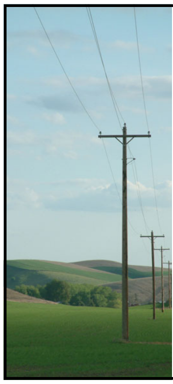


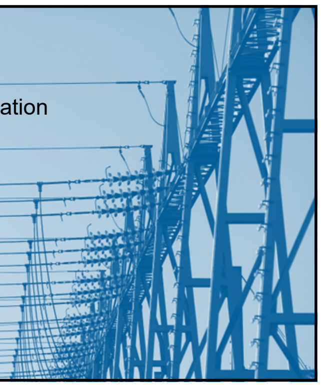
Wide-Area Protection and Control Case Studies

SEL

Miguel Cruz Hernandez P.E.

1

Agenda



- Power system stability classification
- Rotor angle stability
- Voltage stability
- Frequency stability
- Dynamic system studies
- Case studies

2

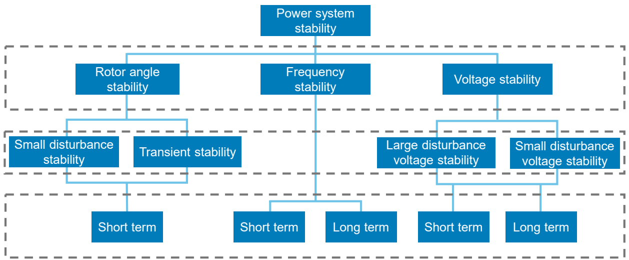
Power system stability

"…is the ability of a Power System, for a given initial operating condition, to regain a state of operating equilibrium after being subject to a physical disturbance, with most system variables bounded so that practically the entire system remains intact."

– IEEE / CIGRE Task Force

3

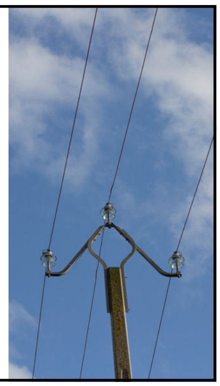
Power system stability classification



4

Rotor angle stability

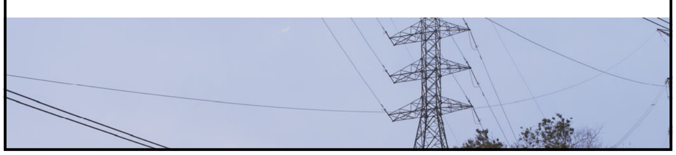
- Ability to remain in synchronism
- Ability to maintain or restore equilibrium
- Instability
  - Run-away situation
  - Increasing angular swings



5

Rotor angle stability size

- Small disturbance stability – small changes of load and generation
- Transient stability – faults, line loss, loss of generation, and load



6

Transient stability

- Large disturbance angle stability
- Ability to maintain synchronism
  - Initial operating condition
  - Disturbance severity
  - Post-fault network strength

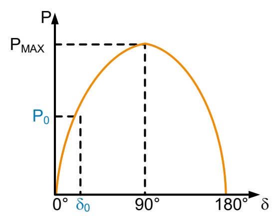
7

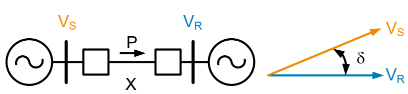
Electric power flow

Lossless system

$$P = P_S = P_R = \frac{V_S V_R}{X} \sin \delta$$

$$P_{MAX} = \frac{V_S V_R}{X}$$





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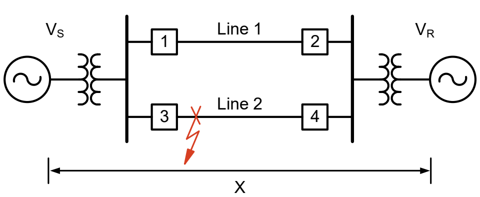
Transient stability concepts

