UNM SCHOOL *of* ENGINEERING

Department of Electrical & Computer Engineering

Electric Grid Control: Algorithms & Open Problems

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Disclosures & Credits

- I know a little about control theory, less about the electrical grid, and until 6 weeks ago almost nothing about much of the material here.
- Material and help from Jason Stamp, David Wilson, Juan Torres, Rush Robinett of SNL, Ed Graham from UNM.

Power System Basics

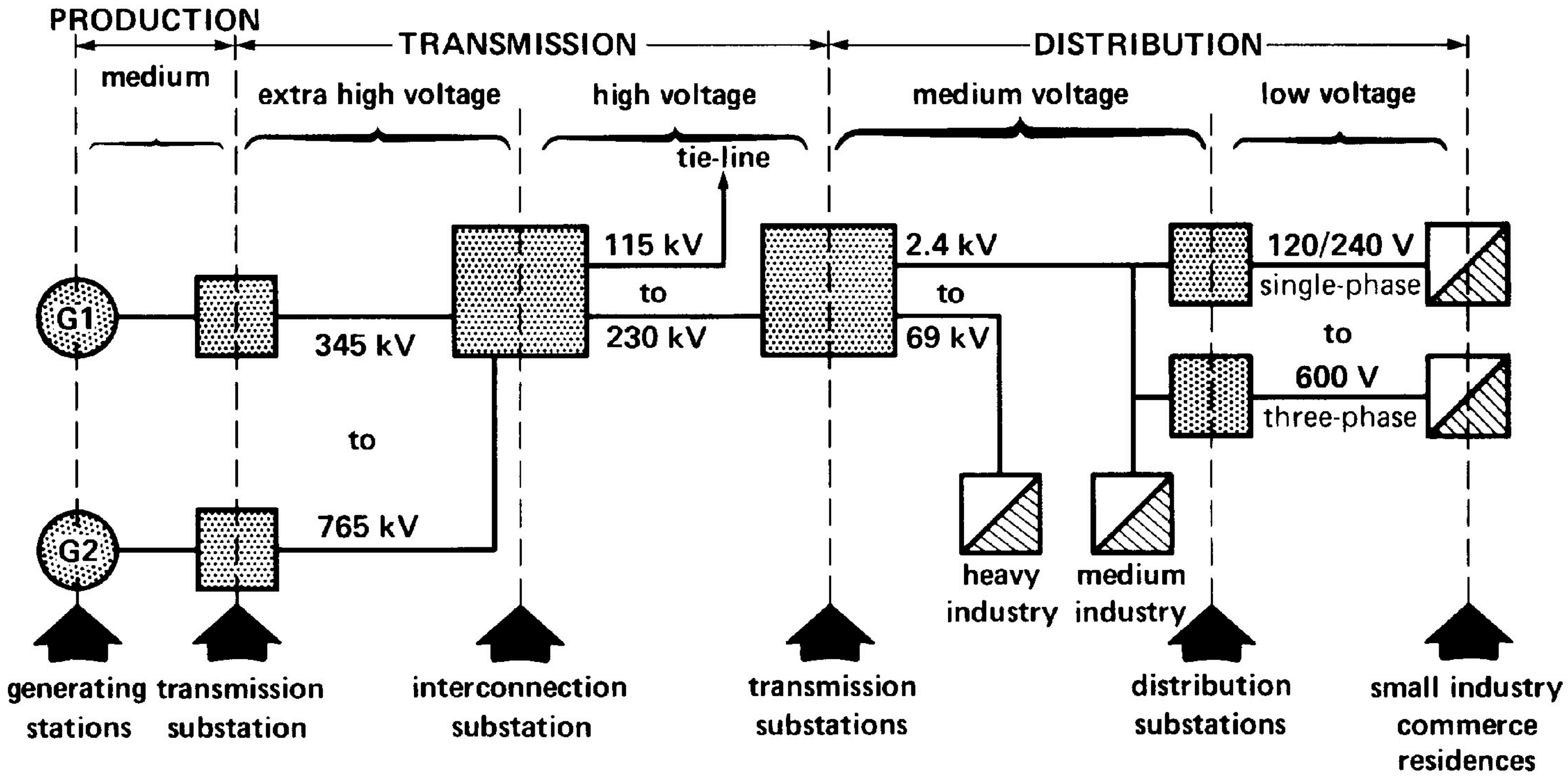
All power systems have three major groups: Generation, Load and Transmission/Distribution.

- Generation/Production: Creates electric power.
- Load: Consumes electric power.
- Transmission/Distribution: Transmits electric power from generation to load.
  - Lines/transformers operating at voltages above 100 kV are usually called the transmission system. The transmission system is usually networked.
  - Lines/transformers operating at voltages below 100 kV are usually called the distribution system (radial).

