Realistic Testing of Power Swing Blocking and Out-of-Step Tripping Protection Functions

Quintin Verzosa, Jr. "Jun"
Doble Engineering Company

66th Annual Conference for Protective Relay Engineers

Texas A & M University

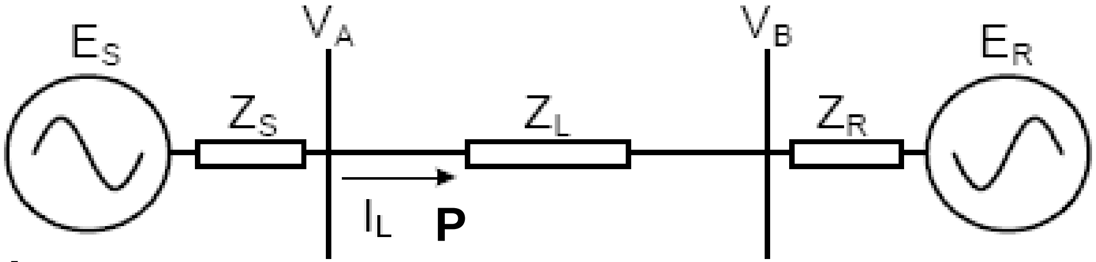
College Station, Texas

8-11April 2013

Topics

- Review of Basic Power System Stability
- Effect of Power Swings and Out-of-step conditions on Line Protection
- Detection Methods for Power Swing Blocking (PSB) and Out-of-step Tripping (OST)
- Methods of Testing OSB and OST Functions

Basic Power System Stability



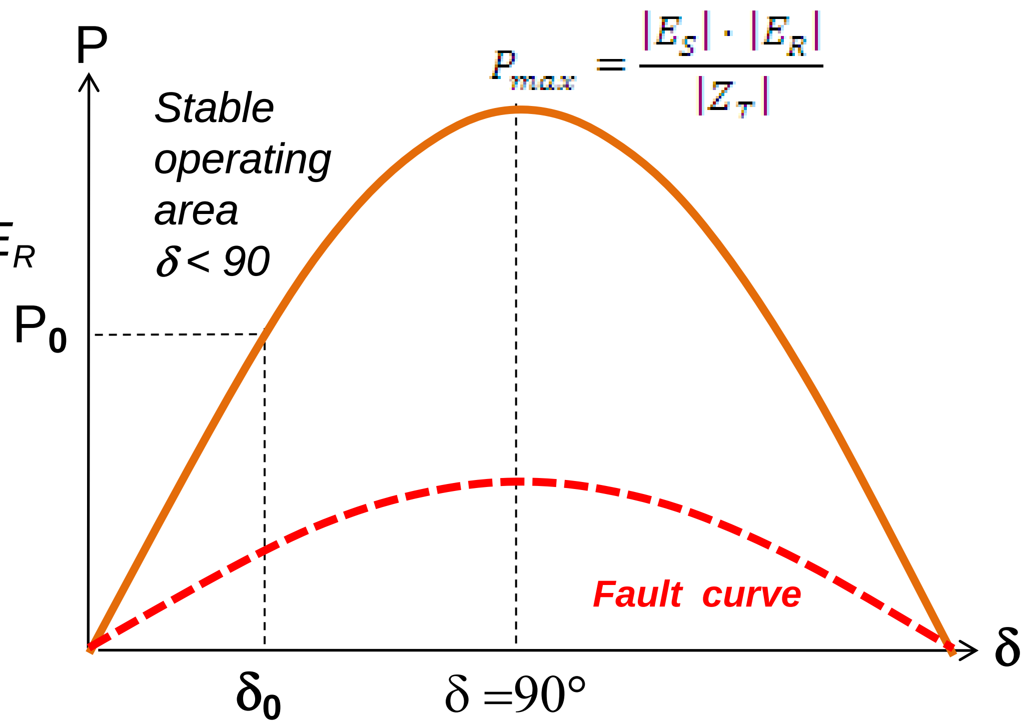
Power Equation:

$$P = \frac{E_S \cdot E_R}{Z_T} \cdot \sin(\delta)$$

δ = rotor angle between E_S and E_R

$$Z_T = Z_S + Z_L + Z_S$$

During a Fault the effective transfer impedance Z_T between the two machines increases. This has the effect of decreasing the maximum power transfer

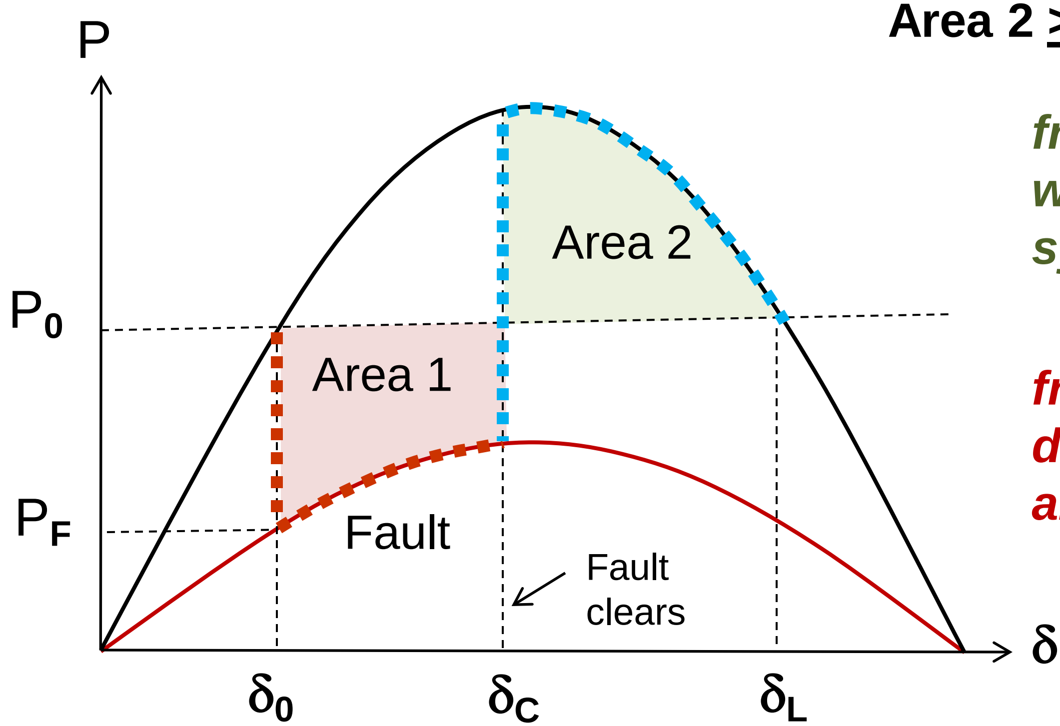


Basic Power System Stability

Equal Area Criterion

Area 2 < Area 1 : Unstable

Area 2 $\geq$ Area 1 : Stable

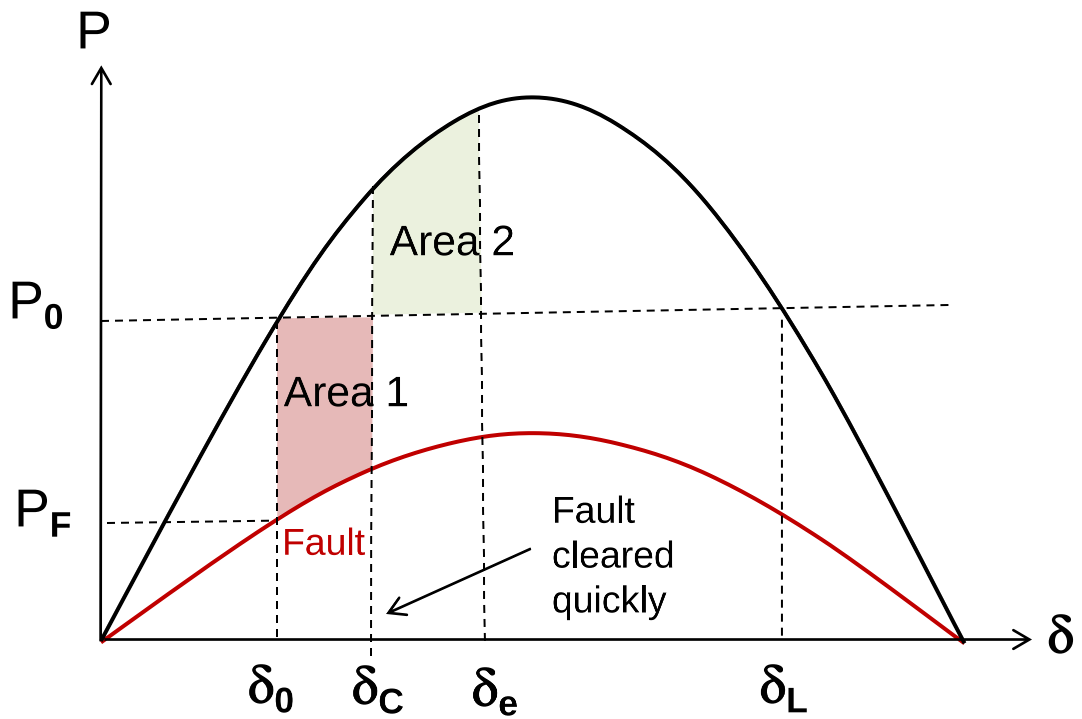


frequency and angle will return to normal if system is stable

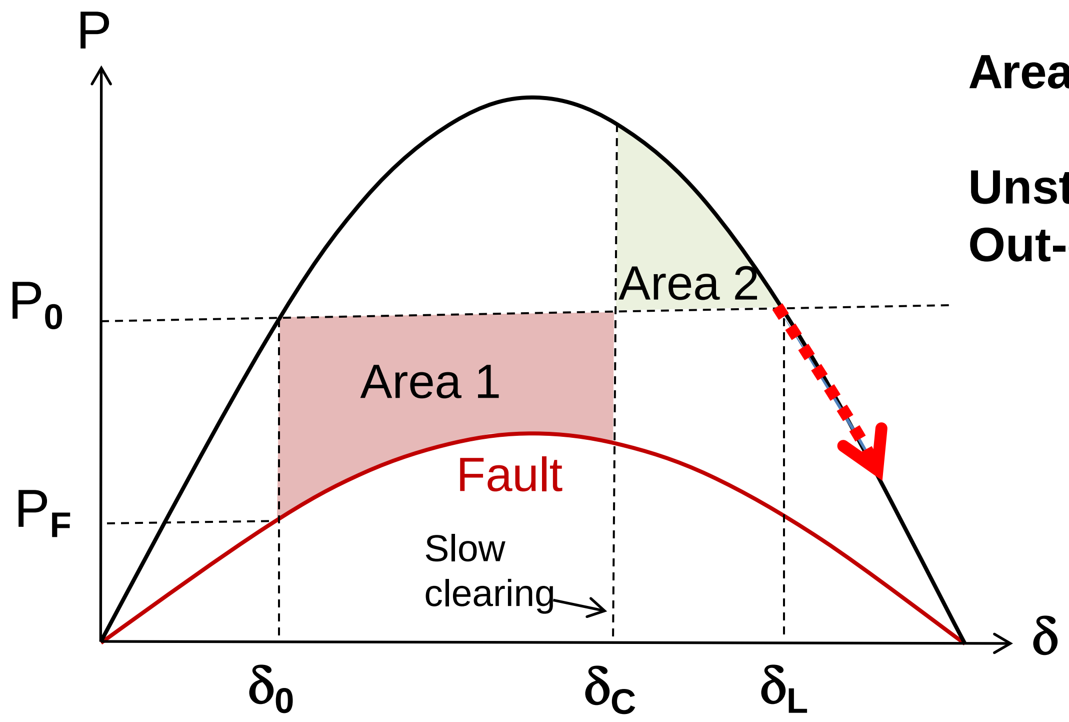
frequency increases during fault and angle advances

Basic Power System Stability

Fast Fault Clearance
Increases system stability



Basic Power System Stability



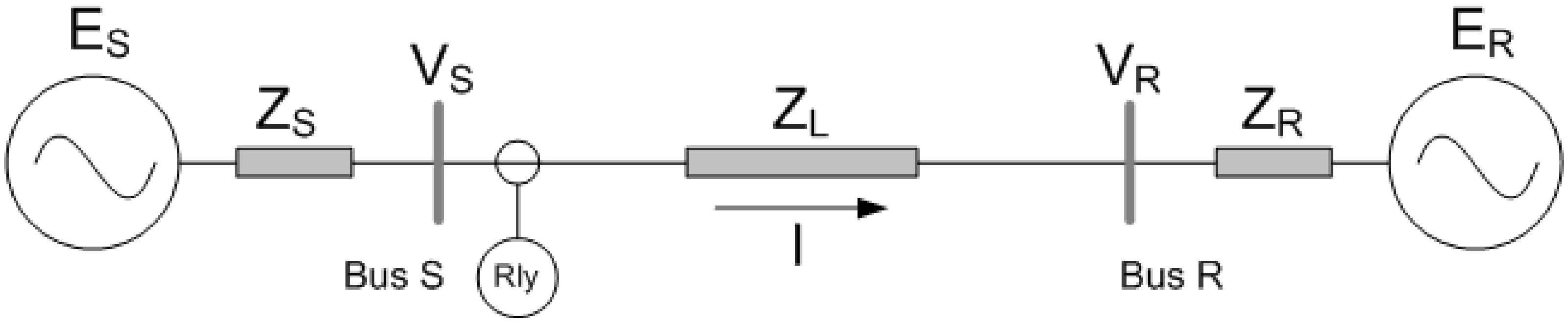
Slow Fault Clearance:

Angle δ increase too far

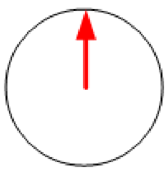
Area 2 < Area 1

Unstable - Resulting in Out-of-step condition

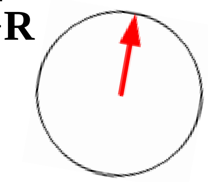
Power Swing and Out-of-step Phenomena



$\mathbf{f_S}$



$\mathbf{f_R}$

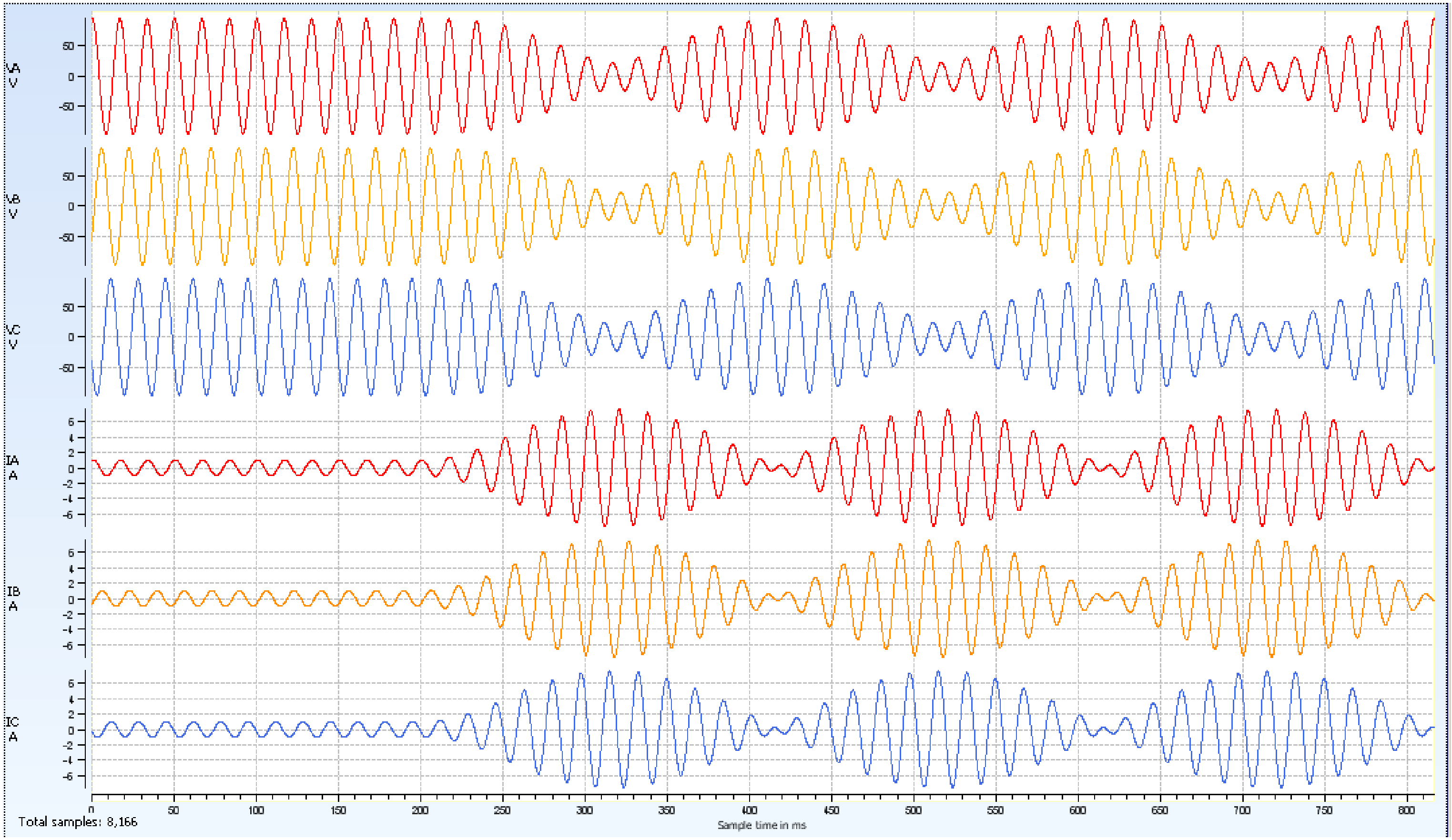


$$f_{slip} = f_S - f_R$$

$$I = \frac{E_S - E_R}{Z_S + Z_L + Z_R} \qquad V_S = E_S - I \cdot V_S \qquad Z_{Rly} = \frac{V_S}{I}$$

