Controlled Islanding Followed by Load Shedding Based on Rate of Frequency Decline

PSERC Internet Seminar

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EPRI/DoD Initiative

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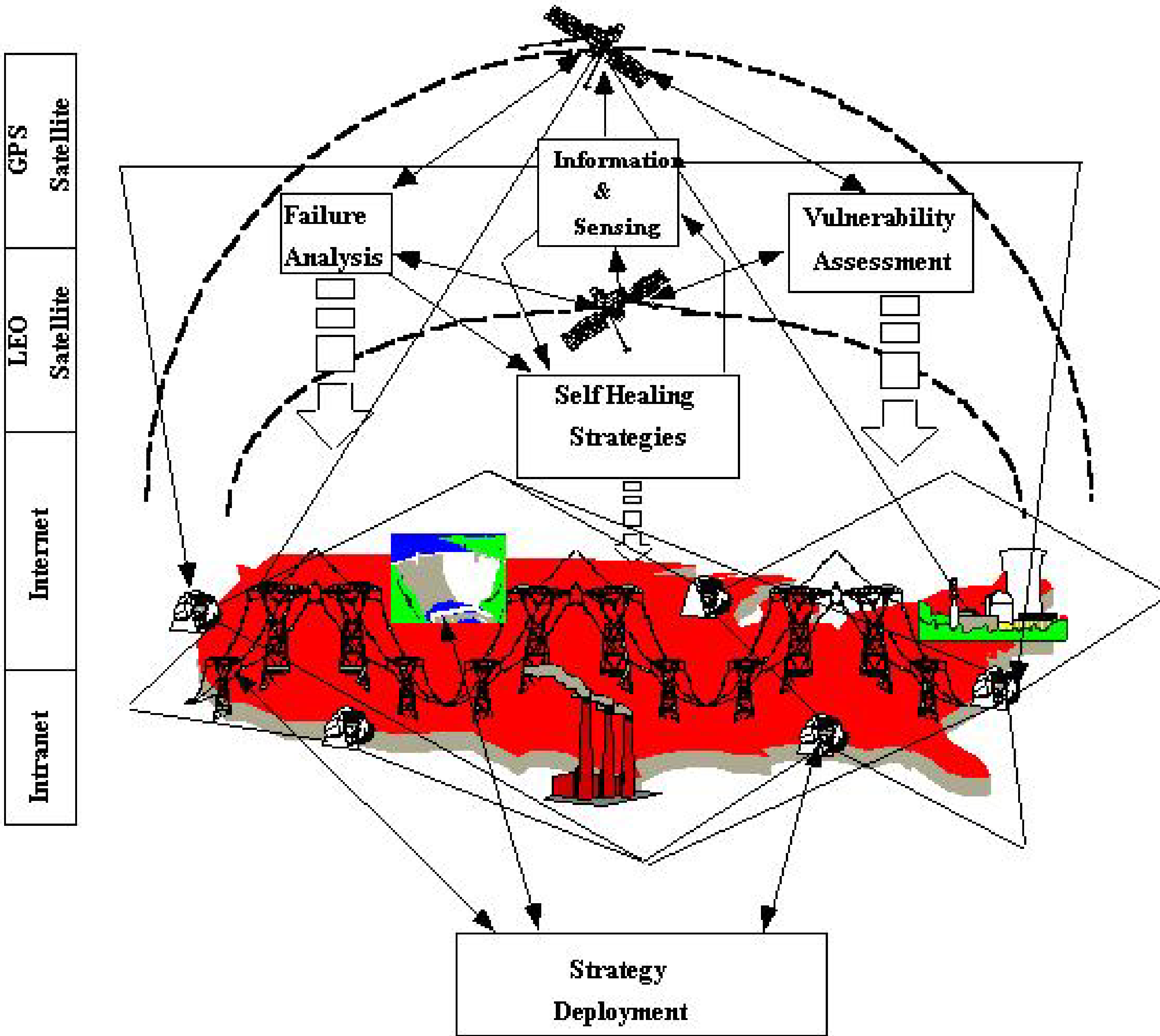
- ***"Our vision is to create a wide-area intelligent, adaptive protection and control system that empowers the future power grids by providing critical and extensive information in real-time, assessing system vulnerability quickly, and performing timely self-healing and adaptive reconfiguration actions based on system-wide considerations." We refer to the system as Strategic Power Infrastructure Defense(SPID) system.***


GPS Satellite
LEO Satellite
Internet
Intranet
Information & Sensing
Failure Analysis
Vulnerability Assessment
Self Healing Strategies
Strategy Deployment

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Task description

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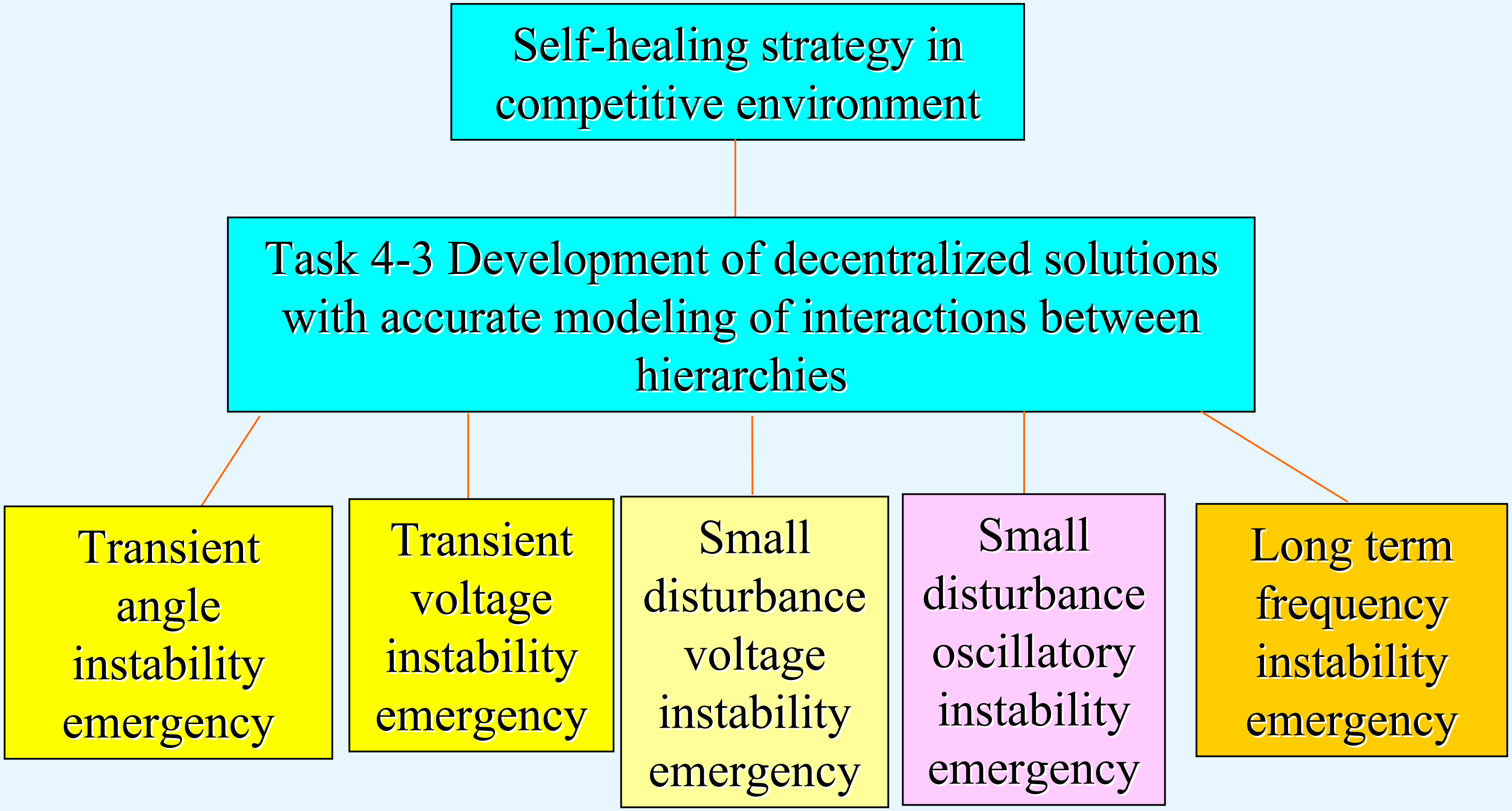

