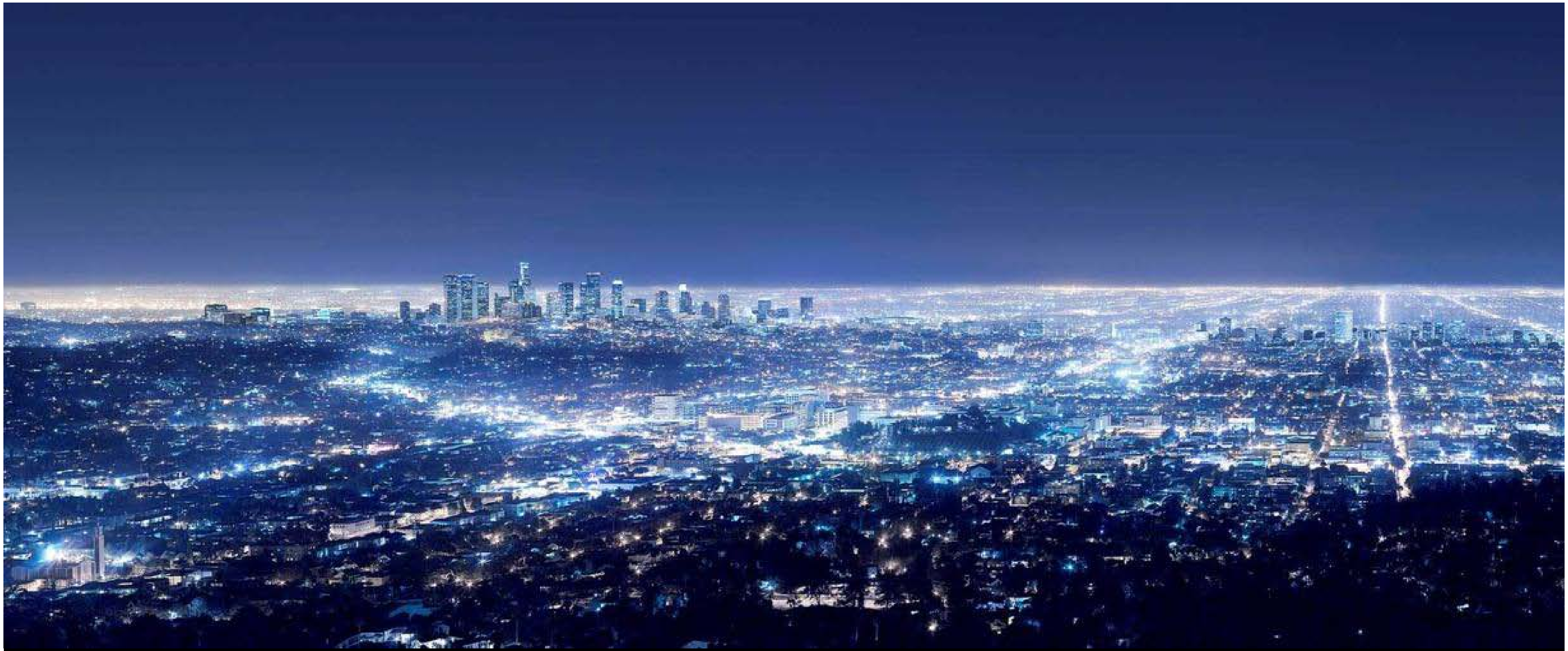

SAMSI Workshop on Scientific Problems for the Smart Grid, Oct 3-5 2011

Smart Grid and Challenges for OT (Optimization Technology)

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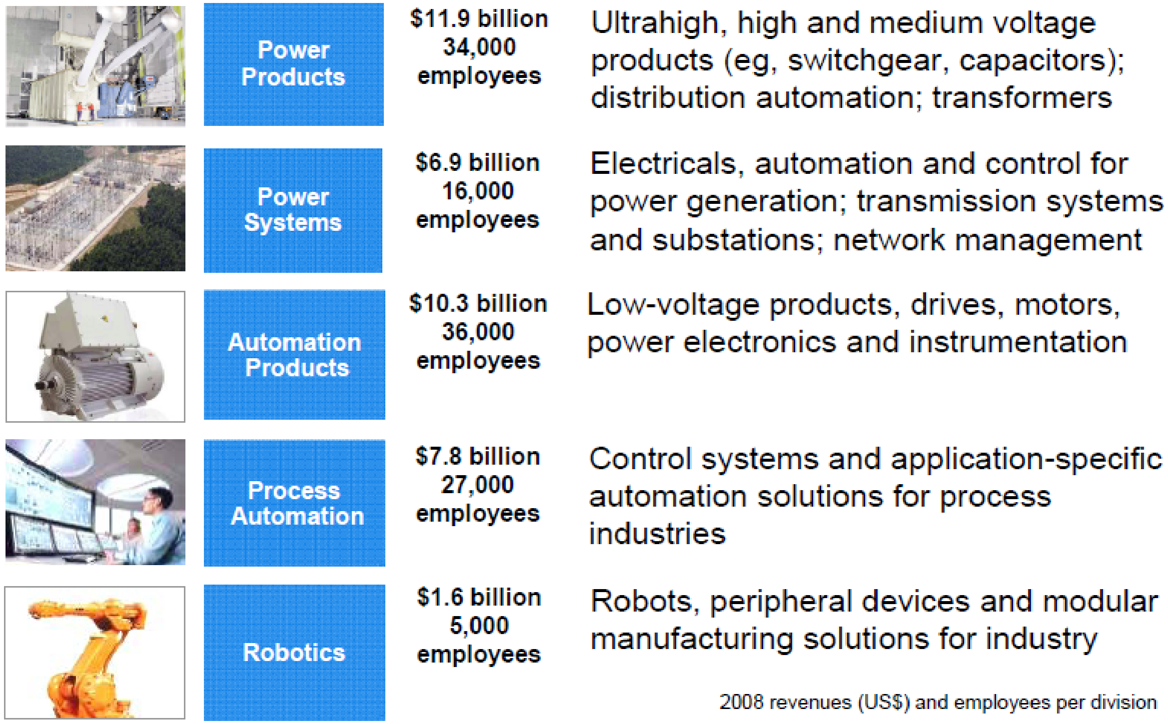
ABB Corporate Research, Raleigh, NC, USA

Outline

- About ABB
- Smart Grid – what, why, how, and value
- Smart Grid application examples and need for robust and efficient optimization methodology
- Complexity of smart grid optimization through the volt and var optimization problem
- Conclusions

General Facts About ABB

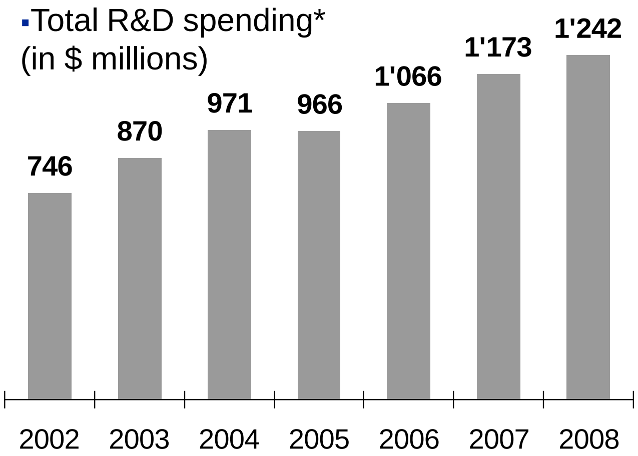
- A leading power and automation technology company with strong market positions in core business
  - Headquarter: Zurich, Switzerland
  - About 120,000 employees in around 100 countries
  - Orders in 2008: $38.3 billion
  - Revenue in 2008: $34.9 billion



Power Products	$11.9 billion 34,000 employees	Ultrahigh, high and medium voltage products (eg, switchgear, capacitors); distribution automation; transformers
Power Systems	$6.9 billion 16,000 employees	Electricals, automation and control for power generation; transmission systems and substations; network management
Automation Products	$10.3 billion 36,000 employees	Low-voltage products, drives, motors, power electronics and instrumentation
Process Automation	$7.8 billion 27,000 employees	Control systems and application-specific automation solutions for process industries
Robotics	$1.6 billion 5,000 employees	Robots, peripheral devices and modular manufacturing solutions for industry

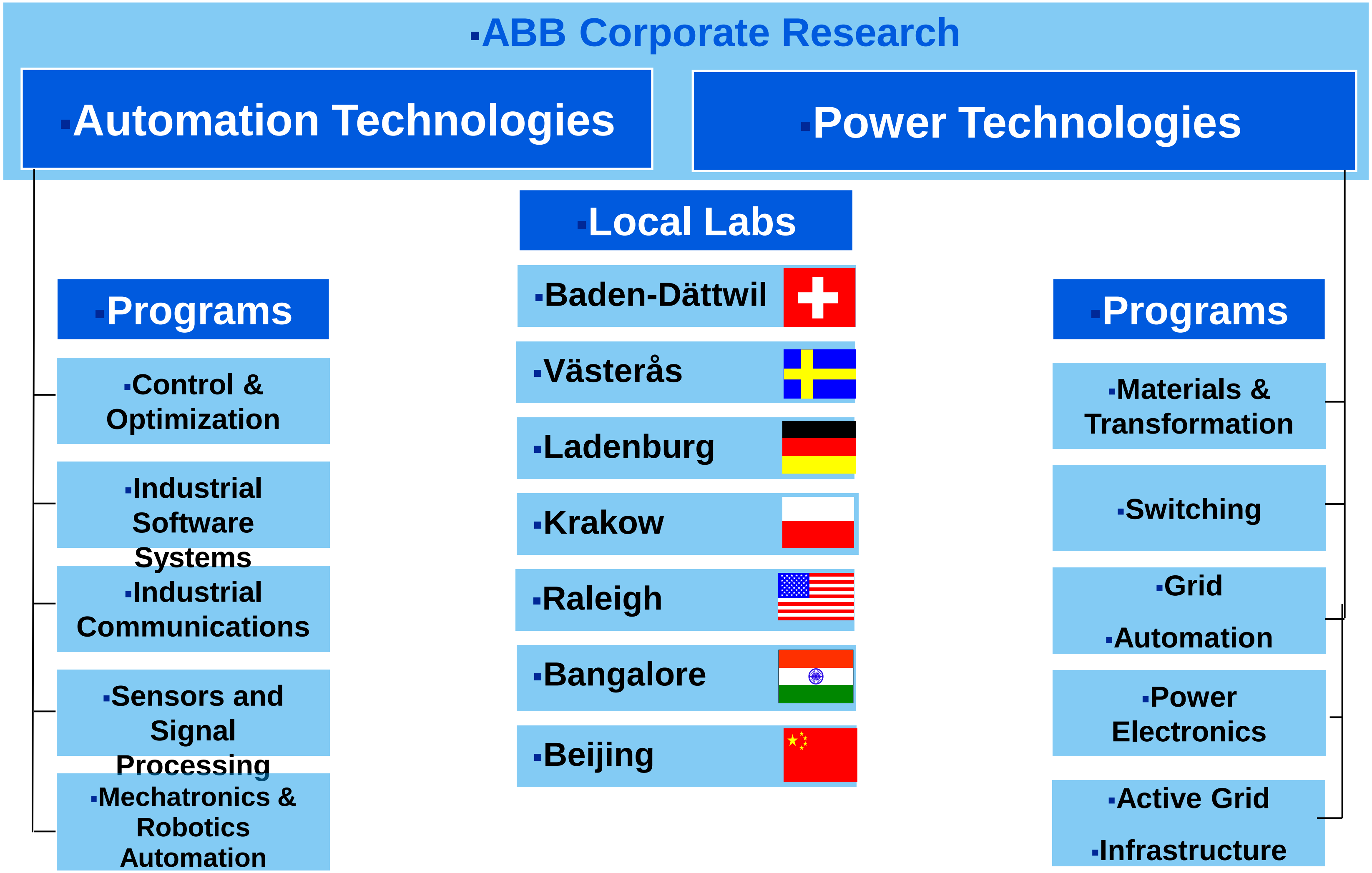
2008 revenues (US$) and employees per division

