Pioneering New Frontiers
in
Revitalizing the Grid

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IEEE PES GM – Emerging Technology Coordinating Committee

Late Breaking News

July 26, 2010

Overview

Smart Grid today

What is the Smart Grid?

Smart Meter & customer benefits

Smart Grid is a journey

Smart Grid standards

The future of Smart Grid for customers

Distributed generation, wind integration, storage / microgrids

DES Challenges

Electric vehicle

Automated demand response

Utility-scale storage

Wide-Area

Synchrophasor Technology Deployment

Situational Awareness & Advance Warning Systems

System Integrity Protection Schemes

Precise Energy Management Systems

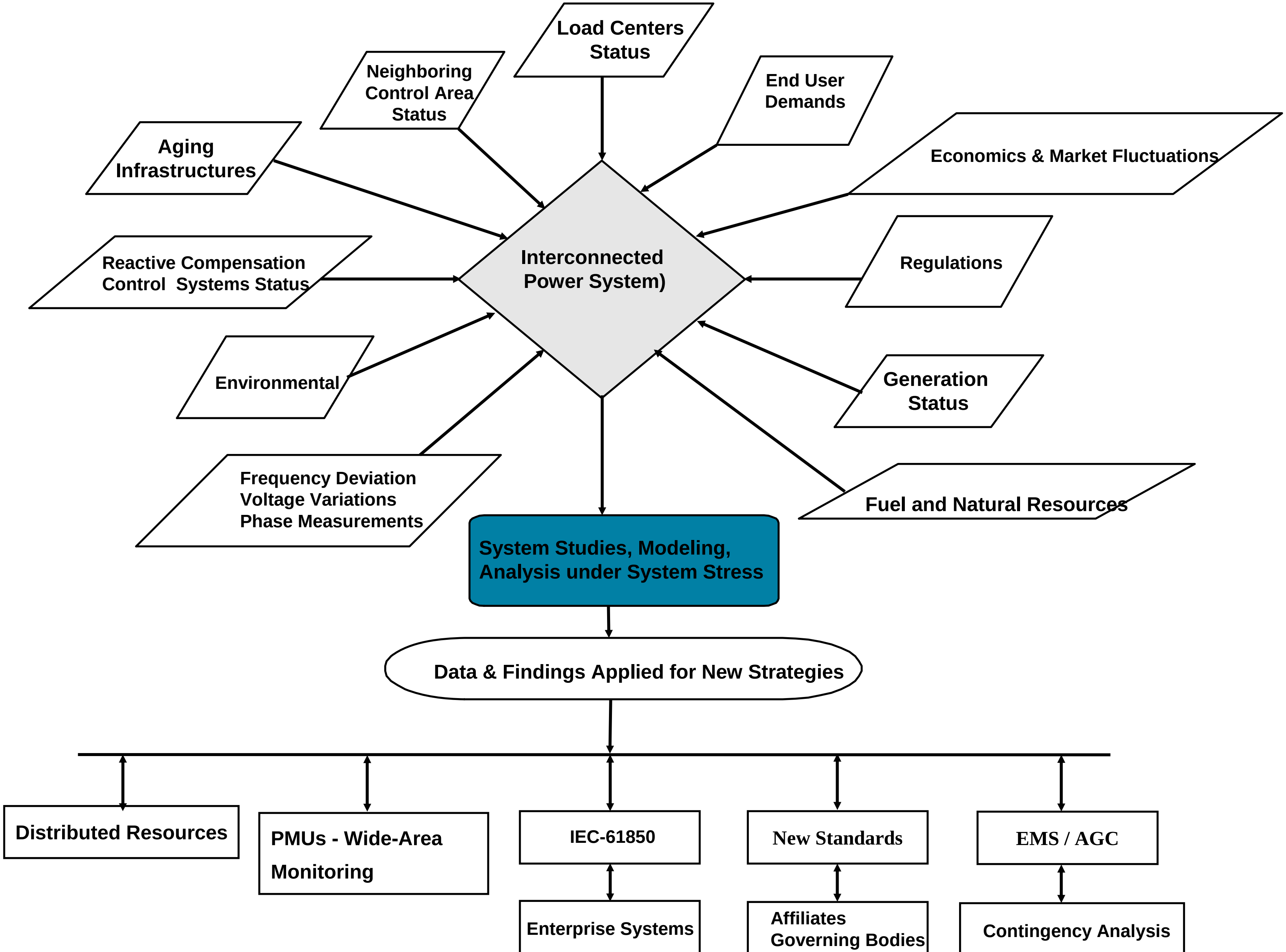
Information processing

Smart Grid integration

Concluding Remarks

Self Managing System

Complex Systems



Load Centers Status

Neighboring Control Area Status

End User Demands

Aging Infrastructures

Economics & Market Fluctuations

Interconnected Power System)

