2nd Smart Grid - Distribution Automation Conference

Real-Time Power Distribution Network Measurement and Control

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Real-Time Power Distribution Network Measurement and Control Agenda

- Legacy Power Grid Issues
- Smart Grid Solutions
- Technologies Required for the Smart Grid
- Wide-area Events for Different Transmission Systems
- Power System State Estimation
- Wide Area Monitoring Systems
- Voltage and Reactive Power Control
- Communication Requirements
- Equipment Performance Monitoring

Legacy Power Grid Challenges

- Improve security, reliability, and efficiency
- Dynamically optimize grid resources and operation
- Integrate DG sources, including renewable resources
- Implement demand response and energy efficiency
- Integrate future smart appliances
- Provide consumers with control options and timely information

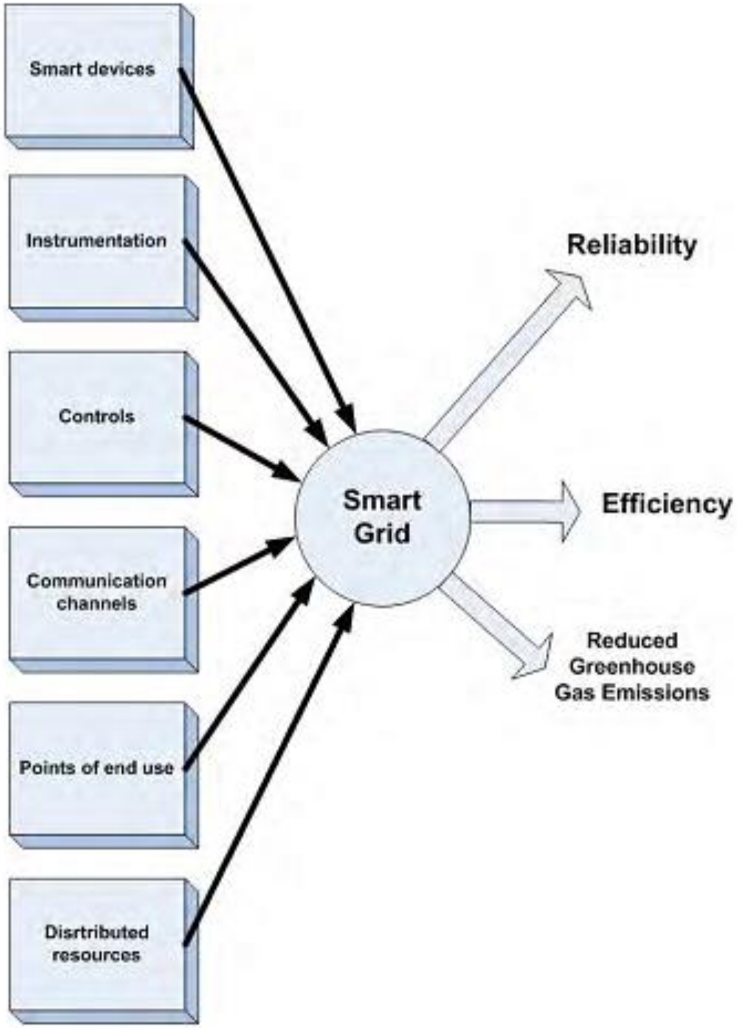
Increased Outage Trends

- According to data assembled by the U.S. Energy Information Administration (EIA) for most of the past decade, there were 156 outages of 100 megawatts or more during 2000-2004; such outages increased to 264 during 2005-2009.
- The number of U.S. power outages affecting 50,000 or more consumers increased from 149 during 2000-2004 to 349 during 2005-2009, according to EIA

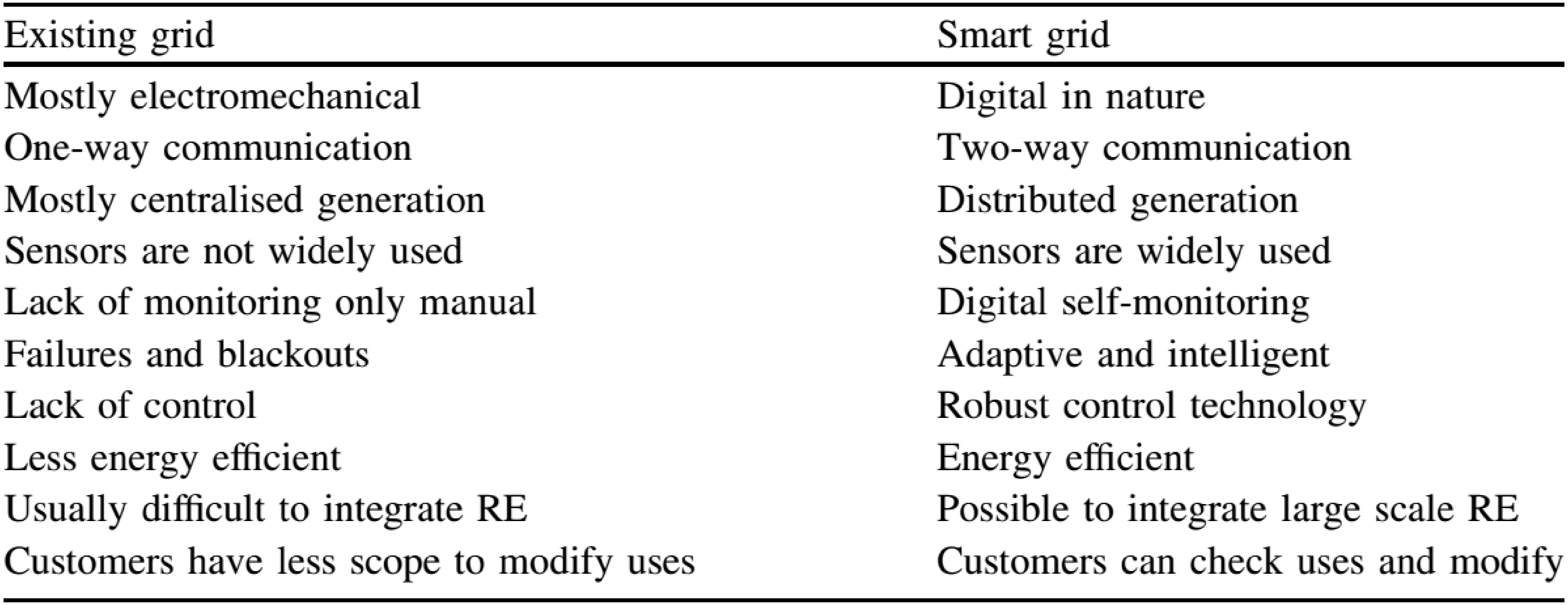
Smart Grid Requirements

- Deployment and integration of distributed resources and generation including renewable resources
- Development and incorporation of DR, demand-side resources, and energy efficiency resources
- Deployment of ‘smart’ technologies (real-time, automated, interactive technologies that optimize the physical operation of appliances and consumer devices) for metering, communications concerning grid operations and status, and distribution automation
- Deployment and integration of advanced electricity storage and peak-shaving technologies
- Provision to consumers of timely information and control options

Smart Grid Concept



Comparison between Existing Grid and Smart Grid

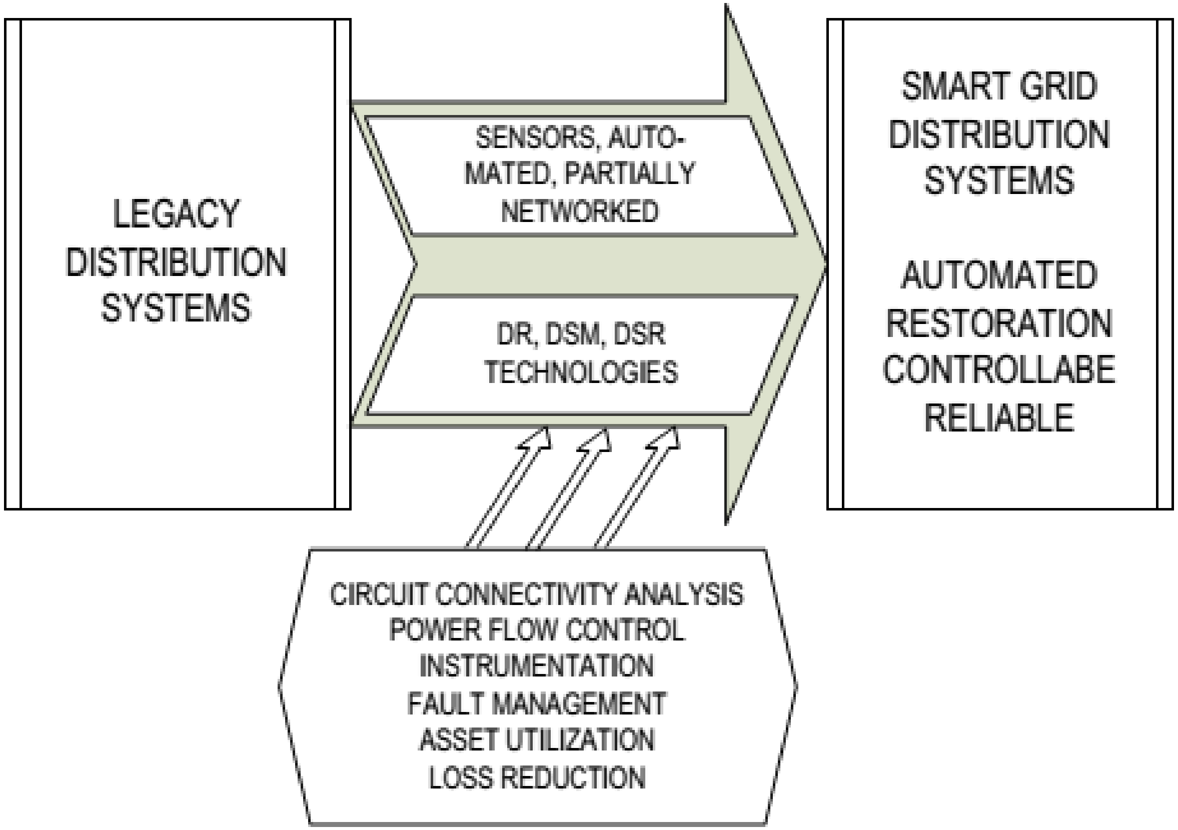


Existing grid	Smart grid
Mostly electromechanical	Digital in nature
One-way communication	Two-way communication
Mostly centralised generation	Distributed generation
Sensors are not widely used	Sensors are widely used
Lack of monitoring only manual	Digital self-monitoring
Failures and blackouts	Adaptive and intelligent
Lack of control	Robust control technology
Less energy efficient	Energy efficient
Usually difficult to integrate RE	Possible to integrate large scale RE
Customers have less scope to modify uses	Customers can check uses and modify

Technologies Required for the Smart Grid

- Information and communications technologies
- Sensing, measurement, control and automation technologies
- Power electronics and energy storage

Transition from Legacy Distribution Systems to the Smart Grid



LEGACY DISTRIBUTION SYSTEMS

SENSORS, AUTOMATED, PARTIALLY NETWORKED

DR, DSM, DSR TECHNOLOGIES

SMART GRID DISTRIBUTION SYSTEMS

AUTOMATED
RESTORATION
CONTROLLABE
RELIABLE

CIRCUIT CONNECTIVITY ANALYSIS
POWER FLOW CONTROL
INSTRUMENTATION
FAULT MANAGEMENT
ASSET UTILIZATION
LOSS REDUCTION

Information and Communications Technologies

- Two-way communication technologies to provide connectivity between different components in the power system and loads
- Open architectures for plug-and-play of home appliances; electric vehicles and microgeneration
- Communications, and the necessary software and hardware to provide customers with greater information, enable customers to trade in energy markets and enable customers to provide demand-side response
- Software to ensure and maintain the security of information and standards to provide scalability and interoperability of information and communication systems

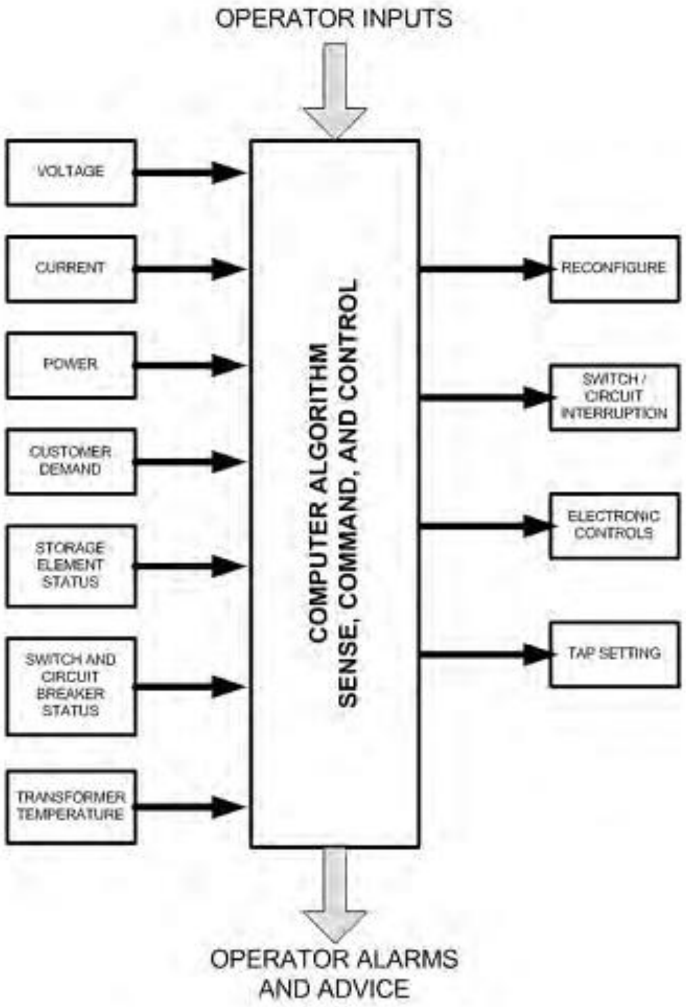
Sensing, Measurement, Control and Automation Technologies

- Intelligent electronic devices (IED) to provide advanced protective relaying, measurements, fault records and event records for the power system
- Phasor measurement units (PMU) and wide area monitoring, protection and control (WAMPAC) to ensure the security of the power system
- Integrated sensors, measurements, control and automation systems and information and communication technologies to provide rapid diagnosis and timely response to any event in different parts of the power system. These will support enhanced asset management and efficient operation of power system components, to help relieve congestion in transmission and distribution circuits and to prevent or minimise potential outages and enable working autonomously when conditions require quick resolution

Sensing, Measurement, Control and Automation Technologies - 2

- Smart appliances, communication, controls and monitors to maximise safety, comfort, convenience, and energy savings of homes
- Smart meters, communication, displays and associated software to allow customers to have greater choice and control over electricity and gas use. They will provide consumers with accurate bills, along with faster and easier supplier switching, to give consumers accurate real-time information on their electricity and gas use and other related information and to enable demand management and demand side participation.