Innovation: key to competitive advantage



- Steadily increasing R&D has paid off in market-leading technologies in every business
- R&D investment rose 5.9% in 2008 vs. 2007
- Focus on energy efficiency and breakthrough technology
- 6,000 researchers and developers worldwide

ABB Corporate Research



▪ABB Corporate Research

▪Automation Technologies

▪Programs

- Control & Optimization
- Industrial Software Systems
- Industrial Communications
- Sensors and Signal Processing
- Mechatronics & Robotics Automation

▪Local Labs

- Baden-Dättwil
- Västerås
- Ladenburg
- Krakow
- Raleigh
- Bangalore
- Beijing

▪Power Technologies

▪Programs

- Materials & Transformation
- Switching
- Grid
- Automation
- Power Electronics
- Active Grid
- Infrastructure

Corporate Research Labs: USCRC

Smart Grid - What

- The entire electric power infrastructure enabled with value delivering applications (The Apps) in
  - System architecture/design
  - System management and optimization
  - Power conversion, storage, transmission, distribution, consumer appliance technology
  - Interactive and participative market structure
  - Equipment diagnostics and monitoring

Smart Grid - Why

- Reliability and security
- Efficiency
- Economy
- Sustainability

Smart Grid - How

- By changing how assets are monitored, diagnosed, maintained
- By changing how resources and demand are managed and balanced
- By continuously optimizing system operation in anticipation and response to changing conditions

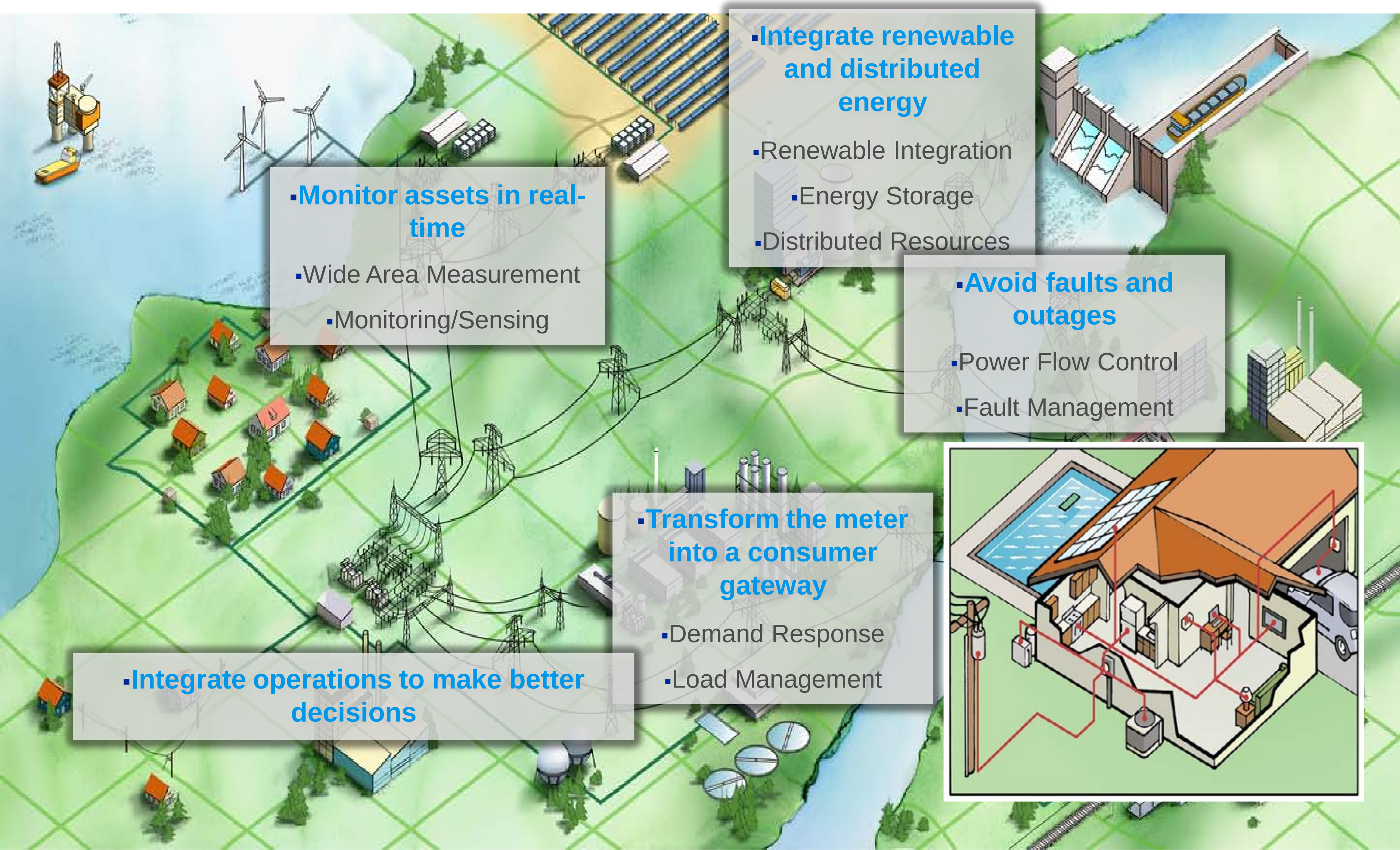
Smart Grid – Technologies

- Sensor technology
- Communication technology
- Information technology
- Advanced actuator technology (FACTS,HVDC, etc)
- Killer applications built on advanced monitoring, diagnostics, scheduling, control, and optimization technology

Smart Grid – What is it is not

- Smart Grid is about the optimal control of MW not MG Bytes
  - Over different time scales
  - Under normal, emergence, or restorative system conditions

Enabling Technology for 21st Century Power Grids



- **Integrate renewable and distributed energy**
  - Renewable Integration
  - Energy Storage
  - Distributed Resources

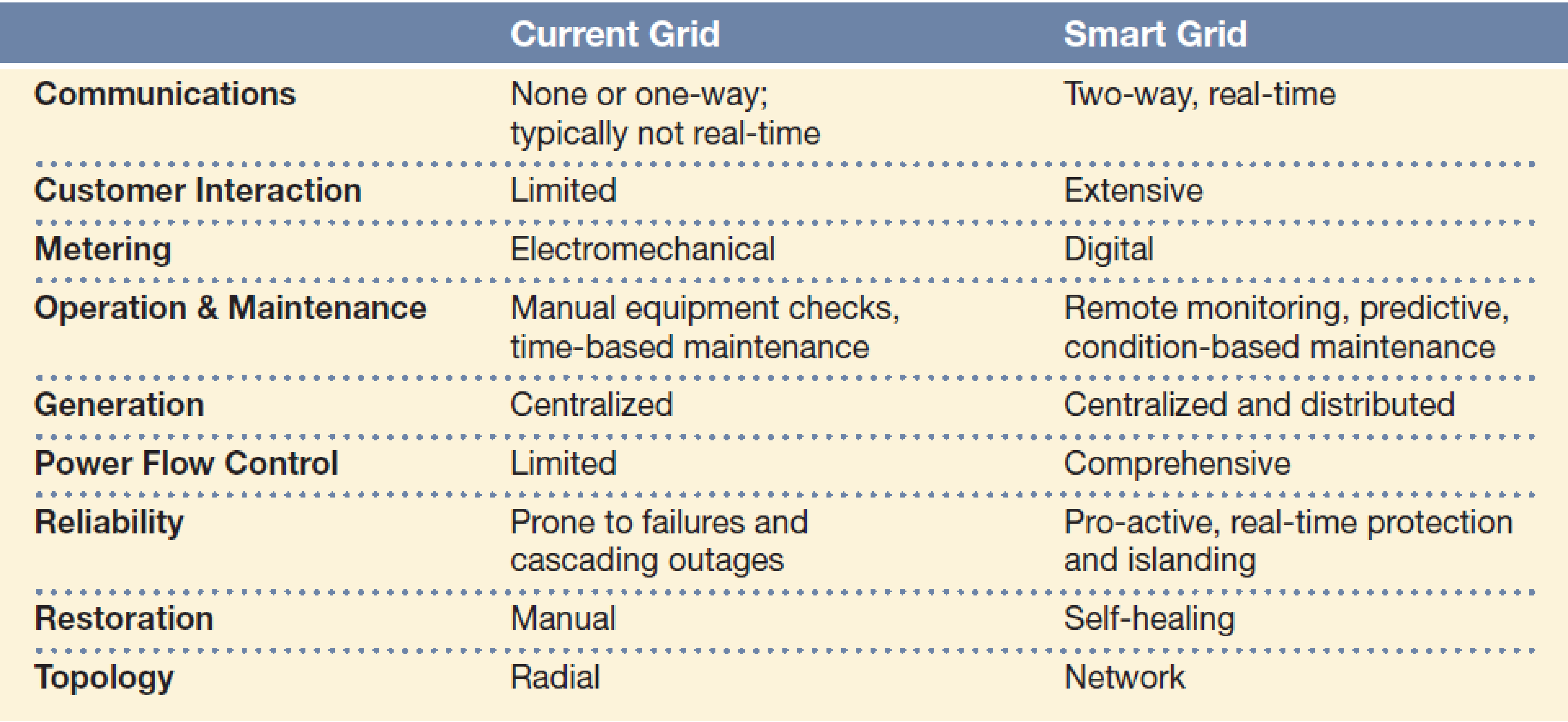
- **Monitor assets in real-time**
  - Wide Area Measurement
  - Monitoring/Sensing