Reactive Compensation Control Systems Status

Regulations

Environmental

Generation Status

Frequency Deviation
Voltage Variations
Phase Measurements

Fuel and Natural Resources

System Studies, Modeling, Analysis under System Stress

Data & Findings Applied for New Strategies

Distributed Resources

PMUs - Wide-Area Monitoring

IEC-61850

Enterprise Systems

New Standards

Affiliates
Governing Bodies

EMS / AGC

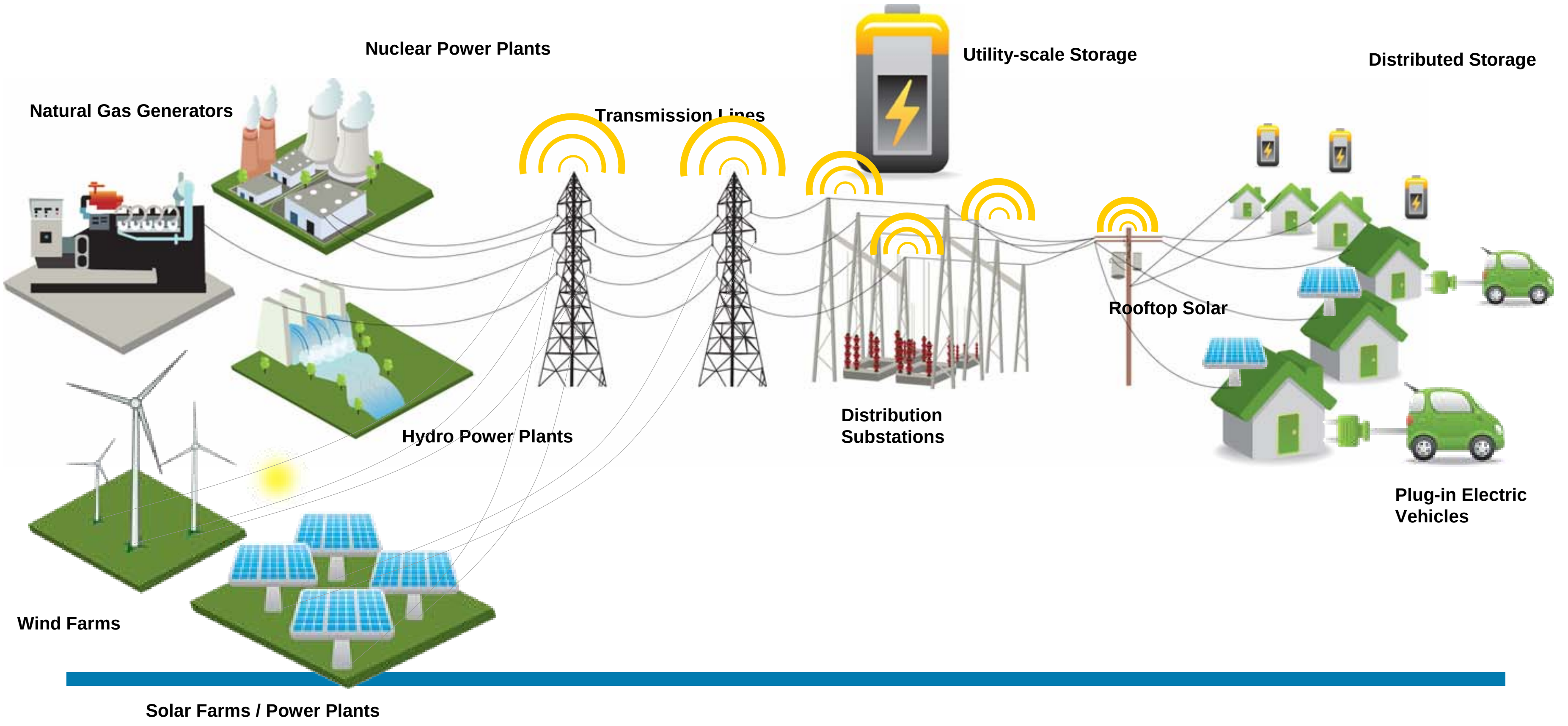
Contingency Analysis

Moving To A Sustainable Electric System

Power Plants

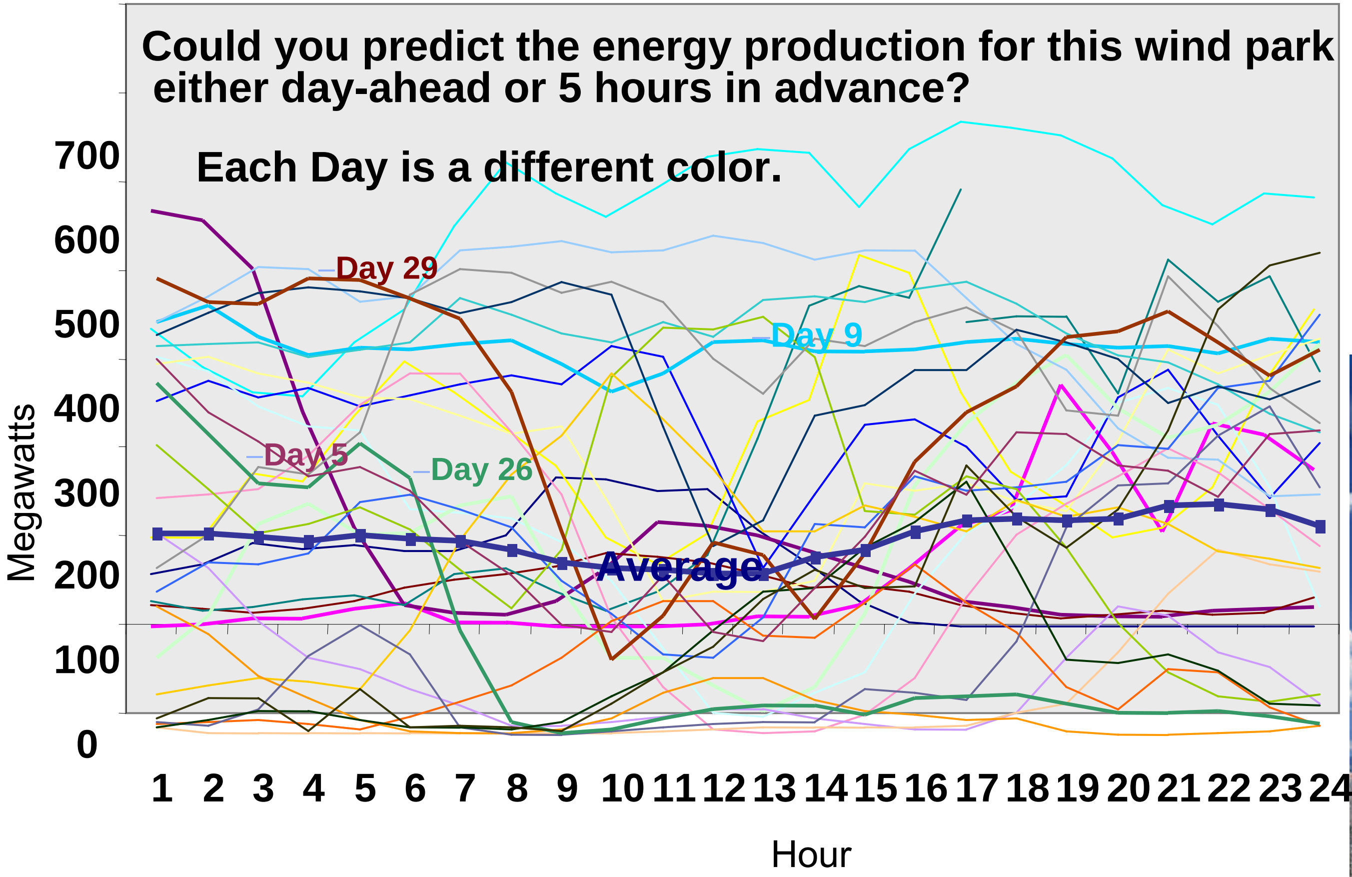
Electric Grid

Customers



Wind Integration Issues

Wind generation tends to be inversely correlated to daily load curve, creating ramping impacts



Could you predict the energy production for this wind park either day-ahead or 5 hours in advance?

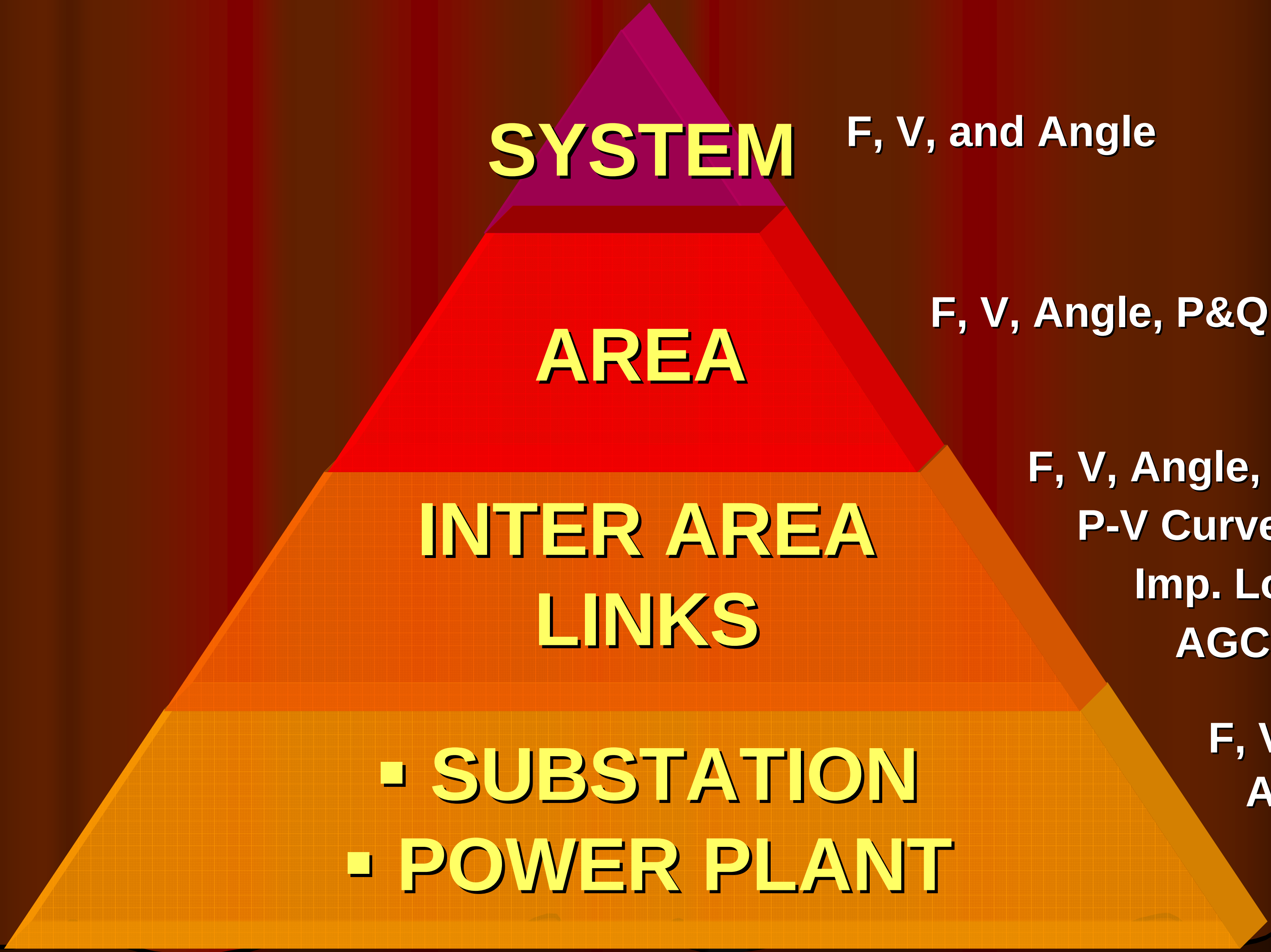
Each Day is a different color.

Tehachapi Wind Generation in April – 2005
Source – AESO - Alberta Electric System Operator

2009 ARRA Stimulus Program - Synchronized Phasors

Application of synchronized-phasors has become a National Priority after the 2003 widespread blackout. The leading cause was identified as lack of corroborating information of power system in real-time.

PMUs APPLICATION LEVELS



SYSTEM

F, V, and Angle

AREA

F, V, Angle, P&Q

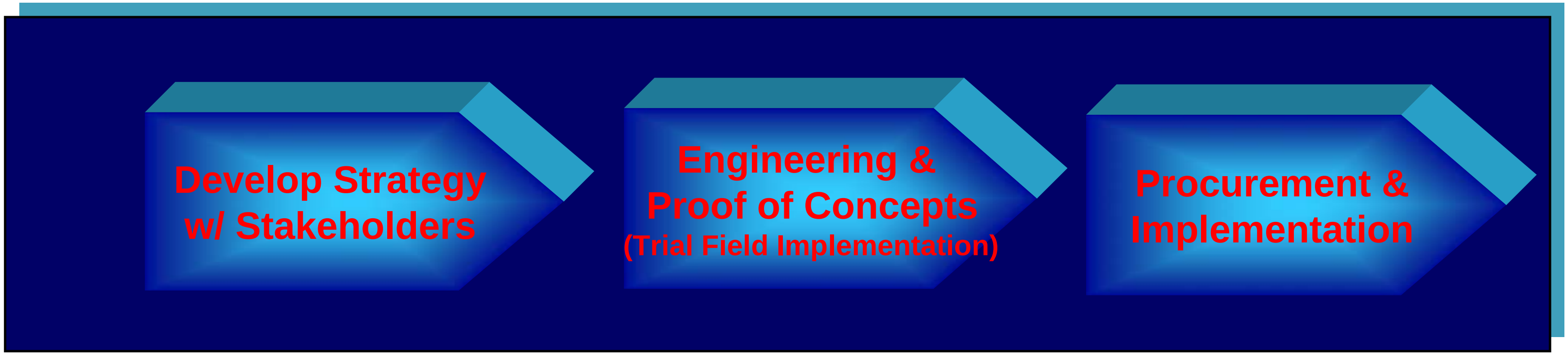
INTER AREA LINKS

F, V, Angle,
P-V Curve,
Imp. Loci R-X,
AGCC

- **SUBSTATION**
- **POWER PLANT**

F, V, Angle,
AGCC, P-V,
Q-V, R-X,
P-F

PG&E Approach to Synchronized Phasor Project



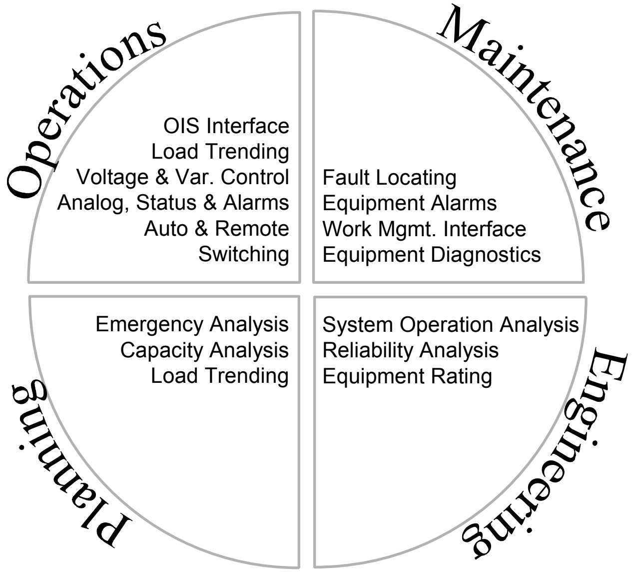
Develop Strategy w/ Stakeholders

Engineering & Proof of Concepts
(Trial Field Implementation)

