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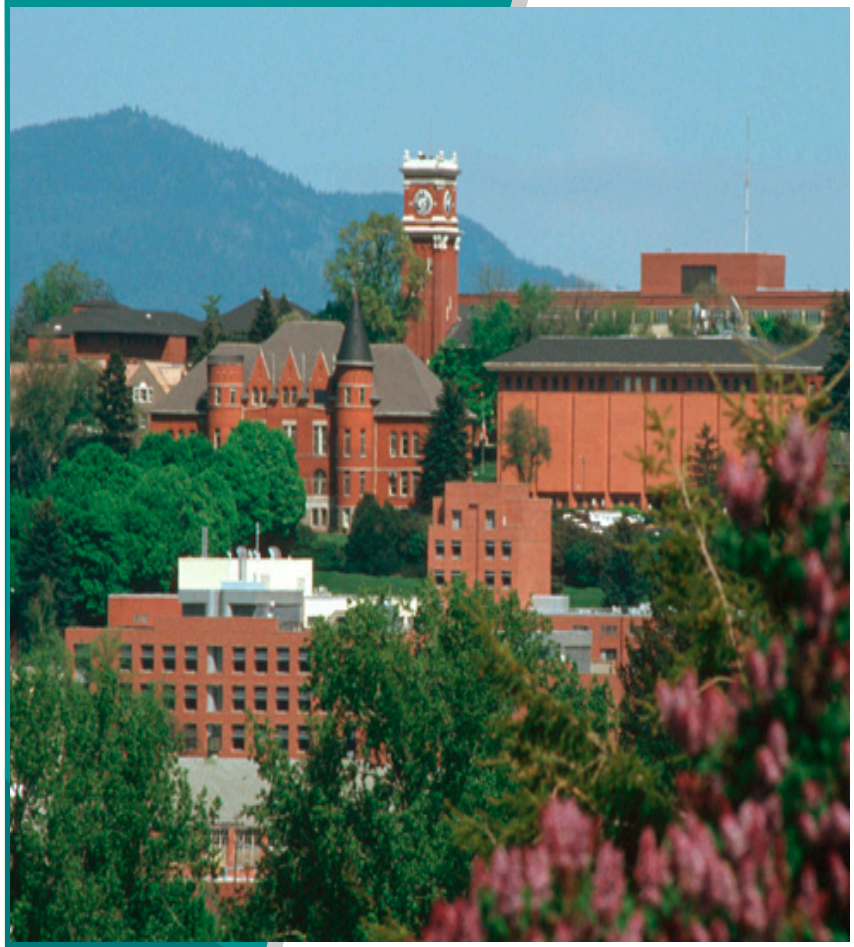

# Evolution of Control for the Smart Transmission Grid

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Washington State University
Pullman, WA

**SCE Smart Grid Research Symposium**
**California Institute Of Technology**
**October, 2011**

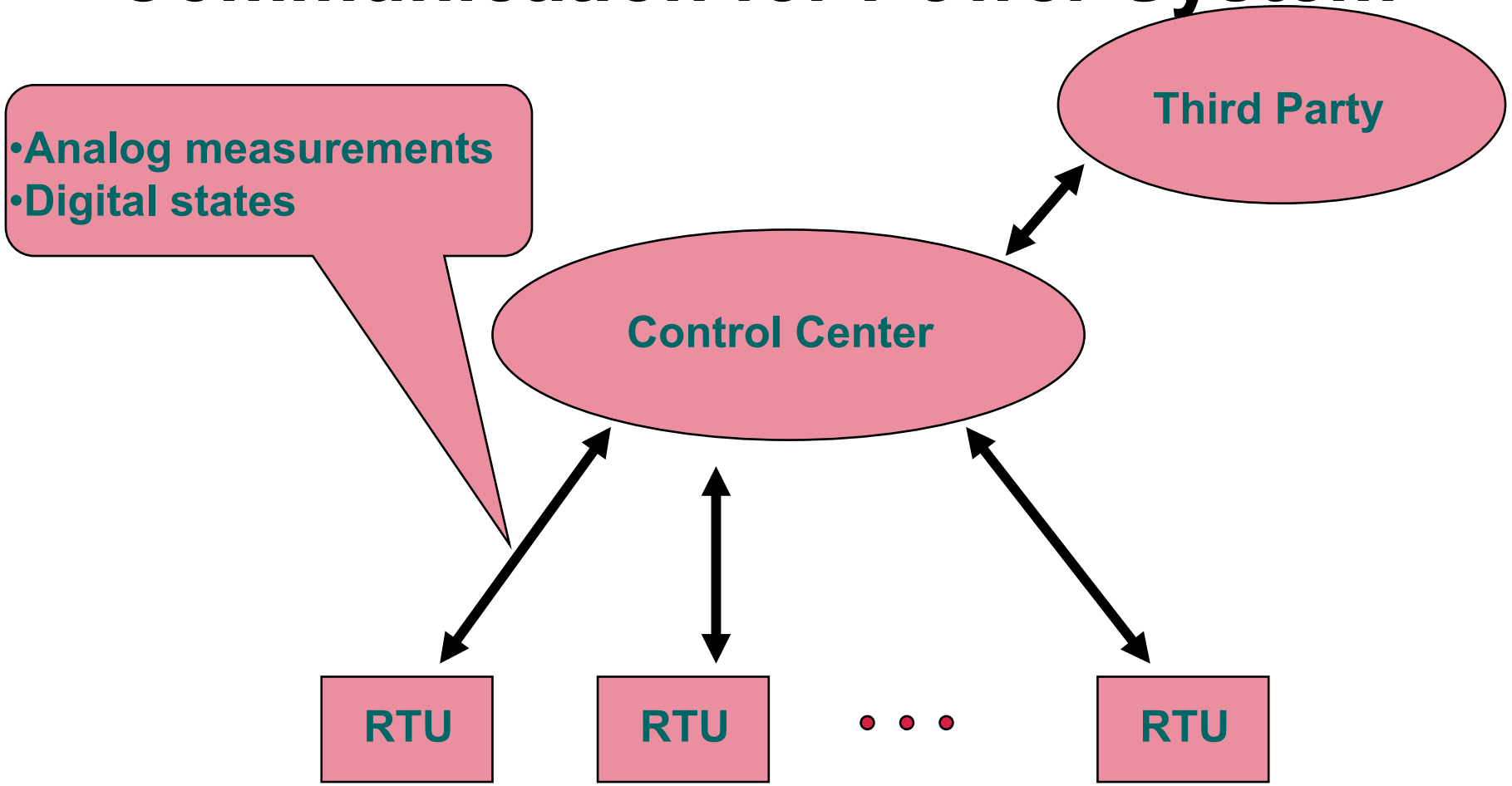
# The Past (before 1960s)

- Hard wired metering
- Ink chart recording
- Light and sound alarming
- Hard wired remote switching
- Analog Load Frequency Control (1930s)
- Economic Dispatch (1950s)
- ED was first to go digital

# The Present (since 1960s)

- The digital control center (SCADA-AGC)
- The RTU to gather digital data at substation
- Comm. channel from sub to control center (CC)
- The SCADA
  - The Data Acquisition from RTU to CC
  - The Supervisory Control signal from CC to RTU
- The screen based operator display
- Automatic Generation Control (AGC)
  - The digital algorithm for ED
  - The digital version of LFC