- **Avoid faults and outages**
  - Power Flow Control
  - Fault Management

- **Transform the meter into a consumer gateway**
  - Demand Response
  - Load Management

- **Integrate operations to make better decisions**

Smart Grid versus Traditional Grid



	Current Grid	Smart Grid
Communications	None or one-way; typically not real-time	Two-way, real-time
Customer Interaction	Limited	Extensive
Metering	Electromechanical	Digital
Operation & Maintenance	Manual equipment checks, time-based maintenance	Remote monitoring, predictive, condition-based maintenance
Generation	Centralized	Centralized and distributed
Power Flow Control	Limited	Comprehensive
Reliability	Prone to failures and cascading outages	Pro-active, real-time protection and islanding
Restoration	Manual	Self-healing
Topology	Radial	Network

Source: Research Reports International

Value of Smart Grid Applications in US

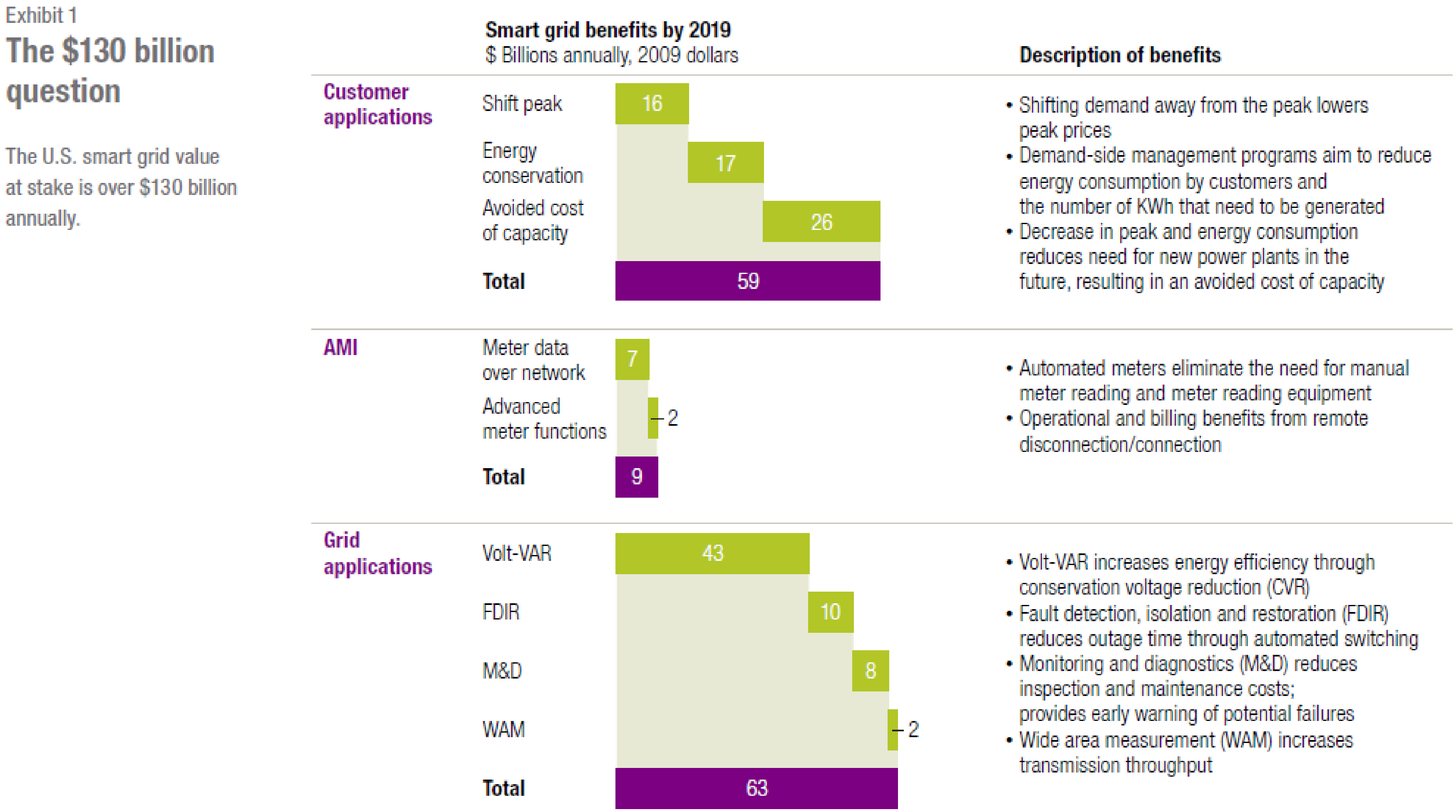


Exhibit 1

The $130 billion question

The U.S. smart grid value at stake is over $130 billion annually.

Smart grid benefits by 2019
$ Billions annually, 2009 dollars

Description of benefits

- Shifting demand away from the peak lowers peak prices
- Demand-side management programs aim to reduce energy consumption by customers and the number of KWh that need to be generated
- Decrease in peak and energy consumption reduces need for new power plants in the future, resulting in an avoided cost of capacity

- Automated meters eliminate the need for manual meter reading and meter reading equipment
- Operational and billing benefits from remote disconnection/connection

- Volt-VAR increases energy efficiency through conservation voltage reduction (CVR)
- Fault detection, isolation and restoration (FDIR) reduces outage time through automated switching
- Monitoring and diagnostics (M&D) reduces inspection and maintenance costs; provides early warning of potential failures
- Wide area measurement (WAM) increases transmission throughput

Source: McKinsey On Smart Grid,2010

Optimization Technology Key to Many Smart Grid Applications - Examples

- FDIR (Fault Location, isolation, and restoration) – Maximizing service restoration, minimize interruption duration
- DERM (distributed energy resource management) – maximizing system benefits of clean energy and energy storage
- (TS) Transmission switching – transmission facility switching to minimize congestion cost
- (FRC) Feeder Reconfiguration – balancing load on distribution feeder to improve voltage profiles and minimize energy loss

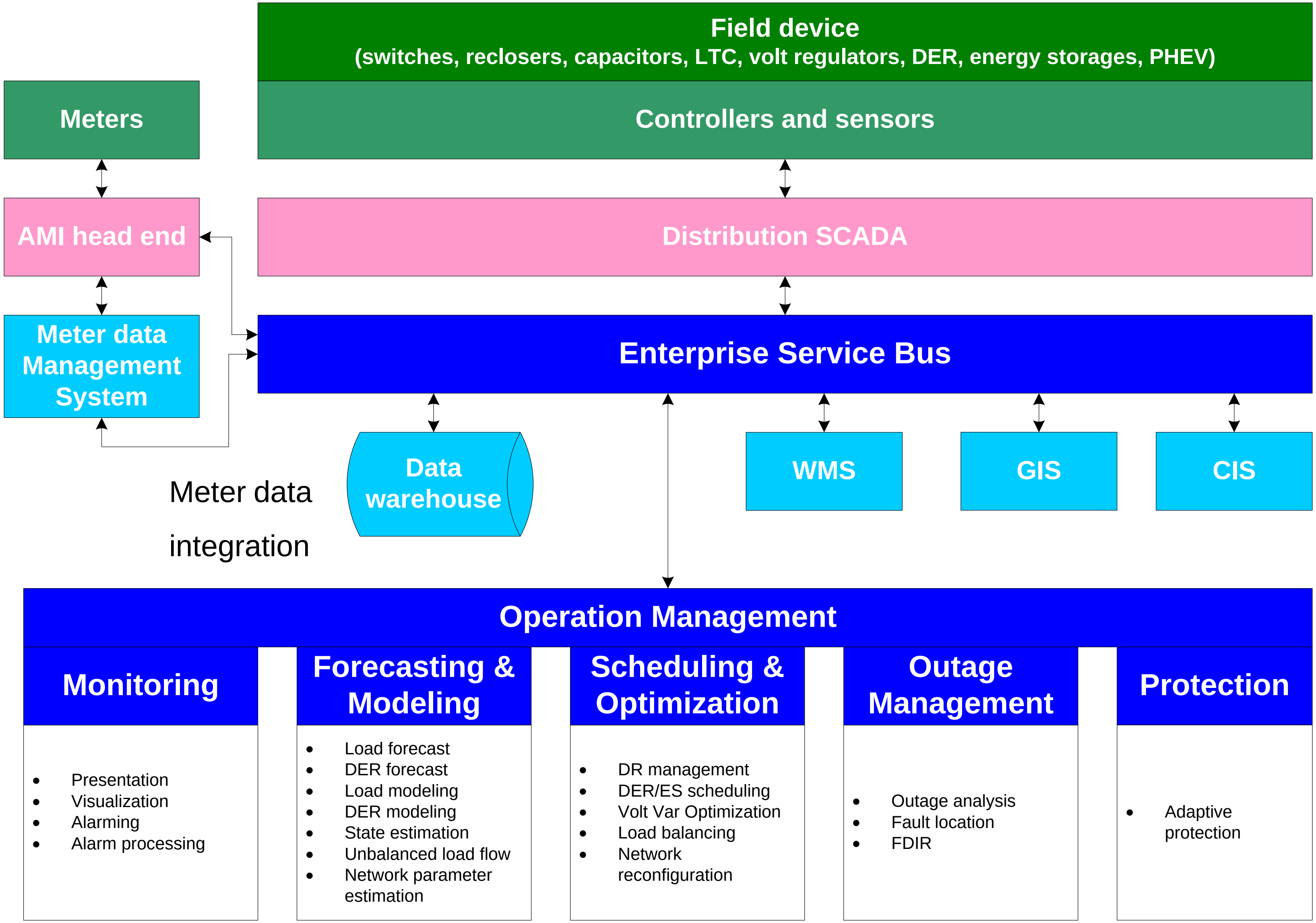
Optimization Technology Key to Many Smart Grid Applications - More Examples

- Integrated AC/DC Grid dispatch – SCUC and SCED enhanced by DC grid power flow scheduling
- (DRM) Demand Response Management – Demand response management (virtual power plant) to optimize system operation and
- VVO (Volt and Var Optimization) – reactive power and voltage regulation optimization for distribution system loss minimization or demand reduction

Common to Most Optimizations Applications

- The network constraints
  - Power flow constraints – real and reactive power balance equations
  - Conducting equipment constraints – thermal (current) constraints, voltage constraints
- Network constraints are nonlinear equality constraints
- They are numerous, and especially so in distribution system
- Let’s take a look at VVO

VVO in DMS for Smart Grid in Distribution



Field device
(switches, reclosers, capacitors, LTC, volt regulators, DER, energy storages, PHEV)