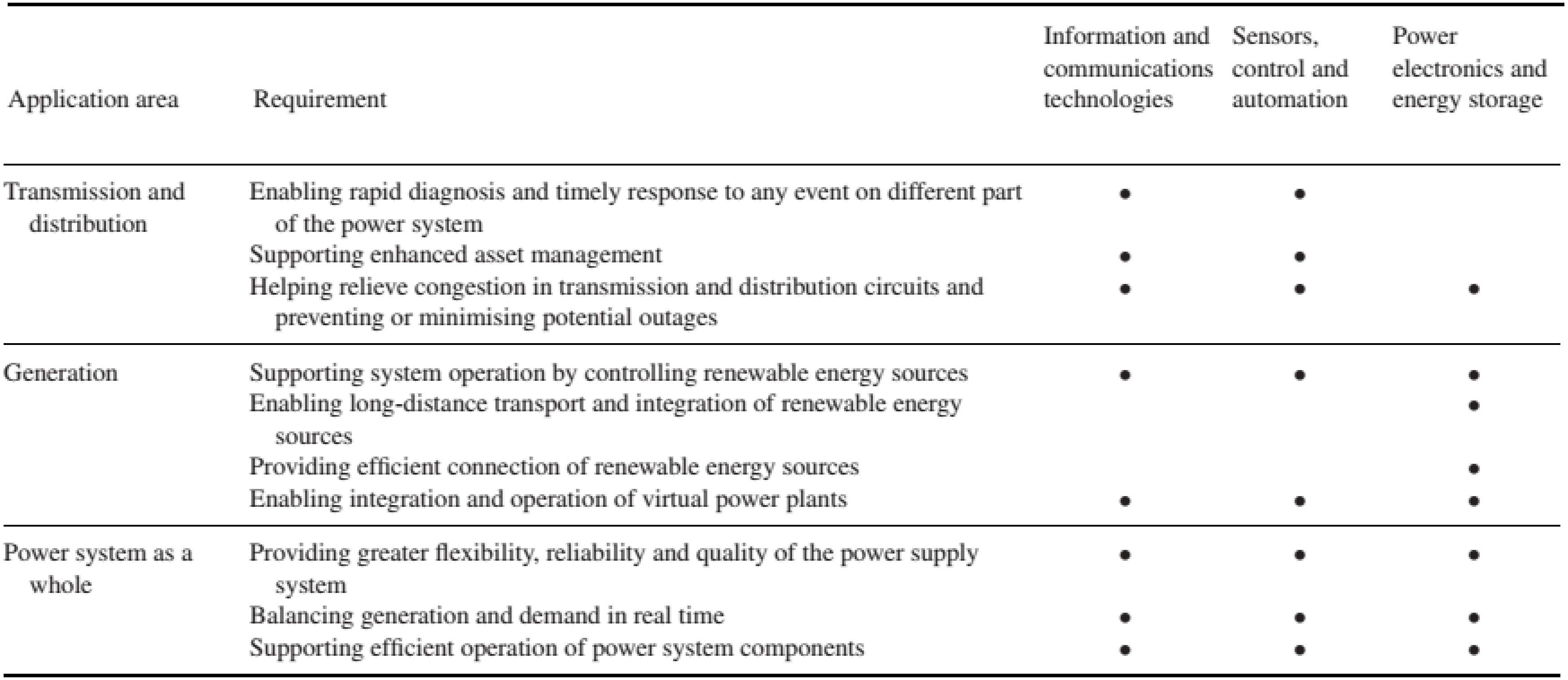
Sensing and Real Time Monitoring of Distribution System Elements



Power Electronics and Energy Storage

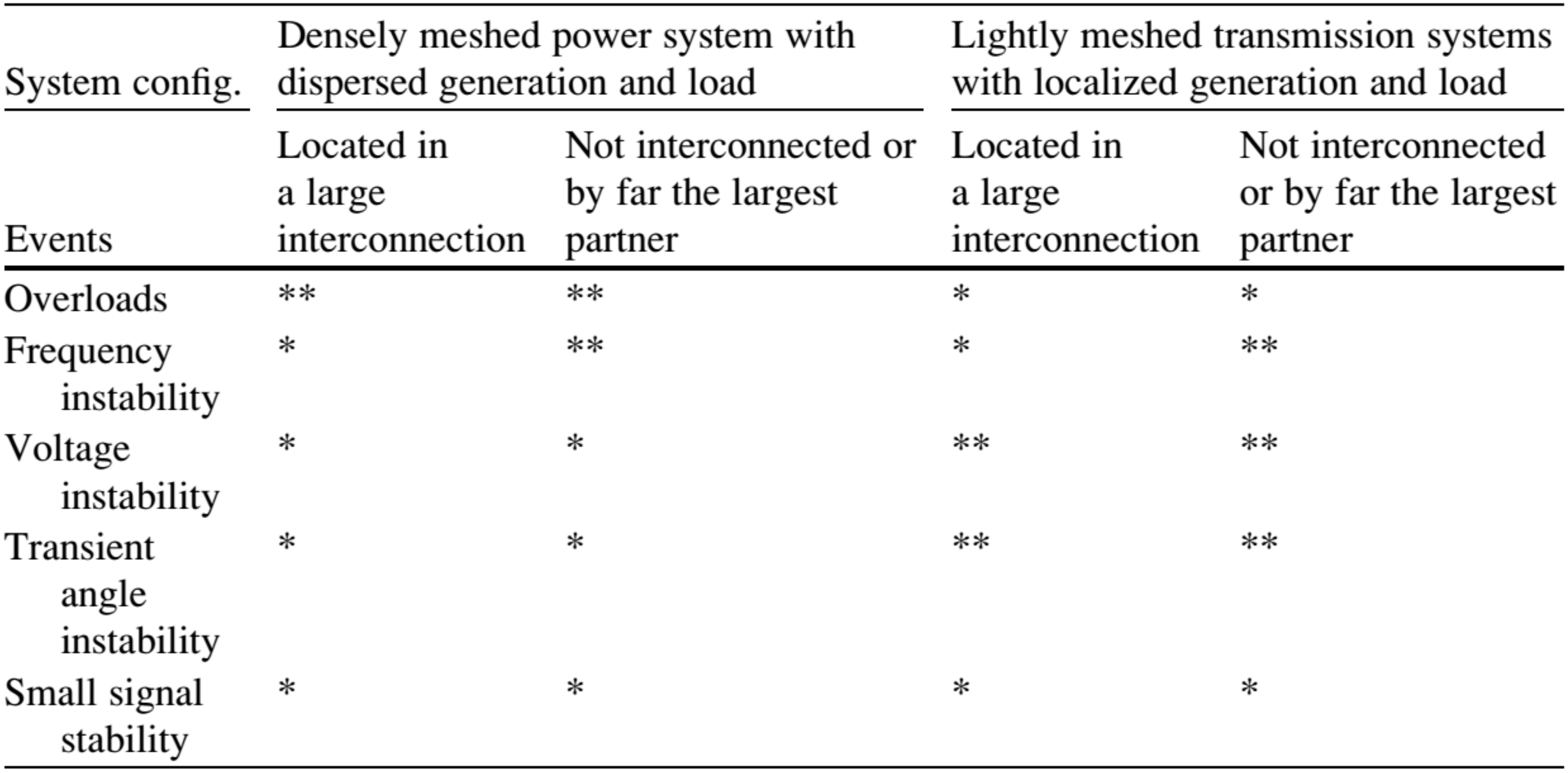
- High voltage DC (HVDC) transmission and back-to-back schemes and flexible AC transmission systems (FACTS) to enable long distance transport and integration of renewable energy sources
- Different power electronic interfaces and power electronic supporting devices to provide efficient connection of renewable energy sources and energy storage devices
- Series capacitors, unified power flow controllers (UPFC) and other FACTS devices to provide greater control over power flows in the AC grid
- HVDC, FACTS and active filters together with integrated communication and control to ensure greater system flexibility, supply reliability and power quality
- Power electronic interfaces and integrated communication and control to support system operations by controlling renewable energy sources, energy storage and consumer loads
- Energy storage to facilitate greater flexibility and reliability of the power system

Application Matrix of Different Technologies



Application area	Requirement	Information and communications technologies	Sensors, control and automation	Power electronics and energy storage
Transmission and distribution	Enabling rapid diagnosis and timely response to any event on different part of the power system	●	●	
	Supporting enhanced asset management	●	●	
	Helping relieve congestion in transmission and distribution circuits and preventing or minimising potential outages	●	●	●
Generation	Supporting system operation by controlling renewable energy sources	●	●	●
	Enabling long-distance transport and integration of renewable energy sources			●
	Providing efficient connection of renewable energy sources			●
	Enabling integration and operation of virtual power plants	●	●	●
Power system as a whole	Providing greater flexibility, reliability and quality of the power supply system	●	●	●
	Balancing generation and demand in real time	●	●	●
	Supporting efficient operation of power system components	●	●	●

Types of Wide-area Events for Different Transmission Systems



System config.	Densely meshed power system with dispersed generation and load		Lightly meshed transmission systems with localized generation and load	
Events	Located in a large interconnection	Not interconnected or by far the largest partner	Located in a large interconnection	Not interconnected or by far the largest partner
Overloads	**	**	*	*
Frequency instability	*	**	*	**
Voltage instability	*	*	**	**
Transient angle instability	*	*	**	**
Small signal stability	*	*	*	*

**Major phenomena

Overloads

- Thermal overload issue:
  - Electrical network capacity and losses limit electric power transmission.
  - Capacity may include real-time weather conditions as well as congestion management.
  - The impact of transmission losses on market power is yet to be understood.

Power System Stability

- Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact.

EEE/CIGRE Joint Task Force on Stability Terms and Definitions, “Definition and Classification of Power System Stability”, IEEE Transactions on Power Systems, 2004

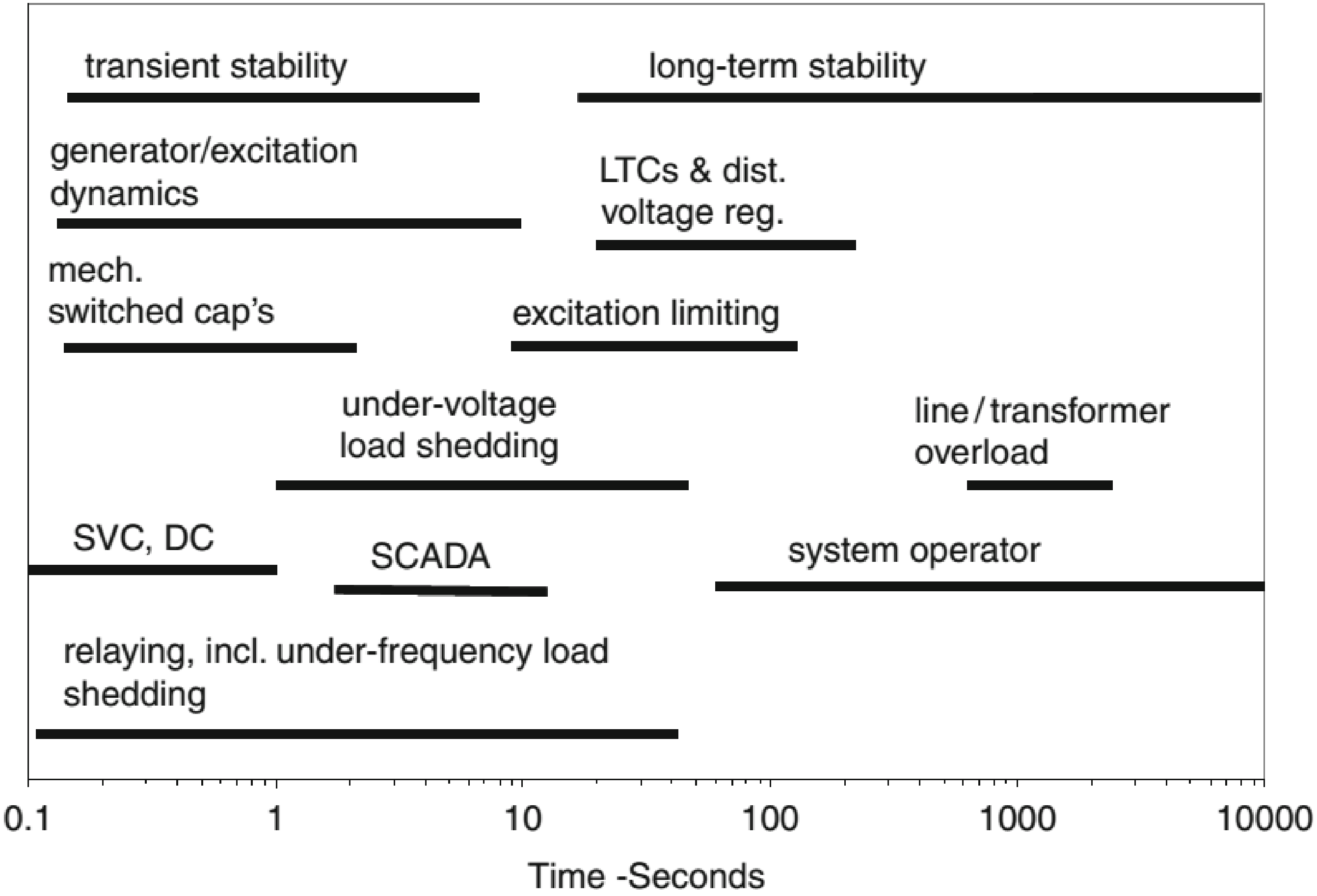
Frequency Stability

- Ability of a power system to compensate for a power deficit
- How a typical power system compensates for a power deficit:
  1. Inertial reserve (network time constant)
     - Lost power is compensated by the energy stored in rotating masses of all generators -> Frequency decreasing
  2. Primary control (1s to 15s):
     - Lost power is compensated by an increase in production of primary controlled units. -> Frequency drop partly compensated
  3. Secondary control (15s to 3min):
     - Lost power is compensated by secondary controlled units. Frequency and area exchange flows re-established
  4. Re-Dispatch of Generation

Voltage Stability

- Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance.
- Small disturbance voltage stability (Steady-state voltage stability)
  - Ability to maintain steady voltages when subjected to small disturbances, e.g. increasing load, change in solar PV output
- Large signal voltage stability (Dynamic voltage stability)
  - Ability to maintain steady voltages after following large disturbances, e.g. transmission line trip

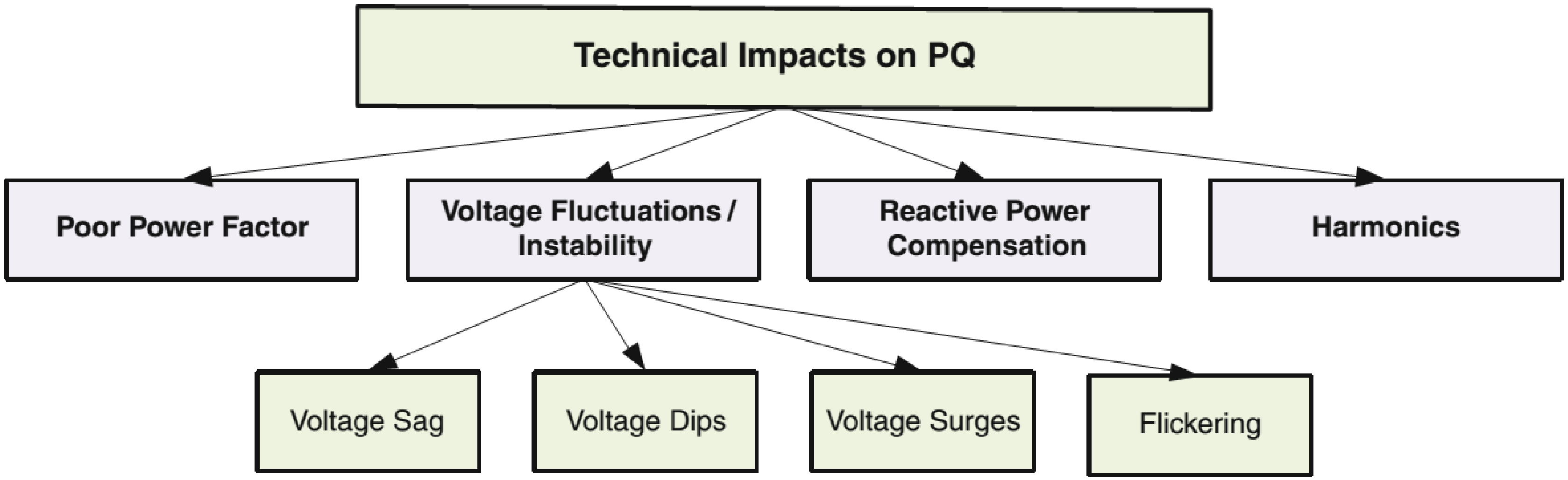
Time Frame Factors of Power System Dynamics