Electric Power Systems

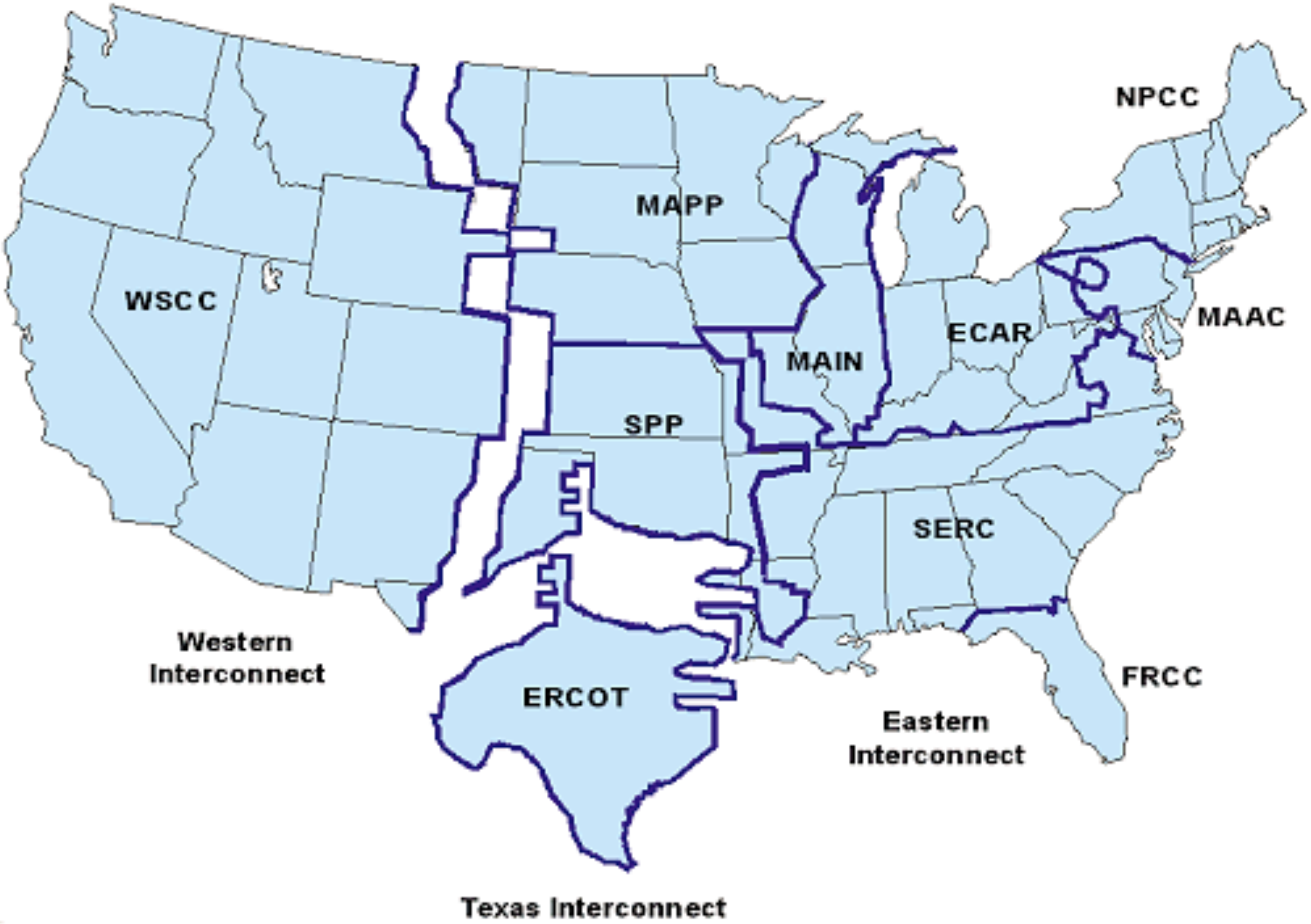
A modern electric power system consists of six components (in the 3 major groups):

1) The power station,
2) A set of transformers to raise the generated power to the high voltages used on the transmission lines,
3) The transmission lines,
4) The substations at which the power is stepped down to the voltage on the distribution lines,
5) The distribution lines, and
6) The transformers that lower the distribution voltage to the level used by the consumer's equipment.


PRODUCTION
TRANSMISSION
DISTRIBUTION
medium
extra high voltage
high voltage
medium voltage
low voltage
tie-line
G1
G2
345 kV
to
765 kV
115 kV
to
230 kV
2.4 kV
to
69 kV
120/240 V
single-phase
to
600 V
three-phase
heavy industry
medium industry
generating stations
transmission substation
interconnection substation
transmission substations
distribution substations
small industry
commerce
residences

