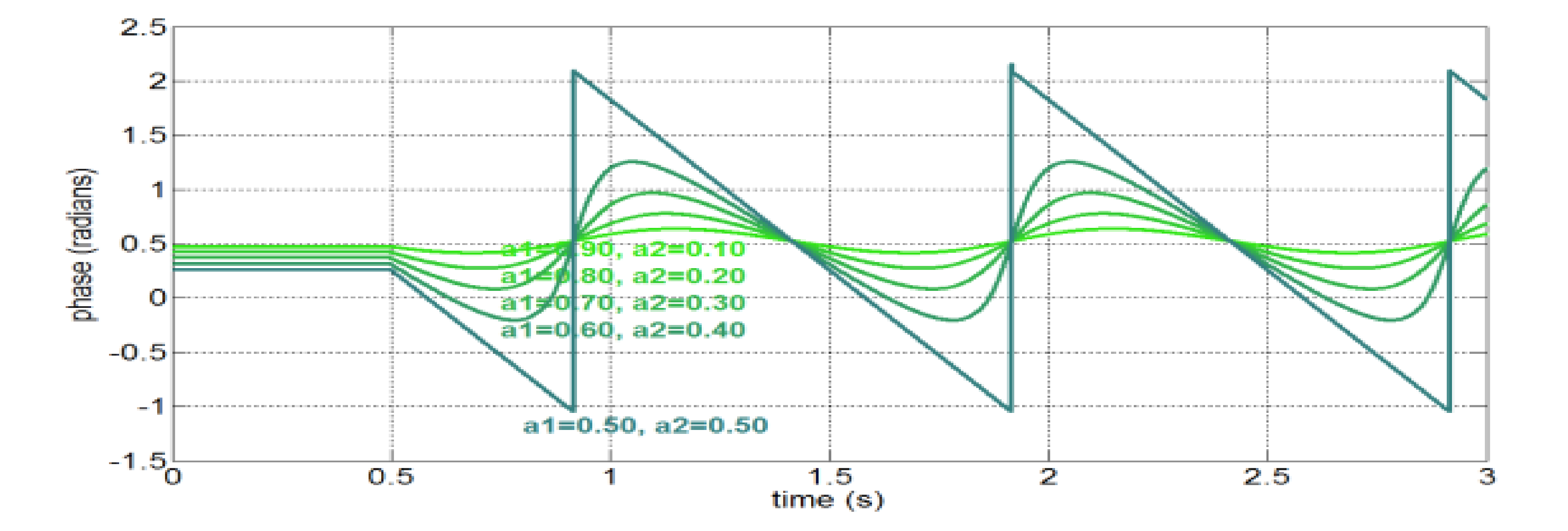
$$ph = tan^{-1}\left(\frac{a_1\,sin\,\beta - a_2\,sin(\omega_1-\omega_0)t}{a_1\,cos\,\beta + a_2\,cos(\omega_1-\omega_0)t}\right)$$

