

# Distribution 101

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Pacific Northwest National Laboratory

**Oregon Public Utility Commission**

**UM 2005 Distribution System Planning Investigation Workshop #1**

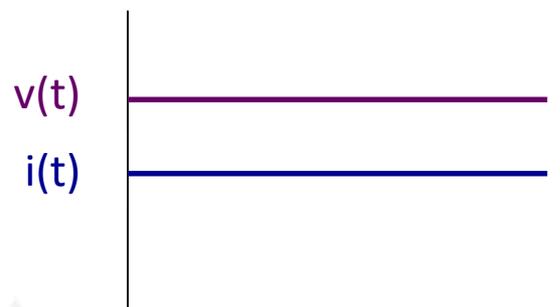
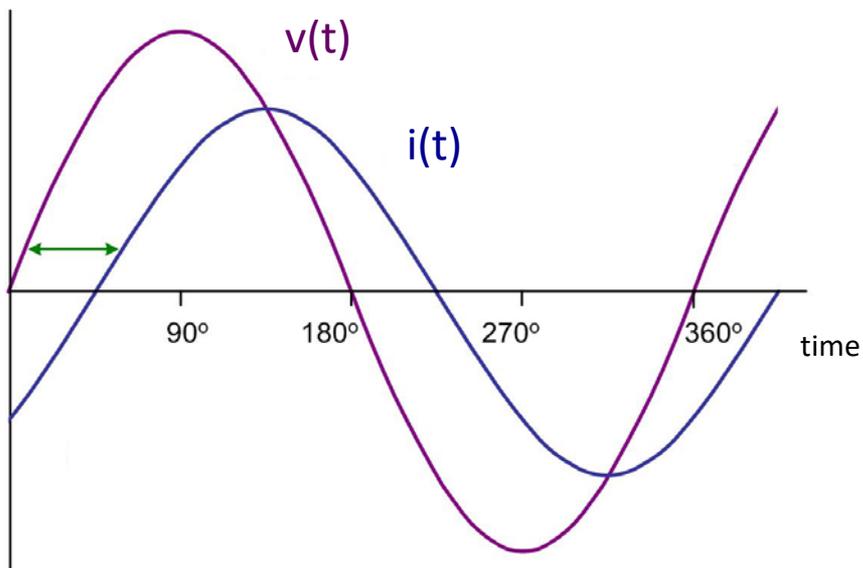
**May 2, 2019**

**Slide credits: Sascha von Meier, UCB**

# What we'll cover

- ▶ Intention of first session: Provide background on the present state of the distribution grid. Answer question: How did we get here?
- ▶ Information covered:
  - ❑ AC power...
  - ❑ Components and functionality
  - ❑ Voltage regulation
  - ❑ Sensing and measurement, including smart meters
  - ❑ What is the smart grid?
  - ❑ Emerging technologies
- ▶ Future reading (included in extra slides)

# Alternating Current (AC) fundamentals



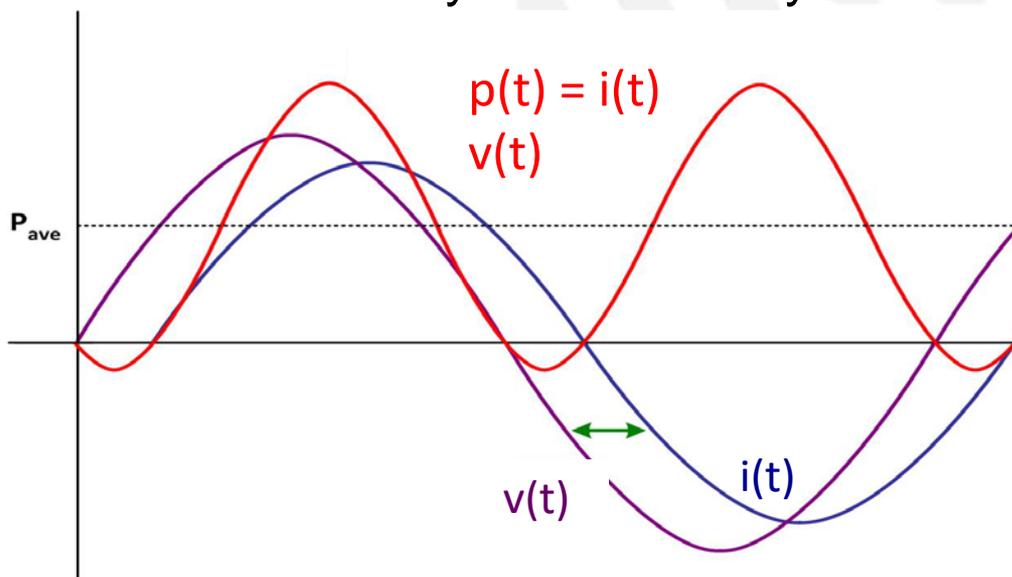
AC voltage and current waveforms are time varying with a 60 Hz fundamental frequency:

each sine wave is described by amplitude and phase angle (assuming constant frequency)

DC voltage and current only vary with changes in the load

# Reactive Power – why do we care?

- ▶ Real (or active) power ( $P$ ) accomplishes useful work to run a motor, heat a home or illuminate a light bulb
- ▶ Reactive power ( $Q$ ) supports the voltage that must be maintained and controlled for system reliability



*Energy conservation  
requires both*

$$P_{IN} = P_{OUT}$$

$$Q_{IN} = Q_{OUT}$$

The time relationship gives rise to the phenomenon of active (average) and reactive (oscillating) power, represented as complex power:

$$\mathbf{S} = \mathbf{P} + \mathbf{j} \mathbf{Q}$$

$$\text{active power } P = S \cos \theta \quad (\text{W})$$

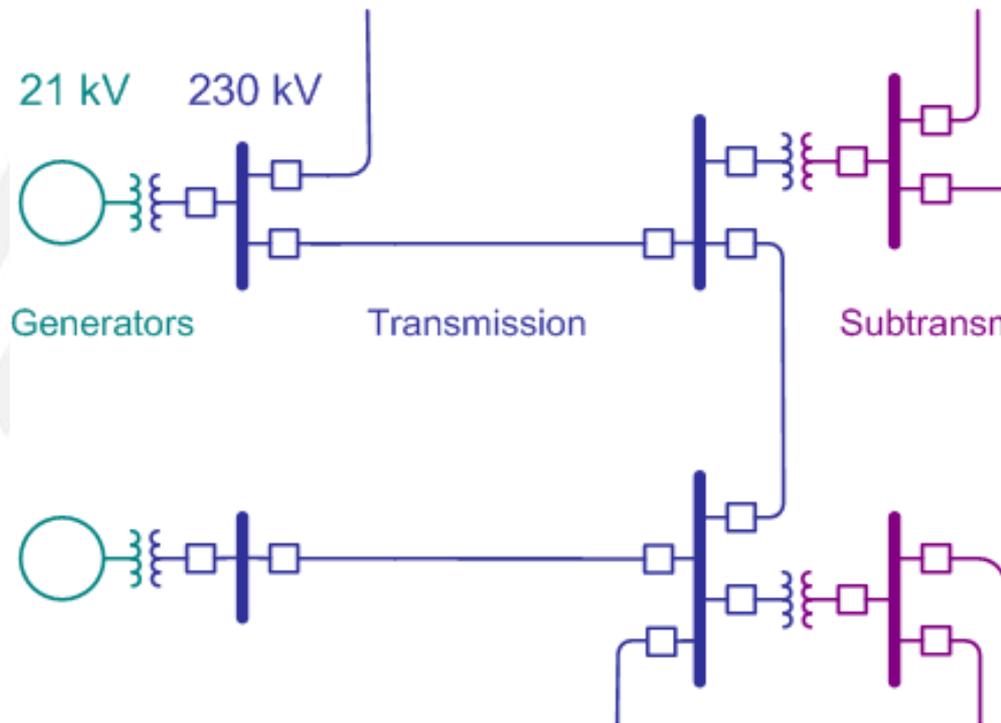
$$\text{reactive power } Q = S \sin \theta \quad (\text{VAR})$$

# Components and Functionality – a basic introduction to the distribution system “as is”

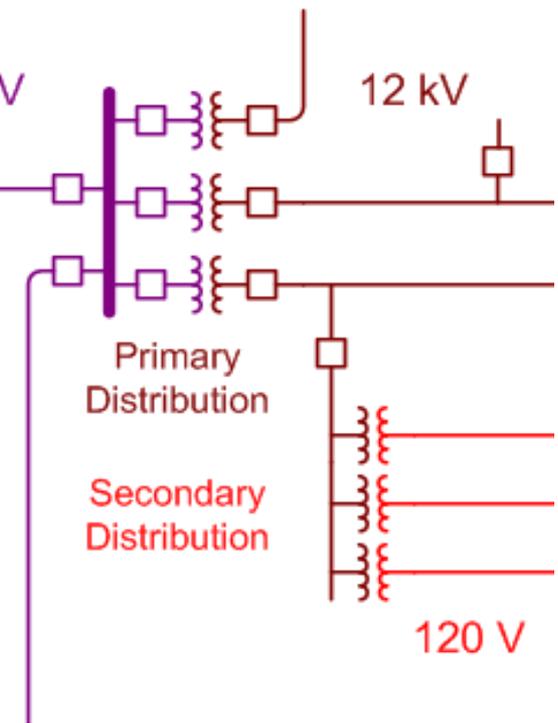
# How distribution systems are different than transmission systems

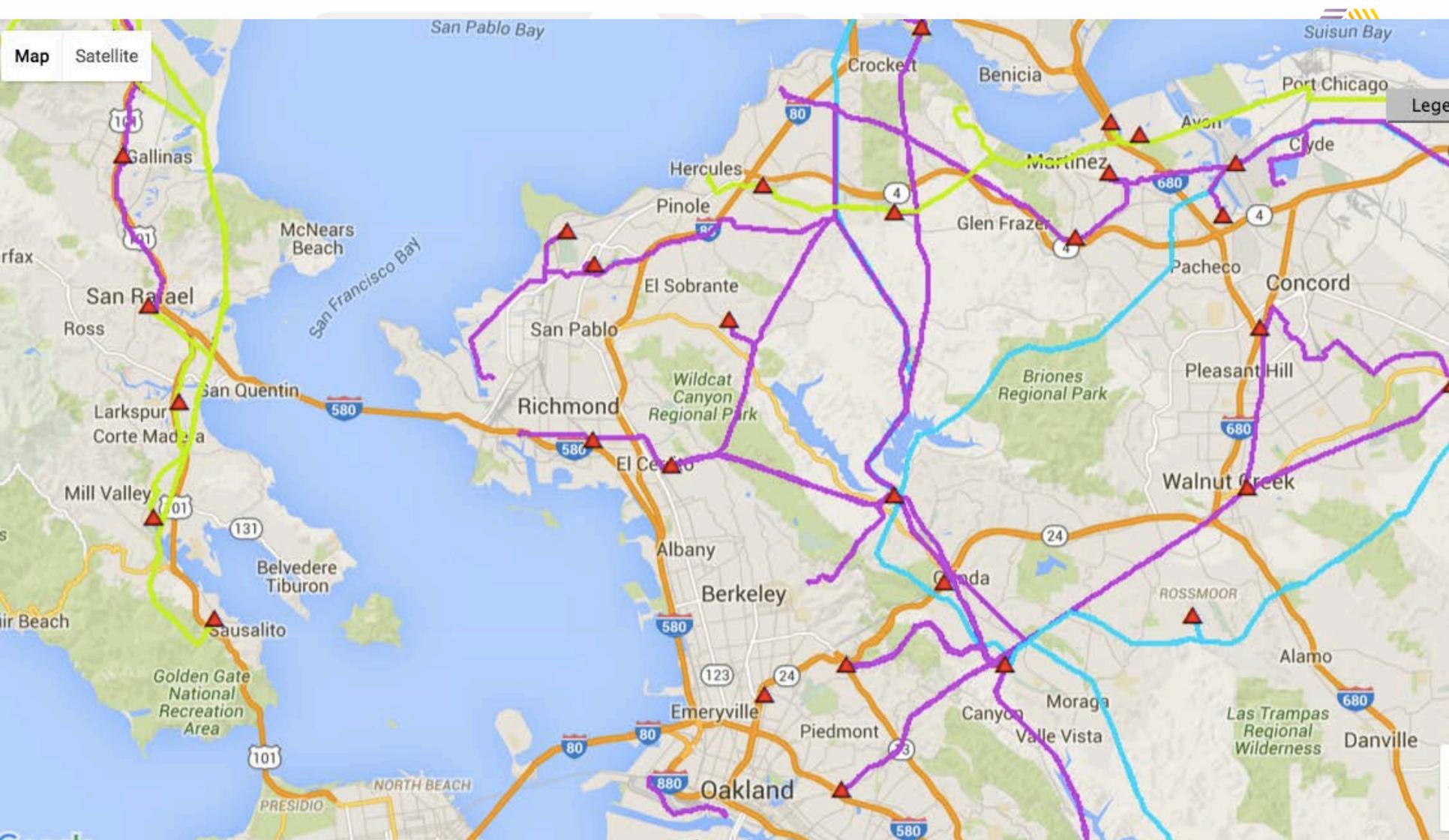
1. Architecture 2. Diversity 3. Variation 4. Vulnerability 5. Opacity

Standard transmission system design:  
**Networked**



Standard distribution system design:  
Operated **Radial** with one-way flow

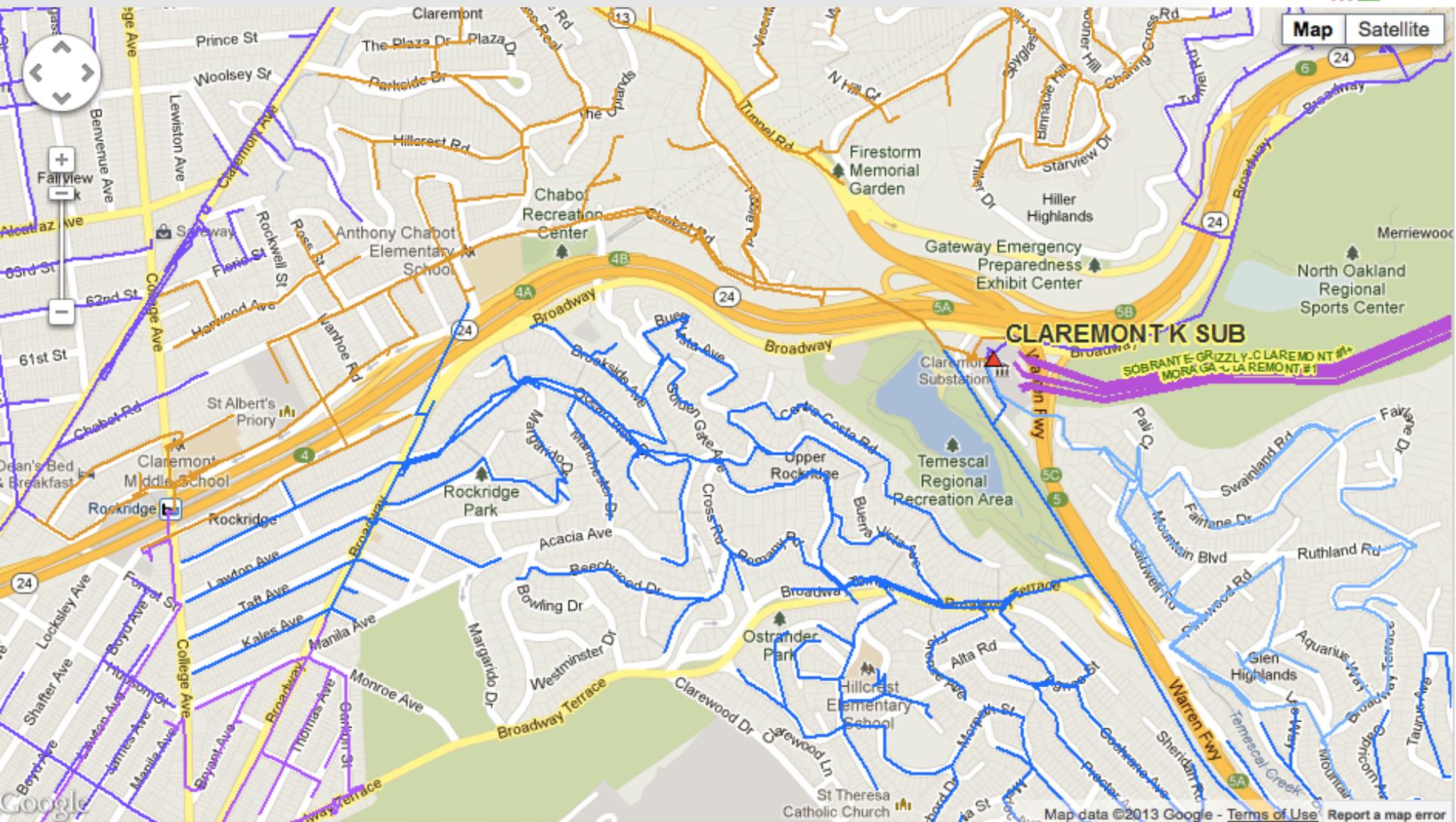




115kV Transmission network

▲ Distribution substations

<https://www.pge.com/b2b/energysupply/wholesaleelectricssuppliersolicitation/PVRFO/PVRAMMap/index.shtml>