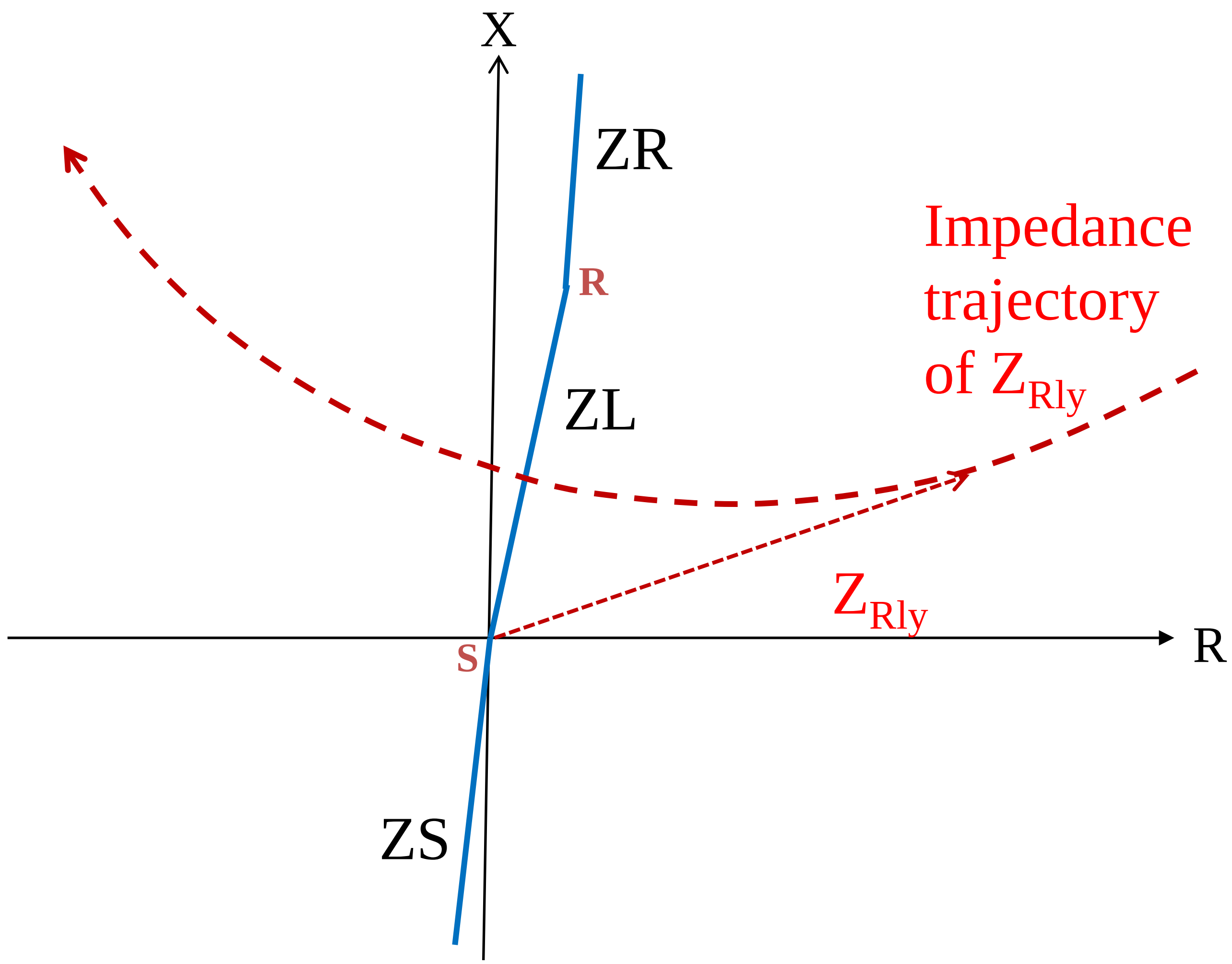
Power Swing and Out-of-step Phenomena

Voltages and currents at bus S

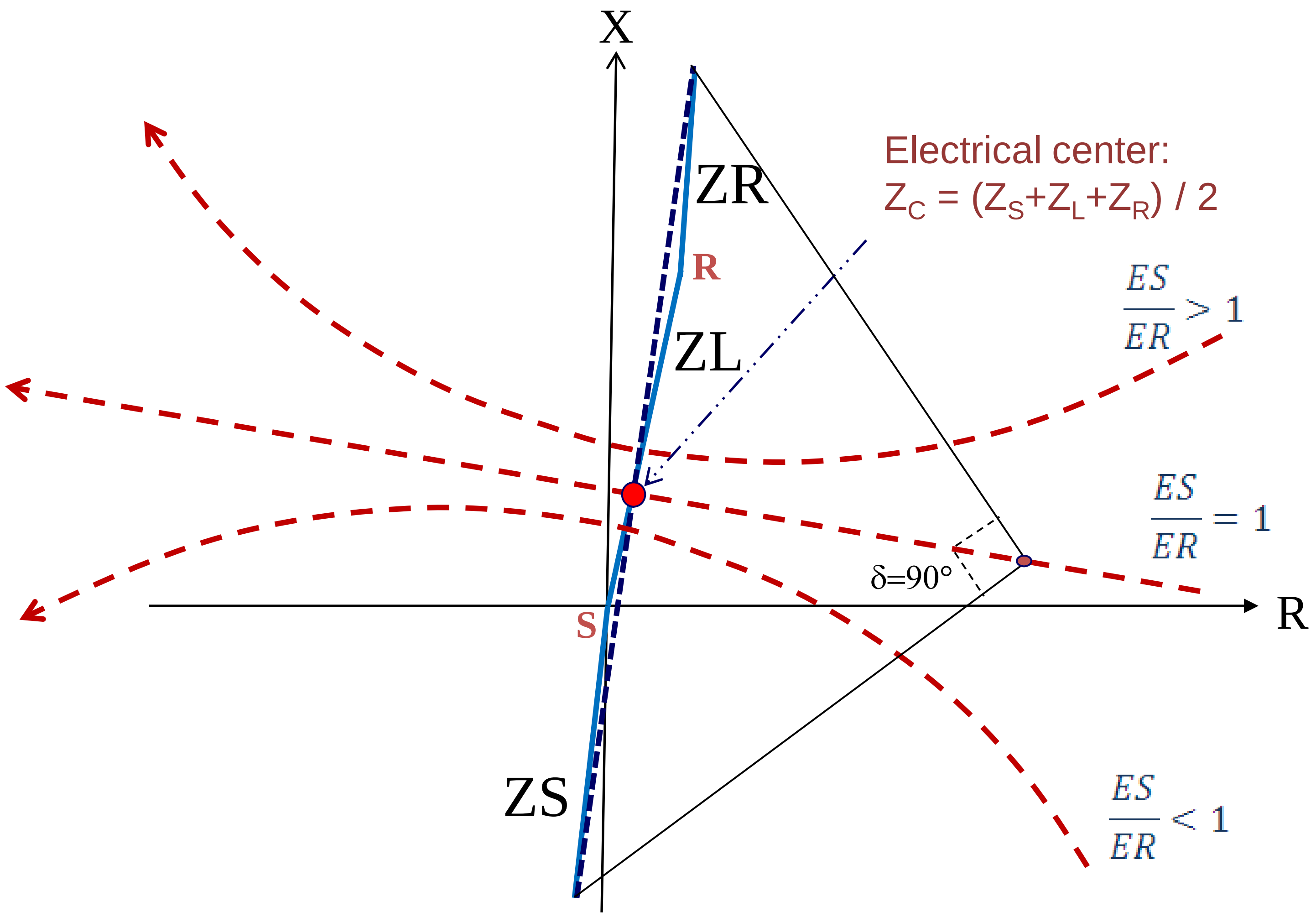


Power Swings are 3-Phase Phenomena

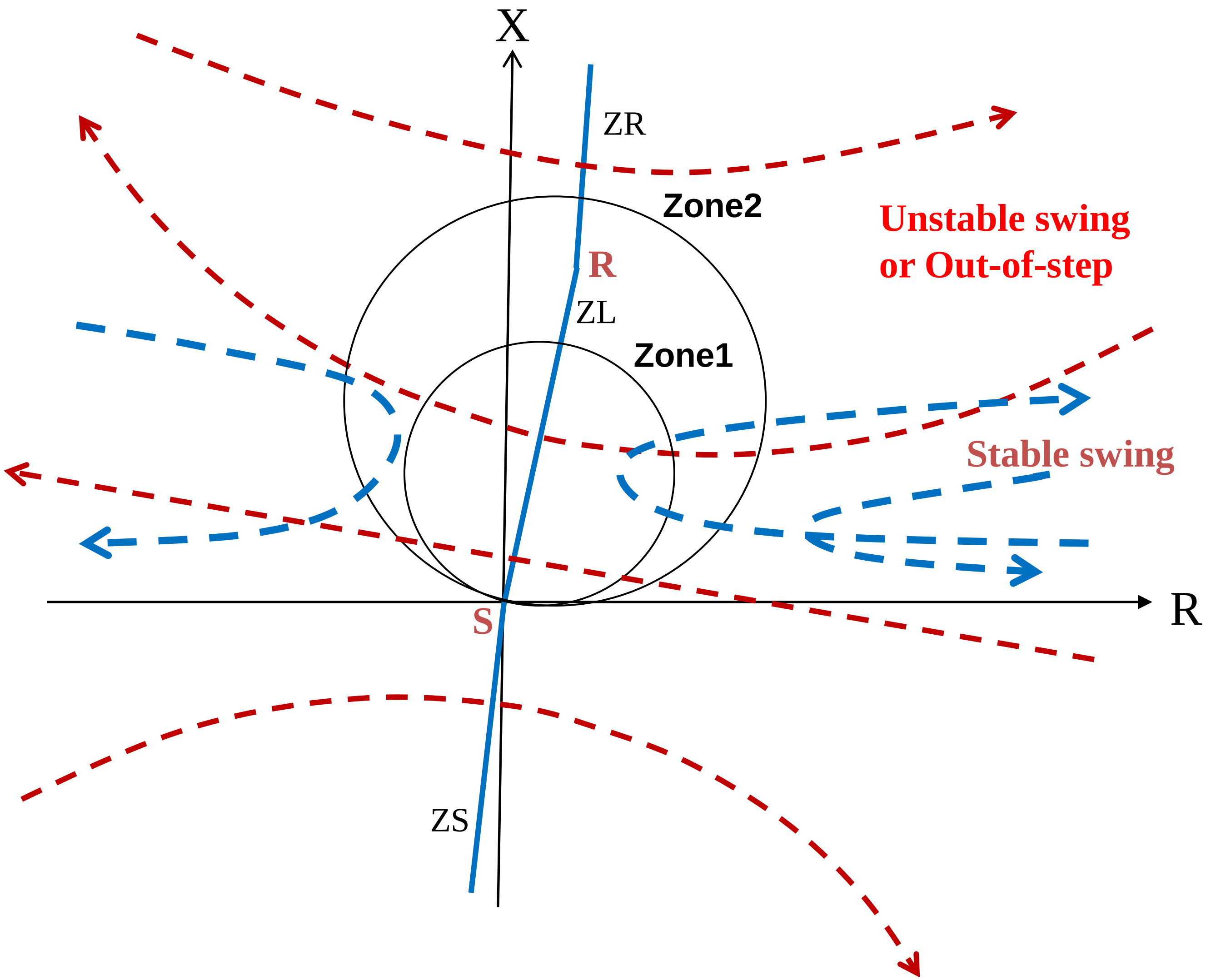
Impedance Seen by Relay at Bus S



Impedances trajectories during Out-of-step conditions



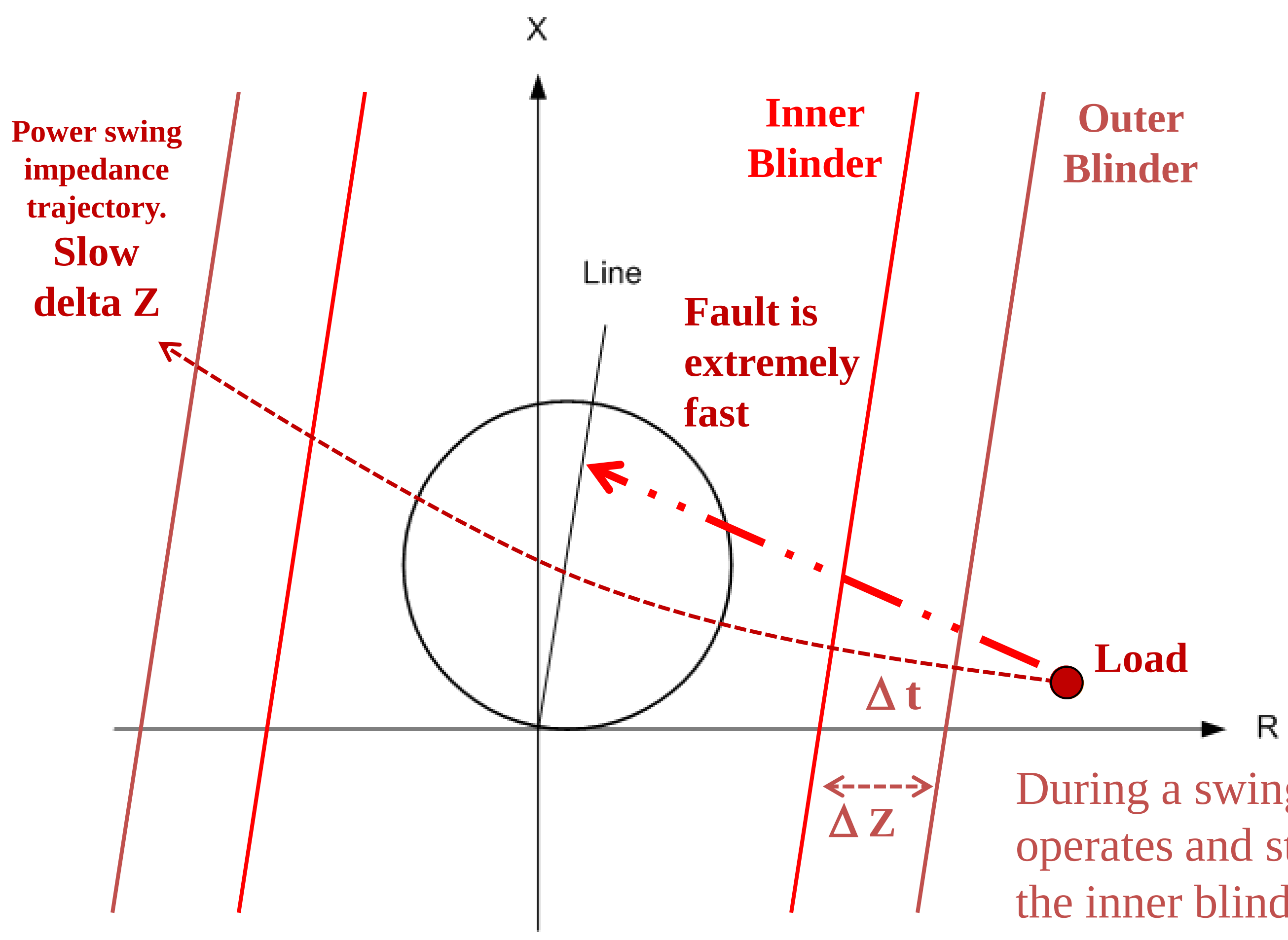
Effect of Power Swings & Out-of-Step Conditions on Relays



Zone 1 will trip instantaneously if swing enters zone

Zone 2 may trip if swing enters and stays inside zone for > t_{zone2}

Dual Blinder Detection Scheme



During a swing the outer blinder operates and starts a timer. If after Δt the inner blinder has not operated then Power swing blocking is asserted.

Power Swing Detection Schemes (Concentric Characteristics)

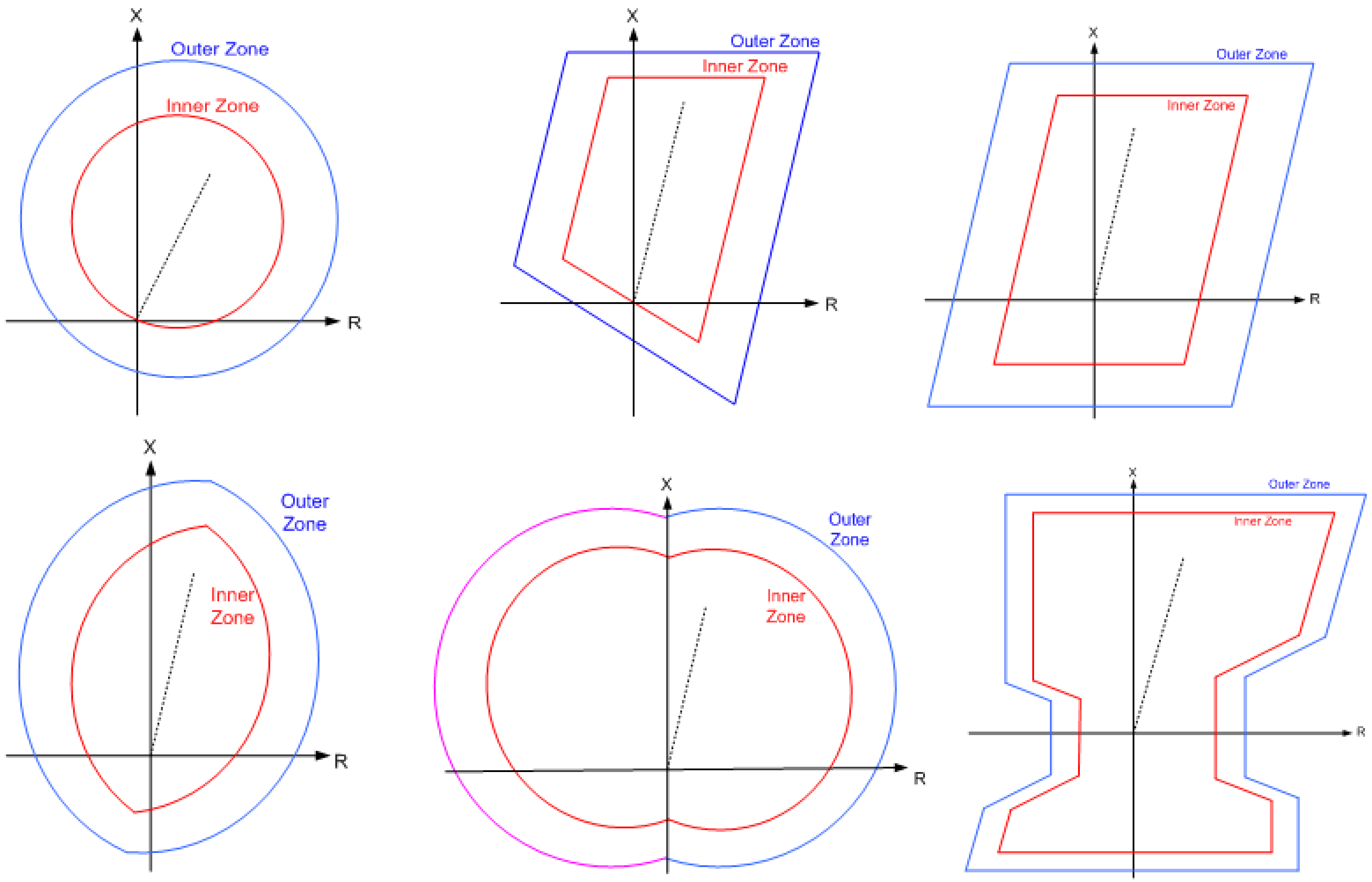
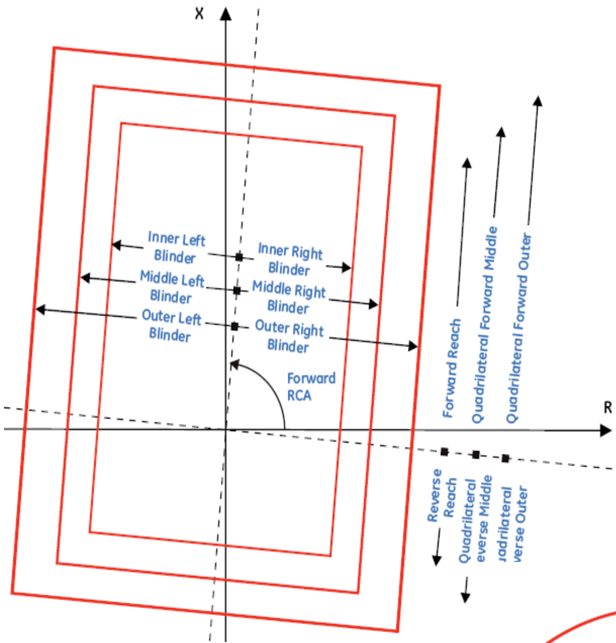
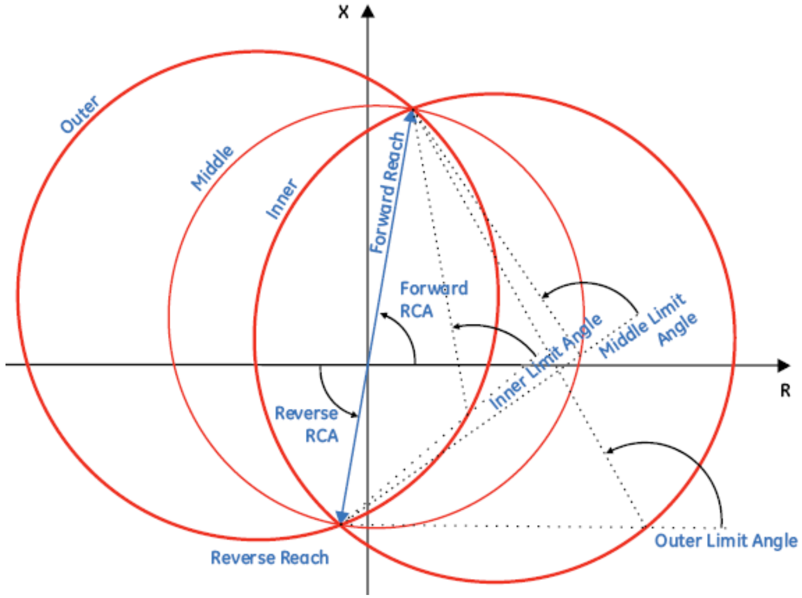
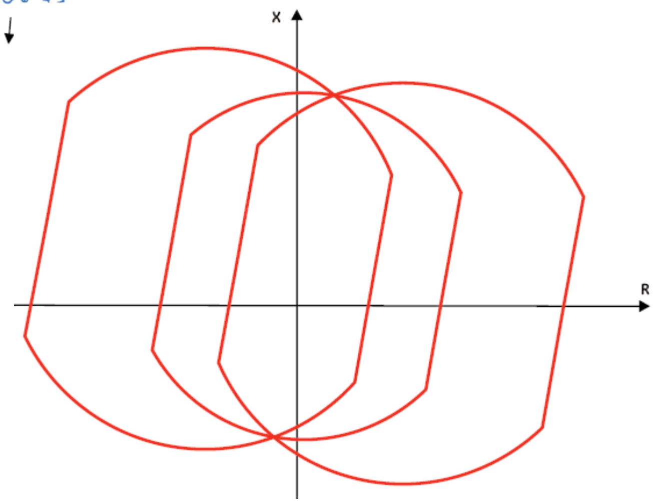


Fig. 11 Concentric Characteristics Used in Power Swing Detection Schemes

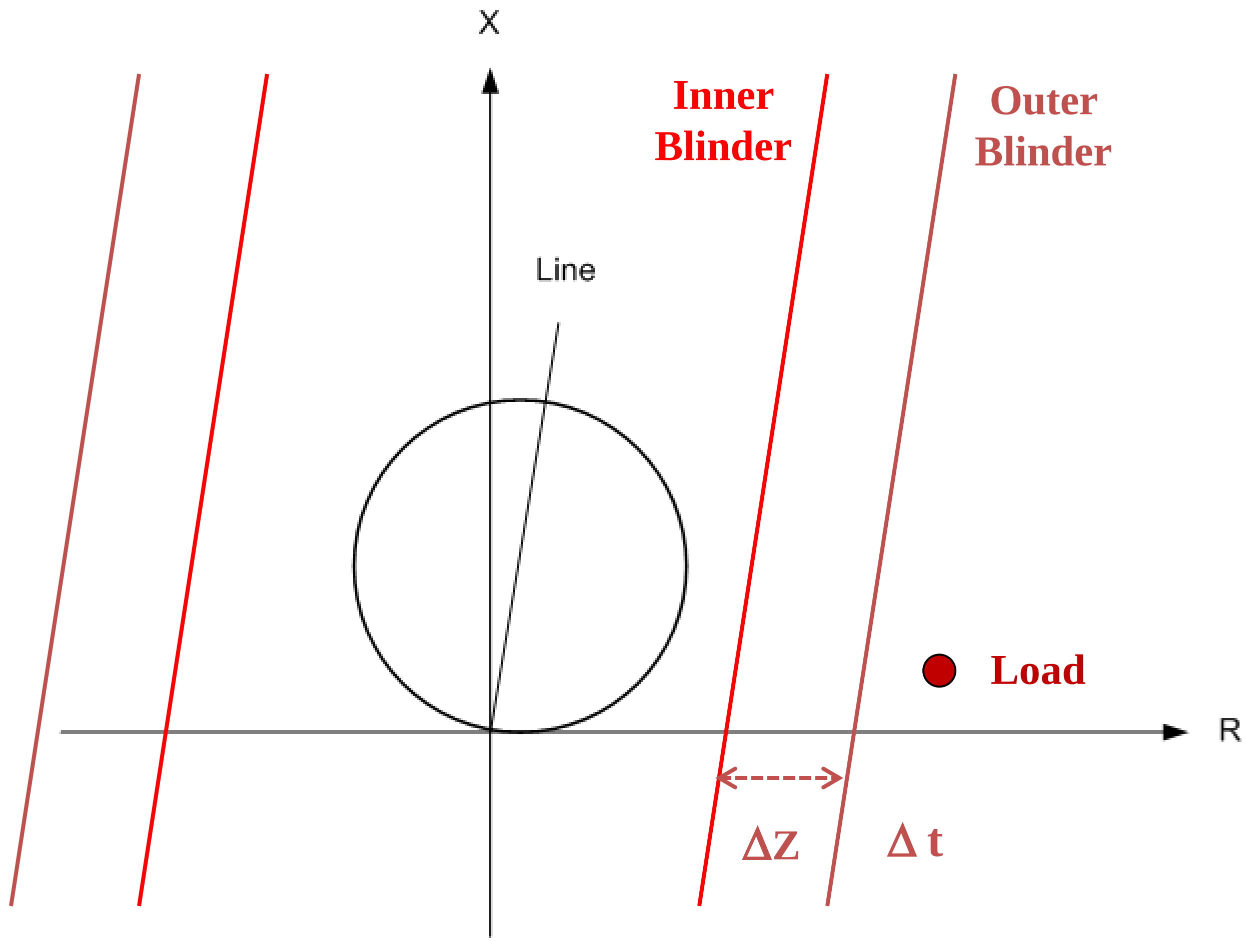
Power Swing Detection Schemes (Other ΔZ/ΔT Schemes)