# Communication for Power System

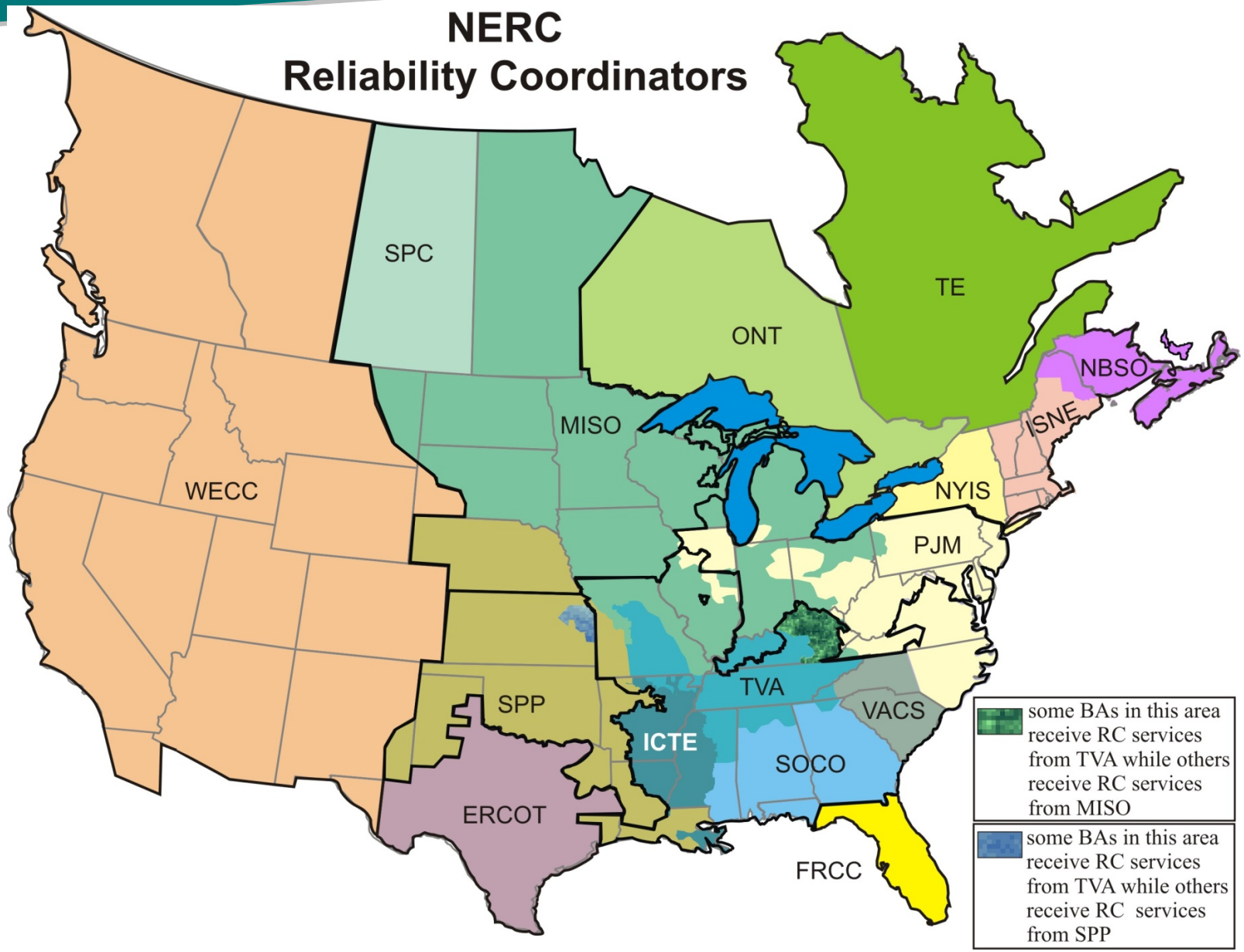


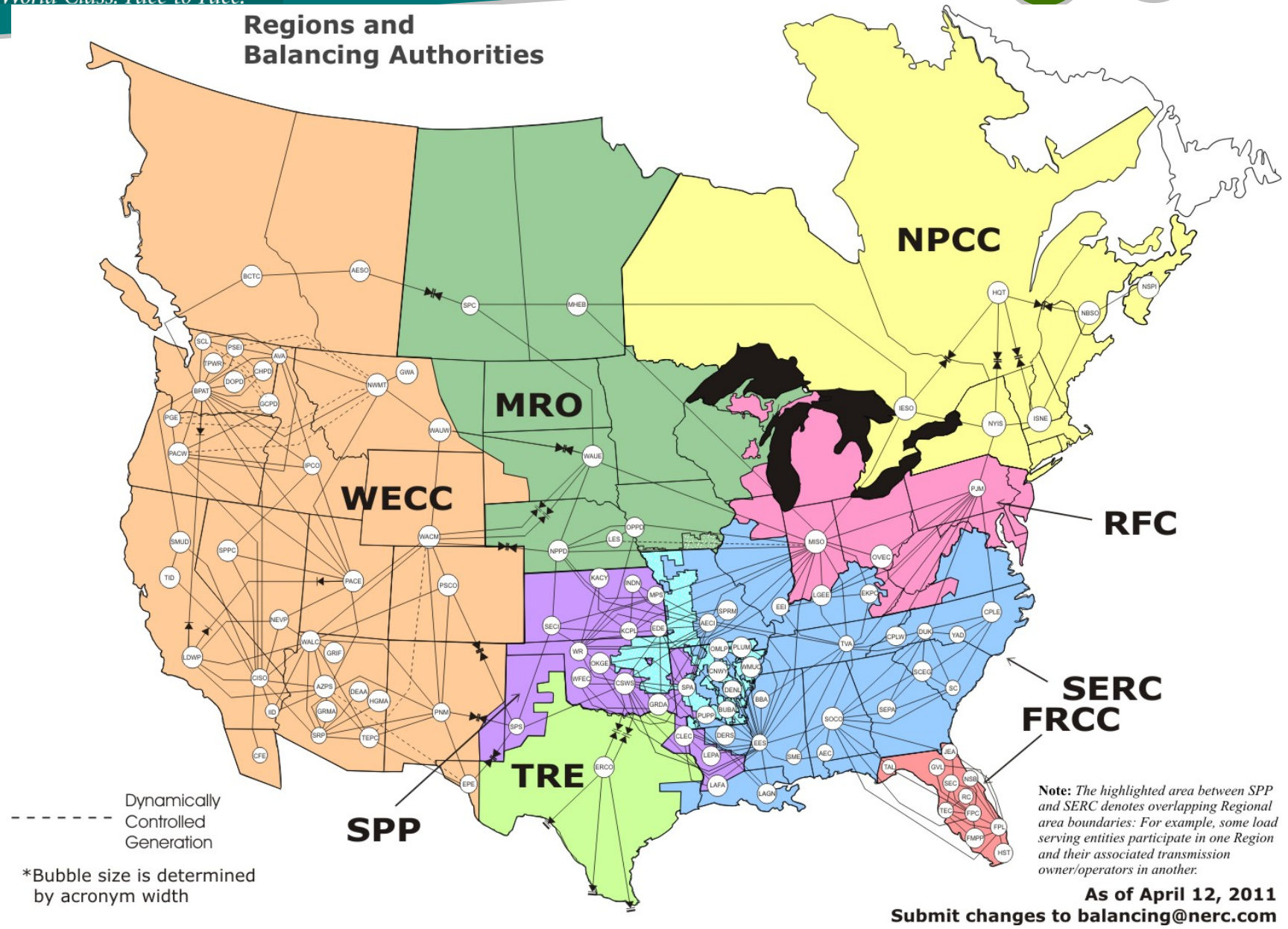
# The Present (since 1970s)

- The Energy Management System (EMS)
- State Estimation (SE)
- Static Security Analysis (n-1)
- Dynamic Security Analysis (stability)
  - Transient, Oscillatory, Voltage
- Optimal Power Flow based analysis
  - Preventive Action calculation
  - Corrective Action calculation