Procurement & Implementation

Initiatives include:

- Develop Strategy and Roadmap
- Working with Partners and Stakeholders
  - Address NERC Security Requirements and Interoperability
  - Address Reliability Requirements
  - Industry Collaboration and Planning
  - Tools to build Applications
  - Develop maintenance practices
  - Training



Operations
OIS Interface
Load Trending
Voltage & Var. Control
Analog, Status & Alarms
Auto & Remote Switching

Maintenance
Fault Locating
Equipment Alarms
Work Mgmt. Interface
Equipment Diagnostics

Planning
Emergency Analysis
Capacity Analysis
Load Trending

Engineering
System Operation Analysis
Reliability Analysis
Equipment Rating

Organizational Stakeholders and Functions in the Planning and Implementation

Technical Scope of Initiative

Objective – To integrate Synchrophasor technology into electrical grid, improve performance (e.g. reliability) and customer service, and improve coordination with ISO and neighboring systems.

1. Architecture development
    a) Use systems engineering approach
    b) Standards based (open protocol)
    c) Performance evaluation (driven by applications)
    d) Storage Capacity and Simultaneous Multi-User Data Access
    e) PMU and Data Concentrator, Data Access, Methodology
    f) Stakeholder engagement
    g) ISO and neighboring systems coordination
    h) Redundancy – PMU, EMS and DMS
    i) Maintenance and asset management
    j) Gap analysis

Technical Scope of Initiative

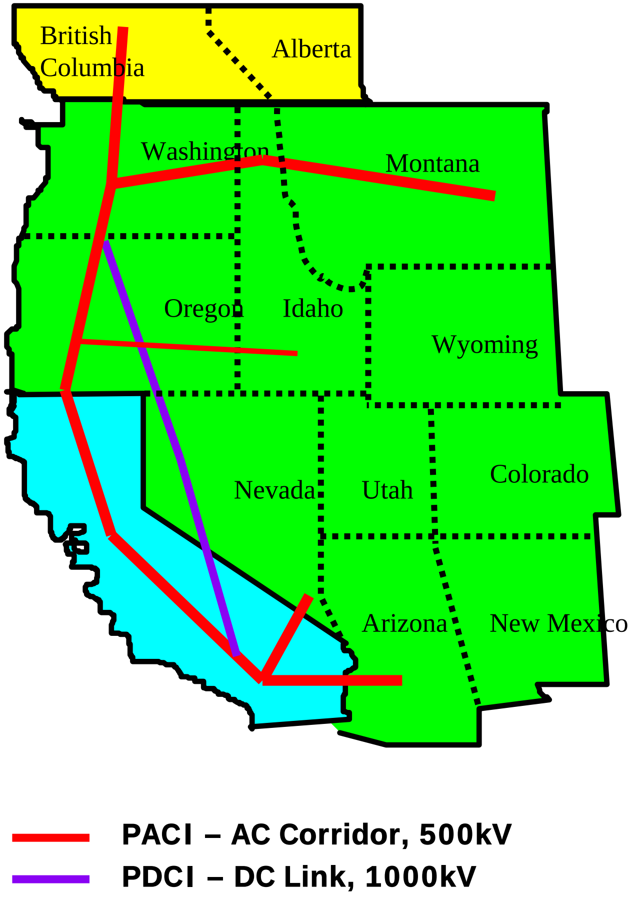
2. Communication infrastructure development
    a) Network availability criteria (for control applications)
    b) Network requirements (Performance, Security, Quality of Service, etc.)
        i. Use of existing infrastructure?
        ii. Completely independent infrastructure ?
        iii. Hybrid infrastructure ?

3. Proof of Concept

4. Application areas
    a) Advanced warning systems
    b) Adaptive protection
    c) Real time control
    d) Dynamic data storage per NERC requirement CRP-002
    e) Integration of renewables into enterprise solutions
    f) Inclusion of phasors into simulation programs – including those used for training
    g) Maintenance
    h) Model validation against existing EMS and future DMS
    i) Integration with existing SCADA

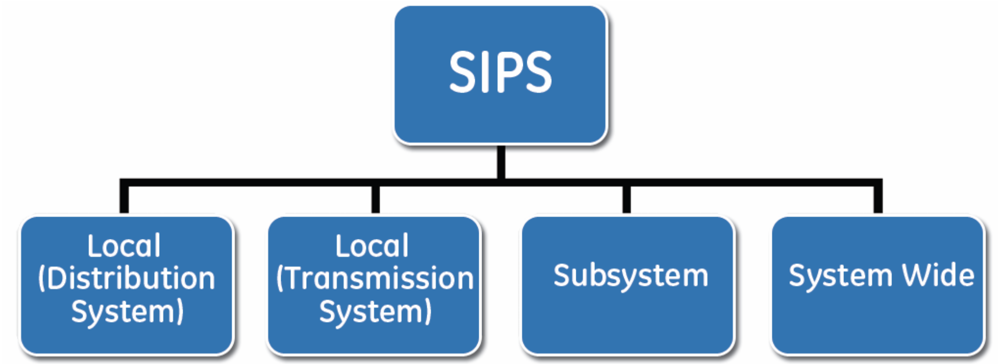
System Integrity Protection Schemes (SISP) Purpose

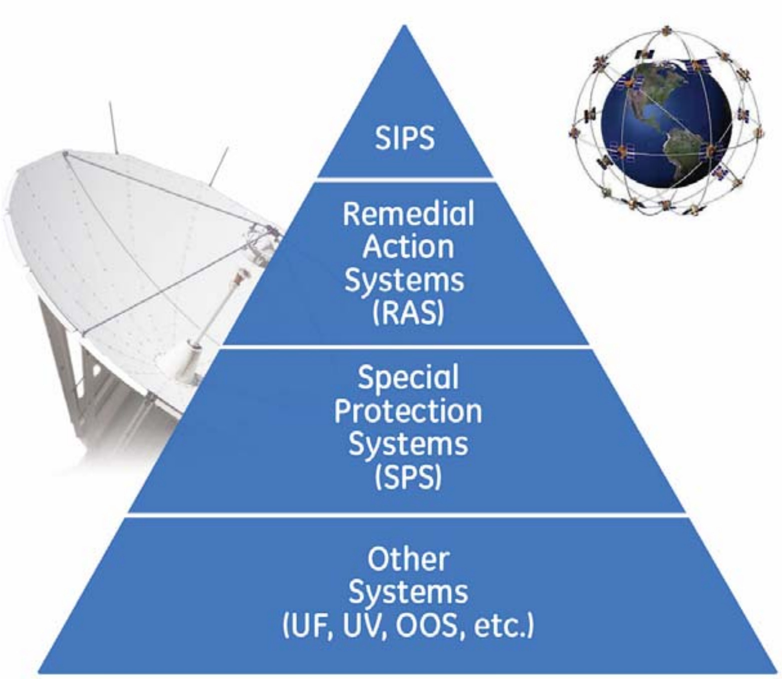
- Goal to prevent propagation of disturbances for severe <u>system</u> emergencies caused by un-planned operating conditions and ensure system security
- Last line of defense to improve system security and prevent disturbance propagation - Could help better utilize system margins
- Stabilize System for Equipment Outages, N-2 or beyond
  - Prevent overloading of the lines
  - Arrest voltage decline
  - Initiate pre-planned separation of the power system, etc.



Wide-Area Systems Technology Enablers

- System Integrity Protection Schemes (SIPS)
  - Remedial Action Schemes (RAS)
  - Special Protection Systems (SPS)
- Integrated system-wide communication infrastructure allowing flexible and secure data collection
- Synchronized Measurements System S