Impact of Renewable Energy into the Grid

- Integration of large-scale distributed energy resources in particular wind and solar energy with adequate PQ into the grid is a challenging task due to the intermittent and weather-dependent nature of these resources.
- The integration of variable generation sources presents unique challenges on system performance, and the key factors include:
  - RE generator design parameters and power movers’ type.
  - RE power generation’s expected types of run.
  - Position of the RE plant’s connection to the grid.
  - Variability in production of RE sources with changing weather conditions.
  - Characteristics of the grid including the loads connected to it

Major Potential Technical Impacts of Integrating RE into the Grid



Technical Impacts on PQ

Poor Power Factor

Voltage Fluctuations / Instability

Reactive Power Compensation

Harmonics

Voltage Sag

Voltage Dips

Voltage Surges

Flickering

Renewable Energy Integration

- Frequency stability:
  - Renewable energy sources are often connected via a converter interface and have no inertia (as seen from the grid)
  - Replacing synchronous generators with sources using a converter interface therefore reduces total system inertia and is more sensitive to frequency deviations
  - Thermal generators may run under minimum load if displaced by renewable energy sources

Potential Mitigation Measures

- Minimum system inertia, i.e. minimum number of synchronous generators online (spinning reserve)
- Under-frequency load shedding
- Energy storage with fast response
- Demand side management (DSM), i.e. smart grid technologies

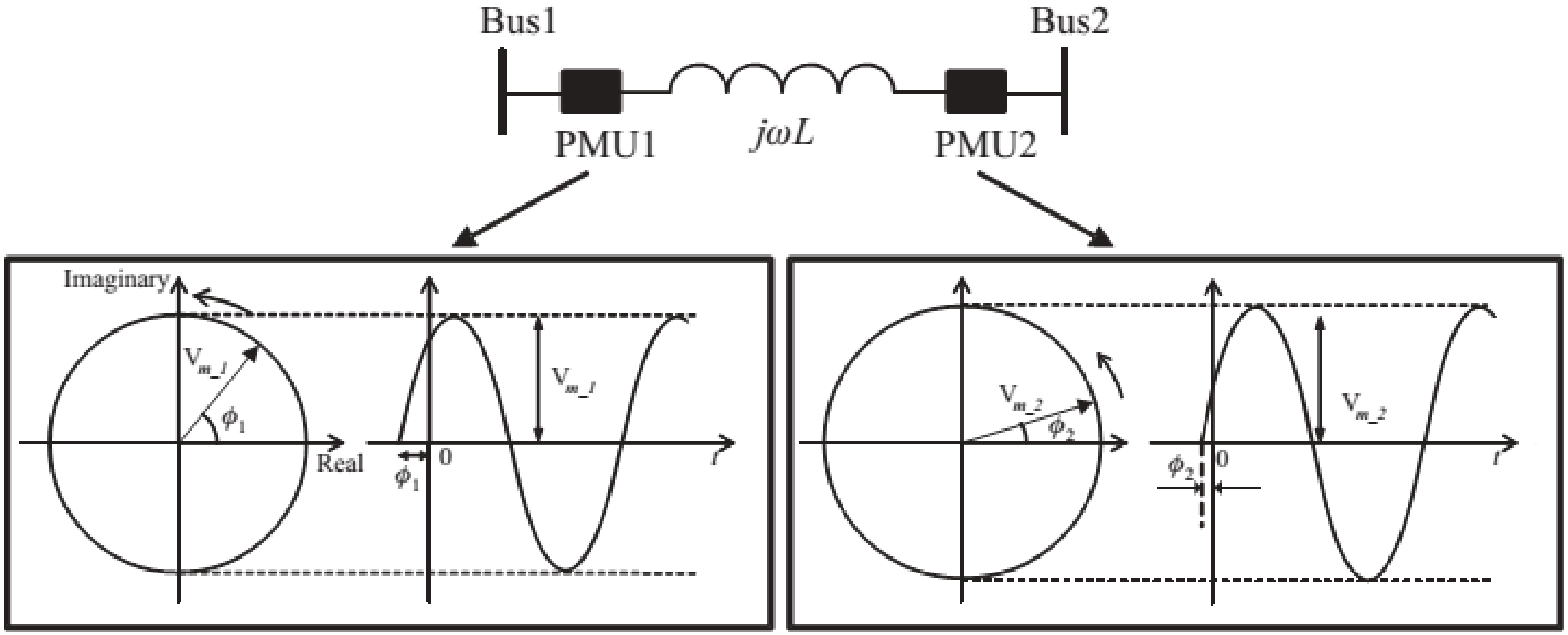
Reliable Power Grid Operation

- Load demand is controlled by the consumers and may change randomly
- Generation must match this demand (and losses) instant by instant
- An elaborate system of controls is put in place at generators and at Energy Management Centres on the power grid
- Controls must take into account the possibility of faults in the system due to natural disasters, equipment failure, or man-made disasters
- The power grid must continue to meet the demands of consumers with minimum interruptions when faced with such contingencies

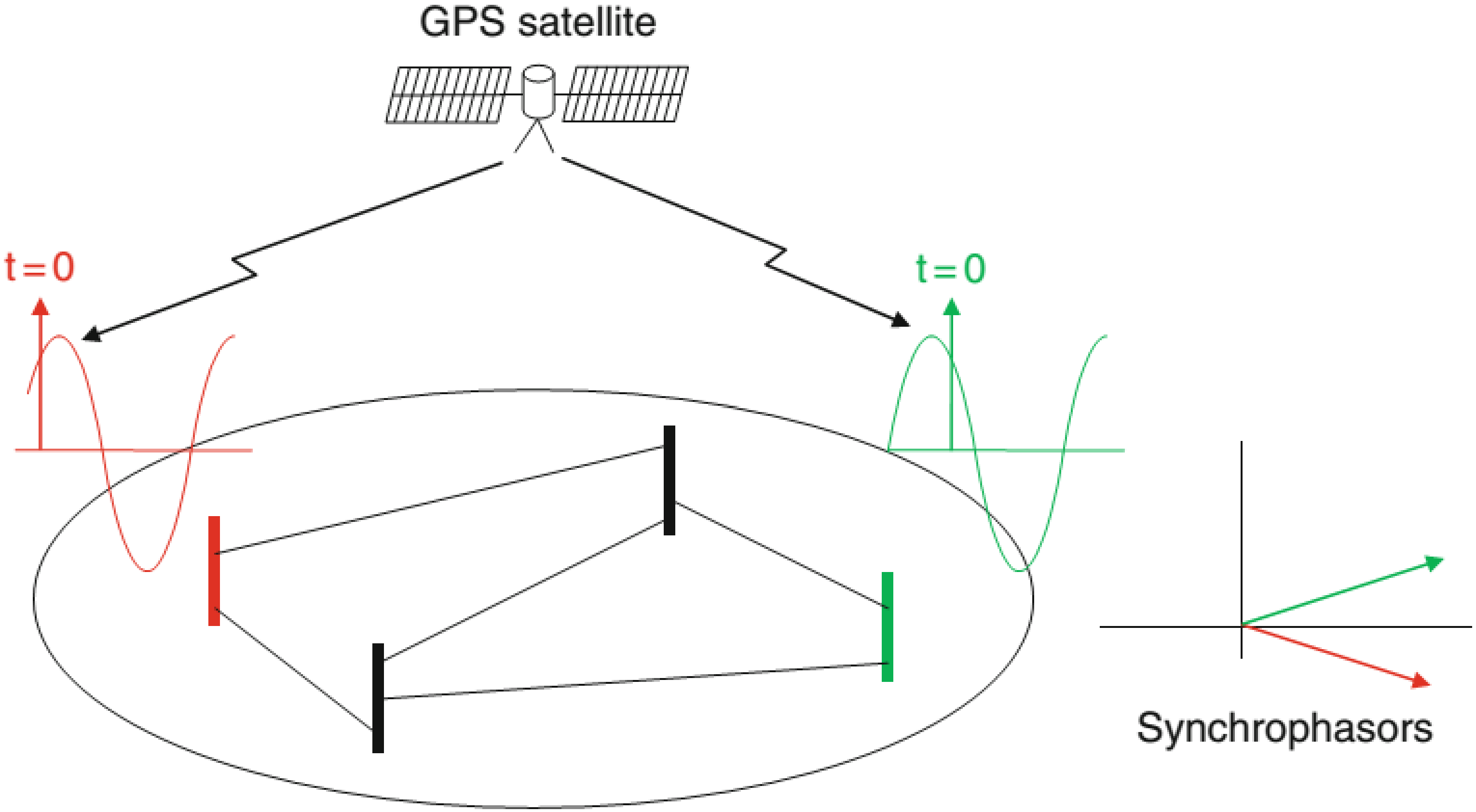
Power System State Estimation

- In order to deal with contingencies, system operators are made aware of the condition of the power infrastructure accurately at all times
- This is achieved through a system of measurements made on the power grid at frequent intervals, from which the network flows and voltages are estimated
- Process is known as “state estimation” of the power system
- The ability of the power system to meet its loads in the presence of contingencies is much enhanced if the state of the system is known precisely and with sufficient frequency so that as the transmission system, loads, and generation change during the day, the changes are tracked accurately by the measurement process

Waveforms and Phasors of Busbar Voltages



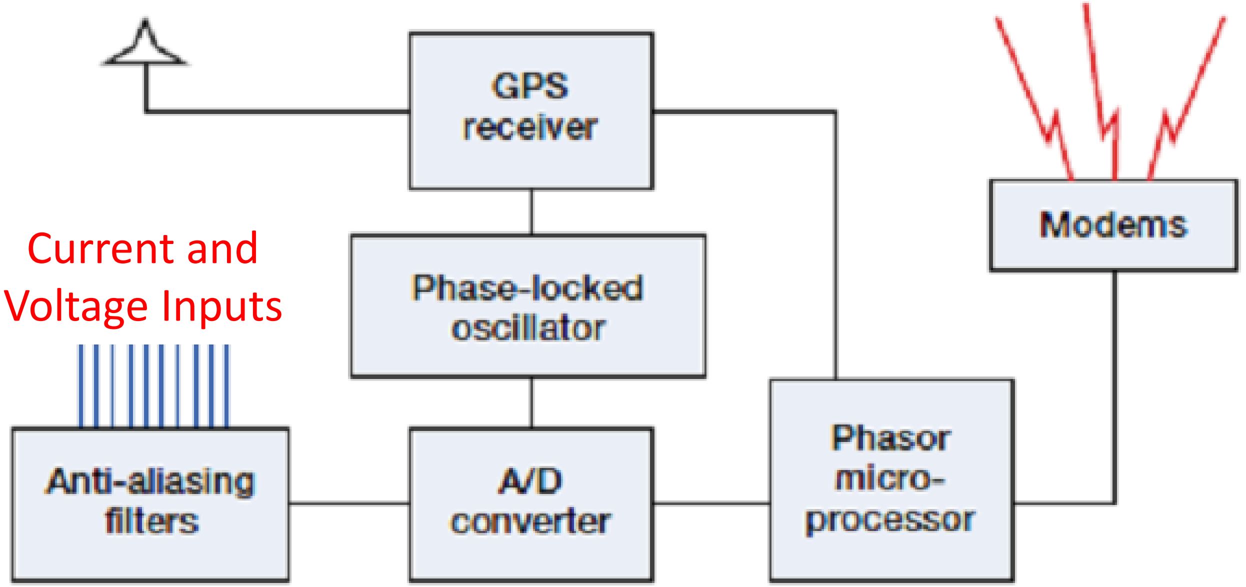
Voltages and Currents in Substations At Different Locations



Phasor Measurement Unit (PMU)

- Synchrophasors are measured by Phasor Measurement Units (PMU) installed in power system substations
- Currents and voltages from the power system are measured and the phasors are time synchronised by using the time reference from a GPS receiver
- The phasor measurements are transmitted over a suitable communication network in real-time to a phasor data concentrator (PDC)
- The synchrophasor measurements are used to perform the state estimation