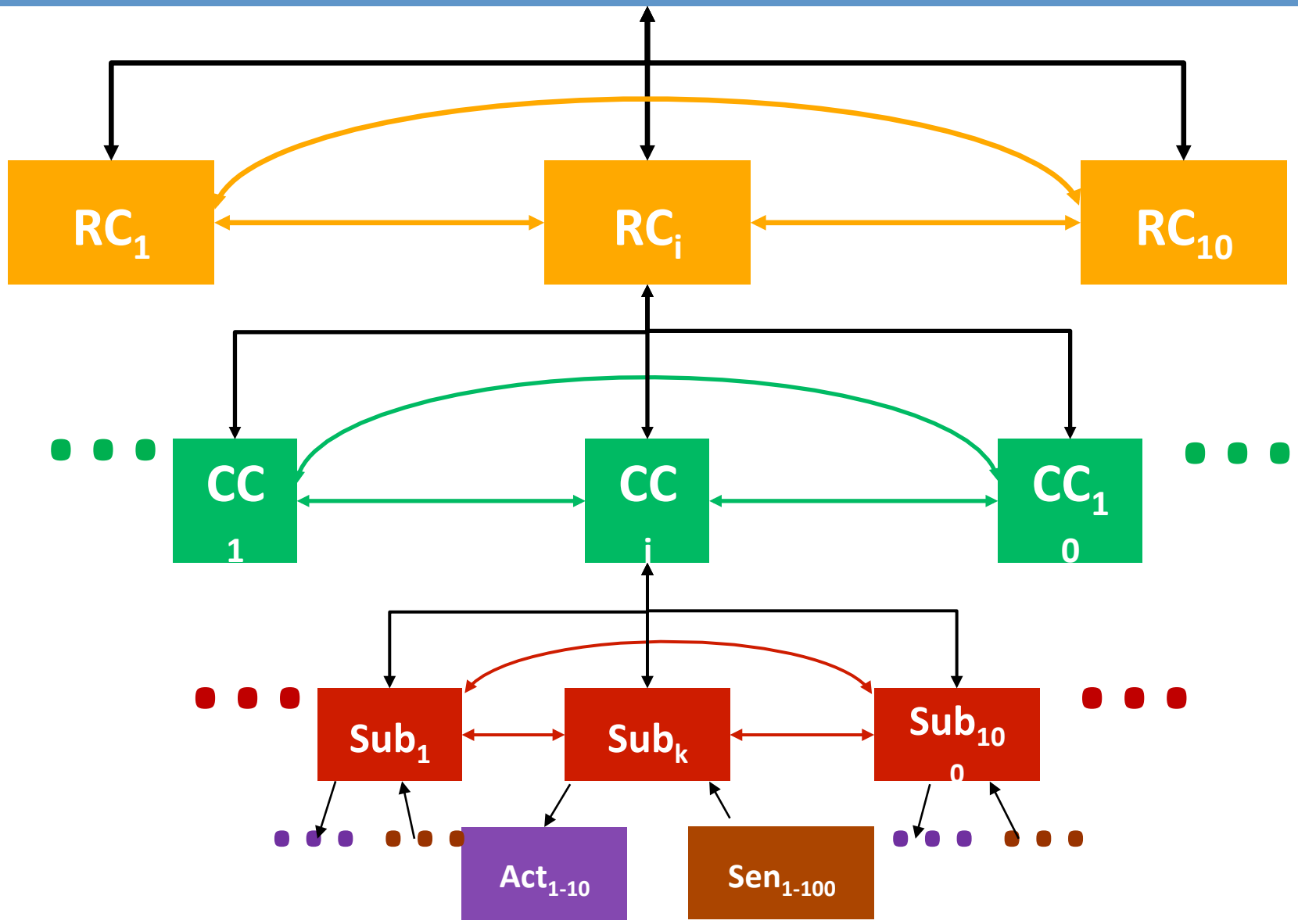
# Evolution of Computer Architecture

- Special real time computers for SCADA-AGC
- Mainframe computer back ends for EMS
- Redundant hardware configuration with checkpoint and failover
- Multiple workstation configuration
  - Back-up is more flexible
- Open architecture initiated
- CIM (Common Information Model) standard

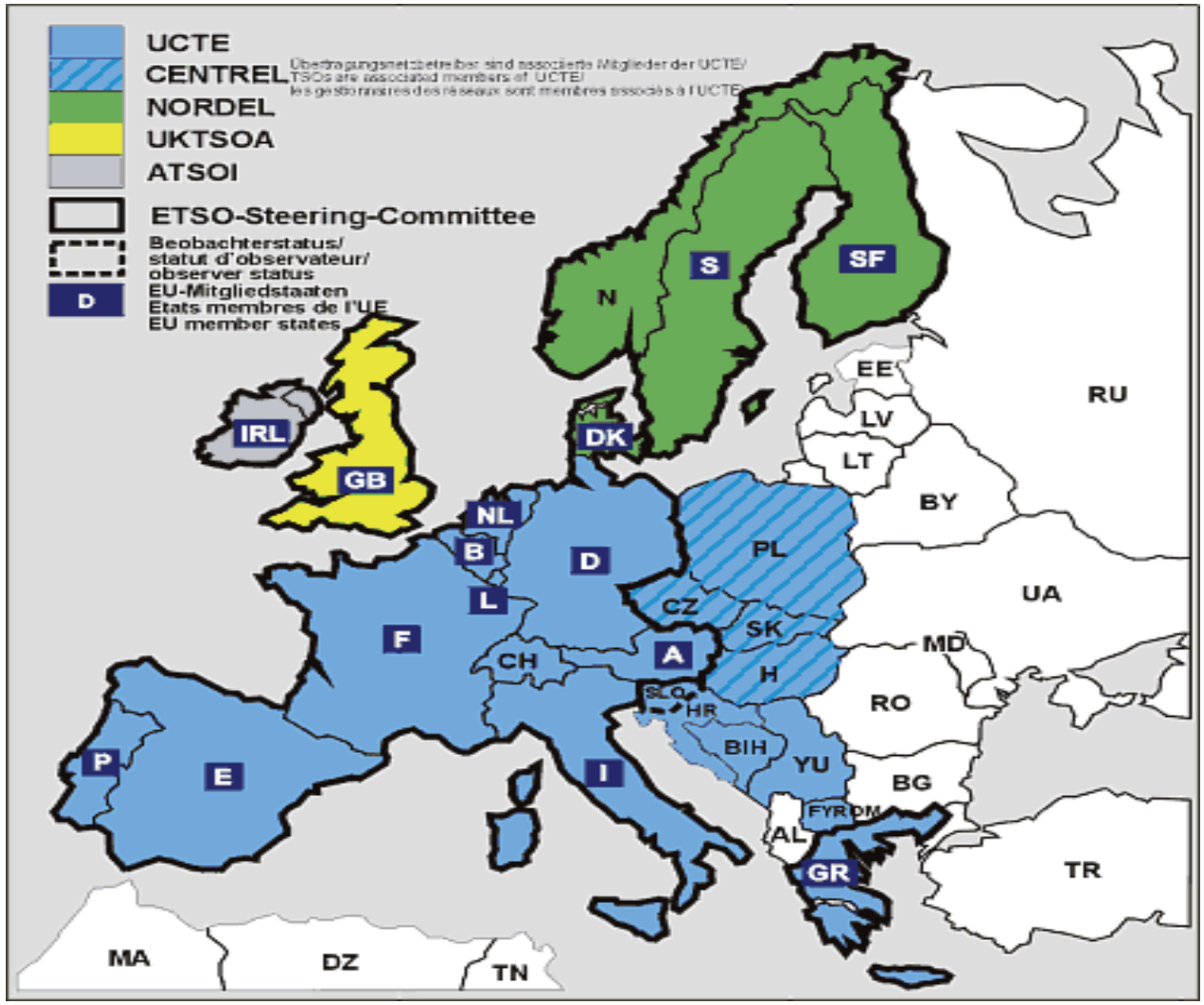

NERC
Reliability Coordinators
SPC
TE
ONT
NBSO
ISNE
MISO
WECC
NYIS
PJM
TVA
VACS
SPP
ICTE
SOCO
ERCOT
FRCC
some BAs in this area receive RC services from TVA while others receive RC services from MISO
some BAs in this area receive RC services from TVA while others receive RC services from SPP