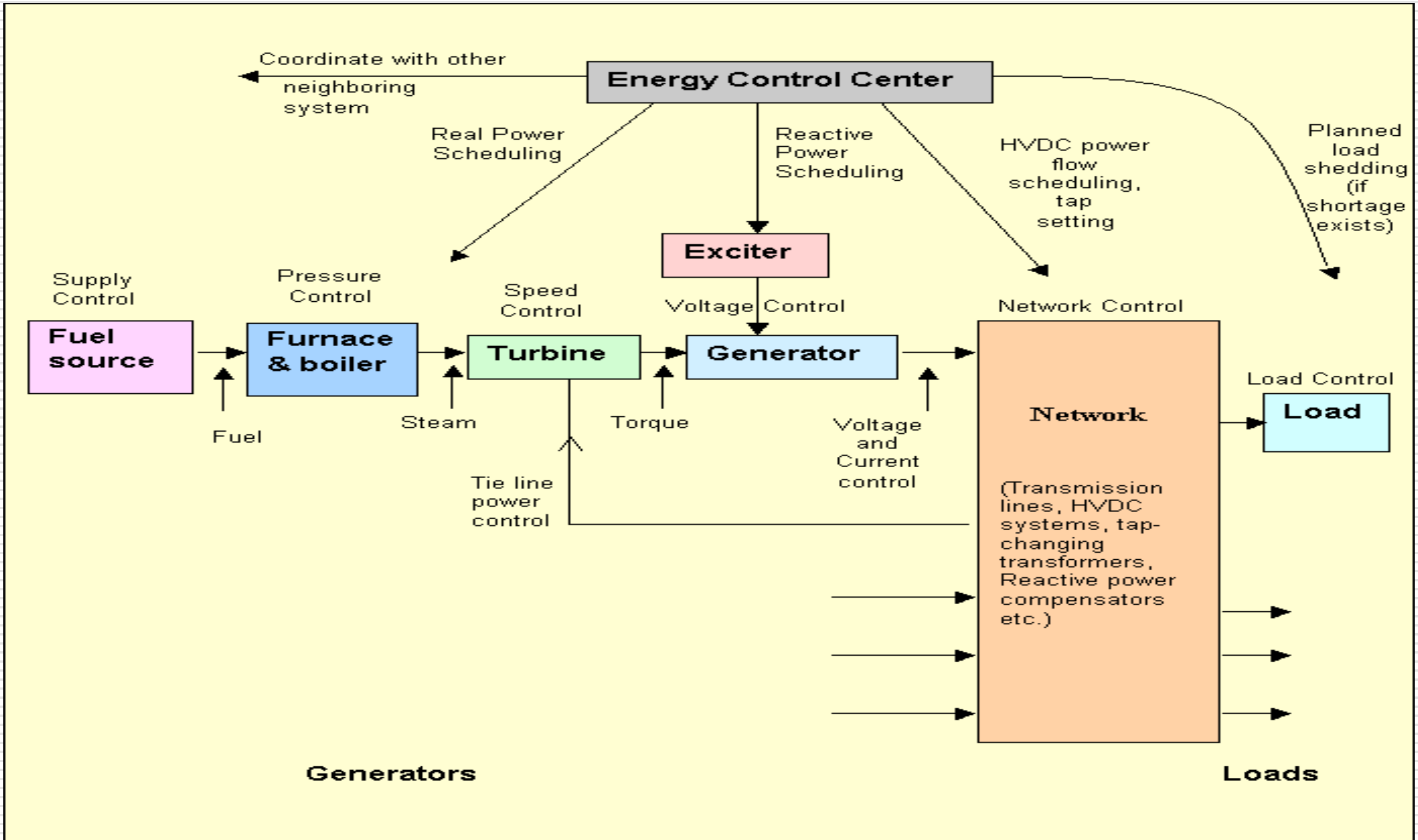
Interconnected Operation

- Power systems are interconnected across large distances. For example most of North America east of the Rockies is one system, most of North America west of the Rockies is another.
- Most of Texas is one interconnected system.
- Individual transmission owners in the East and West own and operate parts of the system, which is referred to an operating area (or an area).
- ERCOT is operated as one area.


NPCC
MAPP
WSCC
MAAC
ECAR
MAIN
SPP
SERC
Western Interconnect
FRCC
ERCOT
Eastern Interconnect
Texas Interconnect

Control Structure in the Power Industry

- Highly Hierarchical.
- In the beginning, everything was open-loop.
- After 1960’s blackout, US utilities built up their EMS and supporting SCADA or EHV and HV within their own power system.



Control Structure

Control Time scales

Action/Operation	**Time Frame**
Wave effects (fast dynamics, lightning-caused overvoltages)	Microseconds to milliseconds
Switching overvoltages	Milliseconds
Fault protection	100 ms
Electromagnetic effects in machine windings	Milliseconds to seconds
Stability	1 second
Stability augmentation	Seconds
Electromechanical effects of oscillations in motors & generators	Milliseconds to minutes

Control Time Scales

Action/Operation	Time Frame
Tie line load frequency control	1-10 seconds, ongoing
Economic load dispatch	10s seconds-1 hr, ongoing
Thermodynamic changes from boiler control action	Seconds to hours
System structure monitoring	Steady-state, ongoing
System state estimation	Steady-state, ongoing
Security monitoring	Steady-state, ongoing
Load management, forecasting	1 hr->1 day, ongoing
Maintenance scheduling	Months to 1-year, ongoing
Expansion planning	Years, ongoing
Power plant building	2-10 years +, ongoing

Control in the Eye of the Beholder

Feed-forward Control

1. Scheduling and forecasting over hours, days, weeks, seasons, etc, planning).
2. Preventive approach for managing uncertain equipment status

Feedback Control

1. Generator control
2. Transmission Supervisory Control & Data Acquisition (SCADA)
3. Transmission Energy Management Systems (EMS)
4. Protective relaying

Control Area (or Balancing Authority Area)

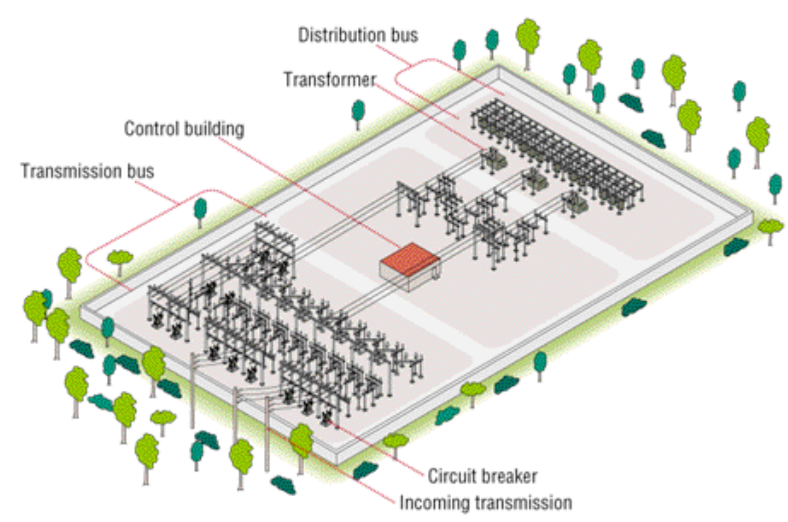
- Transmission lines that join two areas are known as tie-lines.
- The net power out of an area is the sum of the flow on its tie-lines.
- The flow out of an area is equal to

  total gen - total load - total losses = tie-flow

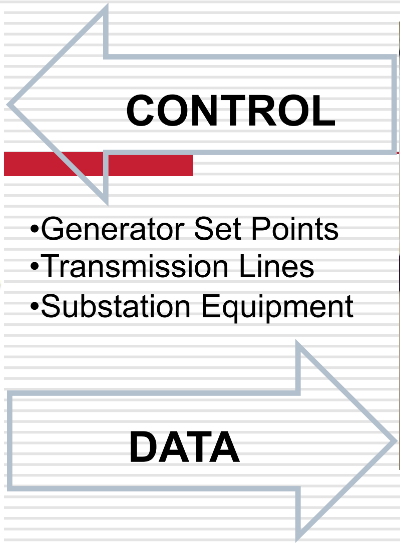
Automation Systems in Electric Power

- SCADA-Supervisory Control and Data Acquisition

  The All-encompassing government term for automation
- EMS-Energy Management System
- Protection-Relaying
- AGC-Automatic Generation Control
- WAP-Wide Area Protection