Basis for Self-Healing

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- When a power system is subjected to large disturbances and the vulnerability analysis indicates that the system is approaching a catastrophic failure, control actions need to be taken to limit the extent of the disturbance.
- In our approach, the system is separated into smaller islands at a slightly reduced capacity.
- The basis for forming the islands is to minimize the load-generation imbalance in each island, thereby facilitating the restoration process.

Task thrust

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- **We propose: Controlled islanding followed by load shedding based on rate of frequency decline. Three thrust points:**
  - **Where to island?**
    - **Slow coherency based islanding.**
    - **A c++ program is developed to identify the tripping sets.**
  - **When to island?**
    - **Corrective controls based on local measurement plus wide area phasor measurement**
    - **A three-layer islanding architecture is proposed**
  - **Load shedding scheme?**
    - **A two-level load shedding scheme based on frequency and rate of frequency decline is designed**

Slow coherency

- **Singular Perturbation Method.**
  - **A theory for decomposing dynamical systems with large eigenvalue difference.**
  - **A method analyzing two-time-scale phenomena by introducing small perturbation parameters.**
- **Electromechanical Model**

$$\left.\begin{aligned}\dot{\delta}_i &= \Omega(\omega_i - 1)\\ 2H_i\dot{\omega}_i &= -D_i(\omega_i - 1) + (P_{mi} - P_{ei})\end{aligned}\right\} \Rightarrow \left.\begin{aligned}\Delta\dot{\delta}_i &= \Omega\Delta\omega_i\\ 2H_i\Delta\dot{\omega}_i &= -D_i\Delta\omega_i - \sum_{j=1}^{n} k_{ij}\Delta\delta_j\end{aligned}\right\}$$

$$\Rightarrow \ddot{X} = -\frac{1}{2}\Omega H^{-1}KX = AX$$

- **A grouping algorithm**
  - **Research has been done to modify the algorithm to consider the load dynamics, second order system and detailed model.**

Islanding Strategy (Where to Island)

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- **Coherency assumptions.**
  - **The coherent groups are independent of the size of the disturbance; Linearized model can be used.**
  - **The coherent groups are independent of the amount of the detail in the generating unit models; Classical model can be used.**
- **Slow coherency features**
  - **Preserve the coherency assumptions.**
  - **Properly states the oscillation feature of the large scale power system: the fast oscillations within a group and the slow oscillations between the groups.**
  - <u>Identifies the weakest connection by grouping the generators with a certain number of slow modes.</u>
  - **Grouping is not sensitive to the changes of the initial condition.**
  - **Nonlinear applicability proved by nonlinear simulations.**

Weak Connection Characteristics

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- Slow coherency solves the problem of identifying theoretically the weakest connection in a complex power system network.
- The weak connection form best states the reason for islanding based on slow coherency.
- It is important when the disturbance happens to separate in the transient time scale the fast dynamics, which could propagate the disturbance very quickly, through islanding on the weak connections.
- In the transient time scale, the slow dynamics will mostly remain constant or change slowly on the tie lines between the areas.
- Once fast dynamics are detected on the tie lines, it means fast dynamics are being propagated through these weak connections. In order to prevent these we cut the ties to form islands identified by slow coherency.

Determination criteria for Island boundary

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- Minimum generation load imbalance in each island.
  - **Reduces the amount of load shedding after the islands are formed.**
  - **Ease of restoration.**
  - **Each island is capable of matching the generation and load within prescribed frequency limit.**
- Physical limits exists between two control areas.
- Restoration considerations.
  - **Each island has the black start capability that is sufficient for critical equipment.(Does it contain a large capacity hydro machine?)**
  - **Each island has proper voltage control capability to maintain a suitable voltage profile.**
  - **Each island is capable of being monitored by the control center for security and coordination.**
  - **Synchronizing devices are available near the boundary of the islands for re-closing the circuit and restoration function.**

Automatic Program to Determine Islands

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- Having determined the generators that form groups by the slow coherency approach, we now need to determine the boundary buses to form the islands that will contain these groups and also meet the islanding criteria.
- We use an adjacent link data structure to save the network information.
- Then through a series of reduction processes, the program forms a small network and performs an exhaustive search on it to get all the possible cut sets.

Islanding Strategy (When to Island)