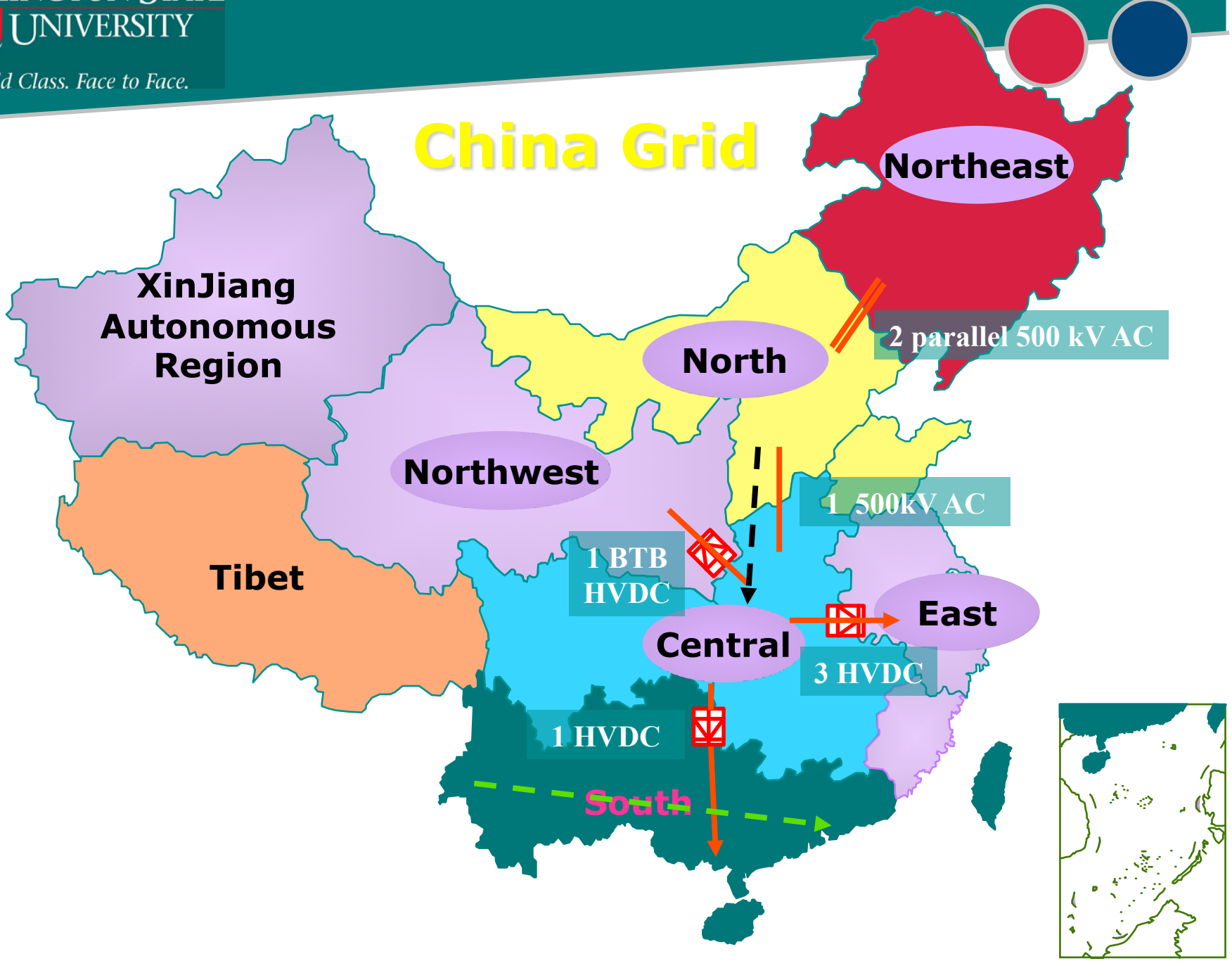

Regions and
Balancing Authorities
NPCC
MRO
WECC
RFC
SERC
FRCC
TRE
SPP
Dynamically
Controlled
Generation
*Bubble size is determined
by acronym width
Note: The highlighted area between SPP and SERC denotes overlapping Regional area boundaries: For example, some load serving entities participate in one Region and their associated transmission owner/operators in another.
As of April 12, 2011
Submit changes to balancing@nerc.com

# Eastern Interconnect Control/Monitoring Center

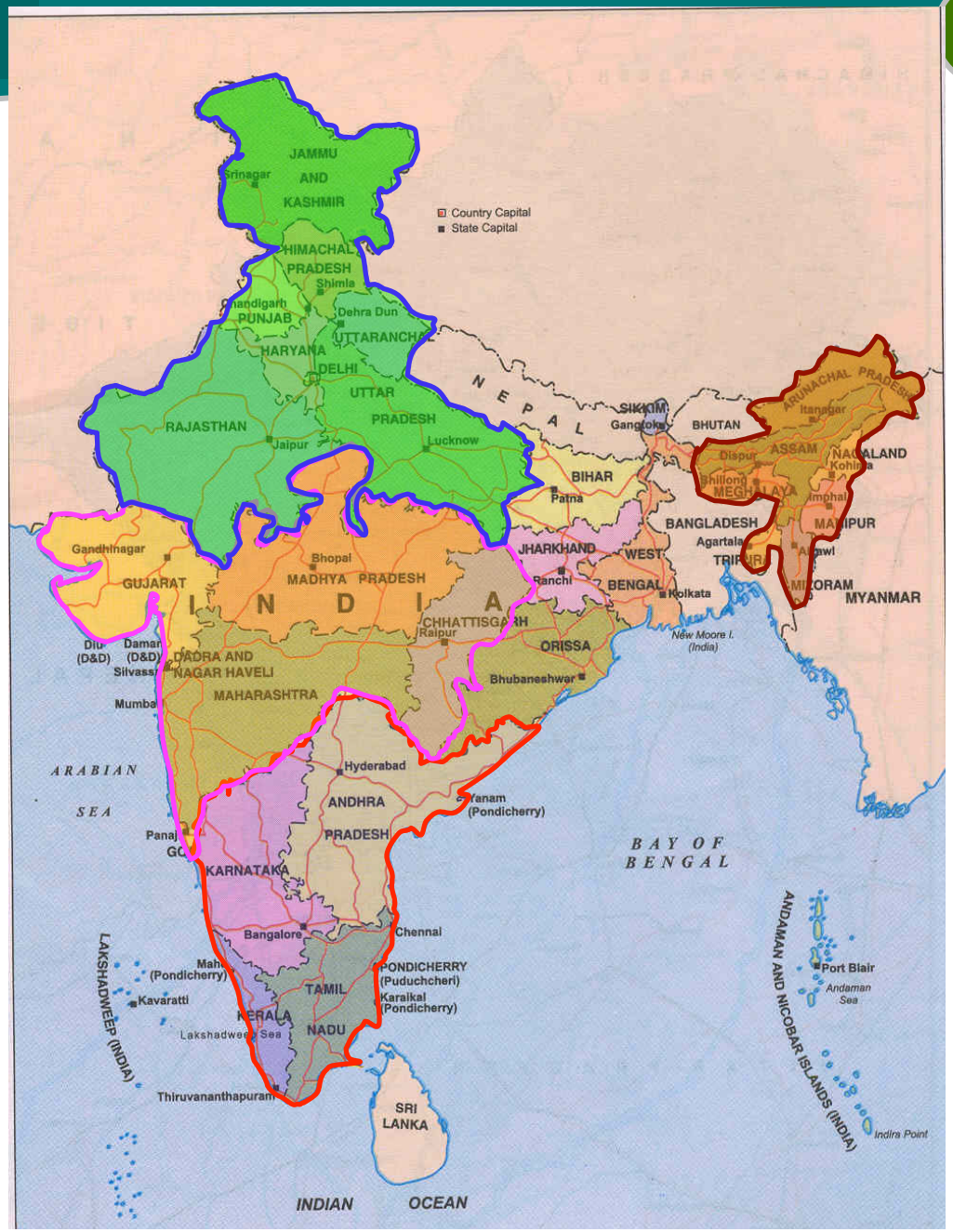


# West European Power Grid

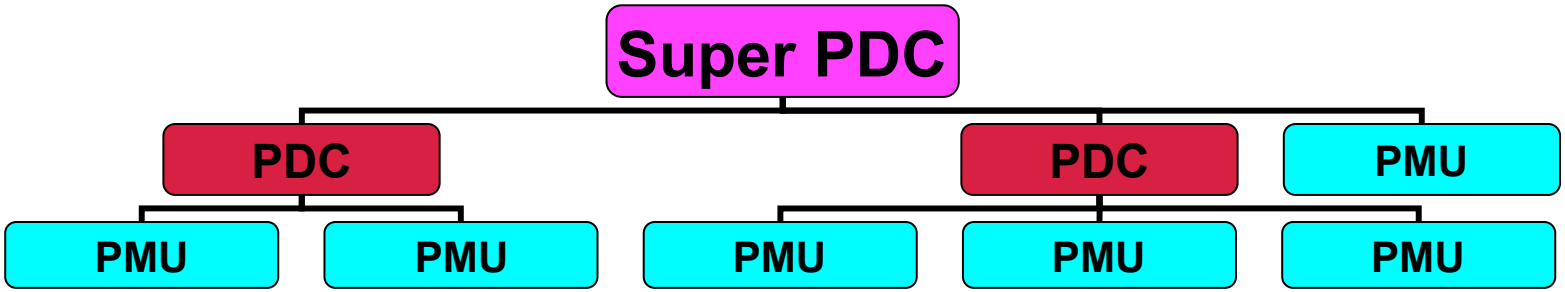



China Grid
Northeast
XinJiang Autonomous Region
North
2 parallel 500 kV AC
Northwest
1 500kV AC
1 BTB HVDC
Tibet
East
Central
3 HVDC
1 HVDC
South