Pre-fault state
Both lines in service

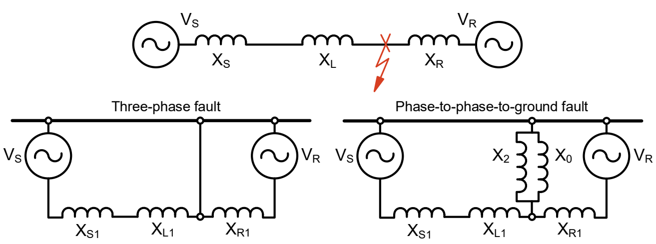
Fault state

Post-fault state
Line 2 out of service



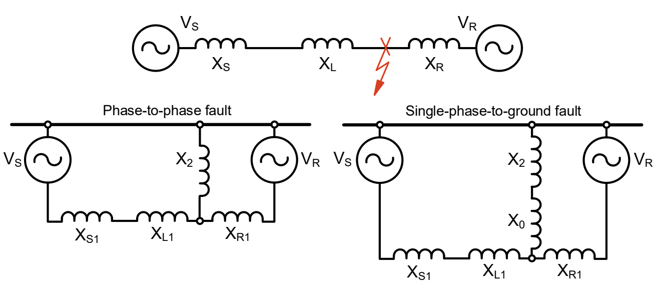
9

Effect of fault type



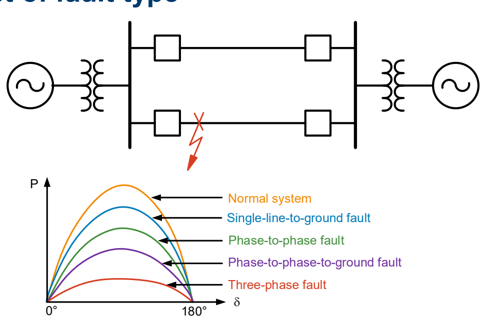
10

Effect of fault type



11

Effect of fault type



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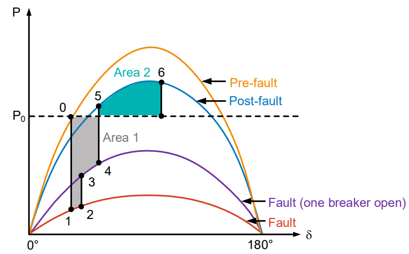
Equal-area criterion
Stable system



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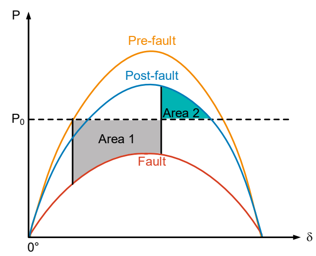
Effect of fault-clearing time
Unstable system



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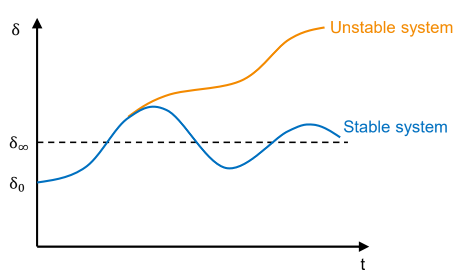
Stable and unstable power swings



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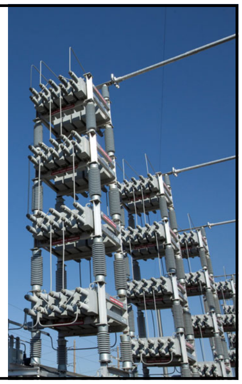
Small-signal (angle) stability

- Ability to maintain synchronism under small disturbances
- Small variations in loads and generation
- Instability
  - Aperiodic increase in rotor angle
  - Oscillatory instability



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Voltage instability is a growing concern of utility operations

- Has contributed to several blackout incidents
- Is mainly due to lack of enough transmission capacity

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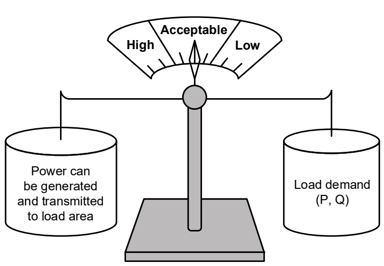
Voltage stability problem

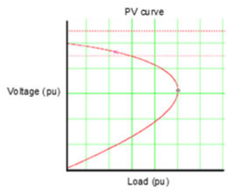


Must maintain balance between load demand and the power source

18

What is voltage collapse?