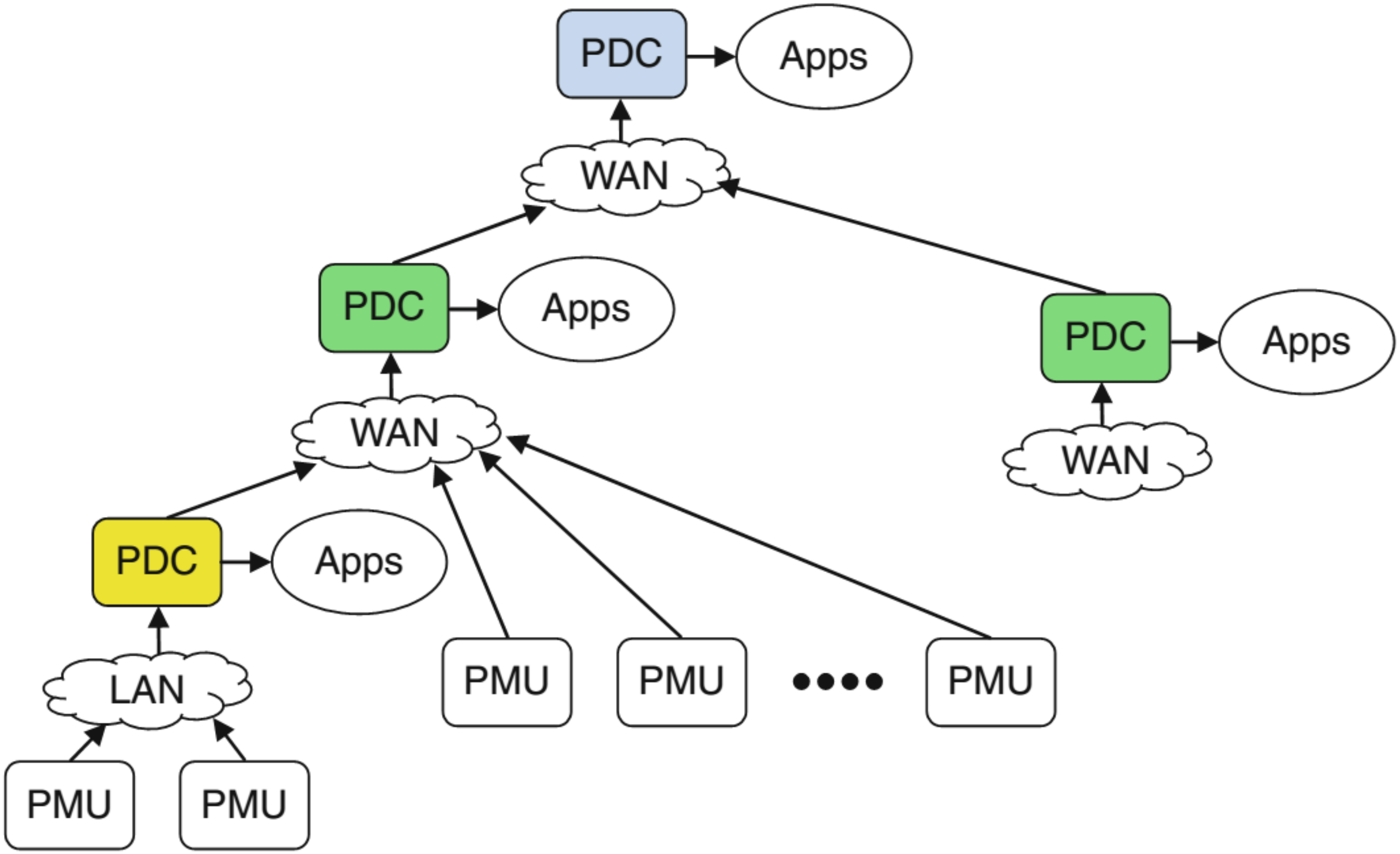
Simplified Block Diagram of a PMU



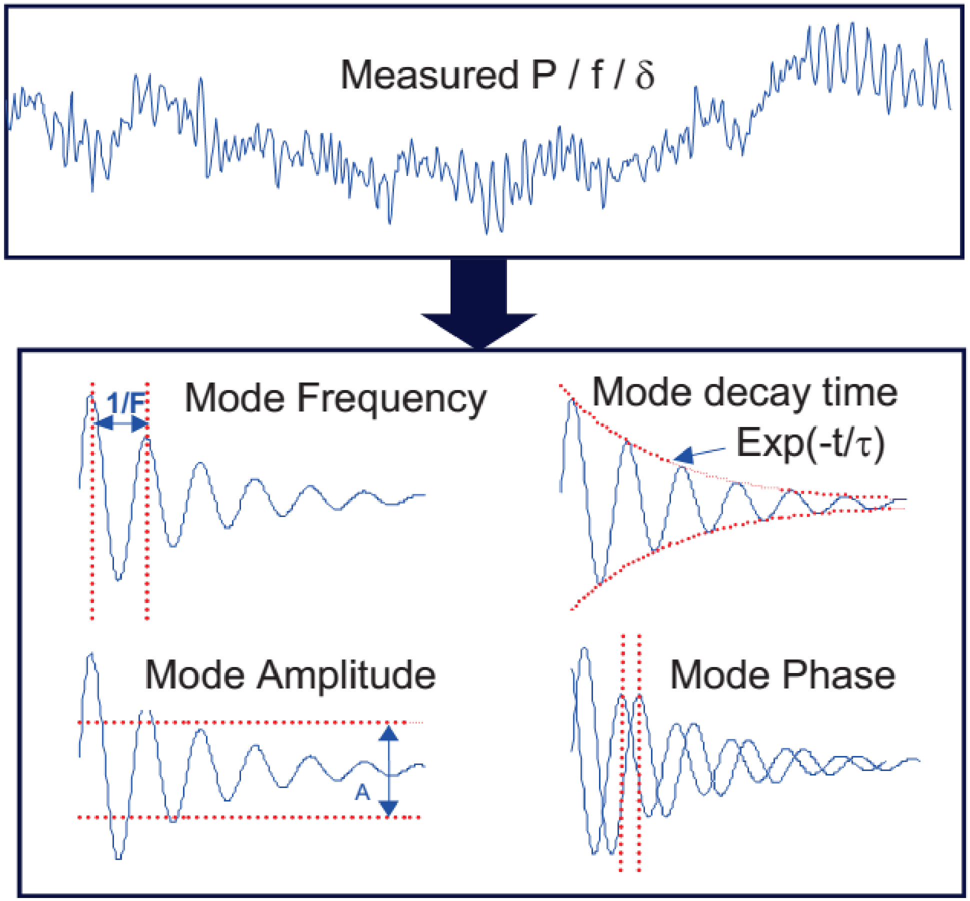
Time synchronised Phasor

Current and Voltage Inputs

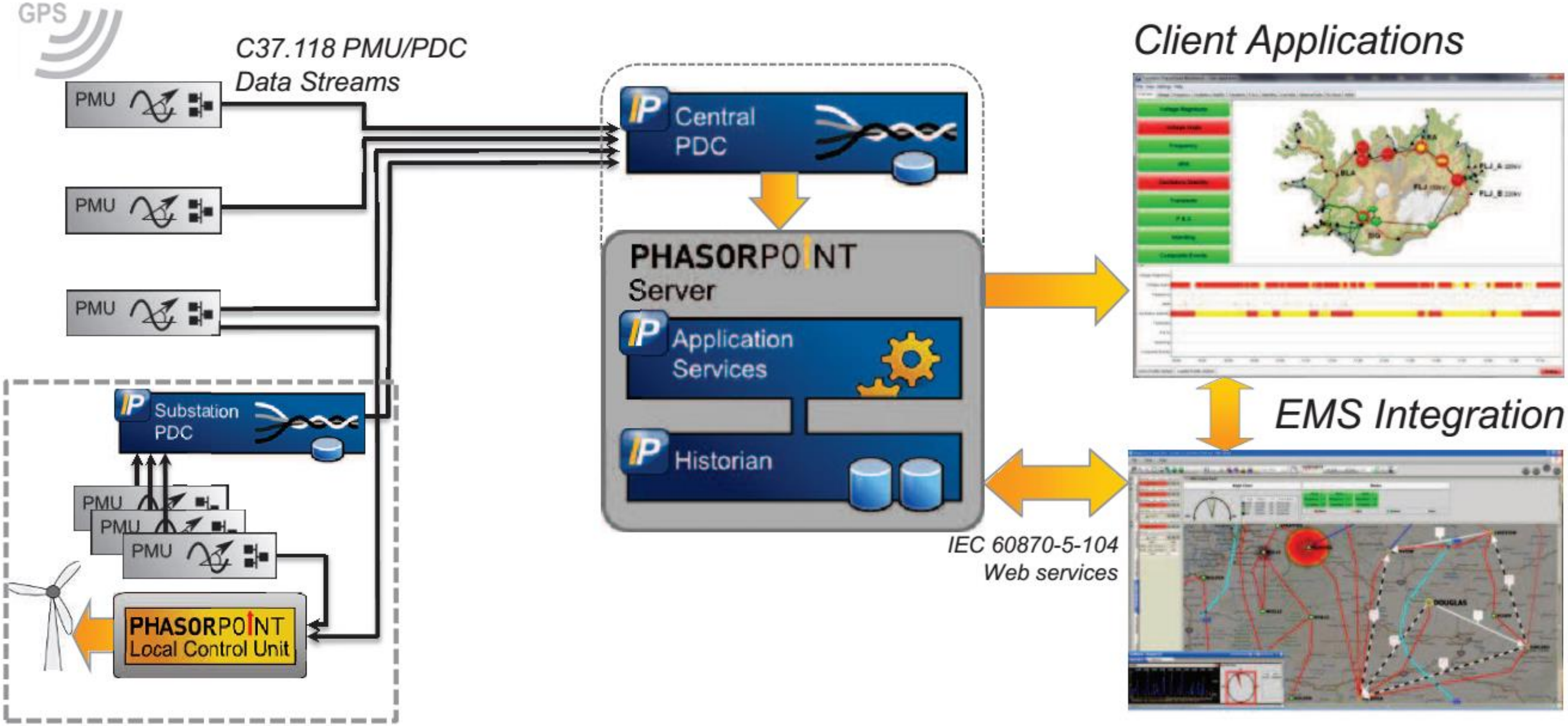
Wide Area Measurement System (WAMS)



Extraction of Dynamic Parameters from PMU-based Signals



Wide Area Monitoring, Protection and Control Solutions



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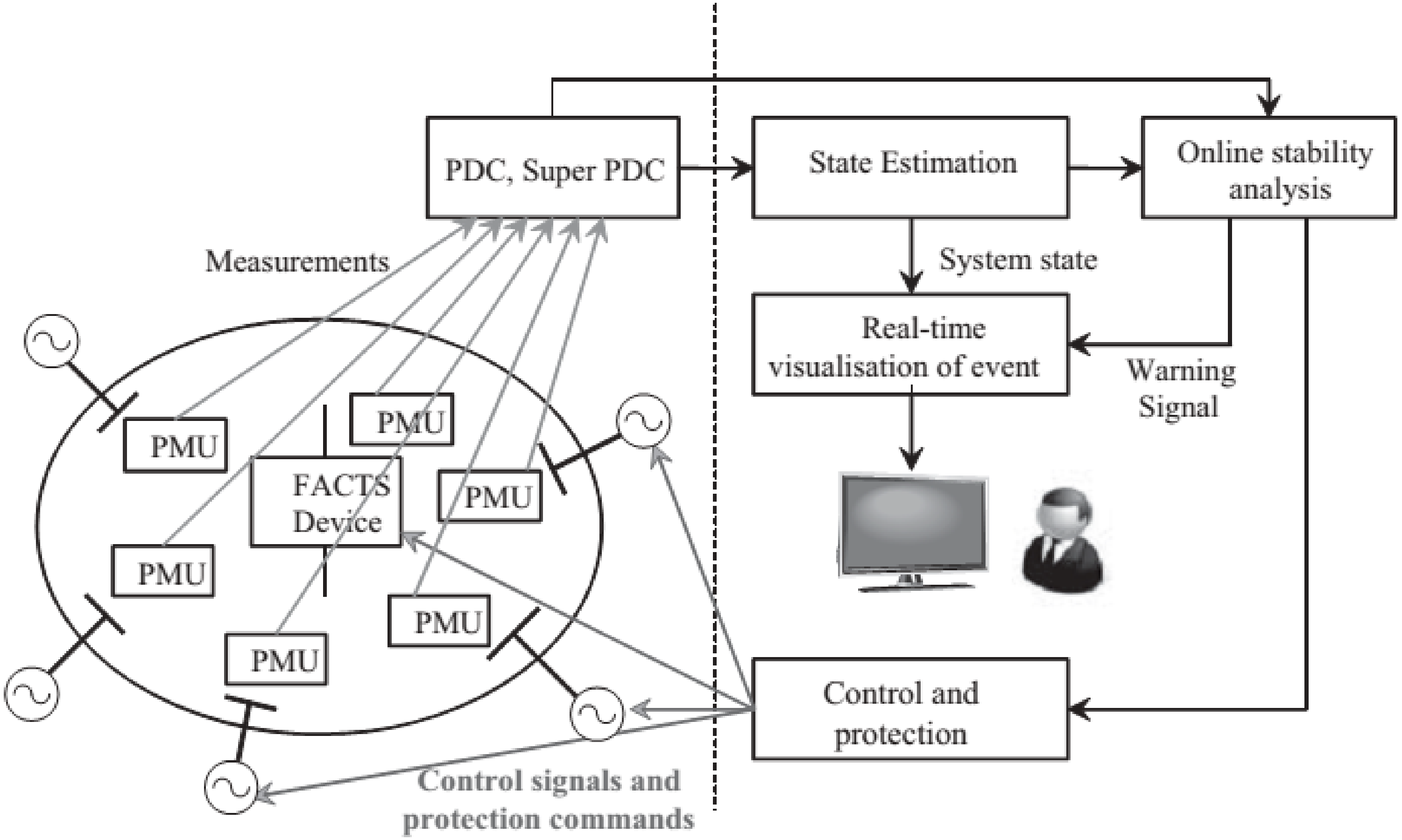
Add Protection and Control



WAMS for Control Purposes

- The design of WAMS for control purposes must take account of:
  - Signal delays and variability due to the non-deterministic nature of IP communications
  - Total delay in measurement through to delivery of the control signal
  - Robustness and redundancy
  - Complexity of wide-area control over local control

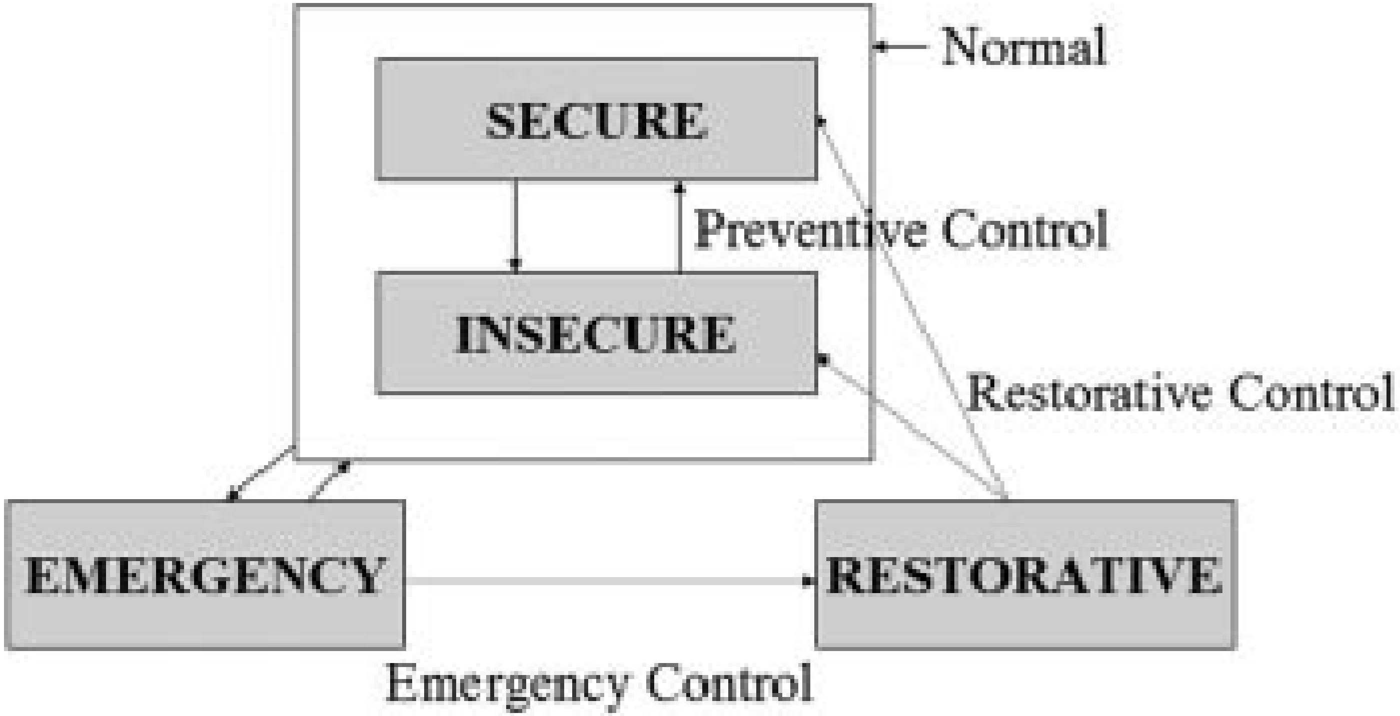
Wide Area Monitoring, Protection and Control (WAMPAC) Applications

- To initiate actions to correct the system once a voltage, angle or oscillatory instability has been predicted.
- This may include switching of generators and controlling devices such as the Flexible AC transmission Systems (FACTS), the Power System Stabilisers (PSS) and HVDC converters.
- To generate emergency control signals to avoid a large-scale blackout (for example, through selective shedding of load or temporary splitting of the network) in the event of a severe fault