SCADA is used extensively in the electricity sector. Other SCADA applications include gas and oil pipelines, water utilities, transportation networks, and applications requiring remote monitoring and control. Similar to real-time process controls found in buildings and factory automation.



CONTROL

- Generator Set Points
- Transmission Lines
- Substation Equipment

DATA

- Critical Operational Data
- Performance Metering
- Events and Alarms

Communication Methods

- Directly wired
- Power line carrier
- Microwave
- Radio (spread spectrum)
- Fiber optic

Control Center

Provides network status, enables remote control, optimizes system performance, facilitates emergency operations, dispatching repair crews and coordination with other utilities.

Example: Area Control Error (ACE)

- The area control error is a combination of:
  - the deviation of frequency from nominal, and
  - the difference between the actual flow out of an area and the scheduled flow.
- Ideally the ACE should always be zero.
- Because the load is constantly changing, each utility must constantly change its generation to "chase" the ACE.

As an example, In ERCOT, ACE is predominantly due to frequency deviations from nominal.

Automatic Generation Control

- Automatic generation control (AGC) is used to automatically change generation to keep the ACE close to zero.
- Usually the utility control center or independent system operator calculates ACE based upon tie-line flows and frequency; then the AGC module sends control signals out to the generators every couple seconds.

Priorities of Control Systems

1. Safety
2. Protect equipment from damage
3. Reliability
4. Economics

Effects of Solar Storms (1/3)

The sprawling North American power grid resembles a large antenna, attracting electrical currents induced by giant solar storms. Severe space weather occurring during solar cycles has the potential to cause a large-scale blackout in North America.

John G. Kappenman, Minnesota Power, Duluth, Minn.; Lawrence J. Zanetti, Johns Hopkins University, Applied Physics Laboratory, Laurel, Md.; and William A. Radasky, Metatech, Goleta, Calif.

Effects of Solar Storms (2/3)

Disturbances caused by solar activity can disrupt these complex power grids. When the Earth's magnetic field captures ionized particles carried by the solar wind, geomagnetically induced currents (GIC) can flow through the power system, entering and exiting the many grounding points on a transmission network. GICs are produced when shocks resulting from sudden and severe magnetic storms subject portions of the Earth's surface to fluctuations in the planet's normally stable magnetic field.

Frequently Used Models

1. Electromagnetic transients
2. Transient stability
3. Mid-term, long-term dynamics
4. Frequency dynamics
5. Steady-state power flow
6. Operational planning
7. Investment planning.

Current practice

- Models 1 and 2 for protection
- Models 2-5 for control
- Models 2-4 for off-line, open-loop control.
- Models 4, 5 for AGC
- Model 5 is used for EMS and SCADA
- Models 5, 5 for scheduling & dispatch
- Models 6, 7 for planning

General DAE Models

$$\frac{dx}{dt} = f(x,u,p,d)$$

$$0 = g(x,u,y,p,d)$$

Where the state vector contains variable such as frequencies, voltages, mechanical power, etc.
The output contains frequencies and voltages
The input is a vector that contains control of generators, etc.
The parameter vector contains forecast demand, inertia & damping, ..
The disturbance vector contains deviation of real and reactive power demand
The control objective is to drive the frequency and the voltage to their desired values.

Simplifying Assumptions

- Real power and its corresponding electromechanical variables (frequency, generator rotor angle) are decoupled from the reactive power and the electromagnetic variables (voltage behind the transient reactance of a generator).
- This reduces the DAE model to the "classical" model of an interconnected power system:

$$\frac{d\delta_G}{dt} = \omega_G - \omega_G^{ref}$$

$$M\frac{d\omega_G}{dt} = P_{mech} - A^T p - D(\omega_G - \omega_G^{ref})$$

Simplify

- Assume steady-state equilibrium for forecast demand in the entire interconnection.
- Assume small deviations and Linearize and obtain under restrictive conditions an ODE model of the form

$$\frac{dx}{dt} = Ax + Bu$$

$$y = Cx$$

Then Simplify

- Assume real power/voltage decoupling. Disconnect the grid (assume isolated control areas), and that each local dynamics is stable.
- Temporal separation of frequency dynamics.
- Temporal separation of voltage dynamics.
- Assume localized response to disturbances and monotonicity.