$$a_1 = \left(1-\frac{Z_M}{Z_\Sigma}\right)$$

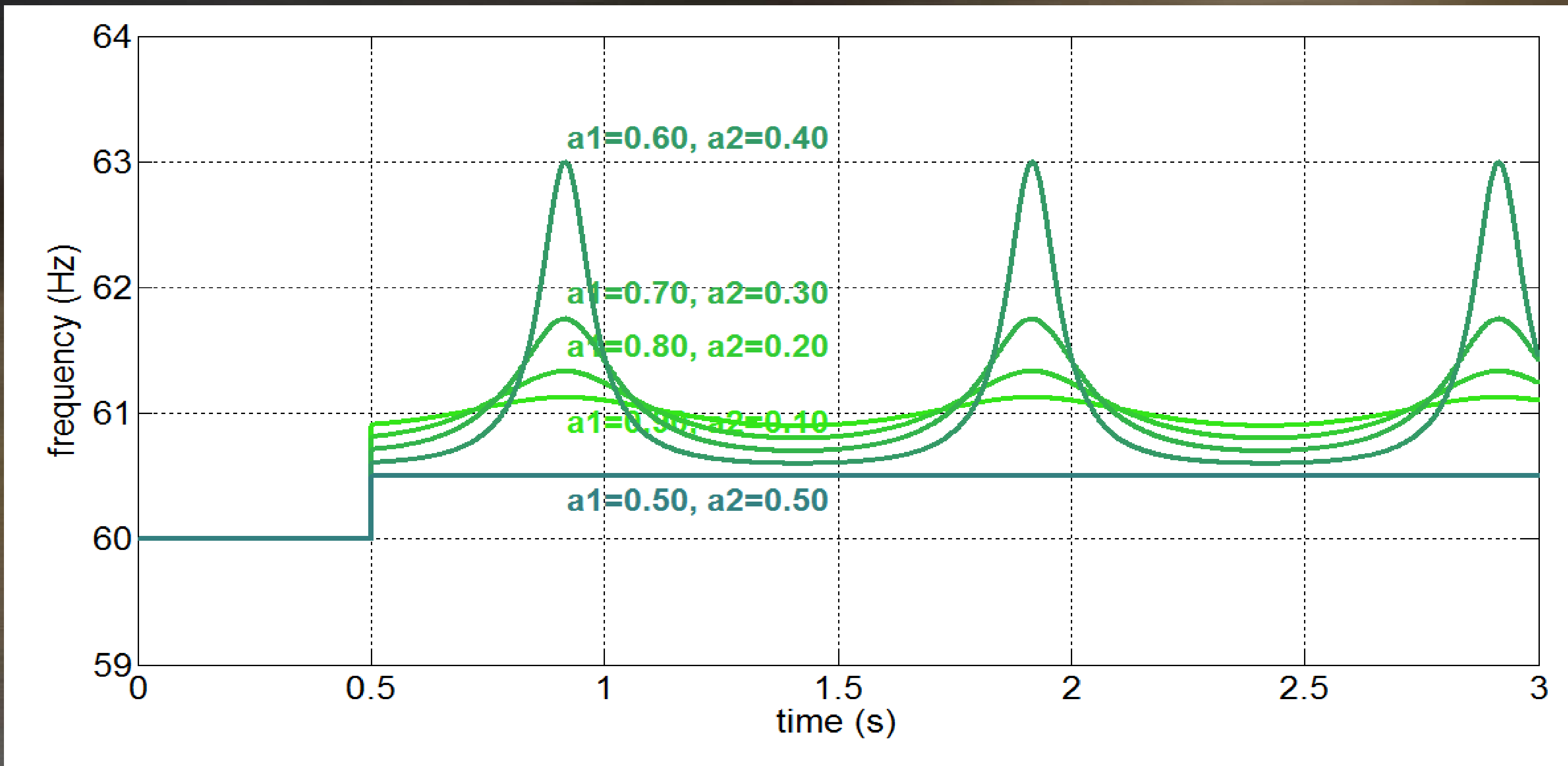
$$a_2 = \frac{Z_M}{Z_\Sigma}$$

Theoretical Analysis of Voltage Signals





Theoretical Analysis of Voltage Signals



$$\mathrm{f}_{\min} = f_0 + \frac{a_1(f_1 - f_0)}{a_1 + a_2}$$

$$f_{max} = f_0 + \frac{a_1(f_1 - f_0)}{a_2 - a_1}$$

Theoretical Analysis of Current Signals

$$i = \frac{e_m - e_n}{Z_\Sigma}$$

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

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

$$= \frac{2\sqrt{2}E}{Z_\Sigma} * Mag\_I * cos(\, 2\pi \boxed{\frac{f_1 + f_0}{2}} t + \boxed{\frac{\beta}{2}})$$

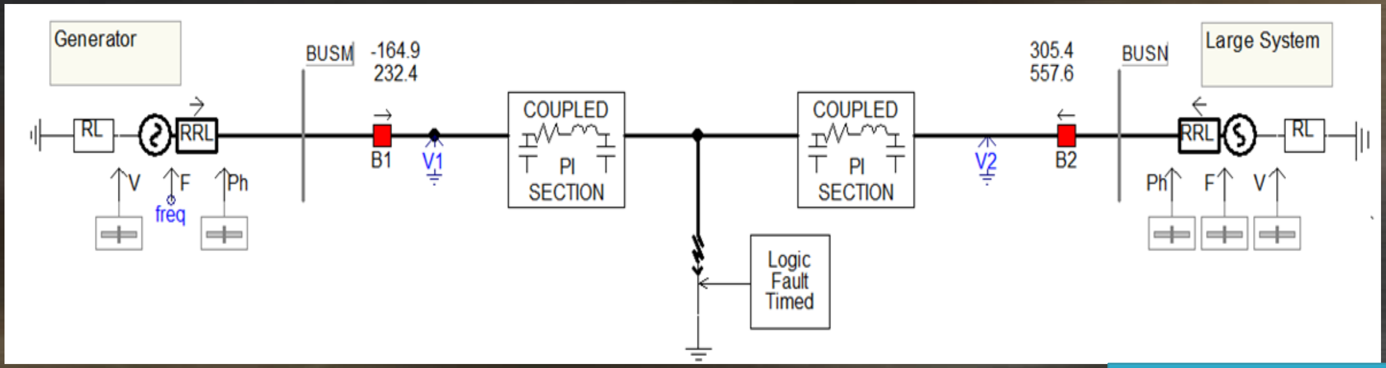
Where $\boxed{Mag\_I = sin(2\pi \frac{f_1 - f_0}{2} t + \frac{\beta}{2})}$