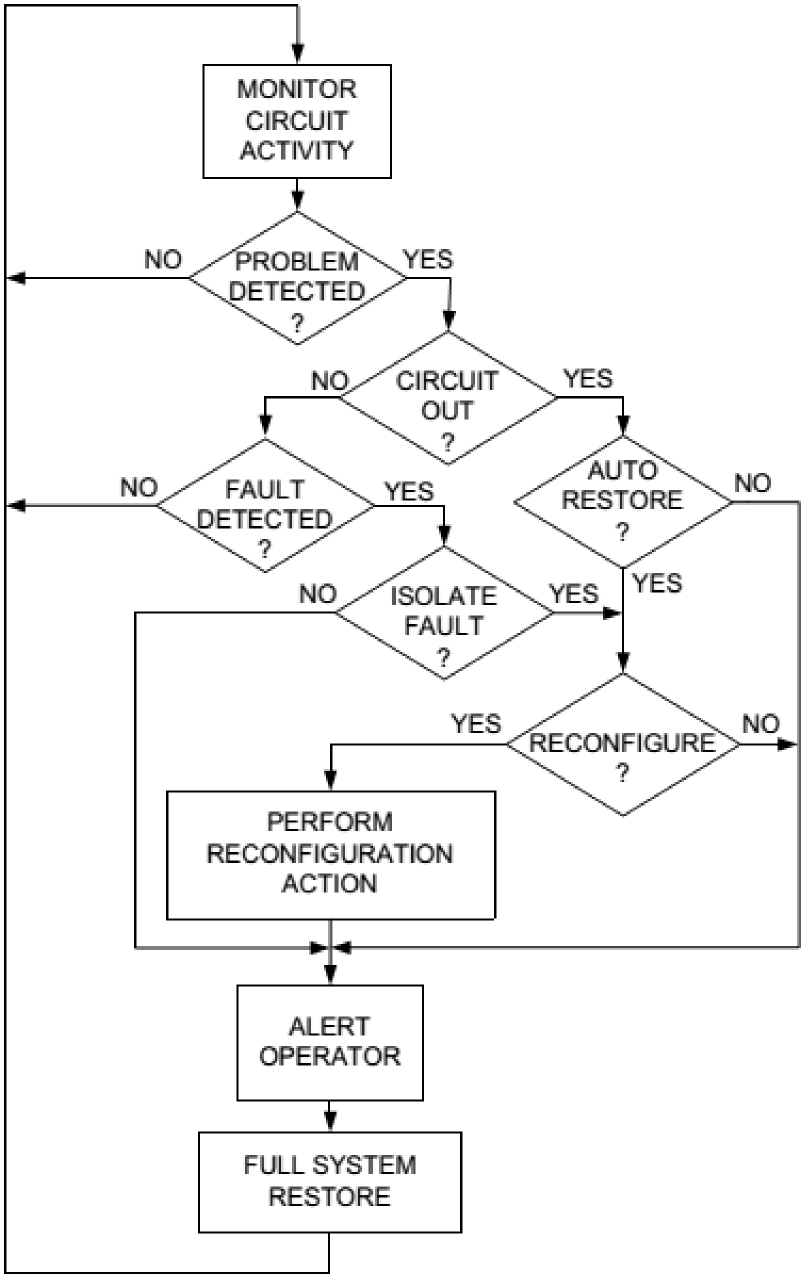
Security Assessment and Control

- This application exercises control to keep the power system in a secure state
- The Dy Liacco framework considers the power system as being operated under two types of constraint:
  - load constraints (load demand must be met)
  - operating constraints (maximum and minimum operating limits together with stability limits should be respected).
- In the normal state, both these constraints are satisfied.

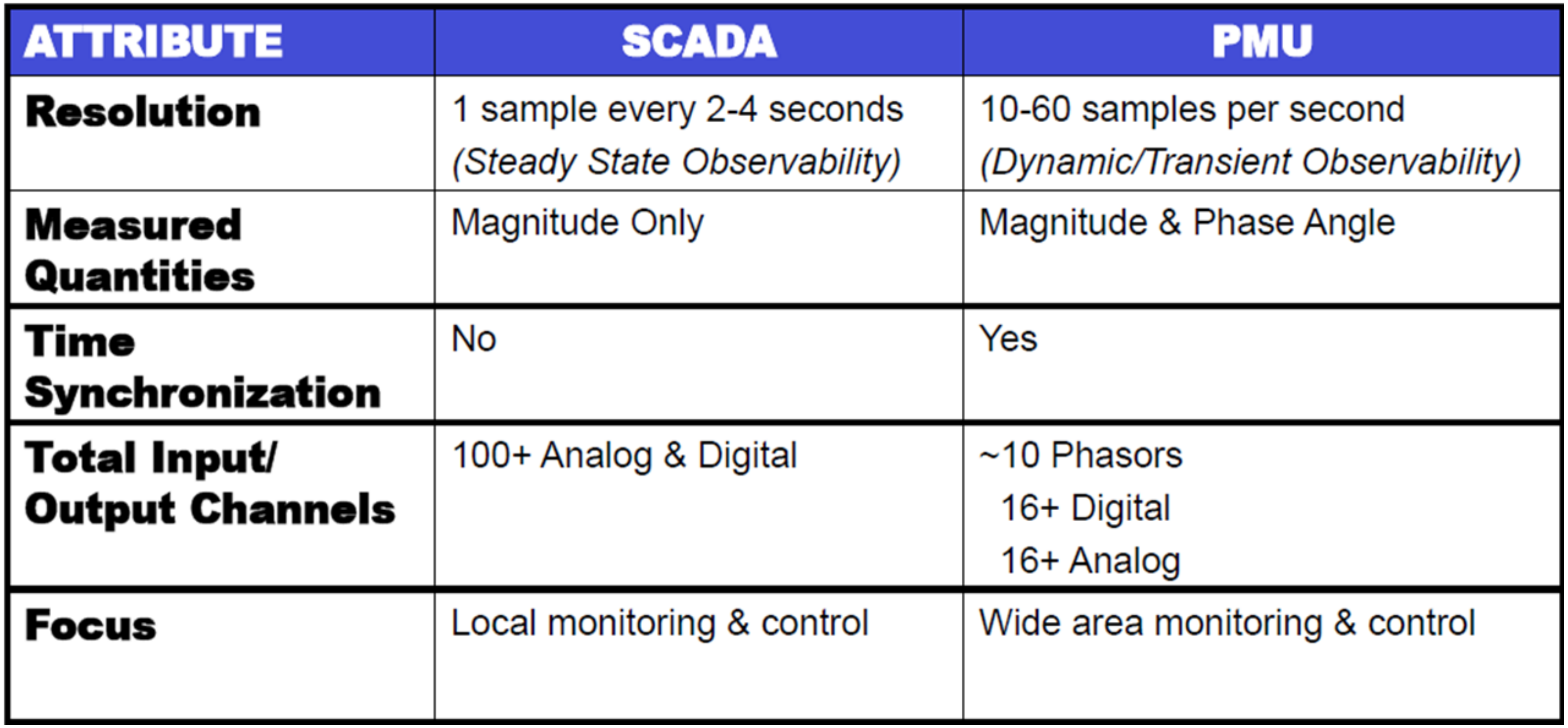
Dy Liacco Framework for Security Assessment and Control



Automated Restoration and Reconfiguration Algorithm

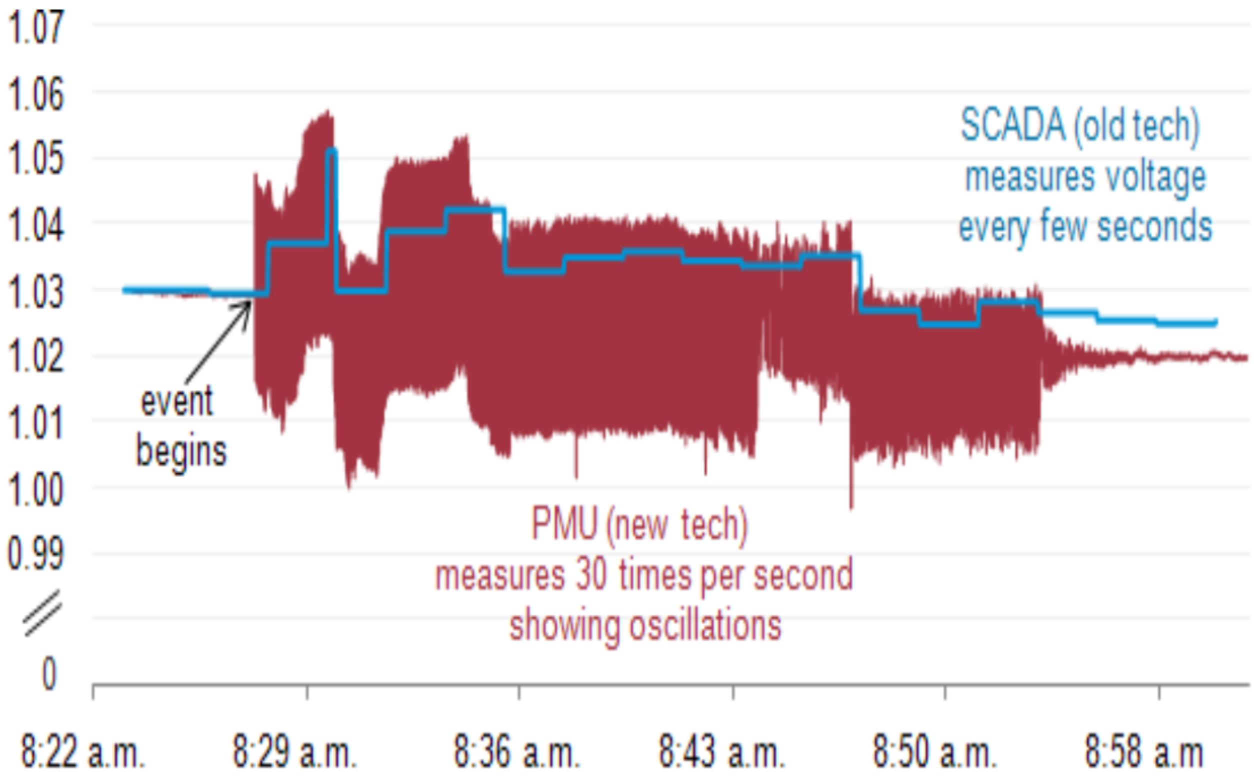


Wide Area Monitoring: PMU vs. SCADA



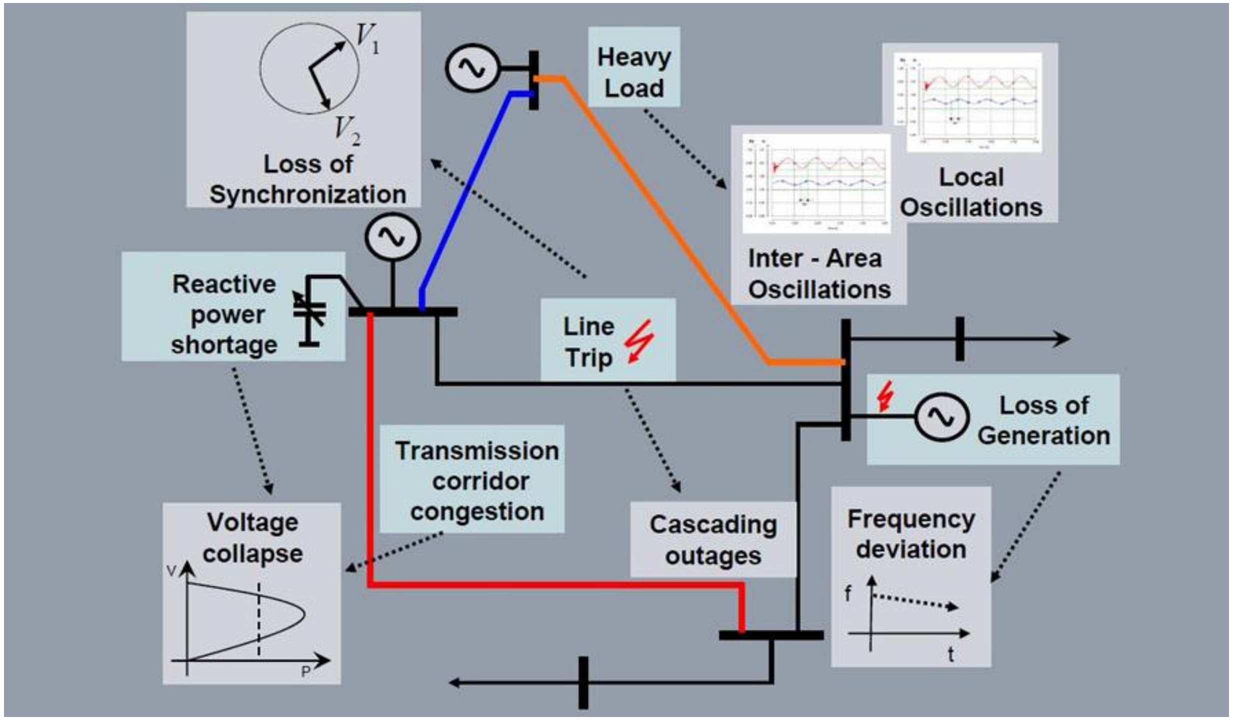
ATTRIBUTE	SCADA	PMU
Resolution	1 sample every 2-4 seconds *(Steady State Observability)*	10-60 samples per second *(Dynamic/Transient Observability)*
Measured Quantities	Magnitude Only	Magnitude & Phase Angle
Time Synchronization	No	Yes
Total Input/ Output Channels	100+ Analog & Digital	~10 Phasors 16+ Digital 16+ Analog
Focus	Local monitoring & control	Wide area monitoring & control

Wide Area Monitoring (WAMS)
SCADA vs. PMU Measurement

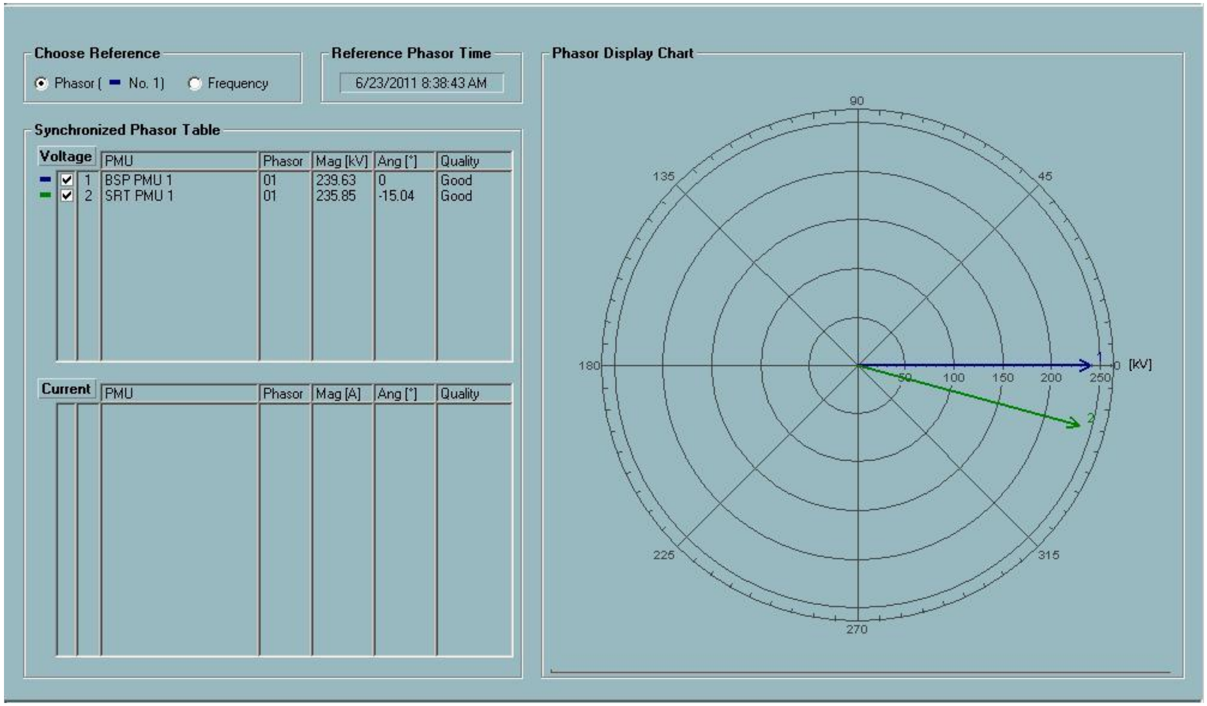


Wide Area Monitoring (WAMS) Real time Application

- Phase Angle Monitoring
- Voltage Stability Monitoring
- Power Oscillation Monitoring