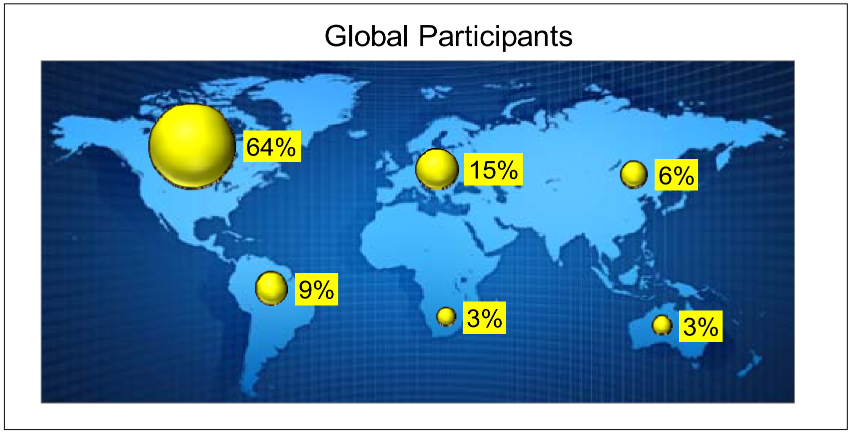


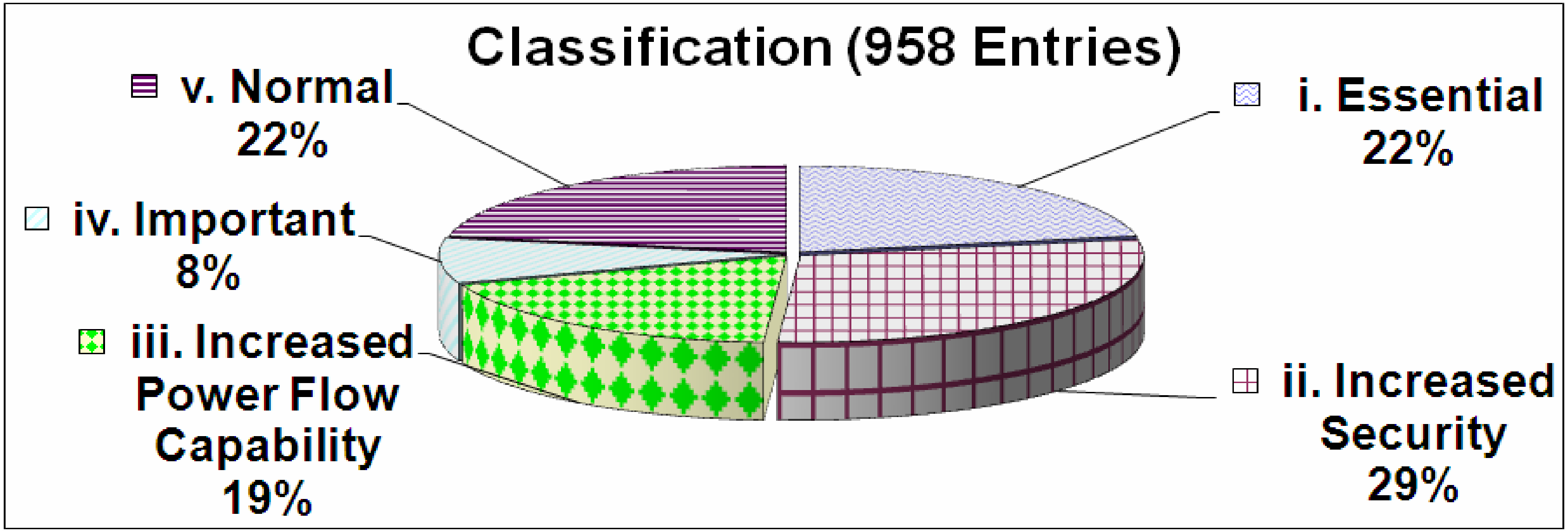
Experiences w/ System Integrity Protection Schemes (SIPS)

IEEE / CIGRE Report - 2009

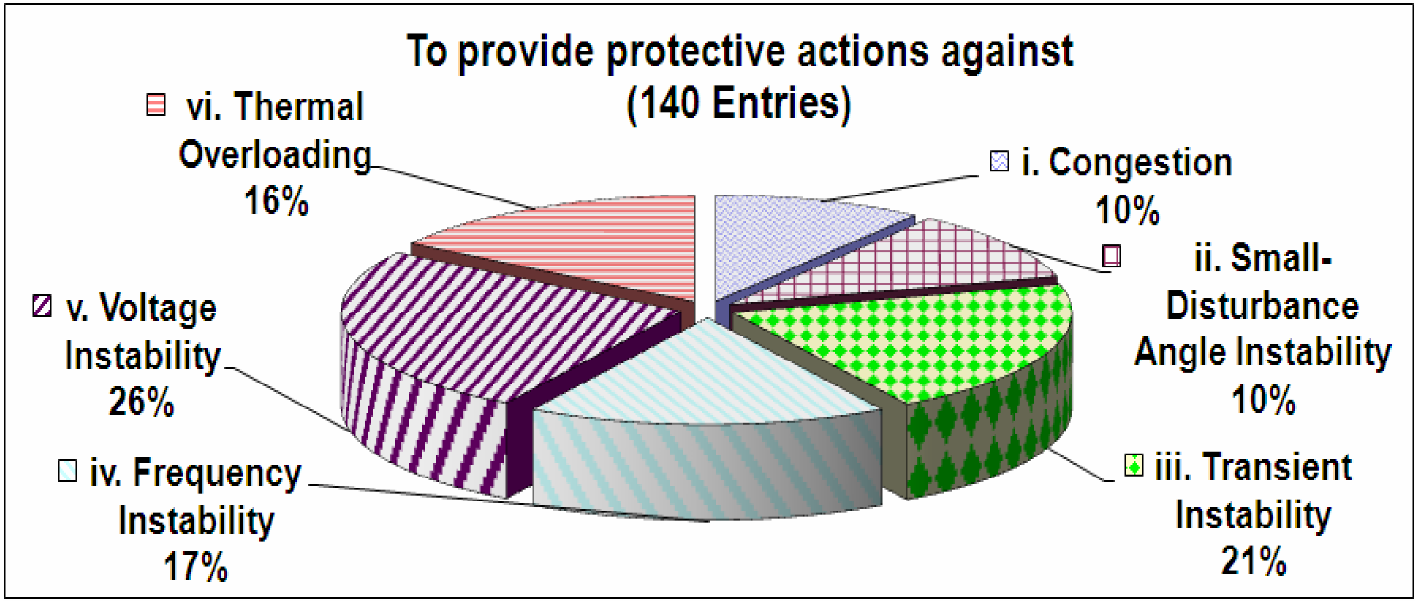
1. Normal Conditions (49%) with three components,
   19% Increased Power Flow
   8% Important,
   22% Normal – Normal system improvements

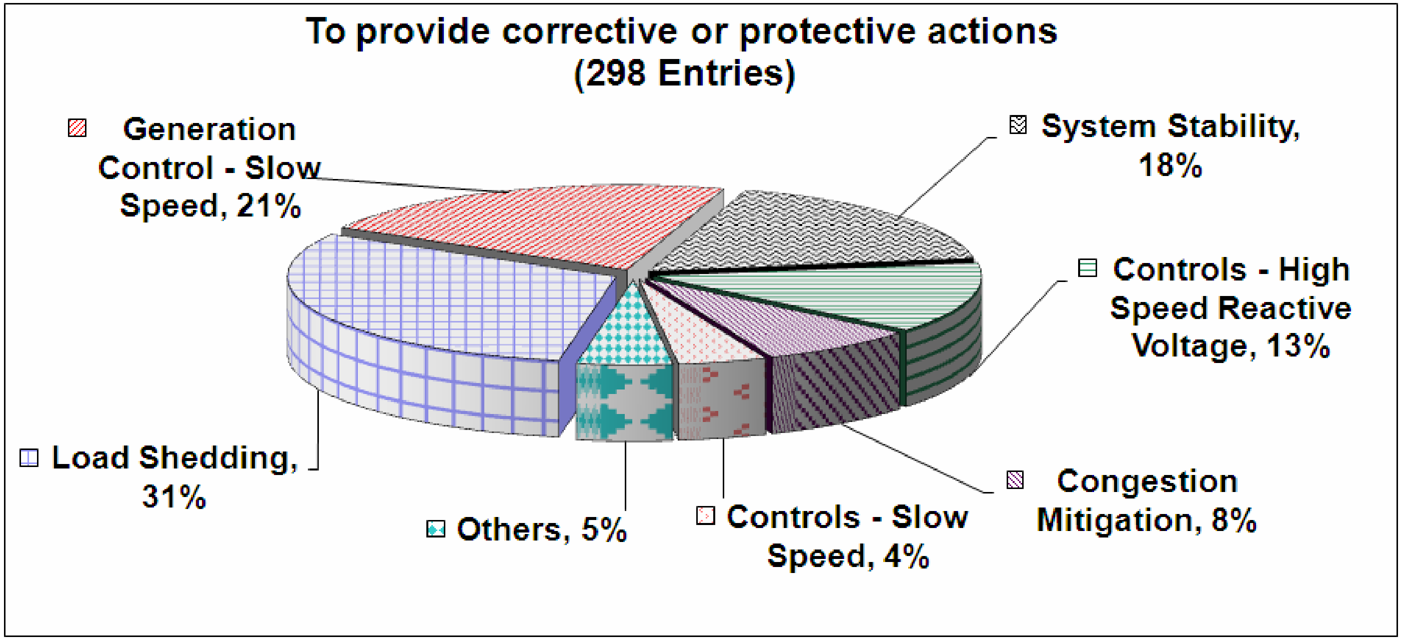
1. System Security (51%) with two components,
   22% Essential
   29% for Increased Security - which at one time was the primary intent of SIPS.





Experiences w/ System Integrity Protection Schemes (SIPS)





Experiences w/ System Integrity Protection Schemes (SIPS)

2009 IEEE Report

Load Shedding	**Generation Control - Slow Speed**
ii. Load Rejection – (%)	i. Generator Rejection – (8%)
iii. Under-Frequency Load Shedding – (8%)	xviii. Power System Stabilizer Control – (3%)
iv. Under-Voltage Load Shedding – (6%)	xix. Discrete Excitation – (1%)
v. Adaptive Load Mitigation – (2%)	xxi. Generator Runback – (3%)
ix. Overload Mitigation – (7%)	xxiv. AGC Actions – (4%)
System Stability	**Controls - Slow Speed**
vi. Out-of-Step Tripping – (7%)	xiv. Tap-Changer Control – (2%)
vii. *Voltage Instability Advance Warning – (2%)*	xvi. Turbine Valve Control – (1%)
viii. Angular Stability Advance Warning – (1%)	xxiii. Black-Start or Gas-Turbine Start-Up – (1%)
xi. System Separation – (7%)	
xx. Dynamic Braking – (1%)	**Congestion Mitigation**
	x. Congestion Mitigation – (3%)
Controls - High Speed Reactive Voltage Compensation	xii. Load and Generation Balancing – (3%)
xxii. Bypassing Series Capacitor – (2%)	xxv. Busbar Splitting – (2%)
xiii. Shunt Capacitor Switching – (5%)	
xv. SVC/STATCOM Control – (4%)	**Others**
xvii. HVDC Controls – (3%)	xxivi. Other, please specify – (5%)