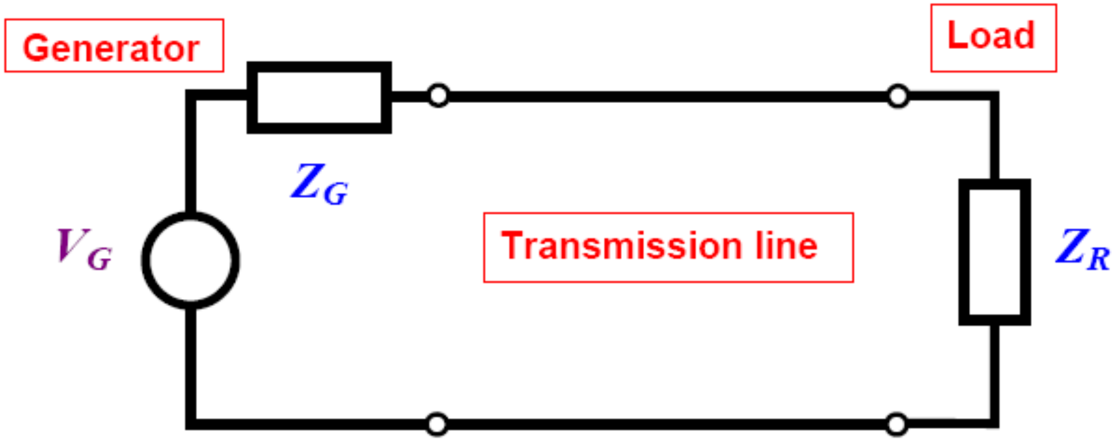
Or use Abstraction

- If each node is stable, can one model the interaction between many nodes in a more efficient way?
- Yes! Using abstraction.
- SNL is doing so, and UNM has done it for a different application.

Transmission Line Equations

A typical engineering problem involves the transmission of a signal from a generator to a load. A transmission line is the part of the circuit that provides the direct link between generator and load.

Transmission lines can be realized in a number of ways. Common examples are the parallel-wire line and the coaxial cable. For simplicity, we use in most diagrams the parallel-wire line to represent circuit connections, but the theory applies to all types of transmission lines.



Review of Phasors

Goal of phasor analysis is to simplify the analysis of constant frequency ac systems

$$v(t) = V_{max}\cos(\omega t + \theta_v),$$

$$i(t) = I_{max}\cos(\omega t + \theta_I).$$

Root Mean Square (RMS) voltage of sinusoid:

$$\sqrt{\frac{1}{T}\int_0^T v(t)^2\,dt} = \frac{V_{\max}}{\sqrt{2}}.$$

Phasor Representation

Euler's Identity: $e^{j\theta} = \cos\theta + j\sin\theta$,

Phasor notation is developed by rewriting using Euler's identity:

$$v(t) = \sqrt{2}\,|V|\cos(\omega t + \theta_V),$$

$$v(t) = \sqrt{2}\,|V|\,\mathrm{Re}\left[e^{j(\omega t + \theta_V)}\right].$$

(Note: $|V|$ is the RMS voltage).

Phasor Representation, cont'd

The RMS, cosine-referenced voltage phasor is:

$$
\begin{aligned}
V &= |V| e^{j\theta_V} = |V| \angle \theta_V, \\
v(t) &= \mathrm{Re} \sqrt{2}\, V e^{j\omega t} e^{j\theta_V}, \\
V &= |V| \cos\theta_V + j |V| \sin\theta_V, \\
I &= |I| \cos\theta_I + j |I| \sin\theta_I.
\end{aligned}
$$

Complex Power

Instantaneous Power :

$$
\begin{aligned}
p(t) &= v(t)\, i(t), \\
v(t) &= V_{\max} \cos(\omega t + \theta_V), \\
i(\mathrm{t}) &= I_{\max} \cos(\omega t + \theta_I), \\
\cos\alpha \cos\beta &= \frac{1}{2}[\cos(\alpha - \beta) + \cos(\alpha + \beta)], \\
p(t) &= \frac{1}{2} V_{\max} I_{\max} [\cos(\theta_V - \theta_I) + \\
&\quad \cos(2\omega t + \theta_V + \theta_I)].
\end{aligned}
$$

Complex Power, cont'd

Instantaneous Power is sum of average and varying terms :

$$p(t) = \frac{1}{2}V_{\max}I_{\max}[\cos(\theta_V - \theta_I) + \cos(2\omega t + \theta_V + \theta_I)],$$

$$P_{avg} = \frac{1}{T}\int_0^T p(t)dt,$$

$$= \frac{1}{2}V_{\max}I_{\max}\cos(\theta_V - \theta_I),$$

$$= |V||I|\cos(\theta_V - \theta_I),$$

Power Factor Angle $= \ \phi = \theta_V - \theta_I .$

Complex Power, cont'd

Re - interpretation of instantaneous Power :

$$
\begin{aligned}
p(t) &= \frac{1}{2} V_{\max} I_{\max} [\cos(\theta_V - \theta_I) + \cos(2\omega t + \theta_V + \theta_I)], \\
&= \frac{1}{2} V_{\max} I_{\max} [\cos(\theta_V - \theta_I) + \cos(2\omega t + 2\theta_V - (\theta_V - \theta_I))], \\
&= \frac{1}{2} V_{\max} I_{\max} [\cos(\theta_V - \theta_I) + \cos(2\omega t + 2\theta_V)\cos(\theta_V - \theta_I)] \\
&\quad + \frac{1}{2} V_{\max} I_{\max} \sin(2\omega t + 2\theta_V)\sin(\theta_V - \theta_I),
\end{aligned}
$$

Second term is power into electric and magnetic fields.

Complex Power

$$S = |V||I|[\cos(\theta_V - \theta_I) + j\sin(\theta_V - \theta_I)],$$

$$= P + jQ,$$

$$= V\,I^*,$$

P = Real Power (W, kW, MW),

Q = Reactive Power (VAr, kVAr, MVAr),

= magnitude of power into electric and magnetic fields,

S = Complex power (VA, kVA, MVA),

Power Factor (pf) = $\cos\phi$,

If current leads voltage then pf is leading,

If current lags voltage then pf is lagging.

Conservation of Power

- At every node (bus) in the system:
    - Sum of real power into node must equal zero,
    - Sum of reactive power into node must equal zero.
- This is a direct consequence of Kirchhoff's current law, which states that the total current into each node must equal zero.
    - Conservation of real power and conservation of reactive power follows since $S = VI^*$.