Magnitude

Frequency

Phase

PSCAD Simulation Confirmation - Voltage



$Z_M=40\angle 80^0$

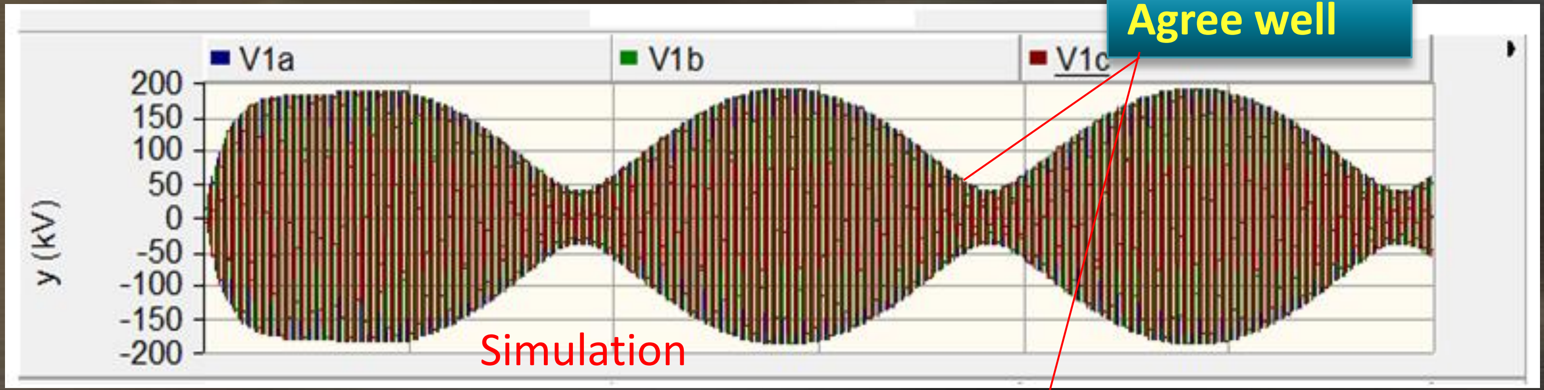
$Z_N=20\angle 80^0$

$Z_L=40\angle 80^0$

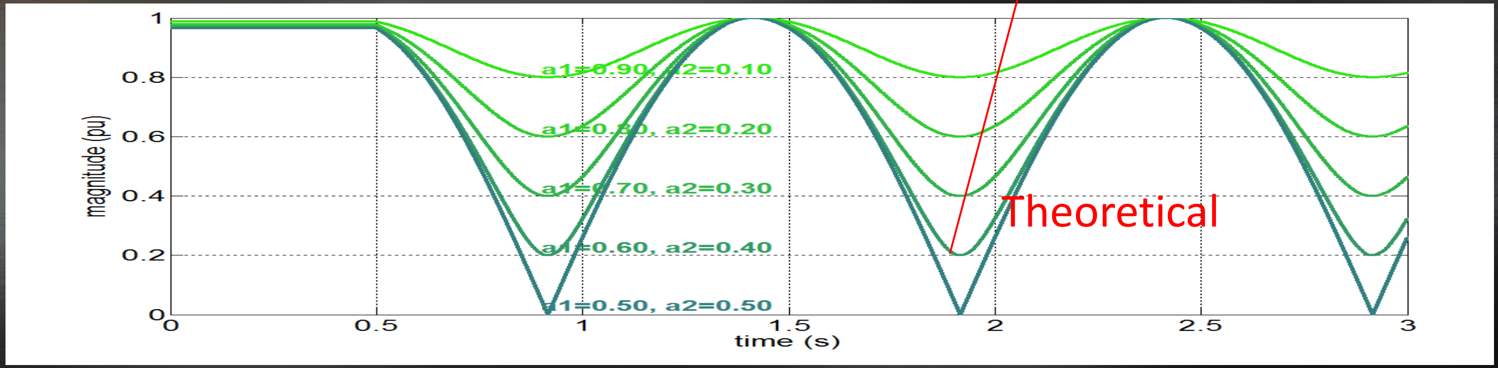
$a_1=(1-Z_M/Z_\Sigma)=0.6$

$a_2= Z_M/Z_\Sigma=0.4$

Agree well



Simulation

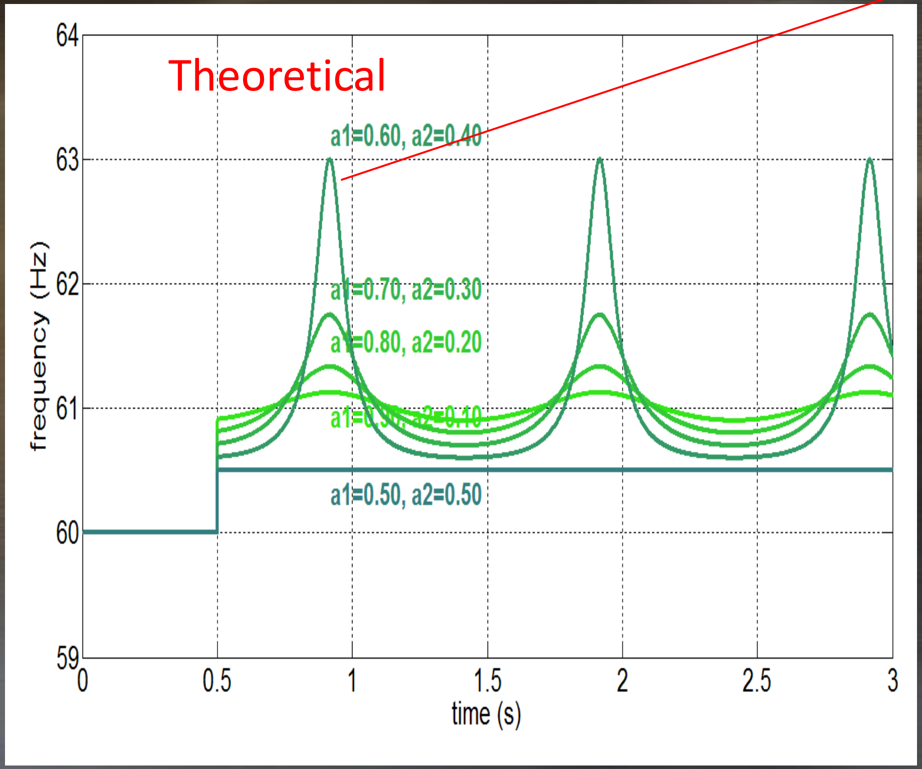


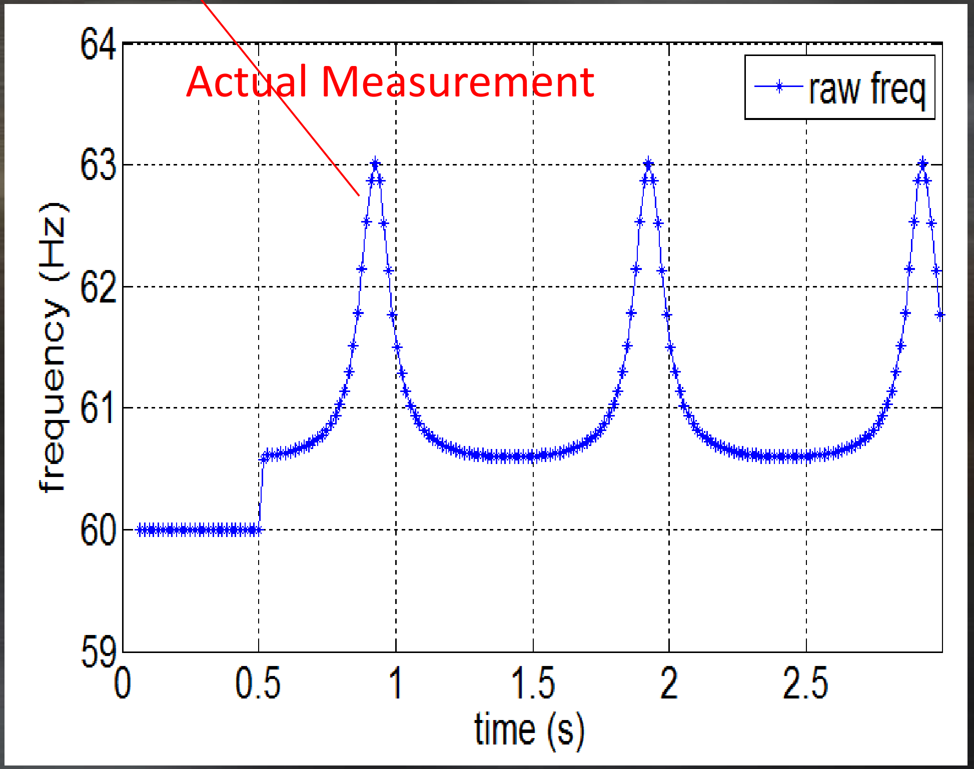
Theoretical

PSCAD Simulation Confirmation – Frequency

- $Z_M=40\angle 80^0$, $Z_N=20\angle 80^0$, and $Z_L=40\angle 80^0$ primary Ohms, result in $a_1=(1-Z_M/Z_\Sigma)=0.6$ and $a_2=Z_M/Z_\Sigma=0.4$

