Distribution 101

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Distribution Systems and Planning Training
for Midwest Public Utility Commissions, January 16-17, 2018

Slide credits: Sascha von Meier, UCB

What are we covering today?

- AC power…
- What is the smart grid?
- Components and functions, substations, visualization, voltage control
- General and present state of distribution systems
- Metering
- Existing and emerging grid technologies

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

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- “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

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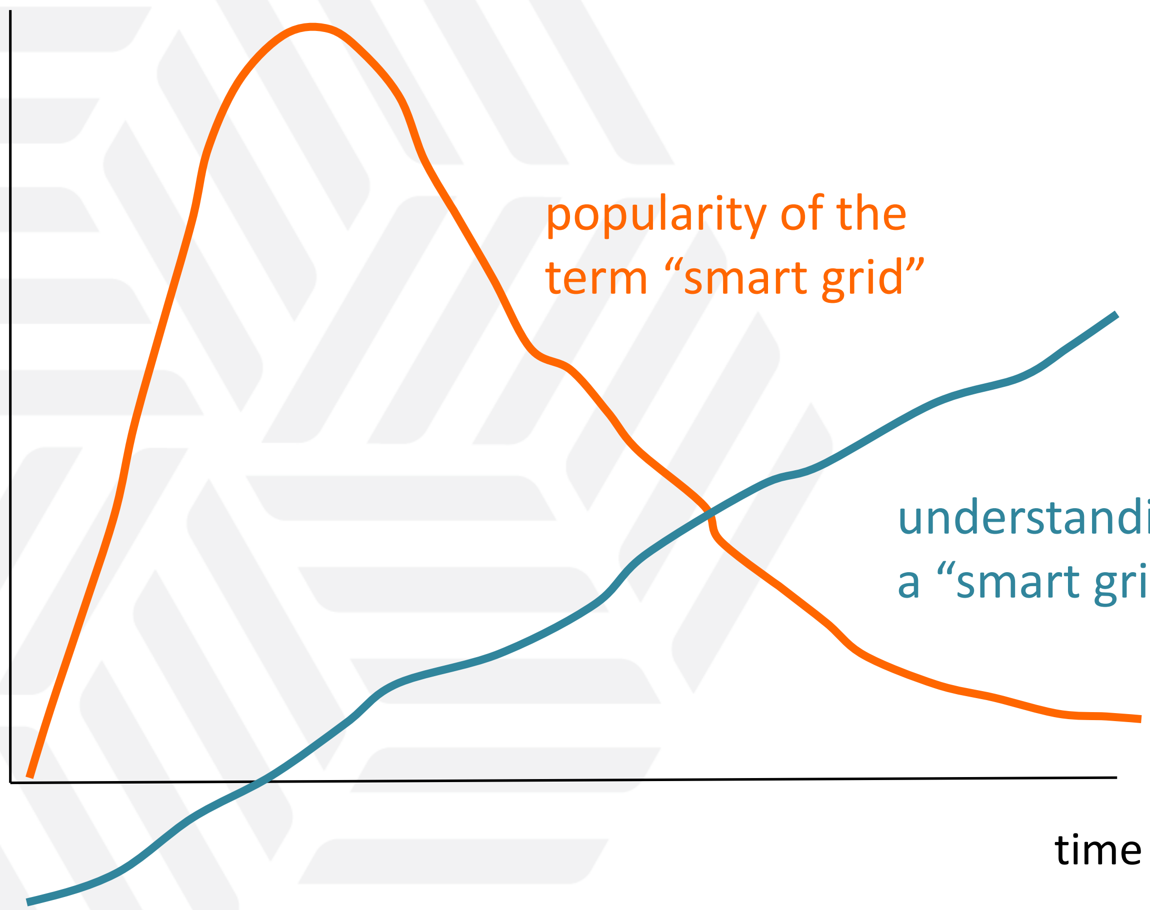
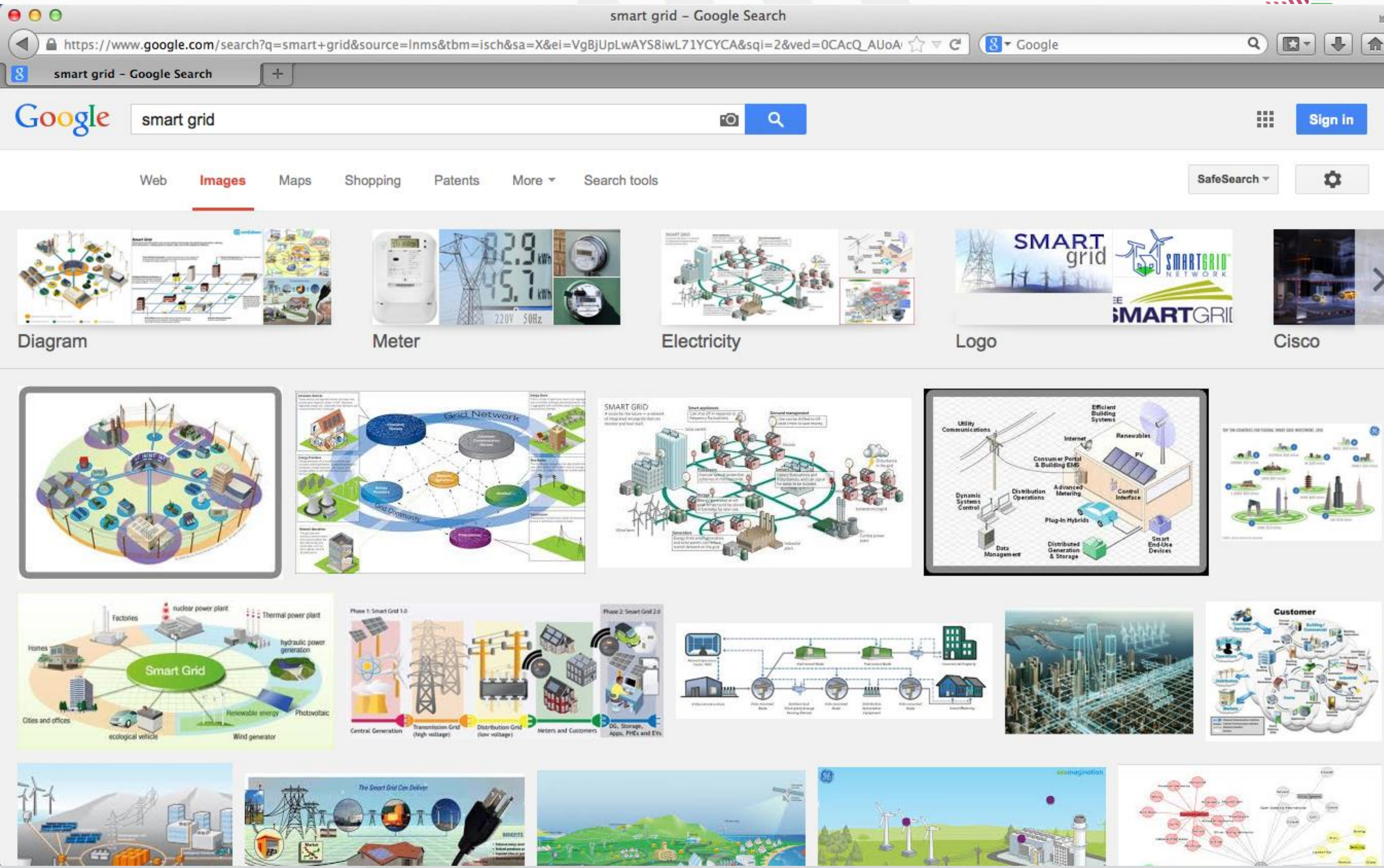
U.S. Department of Energy