Voltage collapse occurs at values beyond which systems can maintain their load



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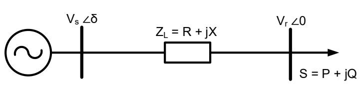
Voltage collapse

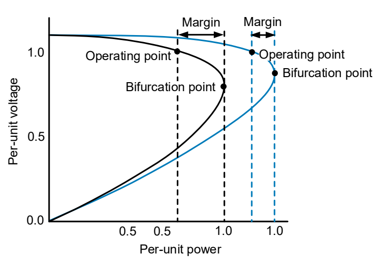
- Power transfer limit depends on transmission impedance (lines) and voltage
- Adding reactive power support increases transfer limit but reduces margin



$$S_{max} = \frac{(1 - \sin(\theta))V_s^2}{2\cos(\theta)^2 X}$$

20

Voltage collapse



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Voltage stability size

- **Large disturbance stability**
  Voltage maintained following large disturbances
- **Small disturbance stability**
  Small perturbations and changes in load

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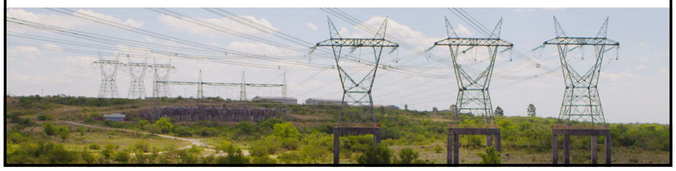
Voltage stability duration

- **Short-term stability**
  Involves dynamics of fast-acting components
- **Long-term stability**
  Involves slow-acting equipment



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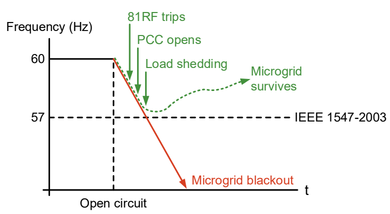
Frequency stability

- Ability to maintain nominal frequency
- Instability duration and corresponding remediation



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Wide-area protection and control projects

Guatemala
Synchrophasor control modal analysis – electromechanical instability

Republic of Georgia
Emergency control system – country-wide mitigation

Uruguay
Over-load and stability control – country-wide mitigation

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Wide-area protection and control projects

Peru
Power angle control – stability

Panama
Voltage collapse – control

Idaho, USA
Generation shedding – stability

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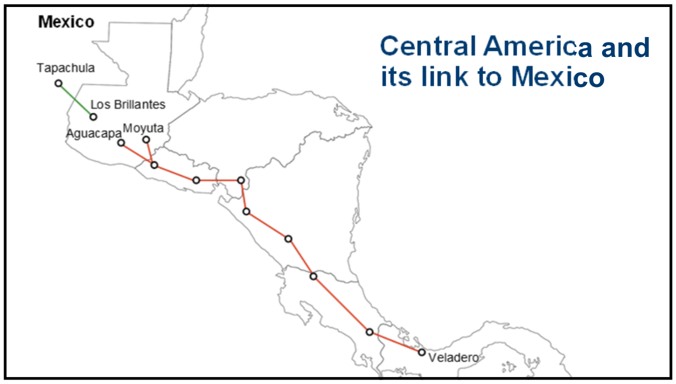
Guatemala and Central America

27

Central America and its link to Mexico



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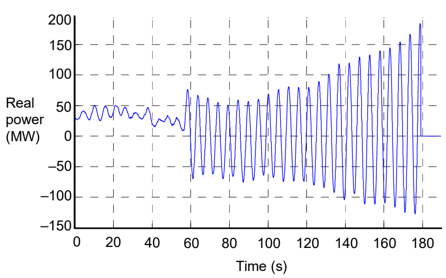
Guatemala supplementary control scheme