WAMS Application Example: Phase Angle Monitoring



Choose Reference

● Phasor (▬ No. 1) ○ Frequency

Reference Phasor Time

6/23/2011 8:38:43 AM

Synchronized Phasor Table

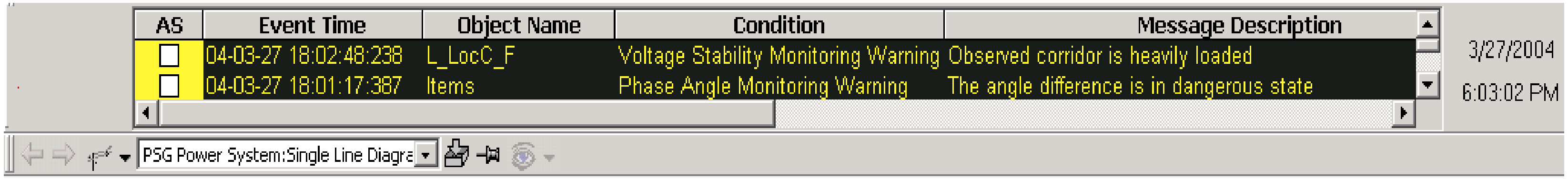
Voltage			PMU	Phasor	Mag [kV]	Ang [°]	Quality
▬	☑	1	BSP PMU 1	01	239.63	0	Good
▬	☑	2	SRT PMU 1	01	235.85	-15.04	Good

Current			PMU	Phasor	Mag [A]	Ang [°]	Quality

Benefits:

Provide operator with real time information about voltage phase angle deviation, Improve voltage control, improve system stability, security and reliability , and operate safety carrying components closer to their limit

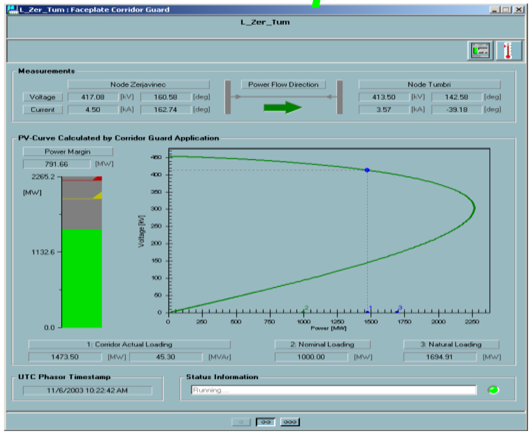
WAMS Application Example: Voltage Stability Monitoring



AS	Event Time	Object Name	Condition	Message Description
☐	04-03-27 18:02:48:238	L_LocC_F	Voltage Stability Monitoring Warning	Observed corridor is heavily loaded
☐	04-03-27 18:01:17:387	Items	Phase Angle Monitoring Warning	The angle difference is in dangerous state

3/27/2004
6:03:02 PM

Normal Operation



L_Zer_Tum : Faceplate Corridor Guard

L_Zer_Tum

Measurements

	Node Zerjavinec				Node Tumbri			
Voltage	417.08	[kV]	160.58	[deg]	413.50	[kV]	142.58	[deg]
Current	4.50	[kA]	162.74	[deg]	3.57	[kA]	-39.18	[deg]

PV-Curve Calculated by Corridor Guard Application

Power Margin: 791.66 [MW]

1: Corridor Actual Loading: 1473.50 [MW] 45.30 [MVAr]

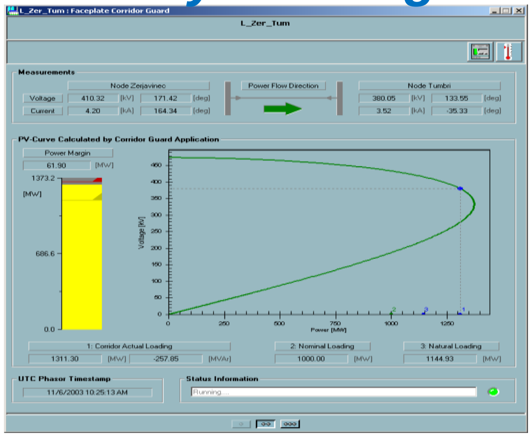
2: Nominal Loading: 1000.00 [MW]

3: Natural Loading: 1694.91 [MW]

UTC Phasor Timestamp: 11/6/2003 10:22:42 AM

Status Information: Running....

Early warning



L_Zer_Tum : Faceplate Corridor Guard

L_Zer_Tum

Measurements

	Node Zerjavinec				Node Tumbri			
Voltage	410.32	[kV]	171.42	[deg]	380.05	[kV]	133.55	[deg]
Current	4.20	[kA]	164.34	[deg]	3.52	[kA]	-35.33	[deg]

PV-Curve Calculated by Corridor Guard Application

Power Margin: 61.90 [MW]

1: Corridor Actual Loading: 1311.30 [MW] -257.85 [MVAr]

2: Nominal Loading: 1000.00 [MW]

3: Natural Loading: 1144.93 [MW]

UTC Phasor Timestamp: 11/6/2003 10:25:13 AM

Status Information: Running....

Emergency alarm

L_Zer_Tum : Faceplate Corridor Guard

L_Zer_Tum

Measurements

	Node Zerjavinec				Node Tumbri			
Voltage	405.79	[kV]	-67.52	[deg]	341.91	[kV]	-110.04	[deg]
Current	4.38	[kA]	-84.07	[deg]	3.81	[kA]	78.33	[deg]

PV-Curve Calculated by Corridor Guard Application

Power Margin: 8.36 [MW]

1: Corridor Actual Loading: 1288.48 [MW] -189.65 [MVAr]

2: Nominal Loading: 1000.00 [MW]

3: Natural Loading: 1118.18 [MW]

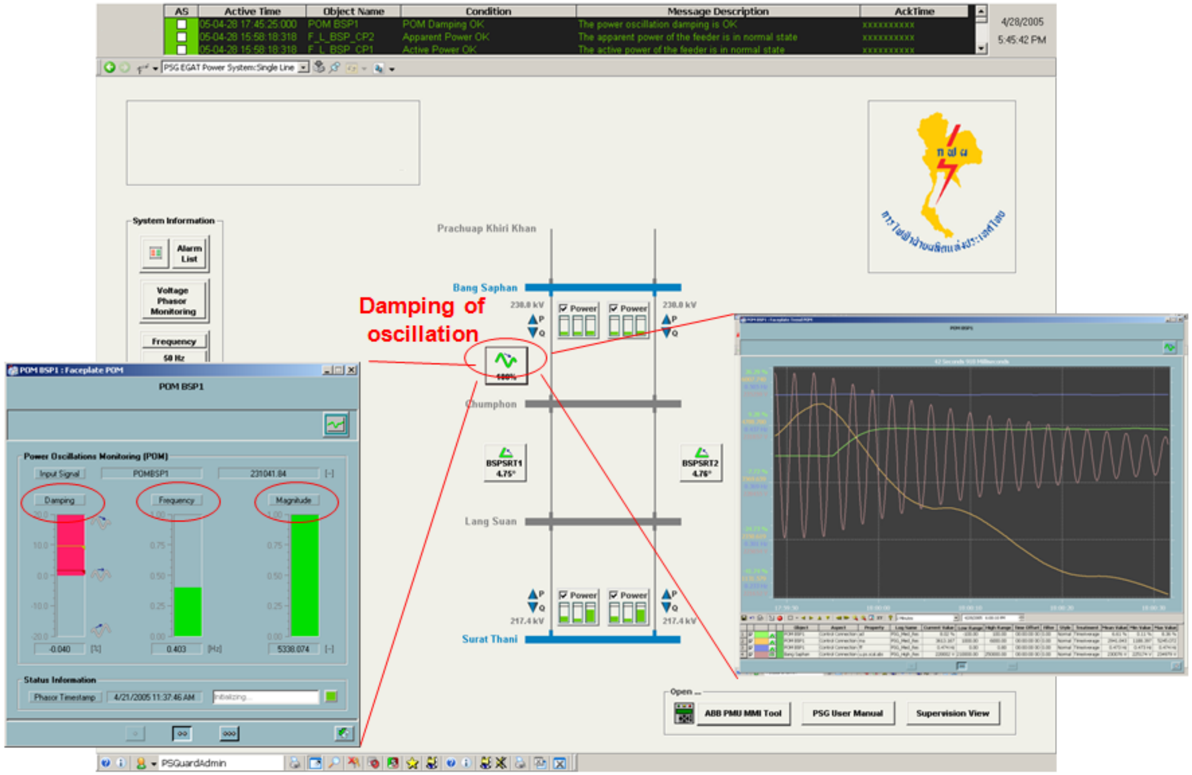
UTC Phasor Timestamp: 11/6/2003 11:38:51 AM

Status Information: Running....

Benefit:

Early warning against voltage collapses, Immediate stop of cascading effects, and Protection against uprising voltage instabilities.

WAMS Application Example: Power Oscillation Monitoring



AS	Active Time	Object Name	Condition	Message Description	AckTime
☐	05-04-28 17:45:25:000	POM BSP1	POM Damping OK	The power oscillation damping is OK	xxxxxxxxxx
☐	05-04-28 15:58:18:318	F_L_BSP_CP2	Apparent Power OK	The apparent power of the feeder is in normal state	xxxxxxxxxx
☐	05-04-28 15:58:18:318	F_L_BSP_CP1	Active Power OK	The active power of the feeder is in normal state	xxxxxxxxxx

4/28/2005
5:45:42 PM

PSG EGAT Power System:Single Line

POM BSP1 : Faceplate POM

POM BSP1

Power Oscillations Monitoring (POM)

Input Signal: POMBSP1 231041.84 [-]

Damping: -0.040 [%]

Frequency: 0.403 [Hz]

Magnitude: 5338.074 [-]

Status Information

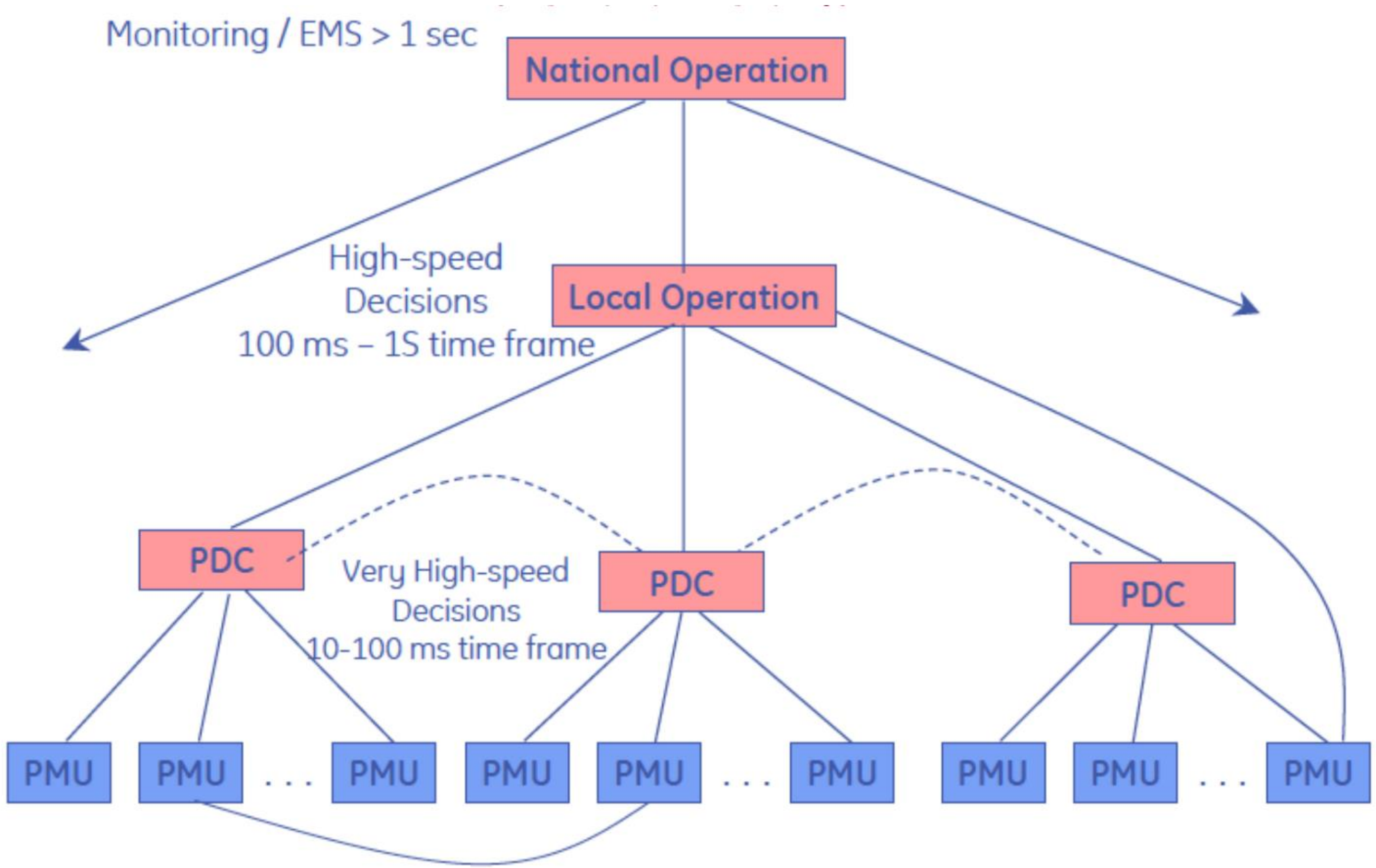
Phasor Timestamp: 4/21/2005 11:37:46 AM Initializing...

Damping of oscillation

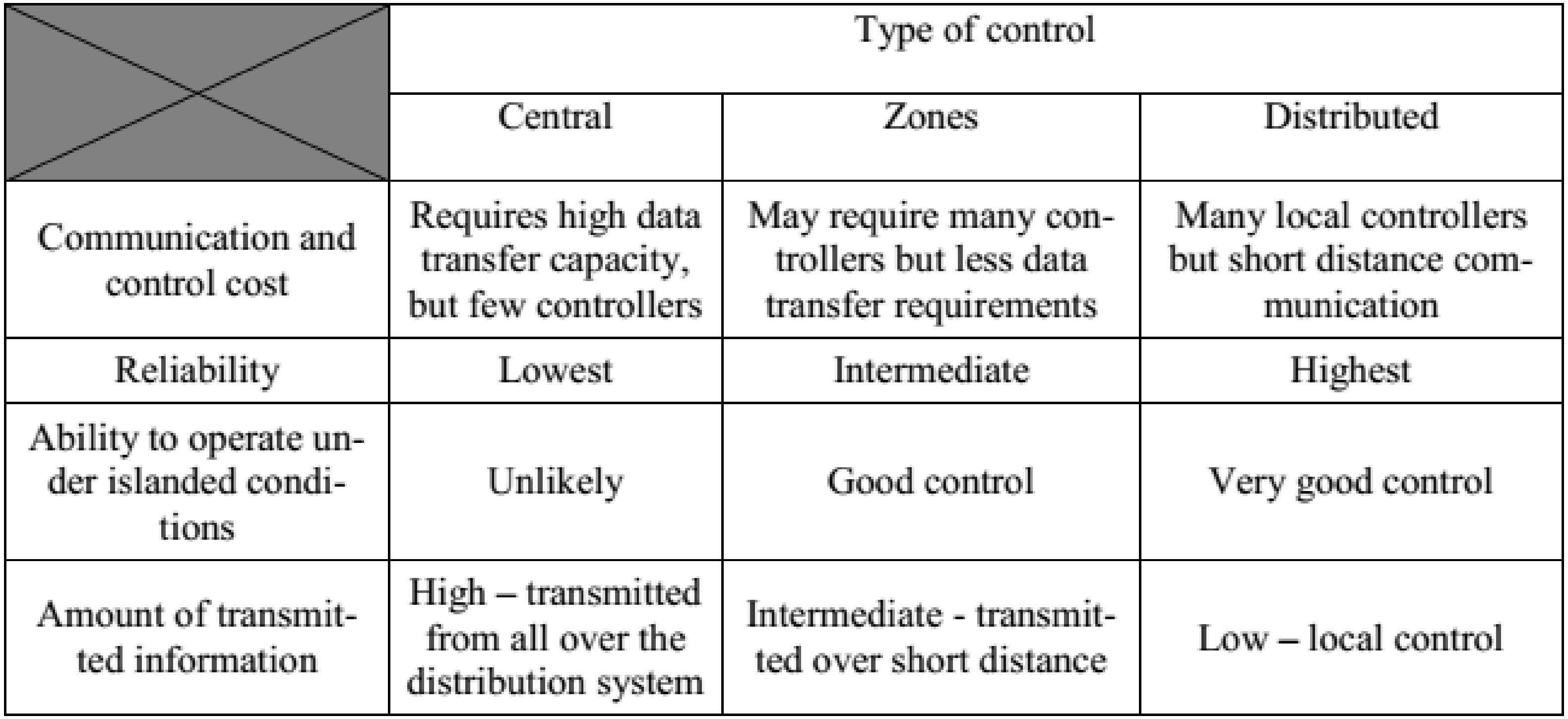
WAMS Benefit:

Detection of oscillation, Assessment of power system damping, Increase power transfer at defined security, and Early warning to avoid power system collapse.