Controllers and sensors

Meters

AMI head end

Distribution SCADA

Meter data Management System

Enterprise Service Bus

Data warehouse

WMS

GIS

CIS

Meter data integration

Operation Management

Monitoring

- Presentation
- Visualization
- Alarming
- Alarm processing

Forecasting & Modeling

- Load forecast
- DER forecast
- Load modeling
- DER modeling
- State estimation
- Unbalanced load flow
- Network parameter estimation

Scheduling & Optimization

- DR management
- DER/ES scheduling
- Volt Var Optimization
- Load balancing
- Network reconfiguration

Outage Management

- Outage analysis
- Fault location
- FDIR

Protection

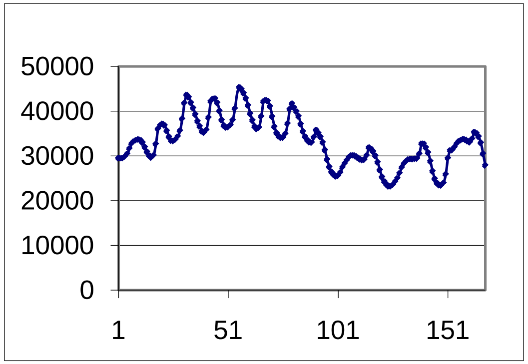
- Adaptive protection

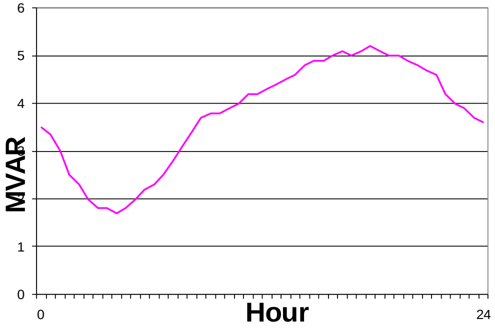
Basic Concept Review

- Real and reactive powers vary in time
- Loads change follow cyclic patterns plus random fluctuations
- Reactive power increase the current through conductors which increase loss
- Real power and lagging reactive power current cause voltage drop
- Var compensation reduces loss and need to match reactive power load

$$\left|\Delta V\right| = RI\cos\theta + XI\sin\theta = RI_d + XI_q$$

$$\Delta E = RI^2 = R(I_d^2 + I_q^2)$$

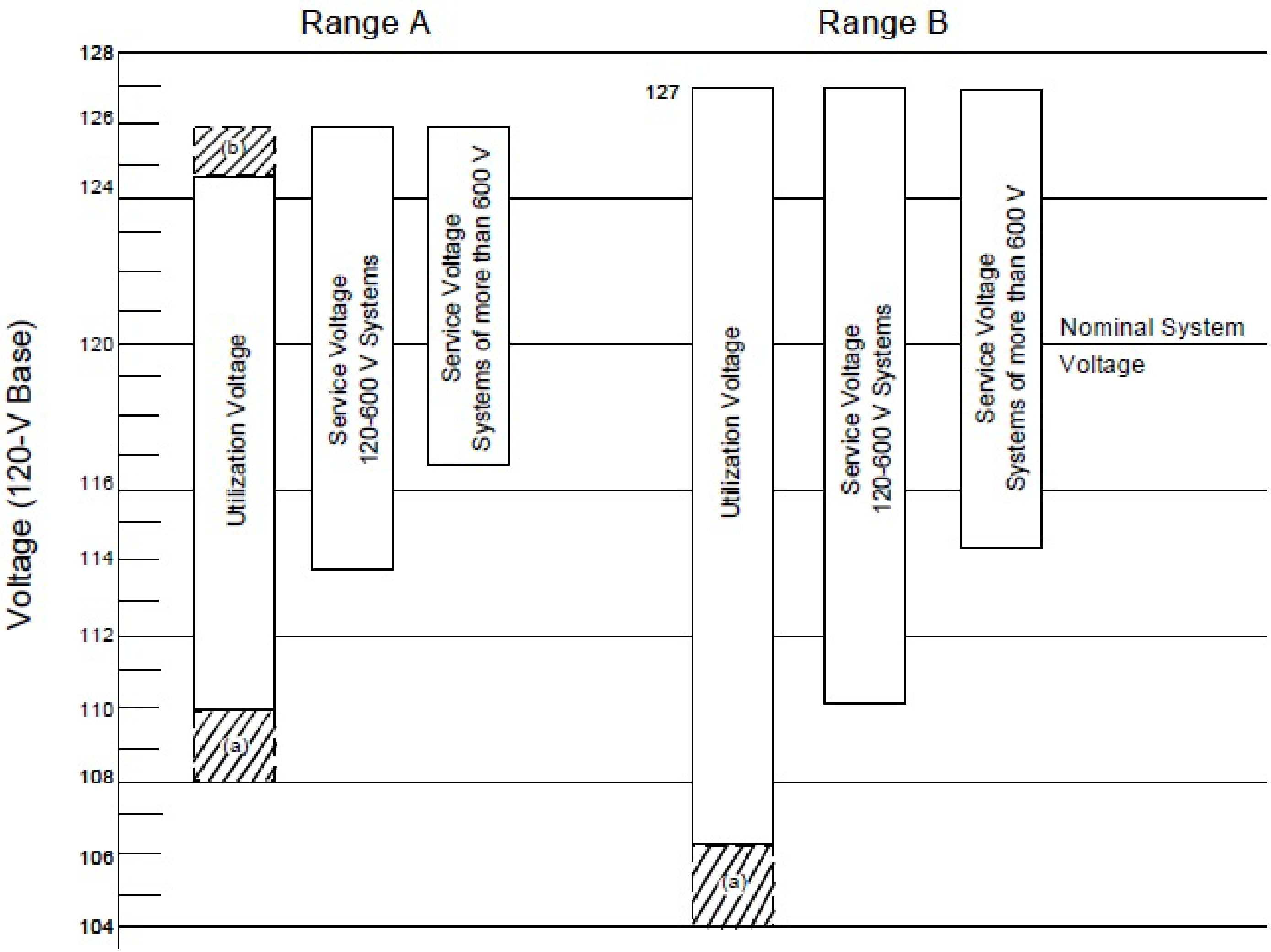




Typical Values of Uncorrected Power Factor:

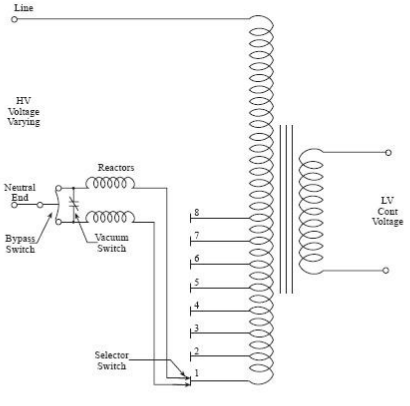
Industrial:	0.60 – 0.80
Residential:	0.85 – 0.90

Distribution Voltage Standard ((ANSI C84.1)

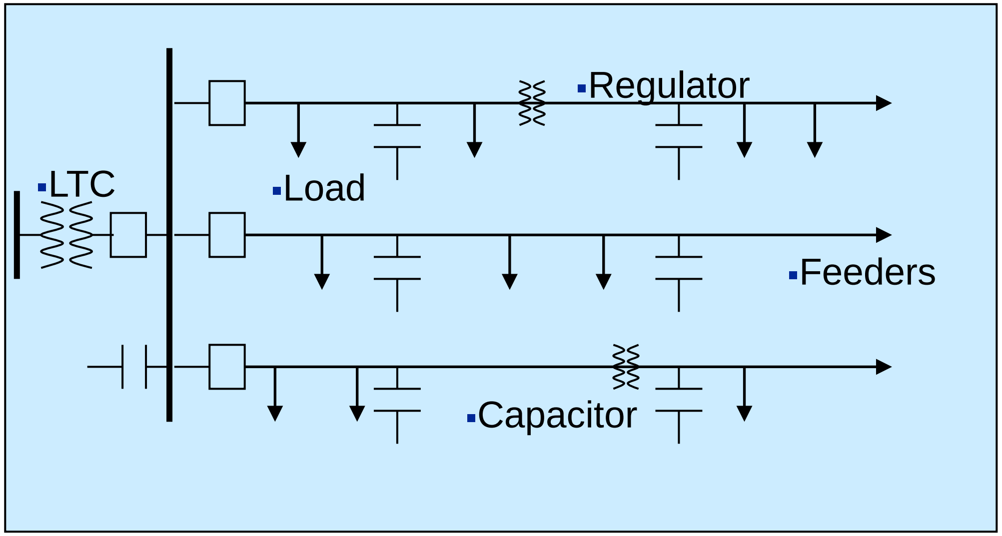


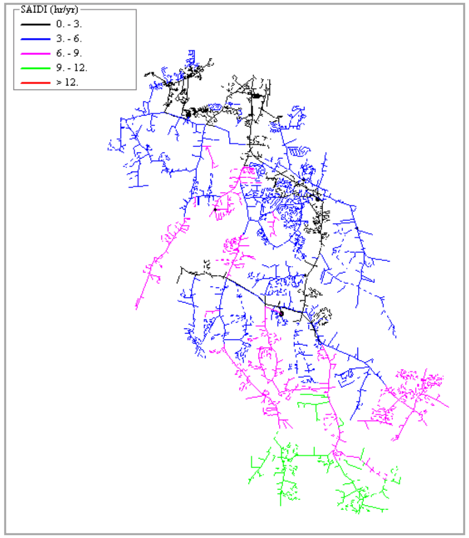
Controls involved in VVC and VVO

- Volt control
  - Substation transformer LTC
  - Voltage regulator taps
- Var control
  - Capacitor bank in substation
  - Capacitor banks on feeders



On-Load Tap Changer

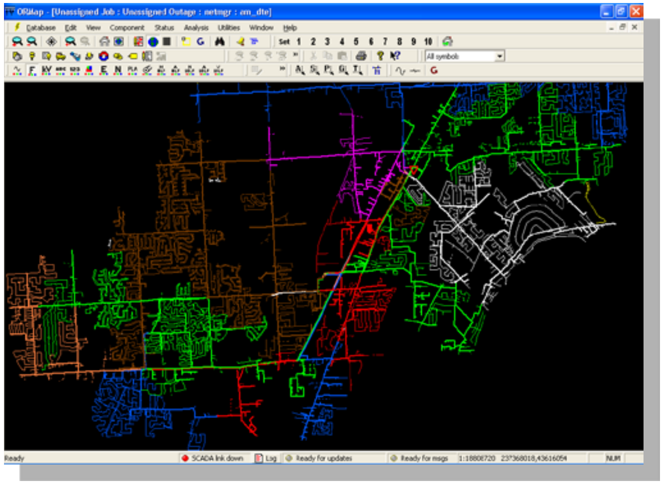




Decisions and objectives

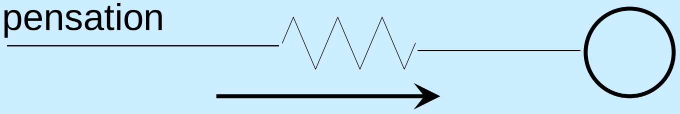
- Which capacitor to switch on or off
- What tap setting to us for the LTC and regulators