29

Unstable oscillation separates Guatemala from rest of Central America

- Oscillation mode 0.17 Hz
- Early wide-area protection system only used active power



30

Modal analysis

- Data window
- Identify modes
- Identify damping constants

$$\hat{x}[n] = \sum_{k=1}^{M} A_k e^{\alpha_k (k-1)T} \cos\left(2\pi f_k (k-1)T + \theta_k\right)$$

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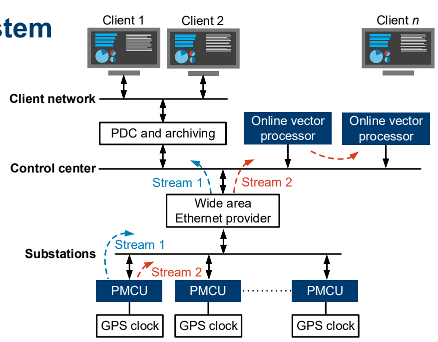
PMCUs in system



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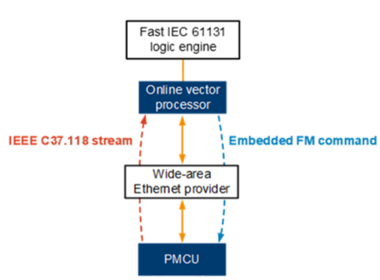
PMCUs and control logic

- PMCUs provide synchronized measurements
- PMCUs receive control commands



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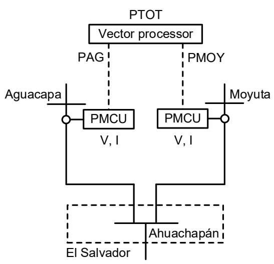
Control scheme



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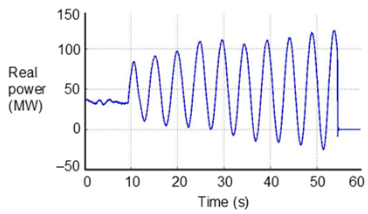
Modal analysis trip

July 28, 2012

- Modal analysis scheme enabled mid June 2012
- Unstable mode shows after synchronizing two parts of Central America system



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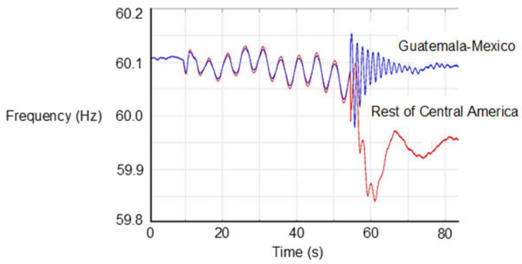
Modal analysis trip frequencies

July 28, 2012



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Control center
SCADA / synchrophasors

