Real Time Monitoring of Cascading Events

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Project Reports (S-19)

- M. Kezunovic, H. Song and N. Zhang, "Detection, prevention and mitigation of cascading events: Part I of final project report," Power Systems Engineering Research Center, 2005, [Online] Available: http://www.pserc.org. (Texas A&M University)
- V. Venkatasubrimanian and J. Quintero, "Detection, prevention and mitigation of cascading events: Part II of final project report," Power Systems Engineering Research Center, 2005, [Online] Available: http://www.pserc.org. (Washington State University)
- V. Vittal and X. Wang, "Detection, prevention and mitigation of cascading events: Part III of final project report," Power Systems Engineering Research Center, 2005, [Online] Available: http://www.pserc.org. (Iowa State University)

Overview

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- Background
- Problems to be Solved
- Our Solution
- Implementation Issues
- Conclusion and Future Work

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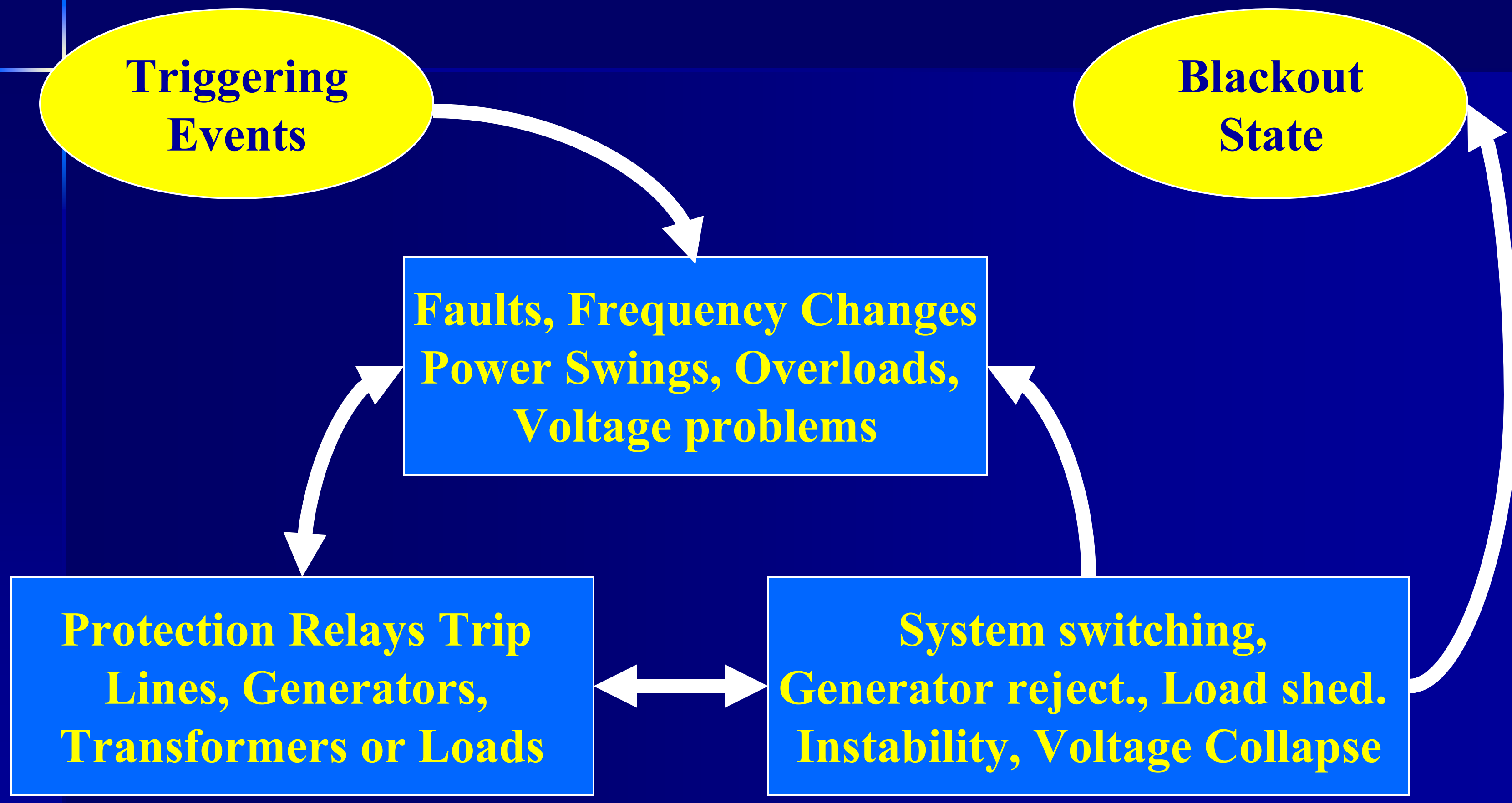
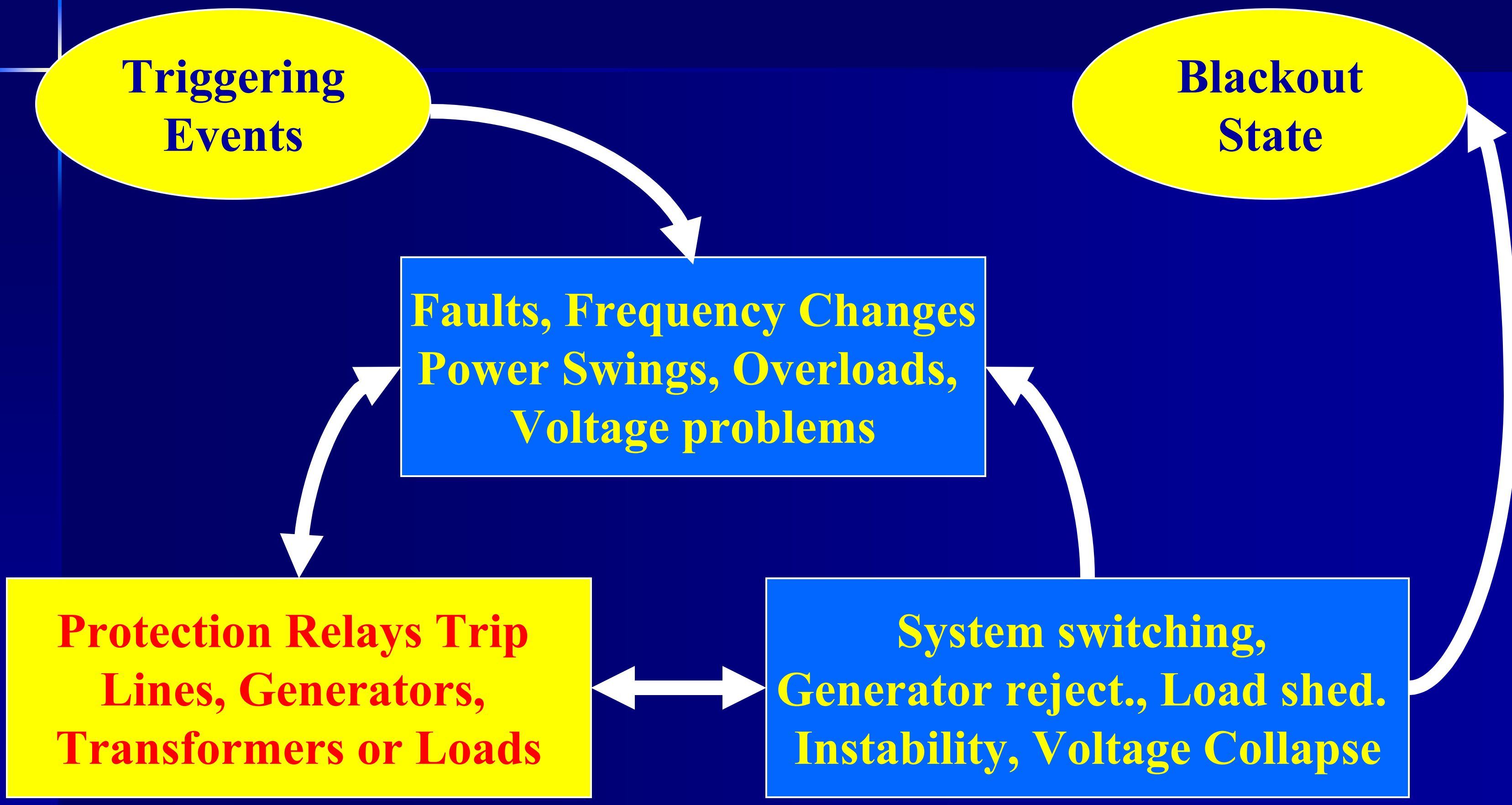
Typical Cascading Blackout



The events are sequential and iterative

Typical Cascading Blackout



Relay operation is a major contributing factor

Cascading Blackouts vs Time

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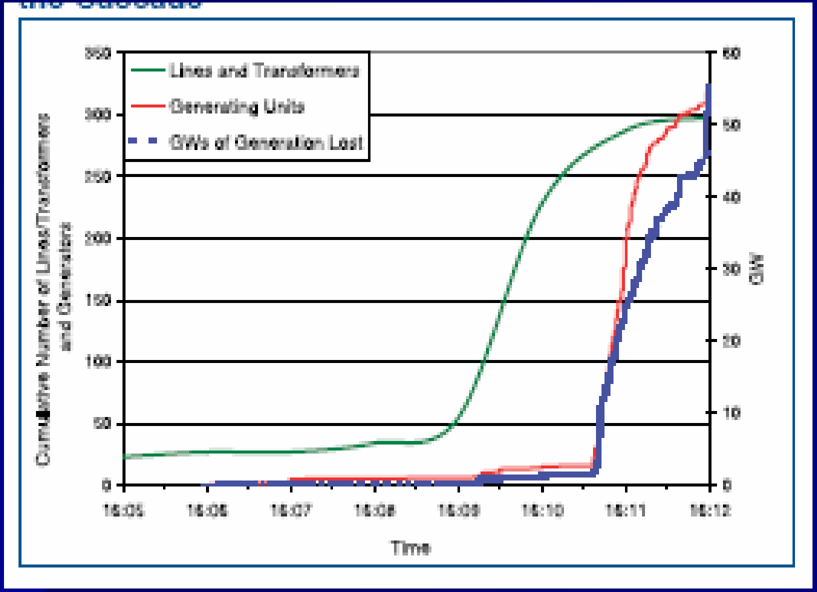
Preconditions | Triggering Events | Slow Progression | Fast Progression | Final Blackout | t