- MW losses minimization
- MW peak demand minimization



Var compensation and energy loss

- Without compensation

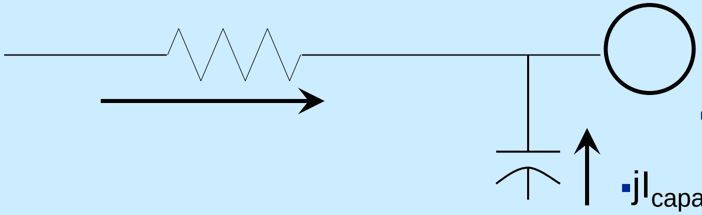


- R
- Motor

$$I_{line}^2 = I_{real}^2 + I_{reactive}^2$$

$$P_{loss} = RI_{line}^2 = R(I_{real}^2 + I_{reactive}^2)$$

- With compensation

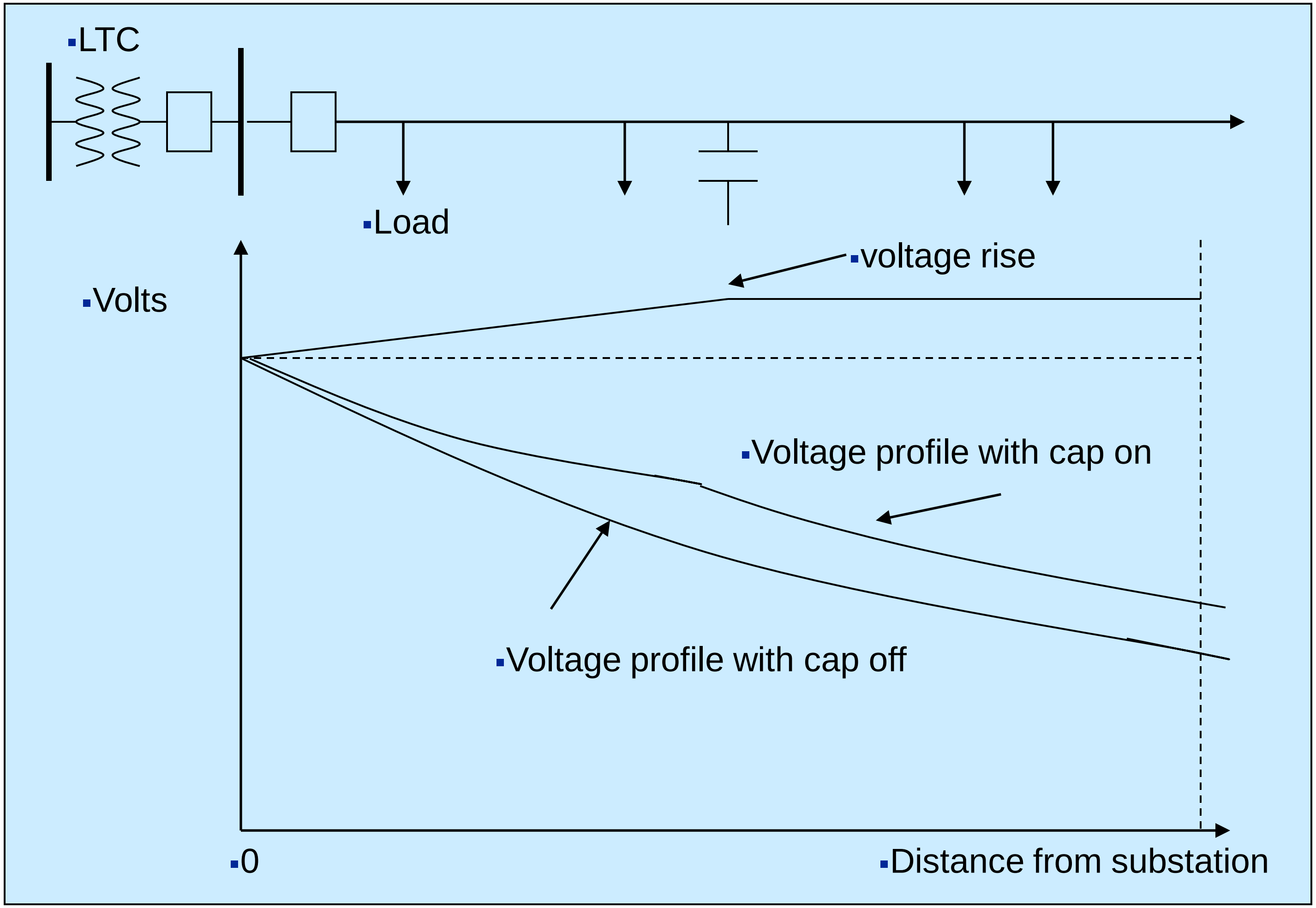


- R
- Motor
- $jI_{capacitor}$

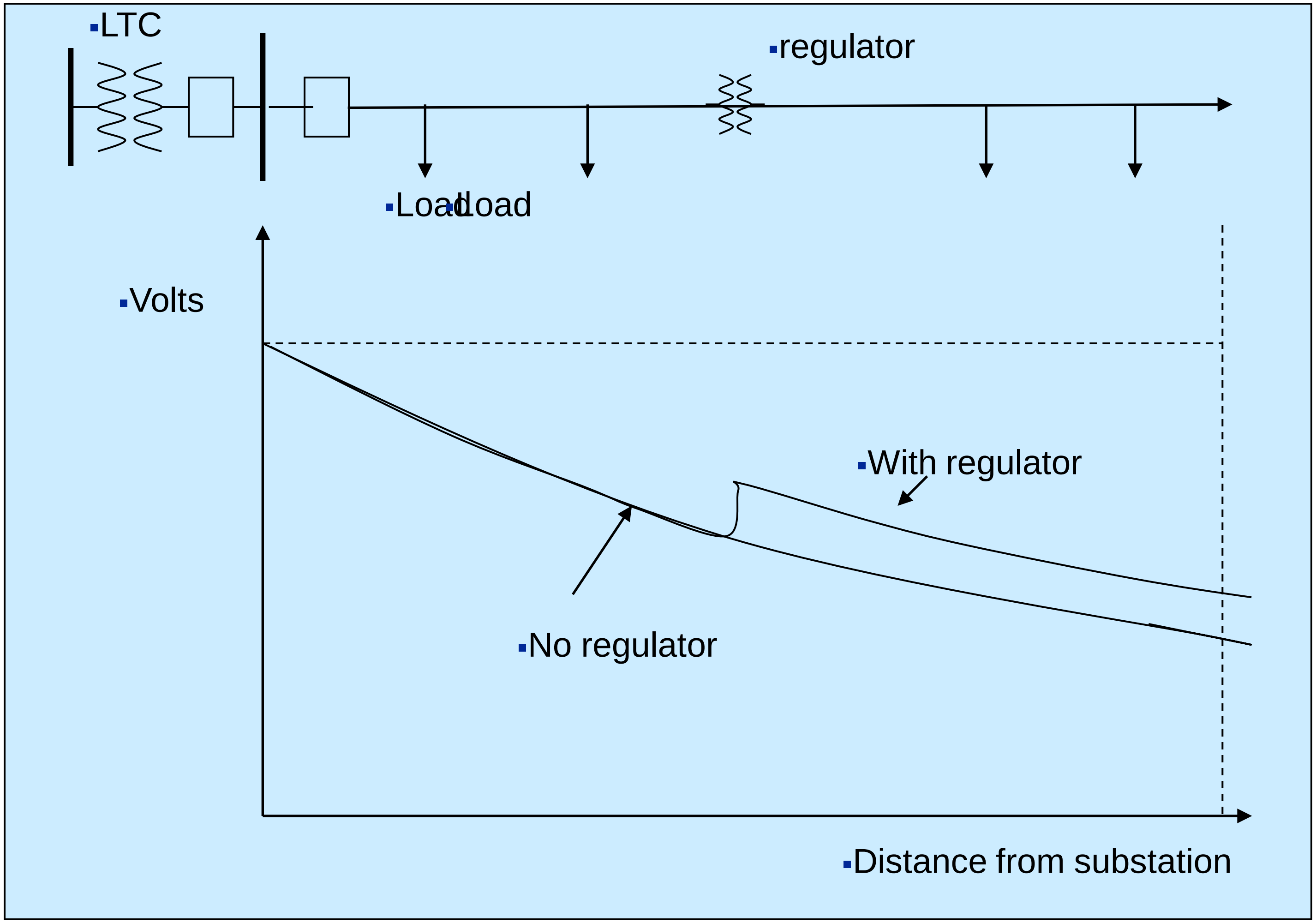
$$I_{line}^2 = I_{real}^2 + (I_{reactive} - I_{capacitor})^2$$

$$P_{loss} = RI_{line}^2$$

Capacitor effect on voltage profile



Regulator effect on voltage profile

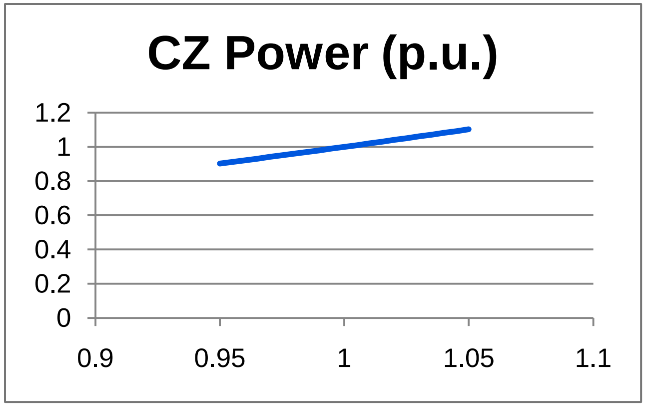


Voltage effect on load

Constant impedance load (Z)

$$P = P_n \left(\frac{V}{V_n}\right)^2$$

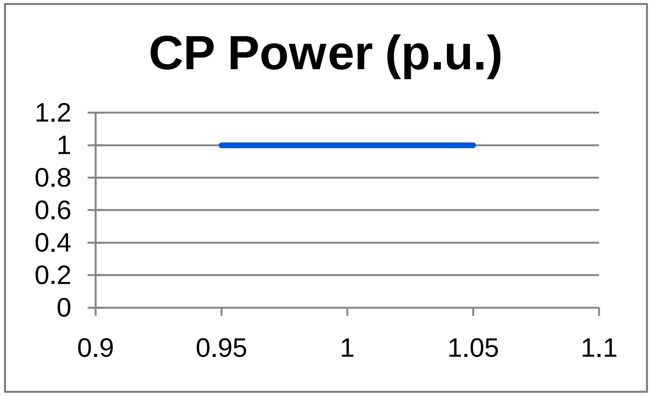
$$CVRf = \frac{dP}{dV}\frac{V_n}{P_n} = 2\frac{V}{V_n} \approx 2$$