# India Grid


JAMMU AND KASHMIR
Srinagar
HIMACHAL PRADESH
Shimla
PUNJAB
Dehra Dun
UTTARANCHAL
HARYANA
DELHI
UTTAR PRADESH
Lucknow
RAJASTHAN
Jaipur
Country Capital
State Capital
NEPAL
SIKKIM
Gangtok
BHUTAN
ARUNACHAL PRADESH
Itanagar
ASSAM
Dispur
NAGALAND
Kohima
MEGHALAYA
Shillong
Imphal
BIHAR
Patna
BANGLADESH
Agartala
TRIPURA
MIZORAM
MYANMAR
JHARKHAND
Ranchi
WEST BENGAL
Kolkata
Gandhinagar
GUJARAT
Bhopal
MADHYA PRADESH
I N D I A
CHHATTISGARH
Raipur
ORISSA
Bhubaneshwar
New Moore I. (India)
Diu (D&D)
Daman (D&D)
Silvassa
DADRA AND NAGAR HAVELI
MAHARASHTRA
Mumbai
ARABIAN SEA
Hyderabad
ANDHRA PRADESH
Yanam (Pondicherry)
Panaji
GOA
KARNATAKA
BAY OF BENGAL
Bangalore
Chennai
Mahe (Pondicherry)
Kavaratti
PONDICHERRY (Puduchcheri)
Karaikal (Pondicherry)
TAMIL NADU
KERALA
Lakshadweep Sea
LAKSHADWEEP (INDIA)
Thiruvananthapuram
SRI LANKA
INDIAN OCEAN
ANDAMAN AND NICOBAR ISLANDS (INDIA)
Port Blair
Andaman Sea
Indira Point

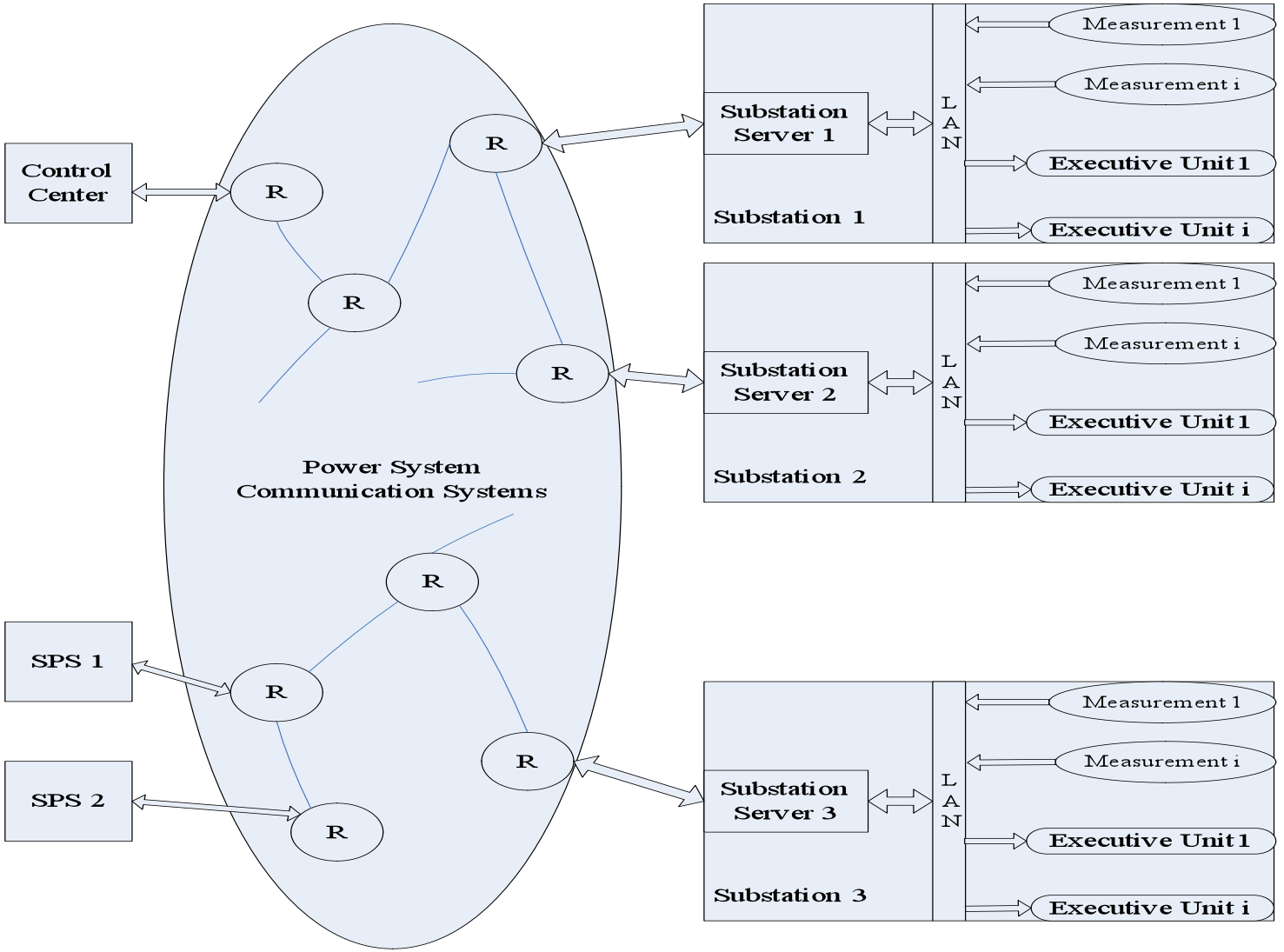
# Phasor Measurements



# What is Wide-Area Monitoring, Protection and Control?

- **Wide-Area Monitoring Systems (WAMS)**
  - First installation of PMUs was called WAMS
- **Wide-Area Protection**
  - Event driven
  - Logic processing of non-local inputs/outputs
  - Switching
  - Now called SPS or SIPS
- **Wide-Area Control**
  - Multiple non-local input/output
  - Analog input/output