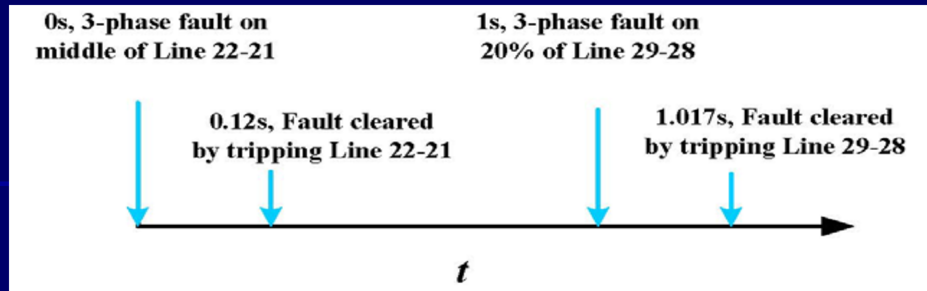
An Example: Tripped elements vs time (from Aug. 14, 2003 blackout final report)

Prevent blackout by acting as early as possible

The slow pace in the Initial stages allows the time for remedial actions

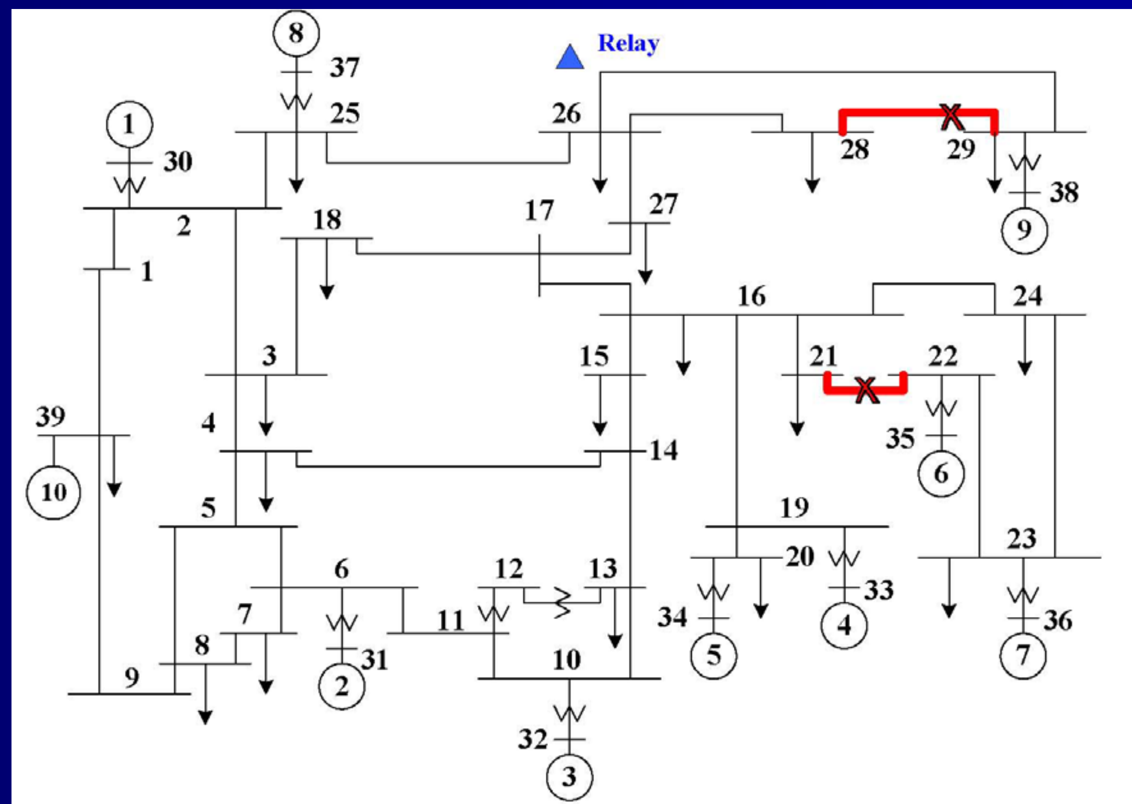
Example on IEEE 39 bus System

Scenarios

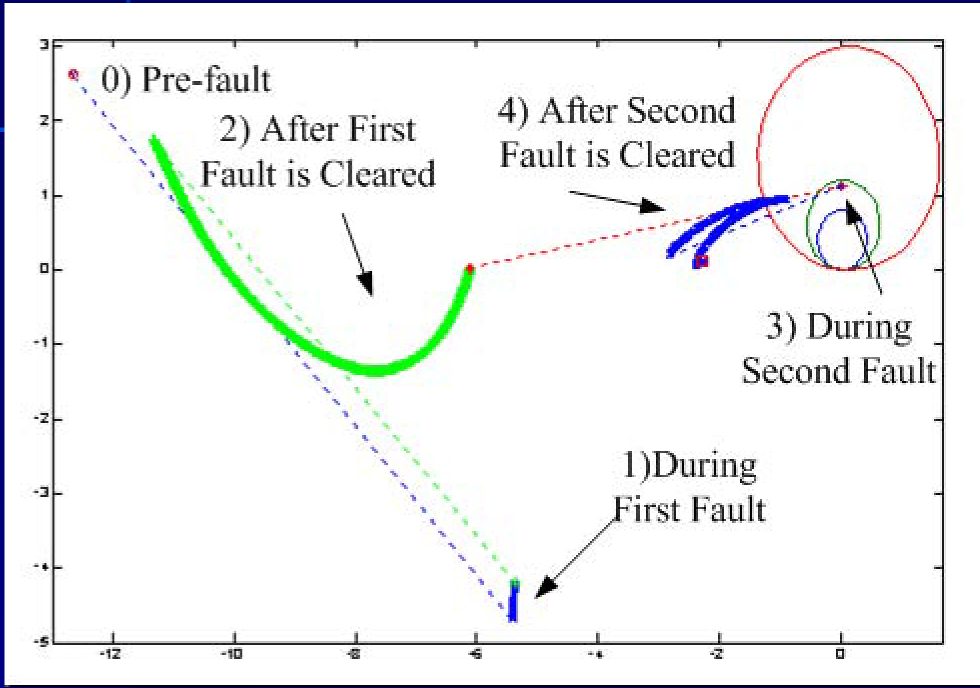


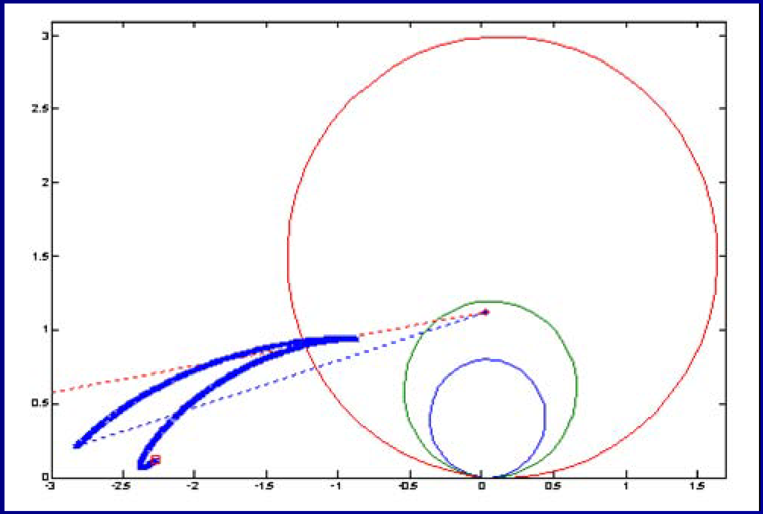
Relay at Line 26-29, its Zone 3 setting over-reaches line 29-28 to provide back-up protection

Sequential faults occur on Line 21-22 and 28-29



Relay at Line 26-29 (Security Issue)





After the two faults are cleared by removing 21-22 and 28-29, the Power swing that follows may cause relay at line 26-29 to operate in Zone 3 although there is no fault on that line.

This is a typical relay misoperation mode!!

Another Case (Dependability Issue)

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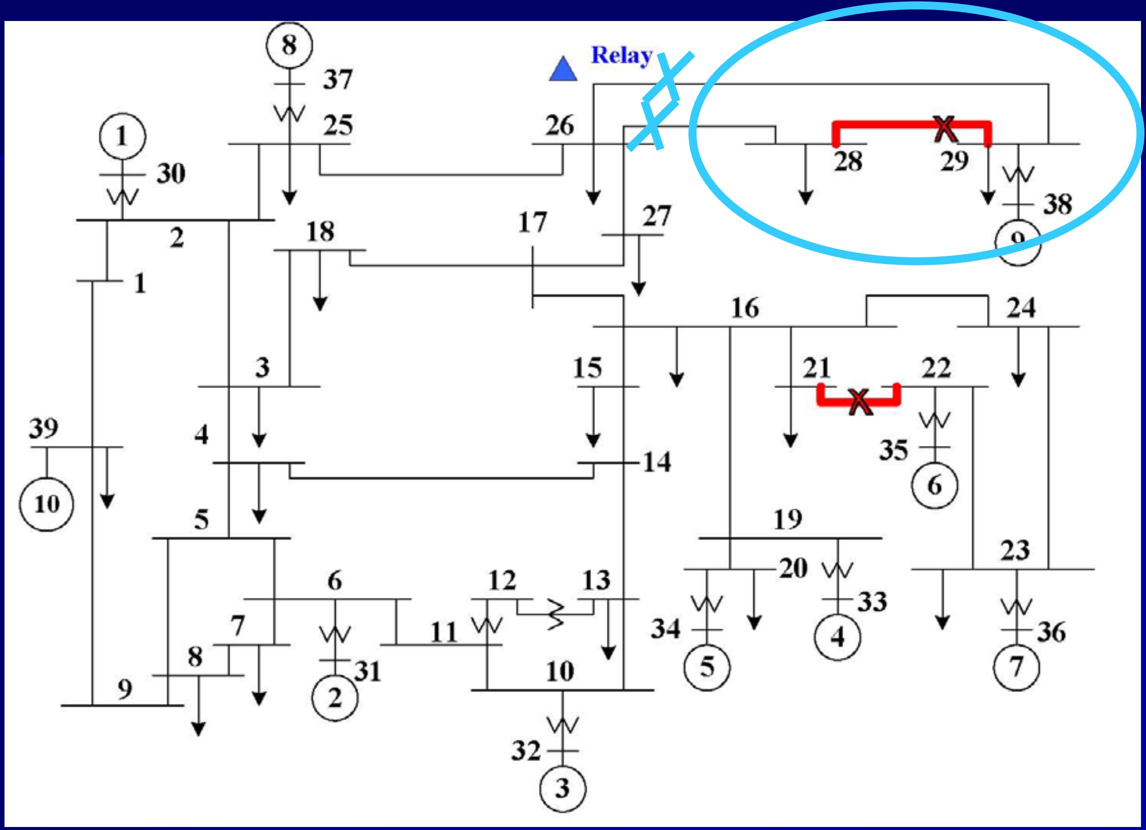
The Same Events as the previous one. But the fault clearance for the second fault in 28-29 by relay 28-29 fails due to the relay or CB physical failure.