# How distribution systems are different than transmission systems

1. Architecture 2. Diversity 3. Variation 4. Vulnerability 5. Opacity

## ► Some distribution feeder attributes:

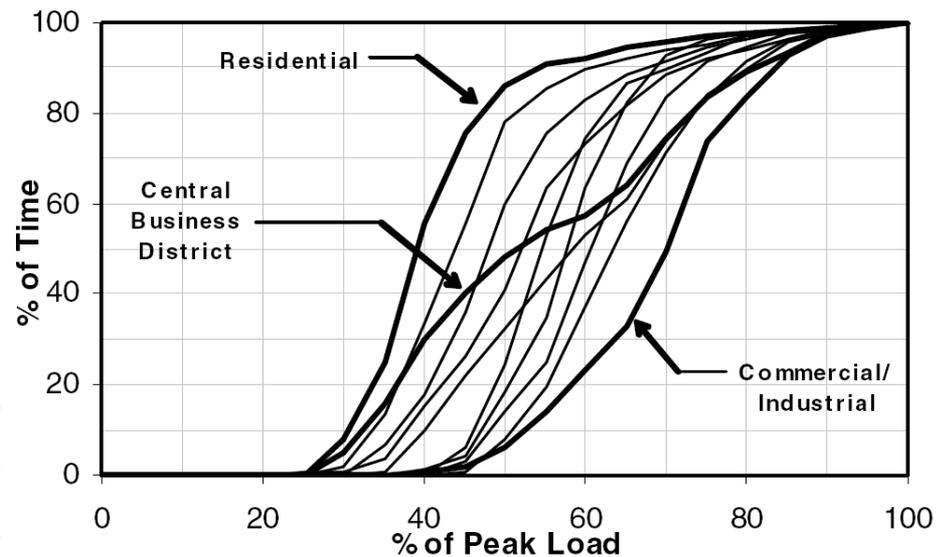
- underground vs. overhead
- topology (e.g. radial, loop, network), sectionalizing options
- circuit length, load density
- load characteristics (time profile, load factor, predictability)
- anticipated load growth, EV, DG
- sensitivity of loads to power quality
- phase imbalance
- extent of SCADA capabilities in place
- type of voltage regulation equipment in place
- type of protective equipment and protection scheme used

# How distribution systems are different than transmission systems

1. Architecture 2. Diversity 3. Variation 4. Vulnerability 5. Opacity

**Less help from statistics → Irregularities play a greater role**

- load (real power)
- power factor (reactive power)
- voltage drop
- phase imbalance
- generation



Source: Richard Brown, IEEE 2007

# How distribution systems are different than transmission systems

1. Architecture 2. Diversity 3. Variation 4. Vulnerability 5. Opacity

**External influences** are always nearby:

- weather
- vegetation
- animals
- vehicles
- people
- ...?



*Note: 80-90% of customer outages originate in the distribution system*

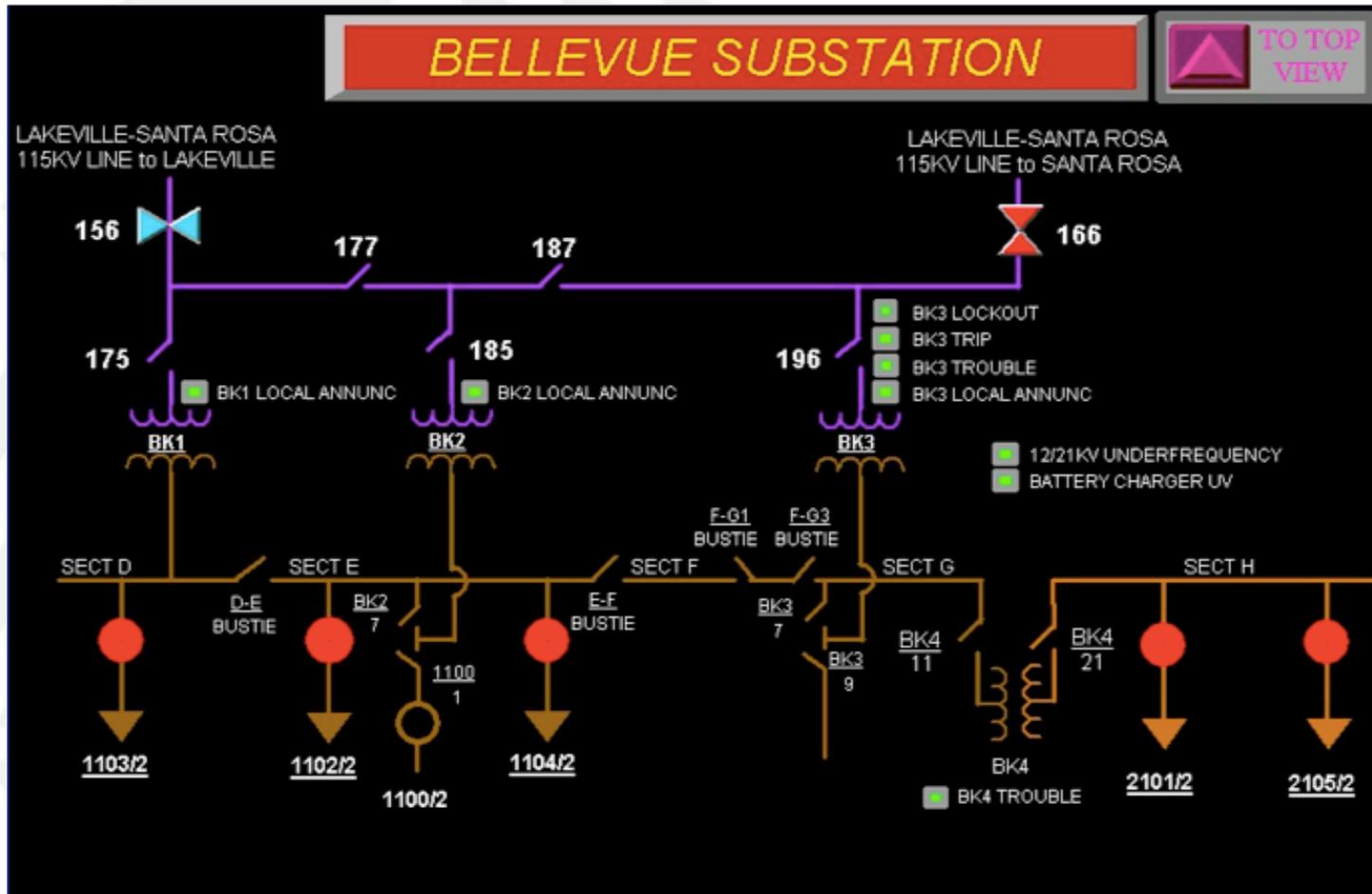


## How distribution systems are different than transmission systems

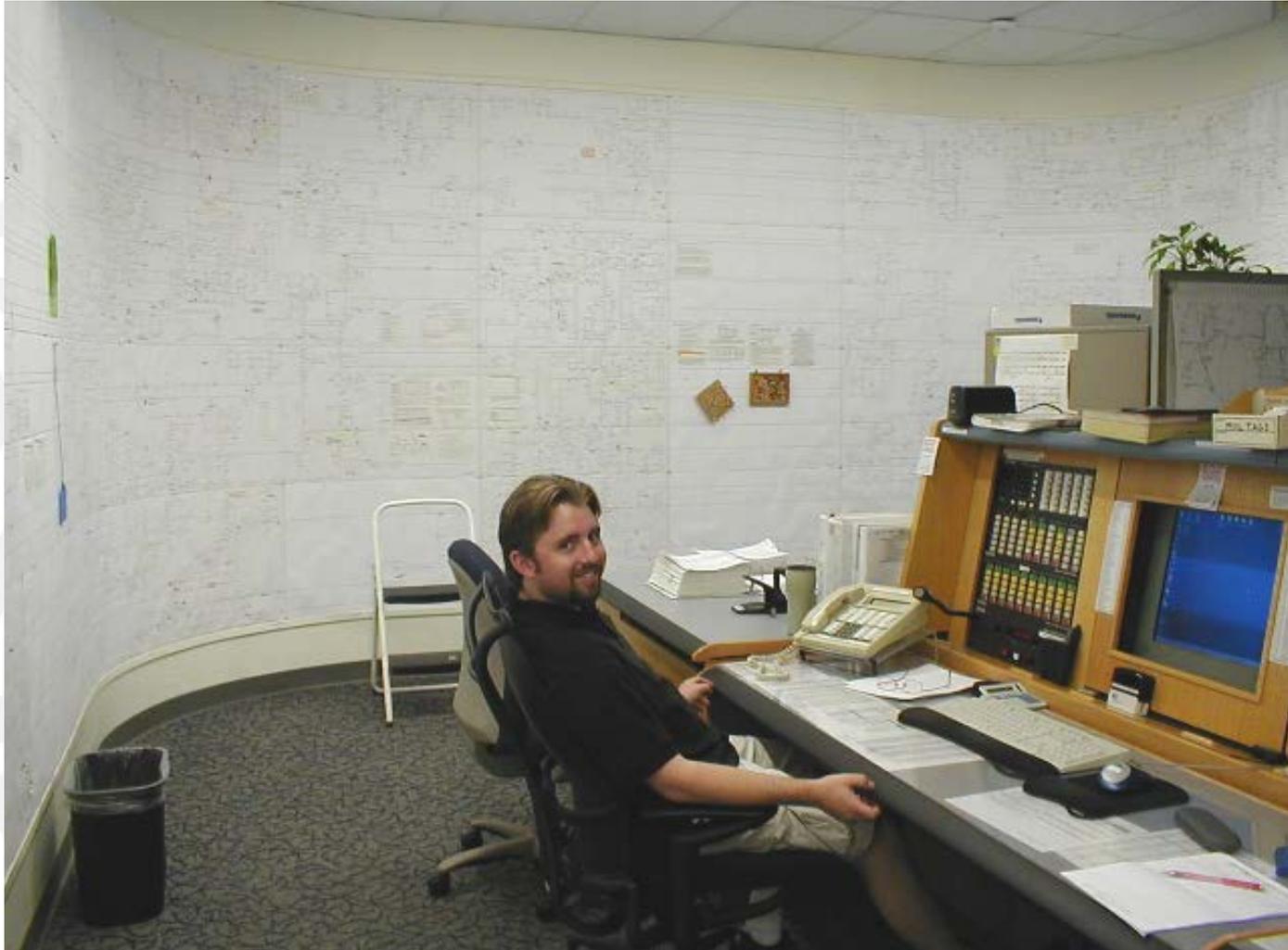
1. Architecture 2. Diversity 3. Variation 4. Vulnerability 5. Opacity

- ▶ Monitoring and control technology has not historically been cost-effective to install, in many cases
- ▶ SCADA\* typically available at substation level, but not on 100% of distribution circuits
- ▶ Many distribution circuits have no sensing beyond substation
- ▶ → **Operators usually can't see what's going on**
- ▶ AMI and smart metering provide customer level visibility – but lacking info past this point to the connected larger system

\* *Supervisory Control and Data Acquisition*



# Present State: Distribution Operator's control room, 2003



# Eyes and Ears in the Field



# Substations



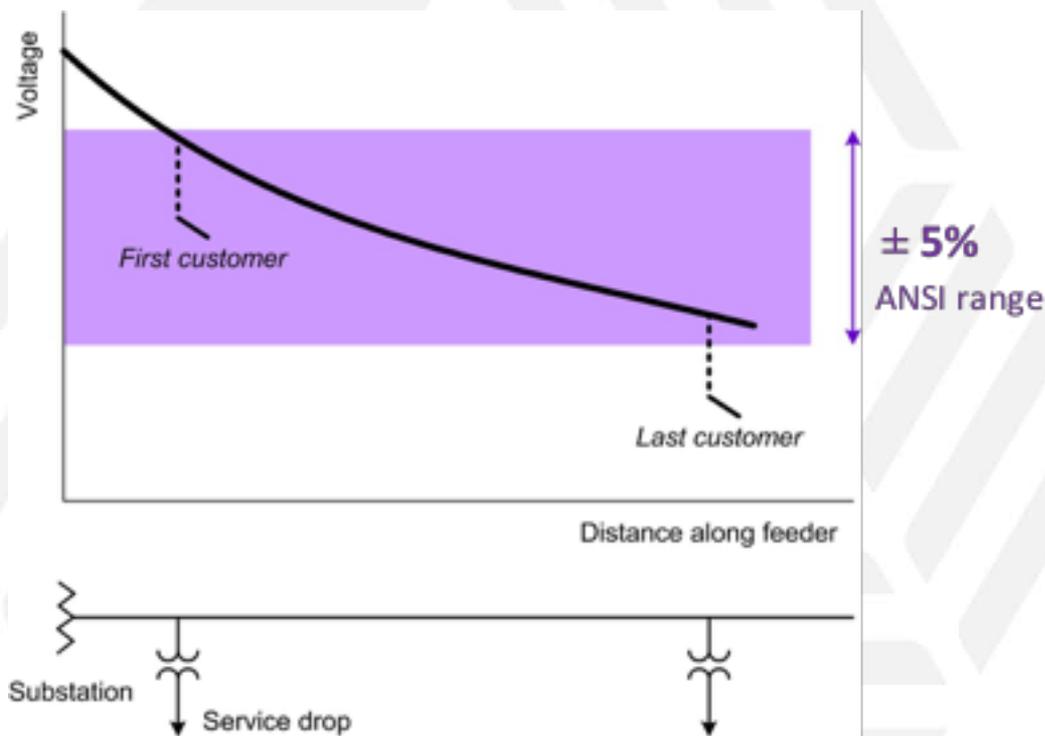
# Important Equipment

- Voltage Control Devices
- Transformers
- Conductors
- Protective devices
- Switches
- Sensors and meters