37


Republic of Georgia

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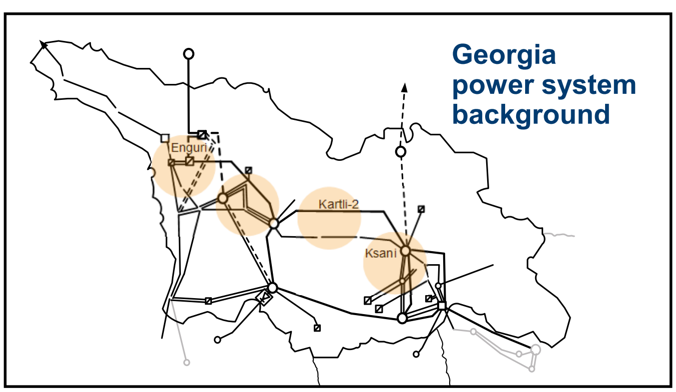
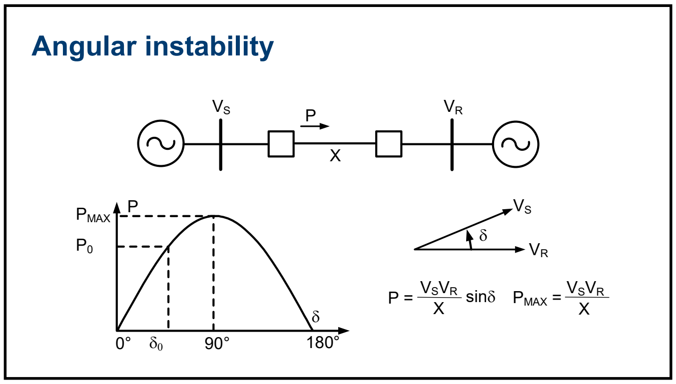
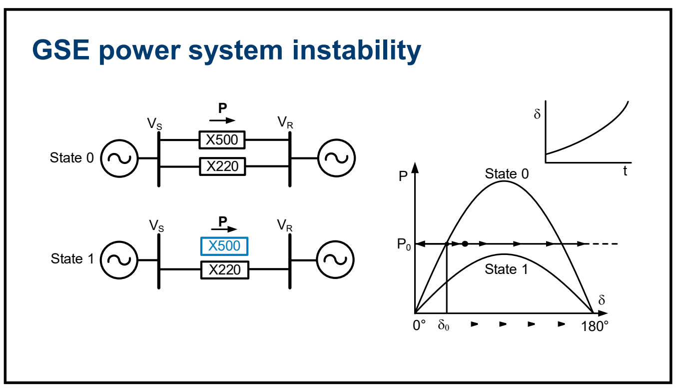

Georgia
power system
background
Enguri
Kartli-2
Ksani

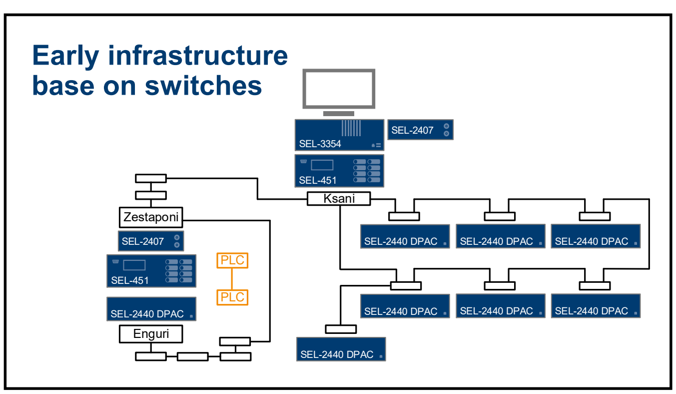
39


Angular instability
V_S
P
X
V_R
P_{MAX}
P
P_0
δ
0°
δ_0
90°
180°
V_S
δ
V_R
$P = \frac{V_S V_R}{X} \sin\delta$
$P_{MAX} = \frac{V_S V_R}{X}$

40


GSE power system instability
State 0
V_S
P
V_R
X500
X220
State 1
V_S
P
V_R
X500
X220
δ
t
P
State 0
P_0
State 1
δ
0°
δ_0
180°

41


Early infrastructure
base on switches
SEL-3354
SEL-2407
SEL-451
Ksani
Zestaponi
SEL-2407
SEL-451
PLC
PLC
SEL-2440 DPAC
Enguri
SEL-2440 DPAC
SEL-2440 DPAC
SEL-2440 DPAC
SEL-2440 DPAC
SEL-2440 DPAC
SEL-2440 DPAC
SEL-2440 DPAC

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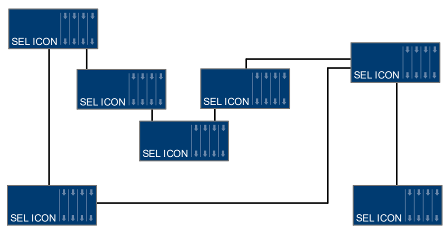
ICON® architecture