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

Beware the buzz words



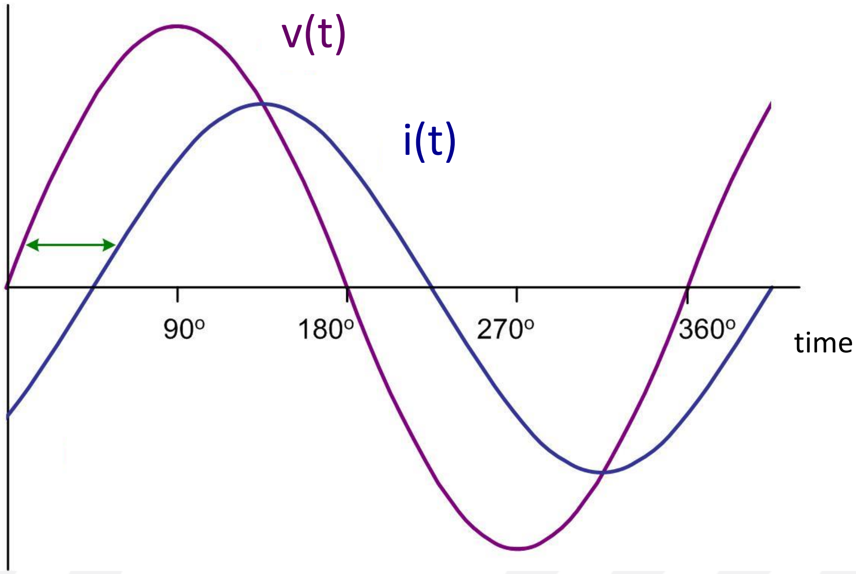
1 picture > 10^3 words?