# Voltage Control Devices

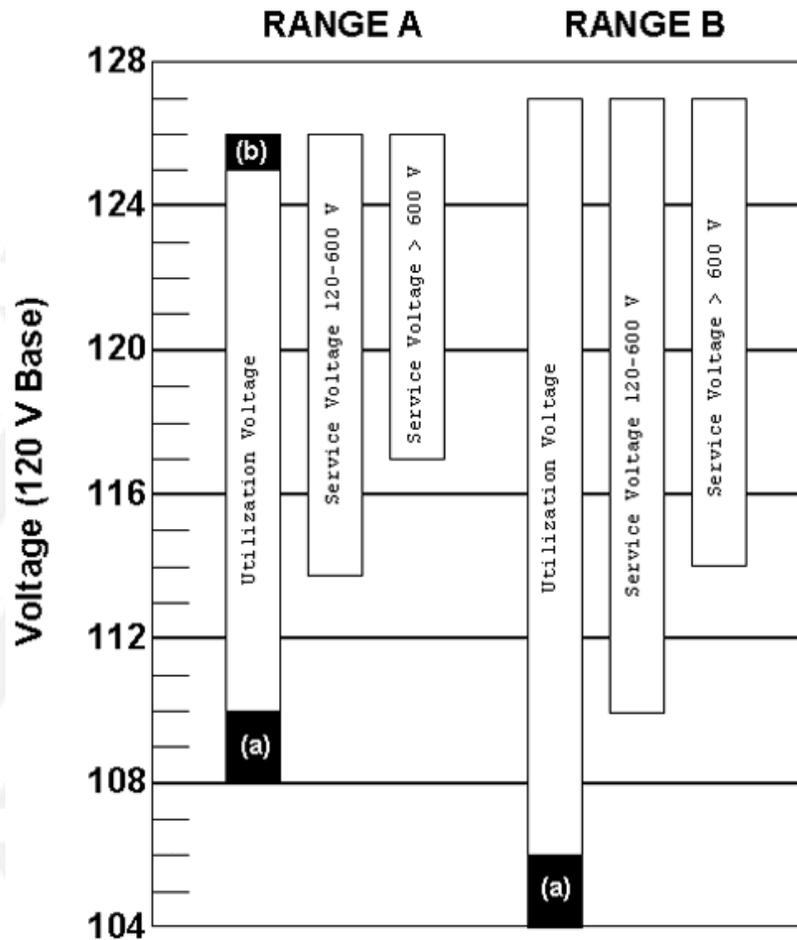
- ▶ Present State
  - Cap Banks
  - In line regulators
  - On Load Tap Changers
  
- ▶ What does not control voltage...
  - Small DG at the POC
  
- ▶ New state
  - CVR
  - VVO
  - Distributed var devices

# Distribution feeder voltage introduction



In most cases...with no regulation in line, from the substation transformer to the feeder end, voltage decreases as a function of resistance and current

# Customer and distribution feeder voltage must be maintained within standards – for safety and efficiency



## ANSI C84.1

American National Standards Institute

Most other countries, incl. European Community, allow  $\pm 10\%$

RANGE B: “for short duration or unusual conditions”

# Current State of Distribution Voltage Regulation

## Traditional voltage regulation

- load tap changer (LTC)
- voltage regulator (VR)
- capacitors

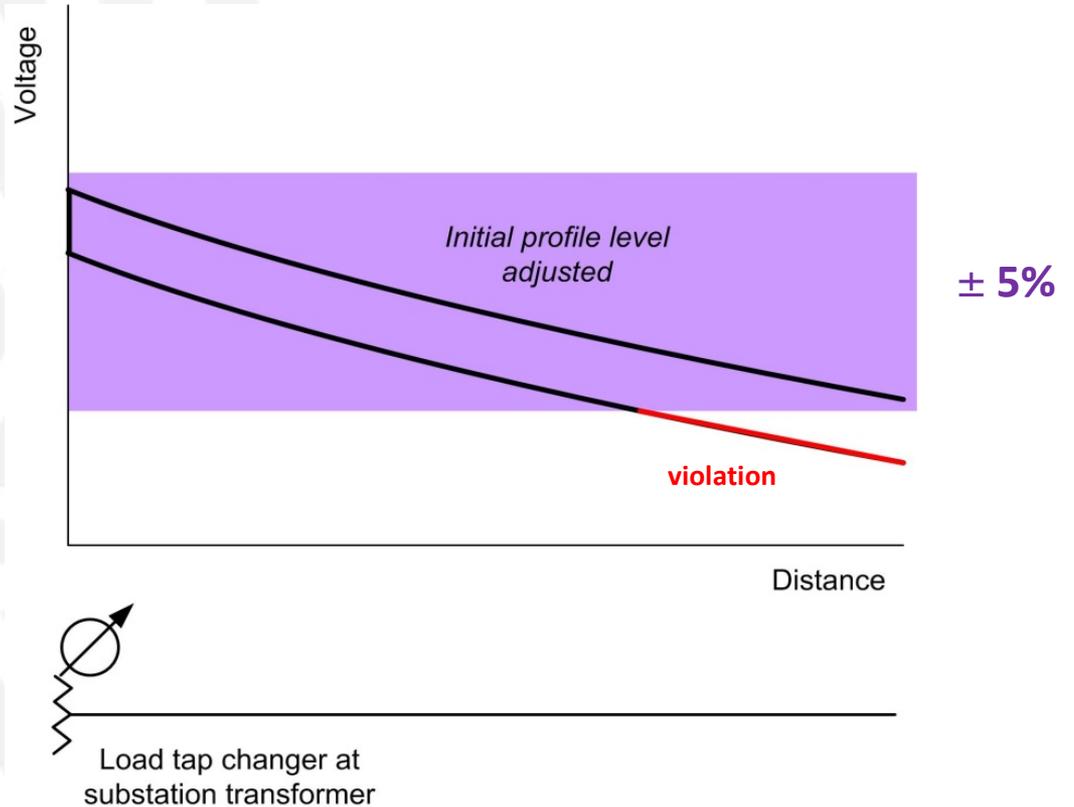
## Emerging technologies (Discussed in future presentations)

- Advanced Inverters
  - Grid-forming (can maintain stable voltage and frequency)
  - four-quadrant ( $\pm P, \pm Q$ )
- solid-state transformers
- static VAR compensators for distribution
- Volt Var/Volt-Watt/CVR

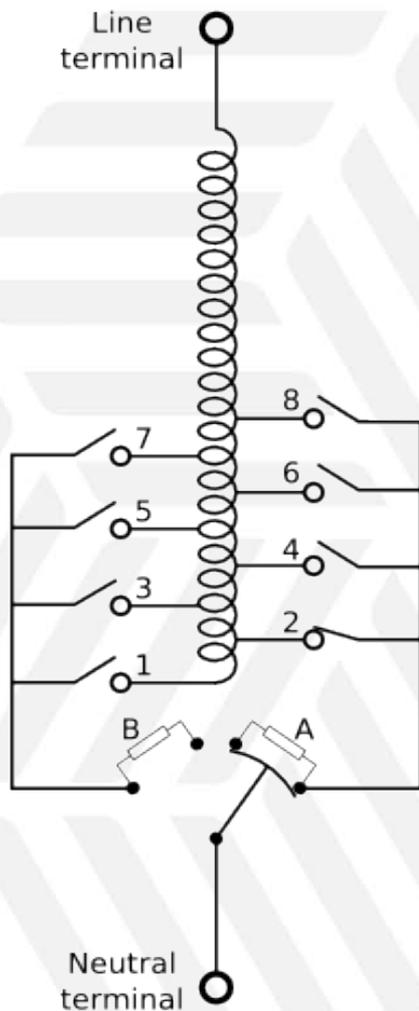
# Traditional Voltage Regulation: Load tap changers



Substation transformer with load tap changer



# LTC's cont



## Mechanical load tap changer

designed to transfer load smoothly, with no interruption and minimal arcing

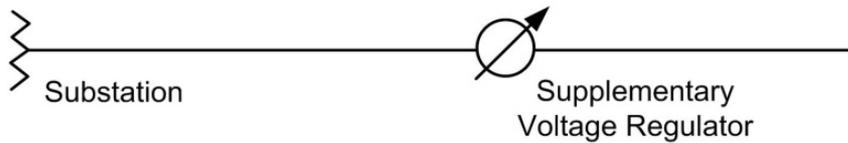
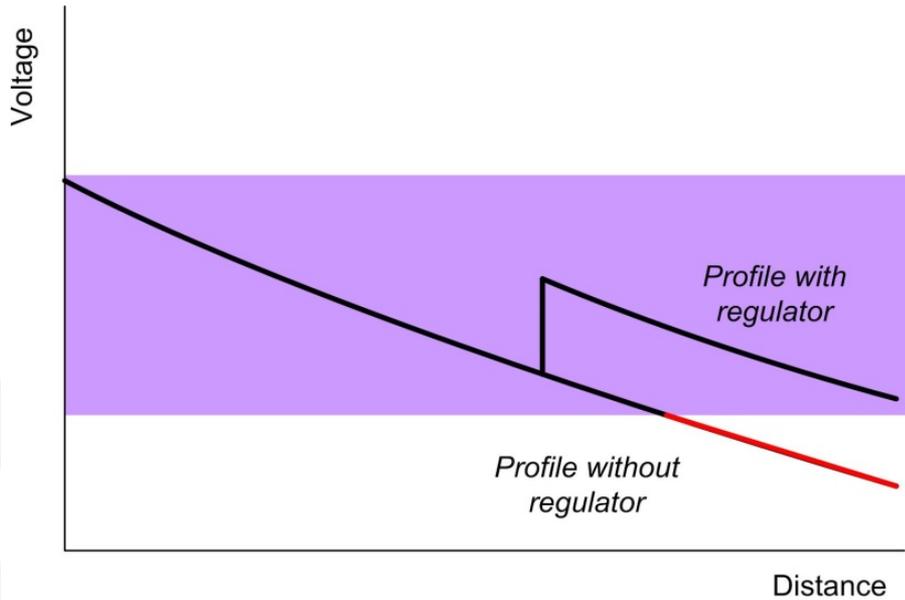
A and B are “diverter” resistors

but some arcing and wear is unavoidable

thus frequent operation is not desirable

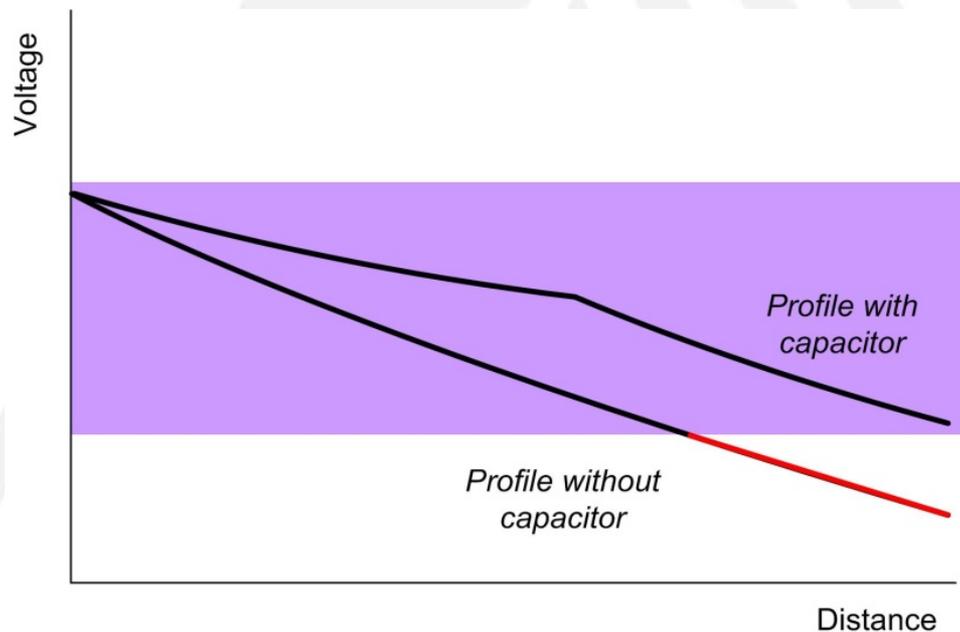
(25K-50K operations between maintenance)

# Traditional Voltage Regulation: in line voltage regulators

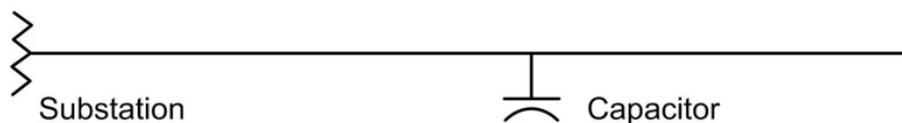


2 Single Phase  
Voltage Regulators

# Traditional Regulation: Capacitor Banks

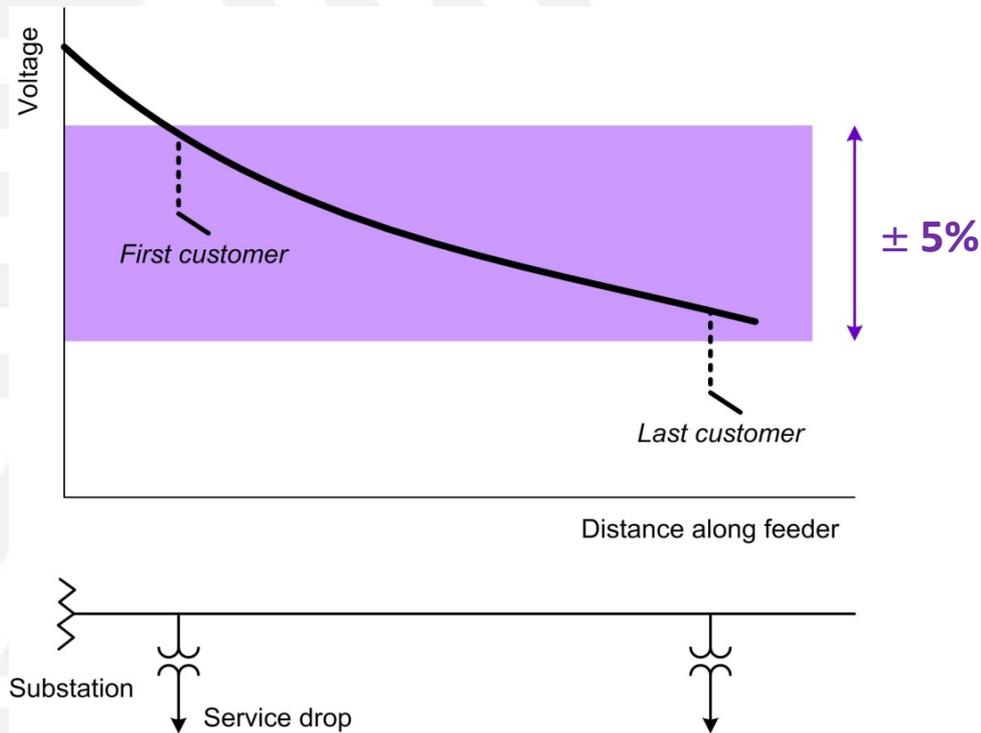


Capacitor Bank

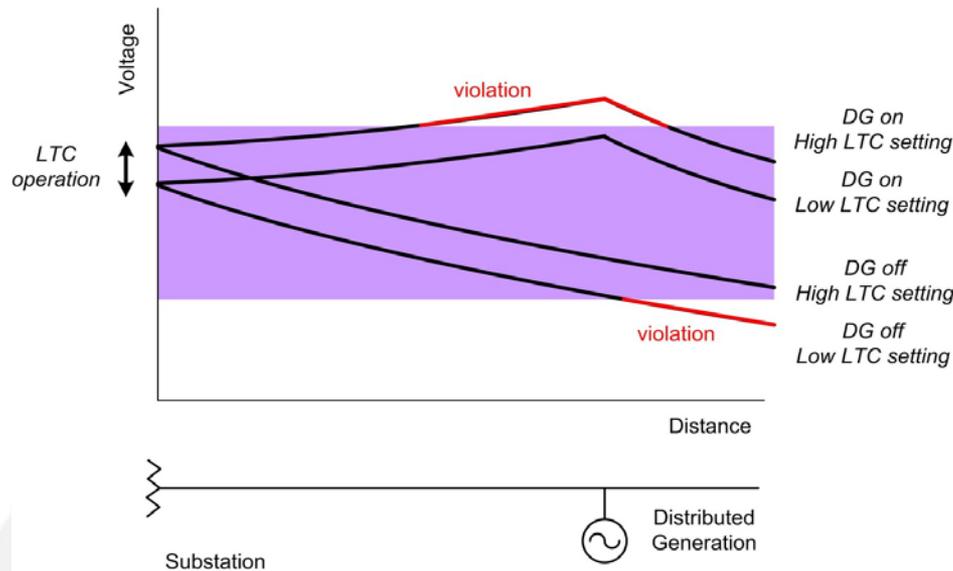


**Problem: What happens to Voltage Regulation when there are sources of P (active power) and Q (reactive power) out on the radial feeder? (i.e. distributed generation)**

The traditional approach assumes one-directional power flow.