1996 IEEE Report

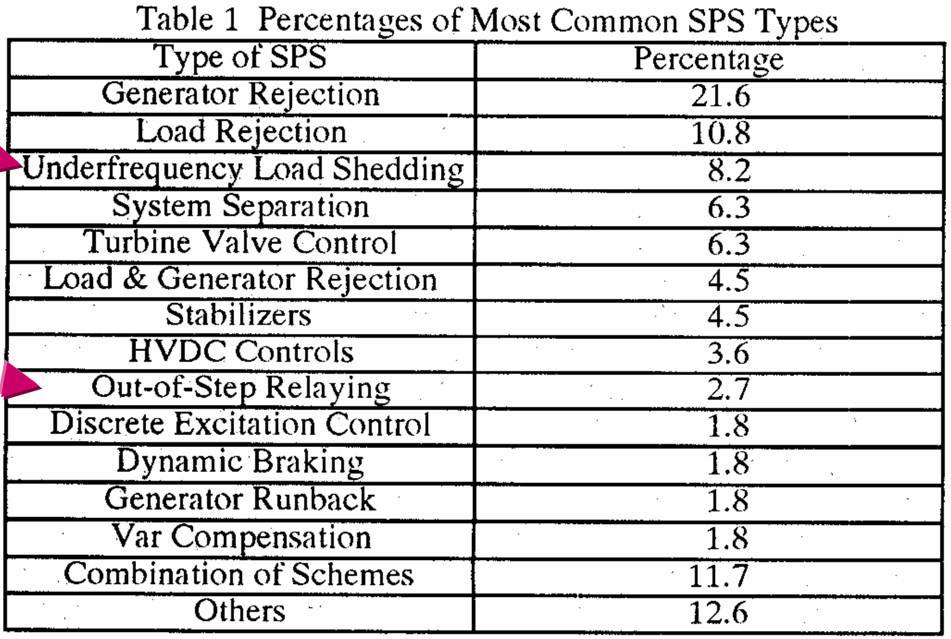
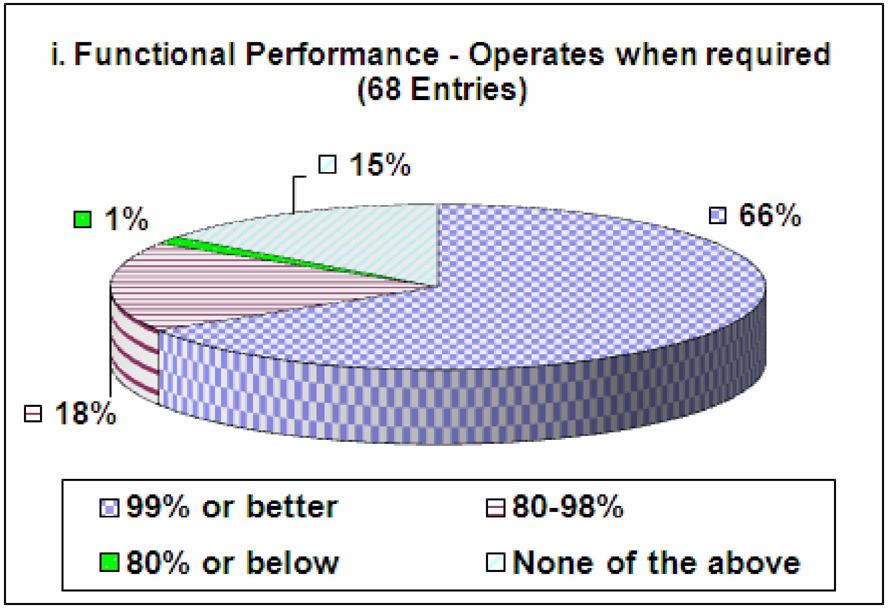
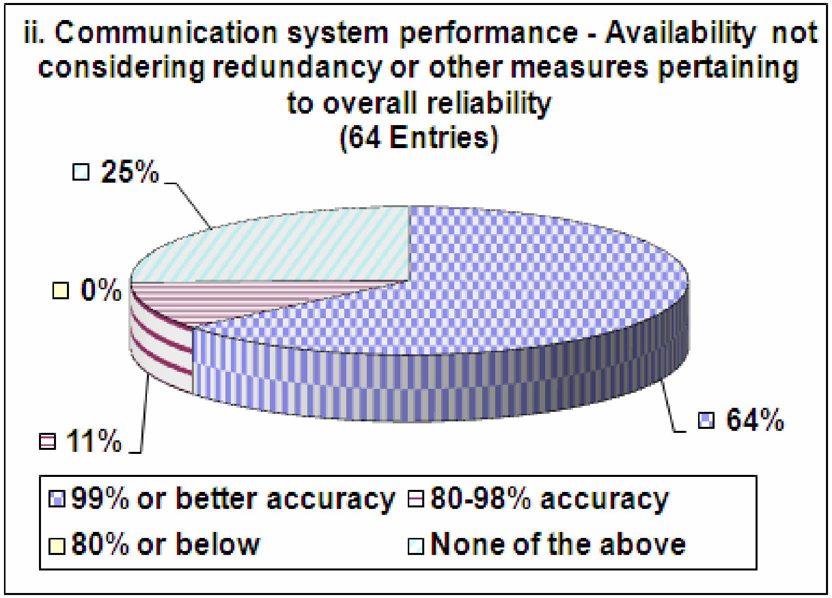


Table 1 Percentages of Most Common SPS Types

Type of SPS	Percentage
Generator Rejection	21.6
Load Rejection	10.8
Underfrequency Load Shedding	8.2
System Separation	6.3
Turbine Valve Control	6.3
Load & Generator Rejection	4.5
Stabilizers	4.5
HVDC Controls	3.6
Out-of-Step Relaying	2.7
Discrete Excitation Control	1.8
Dynamic Braking	1.8
Generator Runback	1.8
Var Compensation	1.8
Combination of Schemes	11.7
Others	12.6

Experiences w/ System Integrity Protection Schemes (SIPS)





Outline - Phasor Technology Applications

- Overview
- PMU Placement Study Goals
- Methodology
- PMU Placement Exercise
- Application Needs
- Infrastructure Considerations
- Interim Results

PMU Placement - Overall Criteria and Studies

Overall Criteria

- Least cost
- Maximum benefit
- Include all costs
  - PMU
  - Communication
  - Secondary hardware and software
- Study Risks & Off Ramos
  - Study integration with multi-function devices
- Include all applications
  - Identify near term vs. long term

PMU Placement Studies

- Criteria - studies for PMU location:
- Situational awareness
  - Abnormal angles
  - Dynamics oscillations
  - Line overloads, and
  - Abnormal voltages
- EMS
- Small Signal Oscillation
- Wind farm locations
- Two-ended fault location - which lines
- SIPS application considerations?
- The DC line availability

PMU Placement Criteria – T&D

APPLICATIONS

- State Estimation
- Critical Corridors & Tie-Lines
- WECC Regional Paths
- Angular Separation
- Phase Angle Balancing
- Major Generation/Load
- Variation in Generation
- Variation in Load Demand
- Congestion Management
- Wind Integration
- Local and Inter-area Oscillations
- Islanding, system restoration
- Adaptive Protection
- FACTS Controls
- Rotor Angle Measurement
- Black Start
- Volt VAR Optimization
- Market Driven Exchanges

INFRASTRUCTURE CONSIDERATIONS

- PMU Ready Equipment
  - Devices
  - Infrastructure
    - Network Exists Today
    - Feasibility and location of Network Aggregate Site
    - LAN/WAN Redundancy
    - Capacity to meet latency requirements
    - Existing Digital Connectivity
- On Critical Cyber Asset (CCA) List
- NERC PRC 002 Sites

Overall Criteria (Guiding Principal)

- Least cost
- Maximum benefit
- Include all costs
  - PMU
  - Communication
  - Secondary hardware and software
- Study Risks and off ramps
- Include all applications

Risk Analysis 1 - Integration with Multi-function & Infrastructure RAS System Relevance

- RAS system has been designed for integrated functionality
  - Telemetry (MW, MVAR, Voltage, Frequency)
  - Other Measurements - Temperature, Wind Speed
  - RAS has been designed with future integration of PMU functionality
    - I.e. 100Mbps Ethernet switches and supporting routers
  - Integration of phasors for RAS functions enhances RAS applications in the future, E.g.:
    - Manual load shedding at transmission level already part of RAS - HMI
      - PMU provides enhancement / supervisory layer
  - RAS devices are redundant over diverse routes
  - Advance Alarm features and monitoring functions already addressed
  - Cyber Security - RAS and EMS are 24/7 monitored & meet CCA
  - RAS is designed to support Disaster Recovery
    - Phasor project architecture needs to support concurrent control centers; i.e.: Redundant EMS, Redundant Situational awareness
    - Integration of PMU into RAS allows concurrent / multi-host EMS
    - Harmonized event records for comprehensive system analysis – Using common time tagged elements and Sequence of Event recording

Risk Analysis 2 - Integration With Multi-function & Infrastructure
RAS System Relevance

- Use of Multifunction devices as PMUs is not a new concept
  - There are benefits and challenges, and well-established processes to manage the challenges.
- RAS system architecture established to facilitate synchrophasors
    - RAS functions are application of synchrophasors
- Other examples of integrated functionalities in use at PG&E
  - Use of feeder protective devices for UFLS (Under-Frequency Load Shedding)
  - Use of line protective devices for out of step protection
  - Modularizations - Automatics and SCADA functions by protective devices

Risks and Mitigation Plans

No	Risk Description	Mitigation strategy or Contingency Plan
6	Upgrades to firmware and/or hardware	The concept of modularization and / or use of modular devices are key to life cycle support and the rapidly evolving technology. Firmware or module upgrades are reality. The risks are minimized by thorough testing, including testing any possible logical interaction between RAS and phasor functions. Important to emphasize that the multifunction device used in the PACI-RAS system is specifically designed to decouple RAS and phasor functions to a great extent (including use of different physical cards and ports, etc.)
7	Reliability and availability of the functions (RAS or phasor functions) as opposed to reliability and availability of a specific device.	Higher system reliability is achieved by using means beyond just using reliable relays/PMUs. Integration with PACI RAS automatically facilitates redundancy. Using redundancy has been a key element of achieving high-level of system reliability and availability.