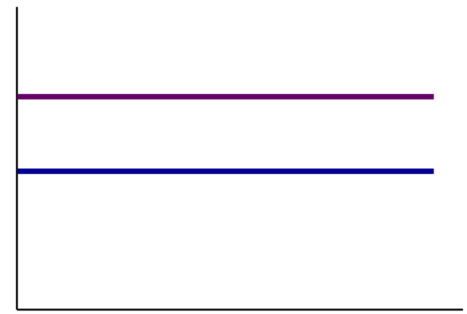


Future of the smart grid

- …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

AC fundamentals



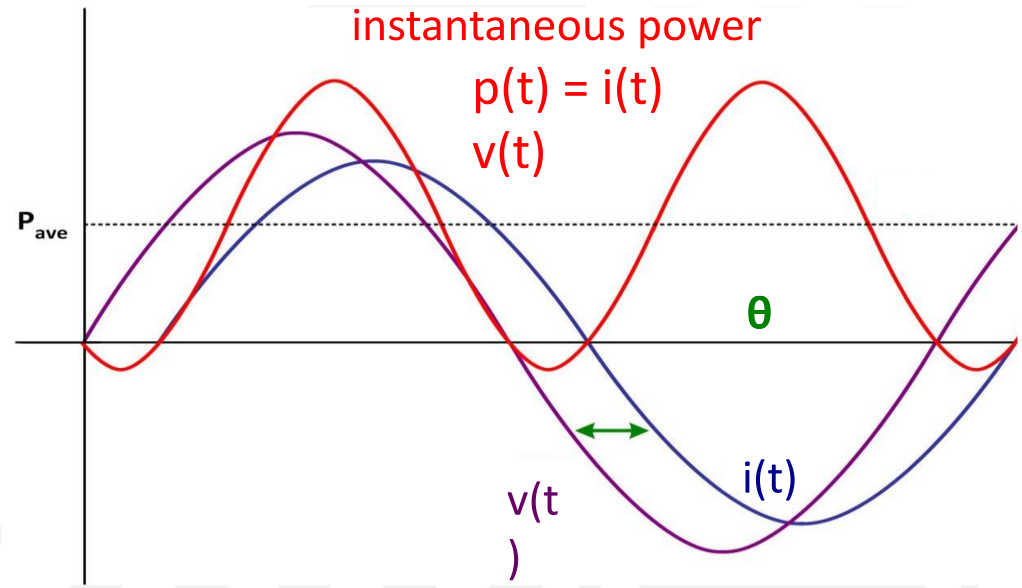


2 degrees of freedom in
a.c. voltage and current:

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

1 degree of freedom for d.c.

Reactive Power



Energy conservation requires both

$P_{IN} = P_{OUT}$

$Q_{IN} = Q_{OUT}$

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

S = P + j Q

real power P = S cos θ (W)

reactive power Q = S sin θ (VAR)