# Moving towards smart voltage control: Coordination issues with uncontrolled DG



- Distributed generation (DG) may drive voltage out of range
- DG may wear out legacy equipment, due to “hunting”
- Existing controls may not be configured for reverse power flows
- Voltage status may become even less transparent to operators
- This will all be presented later!

# Substation Transformers



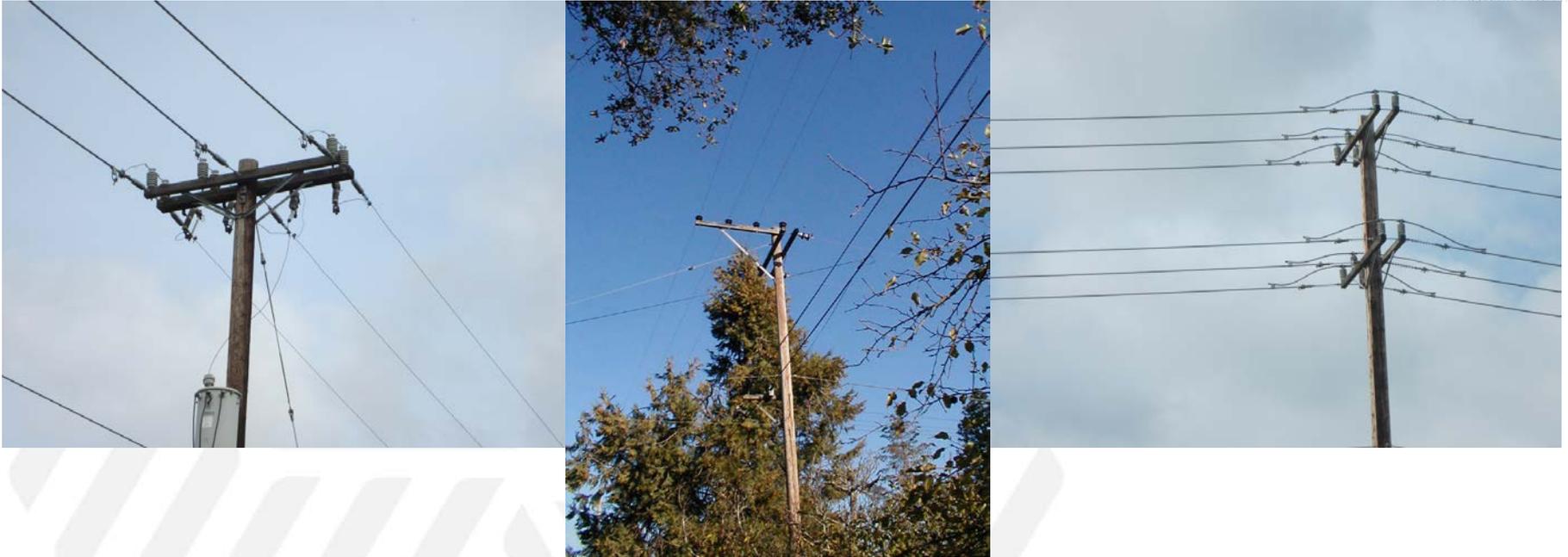
# Substation Transformers

- Substation transformers can perform various functions:
  - Step voltage up from generation to transmission levels
  - Convert between voltages between transmission lines
  - Step voltage down for use at the distribution level
- Power ratings can be from several MVA at the distribution level to greater than 1,000 MVA at the transmission level.
- These transformers are generally very efficient, greater than 98%.
- Even with high efficiencies, thermal losses must be addressed
  - Passive cooling
  - Passive cooling with a radiator
  - Forced air cooling with a radiator
  - Spray cooling with a radiator
  - Circulated oil cooling with a radiator

# Service Transformers

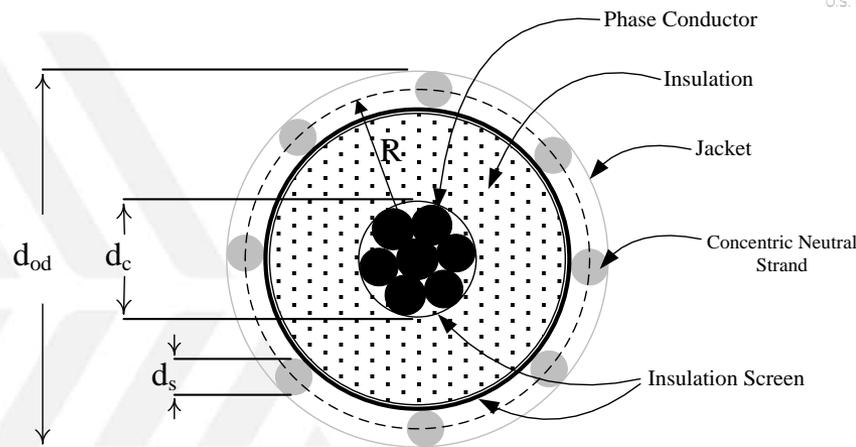


# Overhead Lines



- Much more common than underground cables (\$\$)
- Usually aluminum and steel, not copper (\$\$)
- Usually bare conductors, not insulated
- Faults will occur when the conductor comes into contact with the ground, vegetation, animals, or people...

# Underground Cables



Underground cables may be used in a number of situations:

- In areas where there are numerous momentary faults, e.g. wind storms.
- In urban areas where overhead lines may not be practical or desirable.
- In communities where there is a desire to not have visible infrastructure.

Cables can be directly buried or laid into conduit and vaults.

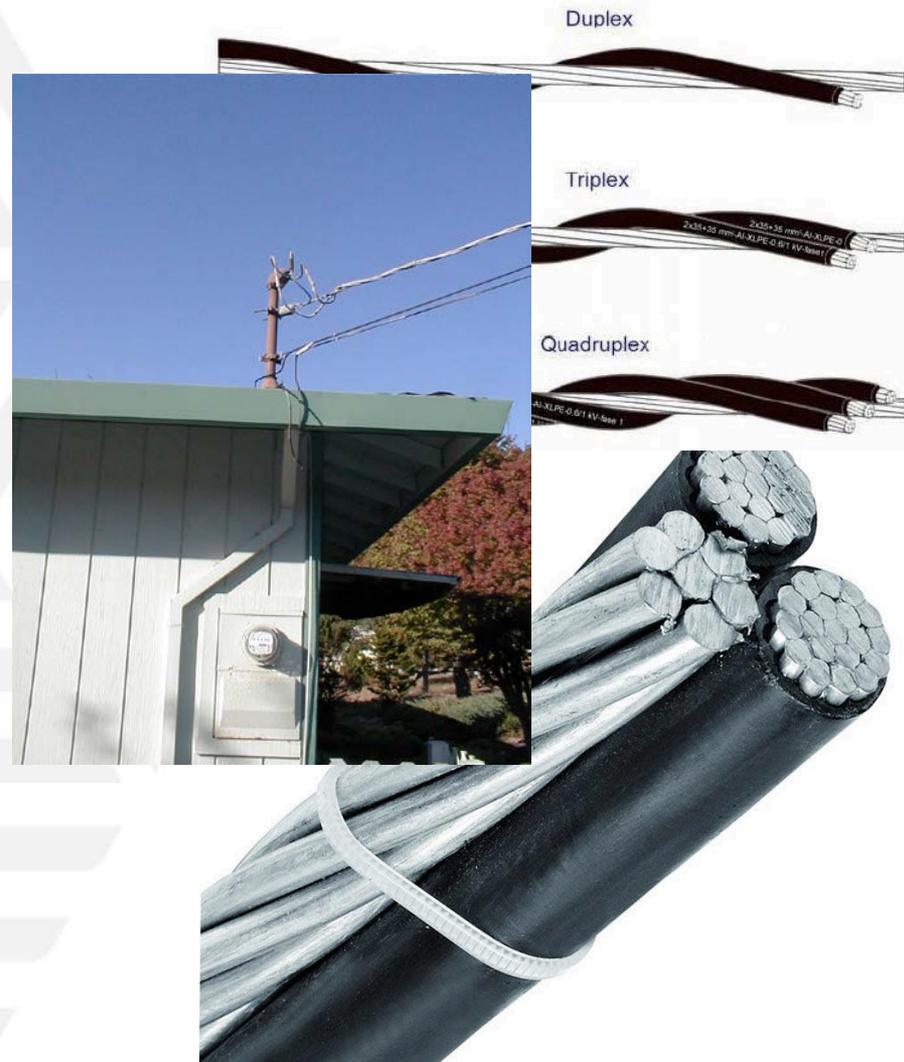
Underground cables have some desirable characteristics but they can be up to ten times the cost of overhead lines.

When faults do occur, it can be difficult to locate and fix the fault. It may be necessary to dig the cable up to fix the fault.



# Triplex Cables

- Triplex cables connect the service transformer to the end-use customer.
- Utilities generally have guidelines for how long these cables can be...
- The voltage drop across these cables is often unknown
- Multiple customers can be serviced from a single service transformer via independent triplex cables.



# Switchgear

Distinguish:

Switches vs Protective Devices

protective devices

- fuses
- circuit breakers
- reclosers





Knife Switch



**GRID**  
MODERNIZATION  
LABORATORY  
CONSORTIUM  
U.S. Department of Energy

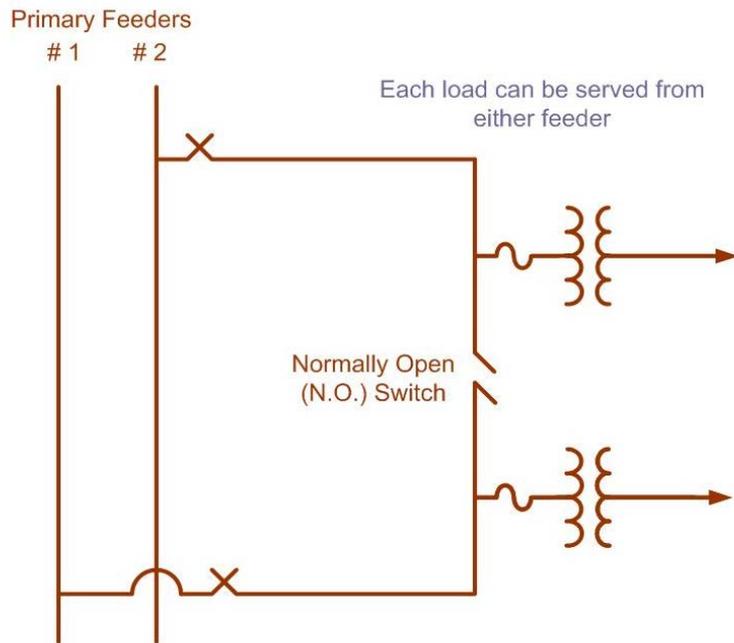


# Distribution System Switches

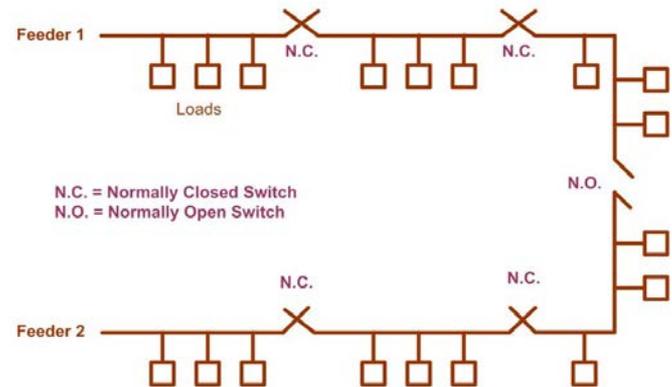
- The primary function of a switch is to provide electrical isolation.
- Switches are not protective devices, unlike breakers they cannot interrupt current.
- Switches at a substation can transfer load between substation transformers.
- At the distribution level switches are used to reconfigure a feeder.
- Switches can be used to transfer load from one feeder to another.
- Switches can also be used as part of a system repair strategy in order to isolate portions of the system while repairs are conducted.
- Switches may be remotely controllable (SCADA) or require manual operation.