- Constant power load (P)

$$P = P_n$$

$$CVRf = 0$$



Volt and Var control effect on system quantities

Input	**Output**	**Output**	**Output**	**Output**	**Output**
Controls	**Var flows (current)**	**Voltages**	**Loads**	**Energy loss**	**Peak Demand**
Capacitors	●●●	●	●	●●●	●
Regulators	●	●●●	●●	●	●●

- Operation concern
- Business Objective

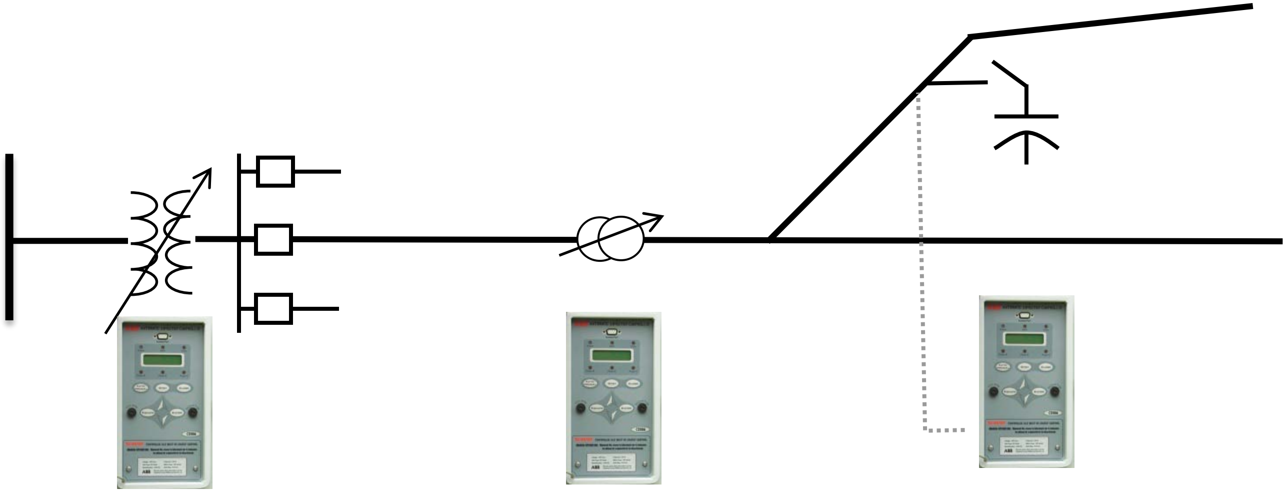
Control Approaches

- Local control
- Centralized control
  - Heuristics based control
  - Model based control

Localized control and common schemes (traditional)

- Measurement at or near the controlled device
- Individual controller compares measurement with preset control reference point to determine control action (on or off, raise or lower)

- Time
- Temperature
- Voltage
- Var control
- Current control

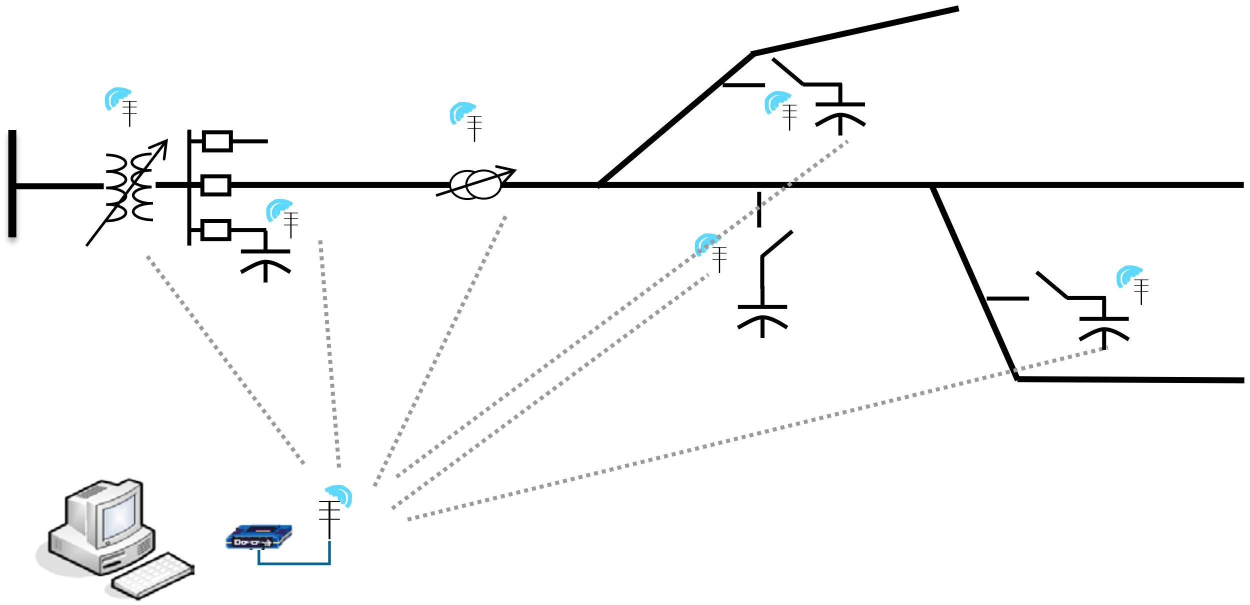


Characteristics of local VVC

- Good for local control objectives (power factor, voltage, current, var flow)
- Local control objective may or may not be consistent with higher level business objective (loss or demand reduction)
- Interaction between local controllers could lead to hunting
- Difficult to coordinate to achieve system level objective
- Coordination (dead band, arming delay) considered at design time
- Little flexibility to adapt to system reconfiguration

Centralized Control

- Telemetry communicated to central location
- Control decisions made considering multiple measurements
- Control commands communicated back to local controllers for execution
- Heuristics or model predictive control



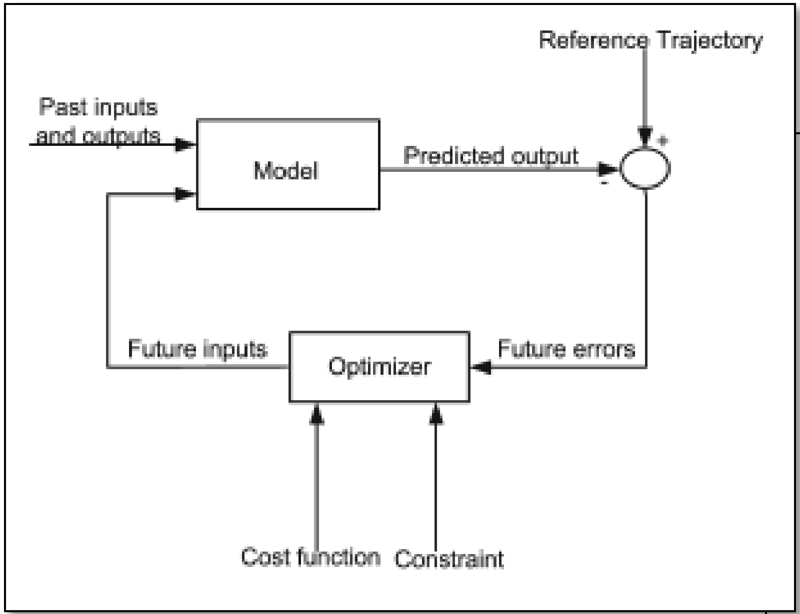
Characteristics of heuristics control

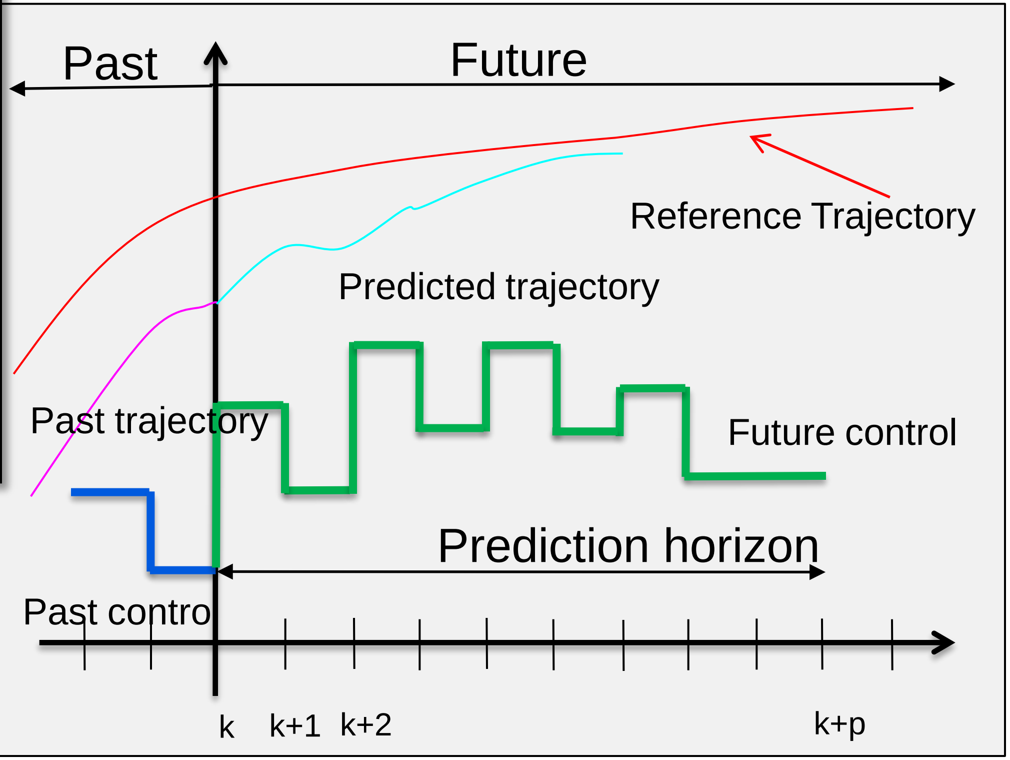
- Control objectives (power factor, voltage profile flattening) do not always correlate positively to business objective
- Rules of thumb lacks rigor and generality, could be system and configuration dependent
- Able to produce improvement under most conditions; Does not optimize the control objective

Model Based VVO – Technology Requirement

- As operated system model
  - Including status of: Breakers, switches, reclosers, taps, fuses, load-break cutouts, jumpers, line cuts, loads
- Load forecast (or state estimation)
- Unbalanced load flow capability
- Communication infrastructure
- Robust and efficient optimization

Model Predictive Control (MPC)





- Optimize explicit objective
- Incorporate constraints
- Reject noise and model error through feedback