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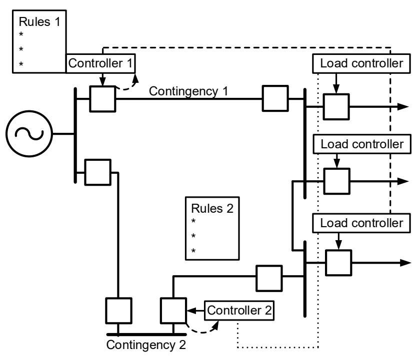
Distributed architecture



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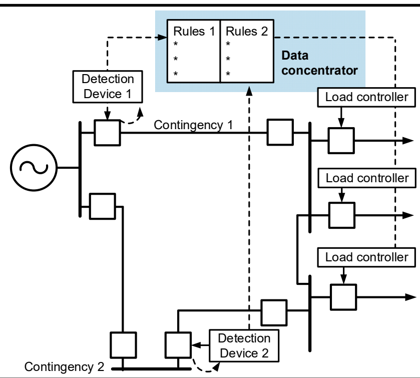
Centralized architecture



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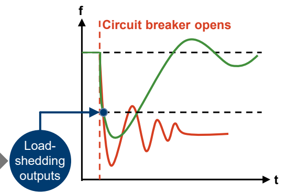
Centralized architecture and use of crosspoint switch for load shedding

Trigger inputs

Contingency	Loads selected to shed					
	1	2	3	4	5	6
Loss of G1		X	X			
Loss of G2	X					X
Loss of G3	X			X		
Loss of G4			X		X	X
Bus tie		X		X	X	



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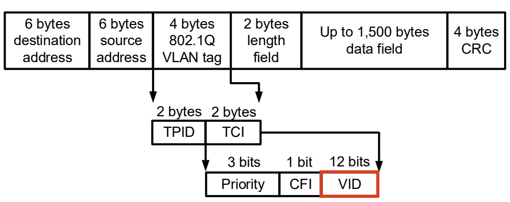
Traffic engineering

- Ethernet frame VlanID routes packets
- IED receives only its subscribed traffic



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Reactive power compensation

(Q_{Ci} – MVAR)

$$Q_{Ci} = X_{Ci} \cdot DAC_{Ci} + Y_{Ci} + \left(Z_{Ci} \cdot \Phi_{500q}\right)$$

- Normalizes reactive power after load shed
- Sorts capacitor banks based on priority
- Trips correct number of capacitor banks

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Peru

49

Comité de Operación Económica del Sistema Interconectado Nacional (COES)

- Peruvian independent system operator
- Nationwide planning and coordination
  - Generation dispatch
  - Transmission operation

50

Cerro Verde facts

- Open-pit copper and molybdenum mine
- Concentrator facilities projected to expand to 360,000 metric tons per day
- 300 MW of load on grid of southern Peru

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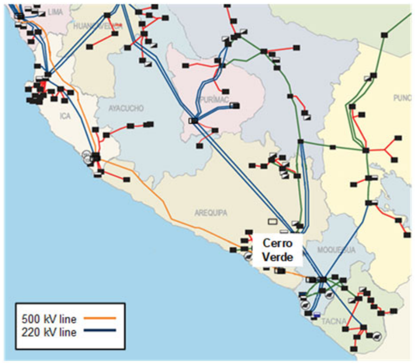
Cerro Verde mine in Peru



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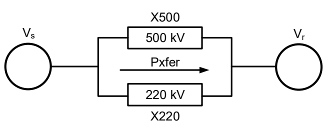
Problem statement

- Mining industry expansion is increasing load
- System stability is jeopardized if 500 kV corridor is lost (single 500 kV transmission lines)
- COES deemed synchrophasor-based RAS necessary