# Distribution configurations

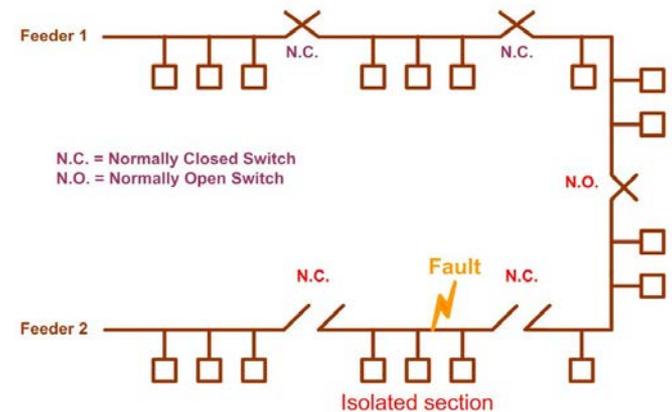
## Loop System



## Sectionalizing a Loop System: Before

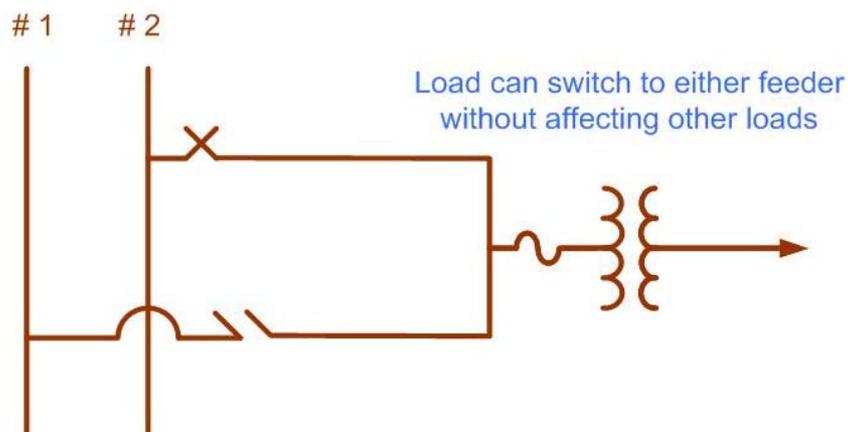


## Sectionalizing a Loop System: After

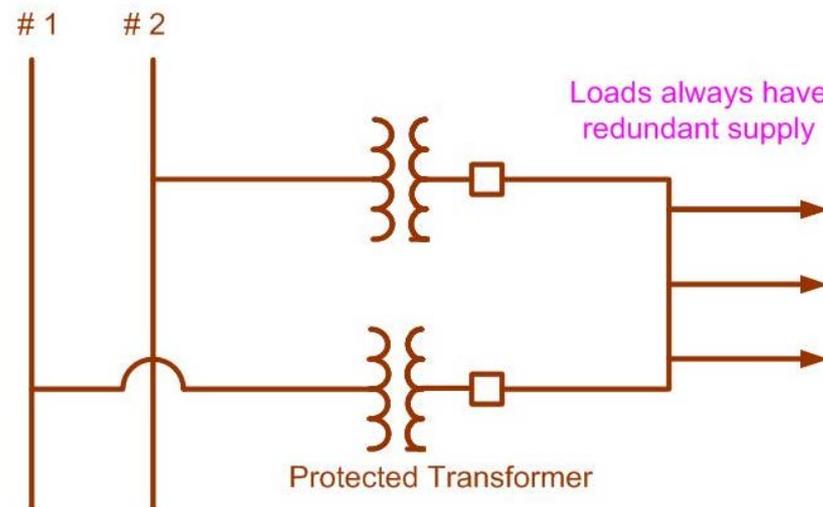


# Distribution Configurations

## Primary Selective System



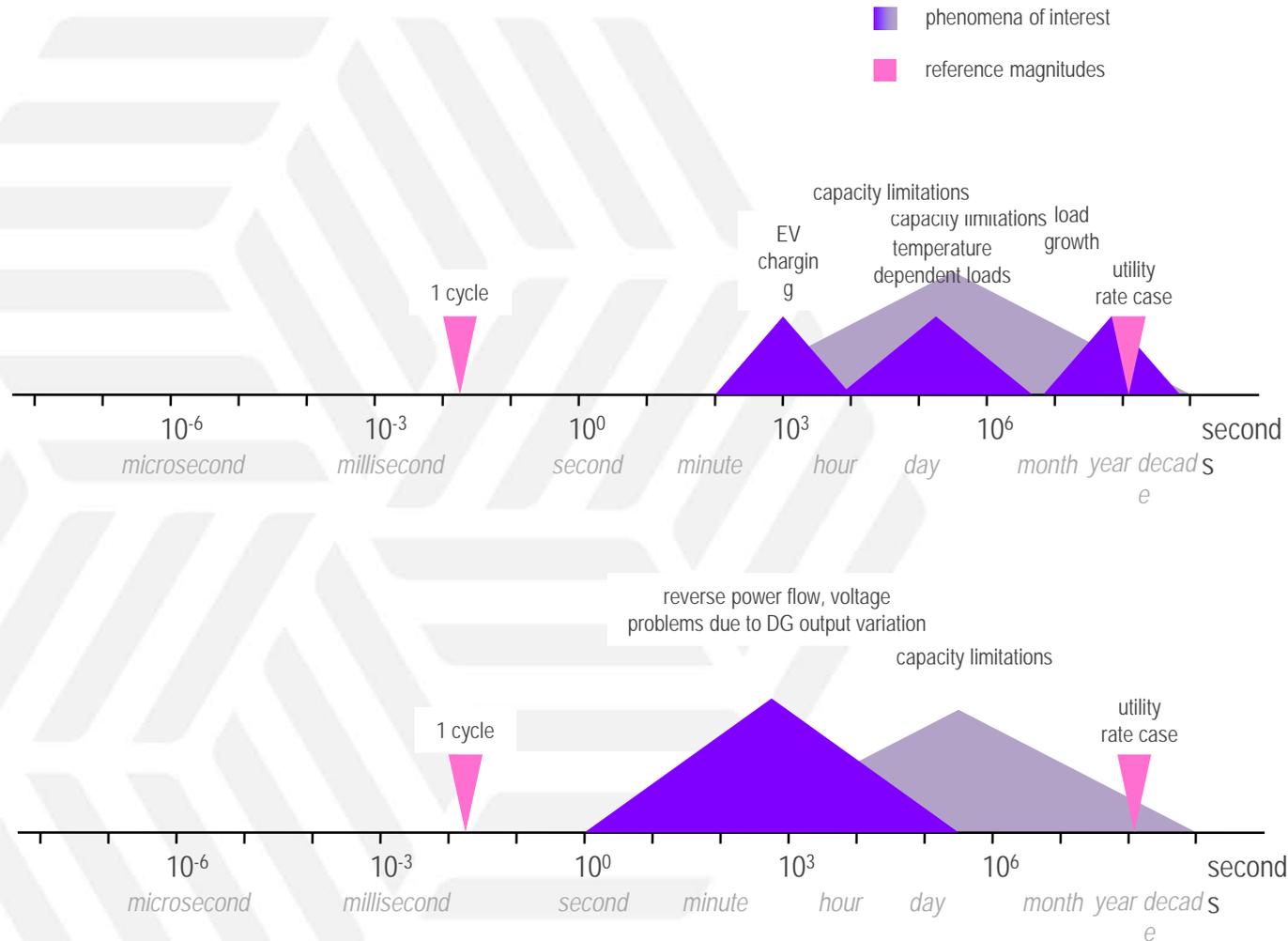
## Spot Network



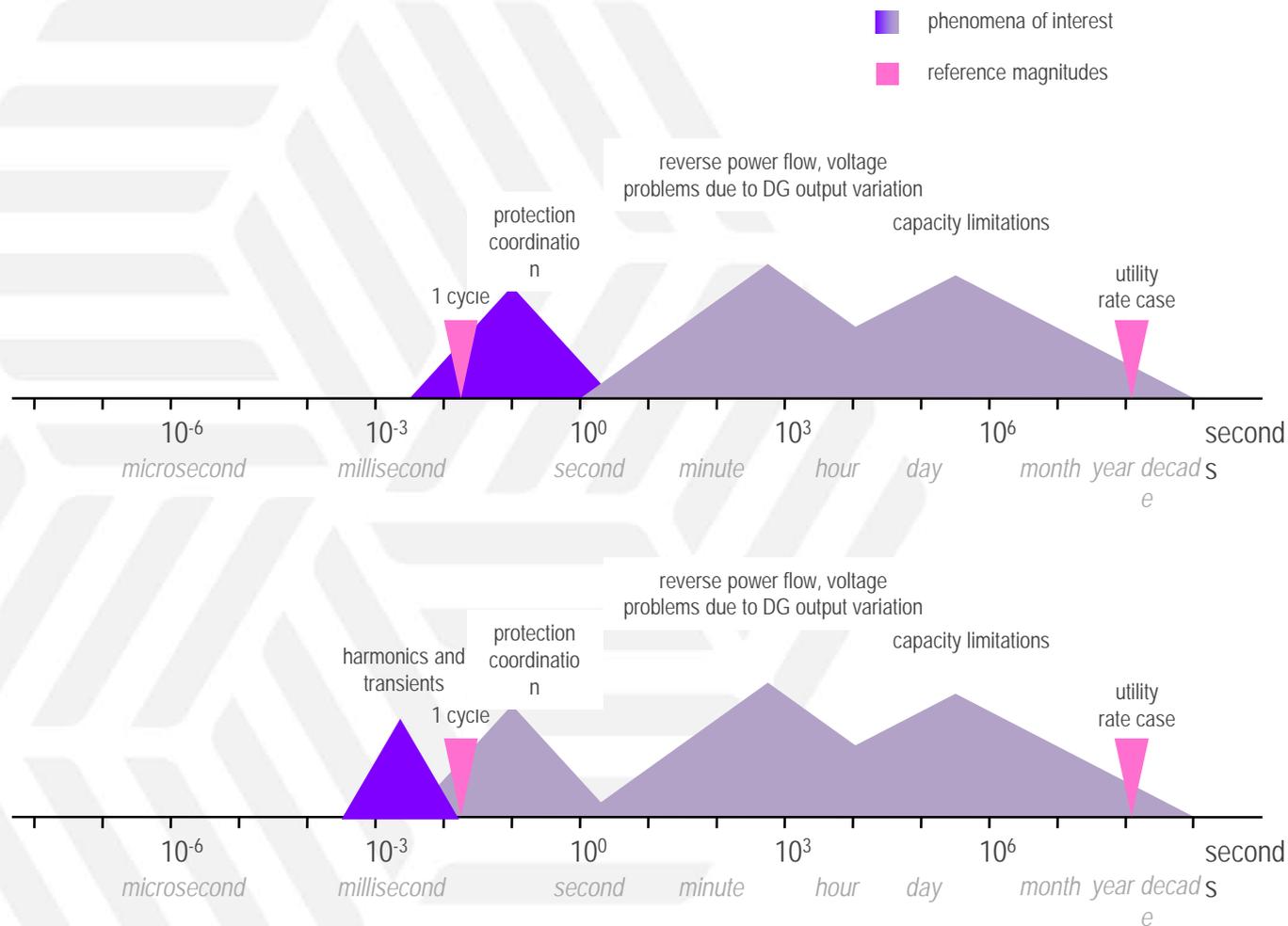
Spot networks are much more expensive and used only in high-stakes settings such as downtown business districts of big cities

# Introduction to Sensing and Measurement for the Distribution System

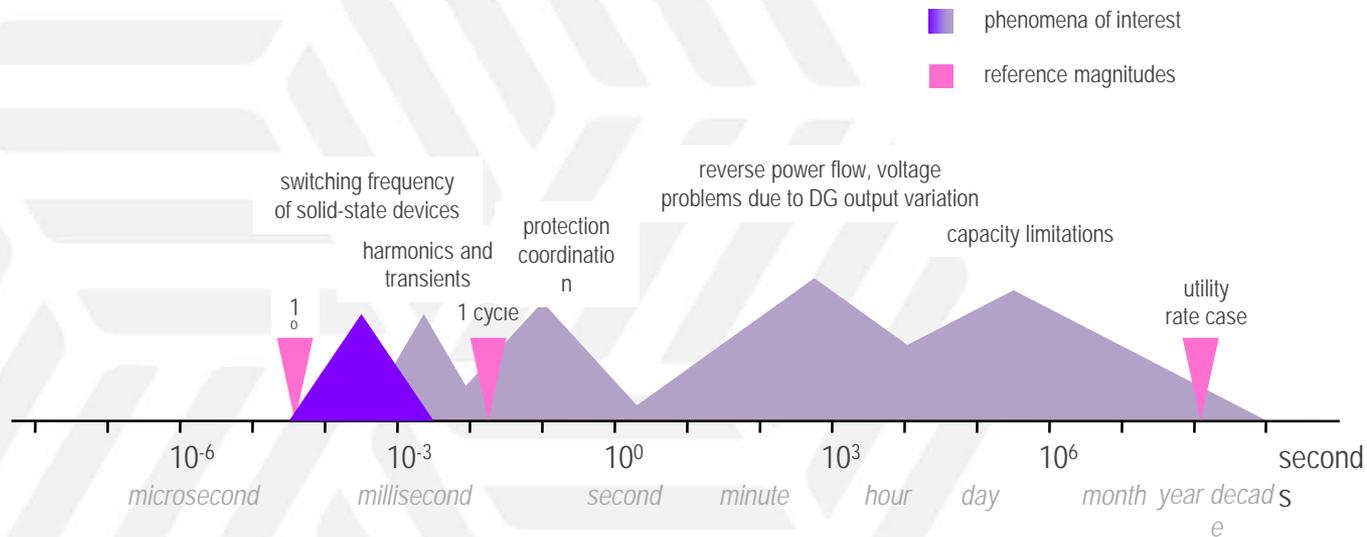
# Distribution System Issues on Different Time Scale



# Distribution System Issues on Different Time Scale

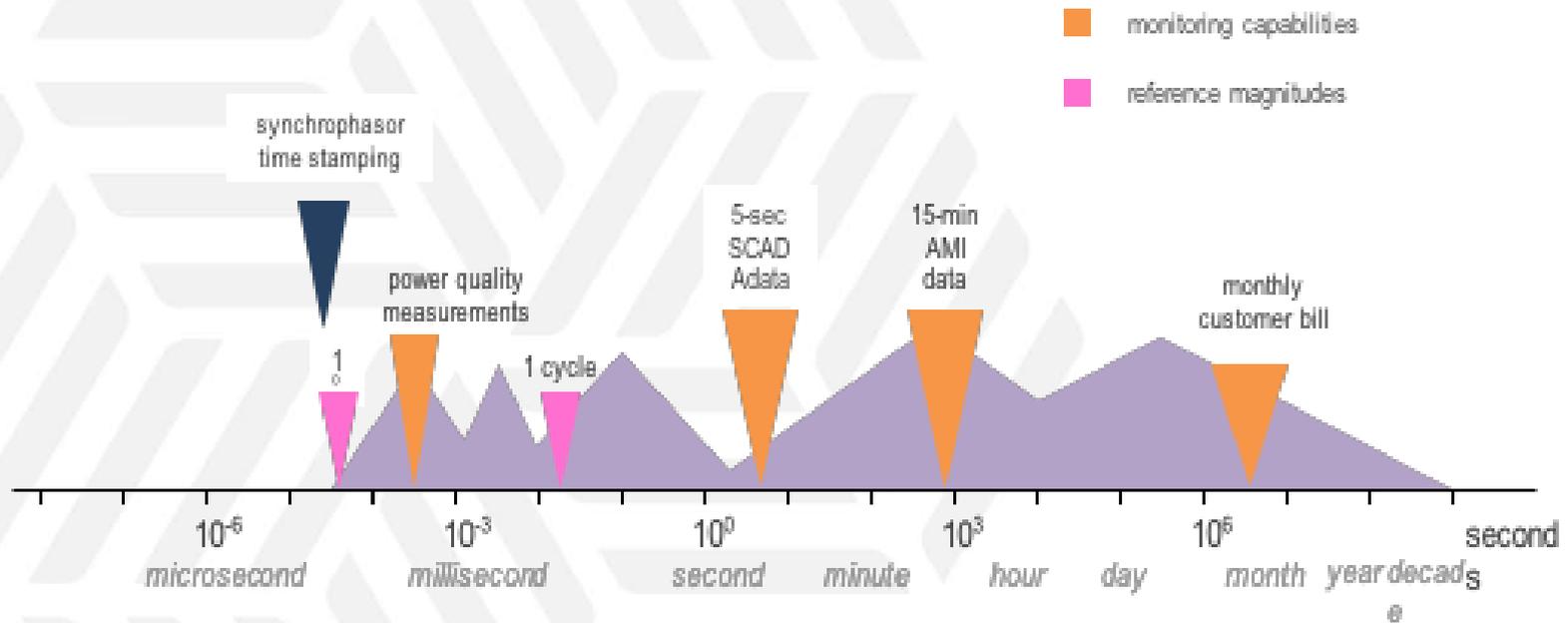


# Distribution System Issues on Different Time Scale



# Monitoring capabilities on different time scales

*Not a given: time synchronization among multiple locations, even at high measurement resolution*