Key Elements of System Management and Solution Risk Mitigation

1. Change Management Plan
2. Clearance Plan
3. Failure Plan
4. Technical Risk analysis
5. Vendor Support program - maybe with additional support plan for a period after commissioning.
6. Spares Plan
7. Maintenance plan

PMU Placement Study Goals

- "*Optimally*" identify locations for PMU deployment to:
  - Maximize benefit for multiple applications
  - Least cost solution: *i.e. leverage existing or planned infrastructure, PMU placement in neighboring systems*

- Applications' criteria:
  - Situational Awareness
    - *Improving State Estimation (observability, critical measurements)*
    - *Monitoring Critical Paths (tie-lines, WECC paths, congested paths, angular separation cut-planes)*
    - *Monitor major generation and loads*
    - *Oscillation Monitoring (Local and Inter-area)*
  - Critical Substation Locations
    - *Renewable Generation*
    - *Islanding Separation & Restoration*
    - *RAS, Adaptive Protection*
    - *FACTS, SVC and HVDC Controls*

- Other Aspects: Upgradable hardware, communications, redundancy, etc.

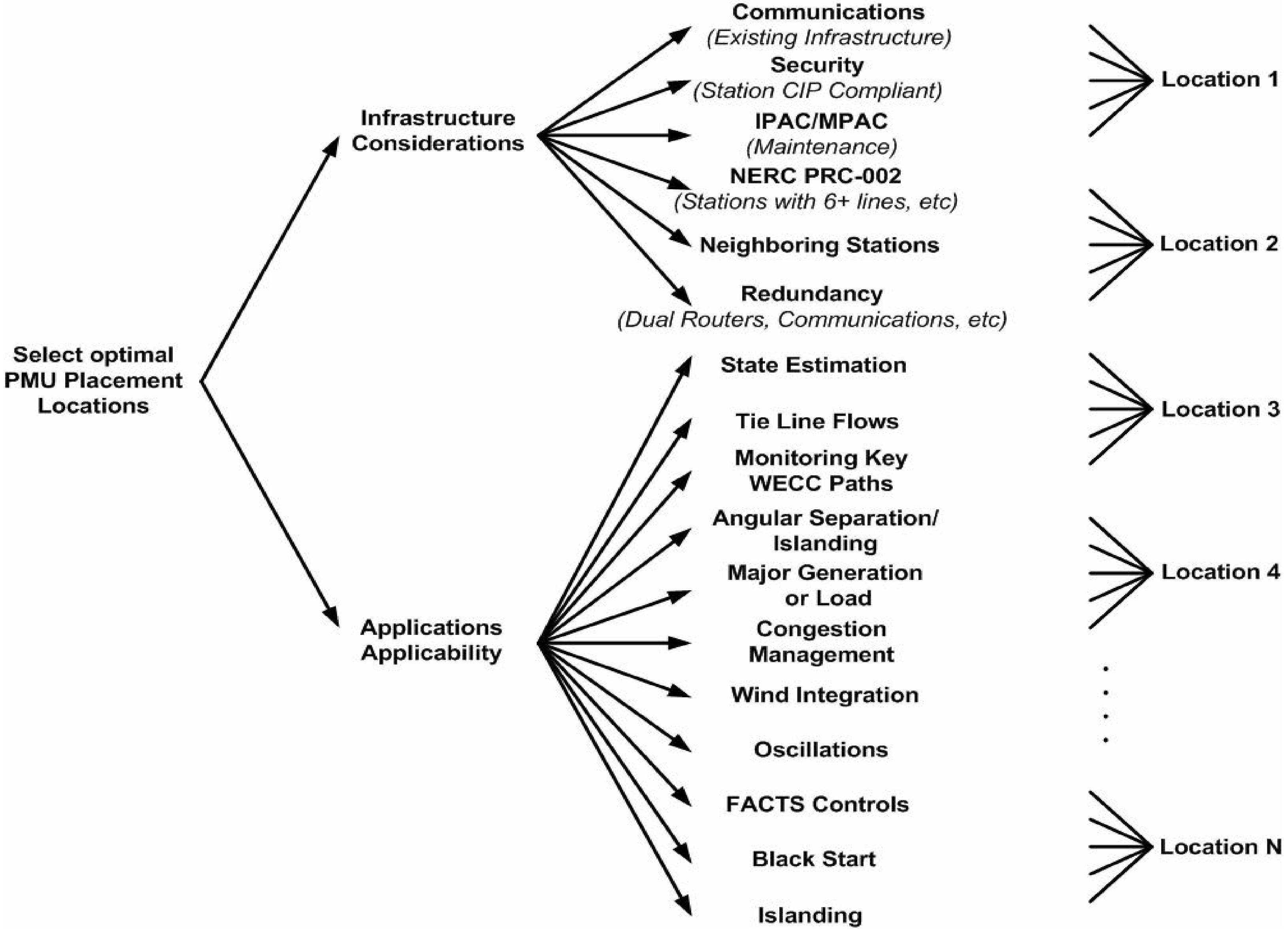
Methodology

Based on the **Weighted Average Criterion:**

Decision process which typically involves choosing among *<u>Alternatives</u>* based on multiple *<u>Criteria</u>* to satisfy a *<u>Goal</u>*

- For each PMU location being considered, independently evaluate its '***applicability/need***' for the decision '***Criteria***' under consideration (e.g. application, networking cost, etc).
- Assign '***weights***' to each of the decision criterion based on:
    - Criterion importance
    - Feasibility / likelihood – Infrastructure support
    - Maintenance over life cycle
- Prioritize PMU location alternates based on the '***aggregated weighted score***'

Hierarchy Structure for PMU Placement Decision Criteria



Select optimal PMU Placement Locations

Infrastructure Considerations

- **Communications** *(Existing Infrastructure)*
- **Security** *(Station CIP Compliant)*
- **IPAC/MPAC** *(Maintenance)*
- **NERC PRC-002** *(Stations with 6+ lines, etc)*
- **Neighboring Stations**
- **Redundancy** *(Dual Routers, Communications, etc)*

Applications Applicability

- State Estimation
- Tie Line Flows
- Monitoring Key WECC Paths
- Angular Separation/ Islanding
- Major Generation or Load
- Congestion Management
- Wind Integration
- Oscillations
- FACTS Controls
- Black Start
- Islanding

Location 1

Location 2

Location 3

Location 4

.
.
.
.

Location N

GOAL **DECISION CRITERIA** **ALTERNATIVES**

Prioritization Based on Weighted Sum Scoring

Priority
(weighted score)

KV level	Station	Name	Applications														SCORE (Priority)
			State Estimation	PG&E Tie Lines	WECC Regional Paths	Regional Angular Separation	Local Angular Separation	Major Generation or Load	Congestion Management	Wind Integration	Inter-Area Oscillations	Local Oscillations	Islanding	Sytem Restoration	Adaptive Protection	Local FACTS Controls	
		ENTER Business Priority Weight for Column Category	2	2	2	1	1	2	1	2	2	2	2	1	1	2	
Substation Location and Voltage Level Applied				2	2	1					2				1		8.0
				1		1		2				2			1		7.0
				2	2	1					2						7.0
				2	2	1									1		6.0
				2			1									2	5.0
				1			1	2									4.0

Applications

Weights

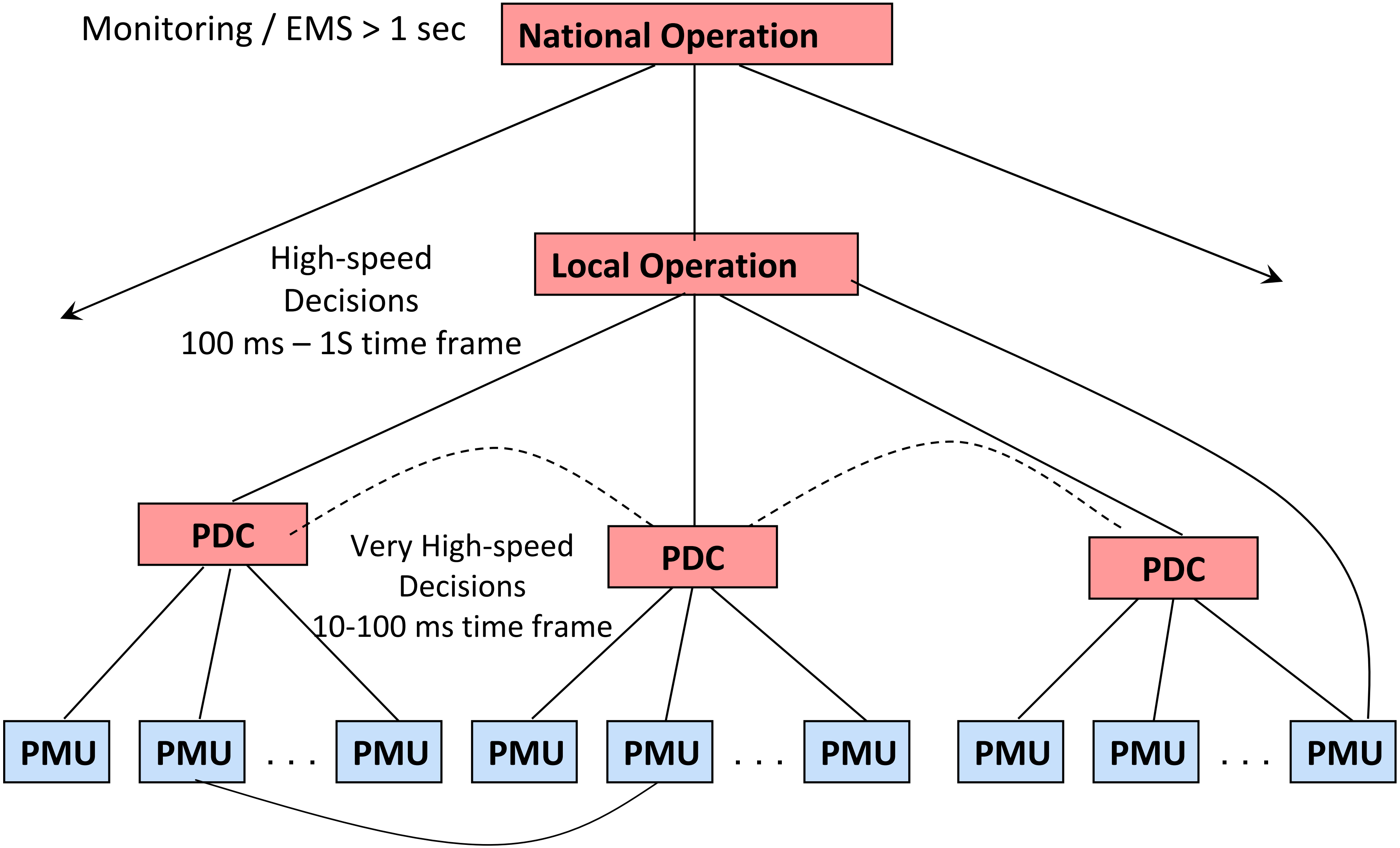
KV level	Station	Name	Infrastructure										SCORE (Priority)	TOTAL SCORE	PMU Location Counter
			PACI RAS PMU-Ready Device	COST (Networked)	On Critical Cyber Asset (CCA) list	IPAC / MPAC	Sites ready for upgrade for PRC 002	Existing PG&E Digital Conectivity	ODN Exists Today?	ODN LAN Redundancy	ODN WAN Reduncancy	Proposed Aggretate Site			
		ENTER Business Priority Weight for Column Category	1	2	1	1	1	1	1	2	2	1			
Substation Location and Voltage Level Applied			1	2	1		1	Yes	Yes		Yes	Aggregate Site or Substation Location	10.0	18	1
			1	2	1		1	Yes	Yes		Yes		10.0	17	2
			1	2	1		1	Yes	Yes		Yes		10.0	17	3
			1	2	1		1	Yes	Yes		Yes		10.0	16	4
			1	2	1		1	Yes	Yes		Yes		10.0	15	5
			1	2	1		1	Yes	Yes		Yes		10.0	14	6