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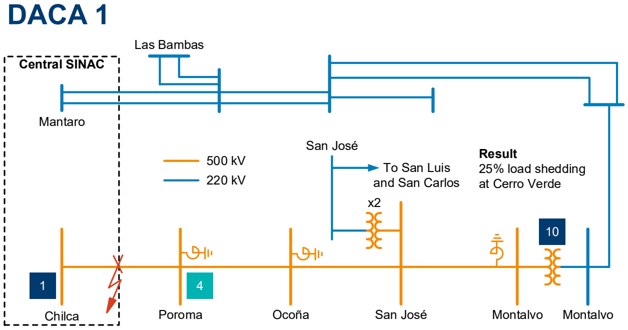
DACA 1



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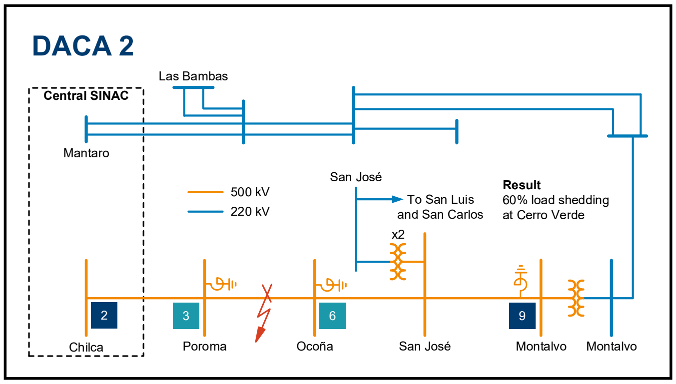
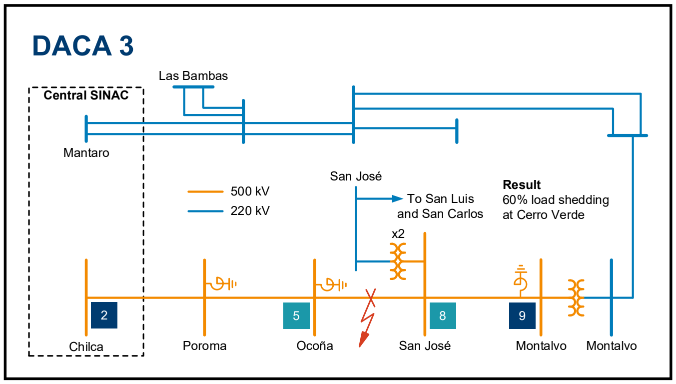
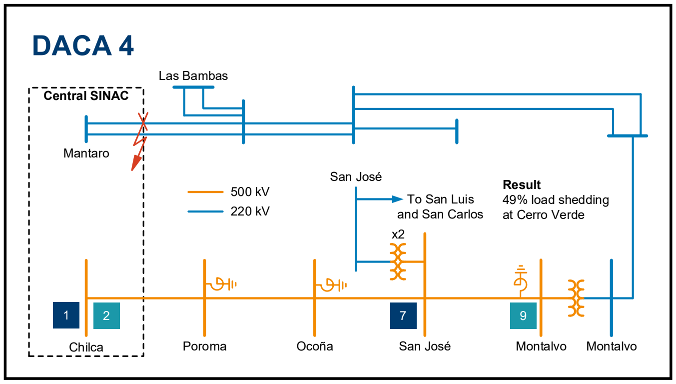

DACA 2
Las Bambas
Central SINAC
Mantaro
San José
500 kV
220 kV
To San Luis
and San Carlos
Result
60% load shedding
at Cerro Verde
x2
2
3
6
9
Chilca
Poroma
Ocoña
San José
Montalvo
Montalvo

55


DACA 3
Las Bambas
Central SINAC
Mantaro
San José
500 kV
220 kV
To San Luis
and San Carlos
Result
60% load shedding
at Cerro Verde
x2
2
5
8
9
Chilca
Poroma
Ocoña
San José
Montalvo
Montalvo

56


DACA 4
Las Bambas
Central SINAC
Mantaro
San José
500 kV
220 kV
To San Luis
and San Carlos
Result
49% load shedding
at Cerro Verde
x2
1
2
7
9
Chilca
Poroma
Ocoña
San José
Montalvo
Montalvo