# Supervisory Control and Data Acquisition (SCADA) Components

**Sensors:** instruments measuring physical quantities (current, voltage)

**Remote terminal units (RTUs):** perform analog-to-digital “A to D” conversion of sensor signals; may include basic control capability

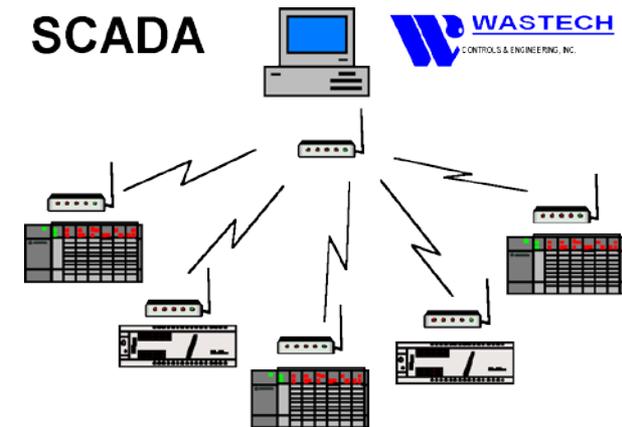
**Programmable Logic Controllers (PLCs):** similar to RTUs, more sophisticated controls

**Telemetry:** provides connection for signals between field devices and control center, using some **physical communication layers** (telephone wires, radio, satellite, microwave, 3G wireless)

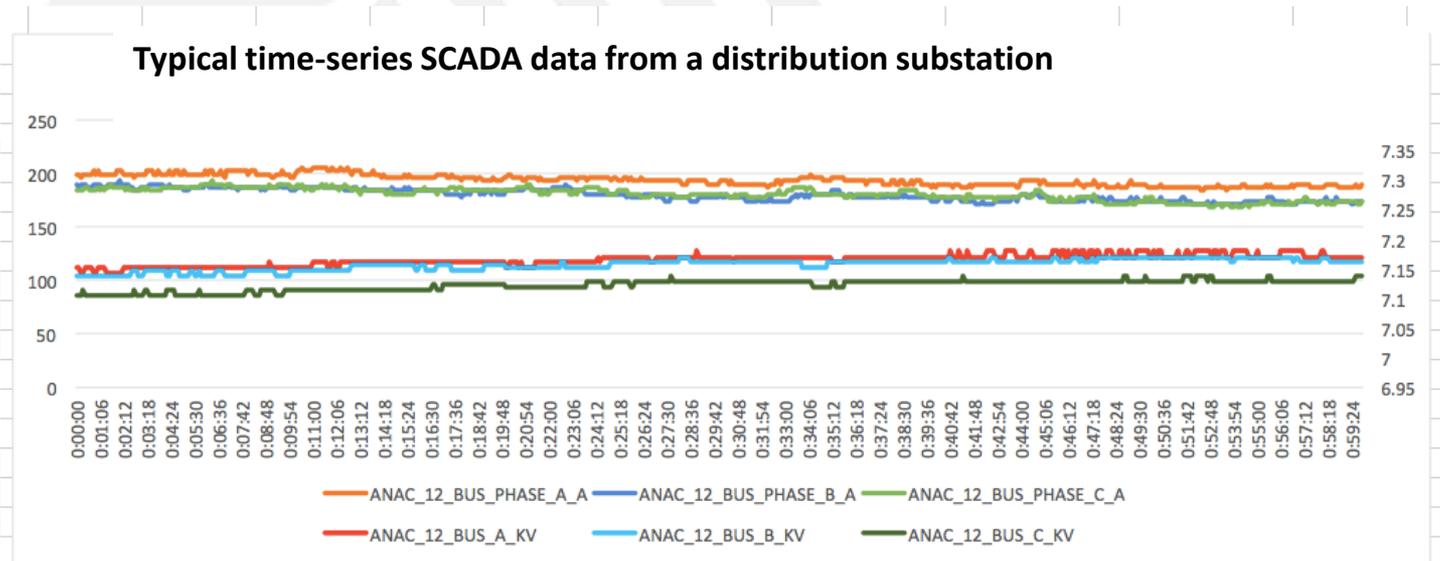
**Data Acquisition Server:** manages data from field devices

**Data Historian:** stores data

**Human-machine interface (HMI):** client for data from server; presents to operator; may receive control inputs from human operator



# Typical SCADA



*One problem: time synchronization among locations!*

# What is AMI & a Smart Meter Intro

- ▶ AMI: Set of technology which encompasses smart meters, communication networks and information systems to inform the utility at a basic level on customer and network behavior as it pertains to billing and performance
- ▶ Smart Metering is a subset of technology within AMI
- ▶ ~65M – 76M meters exist at present in the US
- ▶ Rate of adoption varies depending on state policies, regulatory incentives, and technology experience levels within the utilities.
- ▶ Why is a smart meter different: normal meters provide monthly billing and mechanical
- ▶ Smart meters can provide bi-directional or two way communications and control and can be linked with HAN, thermostats and smart appliances

# Smart Meters

**Primary purpose: Settlement**  
(time-differentiated meter reading)

Secondary purpose:  
identify outages  
other operations support

**Typical activity:**

record kWh usage, voltage at 15-min intervals  
report 8 hrs worth of 15-min kWh data to access point 3x per day  
send “death chirp” in case of outage

Headroom on communications network allows querying subset of meters for some additional data, reported within minutes

Automated Meter Reading (AMR): one-way communication  
Advanced Metering Infrastructure (AMI): two-way communication



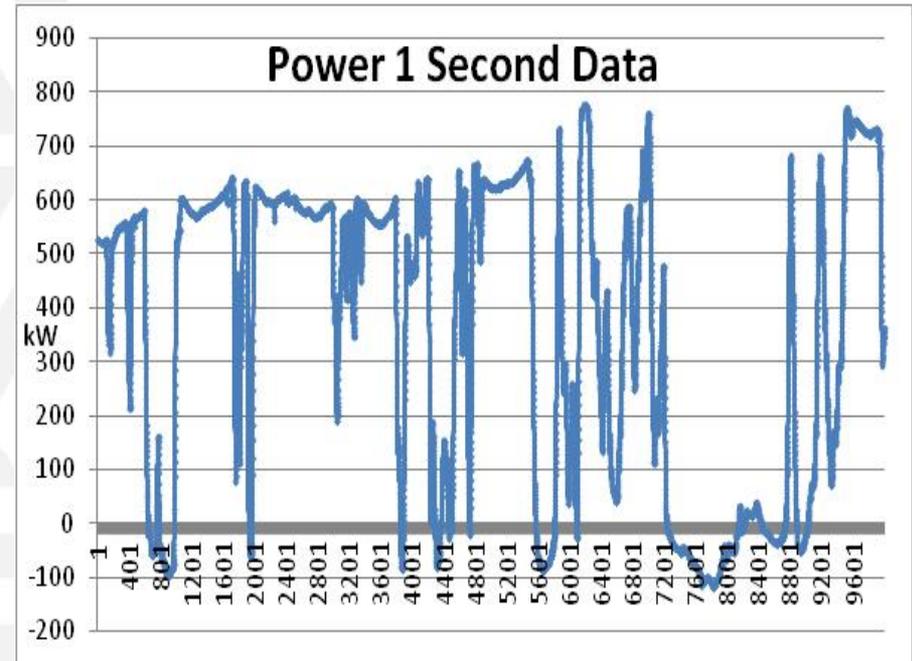
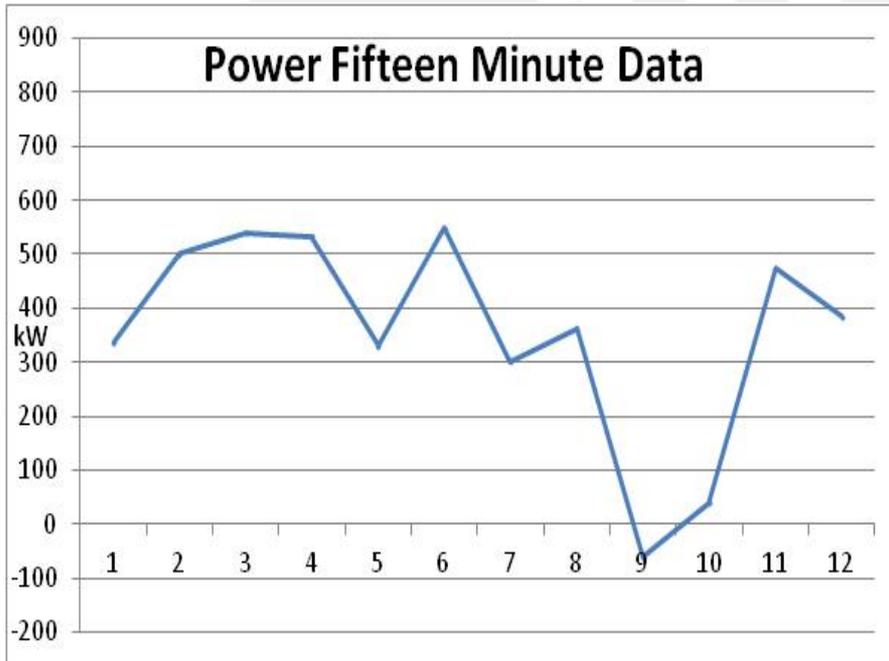
Present State in Normal Deployment

- not enough resolution to observe short-term power variations
- typically do not report voltage (although it is sensed)
- data may not be provided in real-time
- data may be provided only to billing department, not operations
- most likely early operational application: fault location, isolation and service restoration (FLISR)

# Present capabilities of smart meters with application of analytics and integration

- ▶ Improved power quality monitoring and evaluation
- ▶ More efficient utilization of resources (for example remote disconnect versus truck roll – with detailed notification or special requirements)
- ▶ Enhanced reliability (outage detection for example)
- ▶ Allows better more accurate billing (integration of TOU rates for example)
- ▶ Helpful data for short term load forecasting (more real time knowledge and correction)
- ▶ Over the air firmware configurations
- ▶ Automatic meter reading
- ▶ Better oversight and management of energy use for the consumer

# Resolution is important



# Visualization and analytics integration at the utility: Large Plant historical information database



# What is a smart grid? by the U.S. Department of Energy:



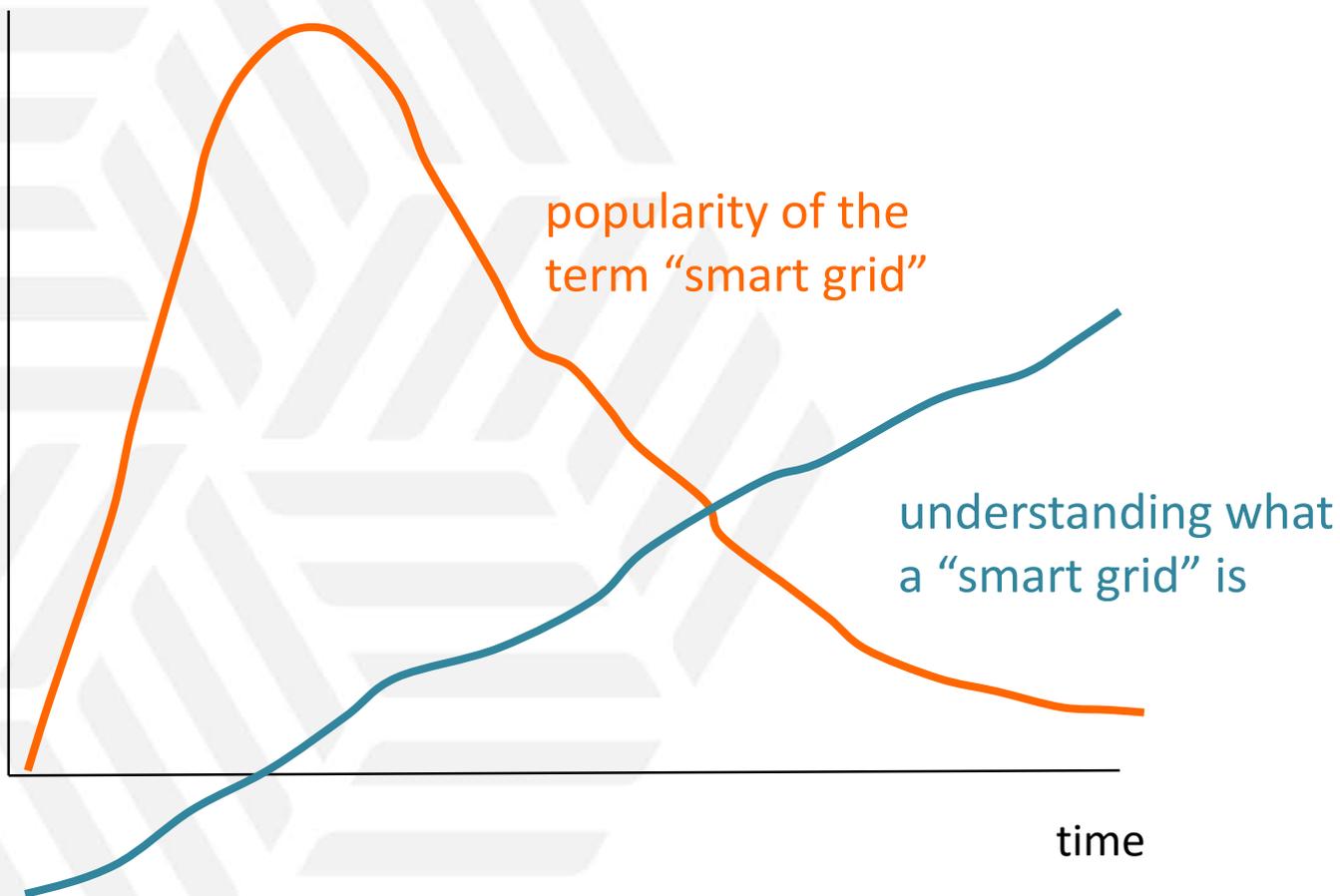
- ▶ “Smart grid” generally refers to a class of technology ... to bring utility electricity delivery systems into the 21st century, using computer-based remote control and automation.
- ▶ These systems are made possible by two-way communication technology and computer processing that has been used for decades in other industries.
- ▶ They are beginning to be used on electricity networks, from the power plants and wind farms all the way to the consumers of electricity in homes and businesses.
- ▶ They offer many benefits to utilities and consumers – mostly seen in big improvements in energy efficiency on the electricity grid and in the energy users’ homes and offices.”