Power Consumption in Devices

Resistors only consume real power:

$$P_{\text{Resistor}} = \left|I_{\text{Resistor}}\right|^2 R,$$

Inductors only "consume" reactive power:

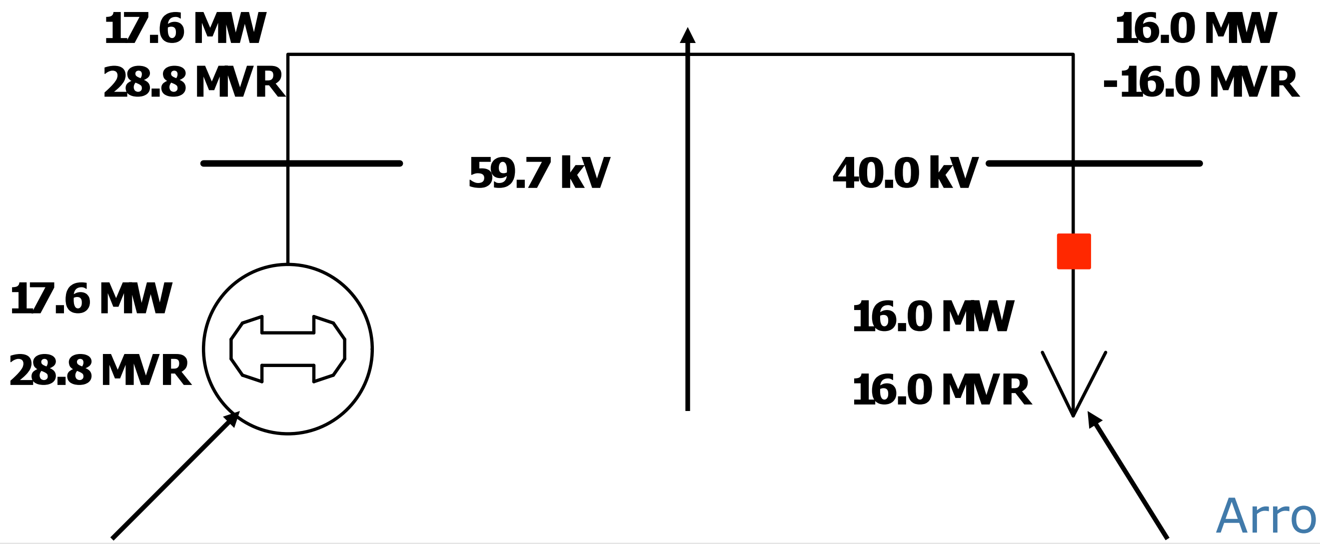
$$Q_{\text{Inductor}} = \left|I_{\text{Inductor}}\right|^2 X_{\text{L}},$$

Capacitors only "generate" reactive power:

$$Q_{\text{Capacitor}} = -\left|I_{\text{Capacitor}}\right|^2 X_{\text{C}} \qquad X_C = \frac{1}{\omega C}.$$

$$Q_{\text{Capacitor}} = -\frac{\left|V_{\text{Capacitor}}\right|^2}{X_{\text{C}}}.$$ (Note-some define X_C negative.)