Agree well





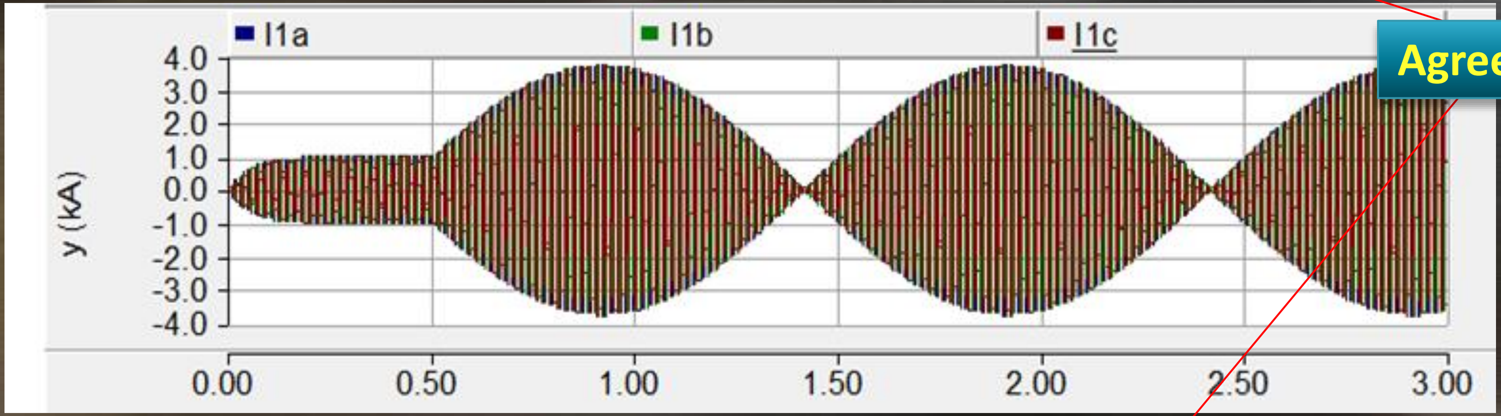
$$f_{min} = f_0 + \frac{a_1(f_1 - f_0)}{a_1 + a_2}$$

$$f_{max} = f_0 + \frac{a_1(f_1 - f_0)}{a_2 - a_1}$$

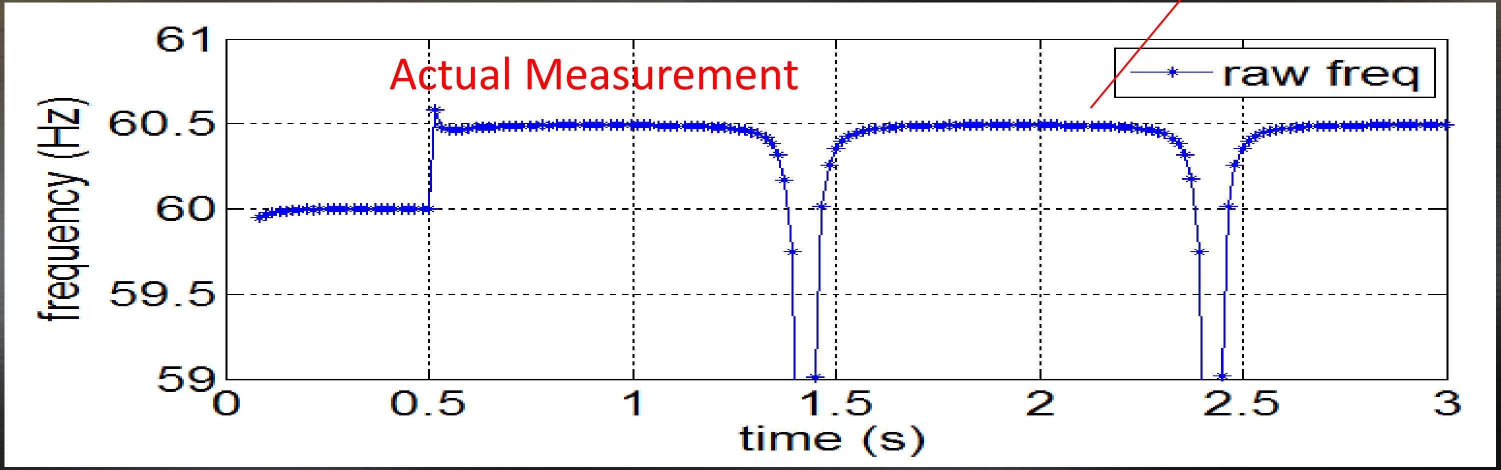
PSCAD Simulation Confirmation – Current

- $$i = \frac{2\sqrt{2}E}{Z_\Sigma} * Mag\_I * cos(2\pi \boxed{\frac{f_1+f_0}{2}} t + \frac{\beta}{2})$$

  Where $Mag\_I = sin(2\pi \frac{f_1-f_0}{2} t + \frac{\beta}{2})$

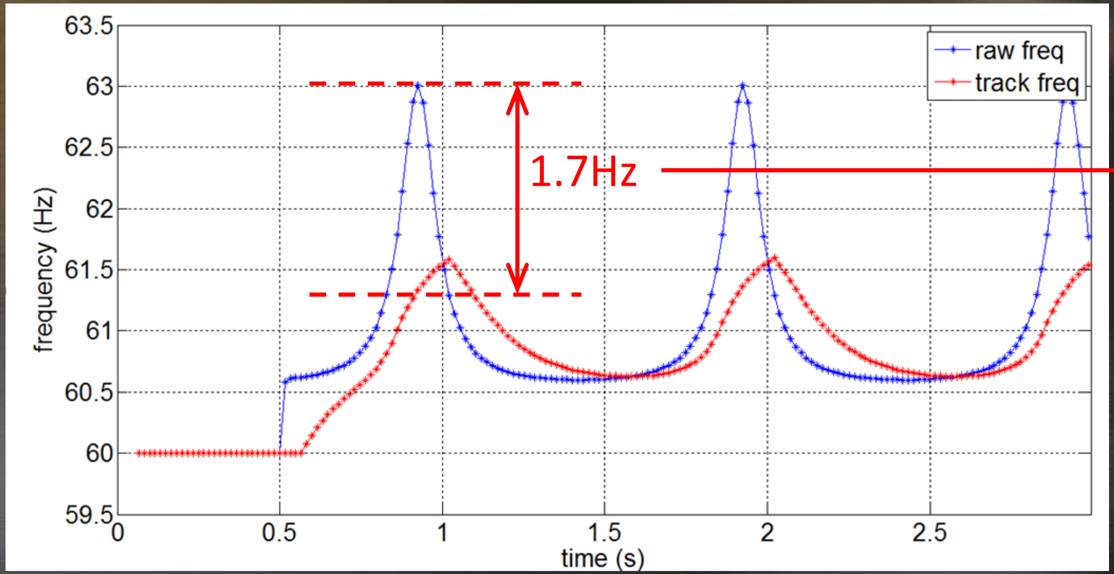


Agree well



Impact to Distance Relay Performance

- Modern digital protective relays typically use variable sampling rate that tracks to the actual system frequency
- An IIR filter is typically applied to smooth out the tracking frequency variation in order to reduce errors



Such large difference not only causes magnitude and phase measurement errors in phasor estimation, but also causes errors in the distance memory polarization.