Relay 26-29 and 26-28 have to operate as backup, causing blackout of the circled area.

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Problems to be Solved

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Local Level

- The dependability and security need to be improved simultaneously.
- A real time monitoring tool to assess the relay failure/misoperation is needed.
- A real-time fault analysis tool as a reference for relay operation verification is a necessity.

Problems to be Solved

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System Level

- Improve situational awareness of system operators during the dynamic changing conditions
- Provide effective interaction between the system-wide and local level analysis
- Implement operator decision-making support tools during emergency

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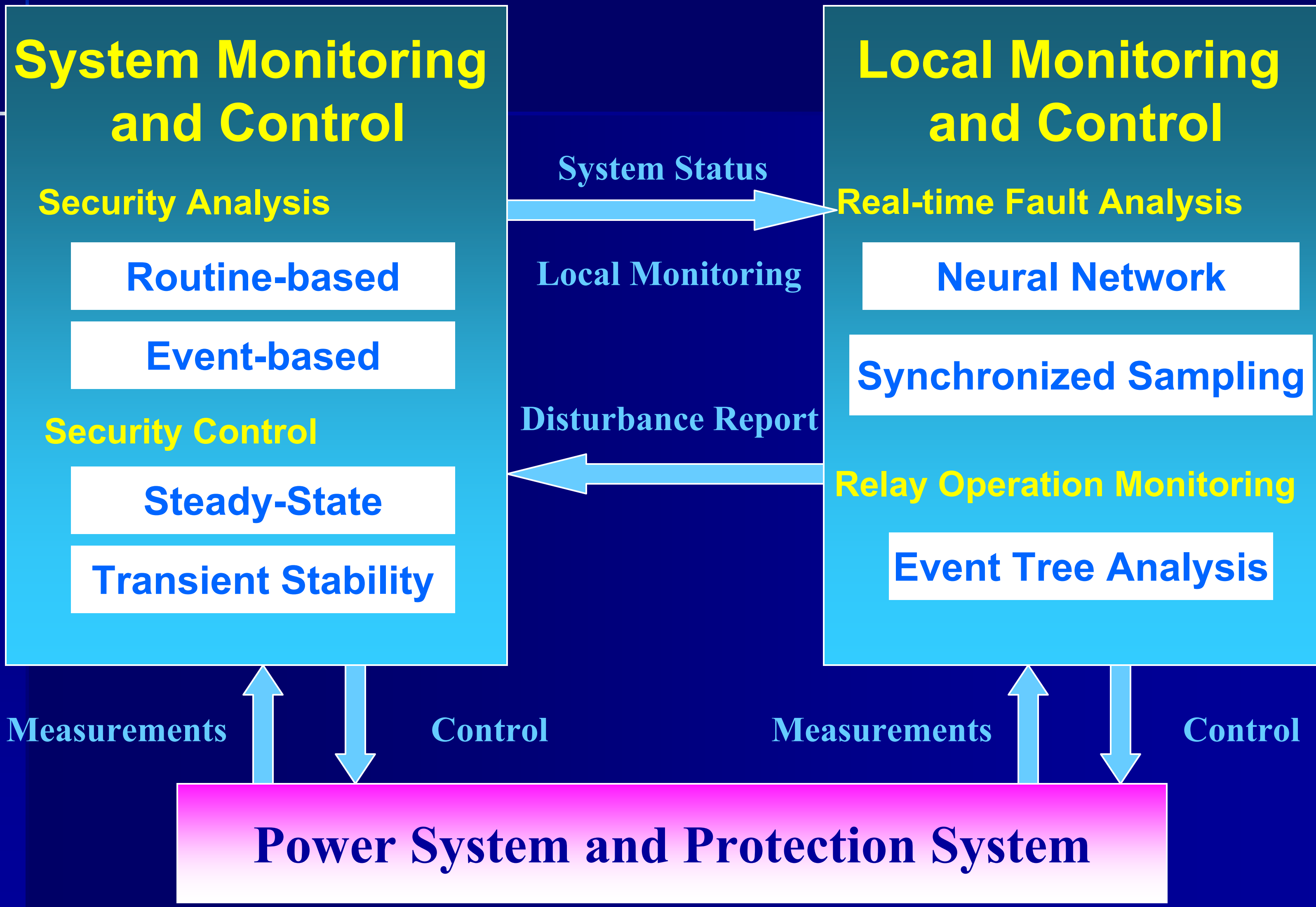
Interaction between System-wide and Local Monitoring and Control



Local Monitoring and Control

Real Time Fault Analysis Tool

- Current operational issues:

  - Performance of a conventional distance relay depends on accuracy of phasor measurements and appropriateness of relay settings.

  - In some extreme conditions (i.e. overload, system stability oscillation), the measurements may be inaccurate and/or settings may be inappropriate causing relay misoperation.

  - Relay misoperation may be due to either a loss of selectivity or physical failure of the relay or circuit breaker.

Real Time Fault Analysis Tool

- Our solution:

  - Fault analysis tool uses time-domain signals directly (not phasors) and stays away from the concept of traditional fixed settings.

  - A very accurate fault analysis is achieved as a result of providing a reference for evaluation of the correctness of conventional relay operation.