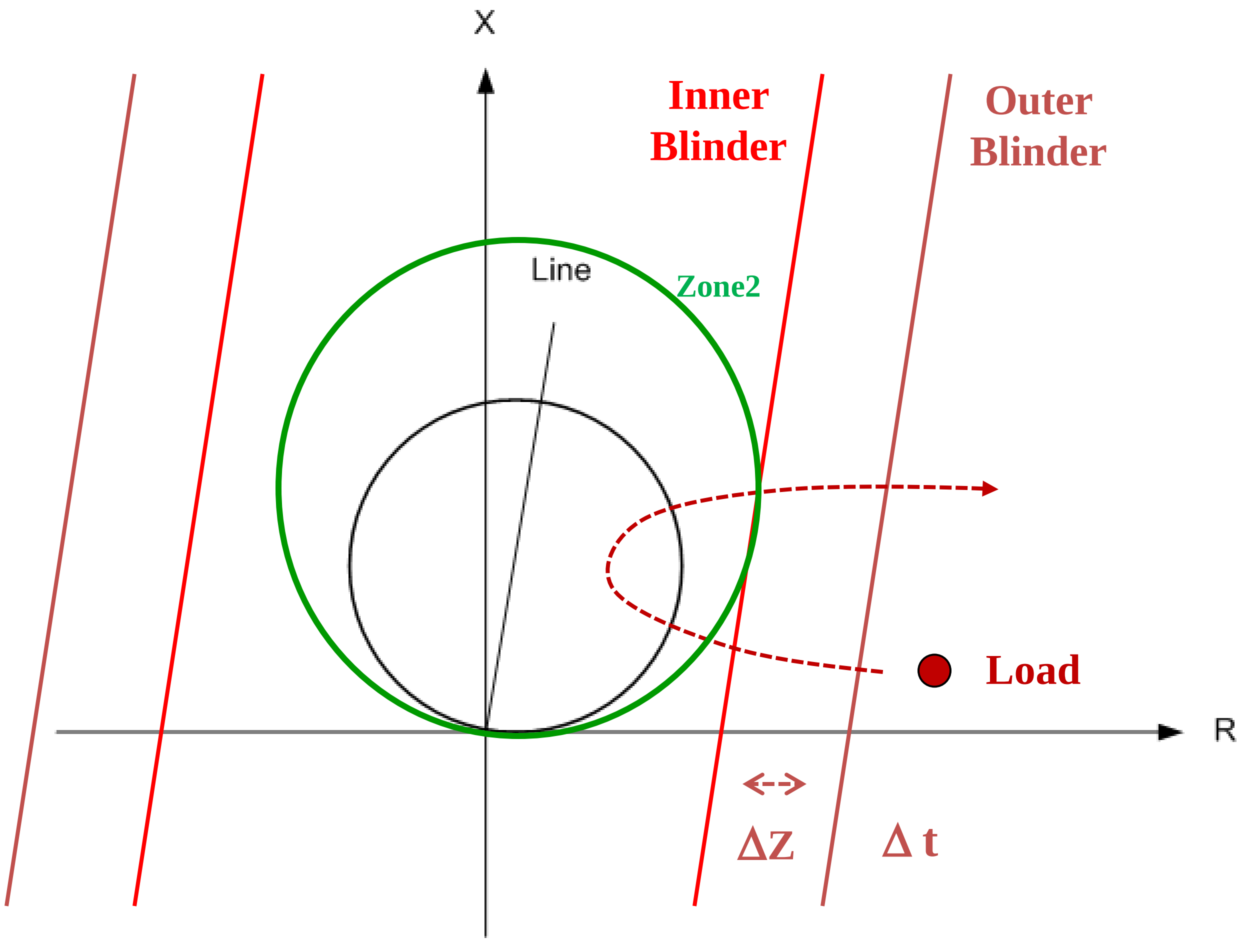




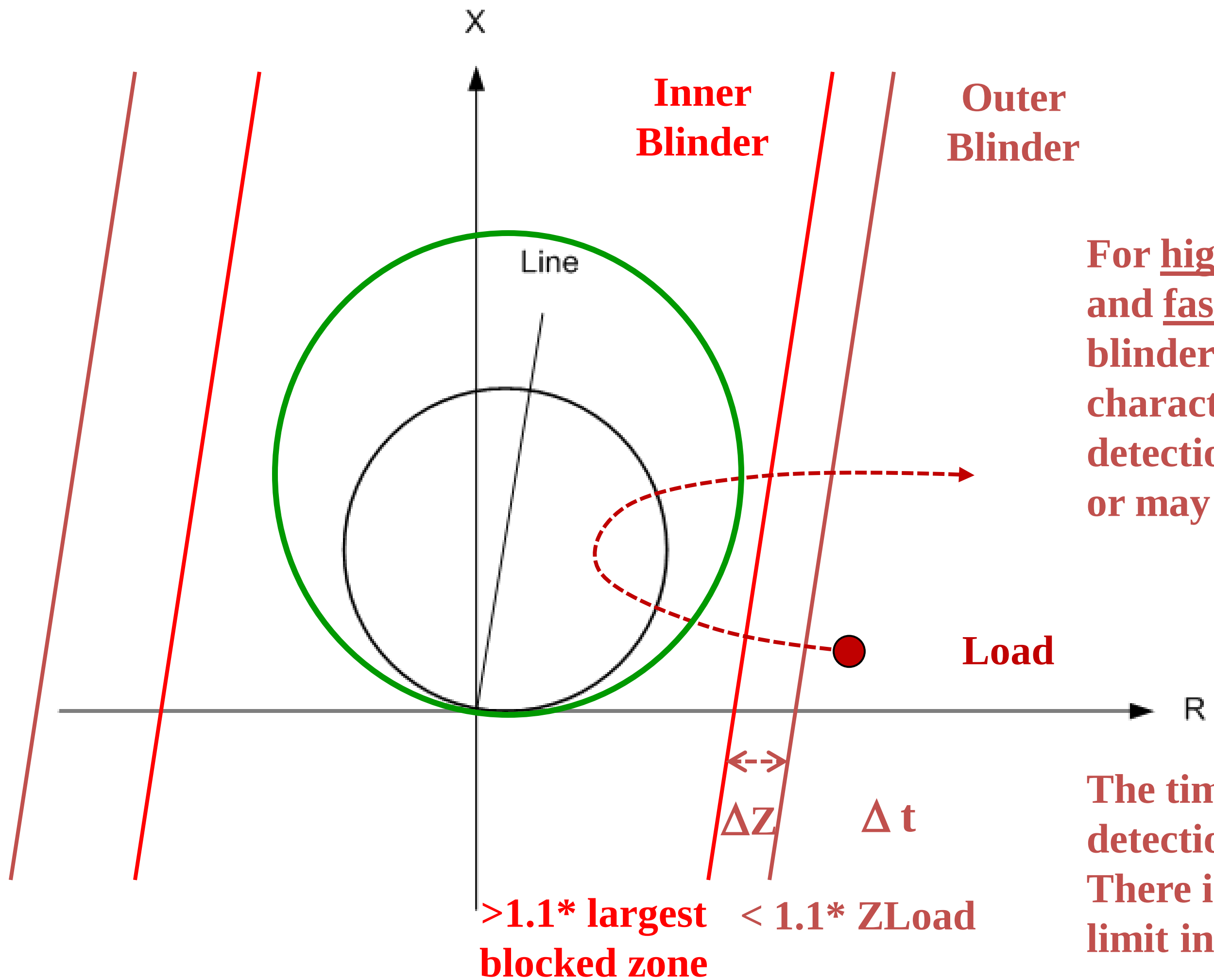
Setting Power Swing Blocking Blinder Schemes



Setting Power Swing Blocking Blinder Schemes



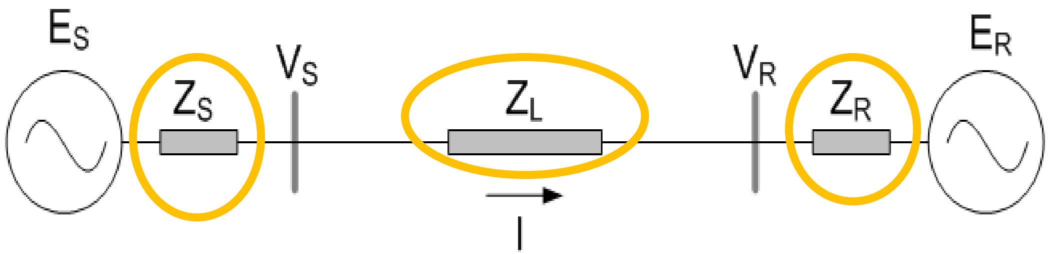
Setting Power Swing Blocking Blinder Schemes



For <u>high load </u>situations and <u>fast swings </u>the dual blinder and concentric characteristics methods of detection are difficult to set or may <u>not</u> be <u>effective</u>.

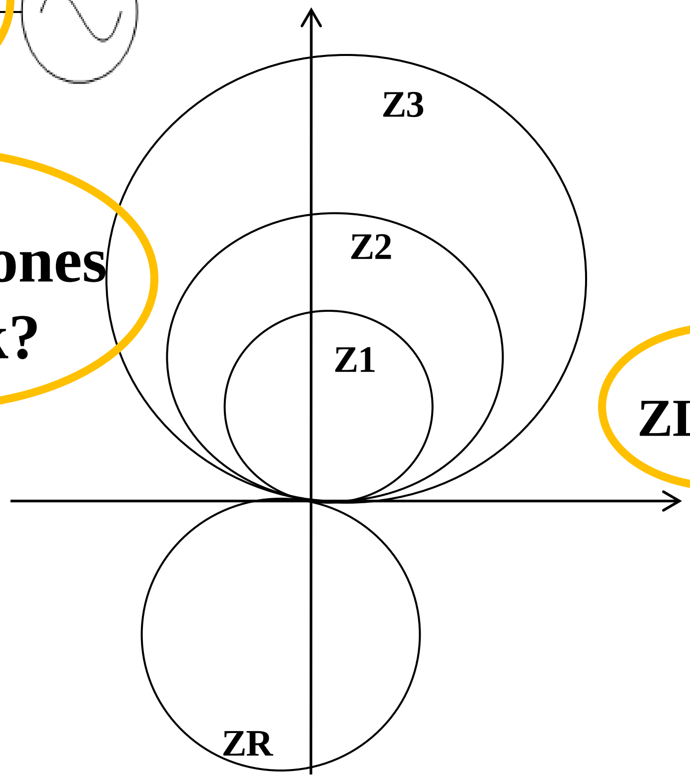
The time available for detection will be too short. There is a practical lower limit in setting ΔZ and Δt

Setting Power Swing Blocking Blinder Schemes



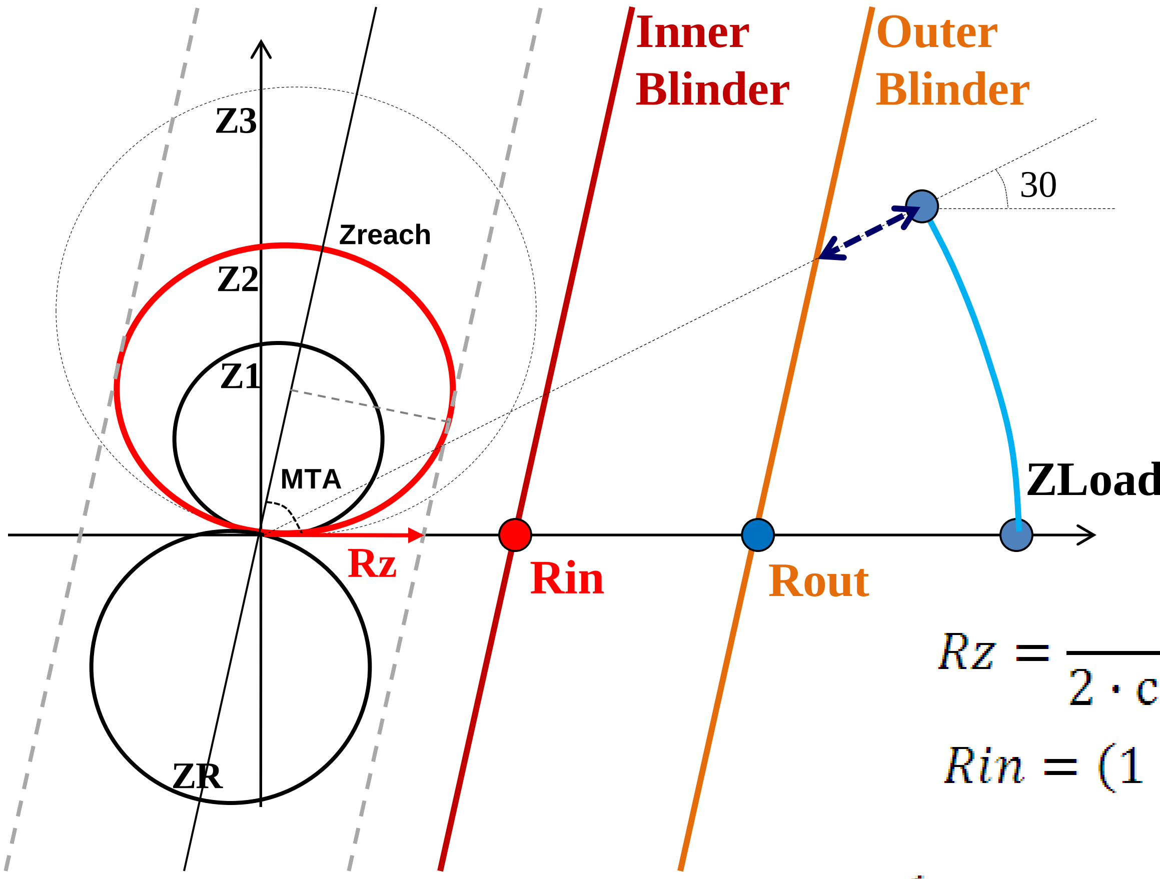
Maximum $\boldsymbol{f_{slip}}$

What zones to block?



ZLoad

Setting Power Swing Blocking Blinder Schemes

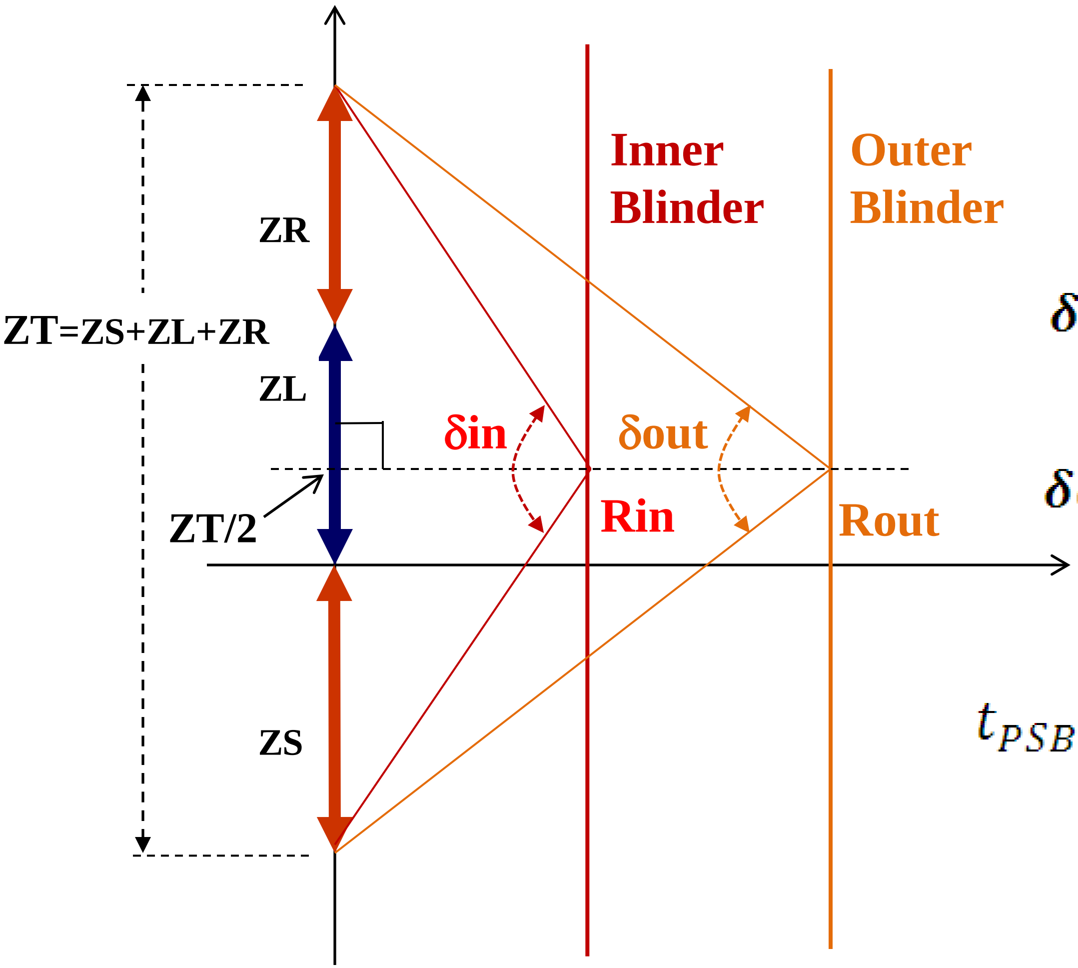


$$Rz = \frac{Zreach}{2 \cdot \cos(90 - MTA)}$$

$$Rin = (1 + Margin) \cdot Rz$$

$$R_{out} = Z_{Load}(1 + margin) \cdot \frac{\sin(\mathrm{MTA} - 30)}{\sin(180 - \mathrm{MTA})}$$

Setting Power Swing Blocking Blinder Schemes



$$\delta in = 2 * \operatorname{atan}\left[\frac{|ZT|}{2 * Rin}\right]$$

$$\delta out = 2 * \operatorname{atan}\left[\frac{|ZT|}{2 * Rout}\right]$$

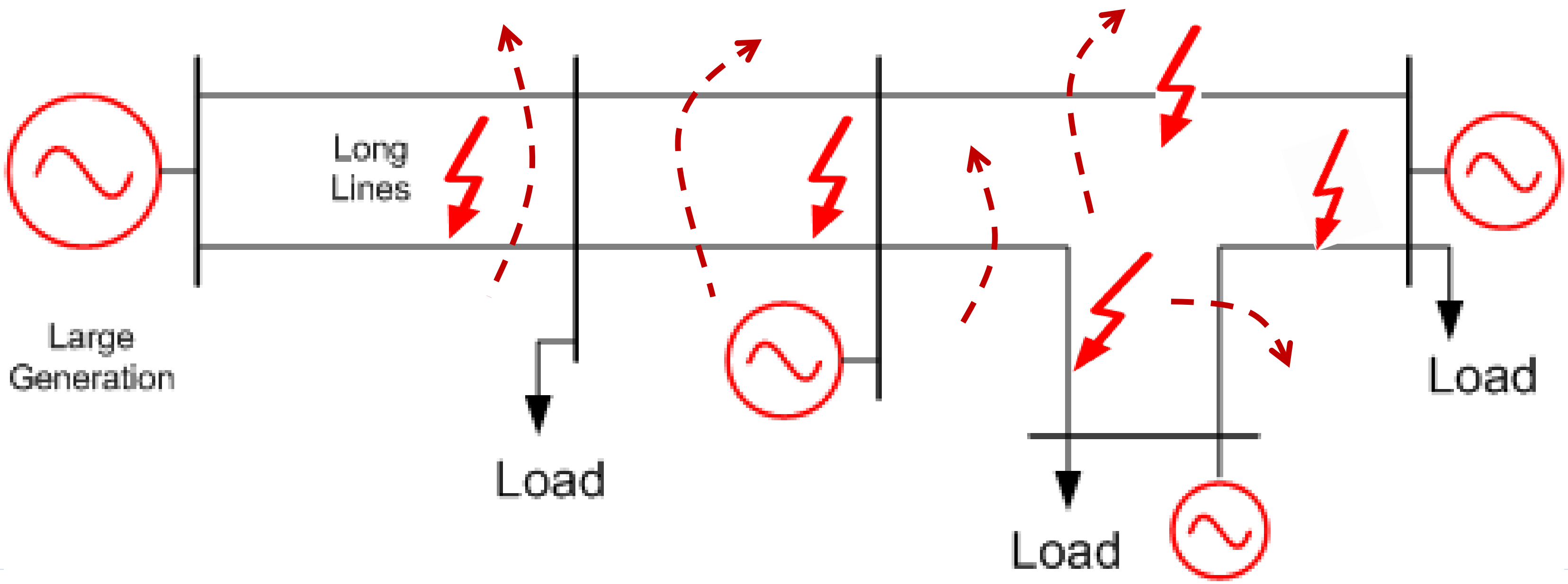
$$t_{PSB} = \frac{(\delta in - \delta out) \cdot fnom}{fslip}$$

Issues in Setting PSB Functions with Dual Blinder and Concentric Characteristics

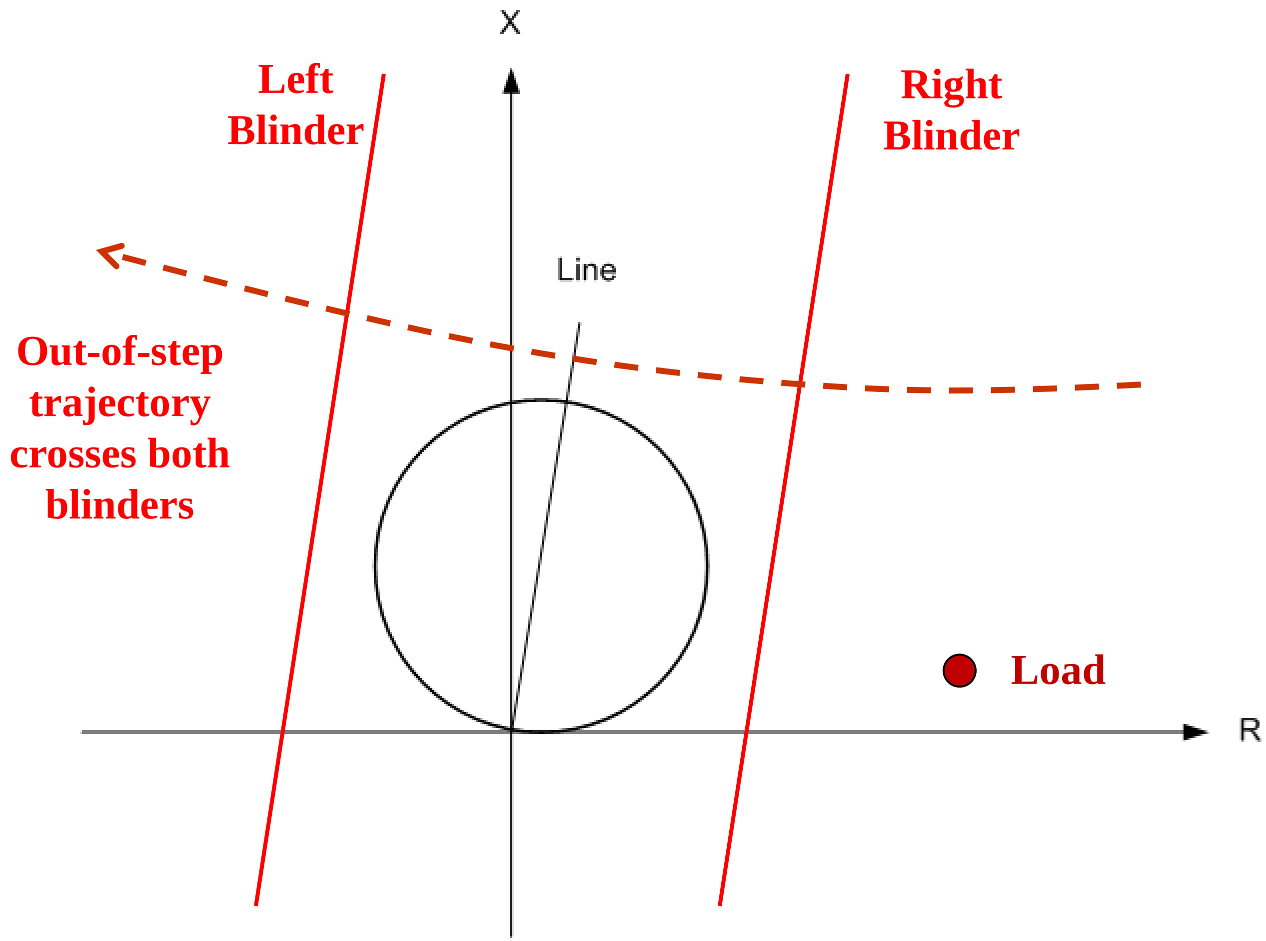
- Requires extensive time-consuming power system transient stability studies
- Heavy load and long set reach of the zones to be blocked can restrict the application of these detection methods
- The slip rate is hard to determine and varies during system disturbances with switching of load and generation
- The source impedances change depending on network topology and change a lot during system disturbances and switching conditions

Out-of-Step Tripping (OST) Function

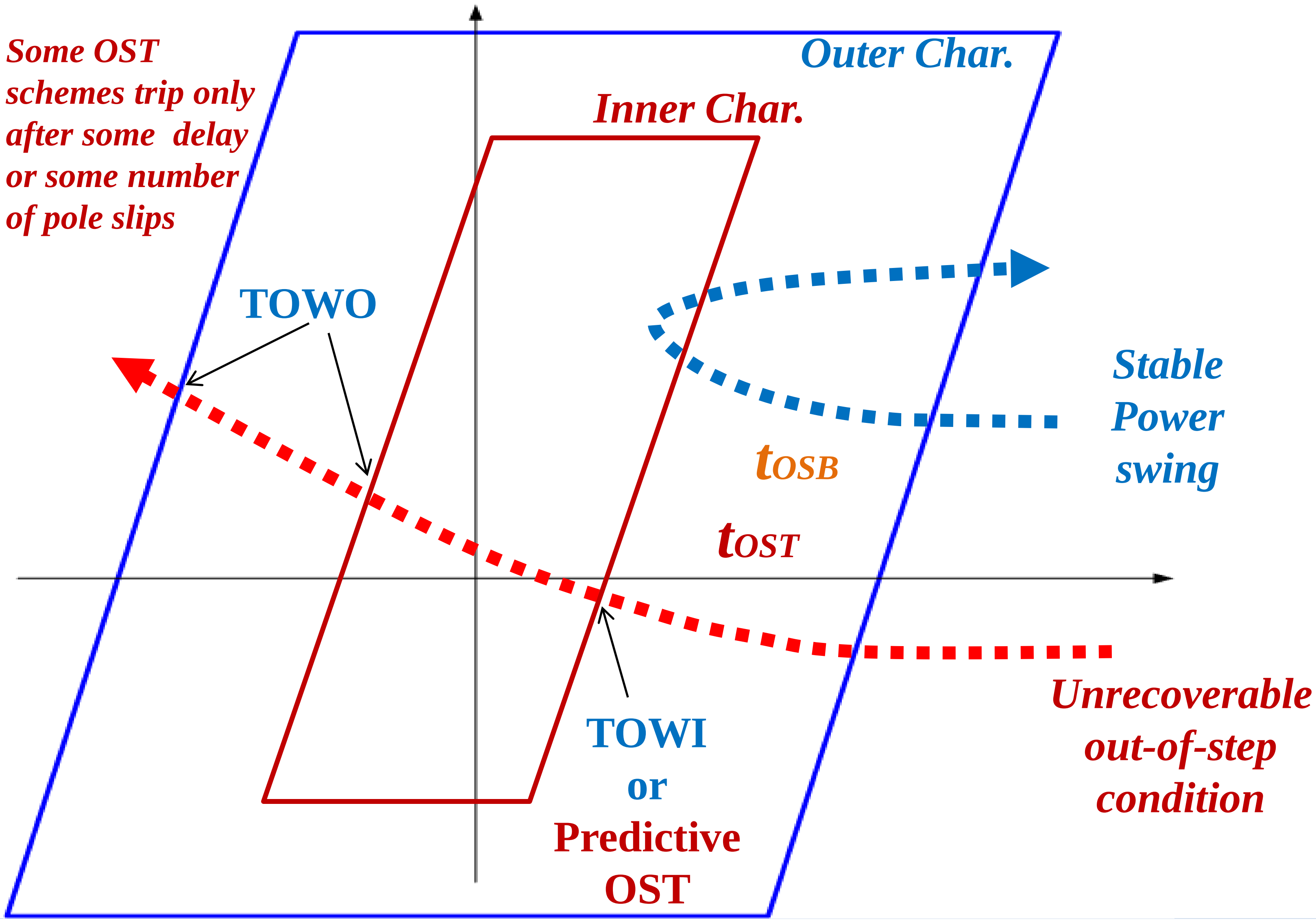
- Determine if the swing is an unrecoverable out-of-step or pole slip condition
- Where is the best place to separate – try to balance load and generation, faster system recovery
- When to separate