PMU Network Architecture



Distribution System Control and Communications Infrastructure



	Type of control		
	Central	Zones	Distributed
Communication and control cost	Requires high data transfer capacity, but few controllers	May require many controllers but less data transfer requirements	Many local controllers but short distance communication
Reliability	Lowest	Intermediate	Highest
Ability to operate under islanded conditions	Unlikely	Good control	Very good control
Amount of transmitted information	High – transmitted from all over the distribution system	Intermediate - transmitted over short distance	Low – local control

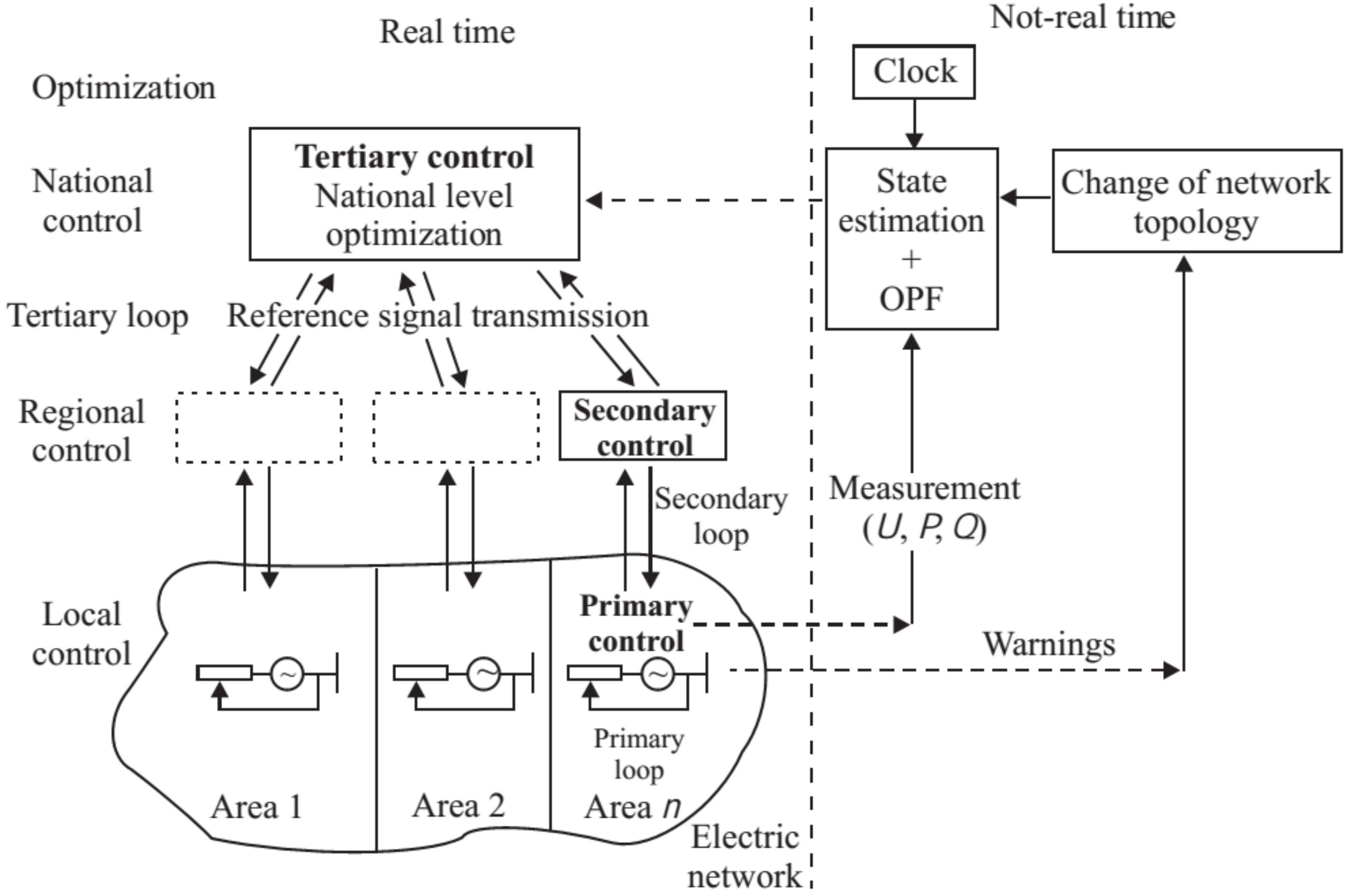
Operating Voltage

- The operating state of power system changes dynamically due to severe change in system conditions such generation, load or line trip.
- Such severe disturbances effect voltage phasor, current phasor and system frequency.
- To improve the monitoring of the dynamics of large power system, wide area synchronized monitoring of voltage phasor, current phasor and system frequency is vital.
- For efficient real time monitoring and operation of power system, high resolution based PMUs should be used

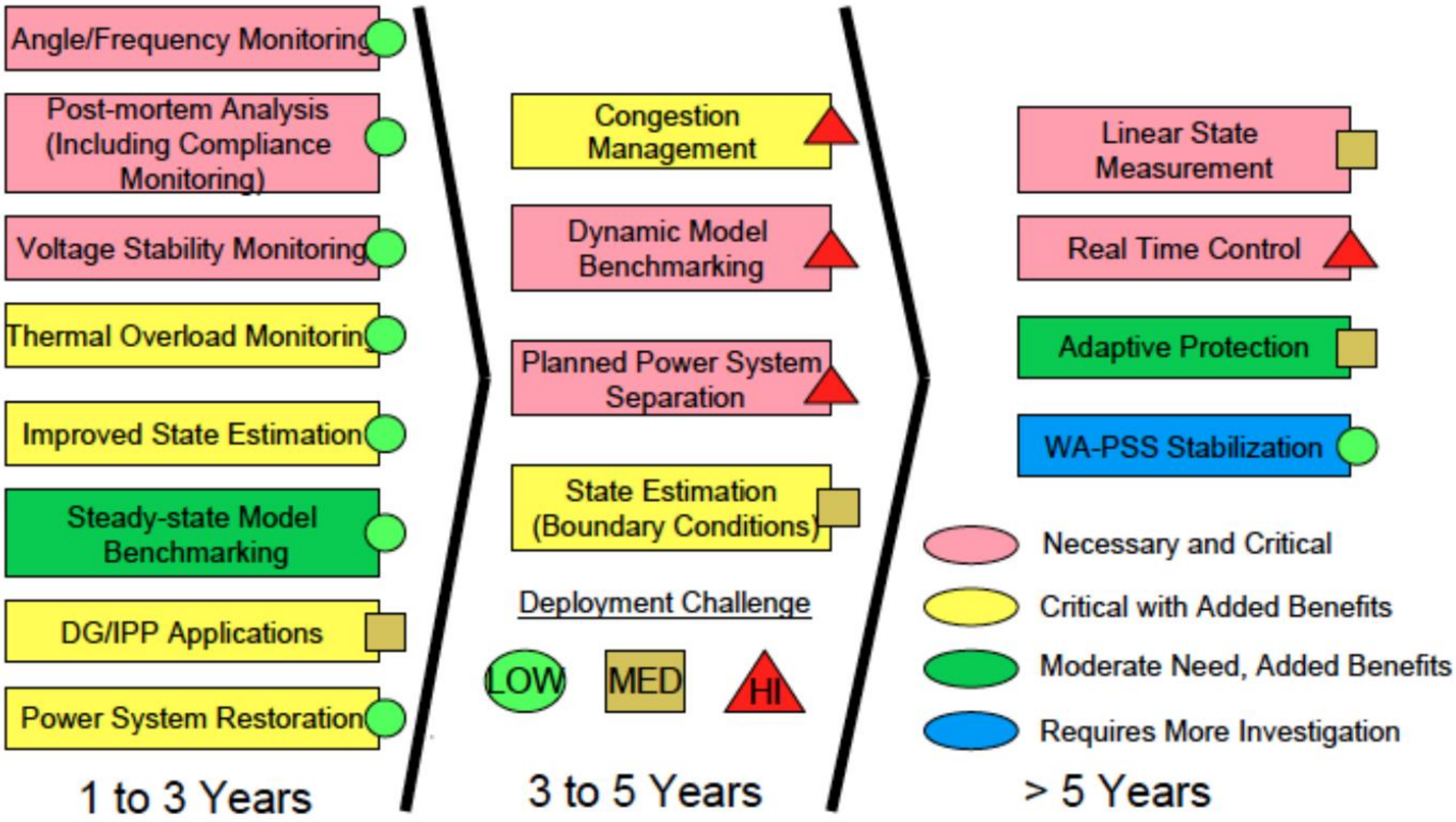
Voltage and Reactive Power Control

- Reactive power–voltage control is indispensable in power systems either under normal or in emergency conditions.
- During the normal operation it ensures the transmission of electrical energy at the required voltage quality and in the most convenient conditions for the suppliers and users.
- Under emergency conditions, the role of voltage control is to increase system security by enlarging the margin with respect to the system voltage instability limits, therefore ensuring continuity in the system operation and proper operating conditions for the largest number of consumers

Hierarchical Voltage – Reactive Power Control



PMU Applications



1 to 3 Years

- Angle/Frequency Monitoring ●
- Post-mortem Analysis (Including Compliance Monitoring) ●
- Voltage Stability Monitoring ●
- Thermal Overload Monitoring ●
- Improved State Estimation ●
- Steady-state Model Benchmarking ●
- DG/IPP Applications ■
- Power System Restoration ●

3 to 5 Years

- Congestion Management ▲
- Dynamic Model Benchmarking ▲
- Planned Power System Separation ▲
- State Estimation (Boundary Conditions) ■

Deployment Challenge

LOW MED HI

> 5 Years

- Linear State Measurement ■
- Real Time Control ▲
- Adaptive Protection ■
- WA-PSS Stabilization ●

⬭ Necessary and Critical

⬭ Critical with Added Benefits

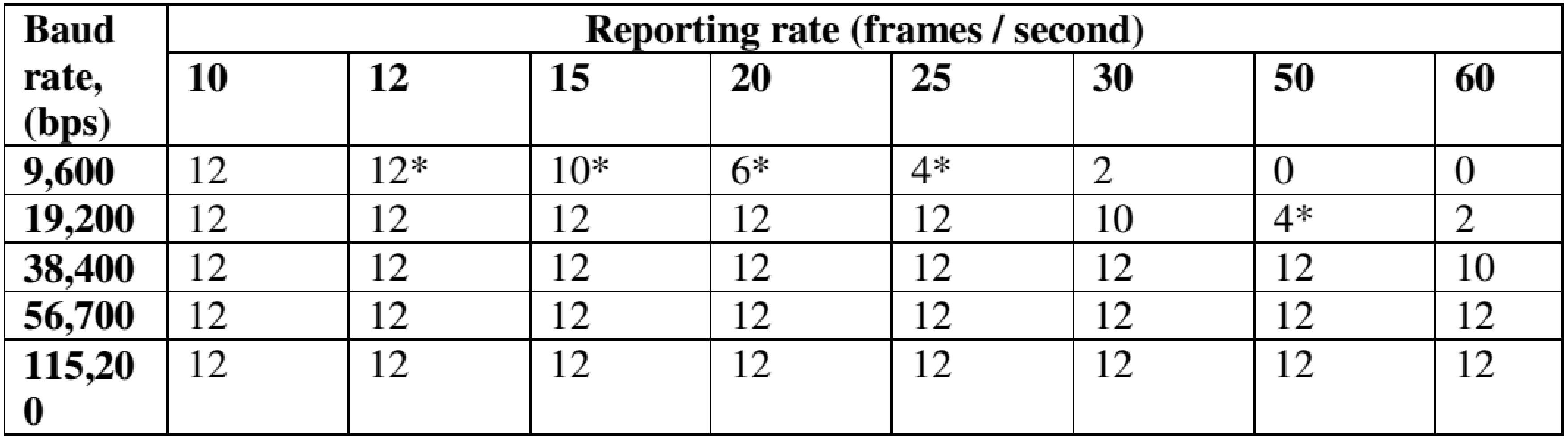
⬭ Moderate Need, Added Benefits

⬭ Requires More Investigation

PMU Communication Protocol

- Synchrophasor standard IEEE C37.118 defines the concept of “frames” for transmitting data from a PMU to a PDC.
- The standard does not impose any restriction on the communication media itself.
- Basically a Configuration frame, Data frame, Header frame and a Command frame are specified which have a particular structure and data type associated with them
- The Data frame is the most frequently transmitted message based on the PMU sample rate, and the typical size is of the order of few hundreds of bytes
- The reporting rate is determined by the communication channel bandwidth