Power System Notation



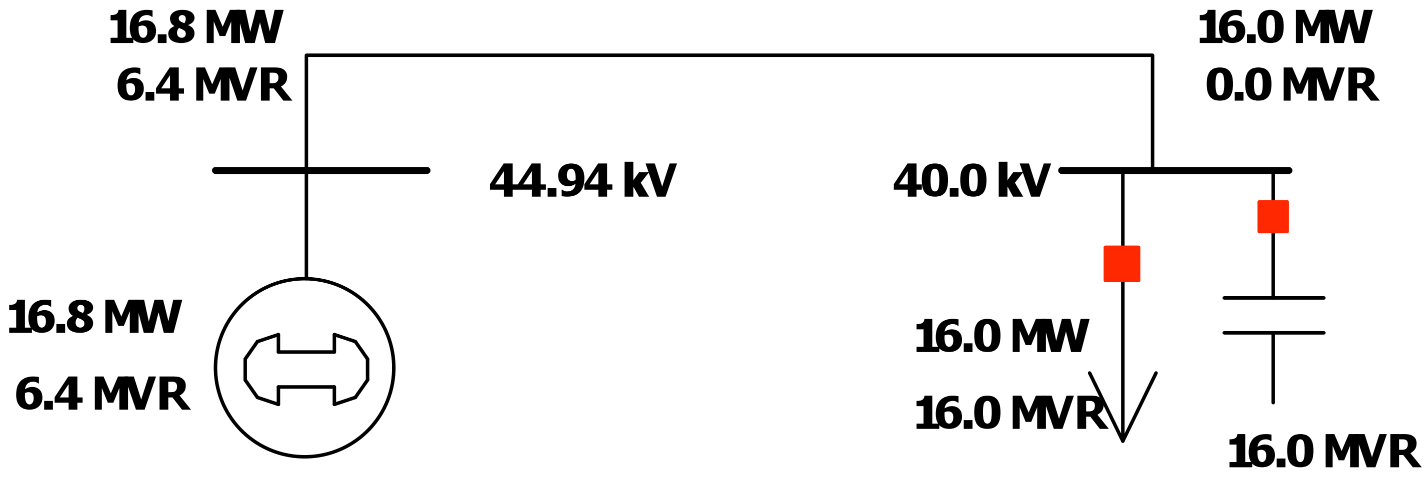
Generators are shown as circles

Transmission lines are shown as a single line

Arrows are used to show loads

Reactive Compensation

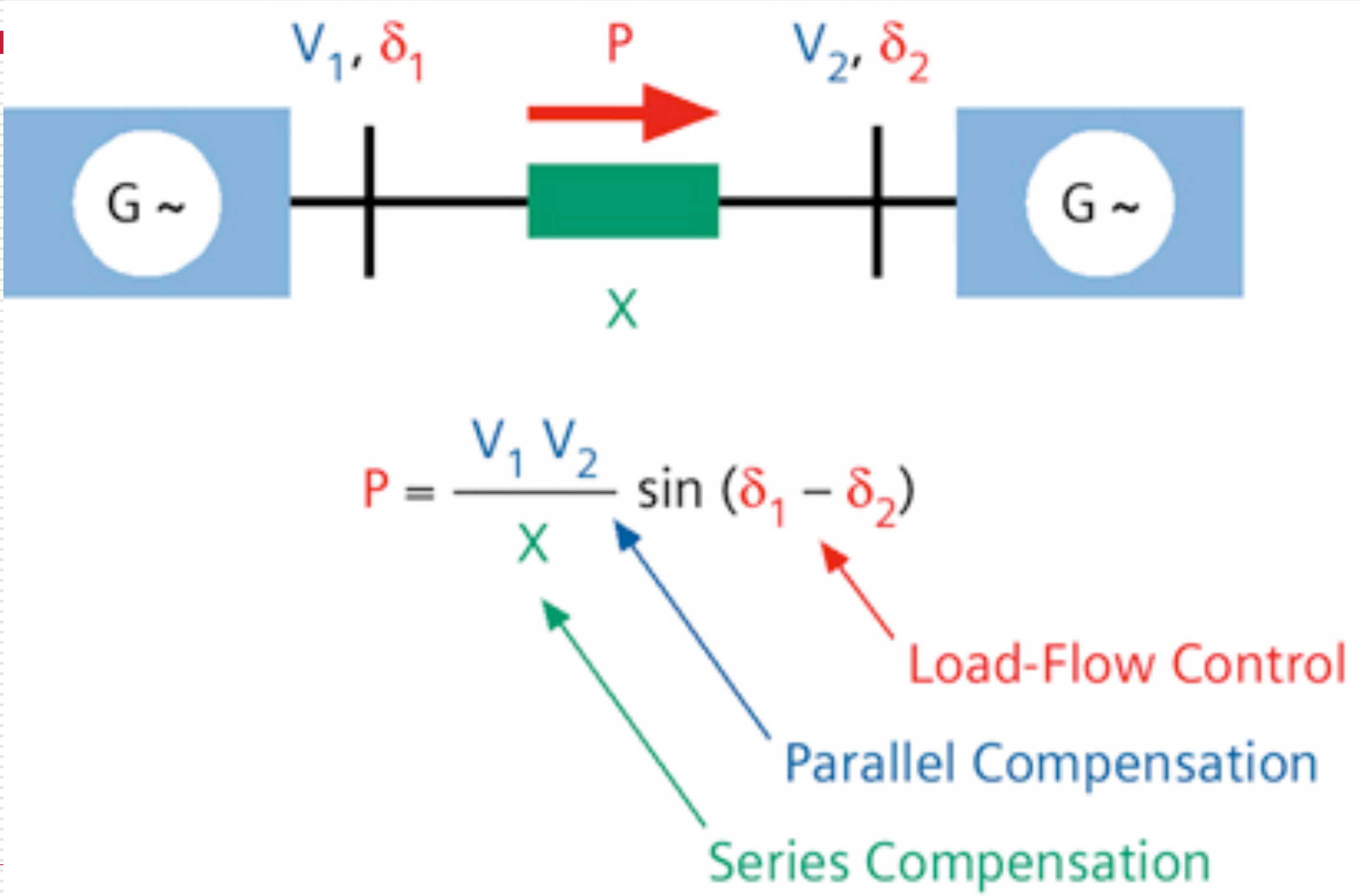
Key idea of reactive compensation is to supply reactive power locally. In the previous example this can be done by adding a 16 MVAr capacitor at the load.



Compensated circuit is identical to first example with just real power load.

Reactive Compensation, cont'd

- Reactive compensation decreased the line flow from 564 Amps to 400 Amps. This has advantages:
  - Lines losses, which are equal to $I^2 R$ decrease,
  - Lower current allows use of smaller wires, or alternatively, supply more load over the same wires,
  - Voltage drop on the line is less.
- Reactive compensation is used extensively throughout transmission and distribution systems.
- Capacitors can be used to "correct" a load's power factor to an arbitrary value.



$$P = \frac{V_1 V_2}{X} \sin(\delta_1 - \delta_2)$$

Load-Flow Control

Parallel Compensation

Series Compensation

Technical Concerns of New Grid

Large Solar and Wind (Bulk System Connected Generation)

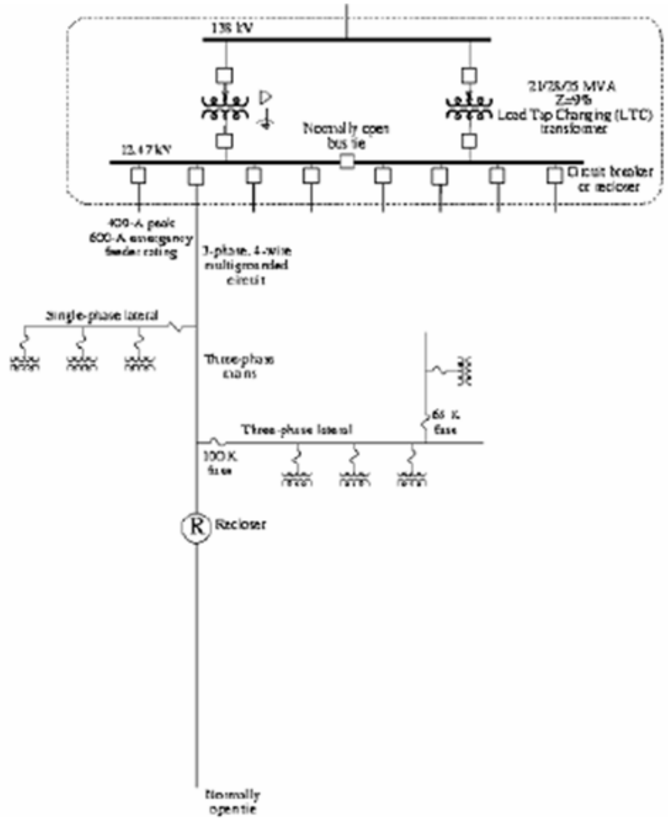
- Steady state and transient stability analysis
- Load/Generation Coincidence (Peak Load and Variability of Source)
- Regulation Requirements
- Integration with Automatic Generation Control (AGC)
- Incorporation of renewable resource forecasting
- Examine current operating practice and new concepts to enable high penetration;
  - frequency responsive (create regulating reserves)
  - demand side coordination