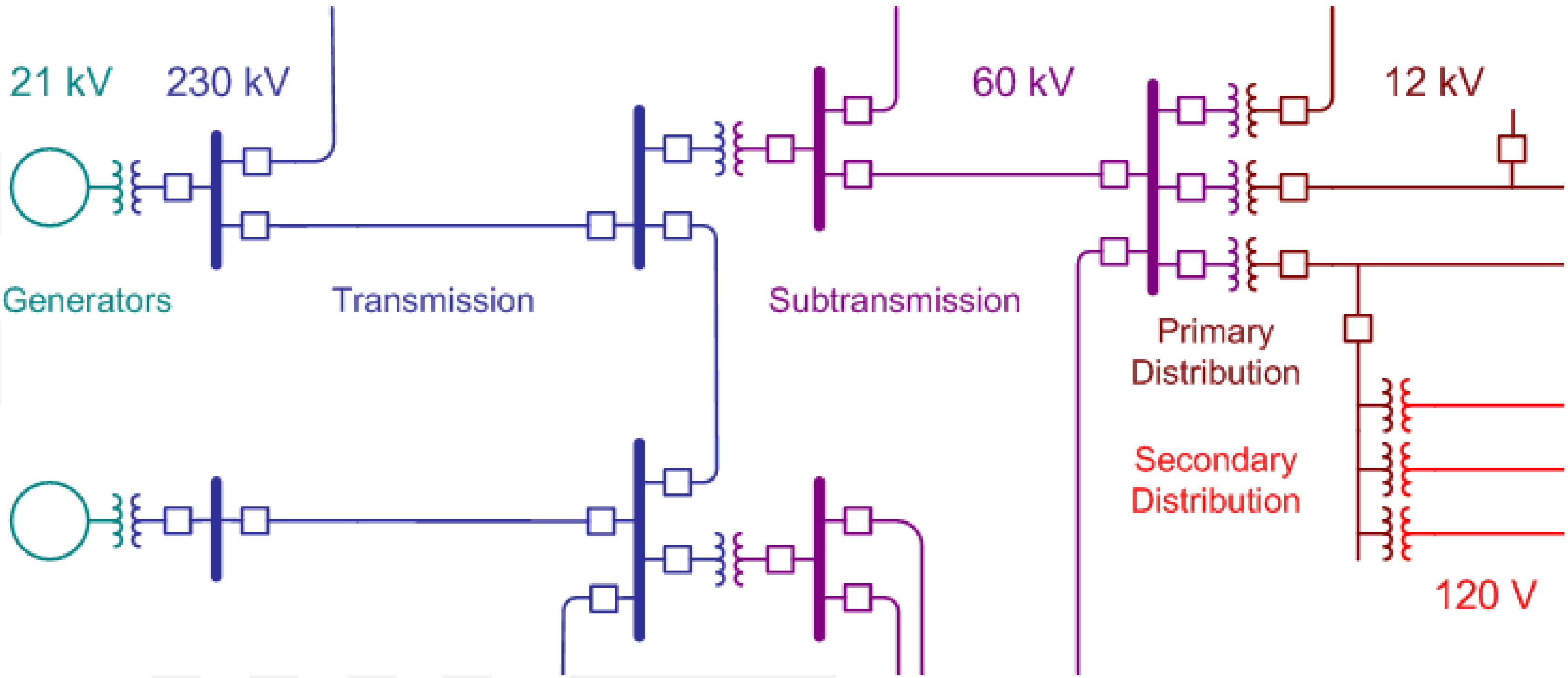
Components and Functionality – a basic introduction to the distribution system “as is”

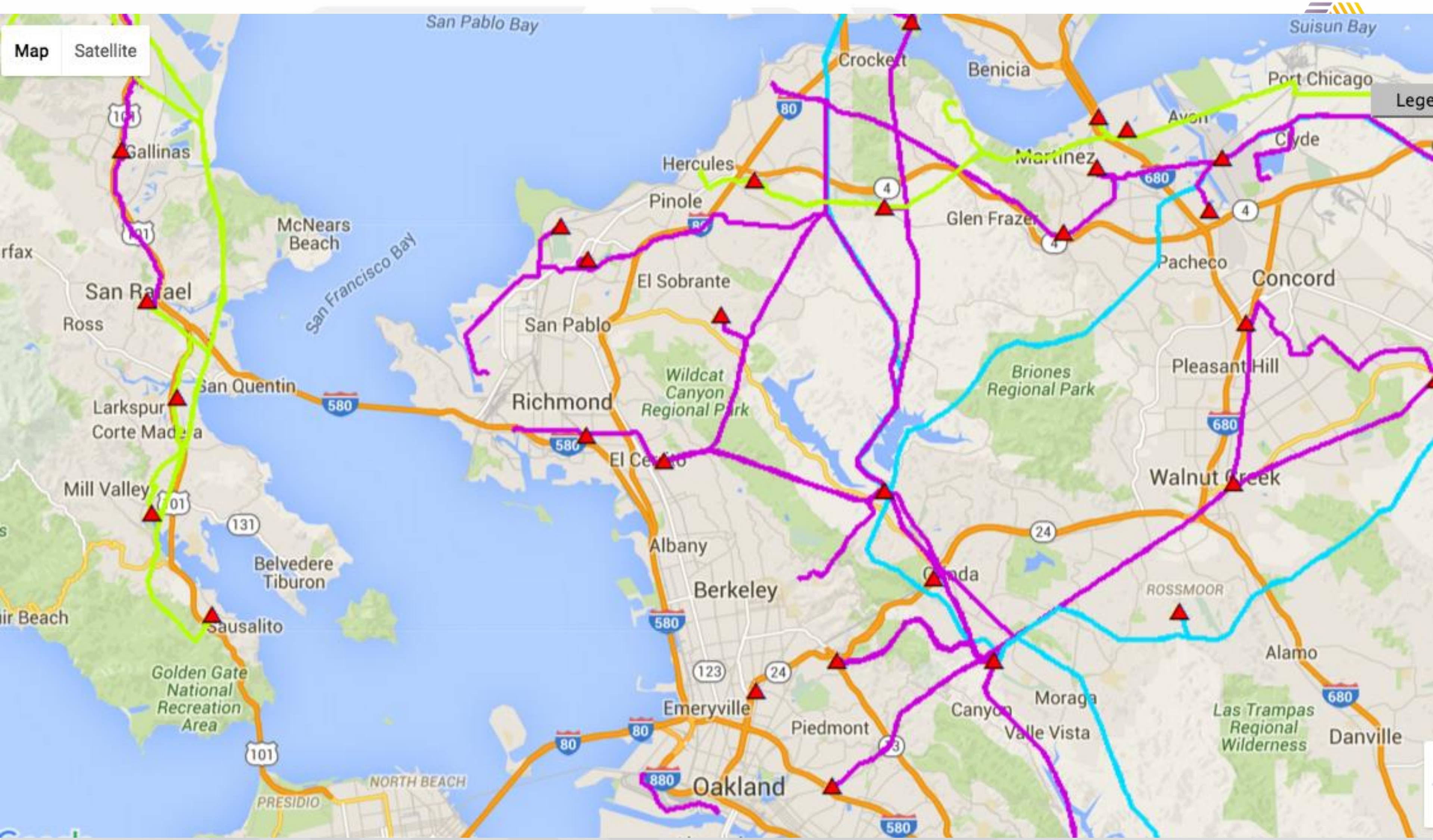
How distribution systems are different than transmission systems