<http://energy.gov/oe/technology-development/smart-grid>

# What a “Smart Grid” should provide, according to the U.S. Department of Energy

- ▶ attack resistance
- ▶ self-healing
- ▶ consumer motivation
- ▶ power quality
- ▶ generation and storage accommodation
- ▶ enabling markets
- ▶ asset optimization

# Beware the buzz words



1 picture > 10<sup>3</sup> words?



smart grid - Google Search

https://www.google.com/search?q=smart+grid&source=lnms&tbm=isch&sa=X&ei=VgBjUpLwAYS8iwL71YCYCA&sqi=2&ved=0CAcQ\_AUoA

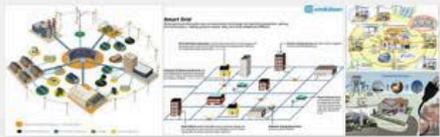
smart grid - Google Search

Google smart grid

Sign In

Web Images Maps Shopping Patents More Search tools

SafeSearch



Diagram



Meter



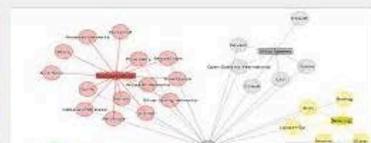
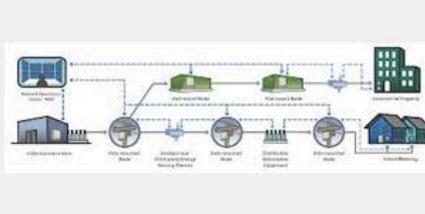
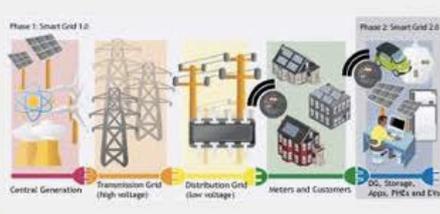
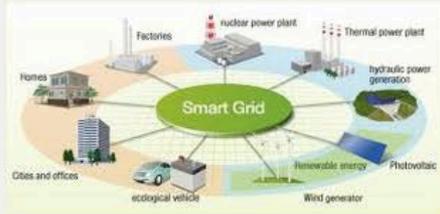
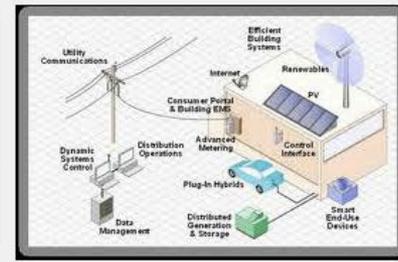
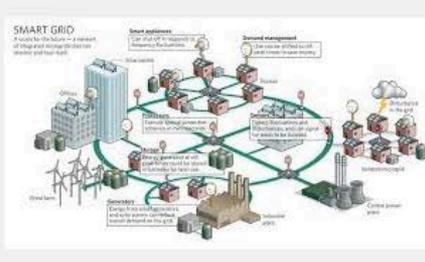
Electricity



Logo



Cisco



# Future of the smart grid

- ▶ ...affords the capability to observe and control components at finer resolution in time and space, while supporting large-scale objectives
- ▶ ...introduces opportunities for new and different actors to participate in observing and controlling various grid components
- ▶ ...allows for better optimization, if it works as intended
- ▶ ...also introduces new options and ambiguities about who can and should do what

# Advanced Metering Use Cases

Excerpt from Progress and Results from ARRA Smart Grid Programs –  
Joe Paladino, DOE, 2015  
Slides provided by FPL & SMUD

# AMI Improvements in Operational Efficiencies

## Results from 15 projects due to automation of metering service tasks and reductions in labor hours and truck rolls

| Smart Meter Capabilities  | O&M Savings           | % Reduction |
|---|-----------------------|-------------|
| <ul style="list-style-type: none"> <li>Remote meter reading</li> <li>Remote service connections/disconnections</li> </ul> | Meter Operations Cost | 13-77       |
|   | Vehicle Miles         | 12-59       |

**Talquin Electric Cooperative** - In 2011 and 2012, smart meters avoided 6,000 truck rolls for service connections and disconnections and 9,000 for non-payments saving more than \$640,000.

| Additional Capabilities  | Expected Benefits  |
|--|--|
| <ul style="list-style-type: none"> <li>Tamper detection and notification</li> </ul>    | Enables potential recovery of ~1% of revenues that may be lost from meter tampering  |
| <ul style="list-style-type: none"> <li>Outage detection and notification</li> </ul>    | Enables faster restoration (e.g., PECO avoided 6,000 truck rolls following Superstorm Sandy and accelerated restoration by 2-3 days) |
| <ul style="list-style-type: none"> <li>Voltage and power quality monitoring</li> </ul> | Enables more effective management of voltages for conservation voltage reductions and other VVO applications                         |

# Transformer Project Background

- ▶ In 2012, FPL began a pilot program based on smart meter data to identify and proactively address or replace transformers
- ▶ Target – transformers with minor coil damage, but still energized
- ▶ Objectives – make operational improvements to:
  - ❑ Shorten outage times
  - ❑ Reduce restoration costs
  - ❑ Improve the customer experience
  - ❑ Reduce customer claims



**FPL leveraged technology to improve the performance of our 878,000 transformers**

**In 2013, the company integrated the proactive transformer replacement program into its distribution operations**

# High-Voltage Transformer Example

FPL is analyzing the history of each high-voltage transformer to identify the root cause



Enter an address, then select from the drop down that appears

Start:  End:  Premise/Address/TLN:

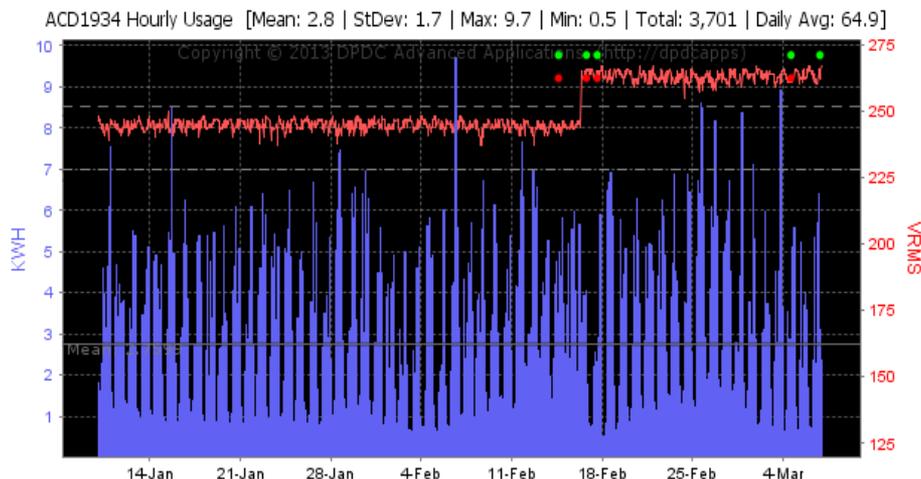
| Premise | Meter                        | Transformer | Lateral     | Feeder | Phase | Substation | Address                              |
|---------|------------------------------|-------------|-------------|--------|-------|------------|--------------------------------------|
| 2114607 | [ACD1934] G0205461934 - Ping | 85233278401 | 85233317406 | 811361 | A     | ANHINGA    | 19755 SW 302ND ST<br>HOMESTEAD,33030 |

Event Summary: 2114607 | [View All](#)

| Count | Event Type     |
|-------|----------------|
| 5     | Power Restored |
| 4     | Power Down     |

Event Detail

| Time             | Event Type     |
|------------------|----------------|
| 3/7/13 4:14:37   | Power Restored |
| 3/4/13 22:08:55  | Power Restored |
| 3/4/13 22:08:50  | Power Down     |
| 2/17/13 22:06:40 | Power Restored |
| 2/17/13 22:02:55 | Power Down     |
| 2/17/13 2:03:43  | Power Restored |
| 2/17/13 2:03:38  | Power Down     |
| 2/14/13 22:13:28 | Power Restored |
| 2/14/13 22:13:24 | Power Down     |



Smart meter voltage data can proactively identify transformers that need to be replaced

# High-voltage Transformer Replacement Program

- 372 high-voltage transformers identified in November of 2012
- 46 high-voltage transformers currently in the system
- 452 replaced since January
- Targeting replacement of units with voltage above 252
- Majority of the units identified are more than 15 years old



Damage to primary winding of high-voltage transformer identified through smart meters

**Using voltage information, FPL can proactively identify and replace transformers before they cause an outage**

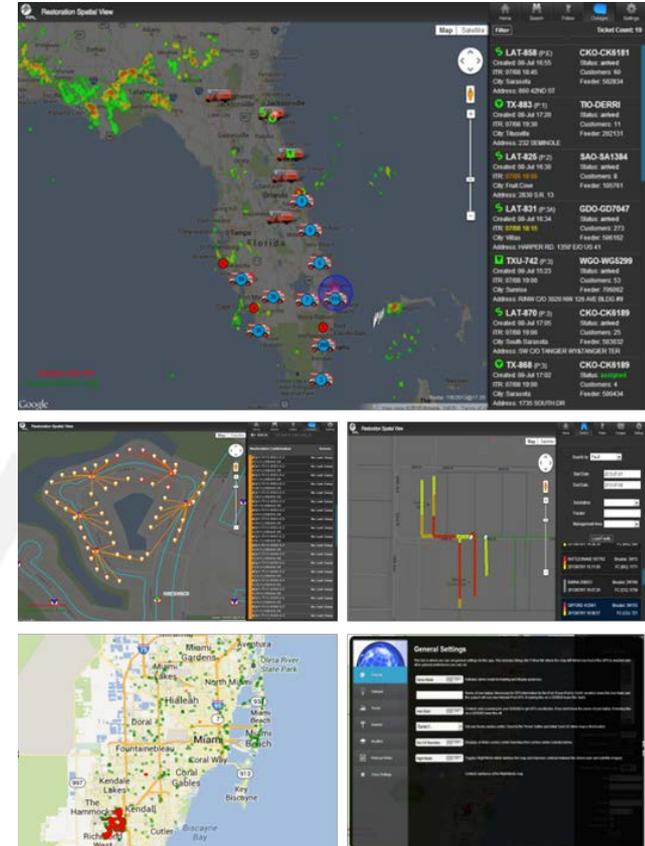
**Scheduled replacements reduce outage times by more than 93 minutes**

# Restoration Spatial View Overview



## RSV 2.0 – State of the art mobile application placing the smart grid in the hands of our crews

- Customer Information
- Trouble Tickets
- Truck Locations
  - FPL, Vegetation and External Crews during Storm (pilot)
- Weather
  - Radar
  - Real-time lightning within 100-mile radius
  - Weather Station
  - Storm information (Tracks/Development Areas)
  - Customized weather alerts based on location
- Street View & Driving Directions
- Restoration Confirmation
- Fault Location (DMS/SynerGEE)
- Device detail, including drawings
- Real-time AMI outage activity
- Fully customizable by user



The goal is to have a single application giving our crews everything they need to restore power safely and efficiently

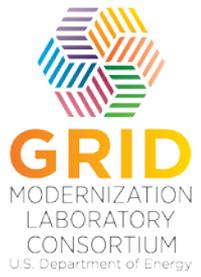
# Emerging Technologies

- ▶ DER
- ▶ ADMS
- ▶ Data & analytics
- ▶ Automation
- ▶ Modeling
- ▶ Communications

# Summary

- ▶ Intention of first session: Provide background on the present state of the distribution grid – how did we get here?
  
- ▶ Information Covered:
  - Present State
  - Equipment and controls
  - Sensing and measurement
  - Smart grid
  - Emerging technologies
  
- ▶ Future reading (included in extra slides)

# Extra Info

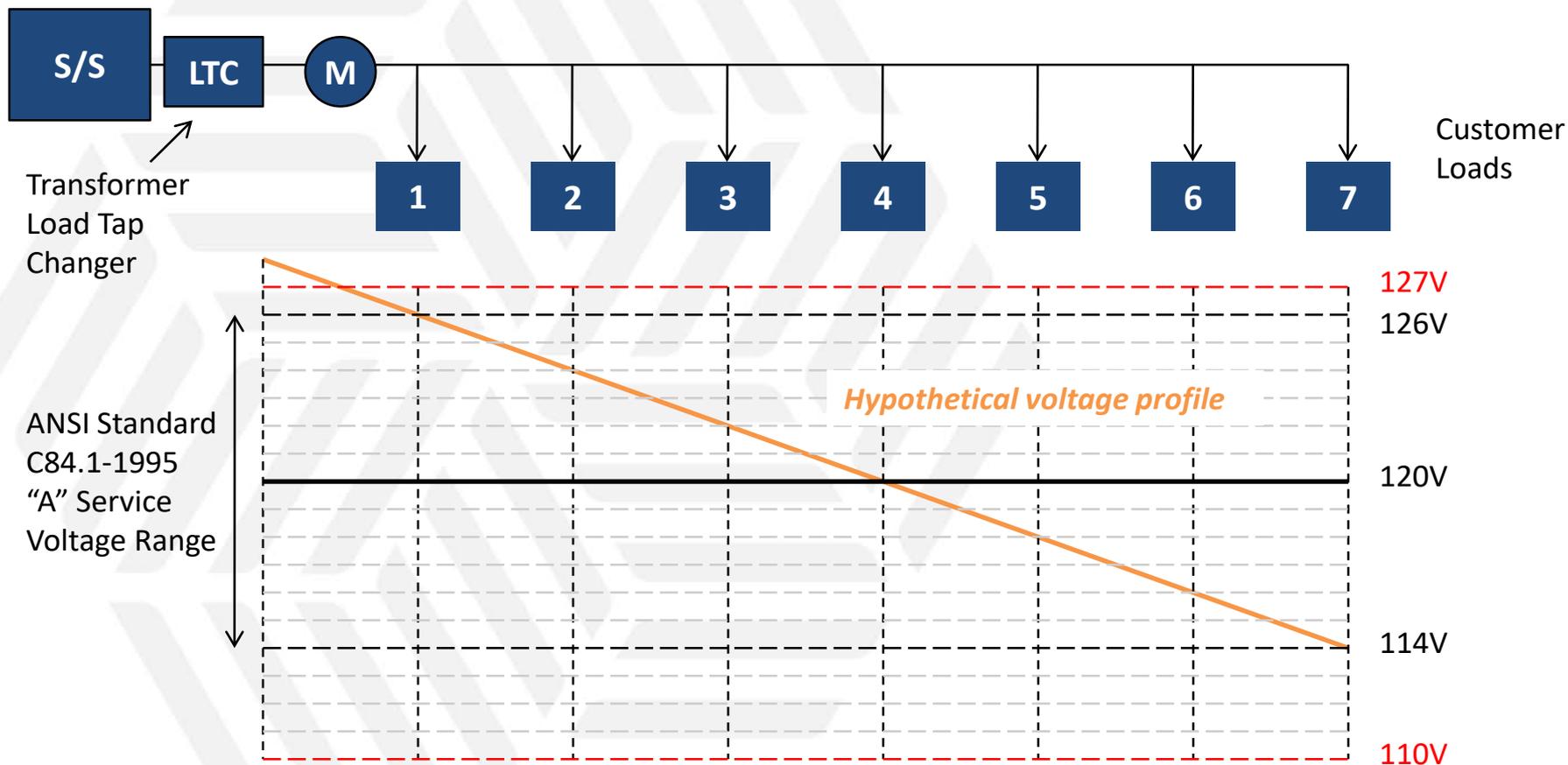


## Further Reading

- ▶ <http://gridarchitecture.pnnl.gov/media/advanced/Sensor%20Networks%20for%20Electric%20Power%20Systems.pdf>
- ▶ [https://gridmod.labworks.org/sites/default/files/resources/1.4.09\\_Integrate%20Multiscale%20Data%20Analytics%20and%20Machine%20Learning%20for%20the%20Grid\\_Fact%20Sheet\\_rev2.pdf](https://gridmod.labworks.org/sites/default/files/resources/1.4.09_Integrate%20Multiscale%20Data%20Analytics%20and%20Machine%20Learning%20for%20the%20Grid_Fact%20Sheet_rev2.pdf)
- ▶ <https://www.osti.gov/scitech/biblio/1353149>
- ▶ [https://esdr.lbl.gov/sites/default/files/lbnl\\_6665e\\_final.pdf](https://esdr.lbl.gov/sites/default/files/lbnl_6665e_final.pdf)
- ▶ <https://pubarchive.lbl.gov/islandora/object/ir%3A186035/>