Local Monitoring and Control

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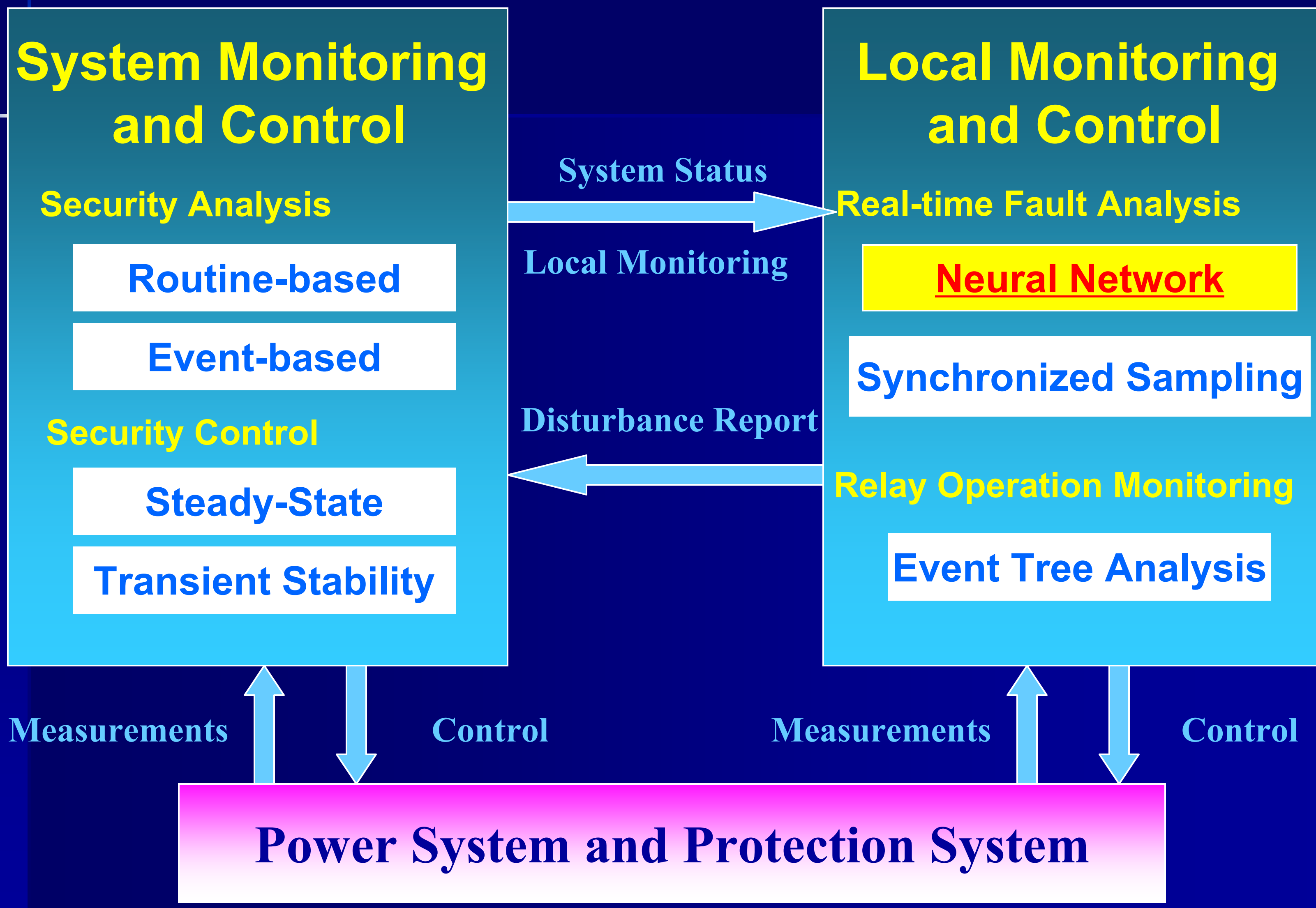
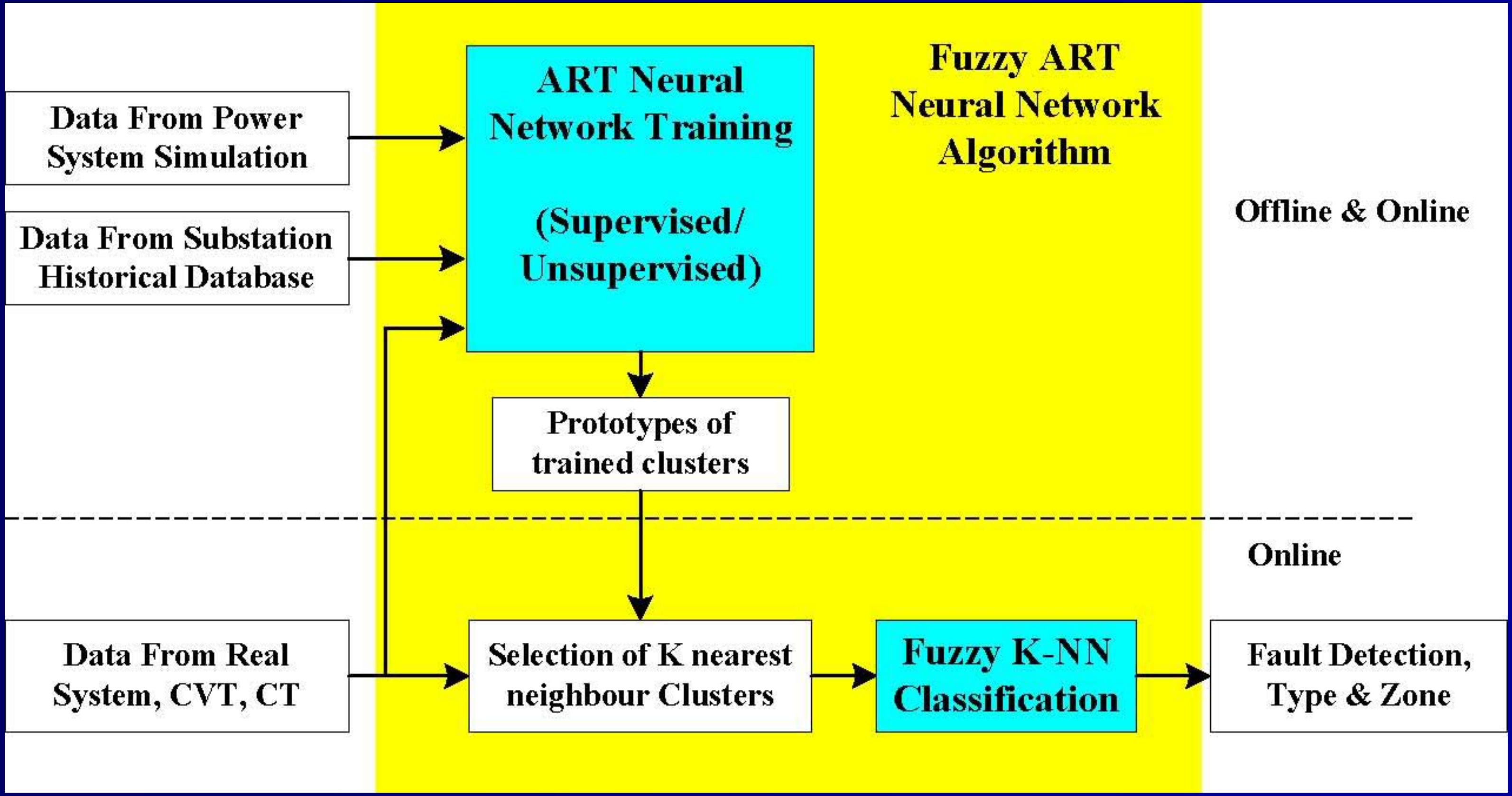
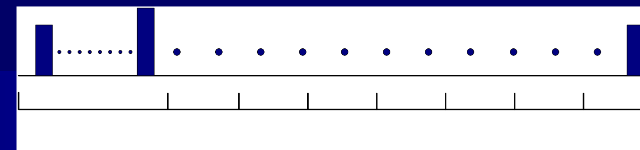


Neural Network Based Fault Diagnosis

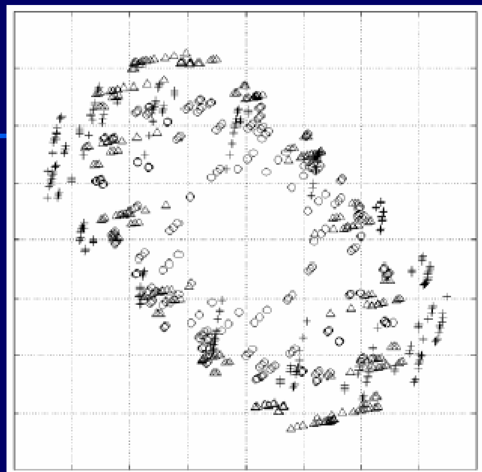


Overall Scheme

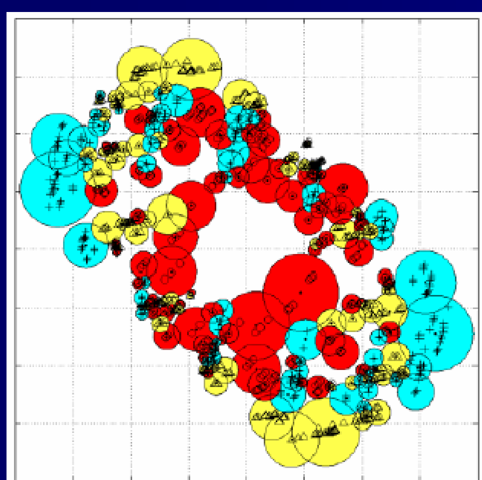
Training and Testing Process



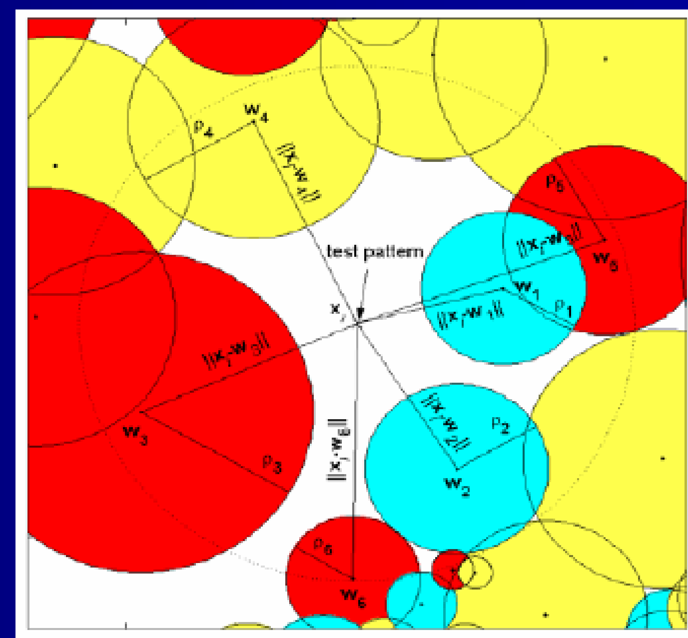
Input Pattern (using normalized raw samples)



Pattern Space (2-D demo)



Training (Self-Organized Clustering Technique)



Testing (Fuzzy K-nearest neighbor classifier)

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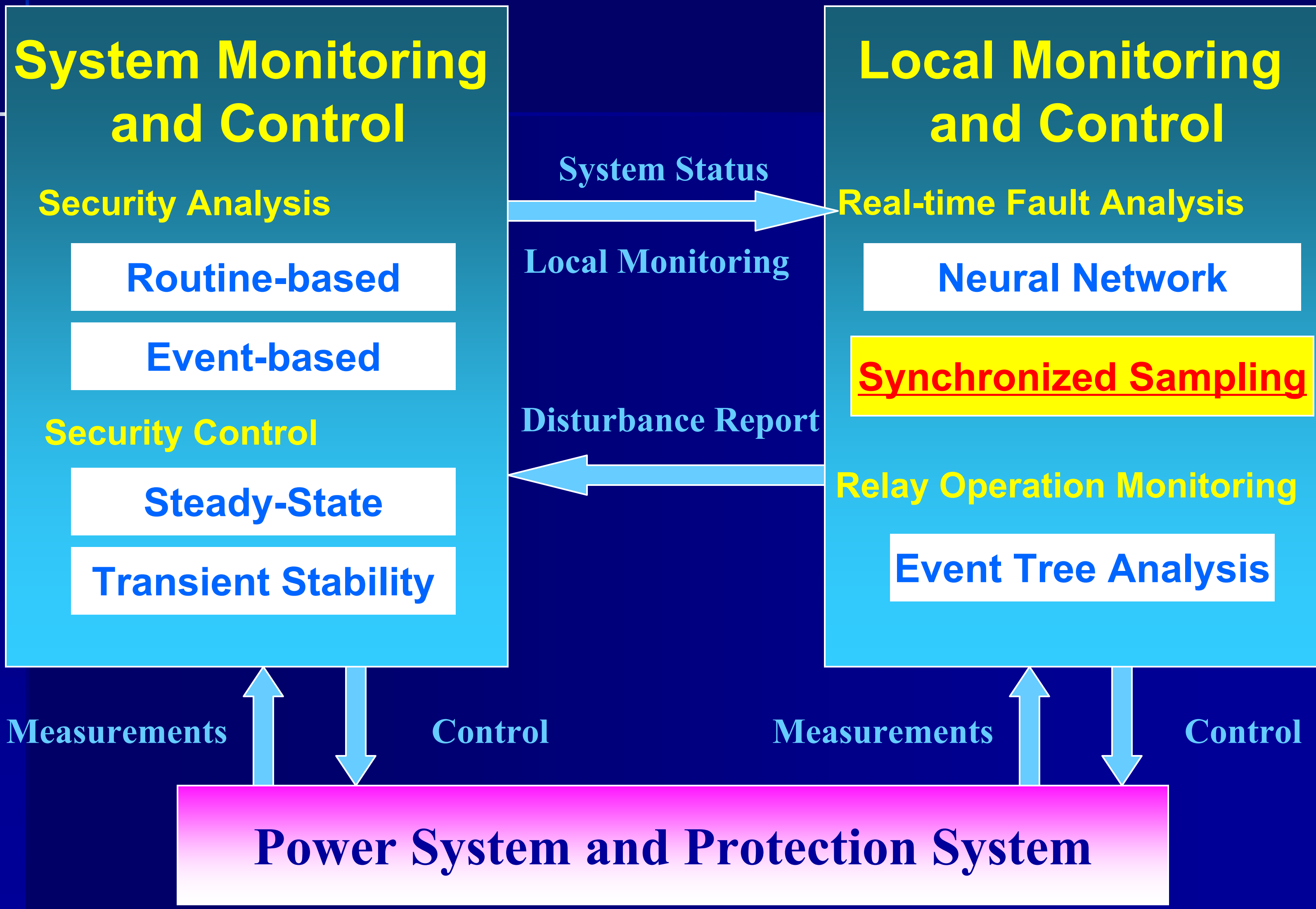
Benefits