Out-of-Step Tripping with Single-Blinder Schemes



OST and PSB Timing



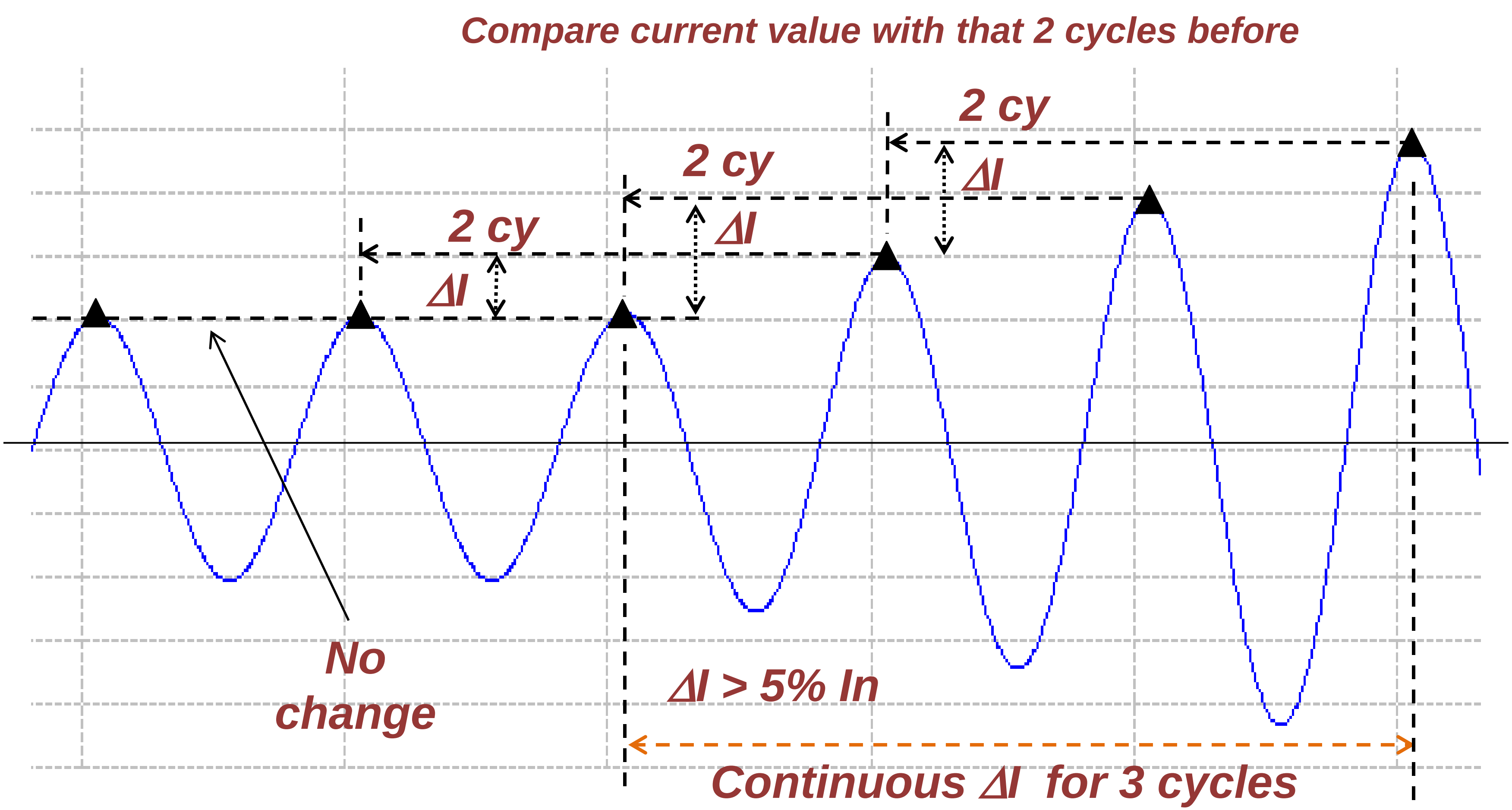
PSB and OST Application Options

- No power swing detection
- Block all elements prone to operate during power swings
- Block Zone 2 and higher zones; Trip with zone 1
- Block All Zones; Trip with OST function

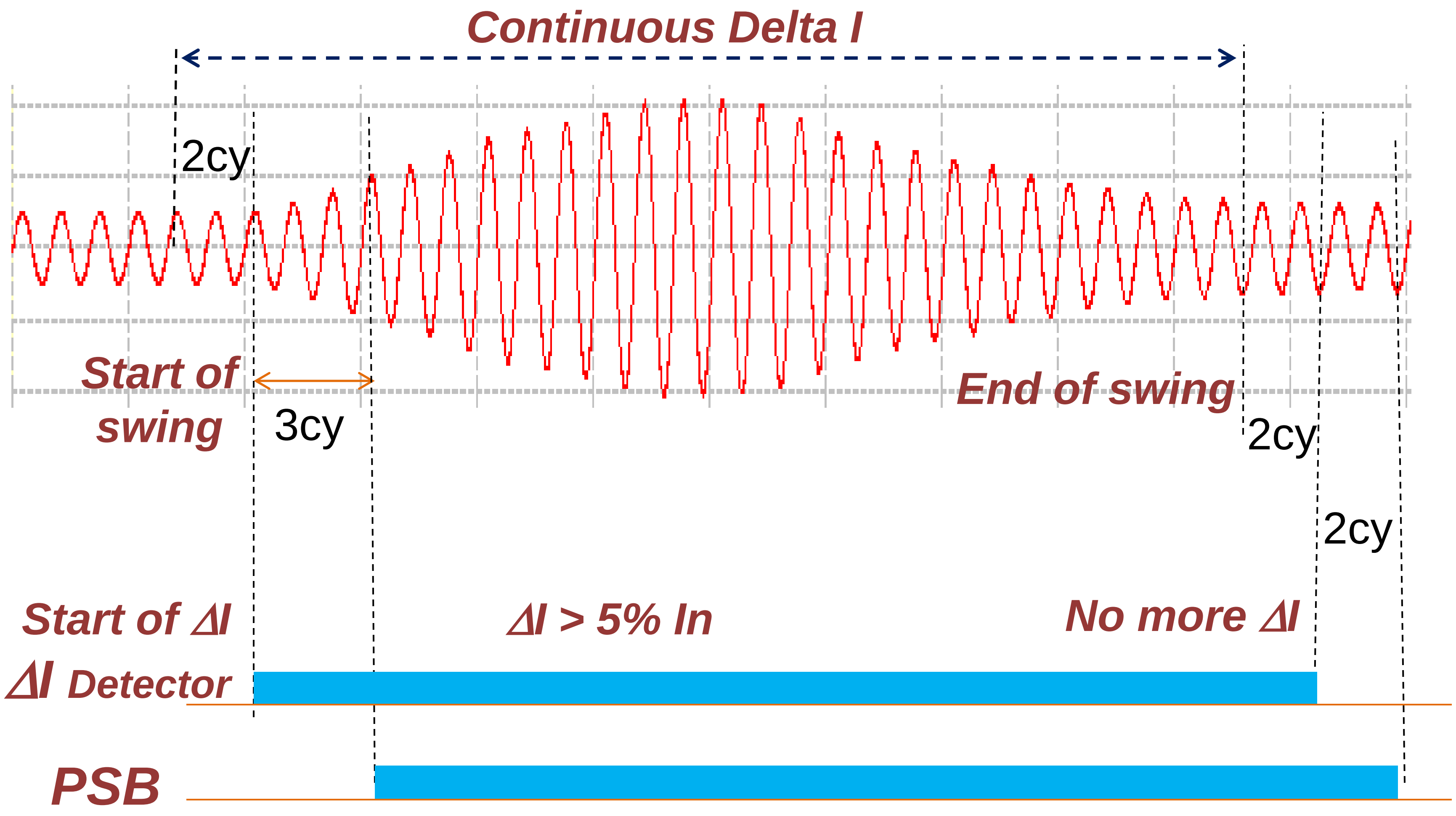
Non-conventional Detection Methods

- Superimposed Current "ΔI"
- Continuous Impedance calculation
- Swing Center Voltage and Its Rate-of-change

Superimposed Current “ΔI” Method

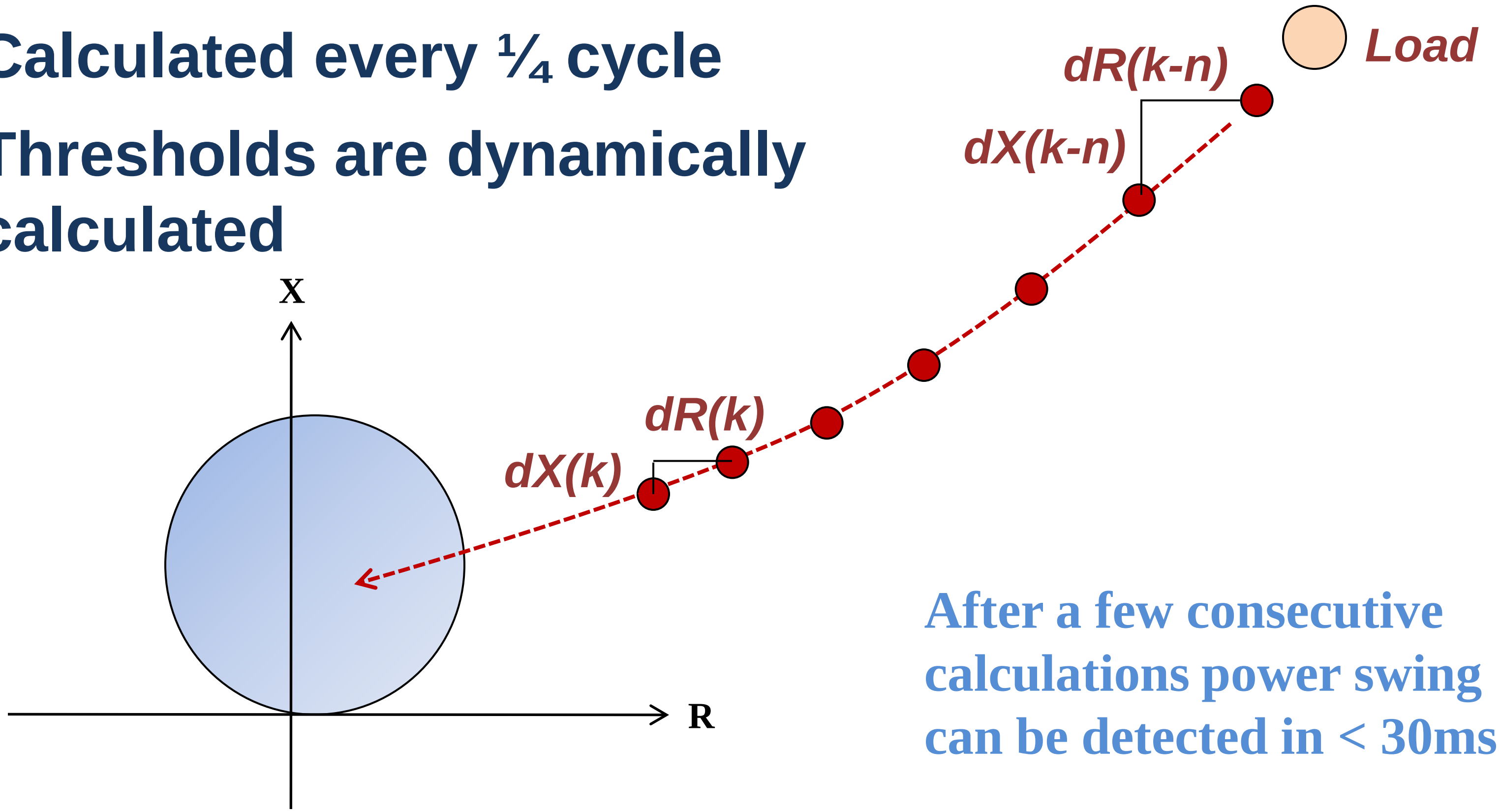


Superimposed Current “ΔI” Method



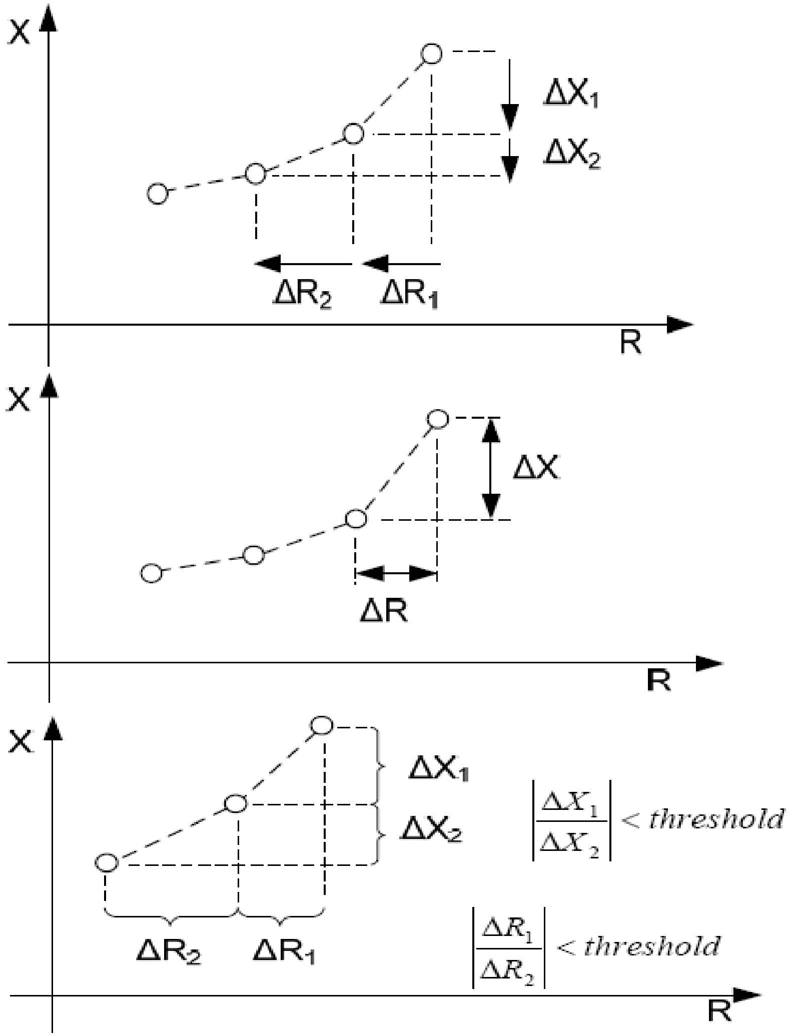
Continuous Impedance Calculation

- Monitors impedance trajectory
- Calculated every ¼ cycle
- Thresholds are dynamically calculated



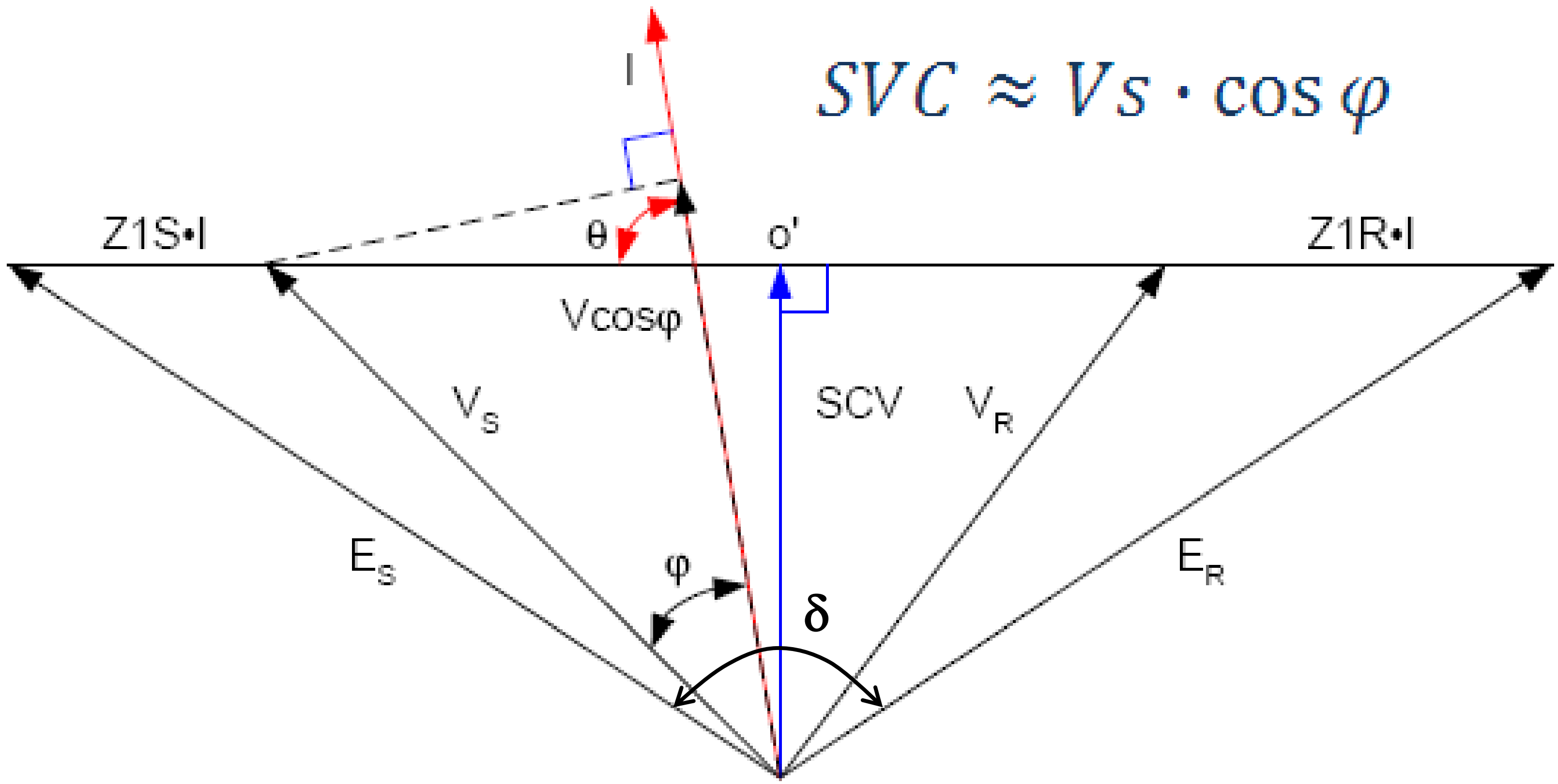
After a few consecutive calculations power swing can be detected in < 30ms

Continuous Impedance Calculation



- Direction is not changing
- Impedance is not stationary
- Movement is uniform, no abrupt changes

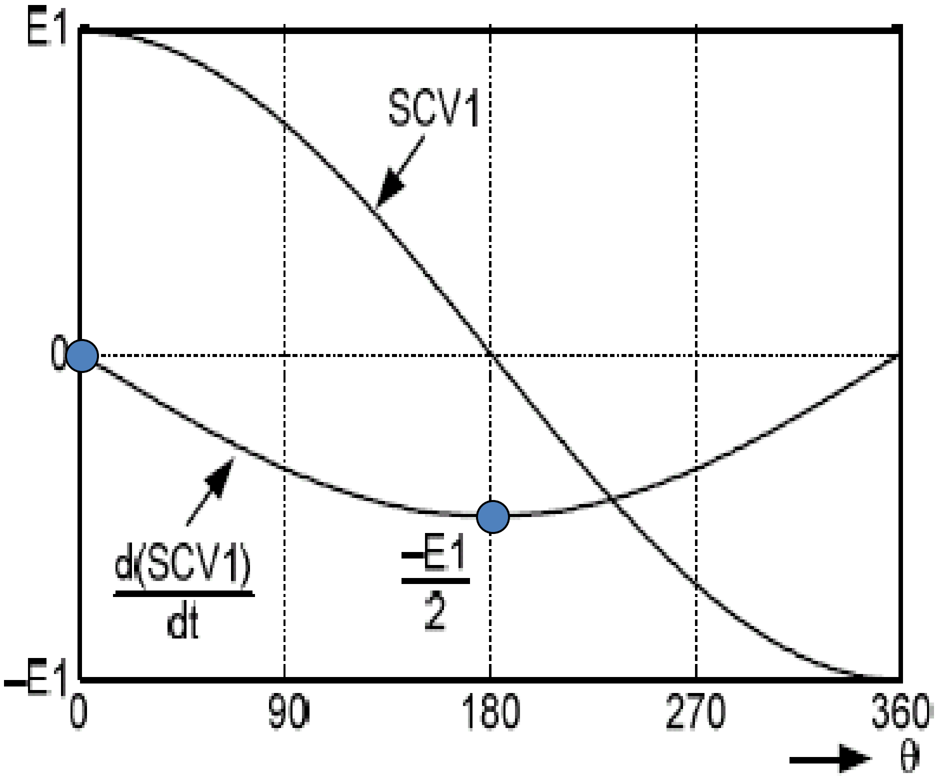
Swing-Center Voltage and Its Rate-of-Change



$$SVC \approx Vs \cdot \cos\varphi$$

$V\cos\varphi$ is a Projection of Local Voltage, VS, onto Local Current, I

Swing-Center Voltage and Its Rate-of-Change



When the angle of the two machines is zero, the rate of change of the SCV1 is also zero

The maximum value of the derivative of the SCV1 occurs when θ is 180 deg

Non-conventional Detection Methods

Advantages

- Power swings are detected by continuous measurements
- Swings are detected < 30ms to 50 ms after start, so much faster than for conventional devices - where the locus must cross into a band which surrounds the trip characteristics.
- No PSB start-up zone, no blinders (or load encroachment issues), no timers to set… "**setting-free**".
- No need of calculation or extensive system studies
- Work for fast swings up to ~ 7Hz slip frequency
- Sudden or step changes detect a fault, remove blocking