MPC VVO – A generic statement

$$
\begin{array}{lll}
\underset{u}{Min} & \sum_{t=1}^{T} f(x(t), u(t), l(x(t))) & \\
s.t. & h(x(t), u(t), l(x(t))) = 0, & t = 1 \ldots T \\
 & g(x(t), u(t), l(x(t))) \leq 0, & t = 1 \ldots T \\
 & q(u_i) \leq 0, & i = 1 \ldots N_c \\
 & u(t) = \{u_c(t), u_{tap}(t)\} & t = 1 \ldots T
\end{array}
$$

$x(t)$: states, $x \in R^n$

$u(t)$: controls, $u \in Z^m$

$l(t)$: load functions

$h(t)$: power flow equations

$g(t)$: voltage & current functions

$q(u_i)$: control counter functions

VVO Problem – A more concrete statement

$$\min \quad \sum_{t \in T} w^{(loss)} f_t^{(loss)} + w^{(load)} f_t^{(load)} + w^{(violation)} f_t^{(violation)}$$

$$s.t.$$

$$f_t^{(loss)} = \sum_{i \in S^{(branch)}} i_{i,t}^2 r_i, \qquad t \in T$$

$$f_t^{(load)} = \sum_{i \in S^{(node)}} P_{i,t}, \qquad t \in T$$

$$f_t^{(violation)} = \sum_{i \in S^{(node)}} v_{i,t}^{(violation)} + \sum_{i \in S^{(branch)}} i_{i,t}^{(violation)}, \qquad t \in T$$

$$v_{i,t}^{(violation)} = \max(v_{i,t} - v_i^{\max}, v_i^{\min} - v_{i,t}, 0), \qquad i \in S^{(node)}, t \in T$$

$$i_{i,t}^{(violation)} = \max(i_{i,t} - i_i^{\max}, -i_i^{\max} - i_{i,t}, 0), \qquad i \in S^{(branch)}, t \in T$$

$$P_{i,t} = P_{i,t}^{(load)}(x(t)) - P_{i,t}^{(DG)}(x(t)), \qquad i \in S^{(node)}, t \in T$$

$$Q_{i,t} = Q_{i,t}^{(load)}(x(t)) - Q_{i,t}^{(DG)}(x(t) - Q_{i,t}^{(shunt)}(x(t)), i \in S^{(node)}, t \in T$$

$$P_{i,t}^{inj}(\mathbb{N}_t, \tau_t, s_t, x(t)) + P_{i,t} = 0, \qquad i \in S^{(node)}, t \in T$$

$$Q_{i,t}^{inj}(\mathbb{N}_t, \tau_t, s_t, x(t)) + Q_{i,t} = 0, \qquad i \in S^{(node)}, t \in T$$

VVO Problem – additional constraints

$$v_i^{Min} \le v_{i,t} \le v_i^{\max}, \qquad i \in S^{(node)}, t \in T$$

$$\left| i_{i,t} \right| \le i_i^{\max}, \qquad i \in S^{(branch)}, t \in T,$$

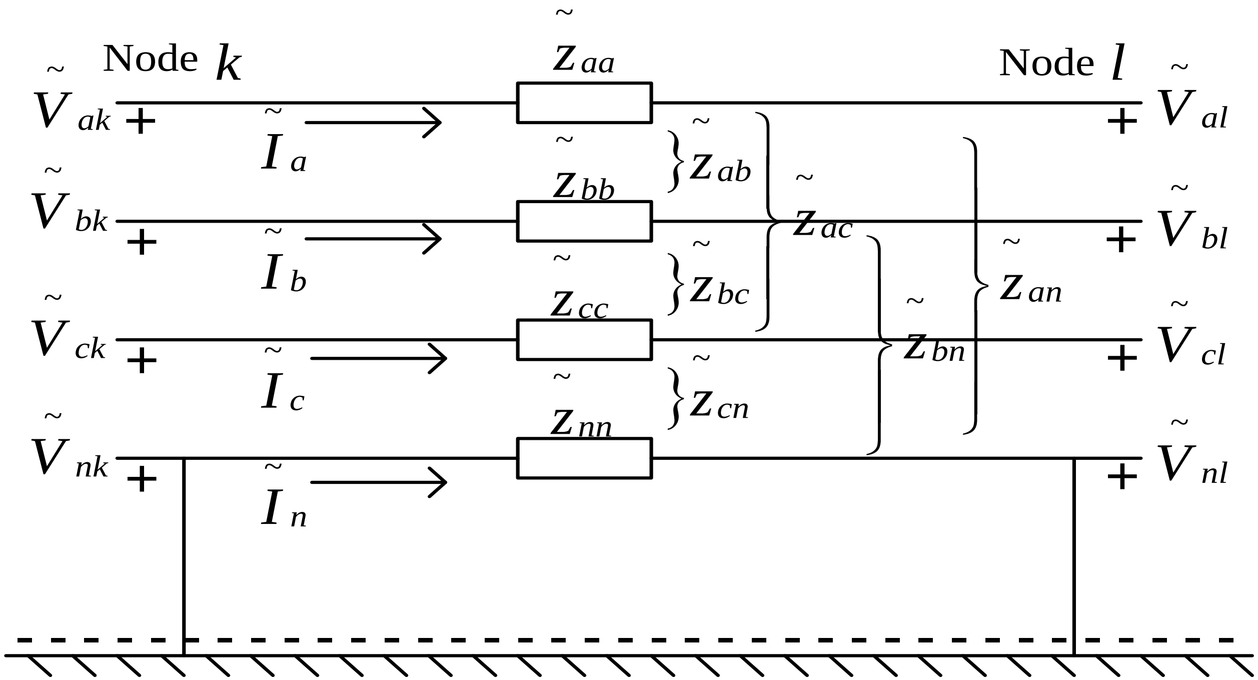
$$\tau_{i,t} - \tau_{i,t-1} \le n_{\max,i}^{(\tau)} z_{i,t}^{(\tau)}, \qquad i \in S^{(\tau)}, t \in T$$

$$s_{i,t} - s_{i,t-1} \le n_{\max,i}^{(s)} z_{i,t}^{(s)}, \qquad i \in S^{(s)}, t \in T$$

$$\sum_{t \in T} z_{i,t}^{(\tau)} \le n_{\max,i}^{(\tau)}, \qquad i \in S^{(\tau)}$$

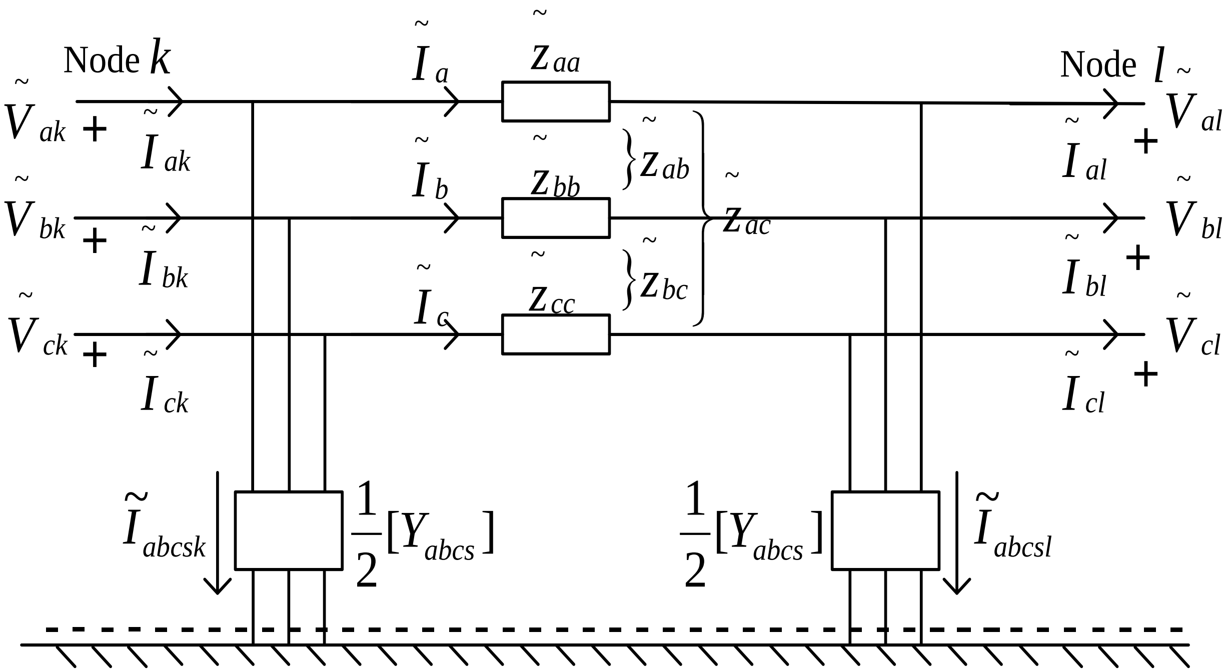
$$\sum_{t \in T} z_{i,t}^{(s)} \le n_{\max,i}^{(s)}, \qquad i \in S^{(s)}$$

Distribution system line model – four wire model



$$\begin{bmatrix}\tilde{V}_{ak}\\ \tilde{V}_{bk}\\ \tilde{V}_{ck}\\ \tilde{V}_{nk}\end{bmatrix}=\begin{bmatrix}\tilde{V}_{al}\\ \tilde{V}_{bl}\\ \tilde{V}_{cl}\\ \tilde{V}_{nl}\end{bmatrix}+\begin{bmatrix}\tilde{Z}_{aa} & \tilde{Z}_{ab} & \tilde{Z}_{ac} & \tilde{Z}_{an}\\ \tilde{Z}_{ba} & \tilde{Z}_{bb} & \tilde{Z}_{bc} & \tilde{Z}_{bn}\\ \tilde{Z}_{ca} & \tilde{Z}_{cb} & \tilde{Z}_{cc} & \tilde{Z}_{cn}\\ \tilde{Z}_{na} & \tilde{Z}_{nb} & \tilde{Z}_{nc} & \tilde{Z}_{nn}\end{bmatrix}\cdot\begin{bmatrix}\tilde{I}_a\\ \tilde{I}_b\\ \tilde{I}_c\\ \tilde{I}_n\end{bmatrix}$$

Distribution system line model – three wire with shunt



$$\begin{bmatrix} \tilde{I}_{ask} \\ \tilde{I}_{bsk} \\ \tilde{I}_{csk} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} \tilde{Y}_{aas} & \tilde{Y}_{abs} & \tilde{Y}_{acs} \\ \tilde{Y}_{bas} & \tilde{Y}_{bbs} & \tilde{Y}_{bcs} \\ \tilde{Y}_{cas} & \tilde{Y}_{cbs} & \tilde{Y}_{ccs} \end{bmatrix} \cdot \begin{bmatrix} \tilde{V}_{ak} \\ \tilde{V}_{bk} \\ \tilde{V}_{ck} \end{bmatrix}$$