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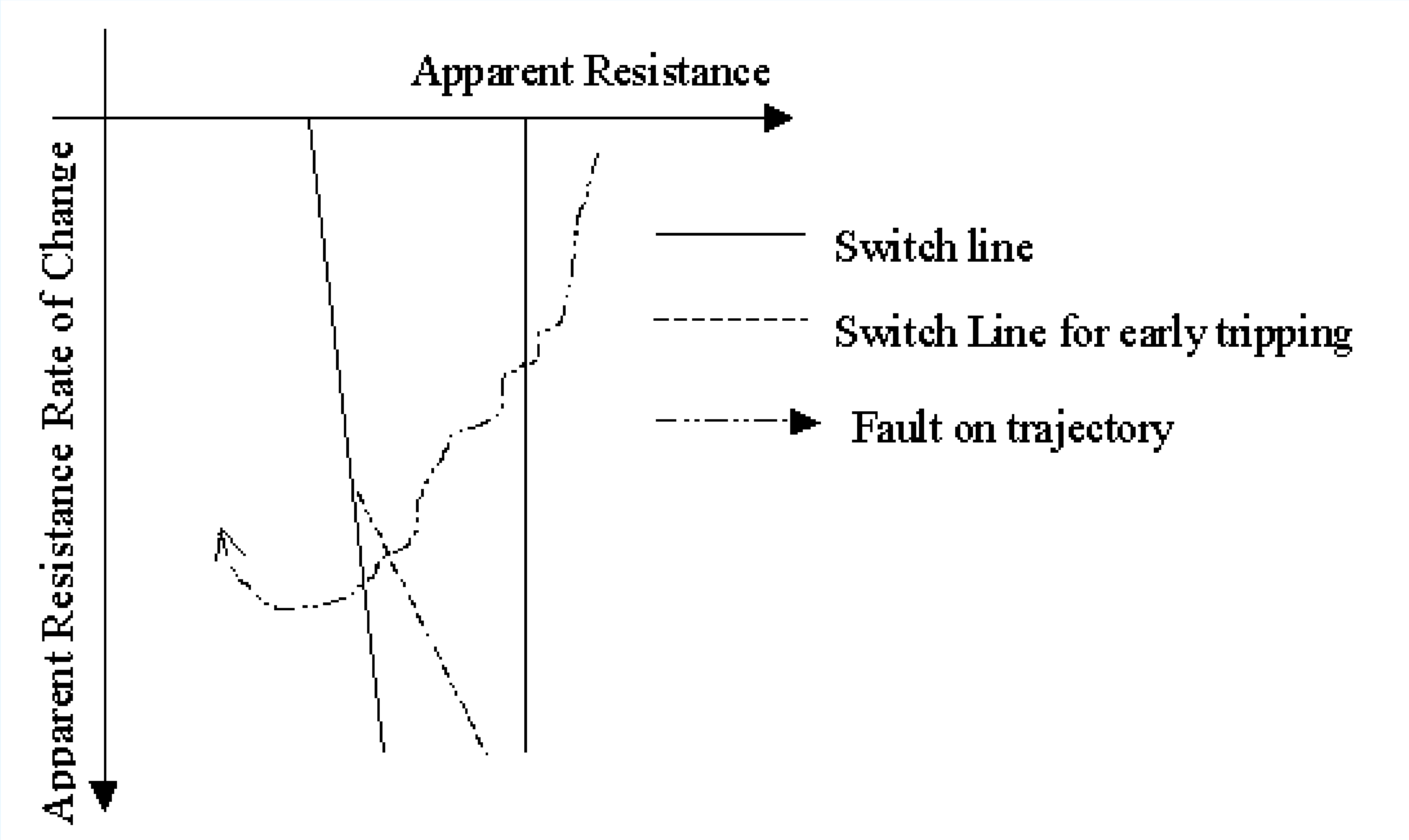
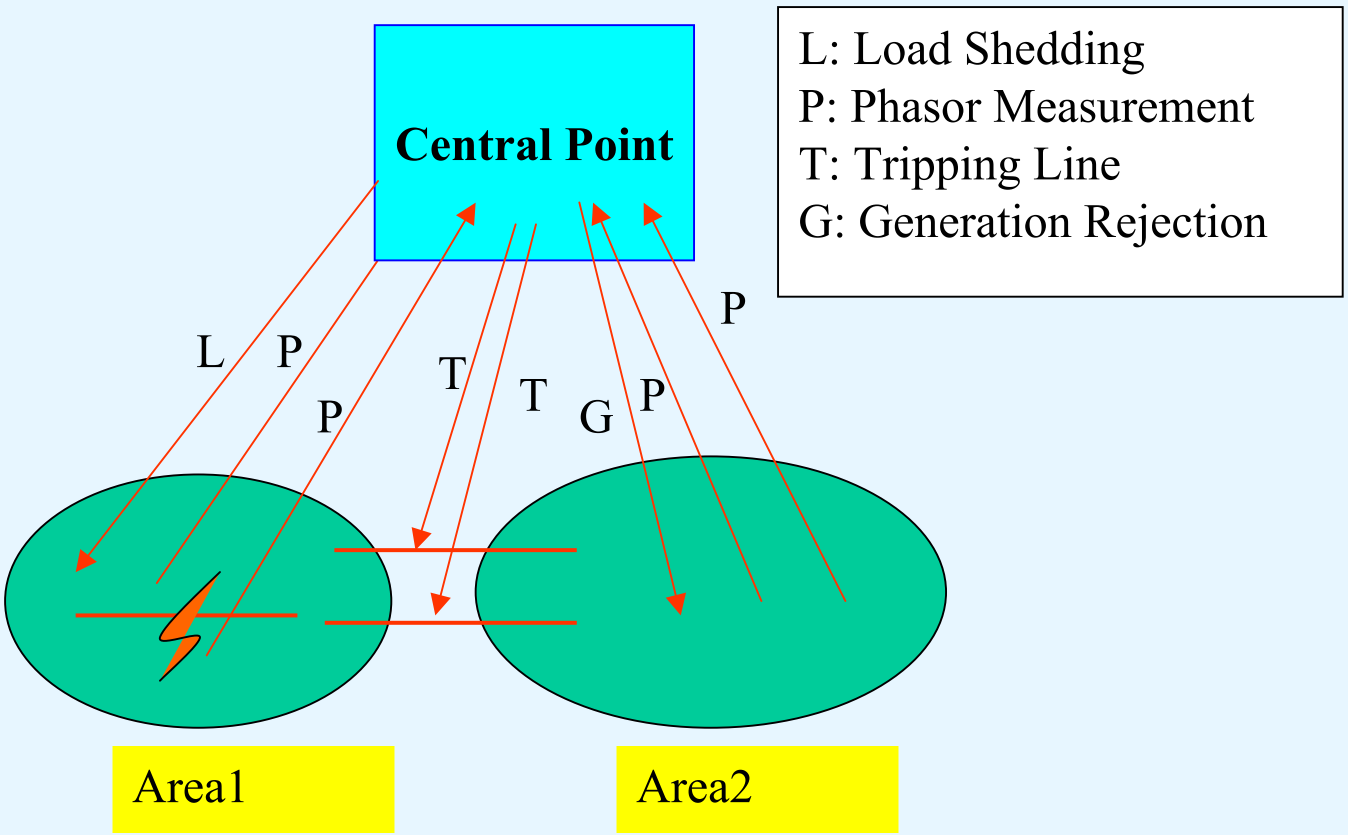
- Three layers identified in the tripping mechanism.
  - BPA's R-Rdot out of step relay.
    - High change rate of the apparent impedance on the tie line is detected in the case simulation.
    - Remote tripping is needed for the implementation of the controlled islanding.
  - Response based R-Rdot out of step relay with decision tree support.
  - Phasor measurement units can be used in control center for higher level switching action.