Tools for Testing PSB and OST Functions

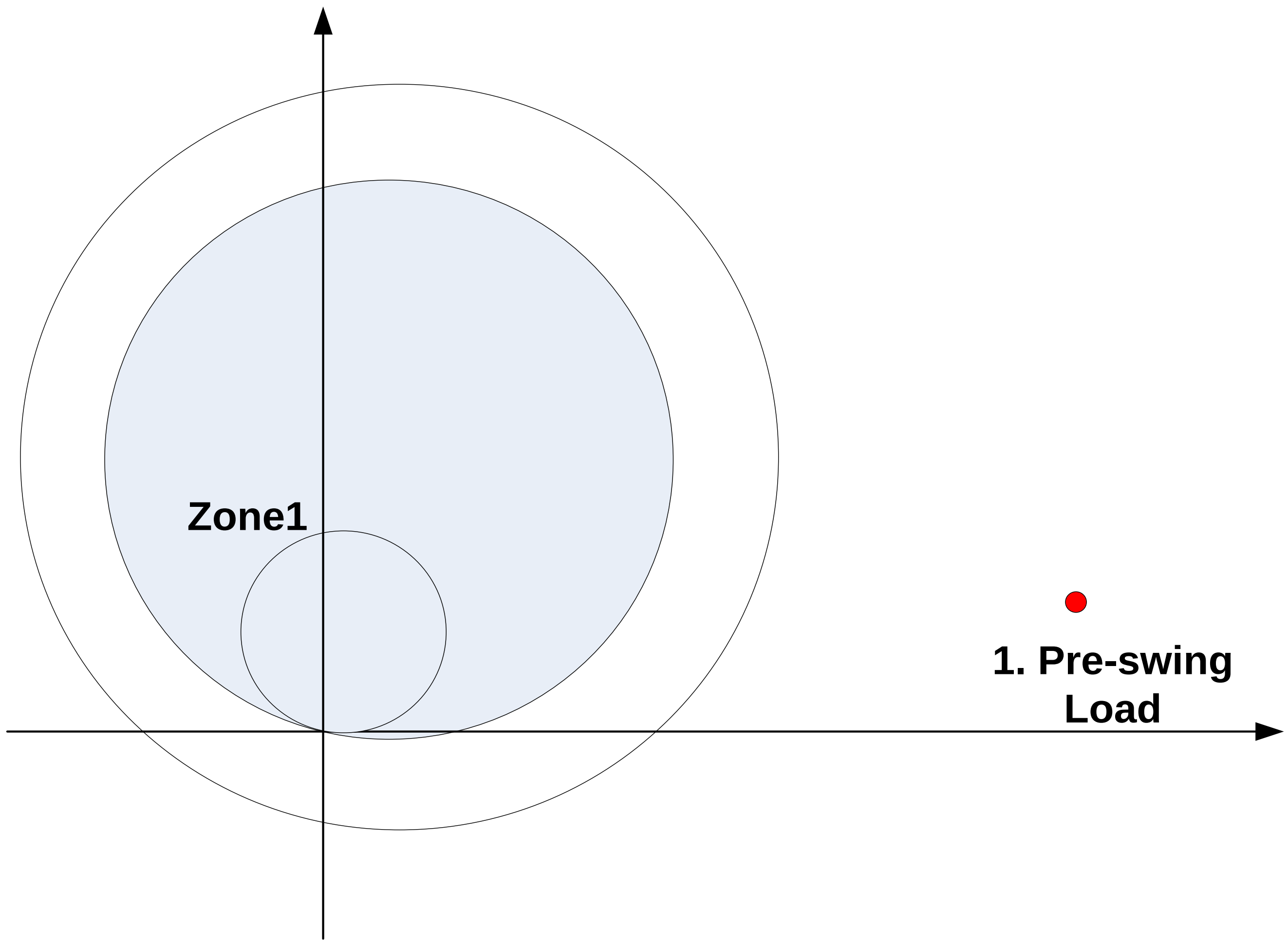
- **Laboratory**
  - RTDS Closed-Loop Simulation
  - Playback of Transient (COMTRADE) Files Using Modern Test Sets
- **Field**
  - Playback of Transient Files Using Modern Test Sets
  - Dynamic State Simulation
  - Ramping of Voltage or Current

Tools for Testing PSB and OST Functions

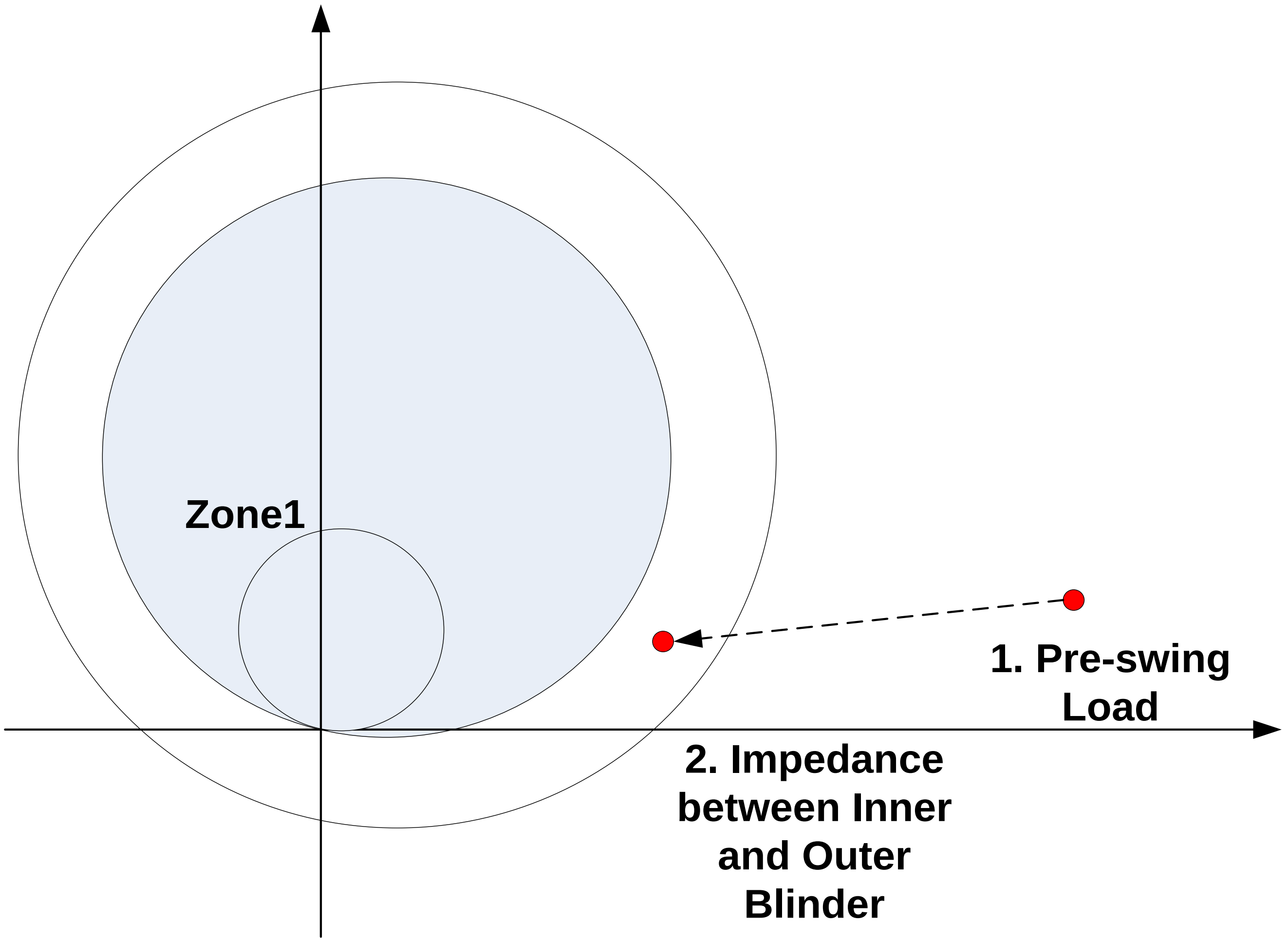
Playback of COMTRADE files

- Recorded waveforms of system disturbances
  - Most realistic
  - May not always be available. Available files do not cover a wide range of possible system conditions involving power swings
  - Available files may not be applicable for the relay under test
- Stability and EMTP Studies, RTDS
  - Essential when applying PSB and OST functions
  - Very realistic
  - Requires highly-specialized personnel
  - Requires a lot of test cases and is time consuming
  - Very expensive
- Hard to target specific portions of the relay characteristics and rate-of-change of impedance for testing the settings

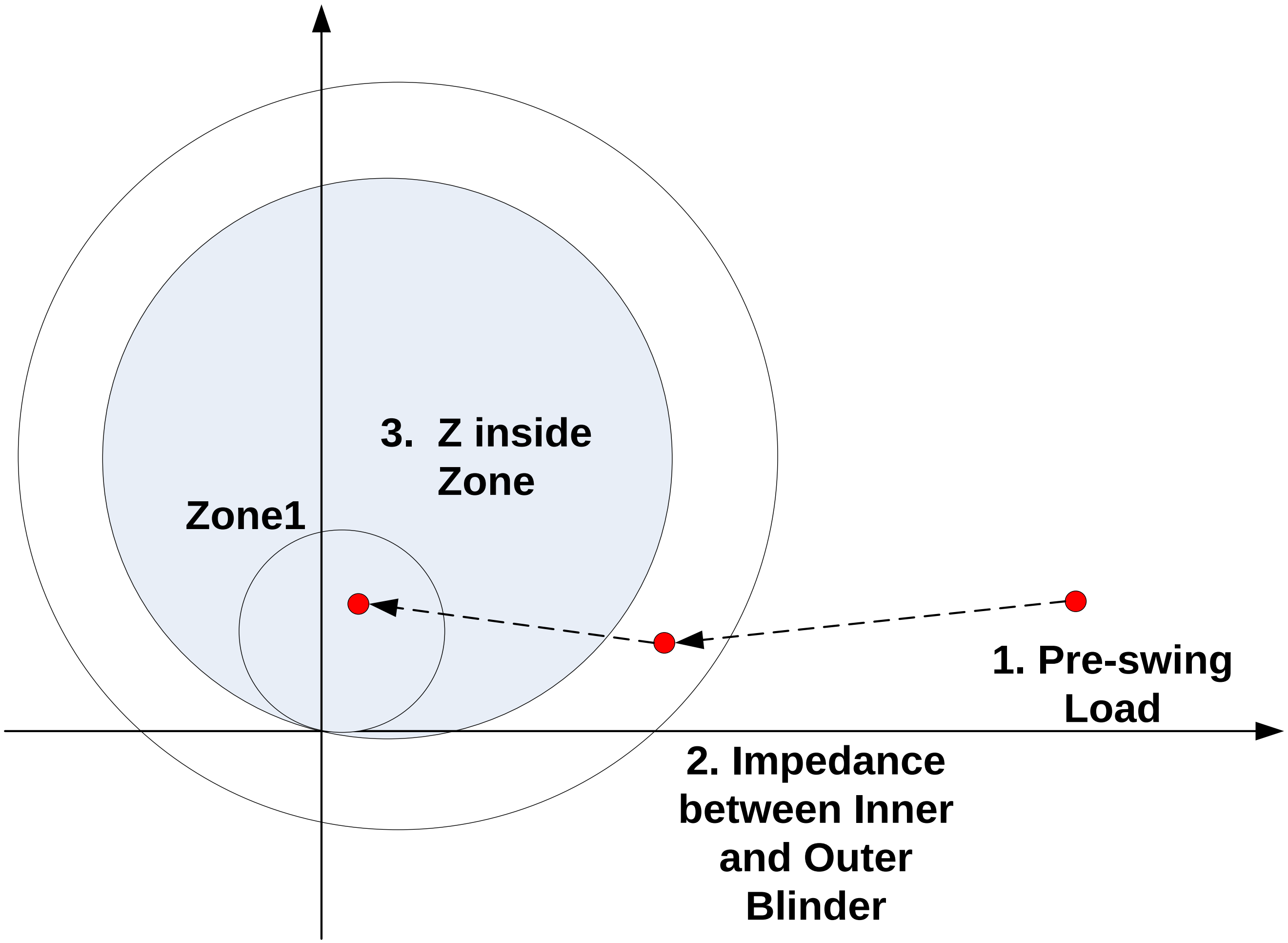
Testing using State Simulation



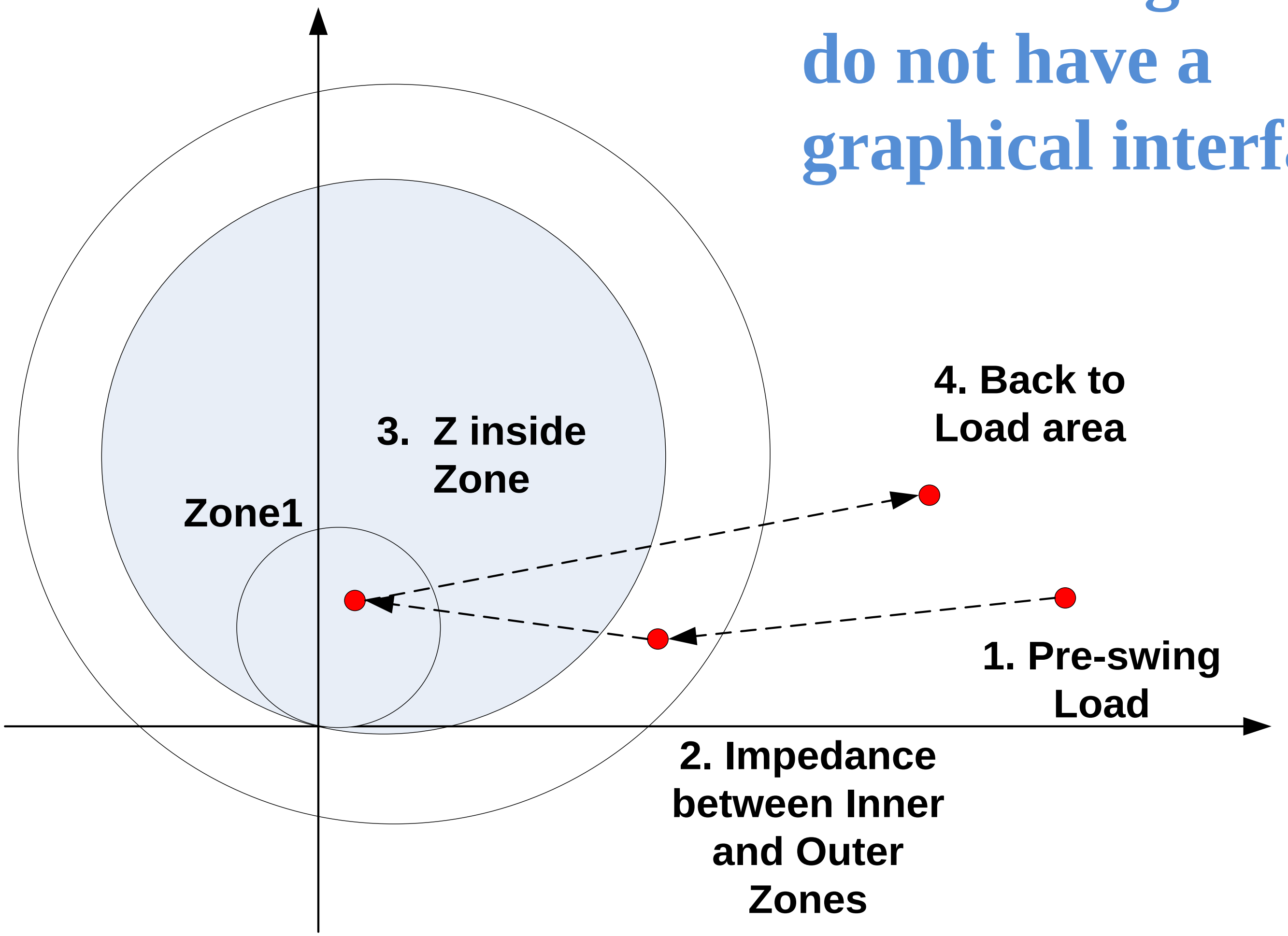
Testing using State Simulation



Testing using State Simulation



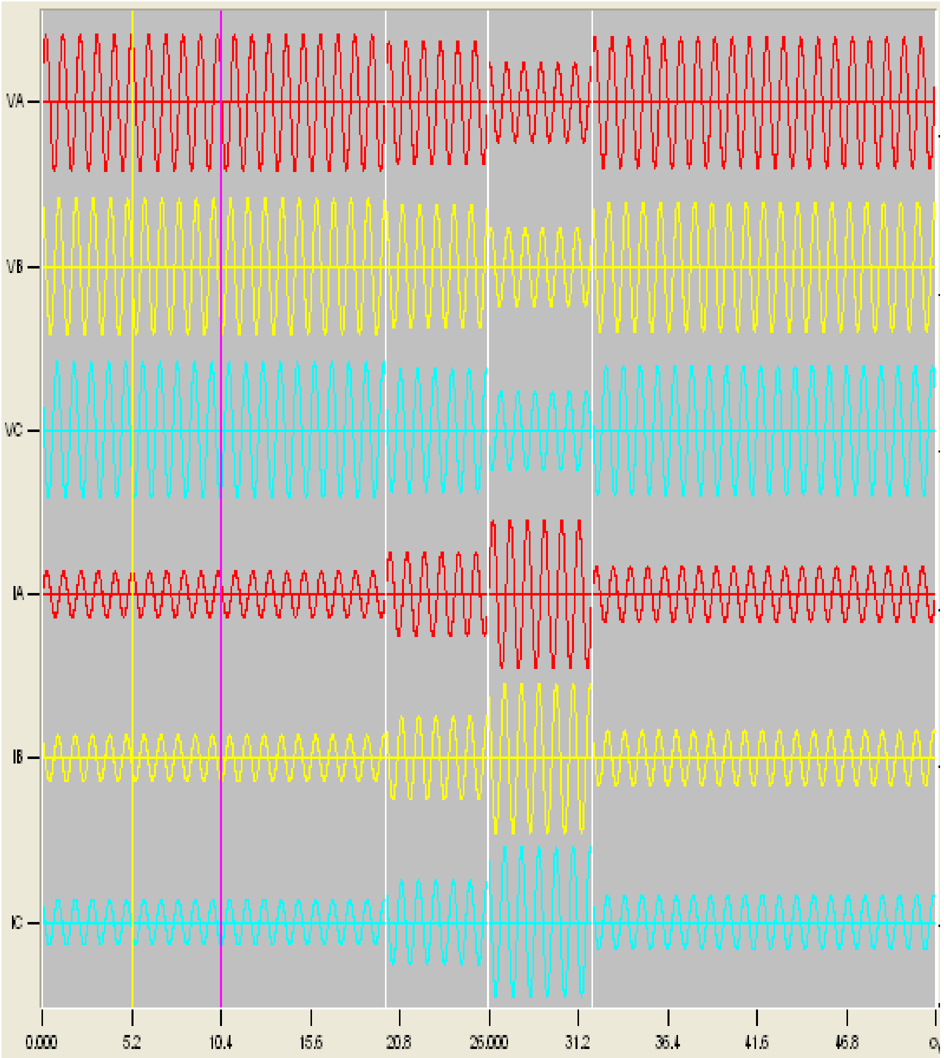
Testing using State Simulation



Most testing software do not have a graphical interface

Testing using State Simulation

- **Not realistic** – State simulation tests have large abrupt step changes.
- Actual swings do not change voltage, current and impedance abruptly.
- <u>Cannot</u> test power swing and out-of-step functions that are based on <u>continuous</u> ΔZ/Δt or ΔI/Δt or SCV



Ramping Currents or Voltages

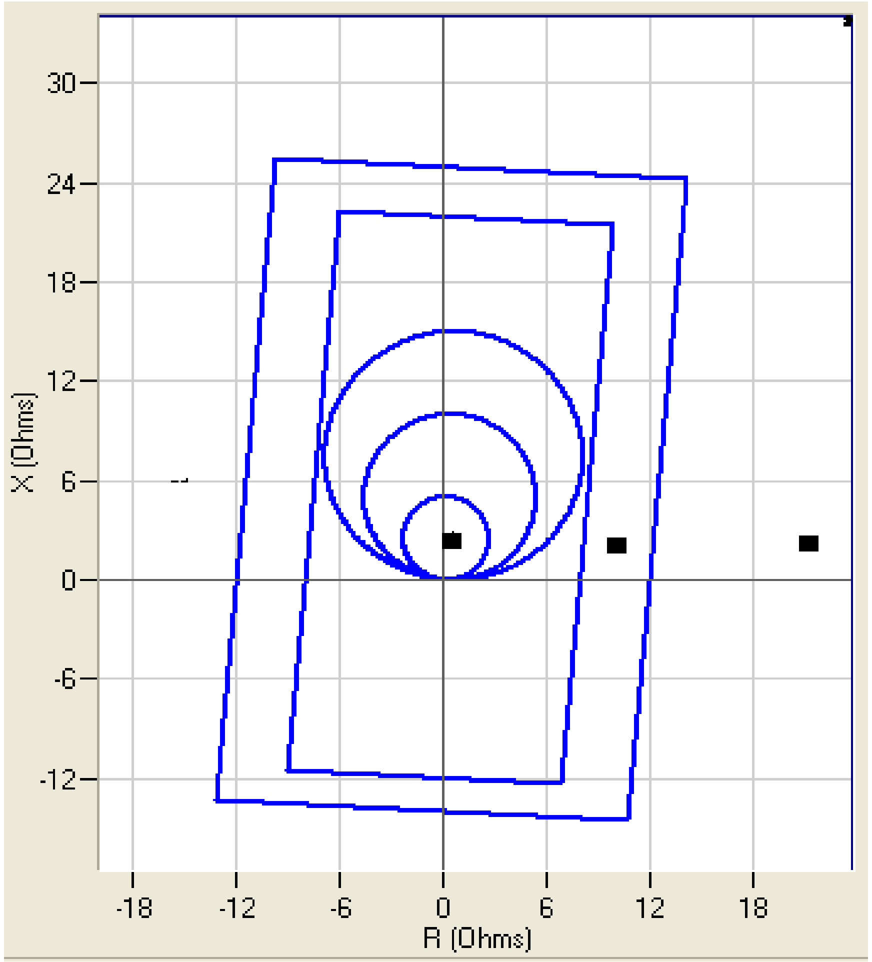
- Ramping of only one test quantity (V or I amplitude) is not realistic.
- May work with some conventional PSB methods
- Inferior to state simulation testing
- Will **not** work for non-conventional PSB and OST detection methods
- Cannot target specific zones to test

We Need Easy-to-Use Field Testing Tools

- Simple and easy to use by technicians with little power system background, with minimum input from the user.
- Visualize on a graphical R-X diagram
  - the characteristics of the PSB and OST elements
  - the characteristics of the protection zones
- Use the GUI to aid in entering simulation points.
- Be able to simulate required system conditions for testing such as stable power swings, out-of-step conditions, load and faults
- Provide visual plot of the V and I current waveforms.