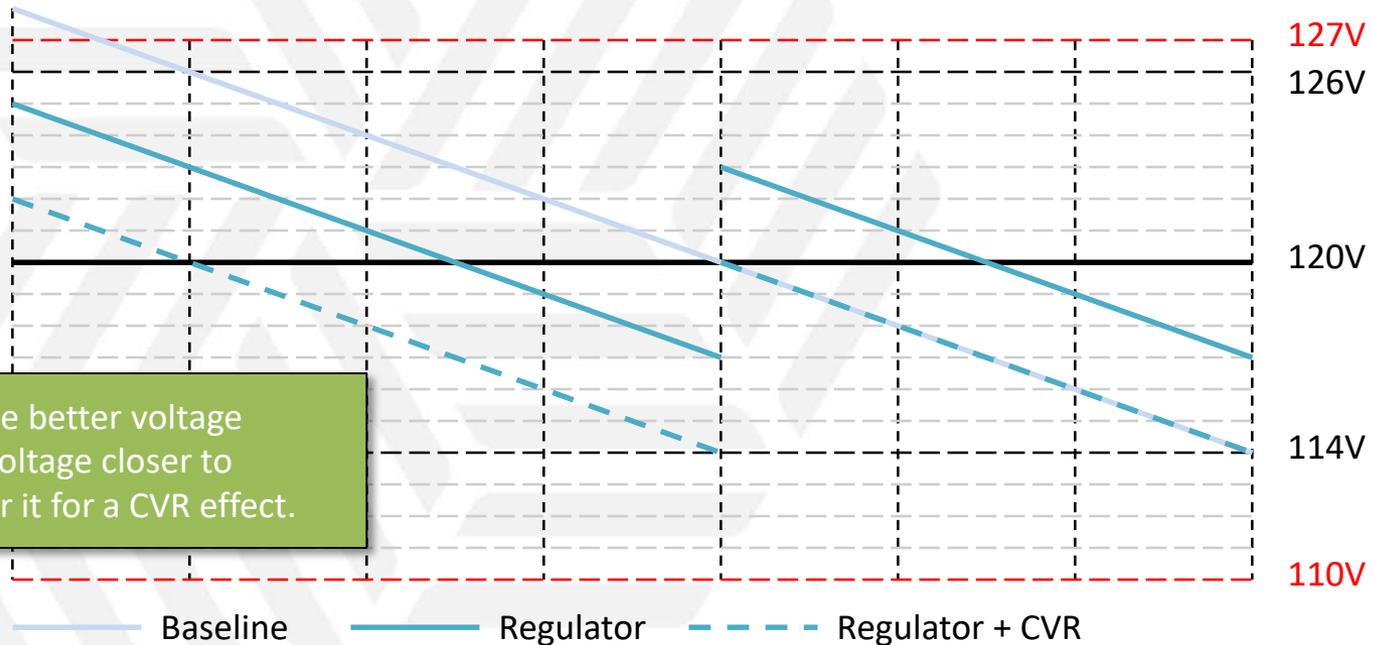
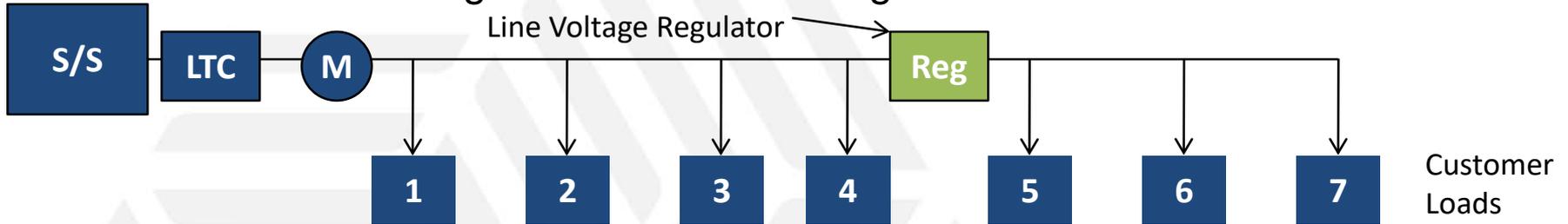
# Voltage Profile

- ▶ Line voltage drops from the LTC at the head of the distribution line to customers farther out on the line.



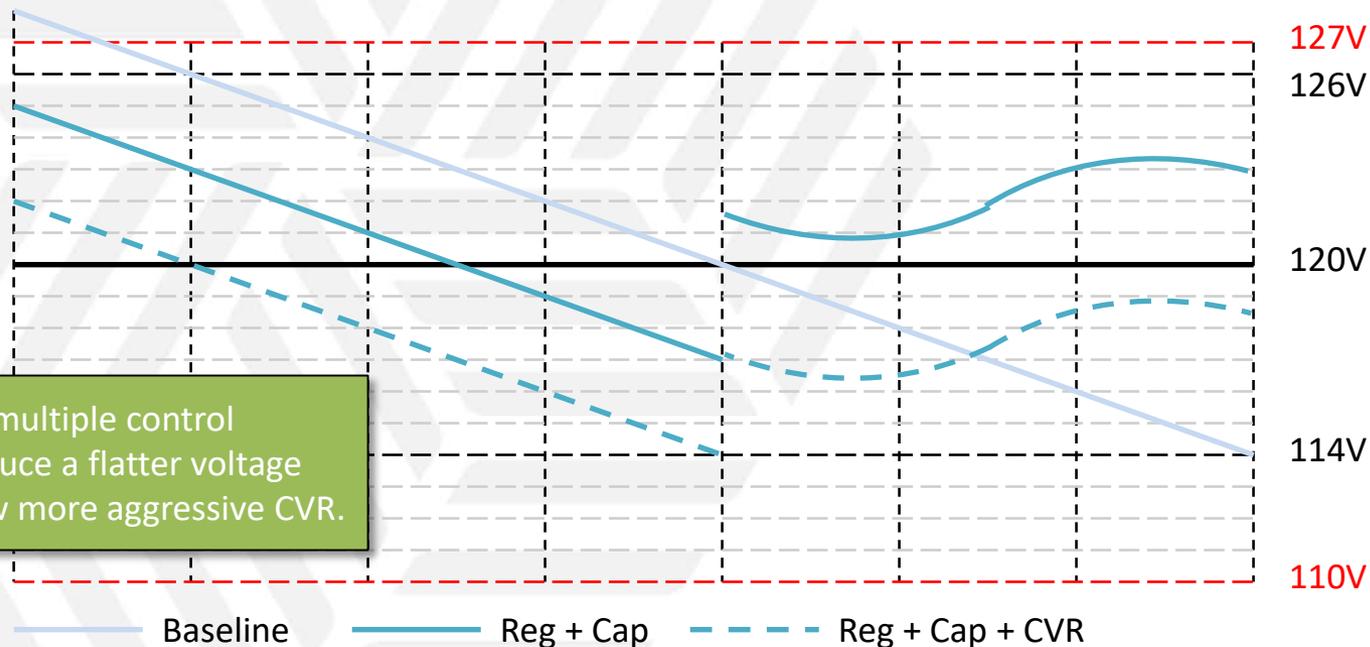
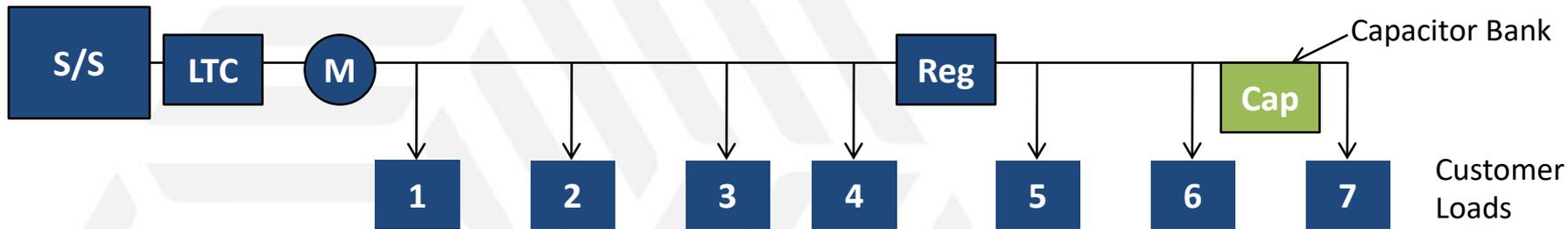
# Voltage Optimization

- ▶ A voltage regulator can boost (raise) or buck (lower) voltage at a point on the distribution line and regulate down-line voltage.



# Coordinated LTC, Regulator and Capacitor Bank

- ▶ A capacitor bank can help regulation by compensating for the lagging power factor of load and the line itself.

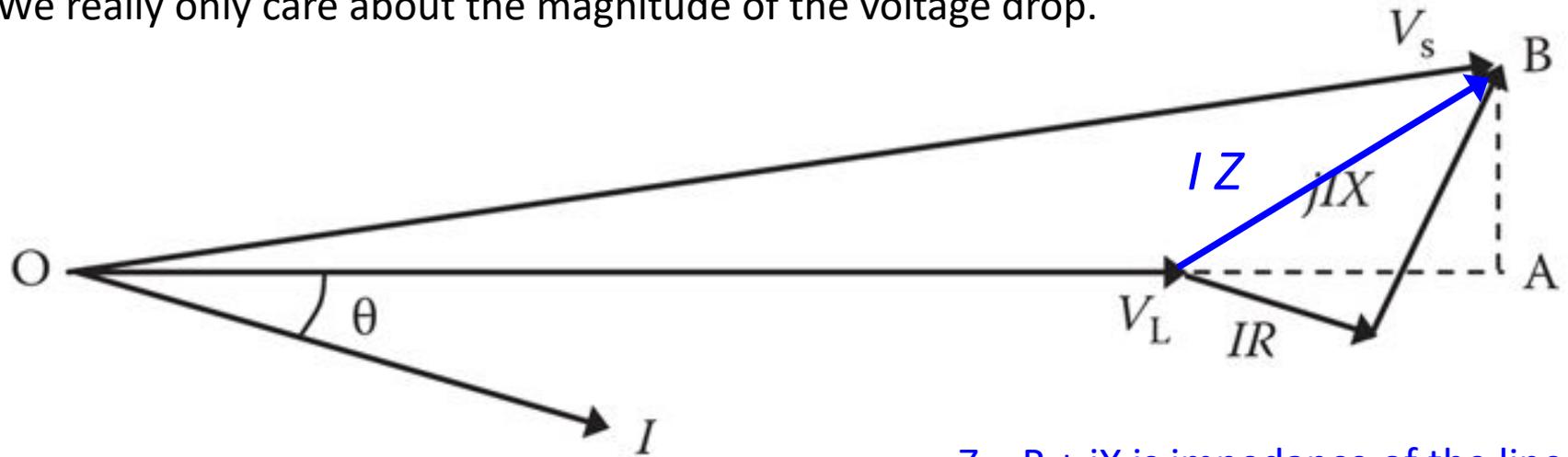


Coordination of multiple control devices can produce a flatter voltage profile, and allow more aggressive CVR.



Geometry problem: is the voltage drop  $I Z$  between sending and receiving end of mostly in phase with the source voltage, or mostly at right angles to it?

We really only care about the magnitude of the voltage drop.



Bottom line:

Changing the phase angle  $\theta$  of current by introducing capacitance changes the direction of  $I Z$  and therefore the sensitivity of voltage drop to load current.

A leading current (due to lots of capacitance) can result in a voltage *rise*.

$Z = R + jX$  is impedance of the line multiplied by load current

$I Z$  gives voltage drop

# Common Sensor Types

| Sensor Type                           | Description  |
|---------------------------------------|--|
| faulted circuit indicator             | Provides a binary indication of the passage of a fault current (based on magnitude) past the sensing point.  |
| line sensor                           | Typically sample voltage and/or current and provide various derived quantities, such as RMS volts and/or amps, real and reactive power, power factor, a small number of harmonics of voltage or current, and THD. Transducers may be electrical, magnetic, or optical. |
| PMU                                   | Phasor measurement unit – provides voltage and current synchrophasors; may also provide line frequency and power flows.  |
| partial discharge                     | Detects and counts arcing partial discharges in power transformers   |
| cable tan delta                       | Measures phase shift on cable insulation   |
| line temperature                      | Measures temperature distributions on power lines - typically done with fiber optics.  |
| residential meter                     | In addition to usage (energy), may measure secondary voltage; may record data on voltage sags as measured on the secondary at the premise; a few also record real and reactive power and power quality measures such as voltage Total Harmonic Distortion (THD)        |
| Commercial and Industrial (C&I) meter | In addition to usage (energy), measures secondary voltage and current, computes real and reactive power, THD and a variety of other configurable quantities; may capture power waveforms on a trigger basis for later retrieval  |
| feeder meter                          | Provides meter quality measurement of feeder primary quantities, including voltage, current; real and reactive power   |

Courtesy of Jeff Taft - PNNL

# Common Grid Devices with Sensing Capability

| Device                                      | Sensing capability  |
|---|---|
| switch controller                           | Measure voltage, may record peak fault currents   |
| capacitor controller                        | Measure voltage, may record peak fault currents, may compute real and reactive power  |
| recloser controller                         | Measure voltage, may record peak fault currents   |
| voltage regulator                           | Measures line voltage   |
| substation IED's<br>(microprocessor relays) | Can take transducer inputs for voltage and current directly; can compute many derived values, including real and reactive power, phasors, THD, power factor, etc; also act as a gateway for other kinds of measurements, such as oil temperature, partial discharge data, etc |

Courtesy of Jeff Taft - PNNL

# Relevant Building Sensors

| Device          | Sensing capability  |
|-----------------|---|
| Smart Metering  | RMS voltage and current and power flow at whole building level      |
| Solar           | Irradiance and kWh generated  |
| Thermal Comfort | Dry bulb air temperature  |
| Occupancy       | Measures presence and number of people based on IR or sound or both |

Courtesy of Jeff Taft - PNNL

# Benefits of Proactive High-voltage Transformer Replacement



## Smart meters help FPL reduce replacement costs and improve the customer experience

- ▶ Average outage time is 93 minutes shorter than an unplanned transformer replacement
- ▶ Costs are 25% lower than unplanned replacements
- ▶ Can improve customer perceptions
- ▶ Reduces potential for customer claims

**Smart meter data has driven results to date, but continued efforts in big analytics will redefine the way FPL does business**