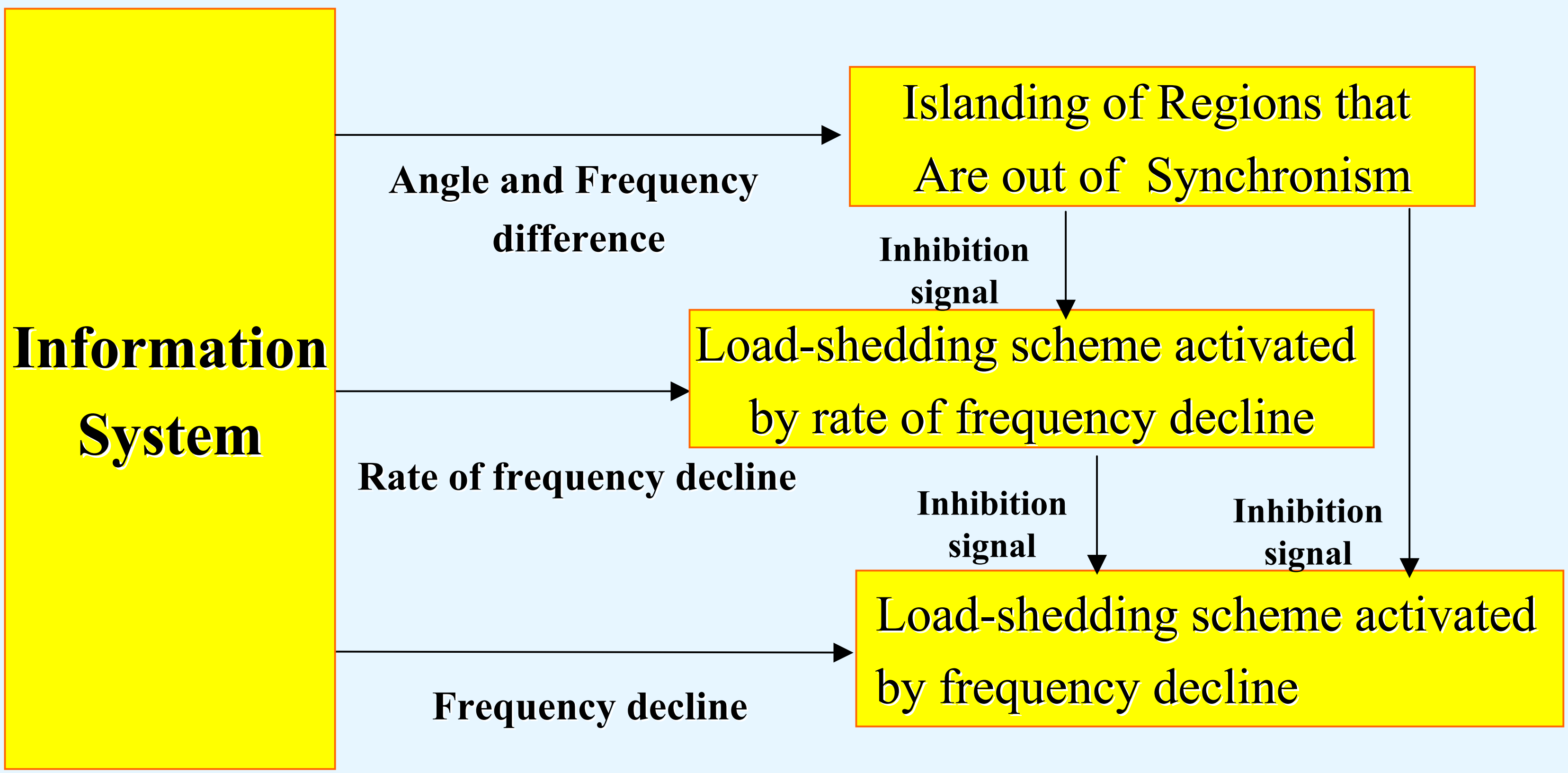
Switching Illustration of R-Rdot Out of Step Relay



Wide Area Measurement Illustration



Under-frequency Load Shedding Scheme based on Subsumption Model



The Reduced Model of Reheat Unit for Frequency Disturbance

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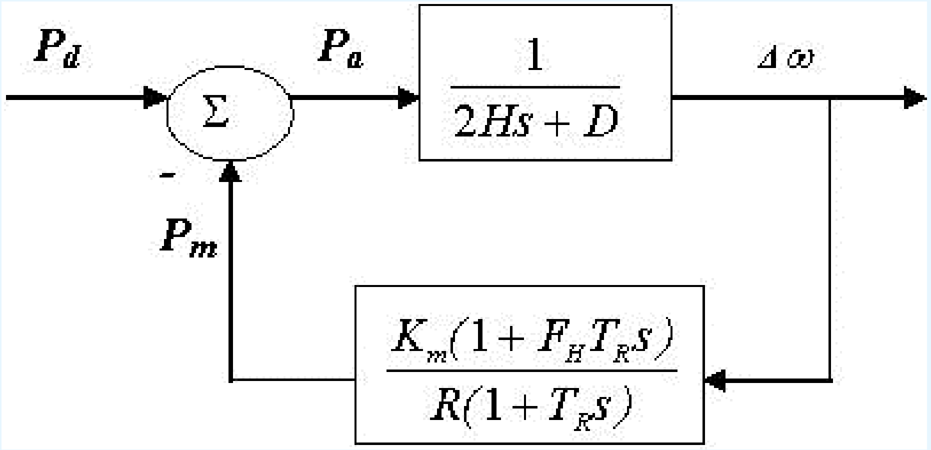

- 57 Hz is selected to be the lowest operable system average frequency considering coordination with the governor-turbine system; coordination with the plant auxiliary system; coordination with the existing operation criteria.
- Using this reduced model and normalizing, we obtain that the lowest system average frequency for this disturbance is 57 Hz when $P_d = 0.3P_{sys}$. So we choose $0.3P_{sys}$ as the threshold value of P_d for the new load shedding scheme.

Rate of Frequency Decline Criteria

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$$M_0 = 60 \frac{P_{step}}{2H} = d\Delta\omega$$

M_0 is the average rate of system frequency declination for disturbance P_{step}. M_i, the rate of frequency declination at each bus can be measured at the beginning of the disturbance.

P_{step} is the size of disturbance

H is the system inertia, which can be computed as follows:

$$H = \frac{\sum H_i \times S_{Bi}}{S_{total}}$$

H_i : Inertia of generator in system

S_{Bi} : Machine MVA Base $\quad$ S_{total} = Total generation

Frequency Threshold, Step Size and Time Delay

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- The thresholds should be chosen not be too close to the normal frequency; but should be more effective to shed load earlier.
- Step size should be increasing in the schemes based on frequency decline; but should be decreasing in our scheme based on rate of frequency decline in order to arrest the frequency decline.
  - Frequency steps must be far enough apart to avoid overlap of shedding due to time delay.
  - The number of steps does not have very great impact on the effect of load shedding
  - Generally, the threshold of the last step of load shedding is chosen no less than 58.3 Hz.
- Delay time for the first step is usually long to avoid unexpected actions due to small frequency oscillations; but it is set 0 cycles in our scheme to prevent sharp frequency declines.

Under-frequency Load Shedding Scheme

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- NPCC Criteria, NPCC Guide are considered for Frequency Emergency.