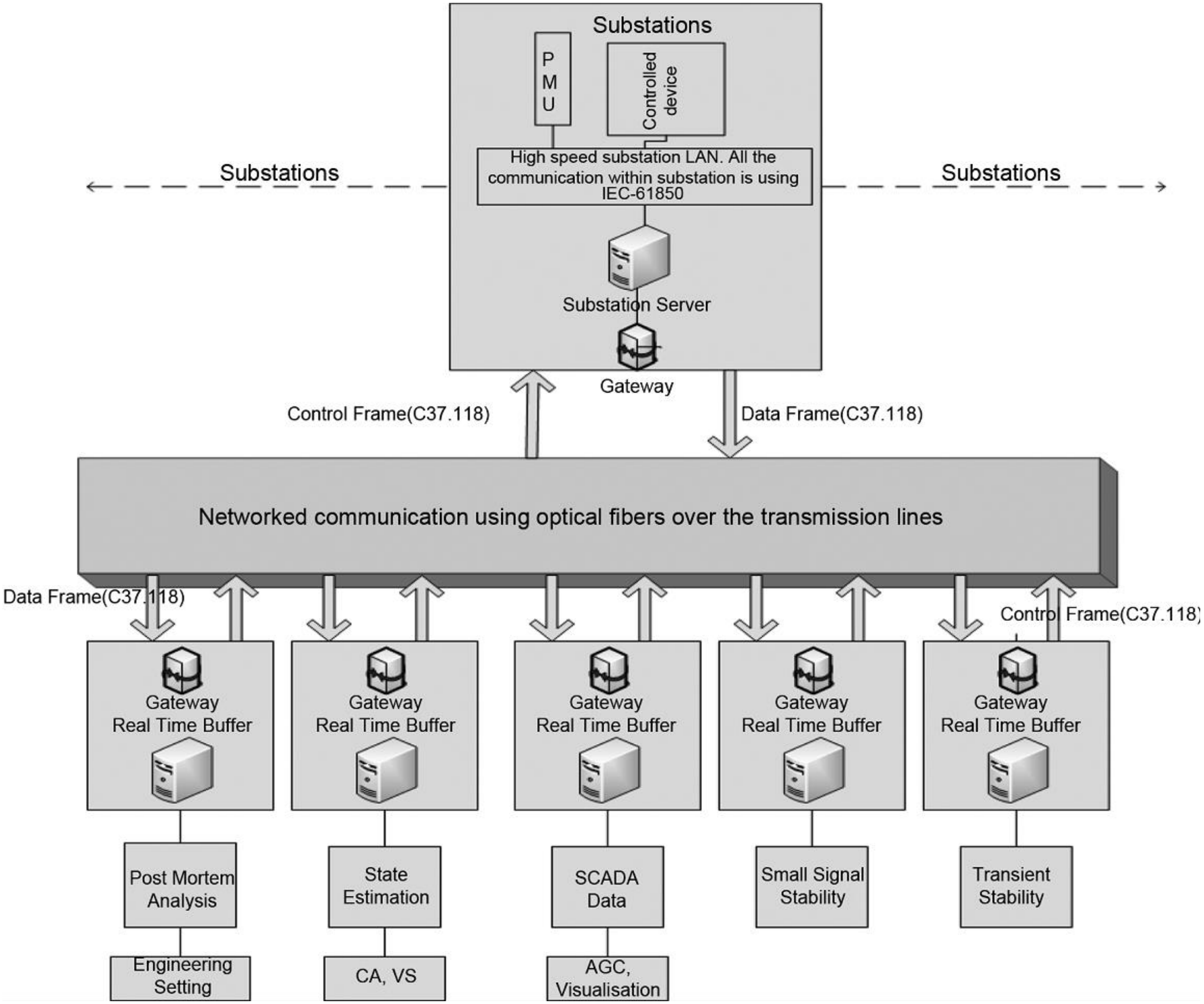
Phasor Channels, Reporting Rate and Channel Bandwidth



Baud rate, (bps)	**Reporting rate (frames / second)**							
	10	**12**	**15**	**20**	**25**	**30**	**50**	**60**
9,600	12	12*	10*	6*	4*	2	0	0
19,200	12	12	12	12	12	10	4*	2
38,400	12	12	12	12	12	12	12	10
56,700	12	12	12	12	12	12	12	12
115,200	12	12	12	12	12	12	12	12

* Indicates at bandwidth limit – number of channels may be less

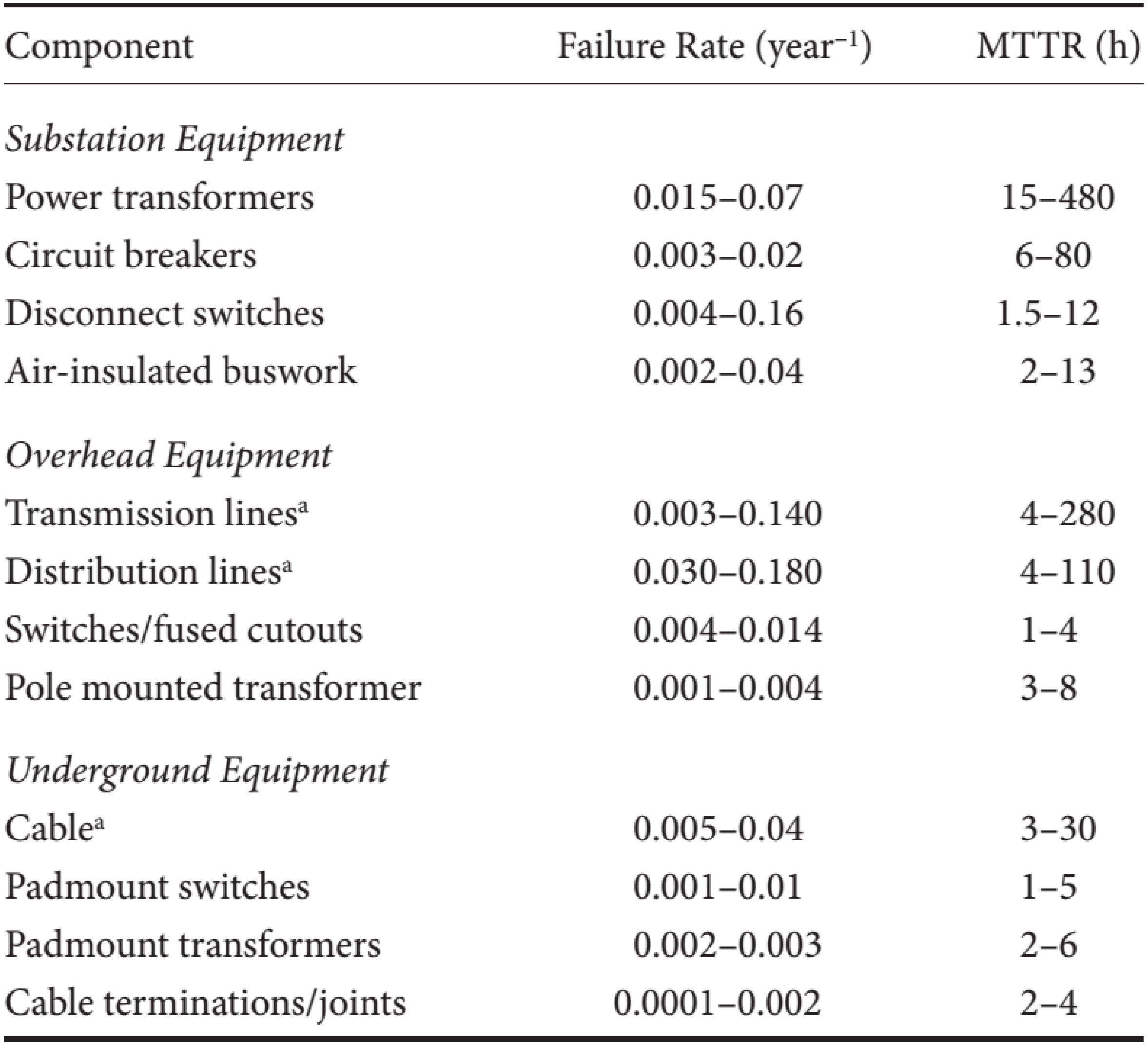
Communication Architecture



Real-time Information vs. Data Collection

- Real-time information can be used for:
  - Operations and control
  - Identification of faults
  - Equipment performance and predictive maintenance
- Historic data for post event analysis, data mining and statistical processing

PS Equipment Reliability

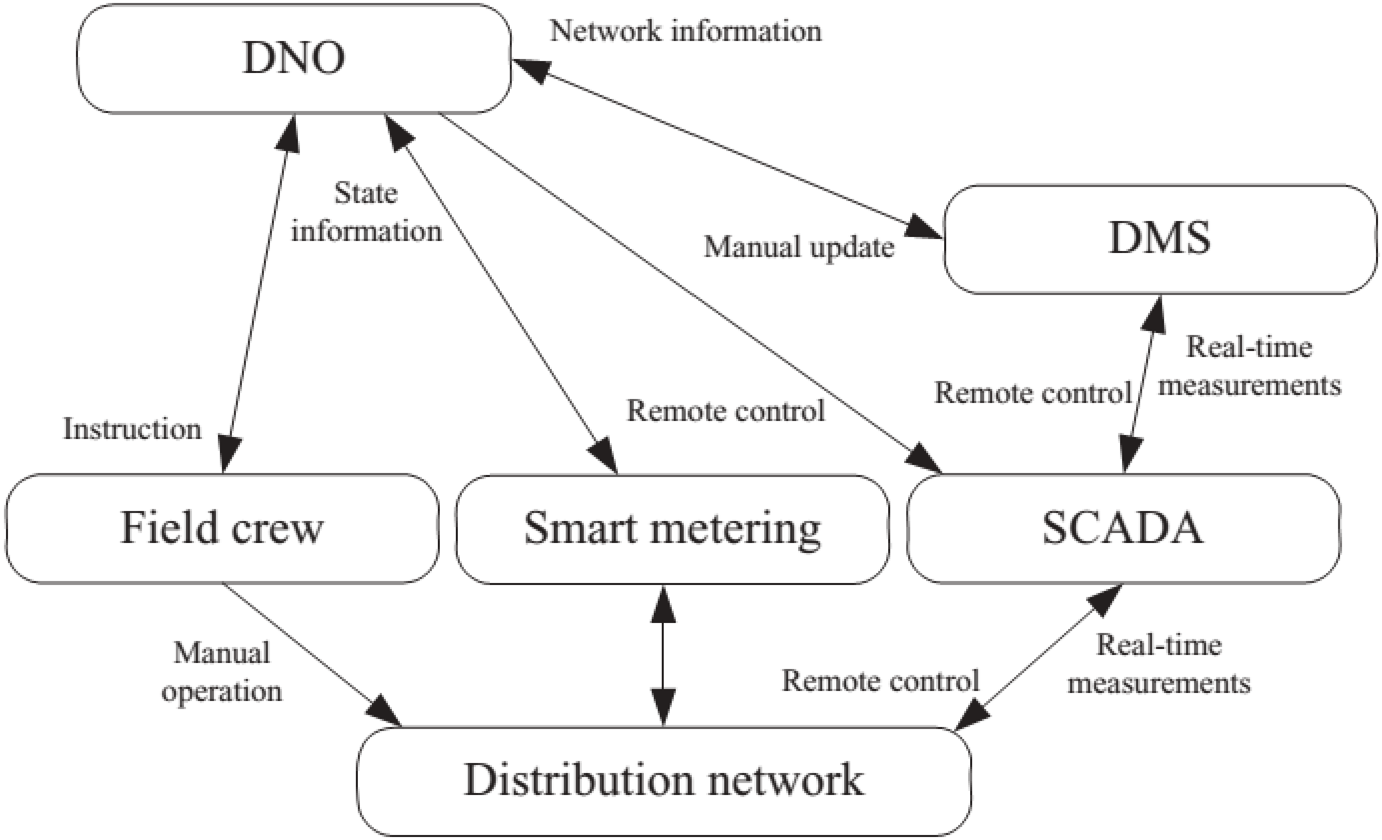


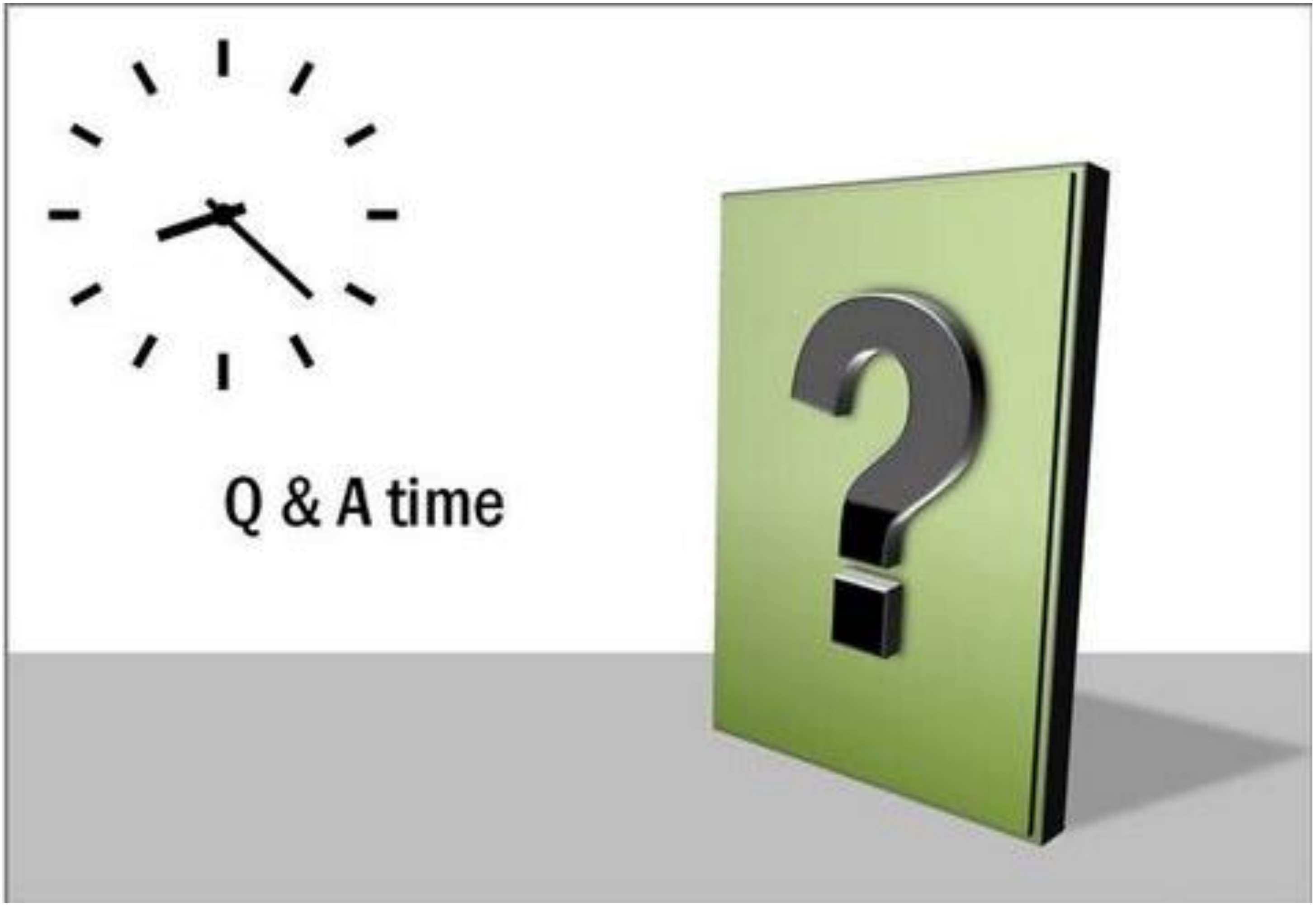
Component	Failure Rate (year^{-1})	MTTR (h)
Substation Equipment		
Power transformers	0.015–0.07	15–480
Circuit breakers	0.003–0.02	6–80
Disconnect switches	0.004–0.16	1.5–12
Air-insulated buswork	0.002–0.04	2–13
Overhead Equipment		
Transmission lines[a]	0.003–0.140	4–280
Distribution lines[a]	0.030–0.180	4–110
Switches/fused cutouts	0.004–0.014	1–4
Pole mounted transformer	0.001–0.004	3–8
Underground Equipment		
Cable[a]	0.005–0.04	3–30
Padmount switches	0.001–0.01	1–5
Padmount transformers	0.002–0.003	2–6
Cable terminations/joints	0.0001–0.002	2–4

Real-time Equipment Performance Monitoring

- Primary task of plant asset management is to reduce costs by identifying performance problems, improving predictive maintenance, and optimizing asset life cycles
- Examples for power generation equipment:
  - Condition monitoring and diagnosis for rotating machinery.
  - Plant performance monitoring and efficiency analysis.
  - Sensor validation.
  - Lifetime monitoring of critical plant equipment.
  - Special instruments for combustion monitoring (e.g. coal flow, flame scanners, etc.).

Measurement and Control Summary




Q & A time

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