Impact to Distance Relay Performance

- Mho Characteristic

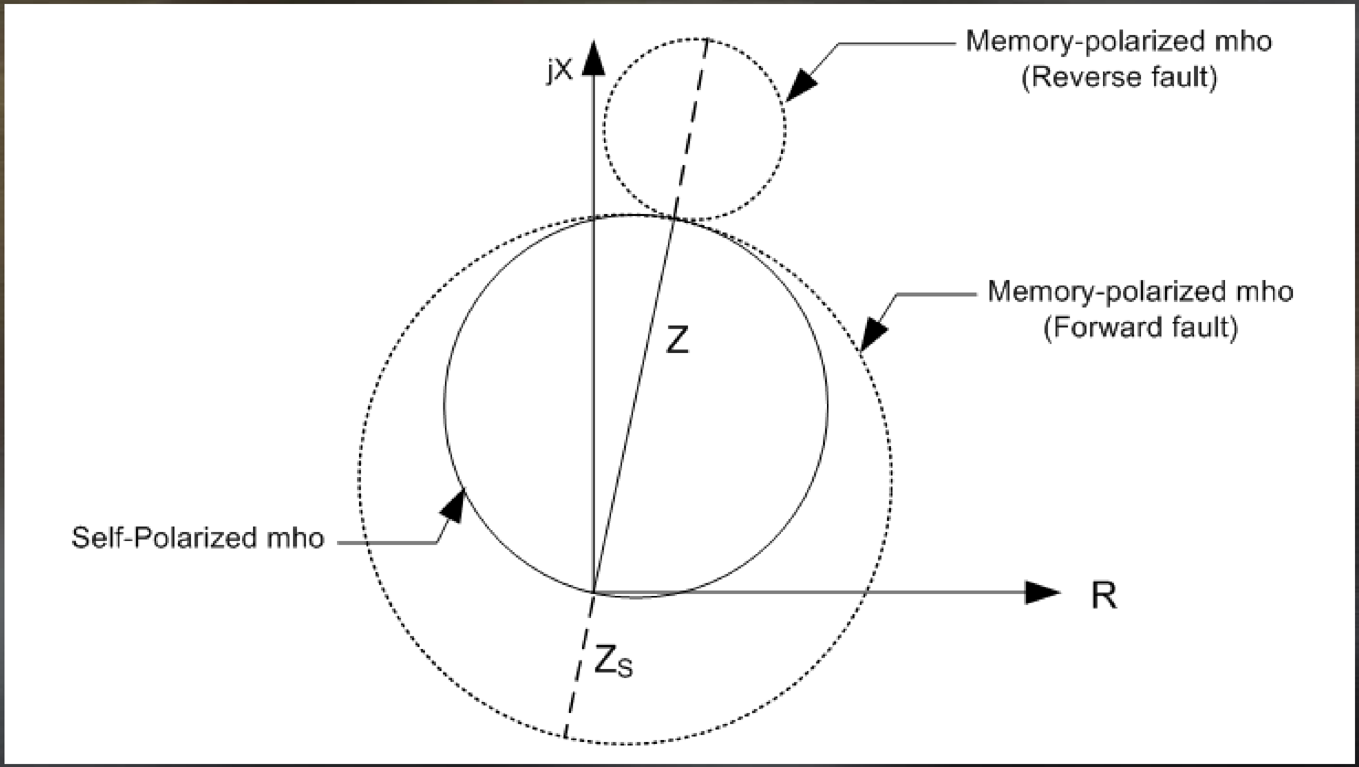
$$V_{OP} = I * Z - V$$

$$V_{POL} = V1_{MEM}$$

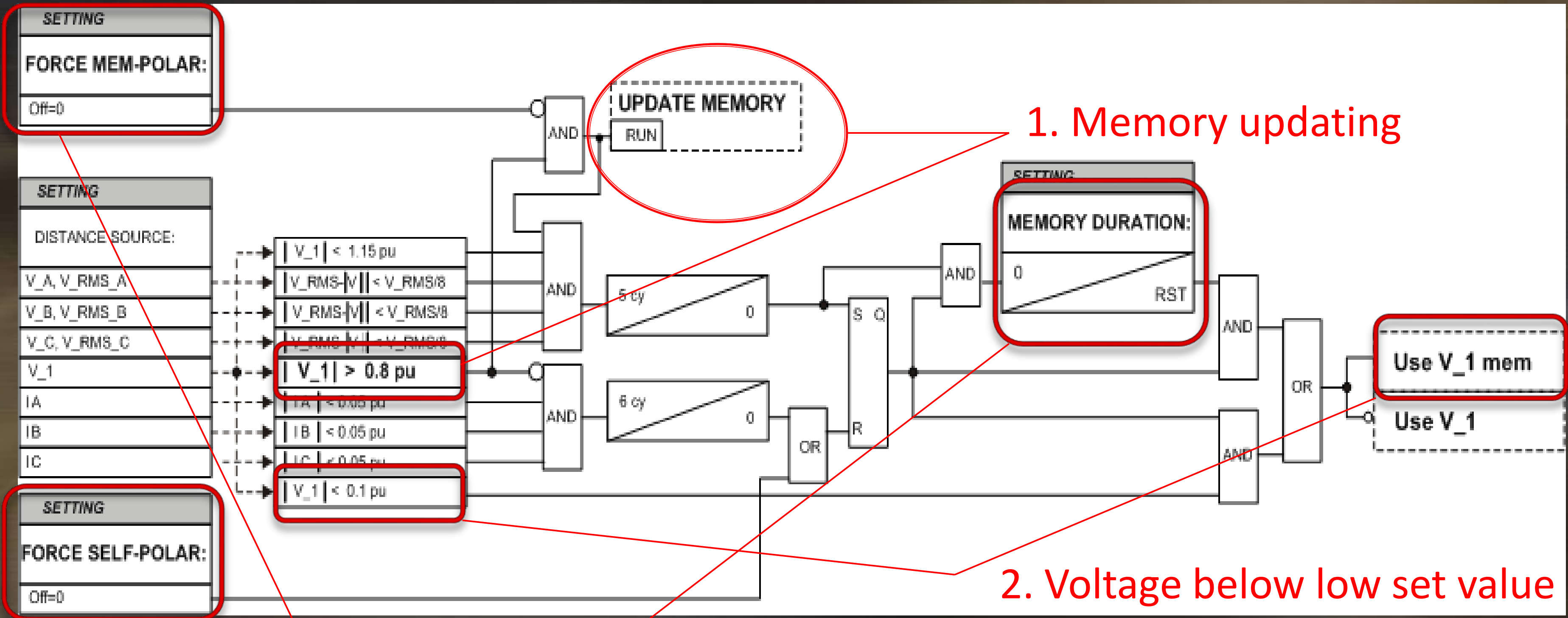
- Directional Element

$$V_{OP} = I * Z_D$$

$$V_{POL} = V1_{MEM}$$



Memory Voltage Mechanism



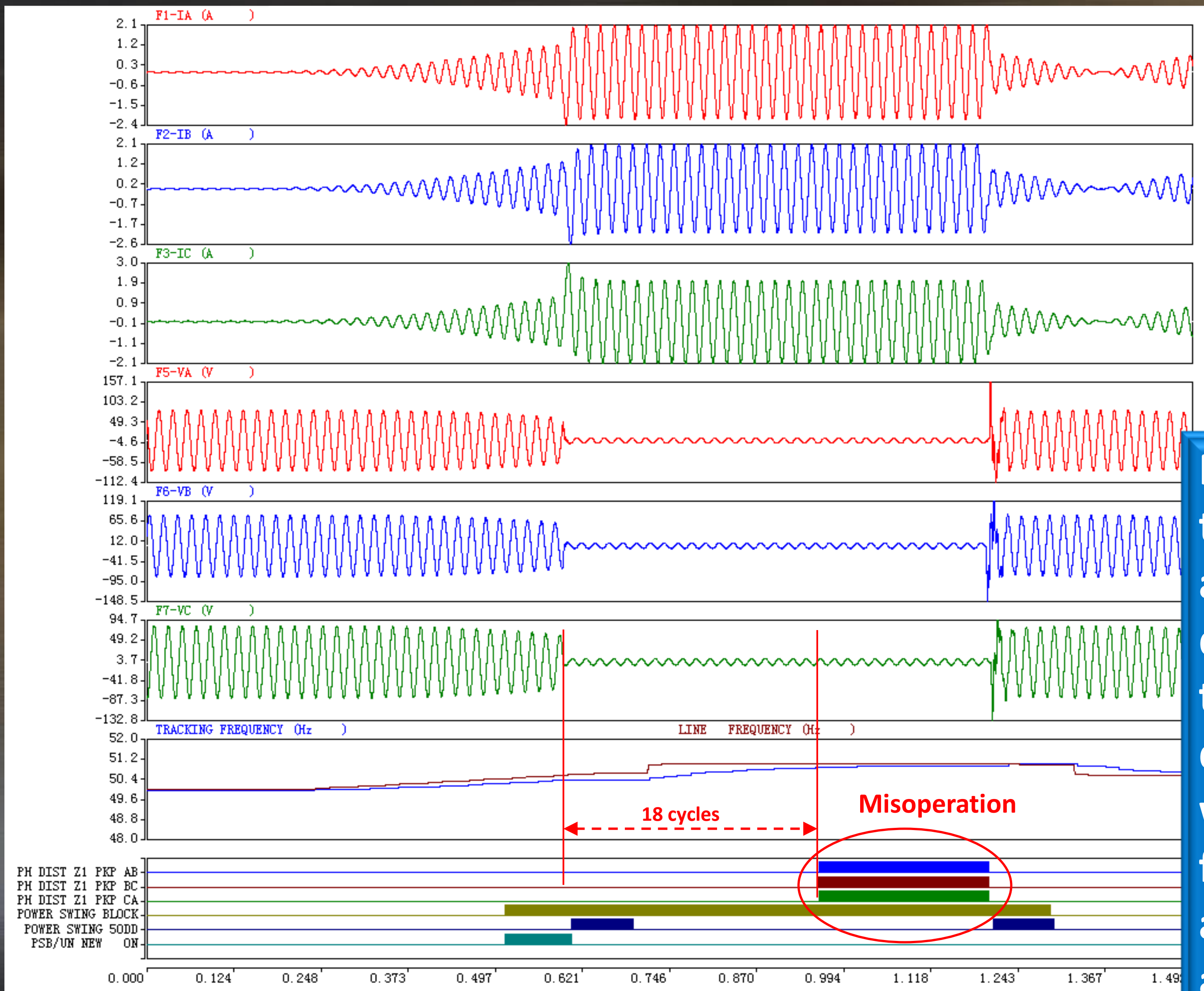
1. Memory updating

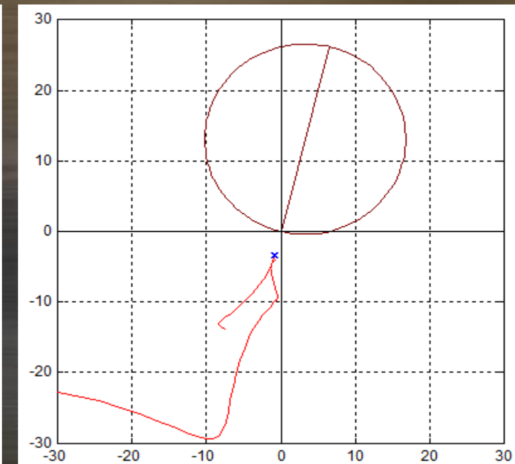
2. Voltage below low set value

3. Voltage above low set value

4. Force "MEM" or "SELF" polarization

Impact to Distance Relay Performance





Phase distance zone1 tripped in 18 cycles after fault inception due to adverse impact to memory voltage during power swing, in which tracking frequency may not be able to keep pace with actual frequency