	59.5Hz	59.3Hz	58.8Hz	58.6Hz	58.3Hz
Load Shedding Activated By rate of frequency decline	20(0c)		5(8c)	4(18c)	4(21c)
Load Shedding Activated By Frequency decline		10(28c)	15(18c)		

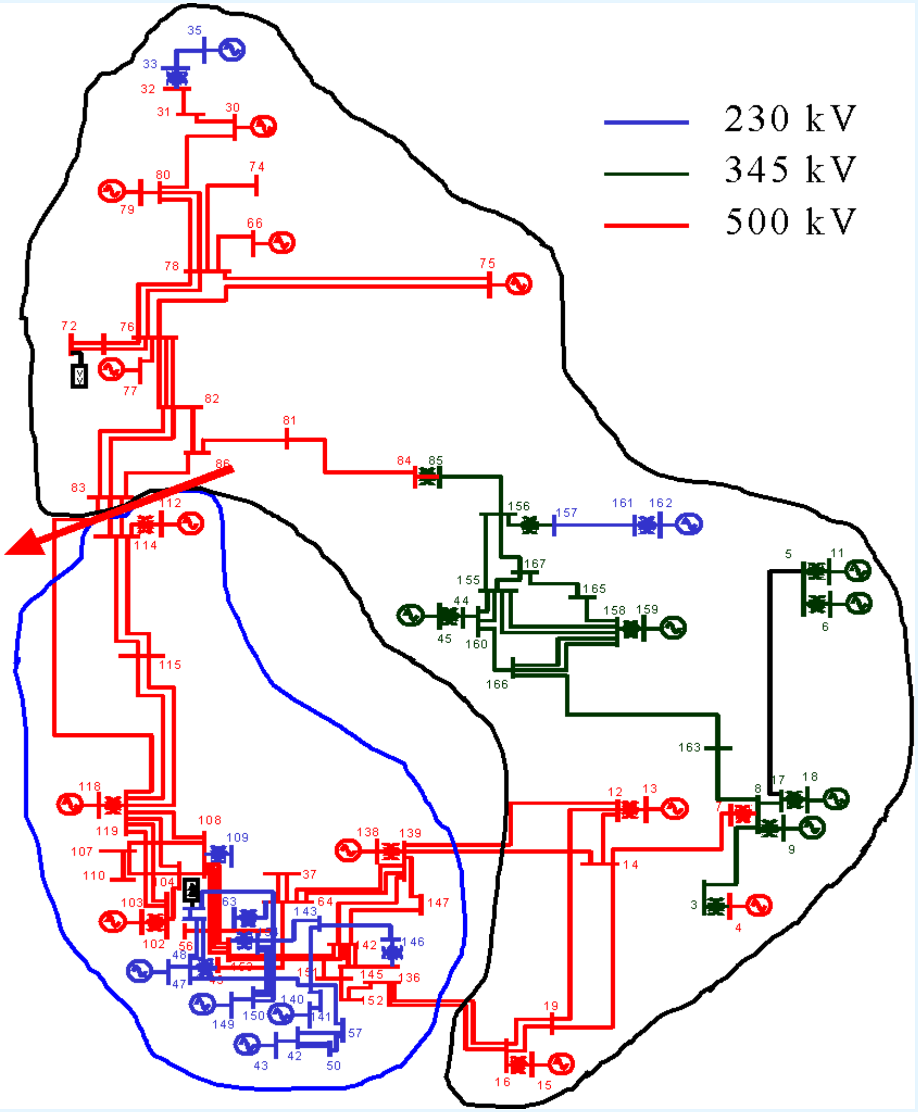
*Note : c represents delay in cycles.

Simulation Cases

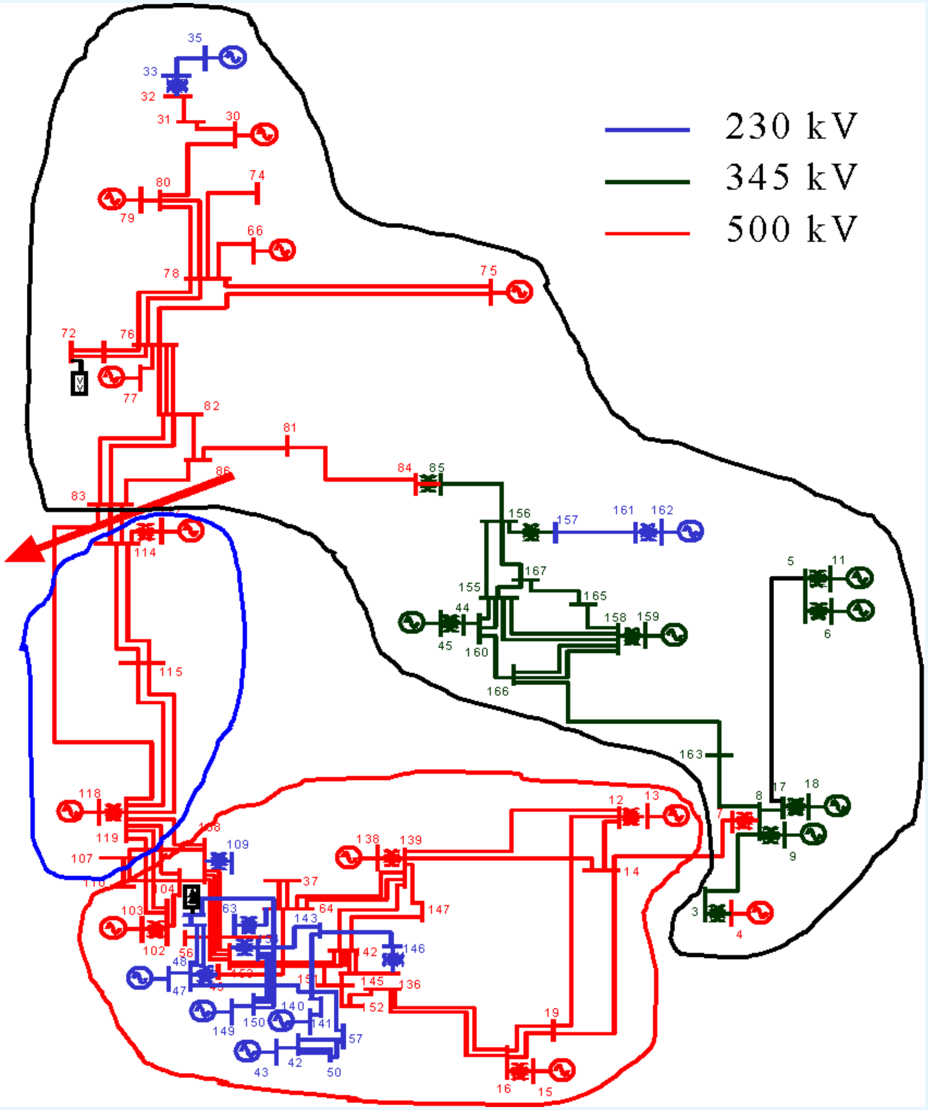
- **Simulated cases include:**
  - One case of WSCC 29-machine system islanding by experience.
  - Two cases WSCC 29-machine system islanding by slow coherency.
- **WSCC System condition:**

Buses	Gens No.	Loads No. (CI, CMVA)	Lines	Trans	Generations (MW,MVAR)	Loads (MW,MVAR)
179	29	104 (67,24)	203	60	61410,12325	60785,15351
Northern part	Southern part	Gens Model	Governor Model	PSS Model		Exciter Model
Gen rich	Load rich	Detailed	Not Available (Added)	Available		Available