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Power system stability and dynamic simulation studies

58

Power system analysis tools

- Aspen
- Power Analytics™
- RTDS®
- ETAP®
- GE PSLF
- EasyPower®
- Cape
- DSA Tools™
- PSS®E

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RTDS simulator and EMTP type simulation

- Numerical integration
- 50 μs simulation time step
- Closed-loop testing

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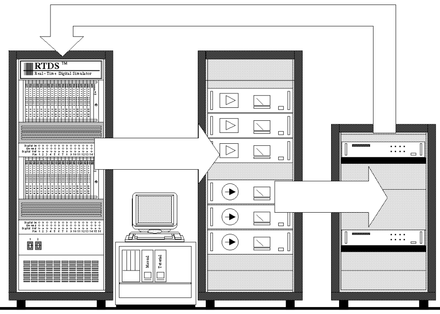
Model development



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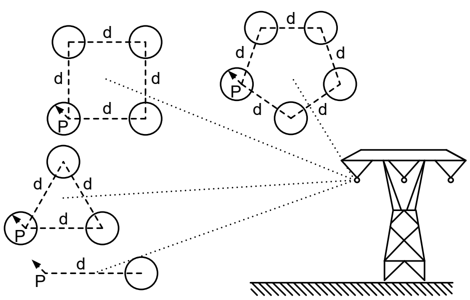
Transmission line physical parameters



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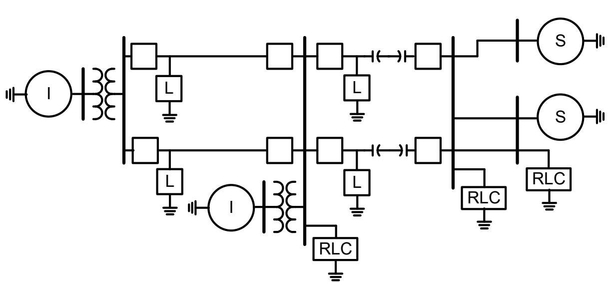
System topology



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Relay interaction

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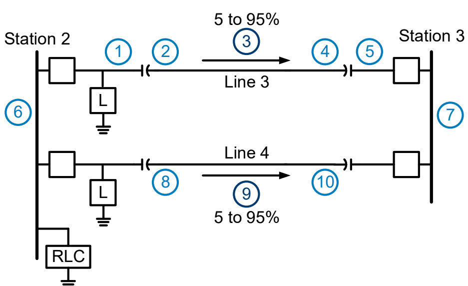
Add faults to system



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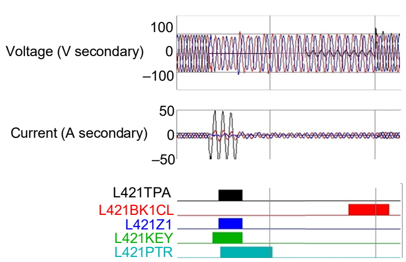
Real-time interaction



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Conclusion

Improve protection scheme confidence

- Gain years of equivalent fault experience in only days
- Discover oversights or weaknesses before they become operational
- Innovate or explore design changes freely
- Connect multiple protection and control system devices in real-time, closed-loop environment

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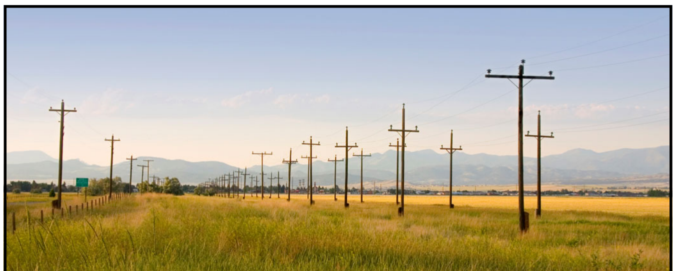

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