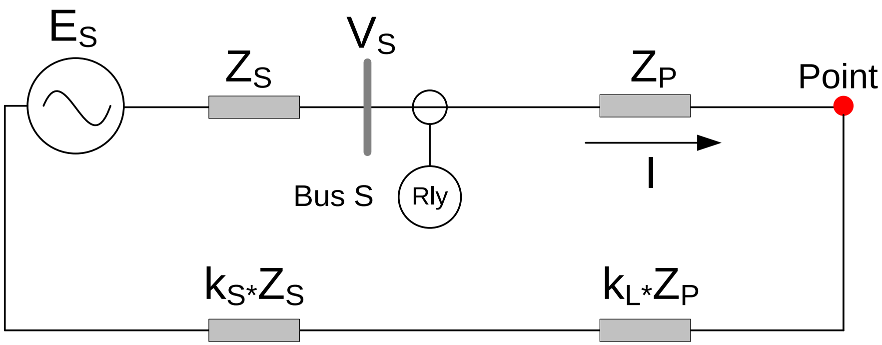
State Simulation enhanced with …

- Graphical display of characteristics on R-X diagram
- Mouse click to add Z points



State Simulation enhanced with …

- System model provides dynamic simulation

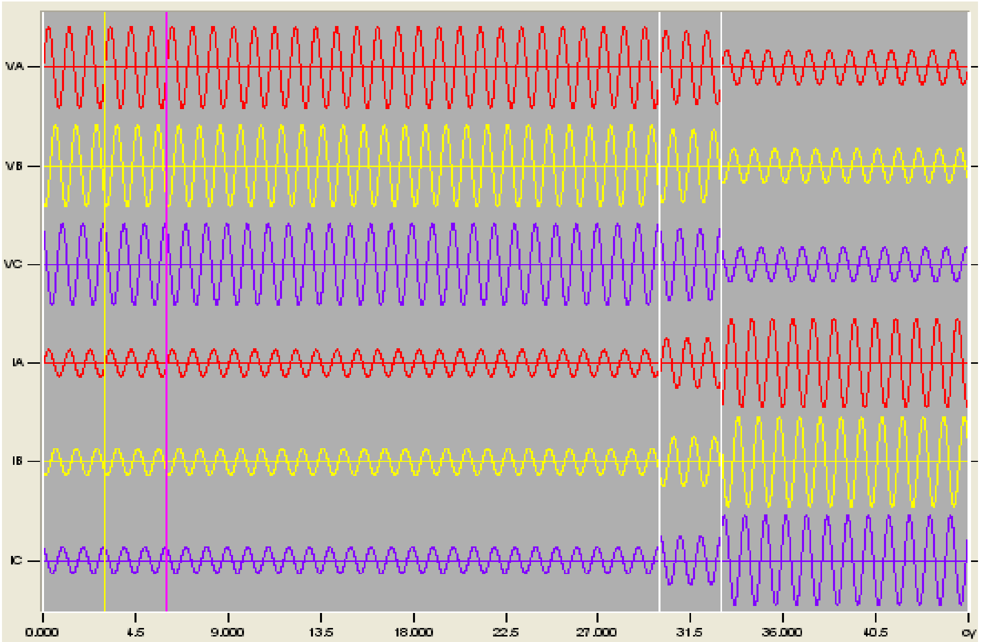


- Voltages and currents are automatically calculated

State No	1			2		3	
State Name	Initial Load			Inside Outer Char		Inside Zone 1	
Source	Ampl.	Ph.Ang	Freq.	Ampl.	Ph.Ang	Ampl.	Ph.Ang
VA	65.79	-10.12	60.0000	58.94	-18.5	27.75	-4.26
VB	65.79	-130.1	60.0000	58.94	-138.5	27.75	-124.3
VC	65.79	109.9	60.0000	58.94	101.5	27.75	115.7
IA	3.104	-16.35	60.0000	5.749	-30.59	10.416	-82.17
IB	3.104	-136.4	60.0000	5.749	-150.6	10.416	-202.2
IC	3.104	103.6	60.0000	5.749	89.41	10.416	37.83
Max.Duration	500.0 ms			50.0 ms		200.0 ms	

State Simulation

- Oscillograph of voltage and current waveforms
- Works for PSB and OST functions that use **conventional** detection methods



- **<u>Not</u> Realistic** due to step changes. Actual power swings do not change V, I and Z abruptly.
- **<u>Cannot</u>** test PSB and OST functions that are based on **<u>continuous</u>** **ΔZ/Δt** or **ΔI** or **SCV**

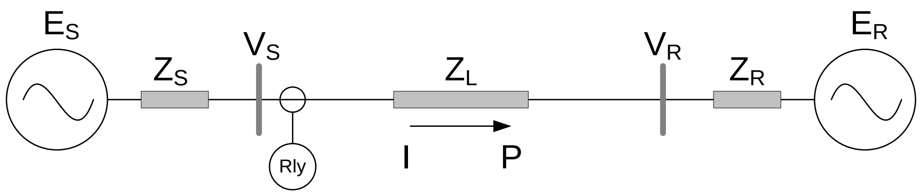
We Need Easy-to-Use, Realistic Testing Tools

- Approximate physical reality to a reasonable degree in order to allow proper testing of all conventional and non-conventional methods and schemes of PSB and OST functions.
- Specify and visualize the power swing impedance trajectory with little effort
- Be able to target specific areas of the protection zones and the zones of the PSB and OST functions
- Be able to control the rate-of-change of Z

We Need Easy-to-Use, Realistic Testing Tools

Two New Testing Tools

- Classical Two-machine Simulation Model
  - Line impedance
  - Source impedances



- User-specified Z Points and rate-of-change dz/dt between points

Classical Two-Machine Simulation Method

PSB1- Classical 2 Machine

Protected Line	|Z|, ohm	Angle, deg	R, ohm	X, ohm
Pos.sequence	6.25	85.00	0.545	6.226
Zero sequence	21.1	74.4	5.674	20.323
KL magnitude	0.8	KL angle	-15.00	deg

Source data	Source 1		Source 2	
Frequencies	60.0000	Hz	58.5	Hz
|E| Amplitudes	69.28	V	65.82	V
Initial E Angles	0.00	deg	0.00	deg
Source Z magnitudes	4.000	ohm	8.000	ohm
Source Z Angles	85.00	deg	85.00	deg

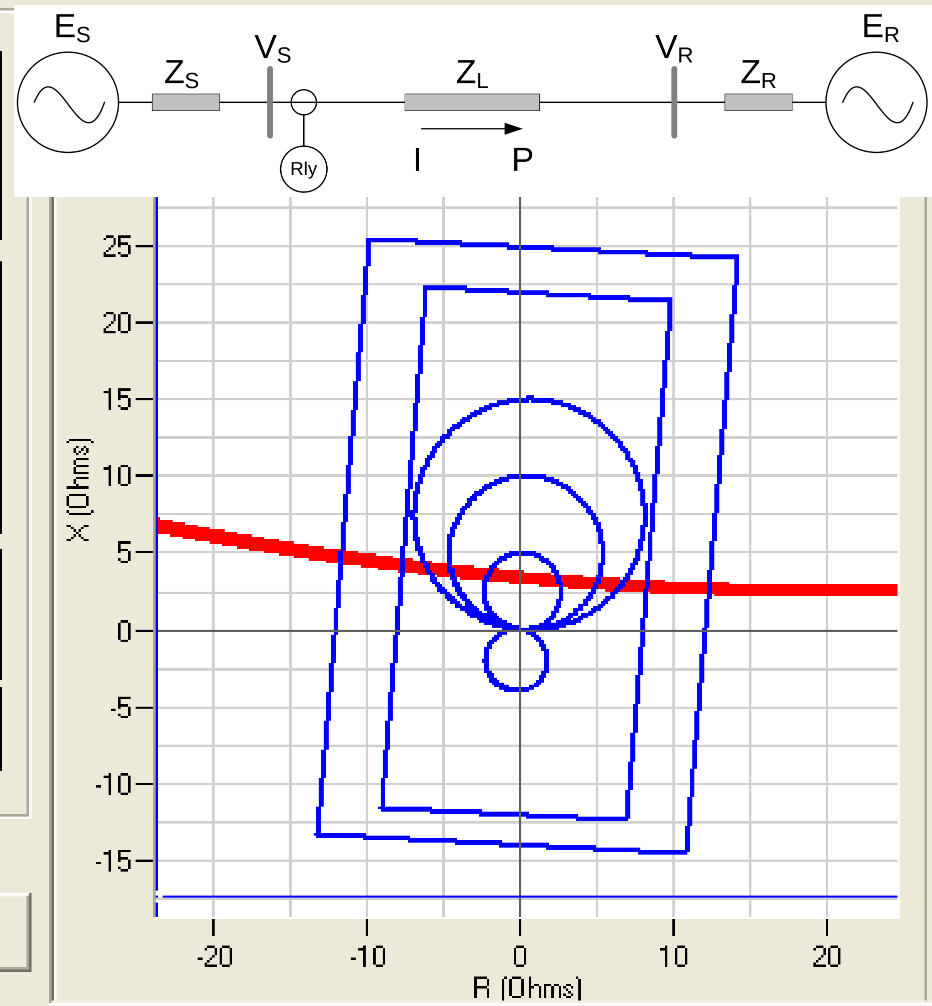
Pre-swing duration	0.5	s
Number of swing turns	1.00	
Total duration	1.1667	s

☐ Limit current amplitude to	10.00	A
☑ Specify Electrical center	50.00	%

Number of Test Repetitions: 1

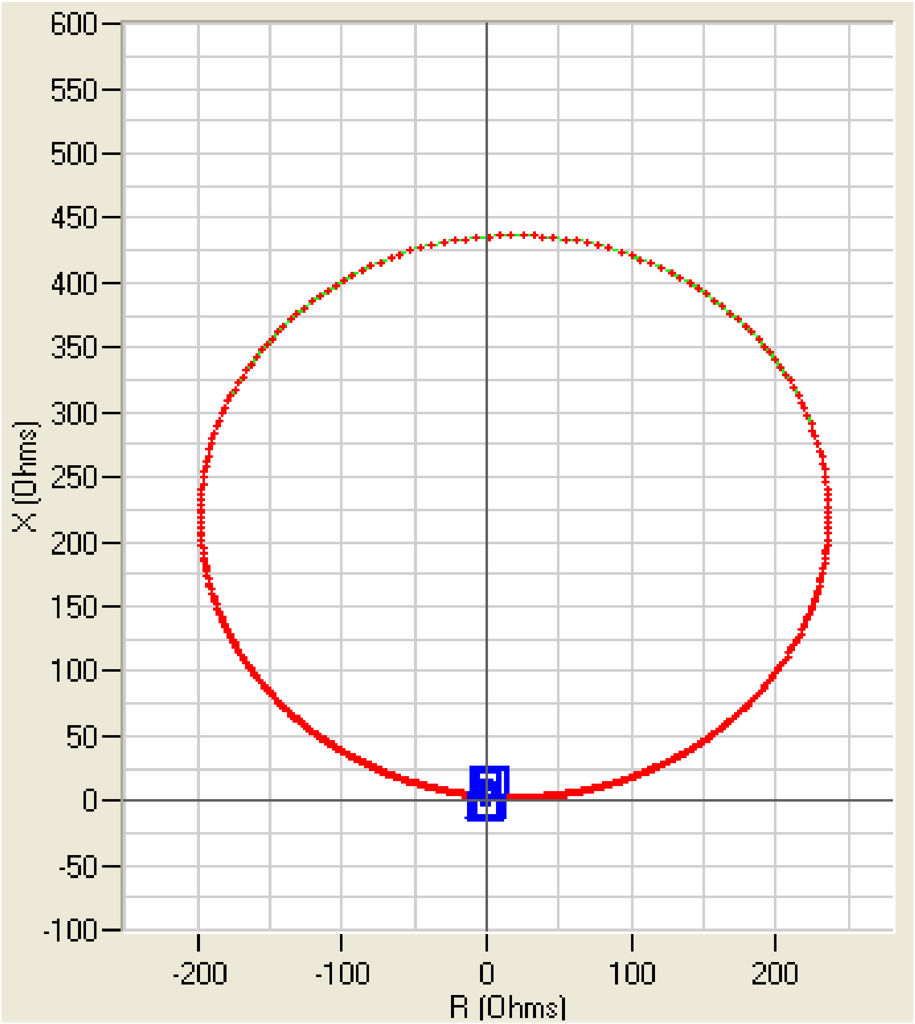
Refresh Graph

Display Waveform



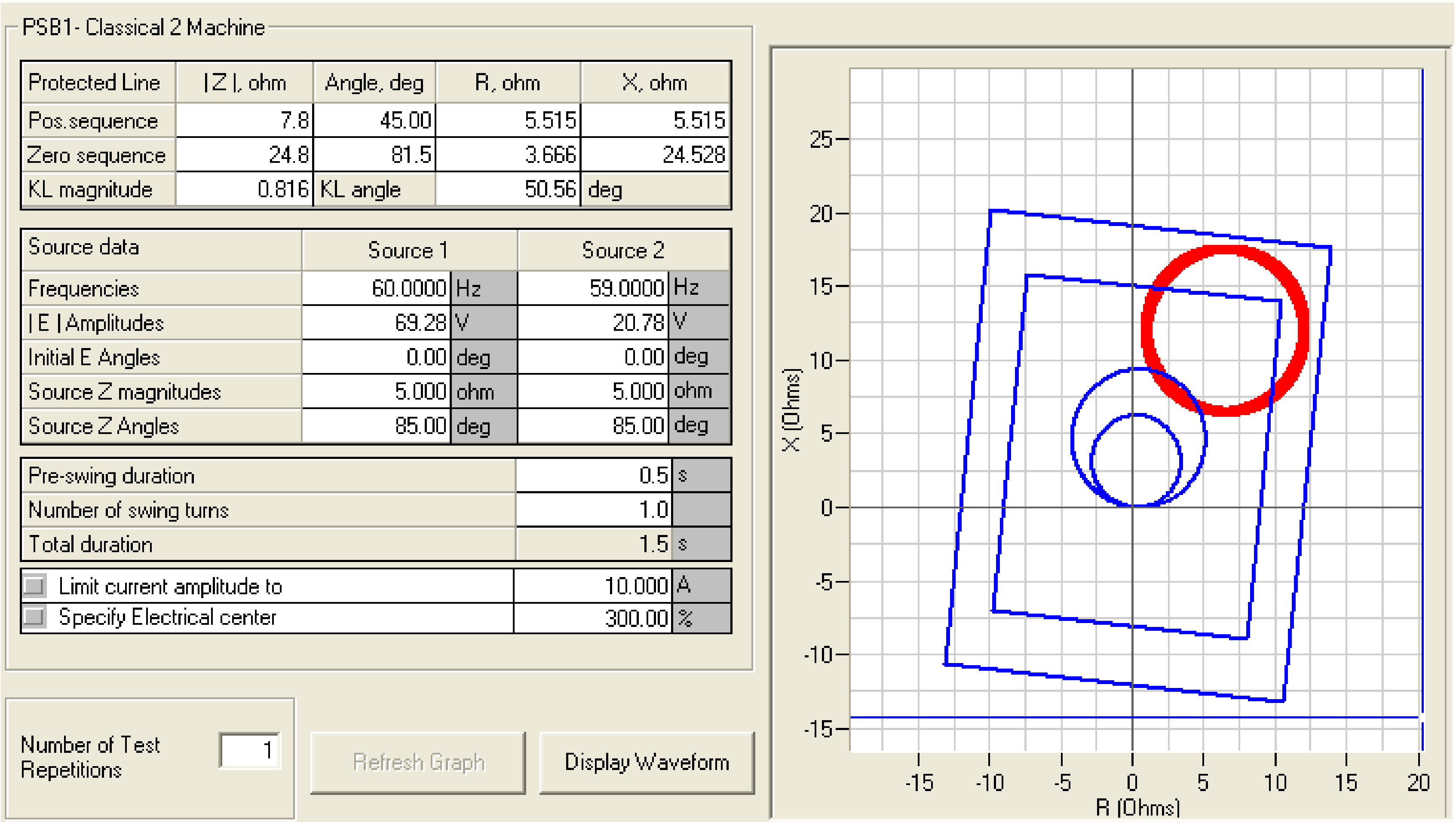
Classical Two-Machine Simulation Method

Zooming out shows entire trajectory

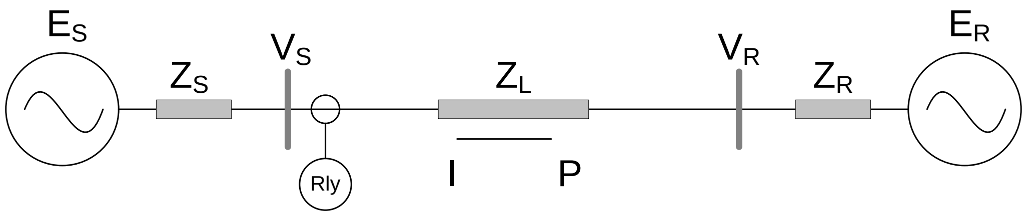


Classical Two-Machine Simulation Method

It is possible to simulate swing locus like this.



Classical Two-Machine Simulation Method



$$\varphi_{E_S}(t) = \theta_{E_S} + 2\pi f_S t$$

$$\varphi_{E_R}(t) = \theta_{E_R} + 2\pi f_R t$$

$$|I|e^{j\varphi_I(t)} = \frac{\left(|E_S|e^{j\varphi_{E_S}(t)} - |E_R|e^{j\varphi_{E_R}(t)}\right)}{|Z_T|e^{j\theta_{Z_T}}}$$

$$|V_S|e^{j\varphi_{V_S}(t)} = |E_S|e^{j\varphi_{E_S}(t)} - |I|e^{j\varphi_I(t)} \cdot |Z_S|e^{j\theta_{Z_S}}$$

$$i(t) = \sqrt{2} \cdot |I(t)| \cdot \sin(\varphi_I(t))$$

$$v_S(t) = \sqrt{2} \cdot |V_S(t)| \cdot \sin(\varphi_{V_S}(t))$$

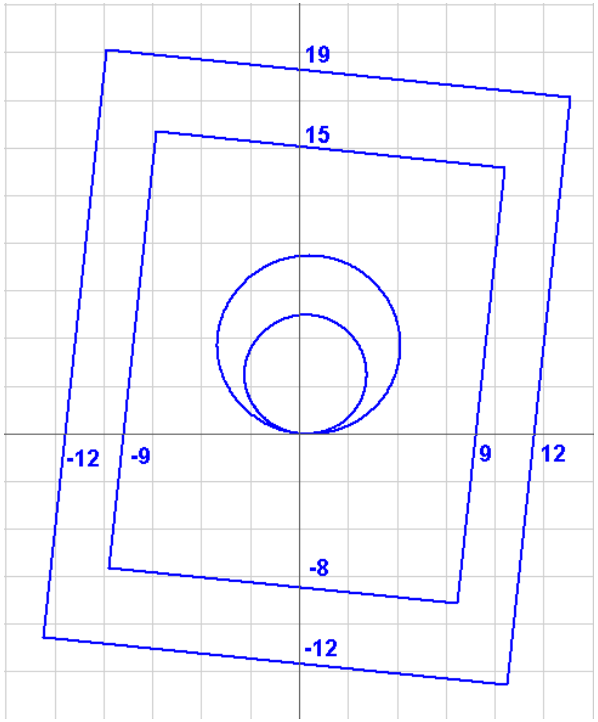
$$v_R(t) = \sqrt{2} \cdot |V_R(t)| \cdot \sin(\varphi_{V_R}(t))$$

Classical Two-Machine Simulation Method

Testing PSB and OST Functions

With settings as shown and using formulas from the relay manual

Ztot	17.789	Ω
Zin setting	9	Ω
Zout setting	12	Ω
AngleIn	89.3	°
AngleOut	73.1	°
OST Enabled (Y/N)	Y	
OST delay	0.386	cy
timer steps	0.25	cy
OST delay setting	0.5	cy
OSB delay	1.25	cy
OSB delay setting	1.25	cy



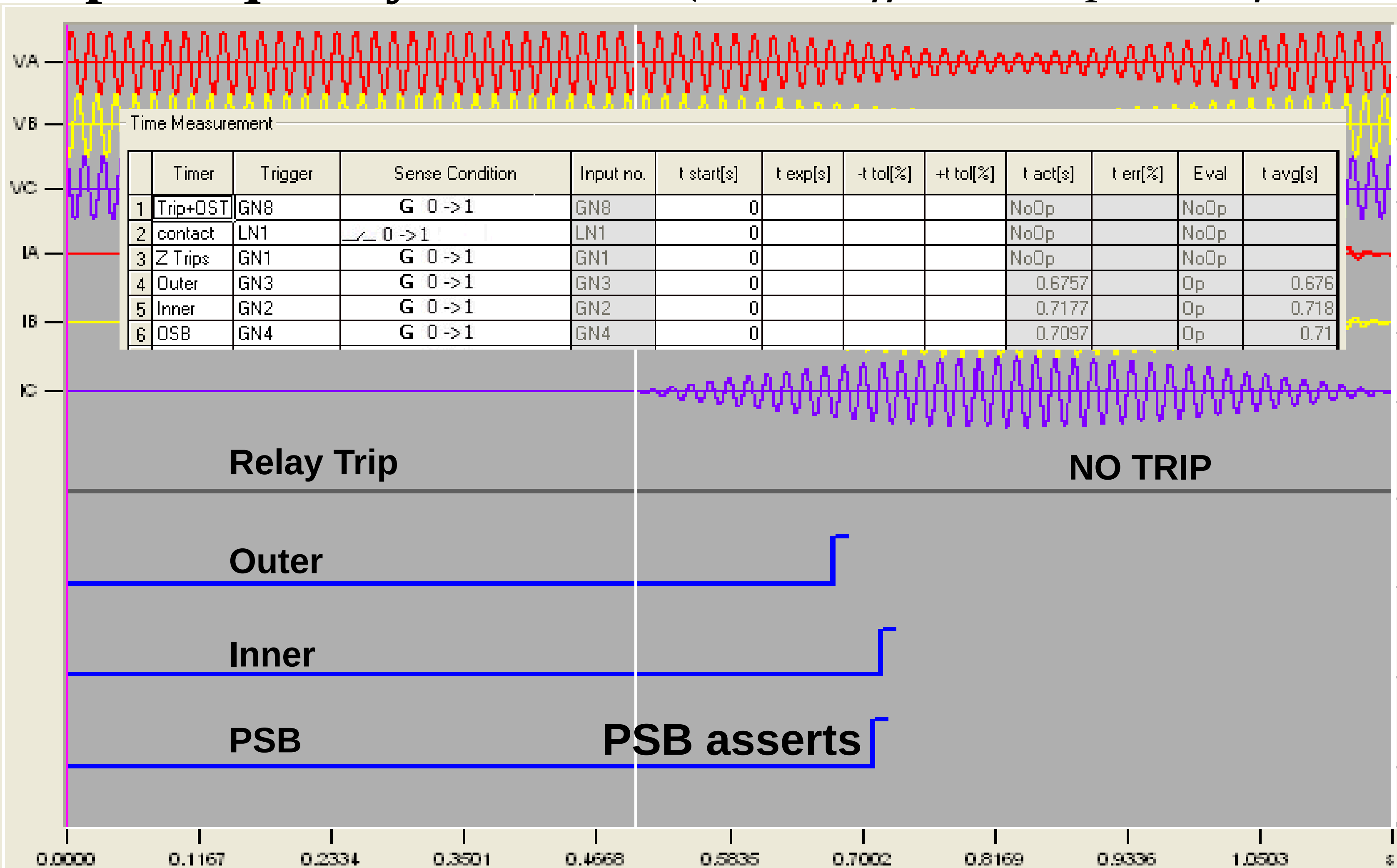
Effective Slip Rate for OOS Blocking			
	= up to	2.16	Hz
Effective Slip Rate for OOS Tripping			
= from 2.16 Hz	up to	5.41	Hz