Case1-Two Islands for 179-Bus System Based on Experience



Case2-Three Islands for 179-Bus System Based on Slow Coherency



Scenario Description

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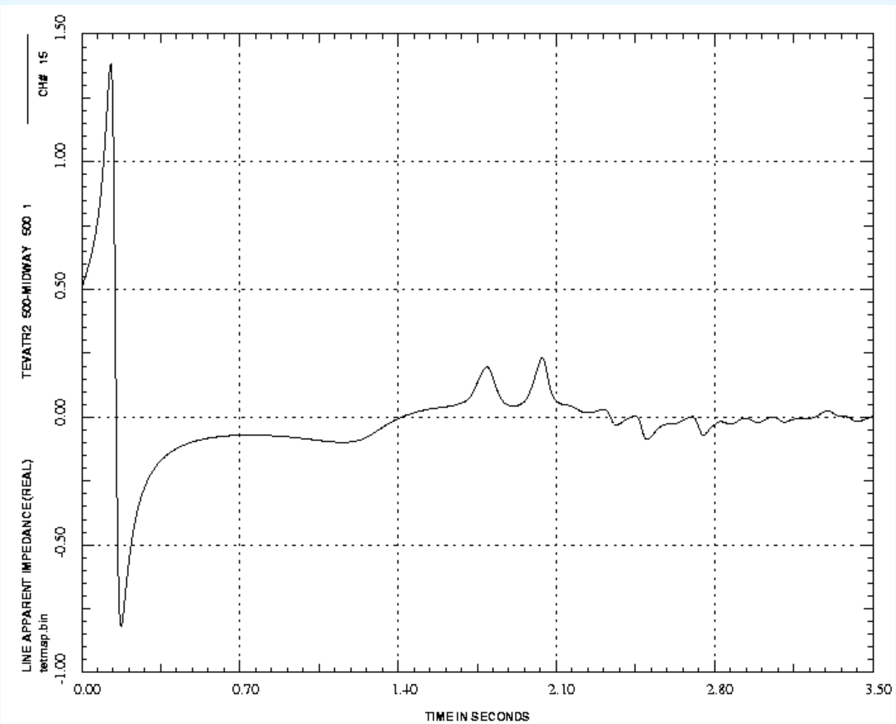
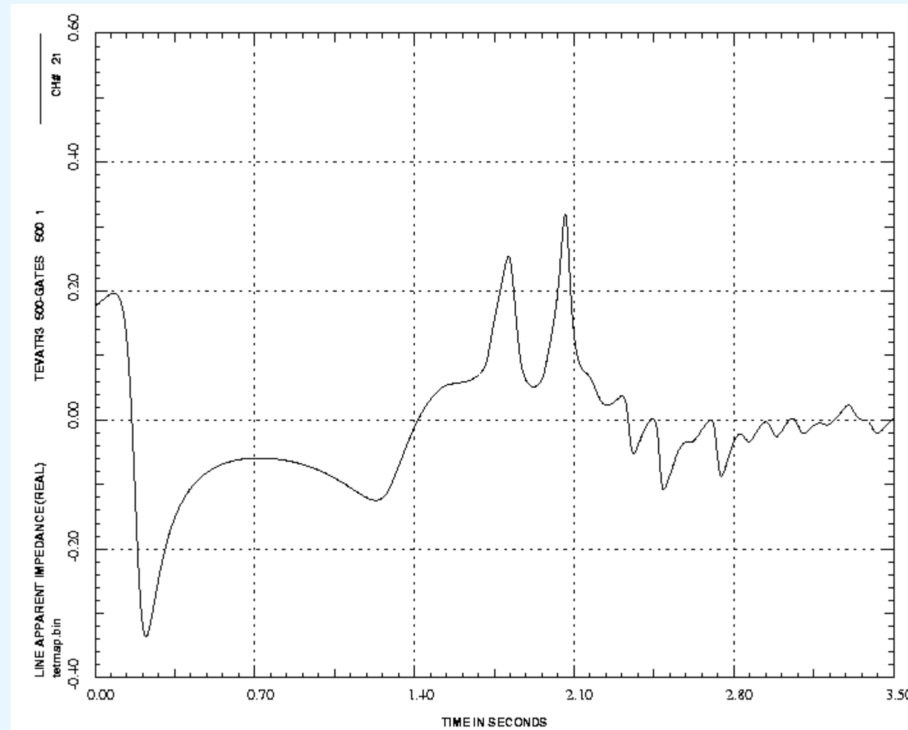
Cases	At 0.0 seconds	At 0.2 seconds
1	REMOVE LINE ; MALIN 500;MALIN3 500;1/ MALIN 500;MALIN5 500;1/ MALIN 500;MALIN7 500;1/	REMOVE LINE ; ELDORADO 500;NAVAJO 500;1/ ELDORADO 500;MOENKOP4 500;1/ PALOVRDE 500;DEVERS 500;1/ PALOVRDE 500;DEVERS 500;2/
2	REMOVE LINE ; MALIN 500;MALIN3 500;1/ MALIN 500;MALIN5 500;1/ MALIN 500;MALIN7 500;1/	REMOVE LINE ; TEVATR2 500;MIDWAY 500;1/ TEVATR3 500;GATES 500;1/ FOURCOR2 500;MOENKOPI 500;1/