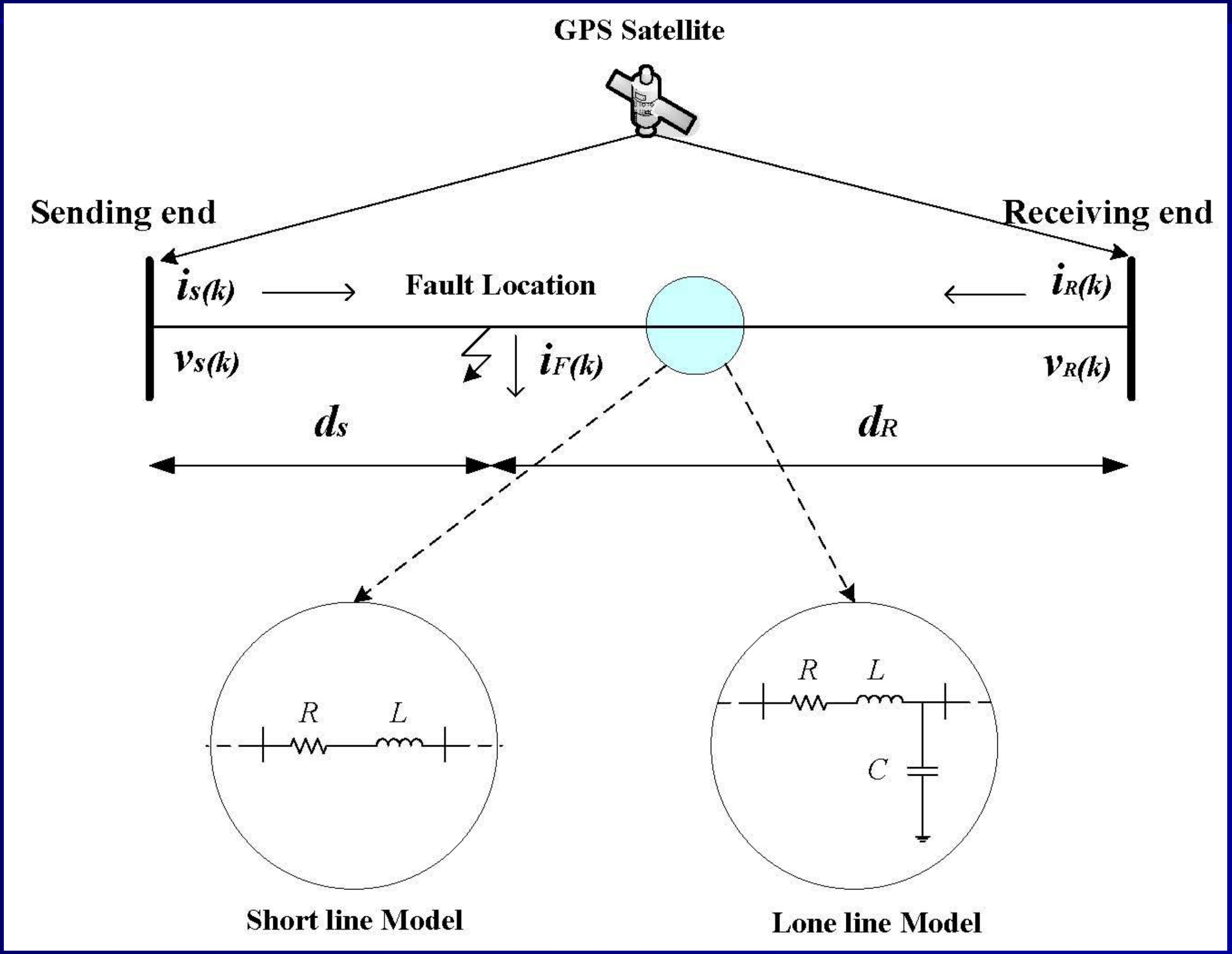
- No phasor calculation, time domain samples only
- No relay settings
- More accurate under complex situations because of the extensive training process
- Signal preprocessing eliminates the impacts from power swing and pre-fault loading
- Use of multiple neural networks enhances the capability of dealing with large data set

Neural Network based approach provides a more accurate fault detection and classification by using the same data inputs as distance relay

Local Monitoring and Control



Synchronized Sampling based Fault Diagnosis



Fault Detection Feature

- Short Line Model

$$i_d(k) = i_S(k) + i_R(k)$$

- Long Line Model

$$i_{d1}(k) = i_S(k-P)\left[1 - \frac{Rd}{2Z_c}\right] + i_R(k)\left[1 + \frac{Rd}{2Z_c}\right] + \frac{v_S(k-P)}{Z_c} - \frac{v_R(k)}{Z_c}$$

When no internal fault, those features equal to zero; When there is an internal fault, those features are related to fault current

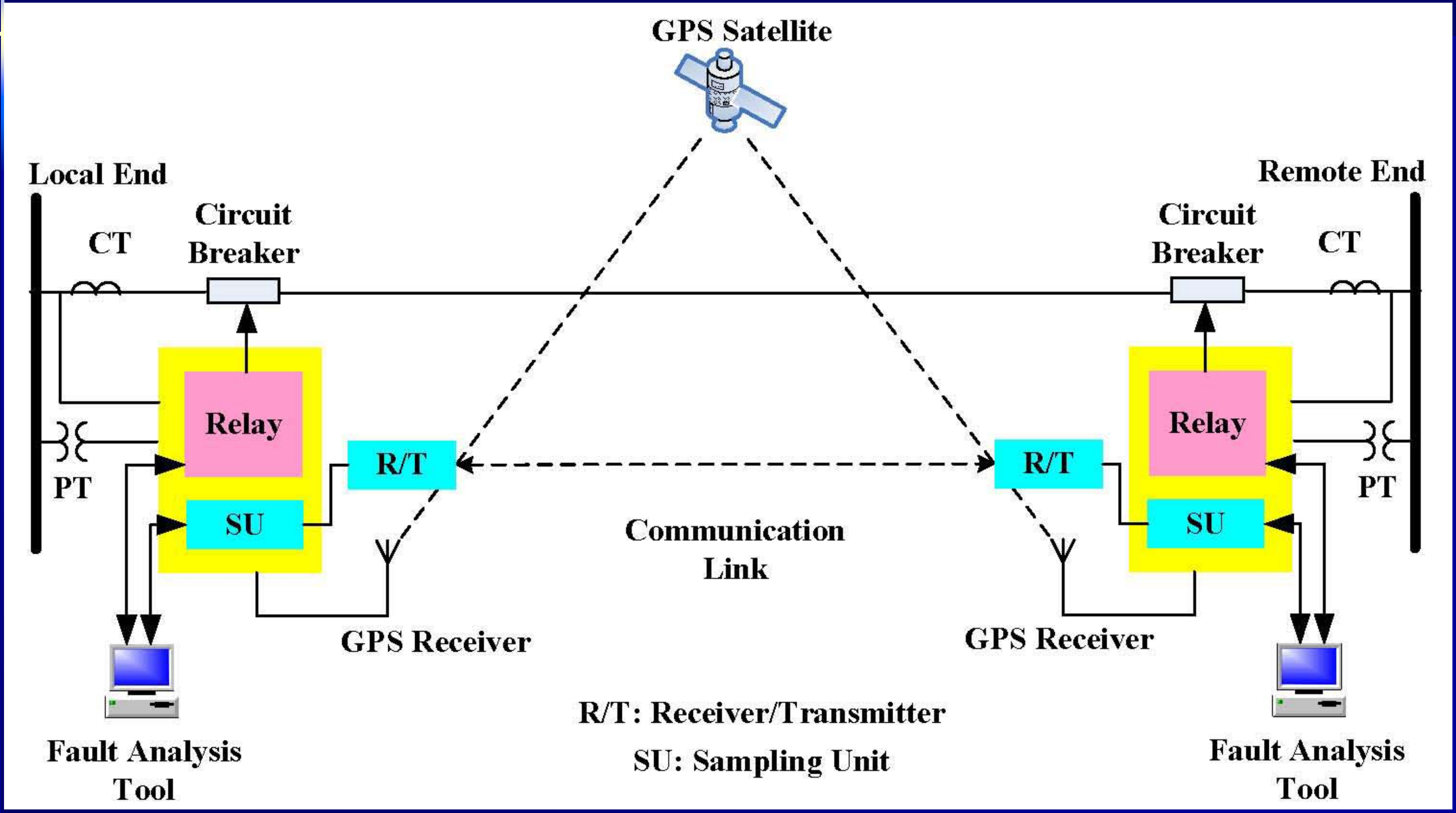
Extremely accurate fault location is achieved

Benefits

- Complete solution of fault detection, classification, and fault location.
- Time-domain calculation, no phasor computation or relay setting issues.
- No assumptions about fault parameters and system conditions.
- Immune from power swing, overload, and other non-fault situation.