Infrastructure

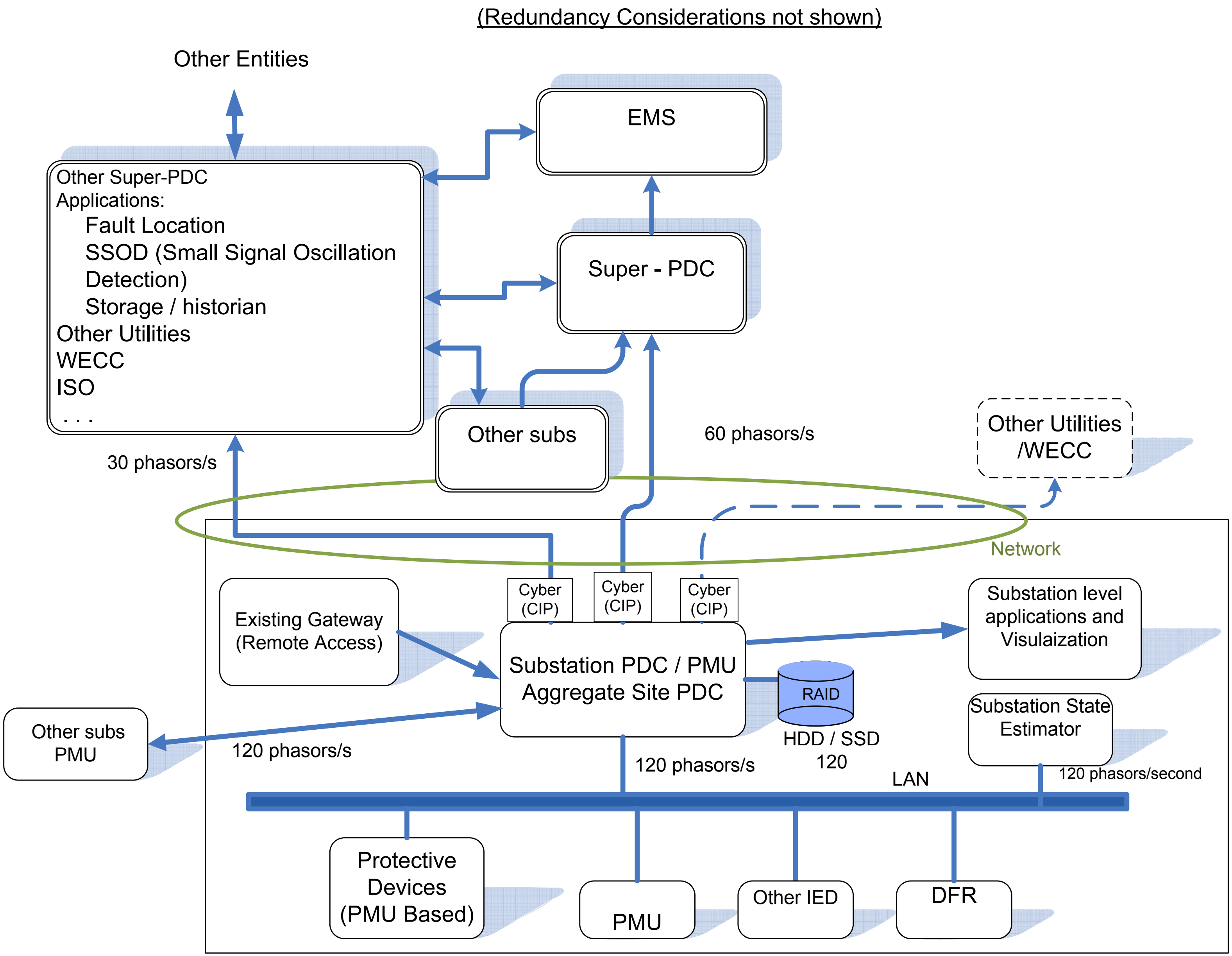
Weights

System Architecture – Reporting Hierarchy

PDC – Phasor Data Concentrator



Example – High Level Architecture



(Redundancy Considerations not shown)

Other Entities

EMS

Other Super-PDC
Applications:
Fault Location
SSOD (Small Signal Oscillation Detection)
Storage / historian
Other Utilities
WECC
ISO
. . .

Super - PDC

Other subs

30 phasors/s

60 phasors/s

Other Utilities /WECC

Network

Cyber (CIP)

Cyber (CIP)

Cyber (CIP)

Existing Gateway (Remote Access)

Substation PDC / PMU Aggregate Site PDC

Substation level applications and Visulaization

RAID

HDD / SSD 120

Substation State Estimator

Other subs PMU

120 phasors/s

120 phasors/s

LAN

120 phasors/second

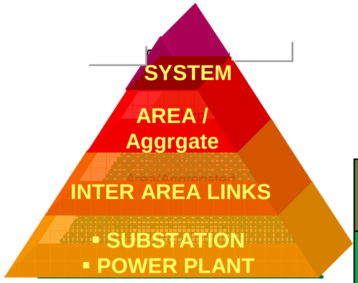
Protective Devices (PMU Based)