Resistance Plot with Fault on

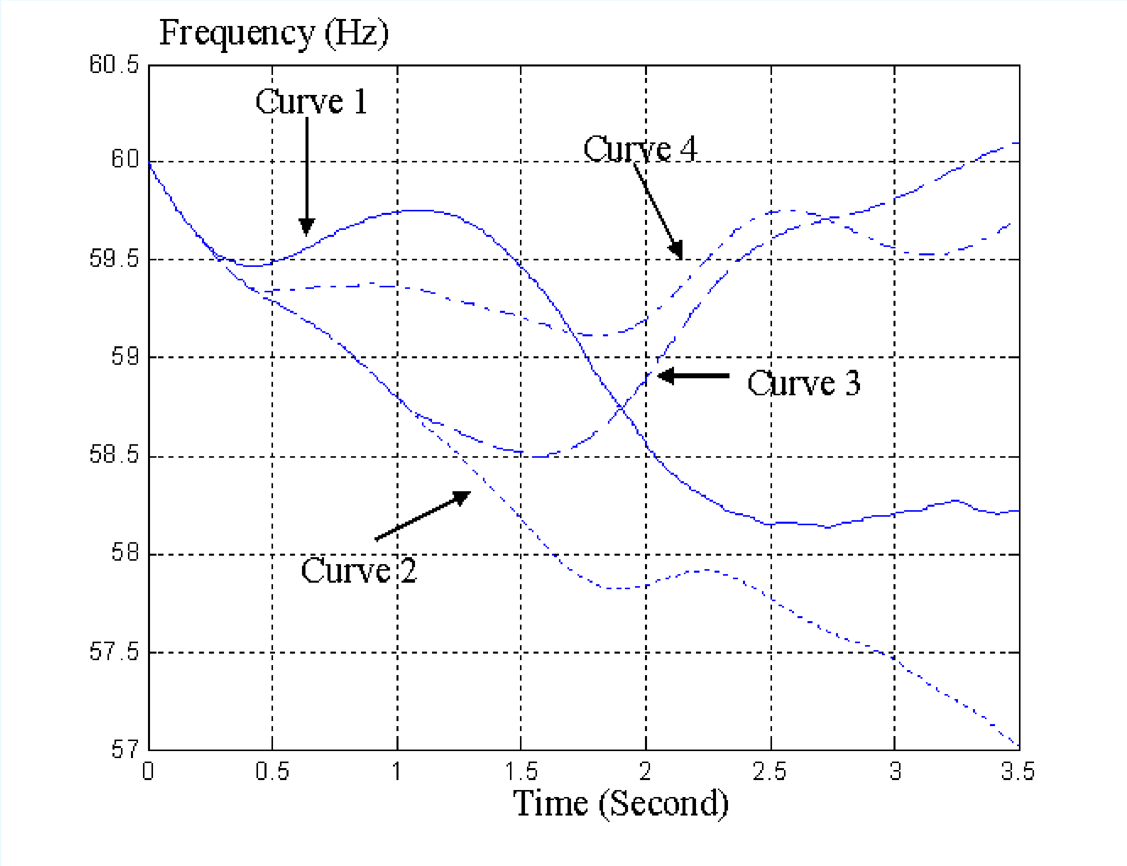
TEVATR2 500;MIDWAY 500



TEVATR3 500;GATES 500

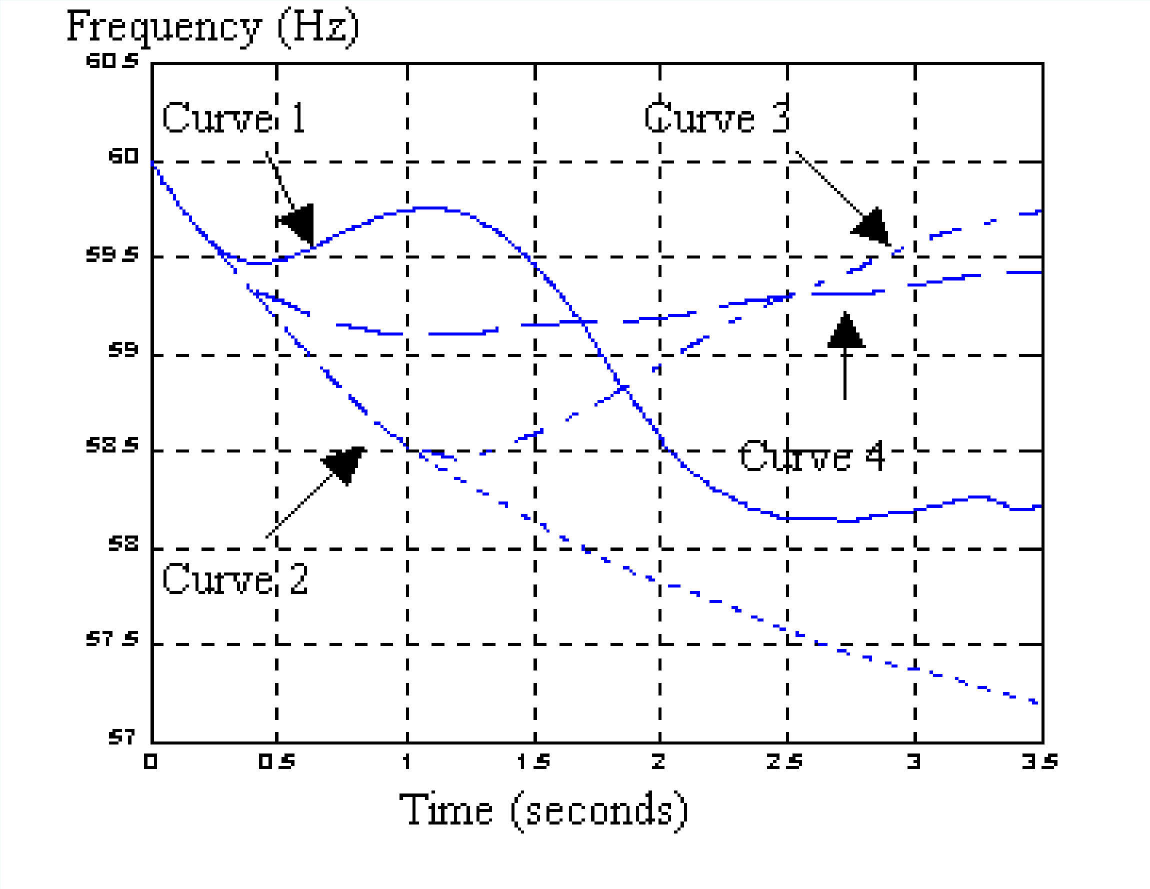


Simulation Result Case No.1



Frequency response of Generator 118 after the contingency of the 179-Bus system. Curve 1: Without self-healing. Curve 2: Islanding with no load shedding. Curve 3: Islanding followed by load shedding based on frequency difference. Curve 4: Islanding followed by load shedding based on the rate of frequency decline.

Simulation Result Case No.2



Frequency response of Generator 118 after the contingency of the 179-Bus system. Curve 1: Without self-healing. Curve 2: Islanding with no load shedding. Curve 3: Islanding followed by load shedding based on frequency difference. Curve 4: Islanding followed by load shedding based on the rate of frequency decline.