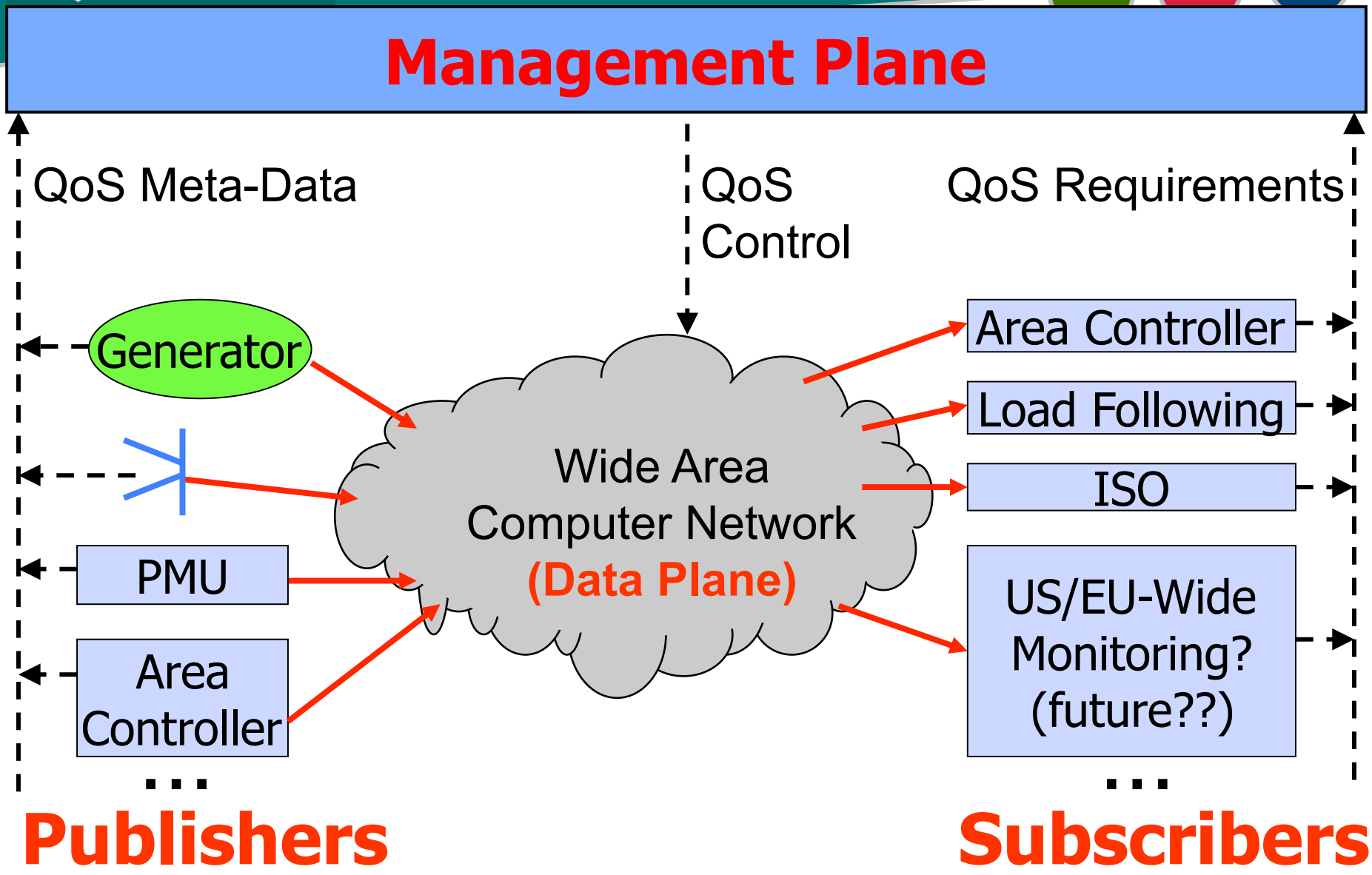
# Proposed Communications



# Each Application – Different Data

- **Monitoring at the control center**
  - Needs all data points
  - But at slow rates (every few seconds)
- **Special Protection Schemes**
  - Needs few data points
  - But at fast rates (many times a second)
- **Each application must access this data in a different way**
  - Moving real time data from source to application is a complex optimization task

# Basic GridStat Functionality



# Data Base Issues

- Real time data base must be distributed
  - Large amounts of calculated data must be part of this data base
- Static data base must be distributed
- Historical data base will require still another design
- Substation data bases and system level data bases have to be coordinated
- All data bases in the same interconnection will have to be coordinated
- Standards will be key

# Model Based Control

- Real Time Model is updated by State Estimator
  - Static model updated in minutes
- Hundreds of Contingency scenarios studied
  - Operator is alerted
- Remedial Action can be calculated by OPF

Can the loop be closed?

  - Faster update of Real Time Model is needed

# State Estimator and PMUs

- Present
  - PMU measurements added to traditional SE
  - Marginal improvement in accuracy
  - No improvement in update frequency
- Future
  - PMU-only SE (observability required)
  - Linear, sub-second updates, higher accuracy
  - Substation level/Area level

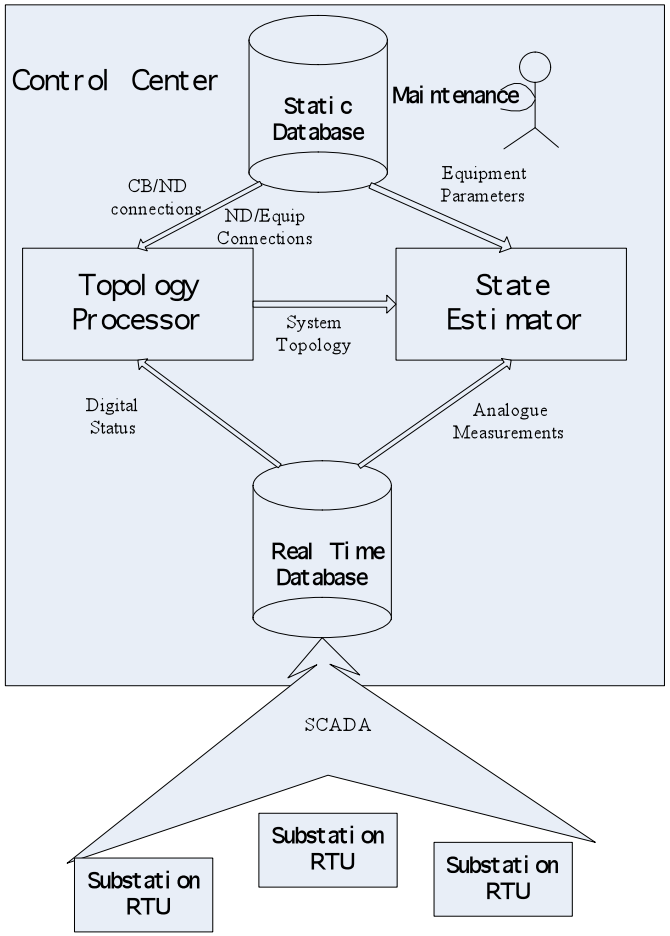
# Two-Level Linear State Estimator

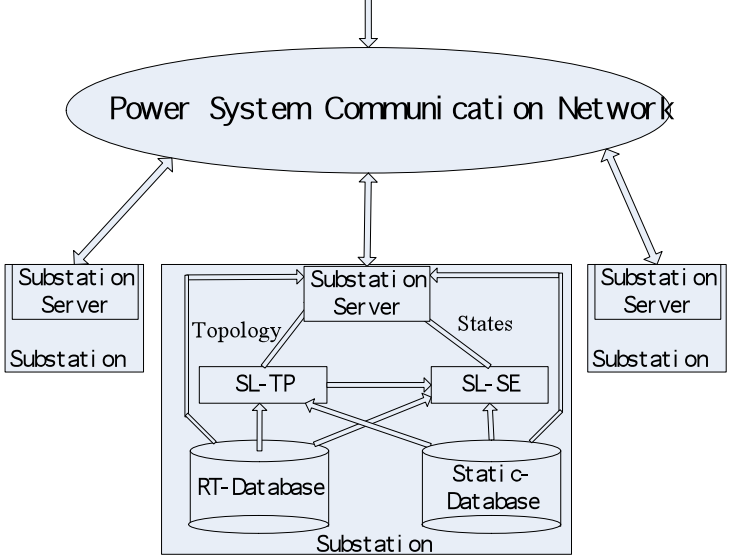
- Substation Level
  - Substation Model
  - Circuit Breaker State Estimator
  - Bus Voltage State Estimator
  - Bad Data Detection & Identification
- Control Center Level
  - System Model
  - Topology Processor (system level)
  - State Estimator
  - Bad Data Detection & Identification

# Closing the Loop

- SE can update faster than SCADA data today
- Use SE output for monitoring
  - Operator visualization
  - Alarming
- Calculate Preventive Control and close loop
- Calculate Corrective control
  - Is it fast enough to close loop?