Synchronized Sampling based fault diagnosis using data from two ends provides a very high accuracy in fault detection, classification, and location.

Real Time Fault Analysis Tool Based on Combination of the Two Algorithms



Used as a reference for evaluation of conventional relay operation

Benefits

- Neither of the two techniques uses the phasor measurement of fixed relay setting concepts.
- The two techniques combined offer a superior fault classification and fault location
- The two techniques complement each other assuring redundant fault analysis result for verifying relay operation.
- Two techniques can share the same hardware for a reduced cost.

The accuracy of Integrated fault analysis is very high based on simulation results. Dependability and Security could be improved simultaneously.

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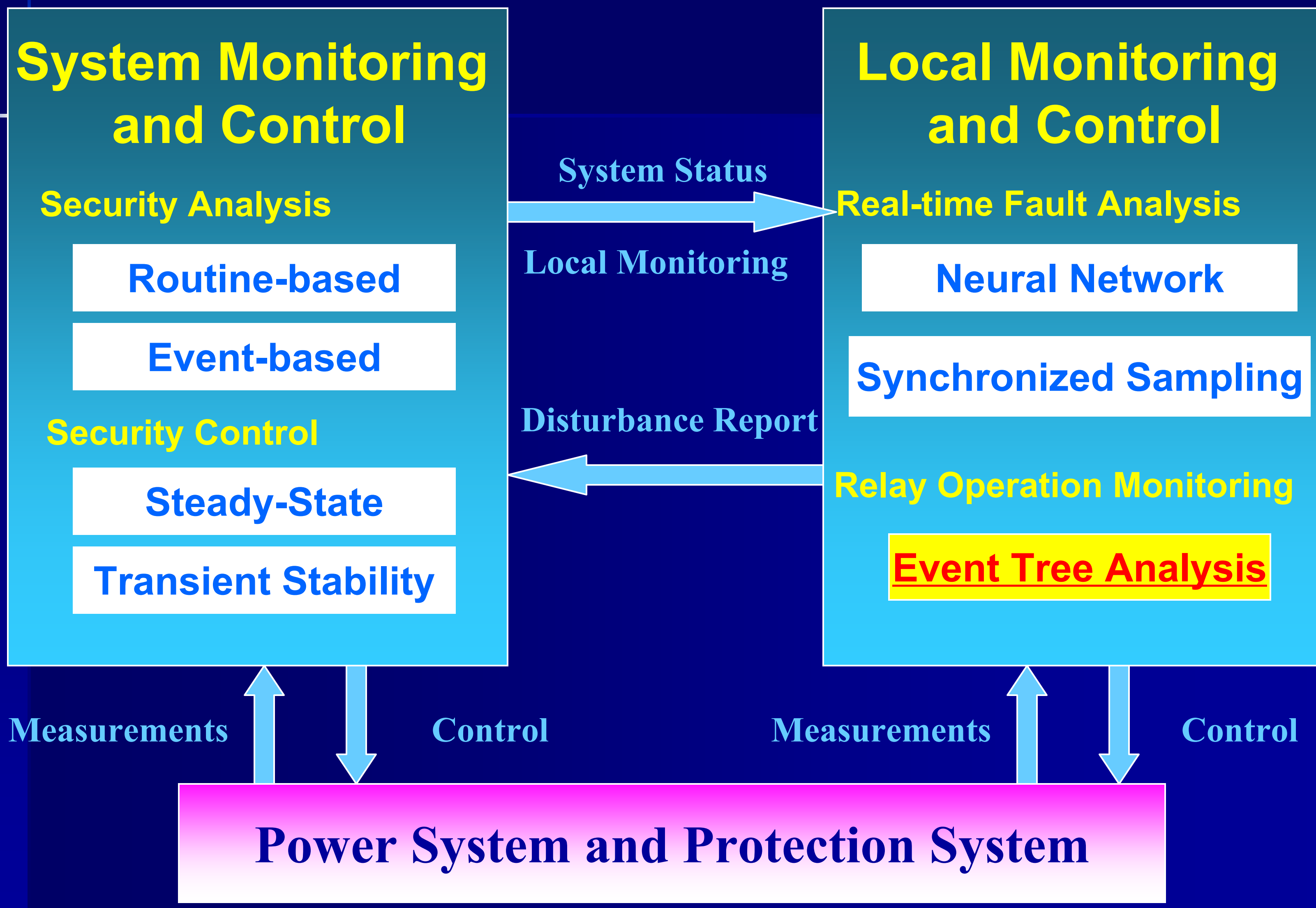
Performance at a Glance

- Comprehensive simulation studies has been conducted using CenterPoint SKY-STP system and WECC 9-bus system. Simulation results have been reported in several references listed at the end.
- Both neural network and synchronized sampling based fault diagnosis offer significant improvement over related functions of a distance relay.
- Neural network is especially good at fault classification and synchronized sampling is good at internal/external fault discrimination and fault location.
- The combination of the two techniques takes advantage of the benefits of each technique.
- Our simulation results show that the power swing and/or overload do not confuse either technique.

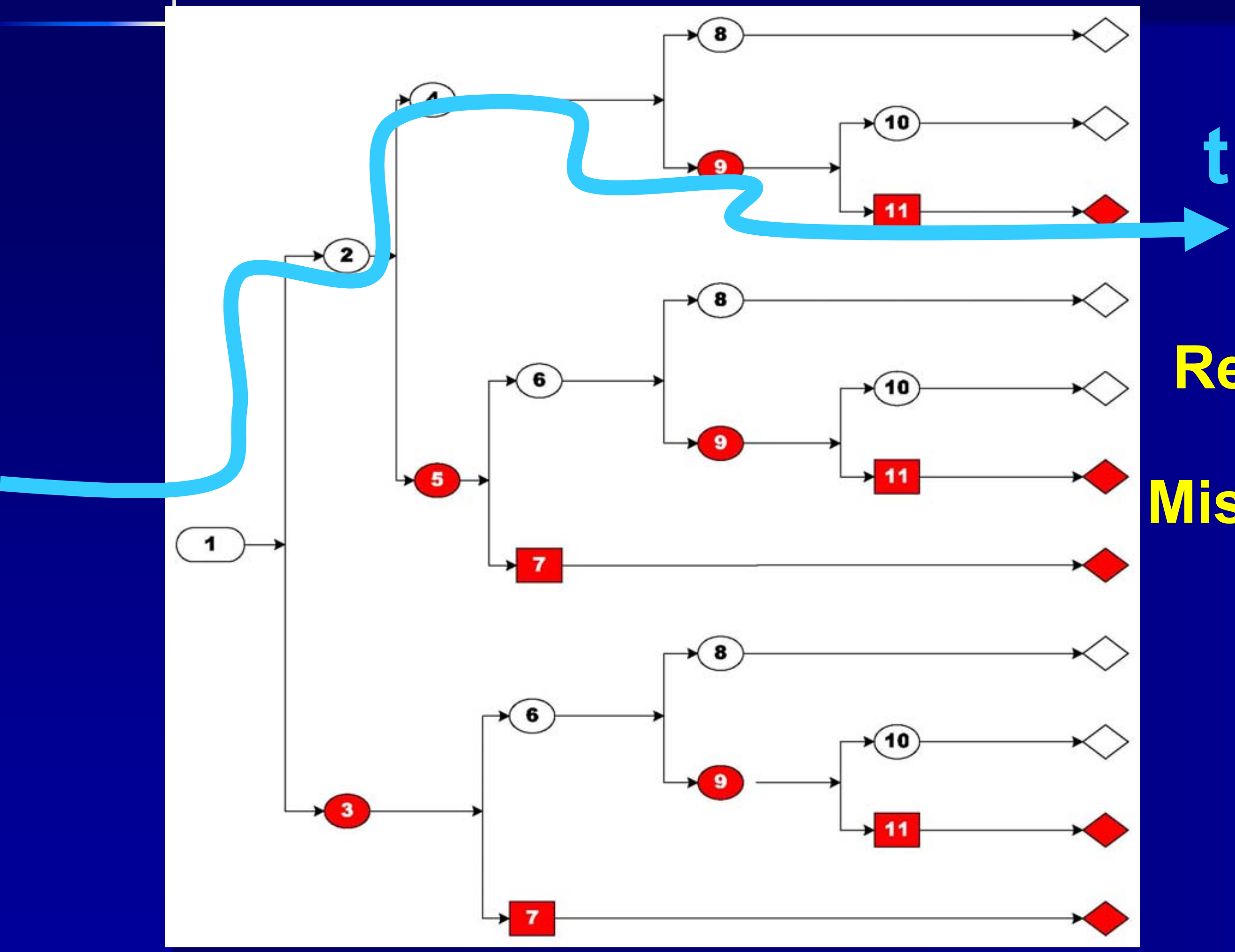
Local Monitoring and Control



Monitoring of Relay Operation

- The existing analysis tools for monitoring relay operation are used off-line. The analysis result off-line tools may not not be helpful in mitigating power system disturbance in real-time.
- We propose a real time relay monitoring tool using event tree analysis. The previously described fault analysis tool will provide the reference for evaluation of relay operation.