Test at slip rates: 1.5 Hz and 2.5 Hz

Test at slip rates: 5 Hz and ≥ 6 Hz

Classical Two-Machine Simulation Method
Testing Power Swing Blocking Function

Slip Frequency = 1.5 Hz *(within effective slip rate of 2.16Hz)*

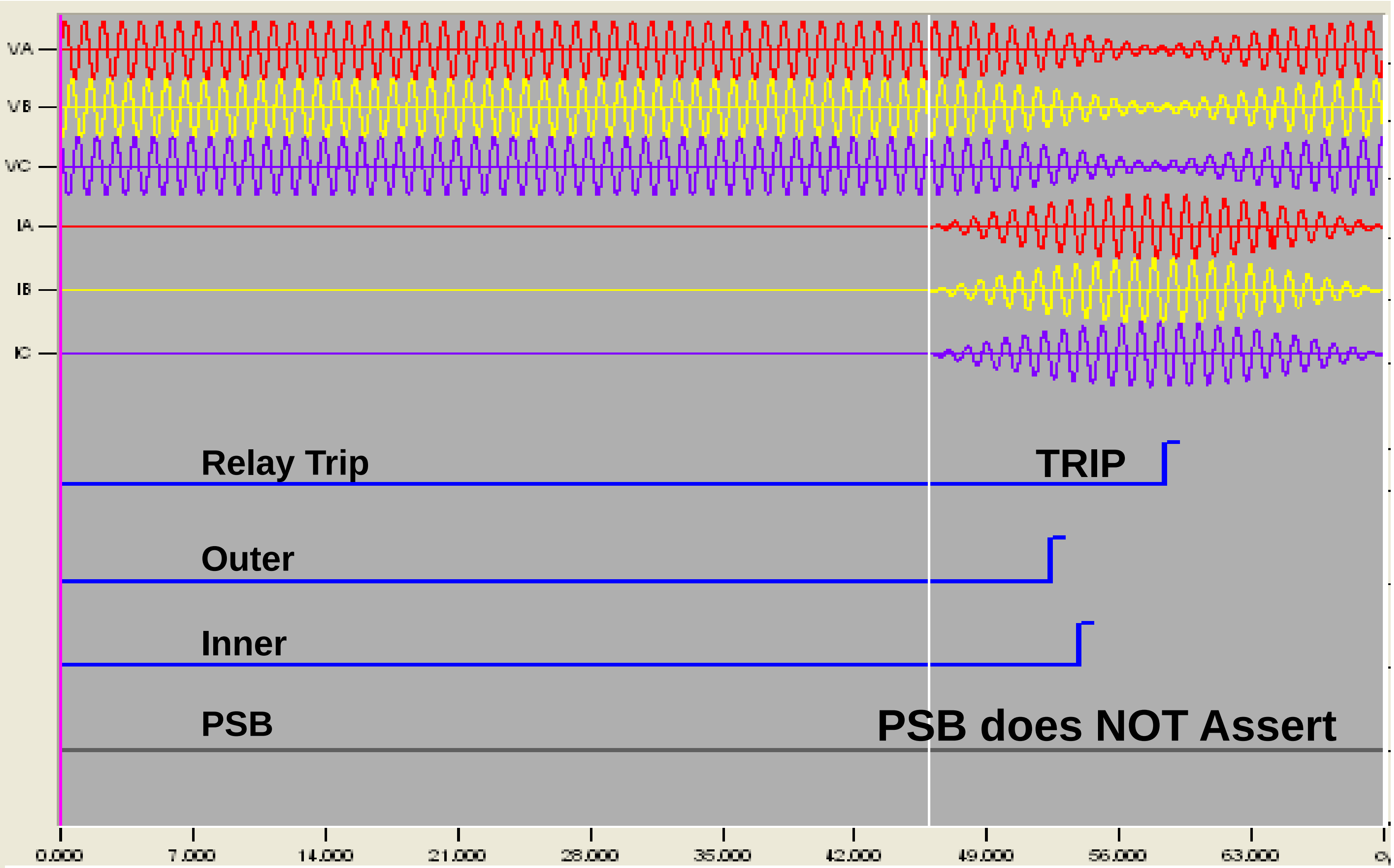


	Timer	Trigger	Sense Condition	Input no.	t start[s]	t exp[s]	-t tol[%]	+t tol[%]	t act[s]	t err[%]	Eval	t avg[s]
1	Trip+OST	GN8	G 0 ->1	GN8	0				NoOp		NoOp	
2	contact	LN1	0 ->1	LN1	0				NoOp		NoOp	
3	Z Trips	GN1	G 0 ->1	GN1	0				NoOp		NoOp	
4	Outer	GN3	G 0 ->1	GN3	0				0.6757		Op	0.676
5	Inner	GN2	G 0 ->1	GN2	0				0.7177		Op	0.718
6	OSB	GN4	G 0 ->1	GN4	0				0.7097		Op	0.71

Classical Two-Machine Simulation Method

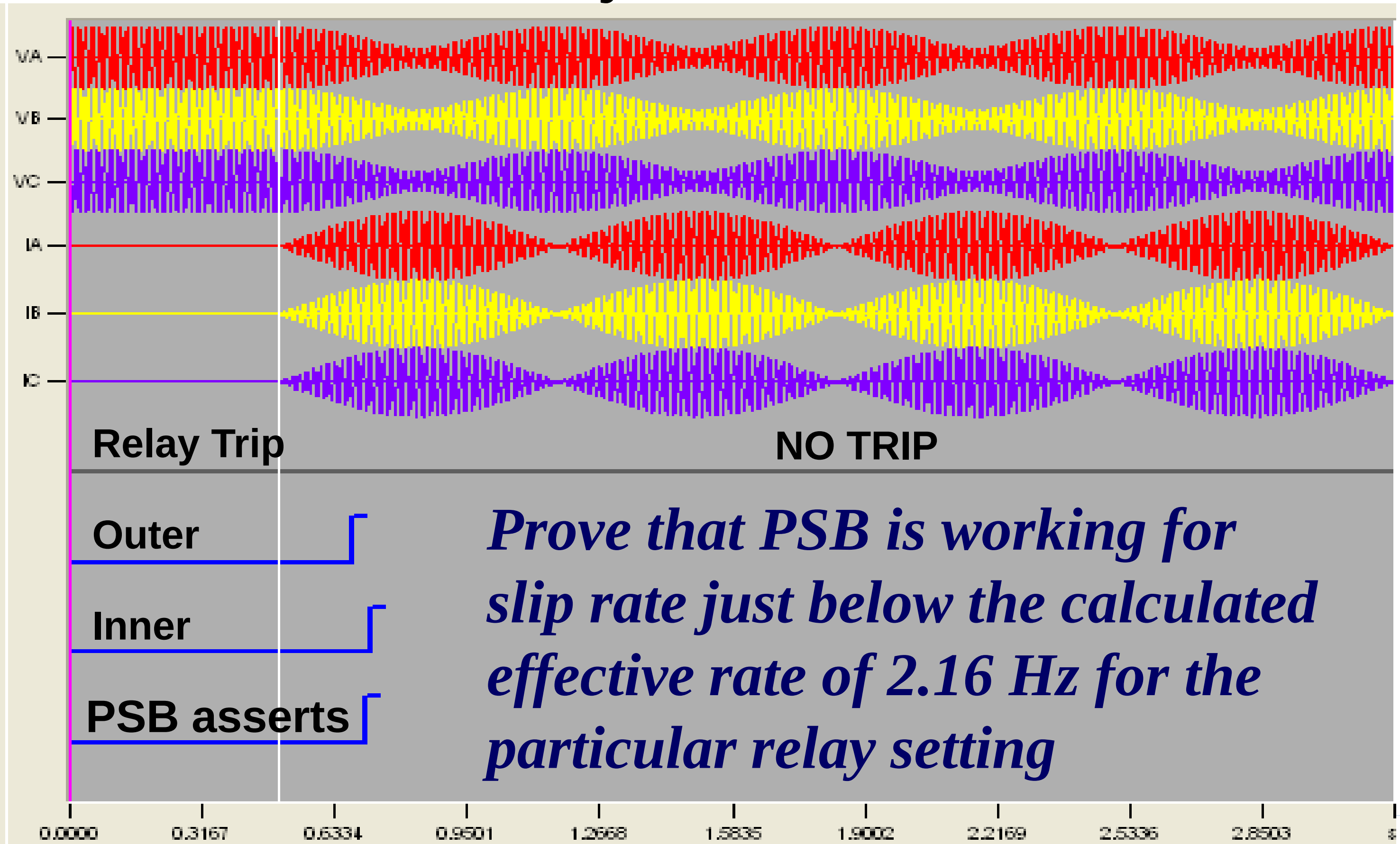
Testing Power Swing Blocking Function

Faster Swing: Slip Freq = 2.5Hz *(> effective slip rate of 2.16Hz)*



Classical Two-Machine Simulation Method
Testing Power Swing Blocking Function

- **f_{slip} = 2 Hz** *(within effective slip rate of 2.16Hz)*
- **with multiple pole slips**
- **PSB asserted correctly**

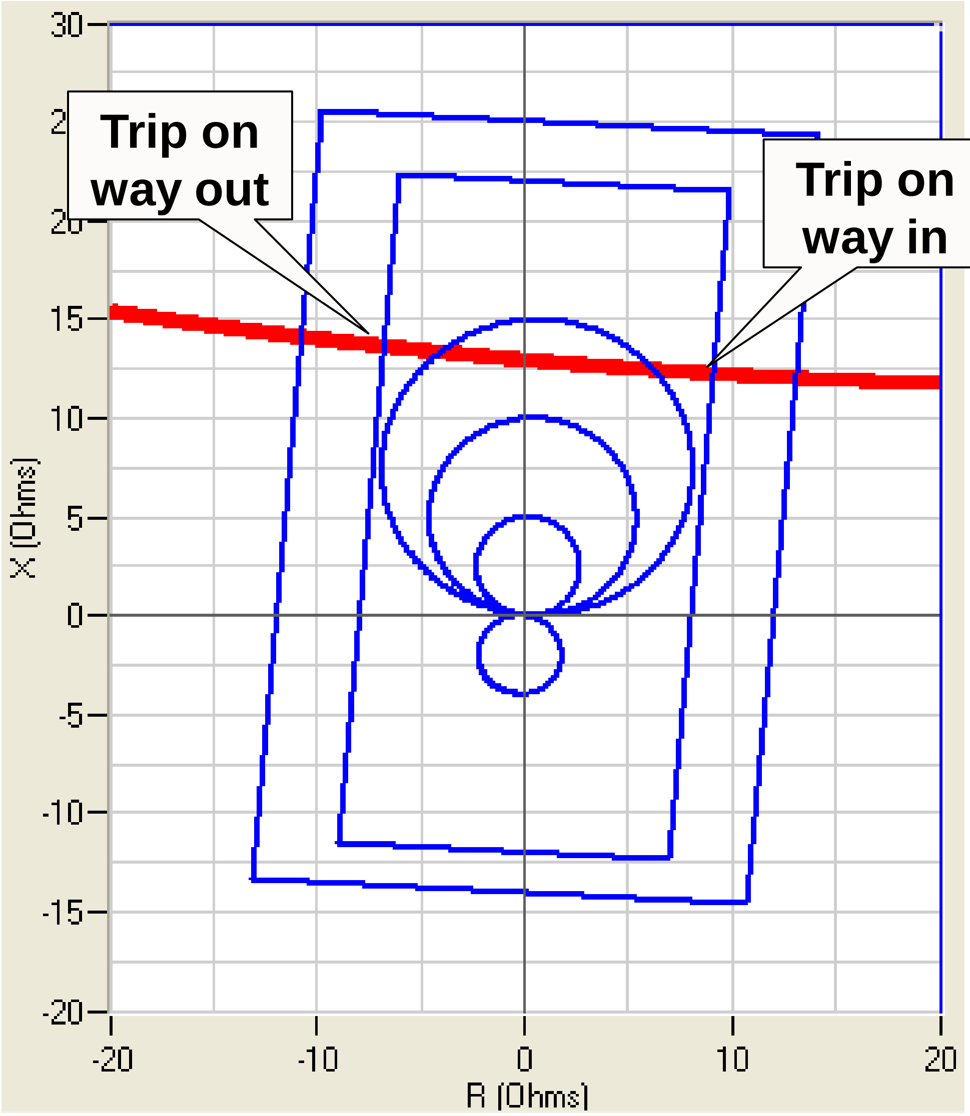


Classical Two-Machine Simulation Method
Testing Out-of-Step Tripping Function

Relay was set and tested for two cases:

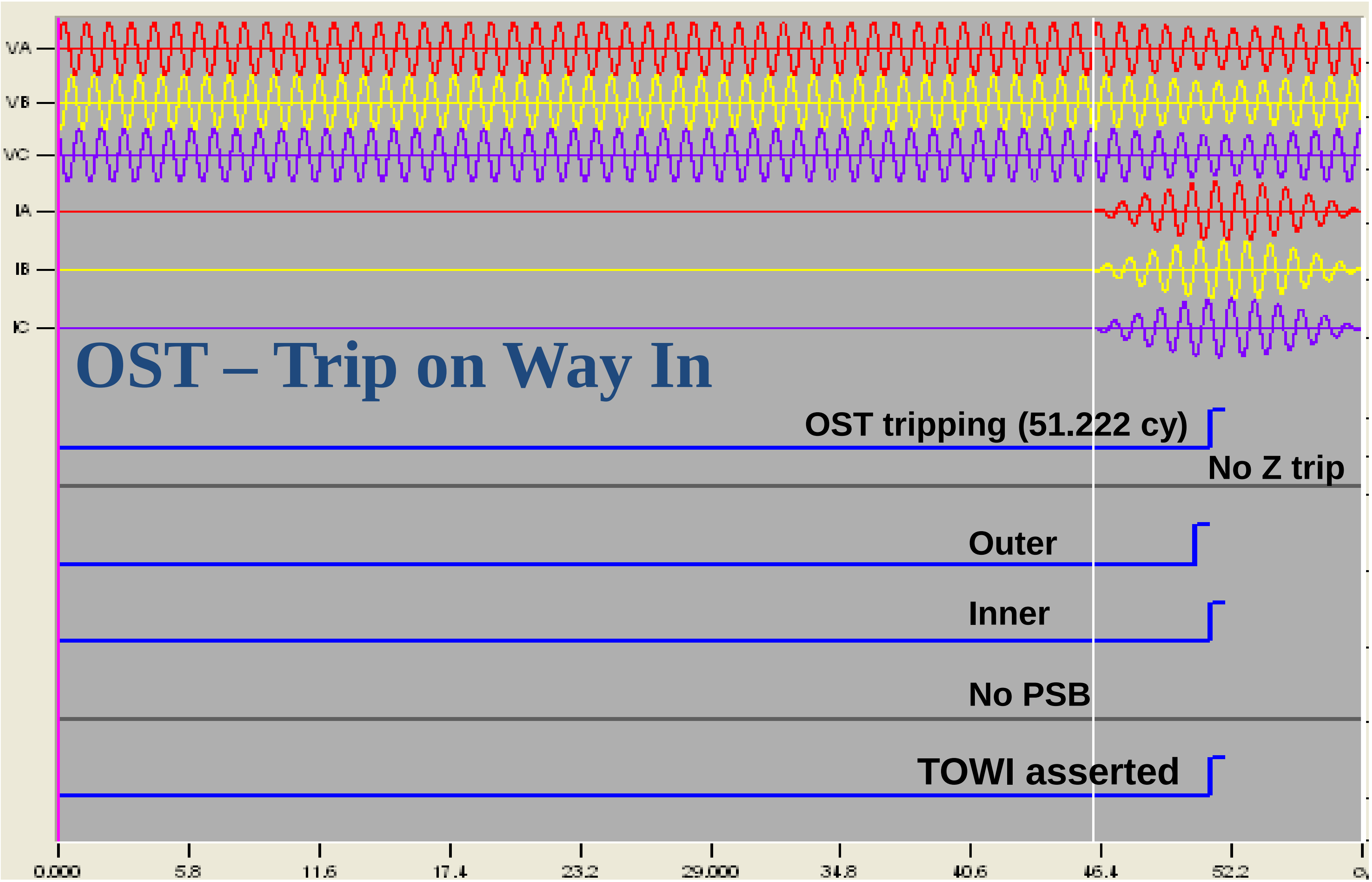
- **Trip On Way In (TOWI)**
- **Trip On Way Out (TOWO)**

f_{slip} was 5 Hz *(just below the calculated OST effective slip rate of 5.41 Hz)*

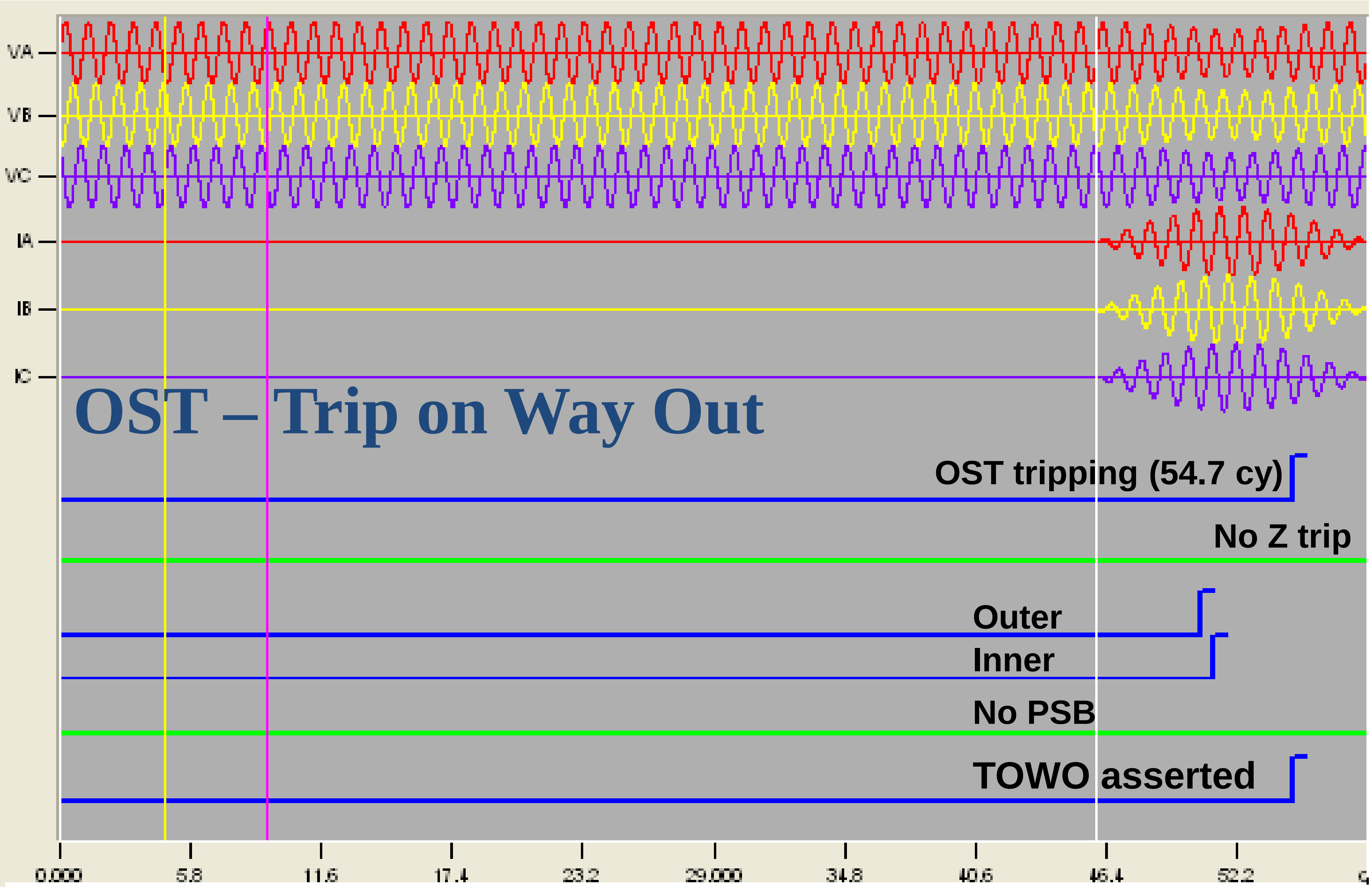


Classical Two-Machine Simulation Method

Testing Out-of-Step Tripping Function



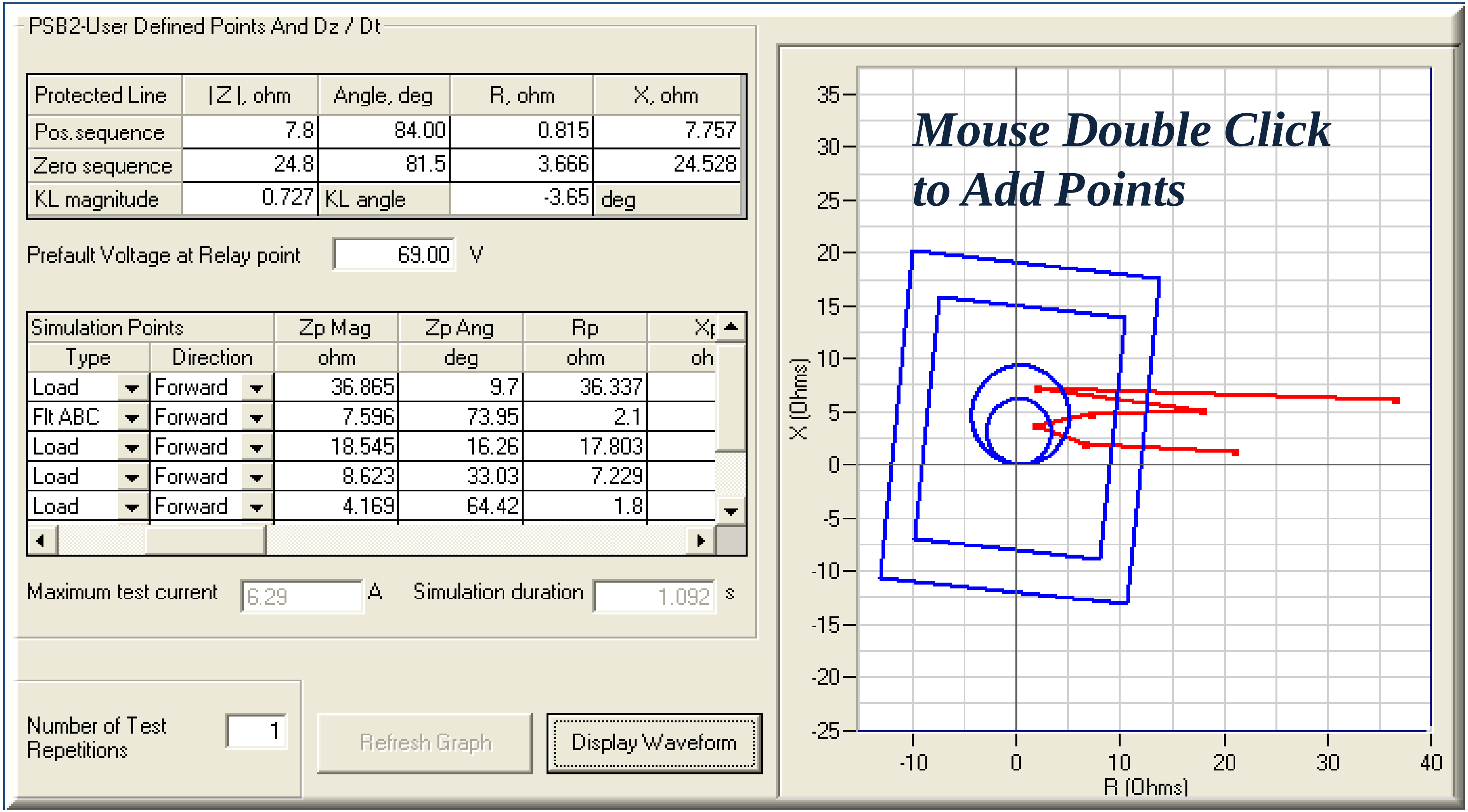
Classical Two-Machine Simulation Method
Testing Out-of-Step Tripping Function