Power flow equations

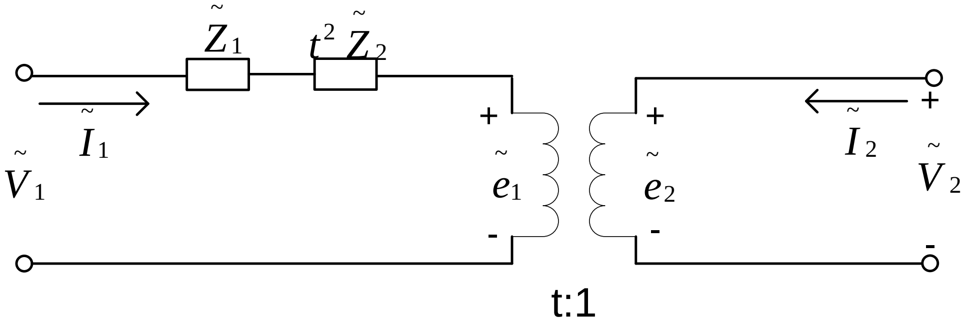
$$P_i + jQ_i = (V_i^* \sum Y_{i,j} V_j)^*$$

$$P_i = \mathrm{Re}(V_i^* \sum Y_{i,j} V_j)$$

$$Q_i = -\mathrm{Im}(V_i^* \sum Y_{i,j} V_j)$$

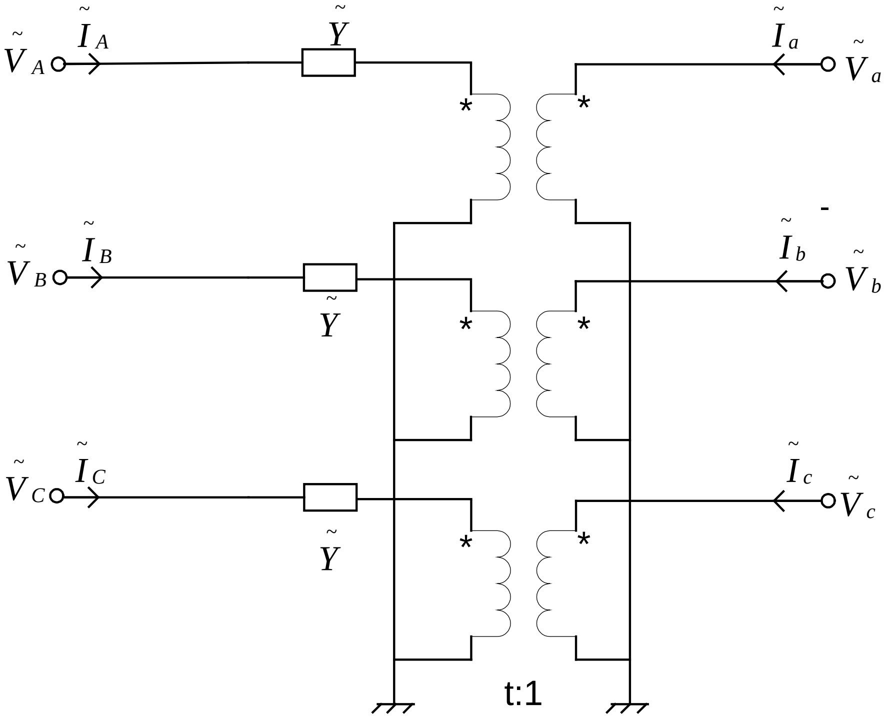
- Two equations for phase of every node in the system

Distribution system Transformer Model



$$\begin{bmatrix}\tilde{I}_1\\ \tilde{I}_2\end{bmatrix} = \begin{bmatrix}\tilde{Y}_{eq1} & -t\tilde{Y}_{eq1}\\ -t\tilde{Y}_{eq1} & t^2\tilde{Y}_{eq1}\end{bmatrix}\cdot\begin{bmatrix}\tilde{V}_1\\ \tilde{V}_2\end{bmatrix}$$

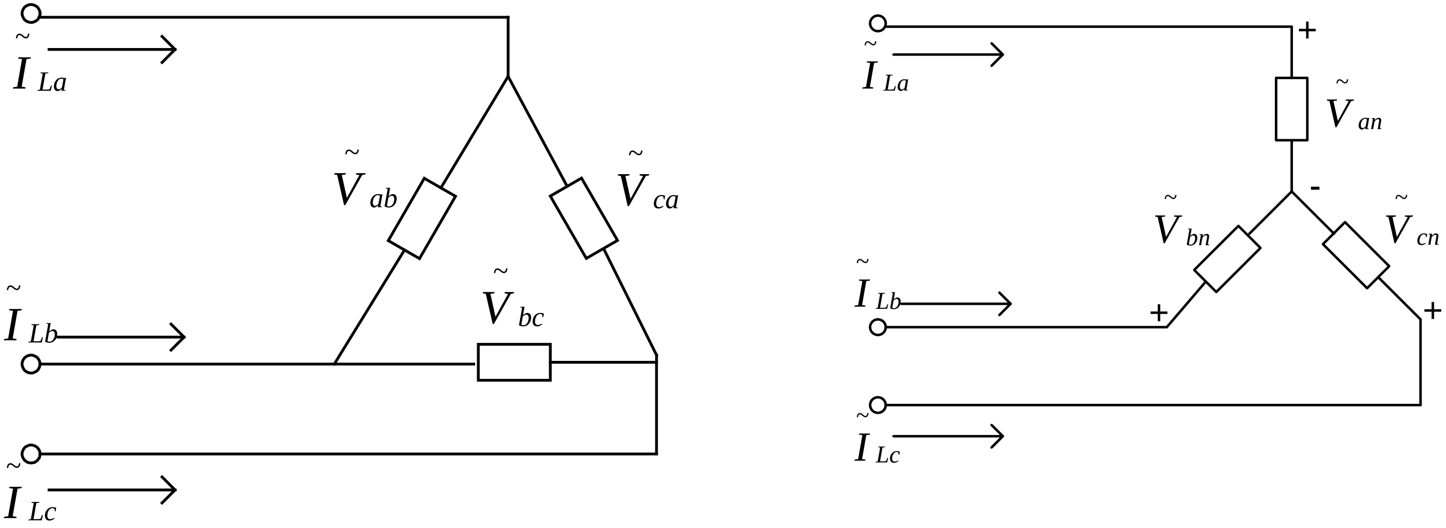
$$\tilde{Y}_{eq1} = \frac{1}{\tilde{Z}_1 + t^2\tilde{Z}_2}$$



transformer connections

- Δ/Δ,
- Y/Y,
- Δ/Y,
- Y/Δ

Distribution load connection and voltage model



Δ or Y connected load

$$P = P_{norm}(\frac{V}{V_{norm}})^{\alpha}$$

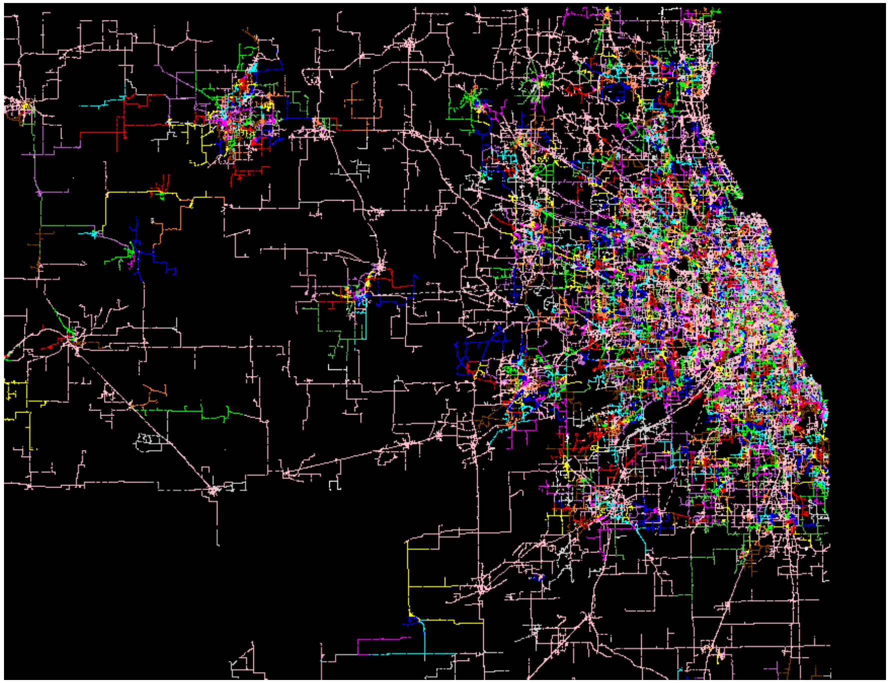
voltage dependence of load

VVO problem characteristics

- Integer decision variables (cap bank switching statuses, regulator tap positions). Number increase quickly for un-ganged control
- Non-linear & non convex objective function
- Objective not directly dependent on controls
- Numerous nonlinear equality constraints (solution space non convex)
- High dimensionality
- Inter temporary linkage makes the problem even bigger

Distribution System Dimension

- ComEd distribution system Chicago
- 2.2 million electrical nodes
- 7.5 million electrical components



Distribution System Problems Dimensions Example

ID	Comp. No.	Feeder No.	Node No.	Load No.	Line No.	Cap. Bank No.	Reg. Xfrm No.
1	1760	4	673	278	699	7	1
2	2455	3	946	431	966	8	1
3	4869	4	1859	865	1916	6	2
4	2327	6	874	308	919	8	1
5	2167	5	820	285	853	6	0
6	1406	4	533	176	560	4	1
7	6987	3	2628	1384	2708	7	2
8	4512	4	1700	858	1759	8	2

- **Most of the node, load, or line in the table have two or three phases**
- **Number of equations ~ Node * 3 * 2**

VVO solution challenges

- No viable commercial solver available, MIP, MIQP only
- General MINLP solvers inadequate even for very small problems (5 node to 30 nodes systems)
- Custom algorithm the only viable option for the near future

The Problem is growing tougher

- Emerging controls
  - DER (distributed energy resources)
  - Solar PV
  - Energy storage
  - EV charging
  - Demand response?
- Should VVO become VVWO (volt, var, and watt optimization)?
- How will the new control affect the control objectives? (demand reduction still valid?)

Conclusions

- It’s the Apps that deliver the value of smart grid
- Many apps are naturally formulated as optimization problems
- Truly feasible and optimal solution can only be found considering electric network constraints
- Even small electric distribution circuit results in problem size comparable to large transmission systems
- The non linear non convex constraints combined with integer controls make finding global or near global solution hard
- Standard MINLP is probably 15-20 years behind

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