Results Comparison

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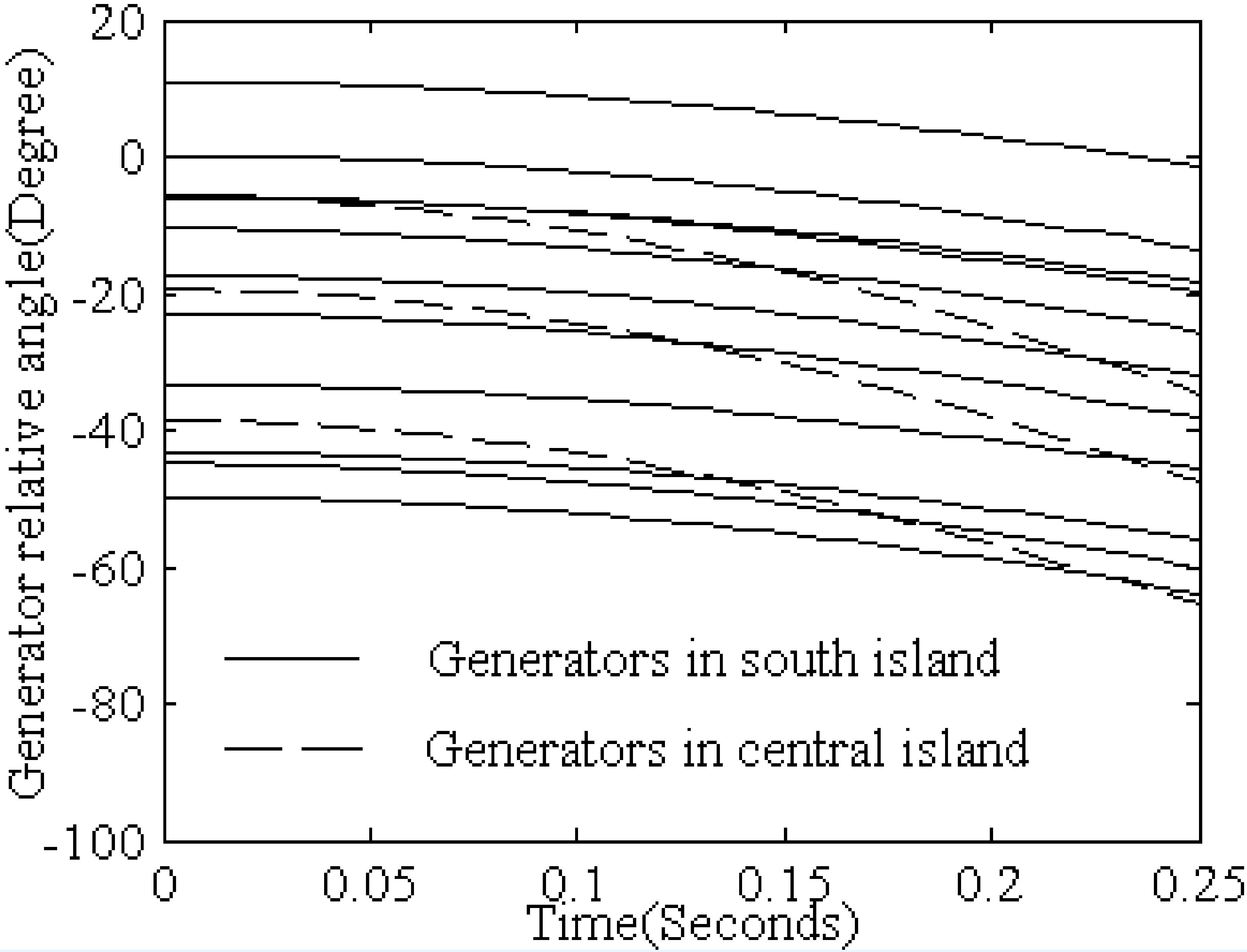
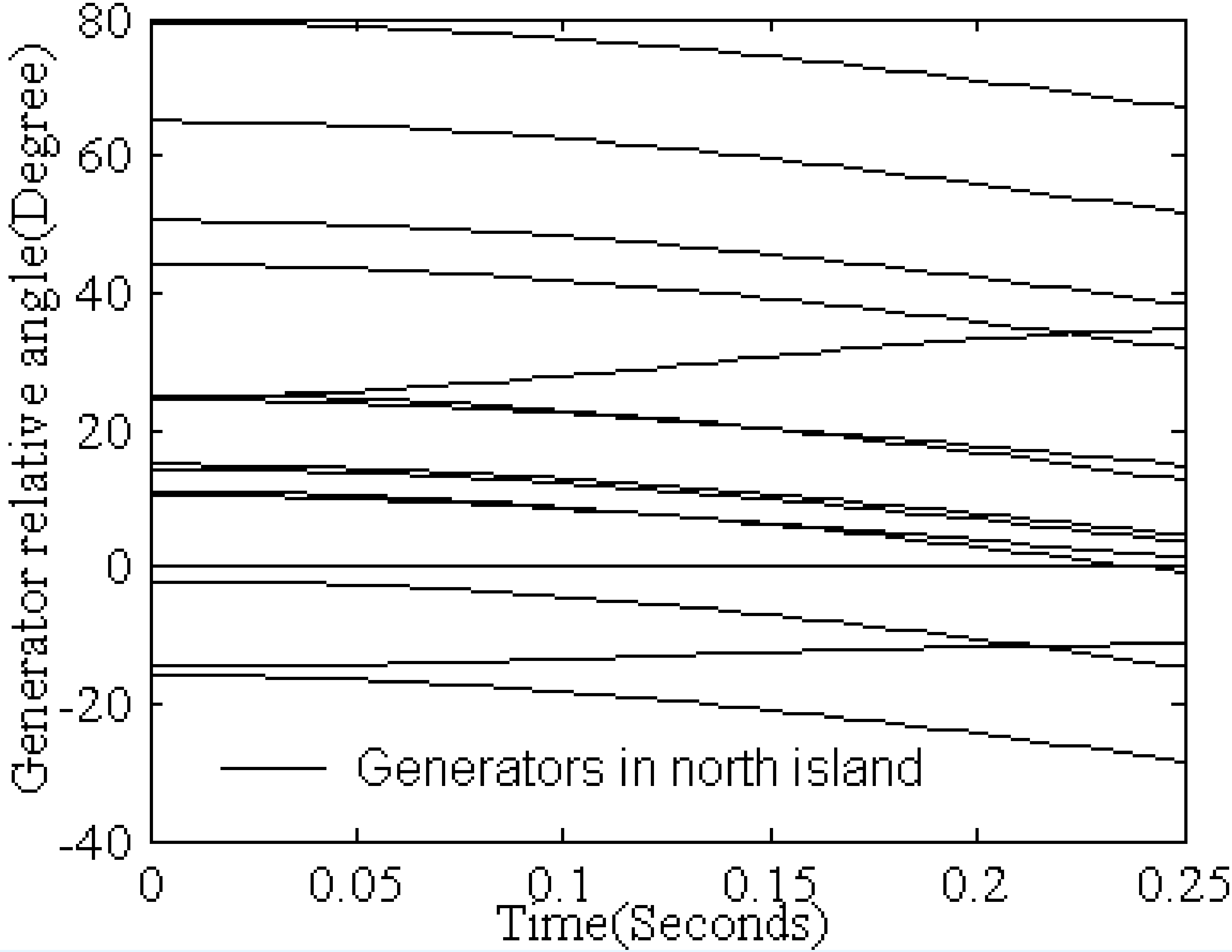
Cases	Generation Load Imbalance (MW)	Load Shed with Conventional Scheme (MW)	Load Shed with New Scheme (MW)
No. 1	Generation 16,265 Load 22,679	6,937 (11.4% 30.6%)	5,698 (9.4% 25.1%)
No. 2	Central Island: Generation 5,118 Load 7,006 South Island: Generation 15,477 Load 17,373	1,810/0 (3.0%/0% 25.8%/0%)	1,450/0 (2.4%/0% 20.7%/0%)

Grouping Changed as the Load Change

Load Change Percentage	<-30%	-30% to -17% (except at -25%)	-16% to 0%	1% to 6% (except at 1% and 5%)	>6%
System Condition	Unstable	Obtain Same Grouping	Obtain Same Grouping	Obtain Same Grouping	Unstable


20
0
-20
-40
-60
-80
-100
0
0.05
0.1
0.15
0.2
0.25
Generator relative angle(Degree)
Time(Seconds)
Generators in south island
Generators in central island



80
60
40
20
0
-20
-40
0
0.05
0.1
0.15
0.2
0.25
Generator relative angle(Degree)
Time(Seconds)
Generators in north island

Future work

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- In-depth research on the slow coherency theory and enhancement of the adaptive feature.
- Designing the restoration procedure to complete self-healing.
- Application of the algorithm on a large system scale.
- Definition and design of the vulnerability index taking into account relay modeling and measurements (New PSERC project with TAMU and WASU)
- Examine issues related to self-healing for voltage stability.
- Incorporation of the islanding agent and load shedding agent into multi-agent architecture and implementation on a large scale system (New CERTS Project)