Solutions for Memory Polarization Issues

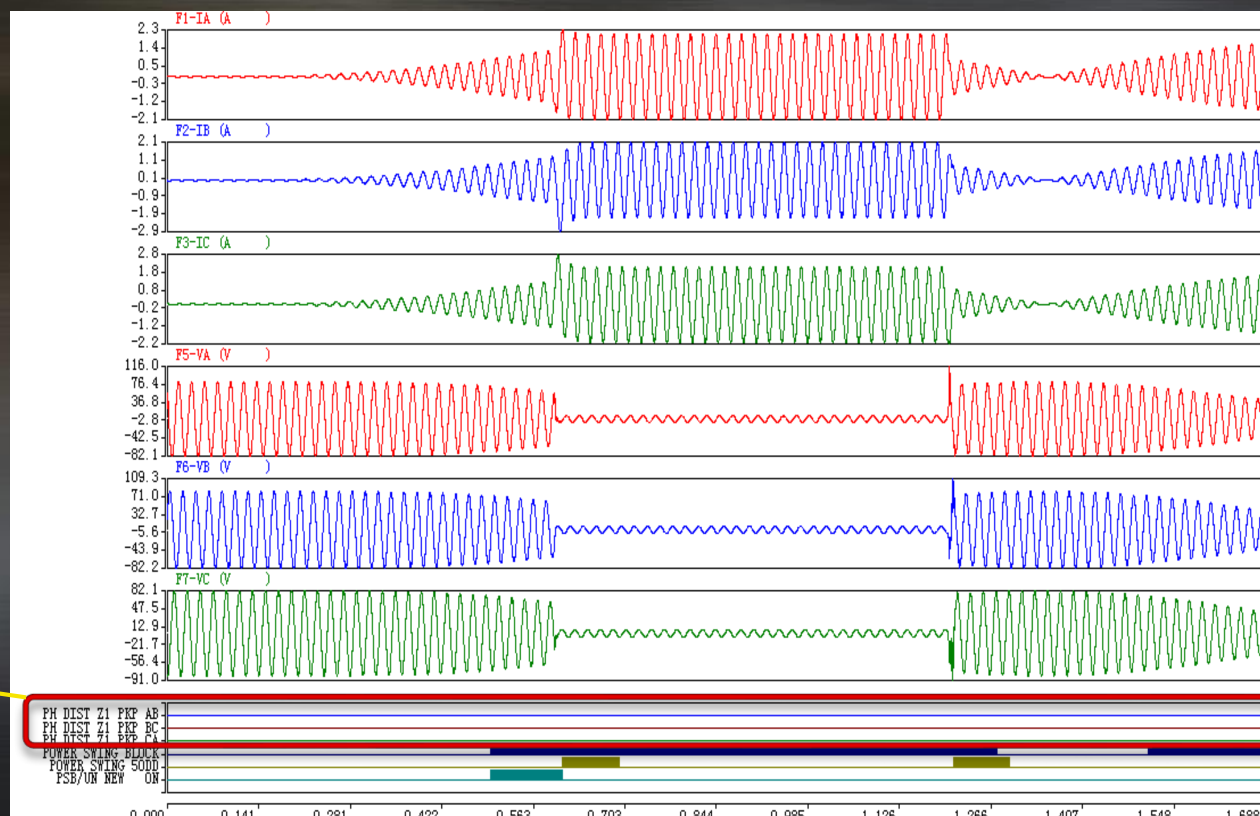
1. Making the memory duration shorter
2. Force self-polarization
3. Memory voltage angle compensation:

$$f = \frac{1}{2\pi}\frac{d\varphi}{dt}$$

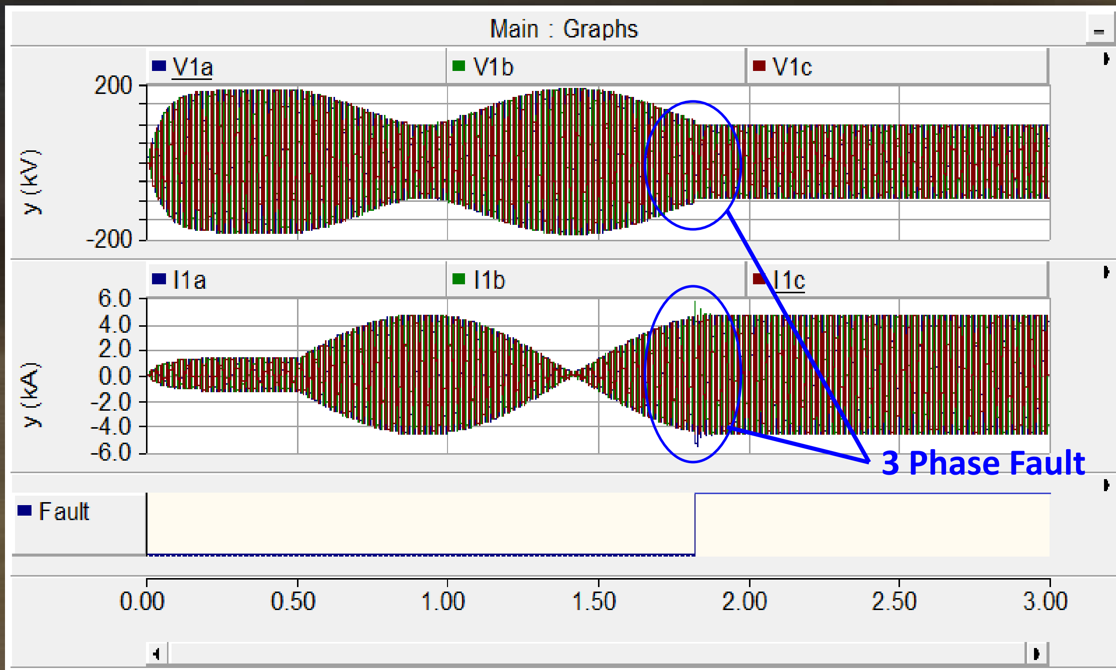
$$\Delta\varphi = 2\pi \cdot f_{slip} \cdot \Delta t$$

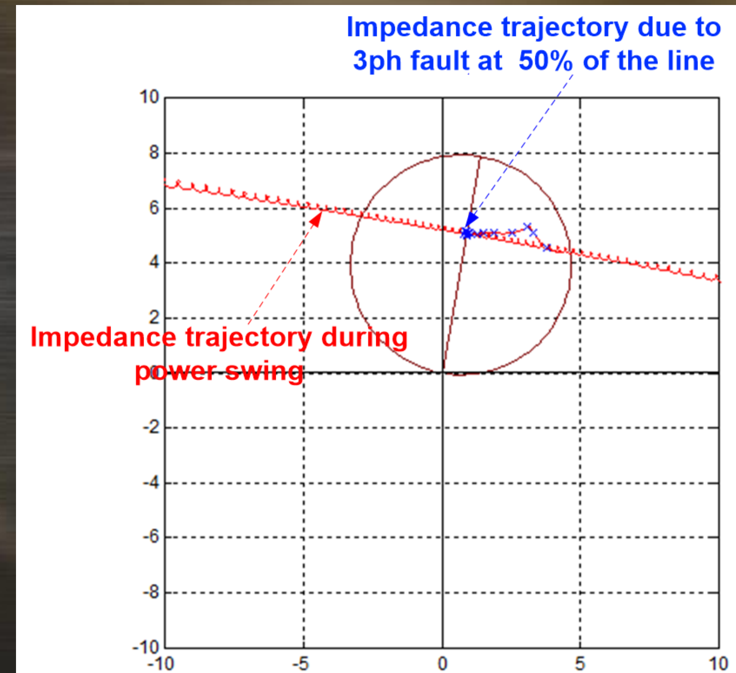
$$\varphi = \varphi_{prev} + \Delta\varphi$$