Event Tree Analysis for relay operation monitoring



Real time Monitoring

Misoperation Alarms (Red Nodes)

Event Tree Analysis

Be informed about relay misoperations and suggested remedial actions

Node	Status	Reference Action
1	Fault occurs in primary zone	
2	Relay detects the fault	
3	Relay does not detect the fault	Check relay settings and hardware
4	Relay detects the fault in a correct zone	
5	Relay detects the fault in an incorrect zone	Check relay settings and hardware
6	Transfer trip signal is received	
7	Transfer trip signal is not received	Send trip signal manually, Check communication channel
8	Circuit breaker opens the line	
9	Circuit breaker fails to open the line	Check the breaker circuit
10	Breaker failure protection trips all the breakers	
11	Breaker failure protection does not work	Check the circuit of the breaker failure protection

Benefits

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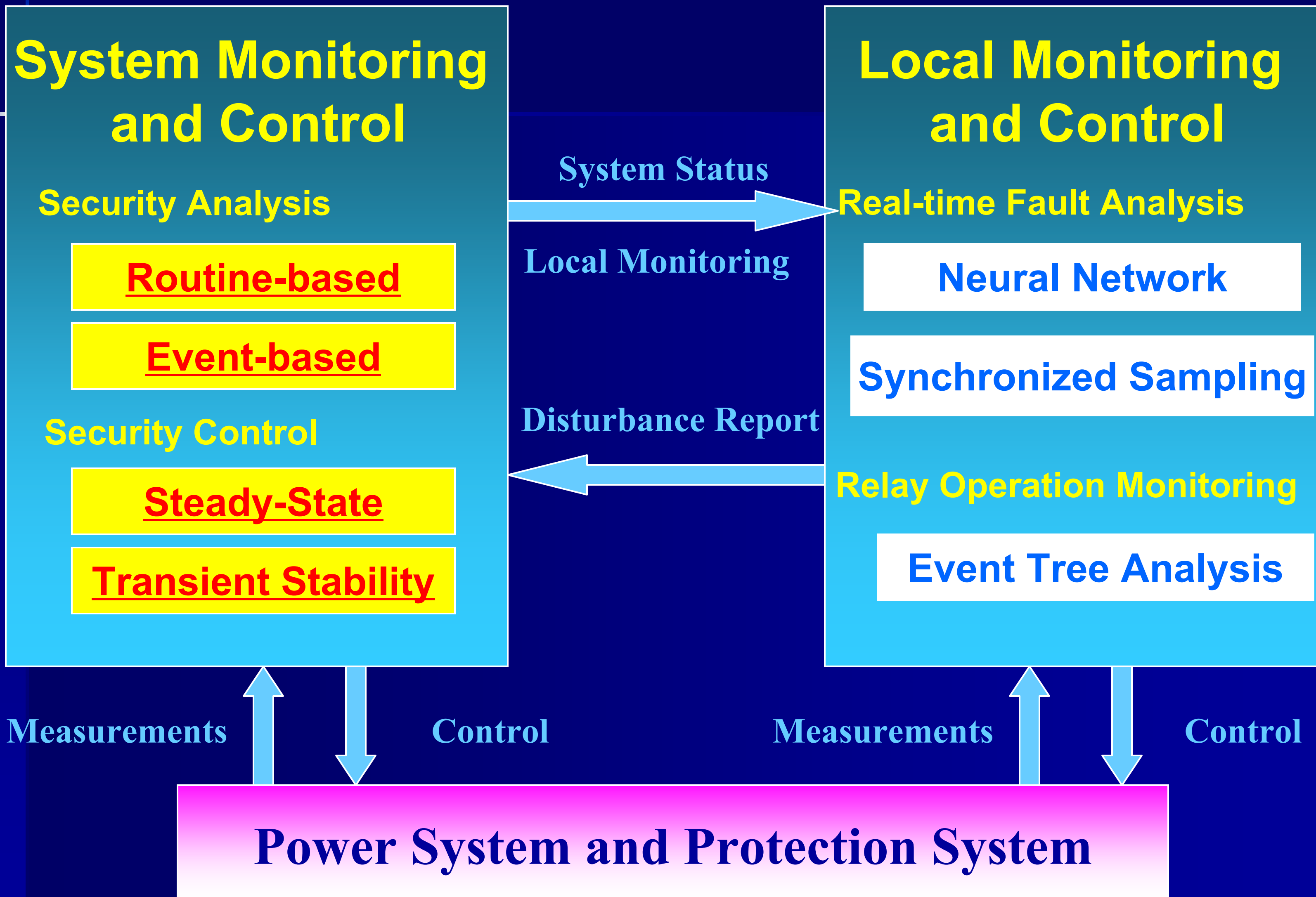
- A self-explainable, user-friendly tool for online monitoring of relay operations.
- Provide informed suggestion of remedial actions for the relay misoperations.
- The generic design of event trees is distributed to each single relay system (for each relay, there are three types of events: no fault, fault in primary zone, fault in backup zone). The number of event trees is finite and the design is feasible.

Event Tree Analysis provides an efficient way for real time observation of relay operations and an effective local disturbance diagnostic support.

System Monitoring and Control

System Monitoring and Control



Functions at a Glance

- Security analysis

  Routine-based: for expected events (contingency analysis, vulnerability analysis)

  Event-based: for unexpected event
- Security control

  Steady state control: solve overload, low/high voltage problem

  Transient stability control: solve stability problem

  Both for expected and unexpected events

Use of Local Information at the System Level

- Know exact local disturbance information in real-time
- Obtain local diagnostic support and predict future events (i.e., line overload, relay misoperation)
- Make better control decision based on correct local information
- Evaluate system security and take actions to preserve it

Benefits: Help operators have good situational awareness
Provide operators with decision-making support

Use of System Information at the Local Level

- Identify threatening contingencies
- Identify vulnerable parts (lines and relays) and initiate local tool for careful monitoring
- Block relay misoperation during extreme conditions or make correction after system-wide analysis
- Find and store emergency control means ready for expected contingencies
- Find emergency control means for real time unexpected events

Benefits: Effective interaction between system and local actions and operator decision making support

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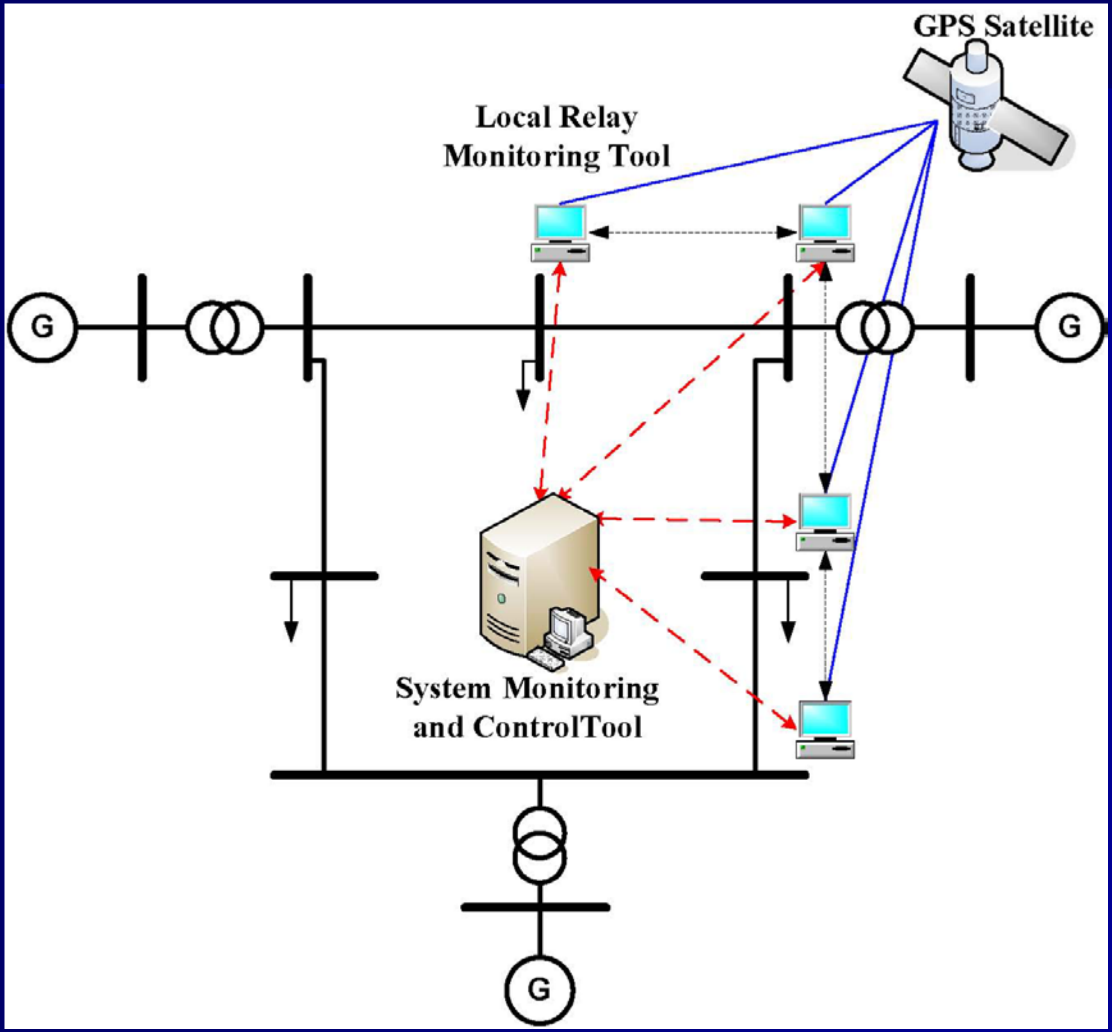
Potential Infrastructure