# Database & Communication Architecture

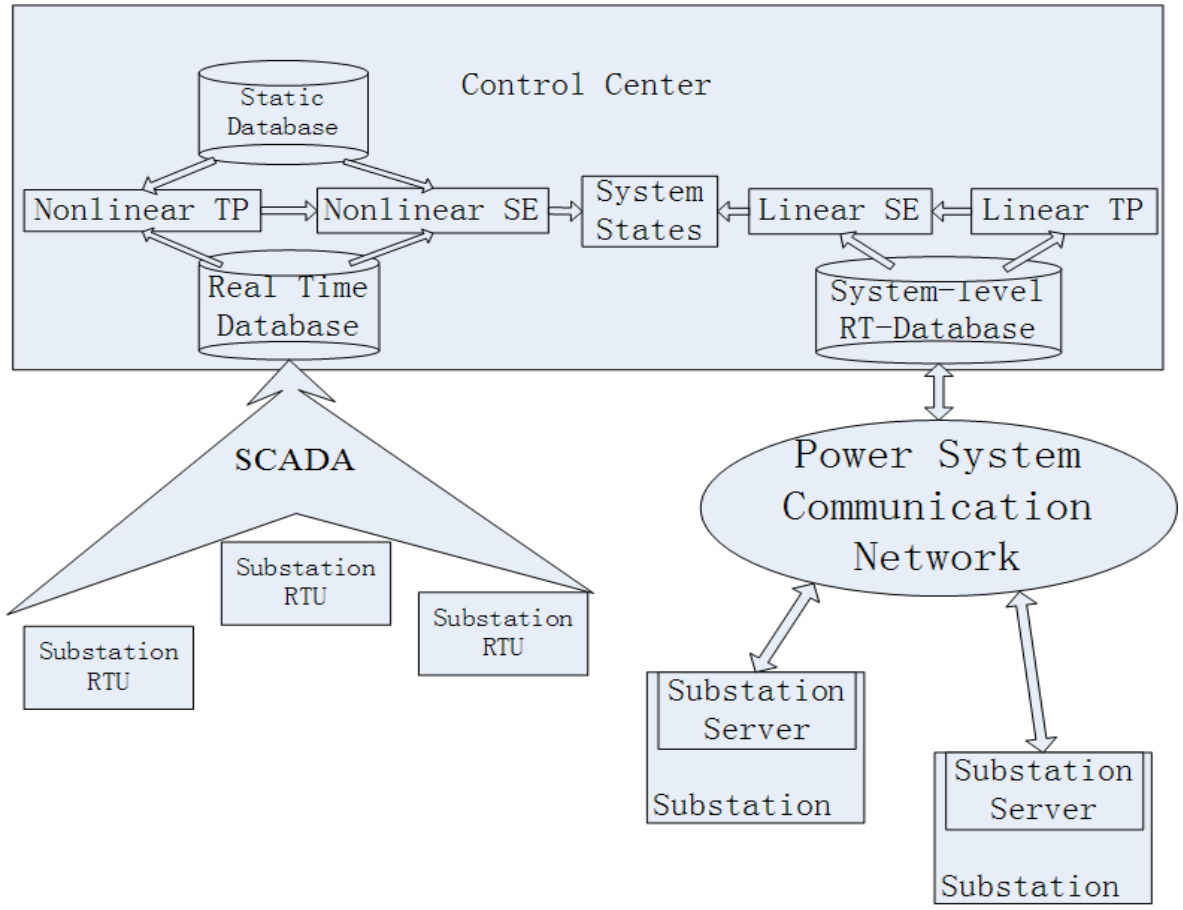



SL-TP: Substation Level Topology Processor
SL-SE: Substation Level State Estimator
RT: Real Time

# Transitional Multi-Area State Estimator

## Database & Communication Architecture



# Transitional Multi-Area State Estimator

- **State Estimation - Whole System**

$$\text{Min}\left(\sum_{i=1}^{p}\tilde{\mathbf{r}}_i^T\tilde{\mathbf{W}}_i\tilde{\mathbf{r}}_i+\sum_{j=1}^{q}\mathbf{r}_j\mathbf{W}_j\mathbf{r}_j\right)$$

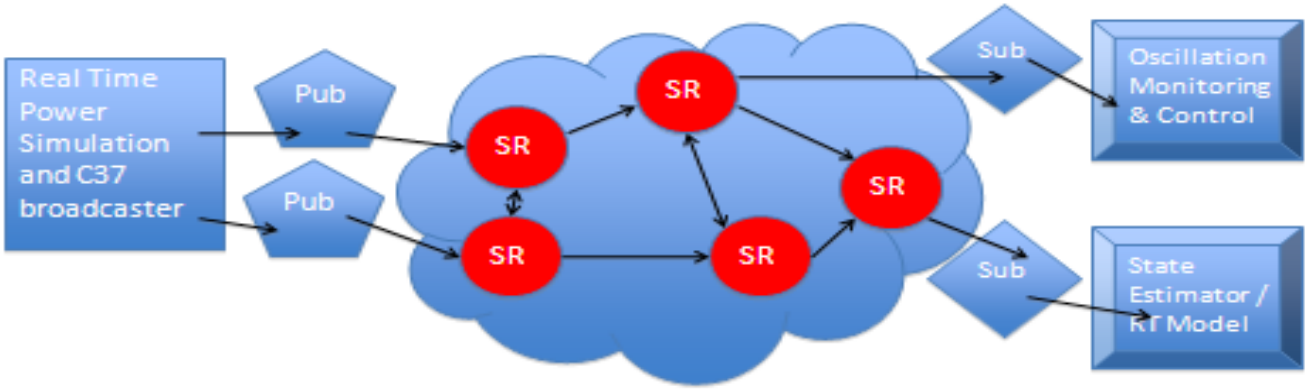
$$\text{s.t. } \tilde{\mathbf{z}}_i=\tilde{\mathbf{H}}_i\tilde{\mathbf{x}}_i+\tilde{\mathbf{r}}_i=\tilde{\mathbf{H}}_i[\tilde{\mathbf{x}}_{i,\text{int}}^T,\tilde{\mathbf{x}}_{i,\text{b}}^T]^T+\tilde{\mathbf{r}}_i$$

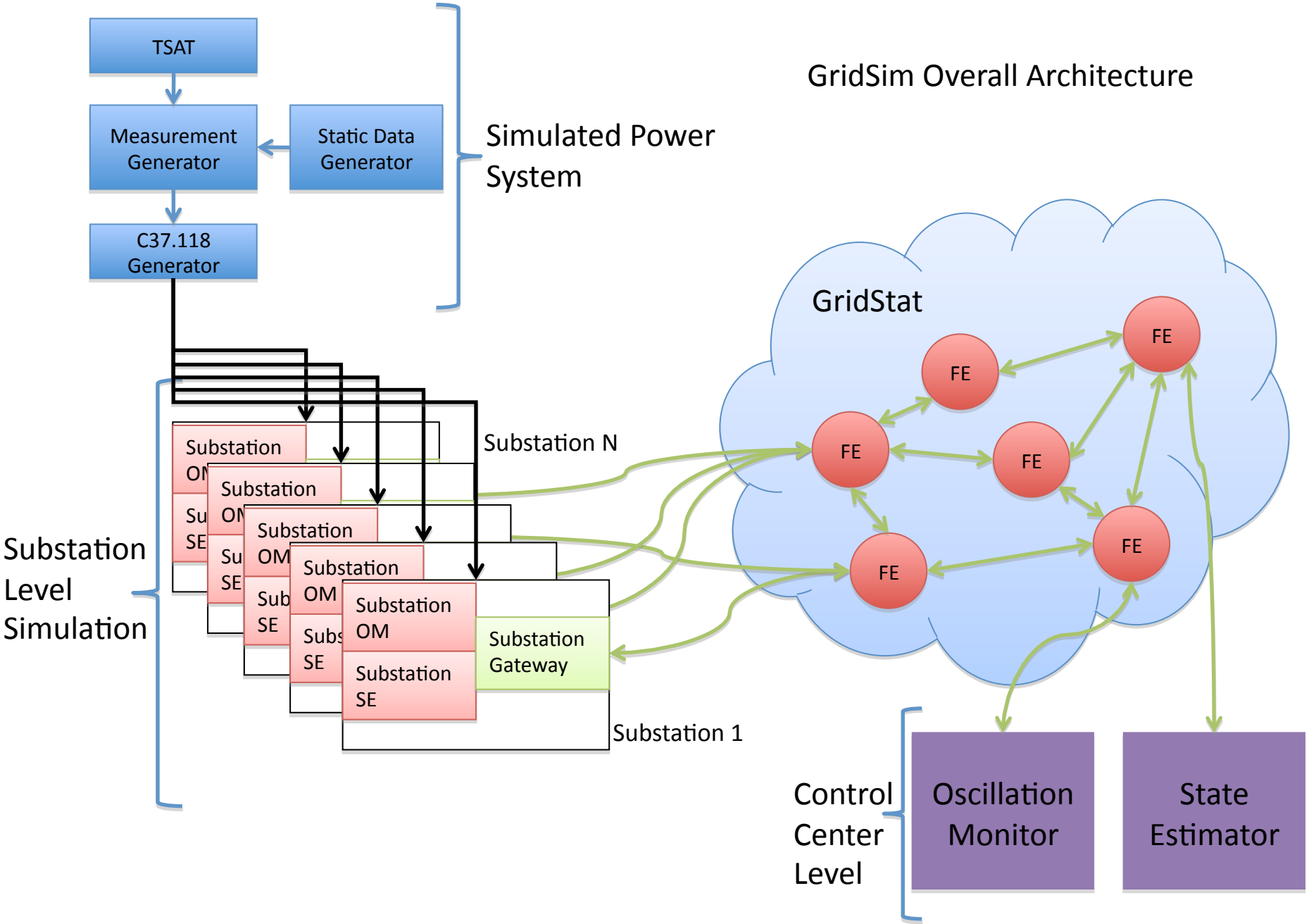
$$\mathbf{z}_j=\mathbf{h}_j(\mathbf{x}_j)+\mathbf{r}_j=\mathbf{h}_j([\mathbf{x}_{j,\text{int}}^T,\mathbf{x}_{j,\text{b}}^T]^T)+\mathbf{r}_j$$