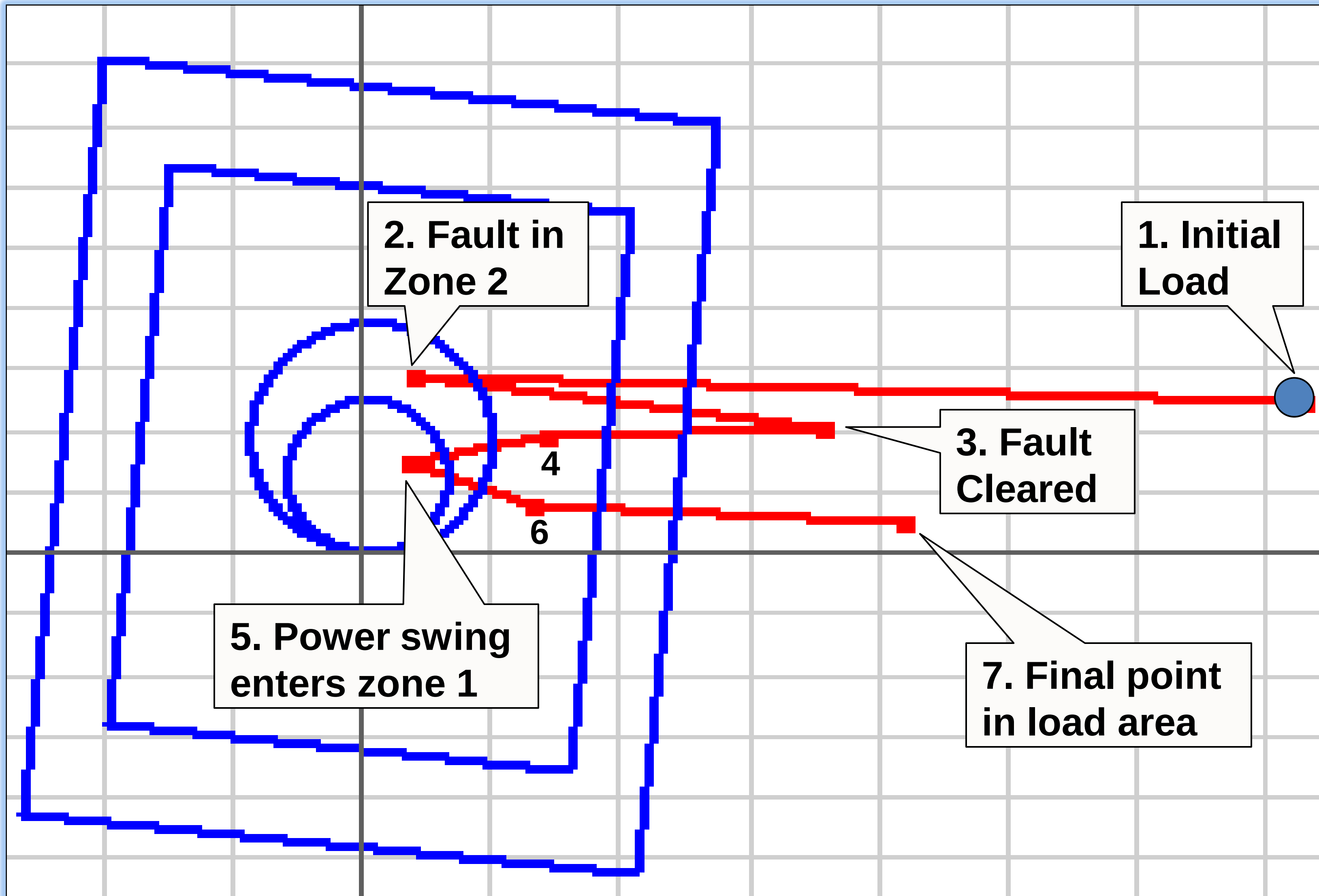
User-specified Points & Smooth dz/dt

- Another Method of Testing PSB and OST
- Easy to target PSB/OST elements and protection zones for testing
- Easy control of impedance trajectory
- Easy control of rate-of-change of impedance
- Supports spreadsheet-like formulas

User-specified Points & Smooth dz/dt



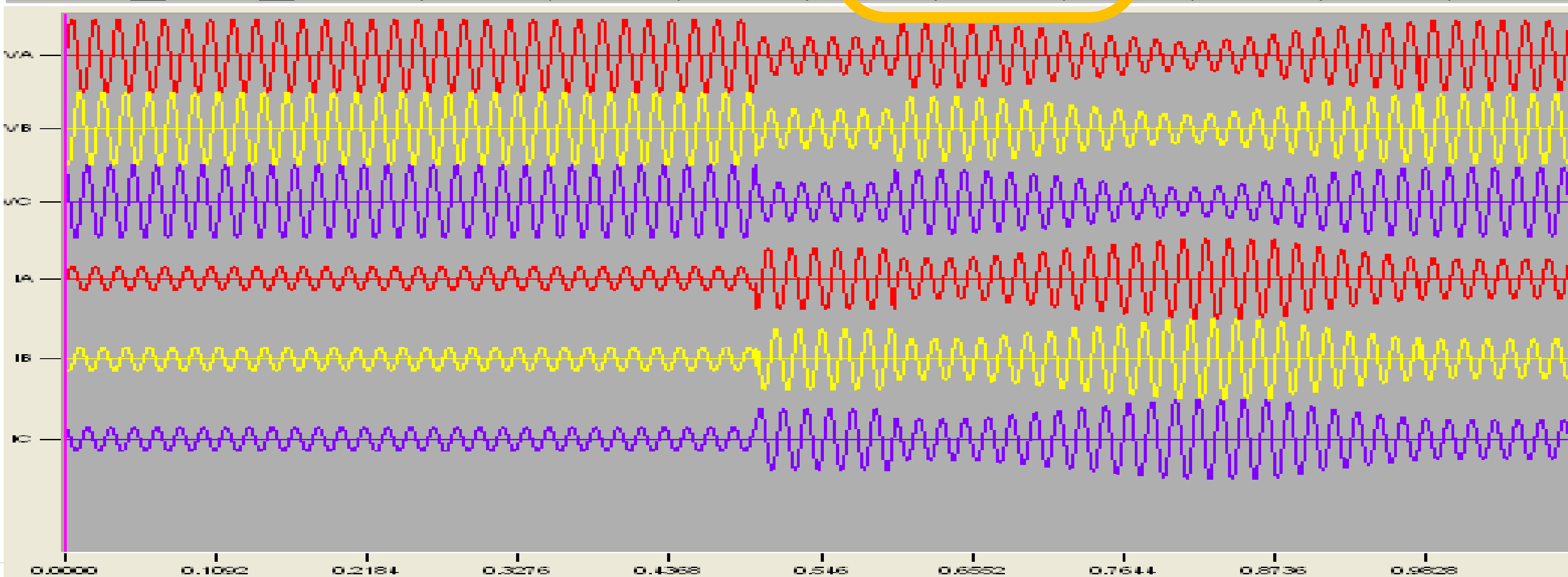
User-specified Points & Smooth dz/dt
Testing Power Swing Blocking function



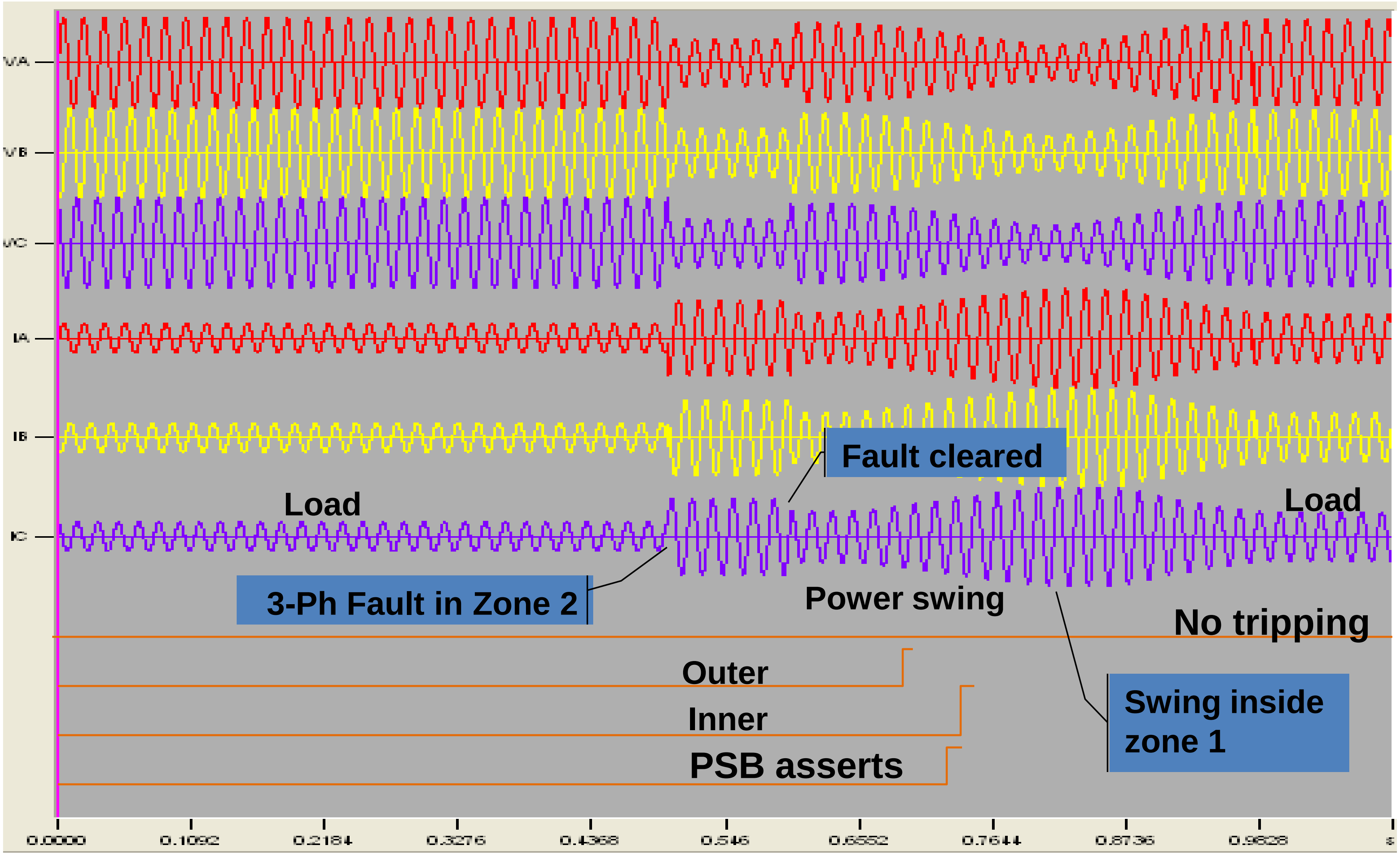
User-specified Points & Smooth dz/dt

Testing Power Swing Blocking function

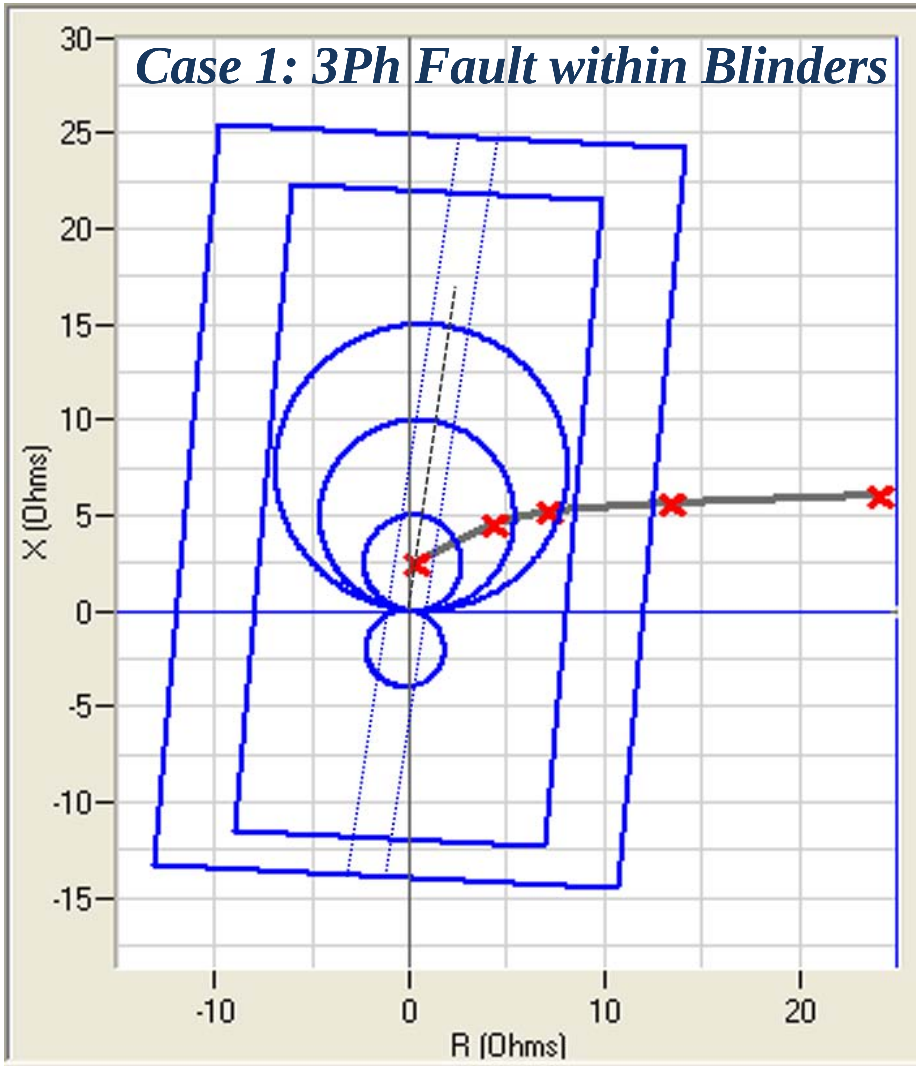
	Simulation Points		Zp Mag	Zp Ang	Rp	Xp	dz/dt	Duration	Zs Mag	Zs Ang	Ks Mag	Ks Ang
	Type	Direction	ohm	deg	ohm	ohm	ohm/s	s	ohm	deg		deg
1	Load	Forward	36.865	9.7	36.337	6.214	-	0.5	7.8	84.00	0.727	-3.65
2	Flt ABC	Forward	7.596	73.95	2.1	7.3		0.1	7.8	84.00	0.727	-3.65
3	Load	Forward	18.545	16.26	17.803	5.194		0.05	7.8	84.00	0.727	-3.65
4	Load	Forward	8.623	33.03	7.229	4.7	125.		7.8	84.00	0.727	-3.65
5	Load	Forward	4.169	64.42	1.8	3.76	75.		7.8	84.00	0.727	-3.65
6	Load	Forward	6.868	16.21	6.595	1.917	75.		7.8	84.00	0.727	-3.65
7	Load	Forward	21.016	3.55	20.976	1.303	125.	0.1	7.8	84.00	0.727	-3.65



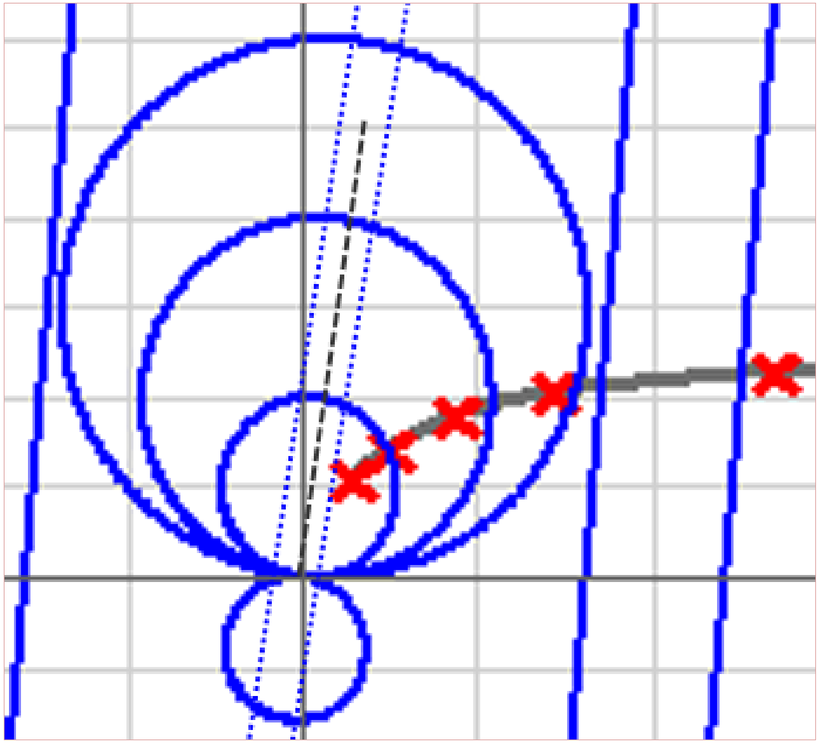
User-specified Points & Smooth dz/dt
Testing Power Swing Blocking function



User-specified Points & Smooth dz/dt -
Test Inner Set of Blinders for Removal of Block

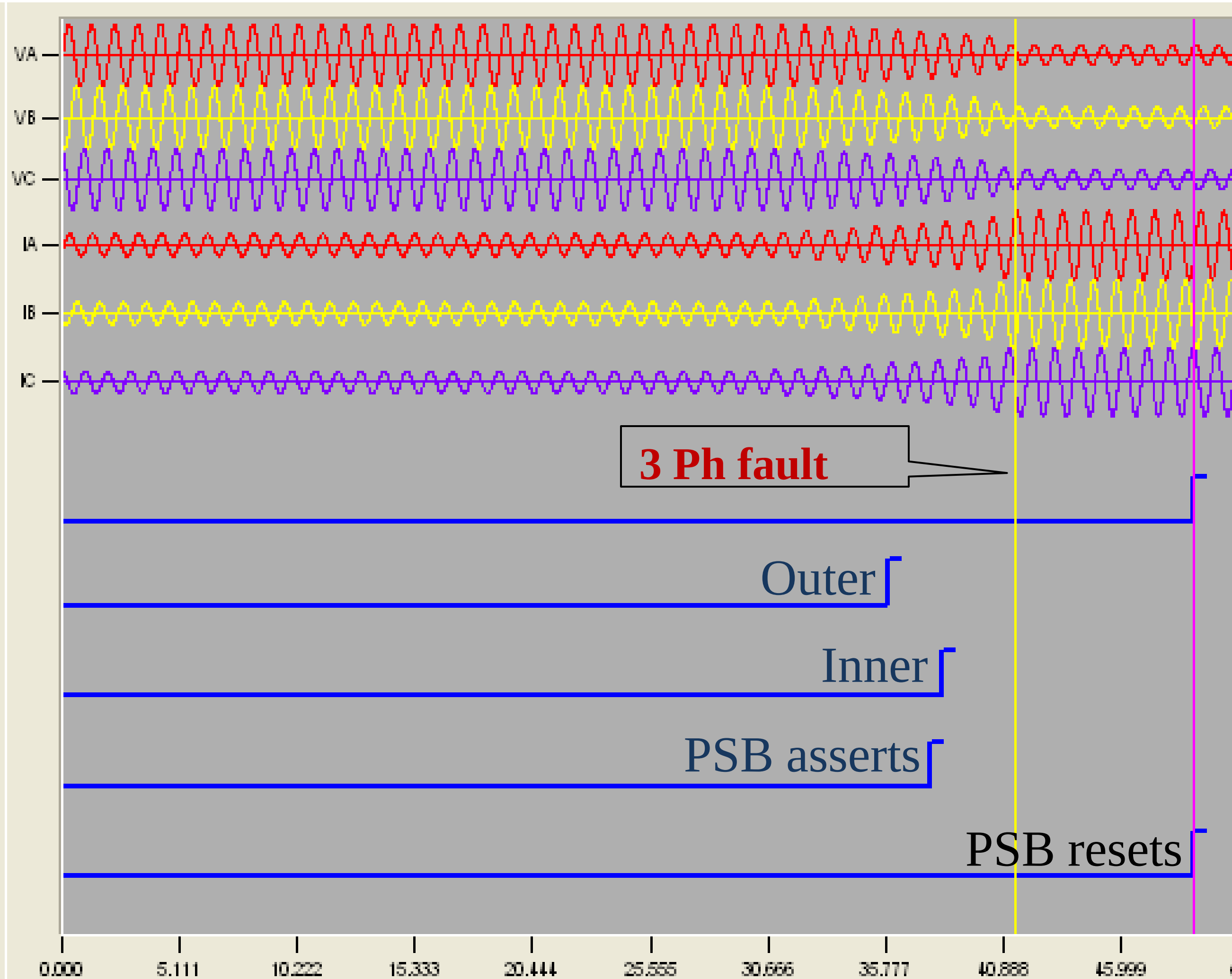


Case 2: 3Ph Fault Outside Blinders but inside Zone 1

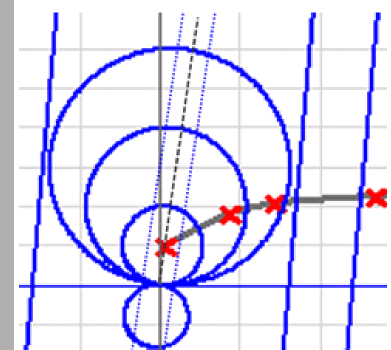


User-specified Points & Smooth dz/dt -
Test <u>Inner Set</u> of Blinders for Removal of Block

Case 1: 3Ph Fault <u>Within</u> Inner Set of Blinders

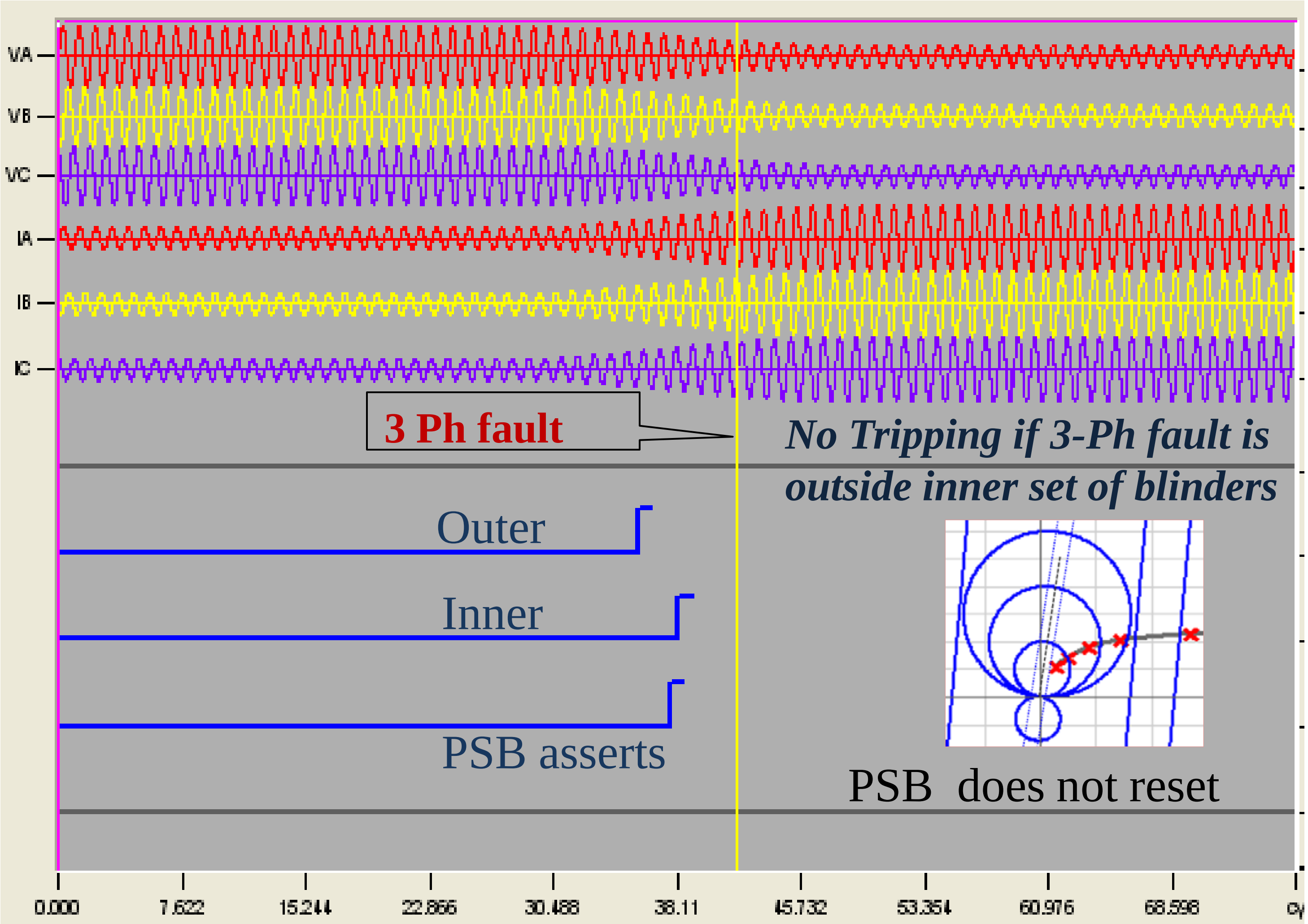


TRIP in 7 cy



User-specified Points & Smooth dz/dt -
Test Inner Set of Blinders for Removal of Block

Case 2: 3Ph Fault Outside Inner Set of Blinders but Inside Zone 1



Summary and Conclusions

- Reviewed basic power system stability, and the effect of power swings and out-of-step conditions on line protection
- Reviewed methods used in PSB and OST functions
- Discussed methods of testing OSB and OST functions
- Discussed the need for, and described new and easier methods of testing PSB and OST functions that are realistic and applicable for all PSB/OST methods.
  - Classical Two-machine model
  - User-specified Z points and smooth dz/dt
  - For Field Testing and testing in the laboratory

Questions?