Distributed Solar and Small Wind (Distributed Generation)

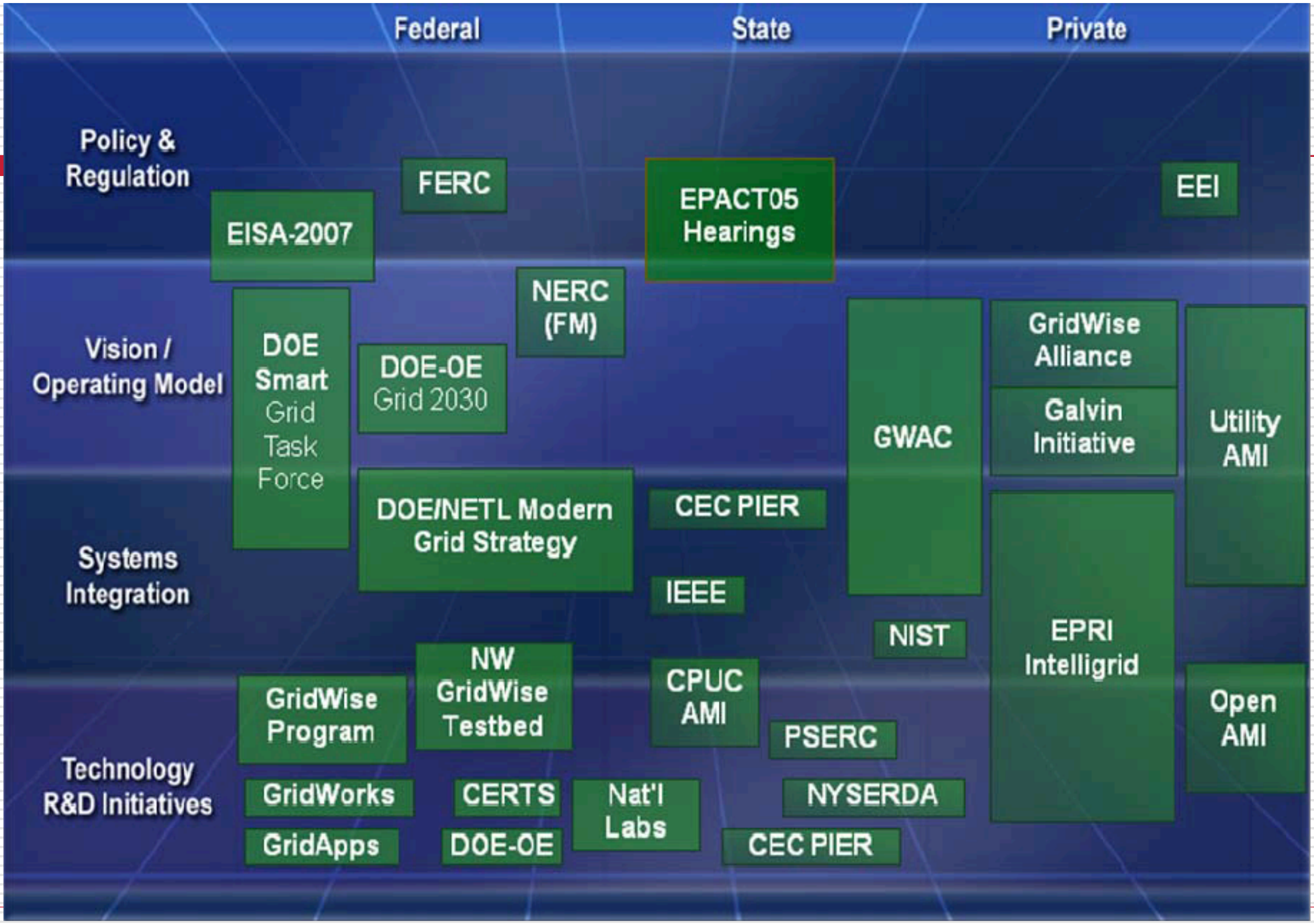
Issues listed above, plus

- Voltage and VAR Regulation
- Power Quality (Harmonics, Flicker, DC Injection)
- Unintentional Islanding
- Protection design and coordination (short circuit, recloser, etc.)
- Equipment grounding
- Load and generation imbalance
- Generation interaction with controllable loads (DSM)
- Storage and storage controls

Moving from Current Radial Distribution System



- Localized controls (voltage, reactive power)
- Limited monitoring – actual voltage and loading throughout the distribution system may not be known accurately
- Lack of communication infrastructure
  - Inability to monitor system conditions in real time
  - Inability to achieve coordinated control with distributed resources
  - No link to customers for demand management, advanced metering, DG integration
  - Inability to take advantage of advanced capabilities of DG and storage to benefit the distribution system (or transmission system)



Selected federal, state, and private Smart Grid initiatives. Source: E. Lightner, 2008 (Lightner-1)

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