  - **Linear Area**
  - **Non-linear Area**
  - **Boundary Buses**

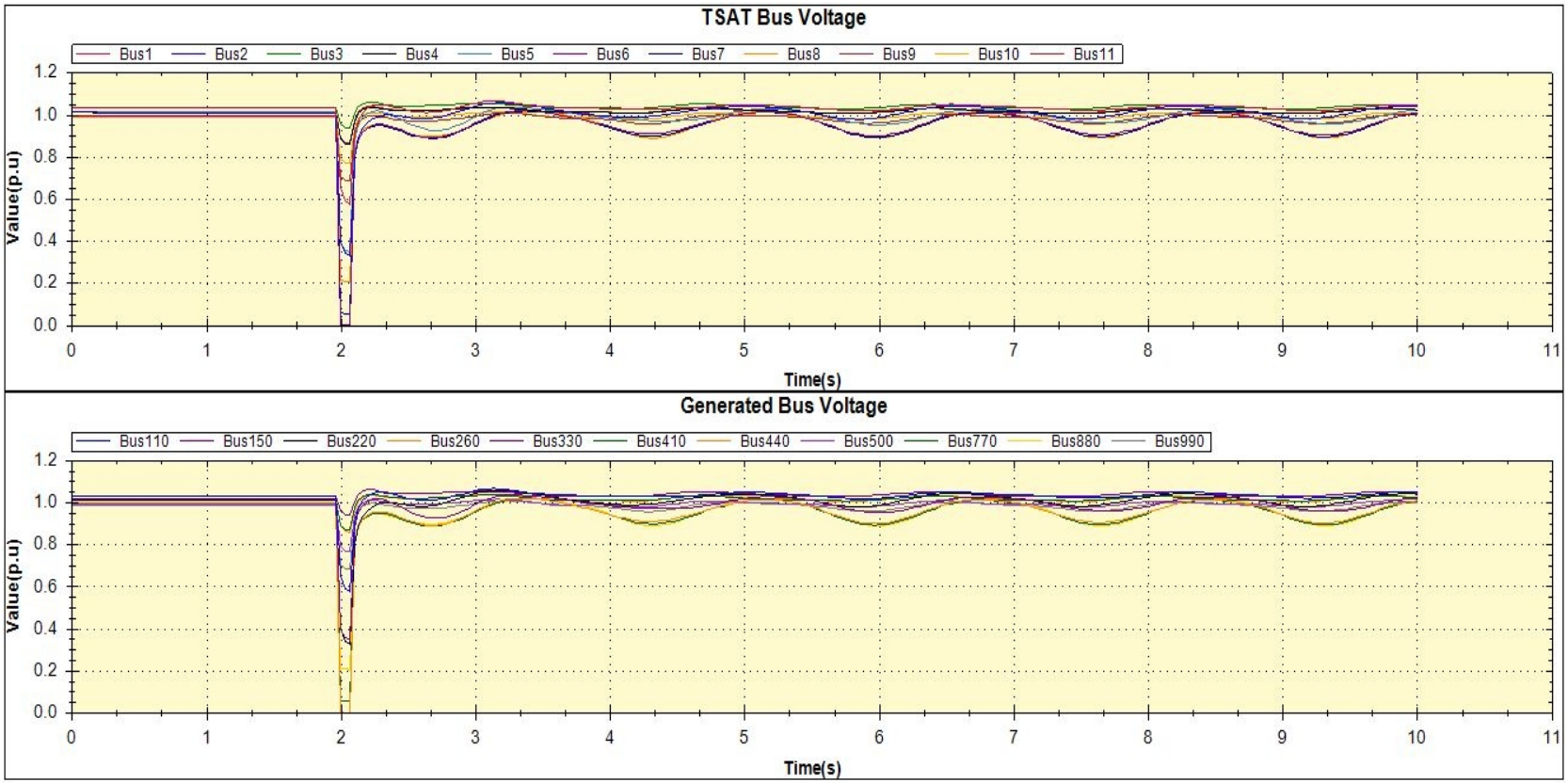
# Design of Wide Area Controls

## Simulation Test Bed for the Smart Grid

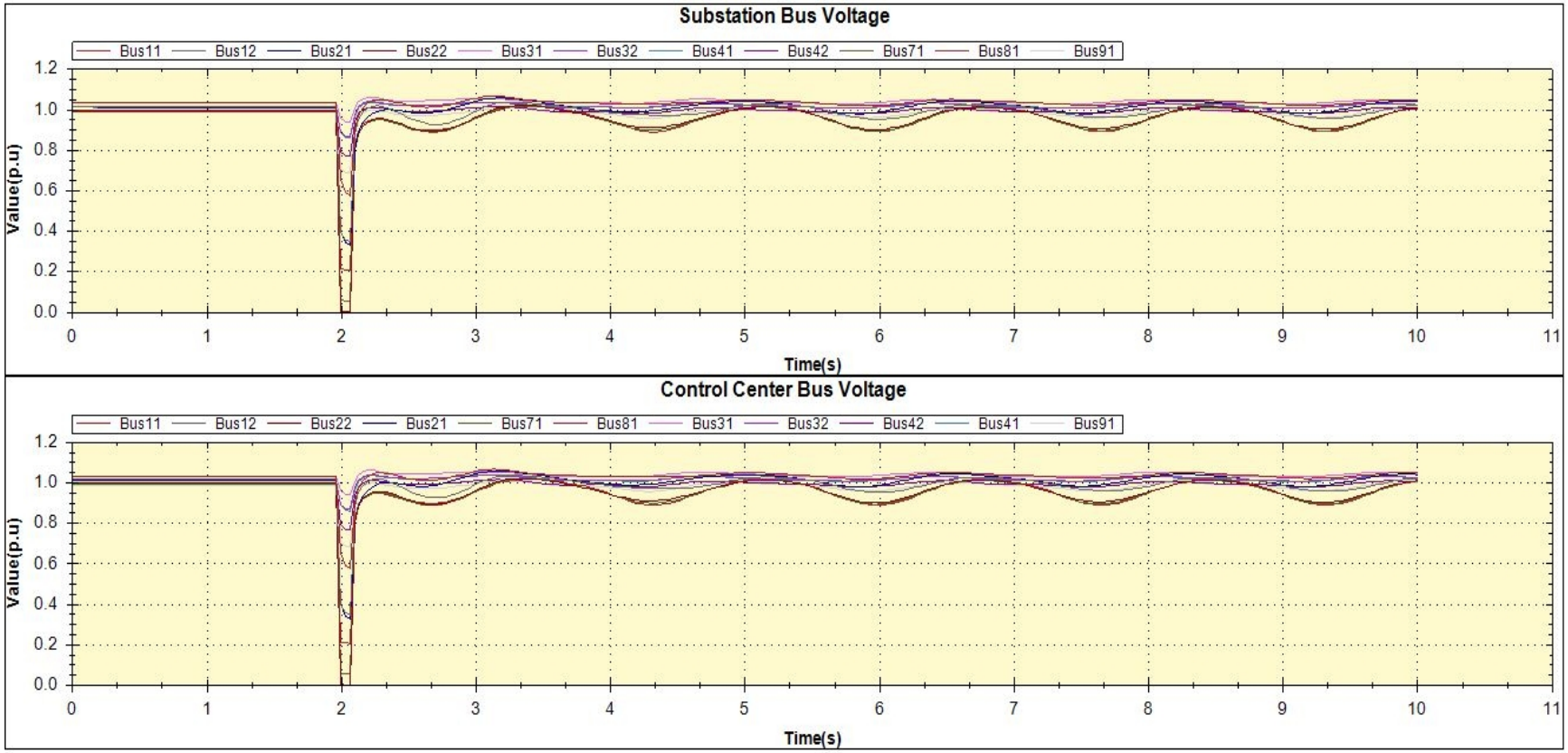



GridSim Overall Architecture
TSAT
Measurement Generator
Static Data Generator
C37.118 Generator
Simulated Power System
GridStat
FE
FE
FE
FE
FE
FE
Substation N
Substation OM
Substation SE
Substation Gateway
Substation 1
Substation Level Simulation
Control Center Level
Oscillation Monitor
State Estimator

# Simulated Bus Voltages by Powertech TSAT Generated PMU Measurements 33 msecs time steps



# SE Solution at Each Substation
# SE Solution at Control Center
# 30 times per second



# Conclusions

- Controls at the substation level get more sophisticated every day
- Real time data collection increases at the subs
- Utilizing these measurements and controls at the system level remains difficult
- The communication infrastructure to move this data has to be built
- The software infrastructure to handle the data has to be built
- Application development and testing environments are needed