Online Implementation

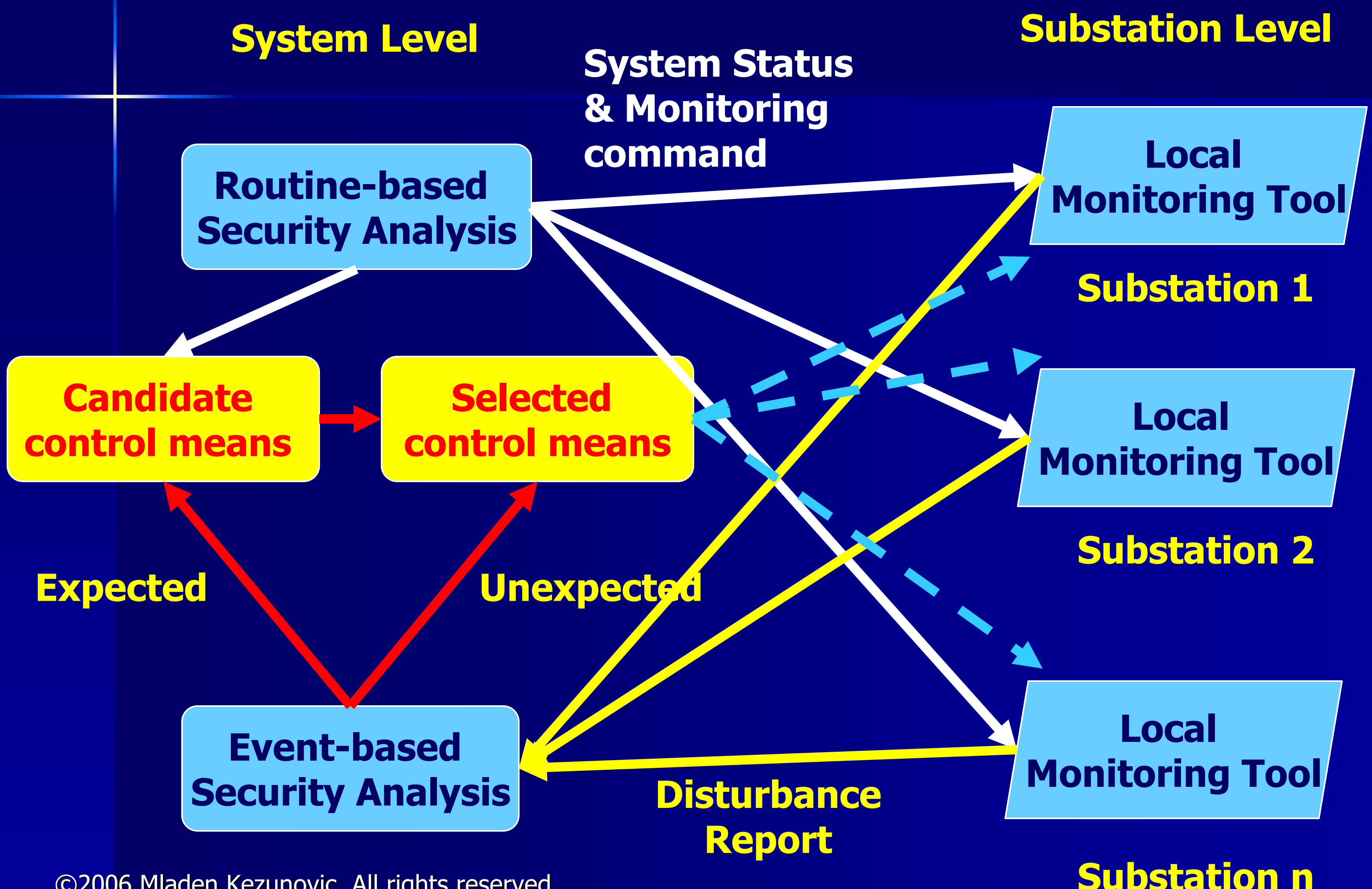
Step 1: Routine security analysis performed by the system tool: (a) decides security level and finds vulnerable elements, then sends monitoring command to the local tool; (b) identifies critical contingencies, and starts associated control schemes to find the control means for those expected events.

Step 2: Local monitoring performed by the local tool: (a) starts analysis when disturbance occurs; (b) if it finds relay misoperation, it makes correction or receives system control command for better control; (c) reports disturbance information and analysis to the system tool.

Step 3: Event-based security analysis performed by the system tool: (a) if it finds a match with expected event, activates the emergency control; (b) if it does not find a match, analyzes if the system is secure or not; (c) if it is not, finds new emergency control and activates it.

Step 4: Update information and go to Step 1.

Graphic Demonstration



Data Measurements Requirement

Local Monitoring Tool

- **Synchronized sampling based approach:**

  Synchronized raw samples of voltage and current from both ends of transmission line, sampling rate in the order of 20KHz. The Data source can be PMU or DFR.

- **Neural network based approach:**

  Raw samples of voltage and current from local end, sampling rate in the order of 16-32 samples/cycle. The data source can be share with synchronized sampling based approach.

- **Event Tree Analysis:**

  Relay trip signal, circuit breaker "a' and "b" contact signal.

Data Measurements Requirement

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System Monitoring Tool

- **For static analysis of routine-based and event-based studies, as well as steady state control scheme:**

  - Voltage, current and power flow phasors from PMU, or SCADA, State Estimation, power flow analysis.

  - Topology information from SCADA or State Estimation.

- **For dynamic analysis of routine-based and event-based studies, as well as transient stability control scheme:**

  Event information from contingency list, relay, DFR, SCADA.

Potential Uses

Local Monitoring Tool to be used in Substations

- Neural network and synchronized sampling based approaches can be used as relay operation reference for enhanced transmission line fault analysis. They can also be used as specific fault analysis functions in IEDs.
- Event tree analysis can be used for real time monitoring of relay operations to provide a local event analysis support.

System Monitoring Tool to be used in Control Center

- Routine-based security analysis can be used for enhanced view of system vulnerability and security.
- Event-based security analysis can be used for timely solution for early detection, prevention and mitigation of possible cascading events.
- Staged control means are selected for the different violations of the system status.

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Conclusions

- Monitoring relay operations in real time and providing system situational awareness are very important for detecting and preventing cascading events.
- Proposed local monitoring tool enables a superior real time fault analysis tool by using combined neural network and synchronized sampling technique. The proposed event tree analysis is an efficient approach for monitoring relay operations.
- The role of system monitoring and control tool is providing the system status in a dynamic situation and selecting the appropriate control knowing the exact disturbance information from the local monitoring tool.
- Interactive system-wide and local schemes can prevent and mitigate the cascading blackouts effectively at the early stage.
- Extensive studies have been implemented both at the local substation level and system level. The simulation result demonstrated the excellent performance of both tools

Future Work

Research

- Algorithm improvement and integration for both system and local tools.
- Large-scale system simulation for system monitoring tool.
- Study of the communication scheme between system and local monitoring tools.

Deployment

- Field data test for local fault analysis algorithms.
- Study of effect from data measurements devices (PMU, DFR) and transducers.
- User interface development for both system and local tools; Development of demonstration software.

Publications

1. M. Kezunovic, B. Perunicic, and J. Mrkic, "An accurate fault location algorithm using synchronized sampling", Electric Power Systems Research Journal, vol.29, no.3, pp. 161-169, May 1994.
2. M. Kezunovic, B. Perunicic, "Automated transmission line fault analysis using synchronized sampling at two ends." IEEE Trans. Power Systems. vol. 11, no. 1, pp. 441-447, Feb. 1996
3. A. Gopalakrishnan, M. Kezunovic, "Fault location using distributed parameter transmission line model", IEEE Trans. Power Delivery, vol.15, no.4, pp.1169-1174, Oct. 2000.
4. S. Vasilic, M. Kezunovic, "Fuzzy ART neural network algorithm for classifying the power system faults ", IEEE Trans. Power Delivery, vol. 20, no. 2, pp.1306-1314, Apr. 2005
5. N. Zhang, M. Kezunovic, "Verifying the Protection System Operation Using an Advanced Fault Analysis Tool Combined with the Event Tree Analysis ", NAPS2004, 36th Annual North American Power Symposium, Moscow, Idaho, August, 2004
6. H. Song, M. Kezunovic, "Relieving Overload and Improving Voltage by the Network Contribution Factor (NCF) Method", NAPS2004, 36th Annual North American Power Symposium, Moscow, Idaho, August, 2004

Publications (Cont'd)

7. H. Song, M. Kezunovic, "A Comprehensive Contribution Factor Method for Congestion Management", 2004 Power Systems Conference & Exposition, New York, October, 2004
8. H. Song, M. Kezunovic, "Stability Control using PEBS method and Analytical Sensitivity of the Transient Energy Margin", 2004 Power Systems Conference & Exposition, New York, October, 2004
9. N. Zhang, M. Kezunovic, " Coordinating Fuzzy ART Neural Networks to Improve Transmission line Fault Detection and Classification", 2005 IEEE PES General Meeting, San Francisco, June 2005.
10. N. Zhang, M. Kezunovic, " A Study of Synchronized Sampling Based Fault Location Algorithm Performance under Power Swing and Out-of-step Conditions", 2005 IEEE St. Petersburg PowerTech, St. Petersburg, Russia, June 2005.
11. N. Zhang, M. Kezunovic, "Implementing an advanced simulation tool for advanced fault analysis", 2005 IEEE PES T&D Asia & Pacific Conference, Dalian, China, Aug. 2005
12. H. Song, M. Kezunovic, "Static Security Analysis based on Vulnerability Index (VI) and Network Contribution Factor (NCF) Method", 2005 IEEE PES T&D Asia Pacific, Dalian, China, August, 2005

Publications (Cont'd)

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13. N. Zhang, H.Song, M. Kezunovic, "New monitoring and control scheme for preventing cascading outage", NAPS2005, Ames, Iowa, Oct. 2005
14. N. Zhang, M. Kezunovic, "Improving Real-time Fault Analysis and Validating Relay Operations to Prevent Cascading Blackouts", 2005/2006 IEEE PES T&D Conference, Dallas, May 2006
15. H. Song, M. Kezunovic, "Static Analysis of Vulnerability and Security Margin of the Power System", 2005/2006 IEEE PES T&D Conference, Dallas, May 2006
16. N. Zhang, M. Kezunovic, "Complete Fault Analysis for Long Transmission Line using Synchronized Sampling," IFAC Symposium on Power Plants and Power Systems Control, Kananaskis, Canada, June 2006.
17. N. Zhang, M. Kezunovic, "A Real Time Fault Analysis Tool for Monitoring Operation of Transmission Line Protective Relay", Electric Power Systems Research Journal, (Accepted, In Press).