PMU

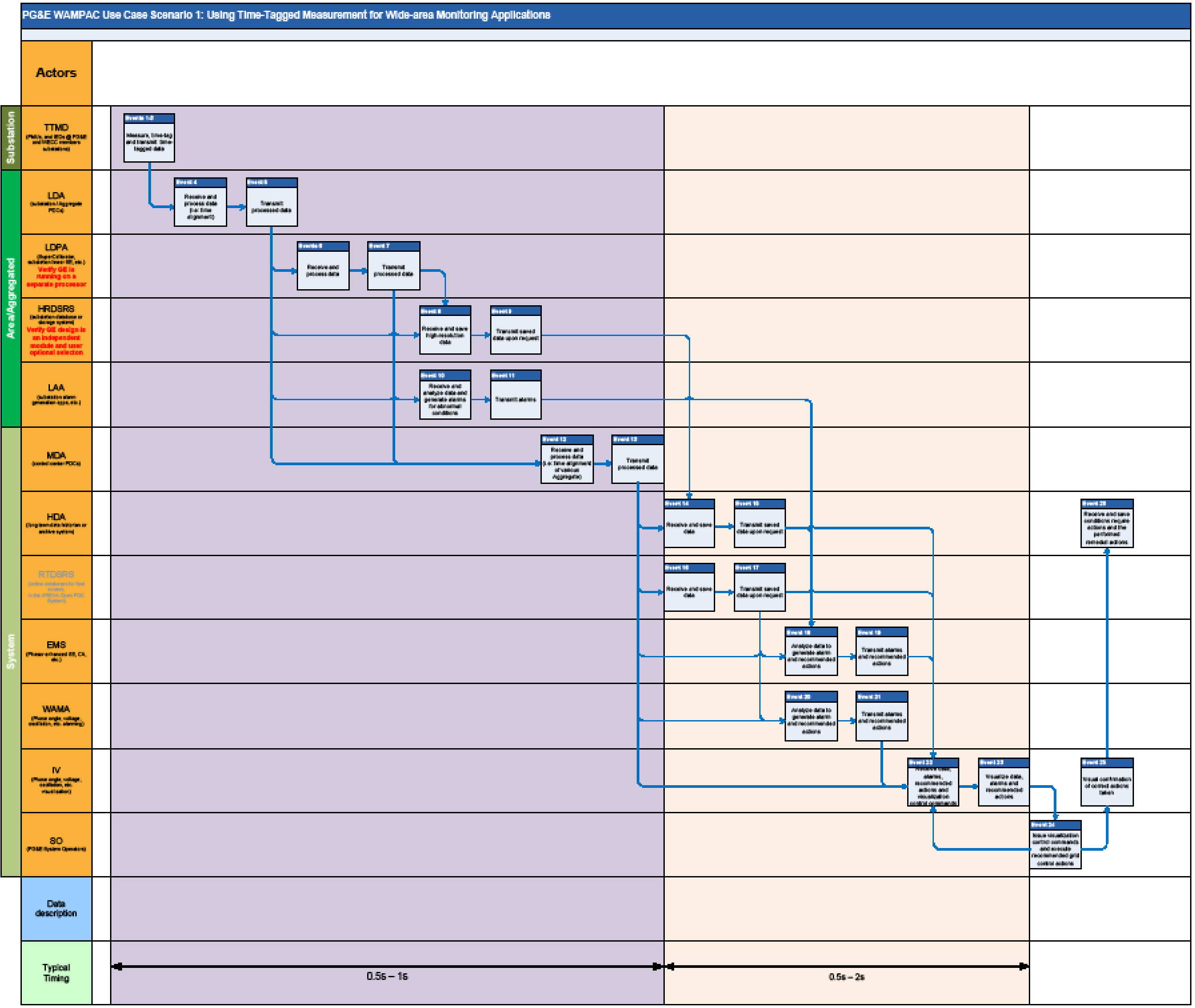
Other IED

DFR

Use Case



AMD: Any measurement devices, include NTTMD and TTMD
NTTMD: Non-Time-Tagged measurement devices, include certain IEDs, RTU, etc.
TTMD: Time-Tagged measurement devices, include PMU etc.
LDA: Local data aggregators, such as substation PDC, etc.
LDPA: Local data processing applications, such as SuperClibrator, substation SE, etc.
LAA: Local analytical applications, such as alarm generator, trig condition detector, etc.
MDA: Main data aggregators, such as control center PDC, etc.
MDPA: Main data processing applications, such as data validation, etc.
RTWAA: Real-time wide-area applications, include WAMA, WACA, and WAPA
WAMA: Wide-area monitoring applications, such as phase angle monitoring, voltage stability assessment, etc.
WACA: Wide-area control applications, such as wide-area coordinated voltage and VAR control, etc.
WAPA: Wide-area protection applications, such as RAS, SPS, SIPS, etc.
WAPEAA: Wide-area post-event analysis applications, such as event playback, etc.
HRDSRS: High resolution data storage and retrieval system, such as substation raw data storage system, etc.
RTDSRS: Real-time data storage & retrieval system, such as online fast access databases
HDA: Historical data archive, such as historians
CED: Command execution devices, include CACED, PACED, etc.
CACED: Control Event command execution devices, such as controllers, etc.
PACED: Protection Event command execution devices, such as relays, etc.
IV: Information Visualization
SO: System Operator



Streaming Data Rates – Single PMU

- Packet Model #1
  - 14 Synchrophasors
    - V0, V1, V2, I0, I1, I2, Va, Vb, Vc, Ia, Ib, Ic, Vn & In
  - 8 Analogs (magnitudes)
    - E.g.: Watts, Vars, Ambient Temperate, Wind Speed, etc.
  - Frequency
  - ROCOF (Rate of Change of Frequency)
  - 1 Digital Word (16 binary inputs)
- All *Real* Numbers (floating points)
- **60** and **120** Measurements or packets / sec (IEEE C37.118)
  - Values above which includes computed phasors
- Communications Bandwidth Requirements:
  - **114,240** and **228,480** Bits/sec
- **Migration to IEC 61850 increases the bandwidth by ~ 20% due to overhead**

Streaming Data Rates

Single PMU

- Packet Model:
  - 6 Synchronized Phasors
    - Va, Vb, Vc, Ia, Ib, Ic
  - Frequency
  - ROCOF (Rate of Change of Freq)
- All Real Numbers (floating points)
- 60 and 120 Measurements or packets / sec
  - Values above
- Communication Bandwidth Requirement:
  - **67,200 at 60 pps (DS0, 64000 bits / seconds)**
  - **134,400 at 120 pps**

For 100 PMUS (60 samples / sec.)

- **6 Phasors from each device**
  - **67,200 (DS0, 64,000 bits / seconds / PMU Streamed Data)**
    - **6,720,0000 ~ 6.7 Mbits / seconds**

DS0 = 64,000 bits / sec

24xDS0 ~ T1 (T1 = 1.544 Mbits/sec)

Or 5 T1 = 5 (1.544) Mbits /sec

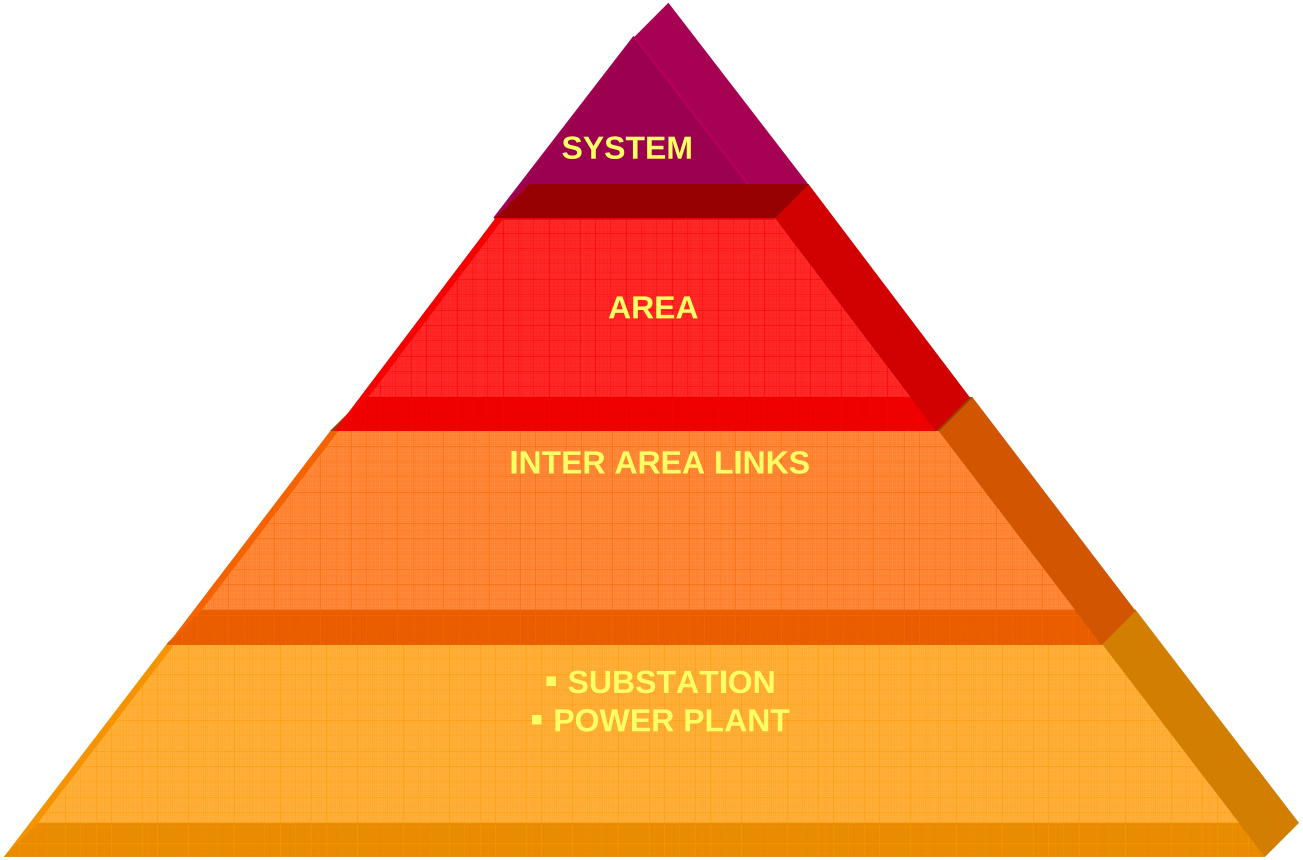
OC 1 (DS3) = 51.84 Mbits / Seconds

DS3 = 28 T1

System Storage Requirements (NERC PRC-002)

- 100 PMU Model, 14 Phasors / PMU @ 120 Packets/sec:
  - 153 Bytes/packet/PMU
  - 15,300 Bytes/packet for 100 PMUs
  - 1.84 MB/sec
  - 111 MB/min
  - 6.6 GB/hour
  - 160 GB/day
  - 4.8 TB/month
  - 57.2 TB/year
- As number of PMUs (or phasors extracted) increase, storage requirements increase

Conclusions



SYSTEM

AREA

INTER AREA LINKS

- SUBSTATION
- POWER PLANT

Smart Grid Is A Journey

Today
Integrate existing services to new platform

- Automated meter reading
- Electric field vehicles

Near Term
Transform existing services

- Automated home energy management
- Plug-in hybrid electric vehicle SmartCharge™

Future
Enable future services and foster innovation

- Integrated local generation and storage
- Deep penetration of Demand Side Management

Years

Large Scale Deployment of PMU Systems

- Stringent and varied requirements
  - Must be a production system (full vendor support), high reliability and availability
  - Accommodate all participants while ensuring interconnection performance
- Address both short and long term needs
  - System expandability ➔ Initially limited number of measurements will grow over time including both synchrophasor and non-phasor data
  - System flexibility and adaptability ➔Start with small number of applications and add new in the future
- Address technology advancements and product development
  - Address relevant standards development that will continue to evolve: NERC CIP 003 – 009; synchro- phasor (IEC 37-118); cyber security; IEC 61850, etc.
- Consider system integration with other enterprise systems, such as EMS/SCADA, DMS, GIS

Self-managing Technologies

A self-managing system can sense its operating environment, model its behavior in that environment, and take action to change the environment or its behavior. An autonomic **self-managing** system has the properties of self-configuration, self-healing, self-optimization and self-protection.

Self-managing systems deliver:

Increased Responsiveness

Adapt to dynamically changing environments

Robustness and Resiliency

Discover, diagnose, and act to prevent disruptions

Operational Efficiency

Tune resources and balance inputs to maximize use of resources

Secure Information and Resources

Anticipate, detect, identify, and protect against attacks

Source: IBM Autonomic Computing white paper