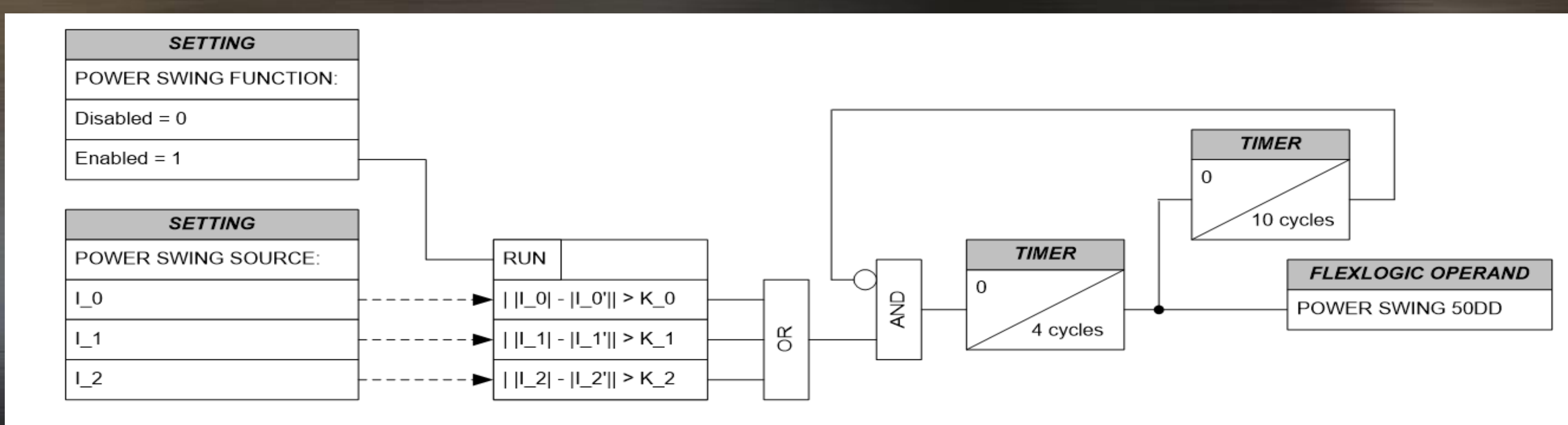
No Operation



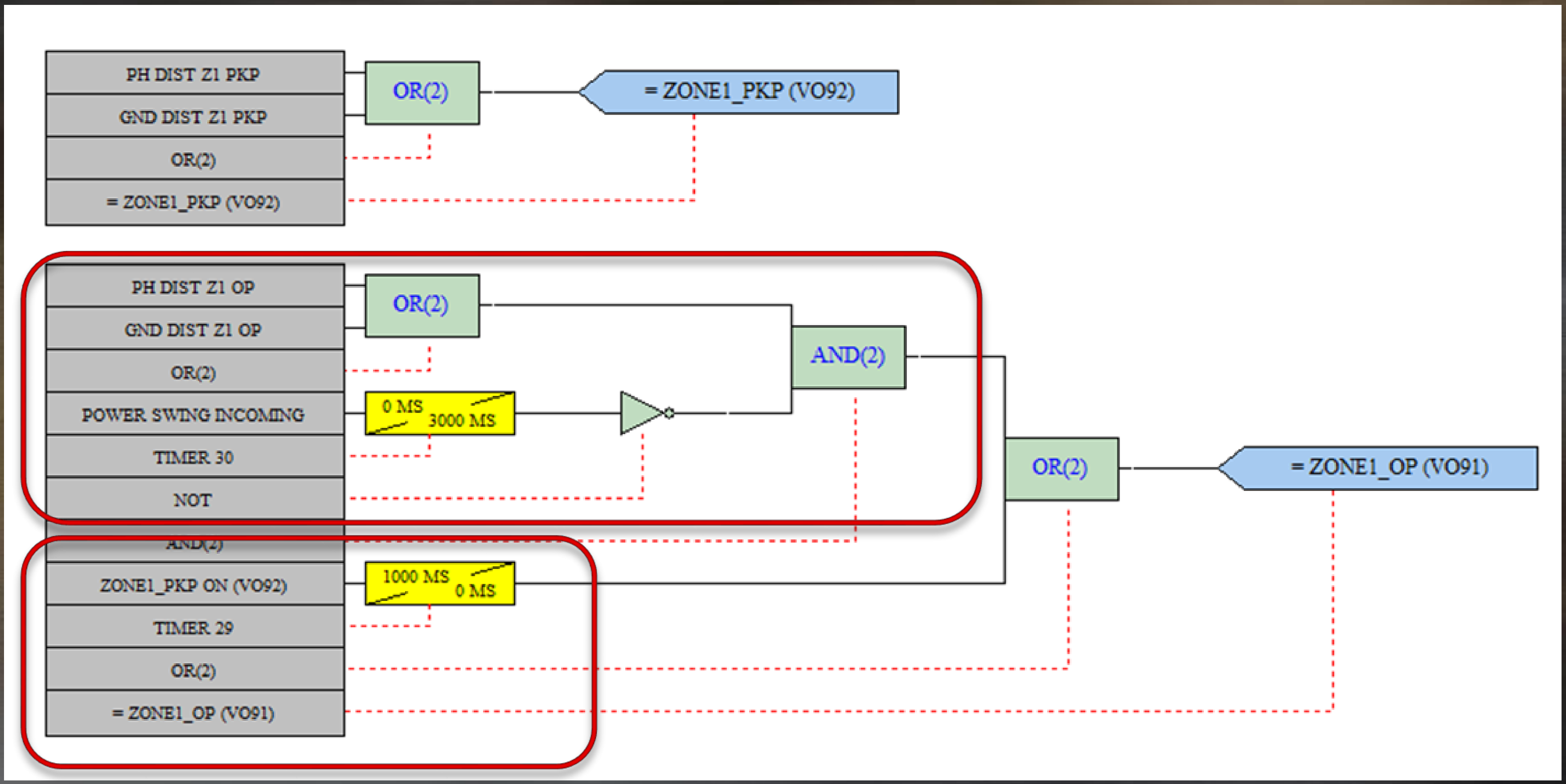
Fault Detection During Power Swing







Security Consideration on PSB Removal



Conclusions

- During power swing, frequency measured from the voltage signal and that from the current signal are not equal. The former is affected by the location where the voltage measurement is taken and varies with time; the latter does not vary with time, which is equal to the average of the two source frequency
- Memory voltage plays an important role in distance protection, which determines the dynamic behavior of the distance characteristic
- Distance element performance can be adversely affected by memory voltage when tracking frequency cannot keep pace with the actual frequency

Conclusions

- Automatic angle compensation to memory voltage based on the slip frequency between the actual and the tracking frequency is a simple and an effective way to eliminate such adverse impact
- Detection of 3 phase fault during power swing might be difficult because the fault current may be buried in the high magnitude swing current. A readily available distance spare zone in the digital relay can be used to detect such 3 phase fault
- Additional delay is required upon the removal of the PSB signal on distance elements to ensure security

Thank You

Questions?