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

Standard transmission system design: **Network**

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

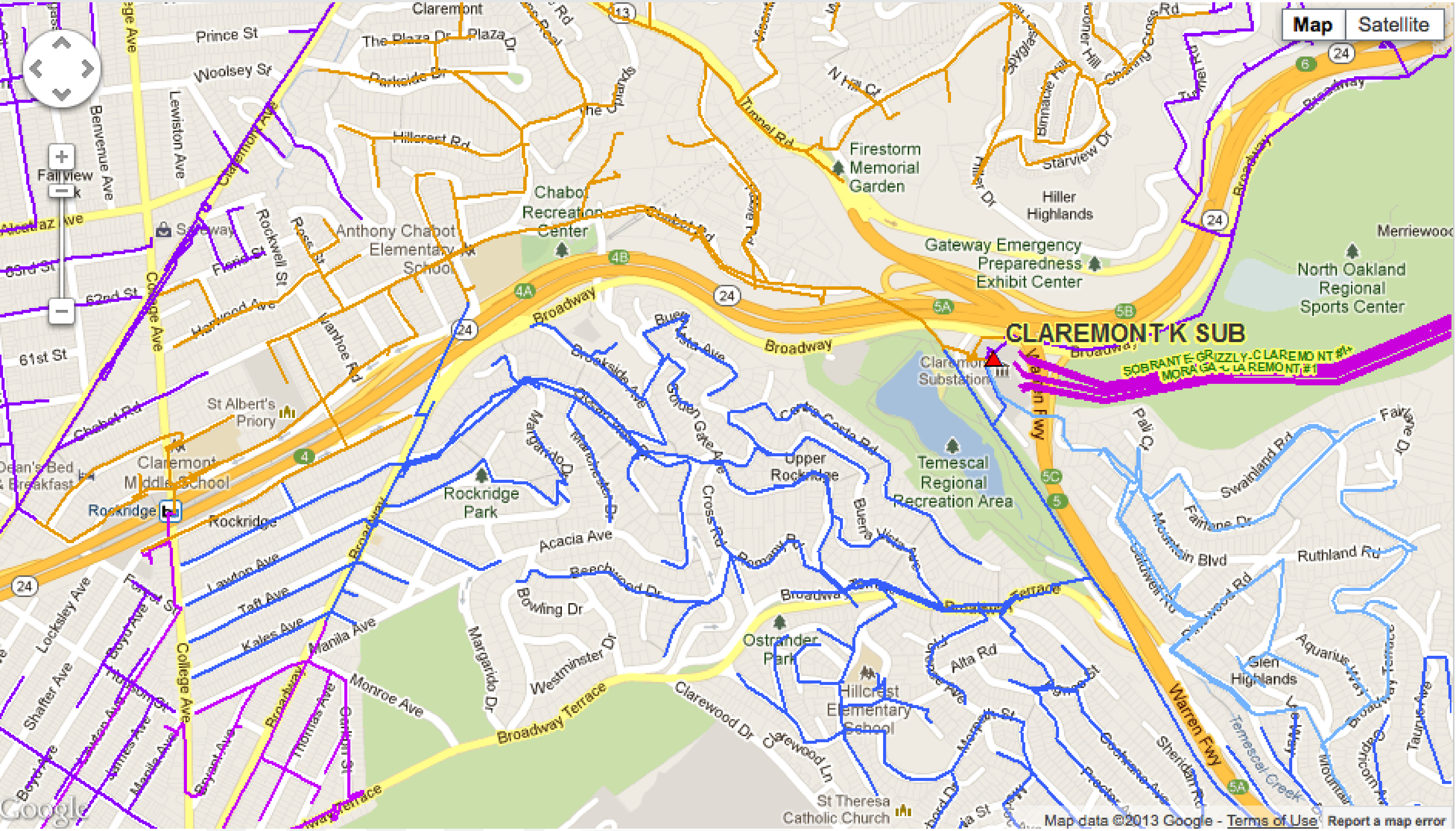




115kV Transmission network

Distribution substations

https://www.pge.com/b2b/energysupply/wholesaleelectricsuppliersolicitation/PVRFO/PVRAMMap/index.shtml



CLAREMONT K SUB
SOBRANTE-GRIZZLY-CLAREMONT #1
MORAGA - CLAREMONT #1
Claremont Substation
Temescal Regional Recreation Area
Gateway Emergency Preparedness Exhibit Center
Firestorm Memorial Garden
Chabot Recreation Center
Anthony Chabot Elementary School
North Oakland Regional Sports Center
Hiller Highlands
Upper Rockridge
Rockridge Park
Ostrander Park
Hillcrest Elementary School
St Albert's Priory
Claremont Middle School
St Theresa Catholic Church
Broadway
Broadway Terrace
Warren Fwy
Tunnel Rd
College Ave
Claremont Ave
Map
Satellite
Map data ©2013 Google - Terms of Use
Report a map error

How distribution systems are different than transmission systems

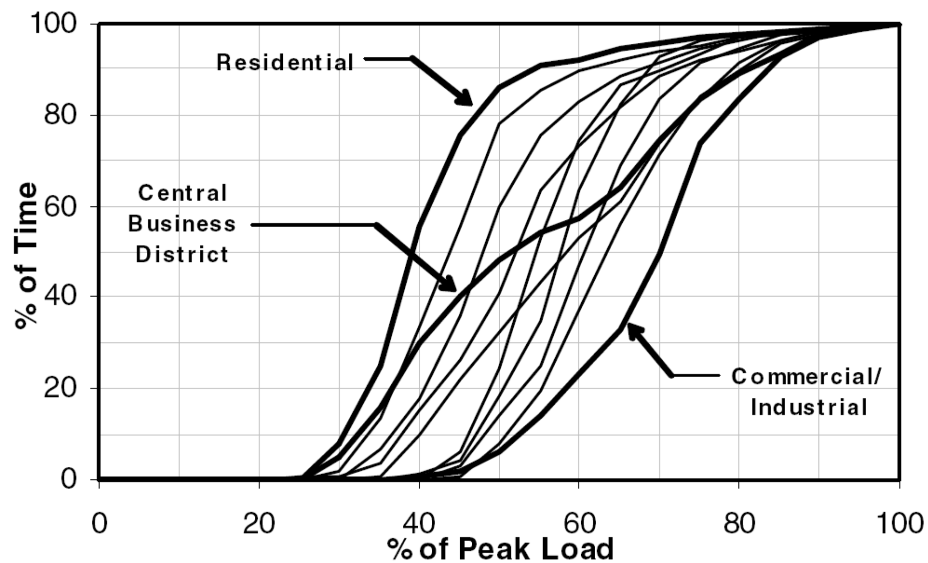
1. Architecture 2. Diversity 3. Variation 4. Vulnerability 5. Opacity

► **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

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

External influences are always nearby:

- weather
- trees
- animals
- vehicles
- people
- …?

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


CAUSEWAY

- Monitoring and control technology has not historically been cost-effective to install, in many cases

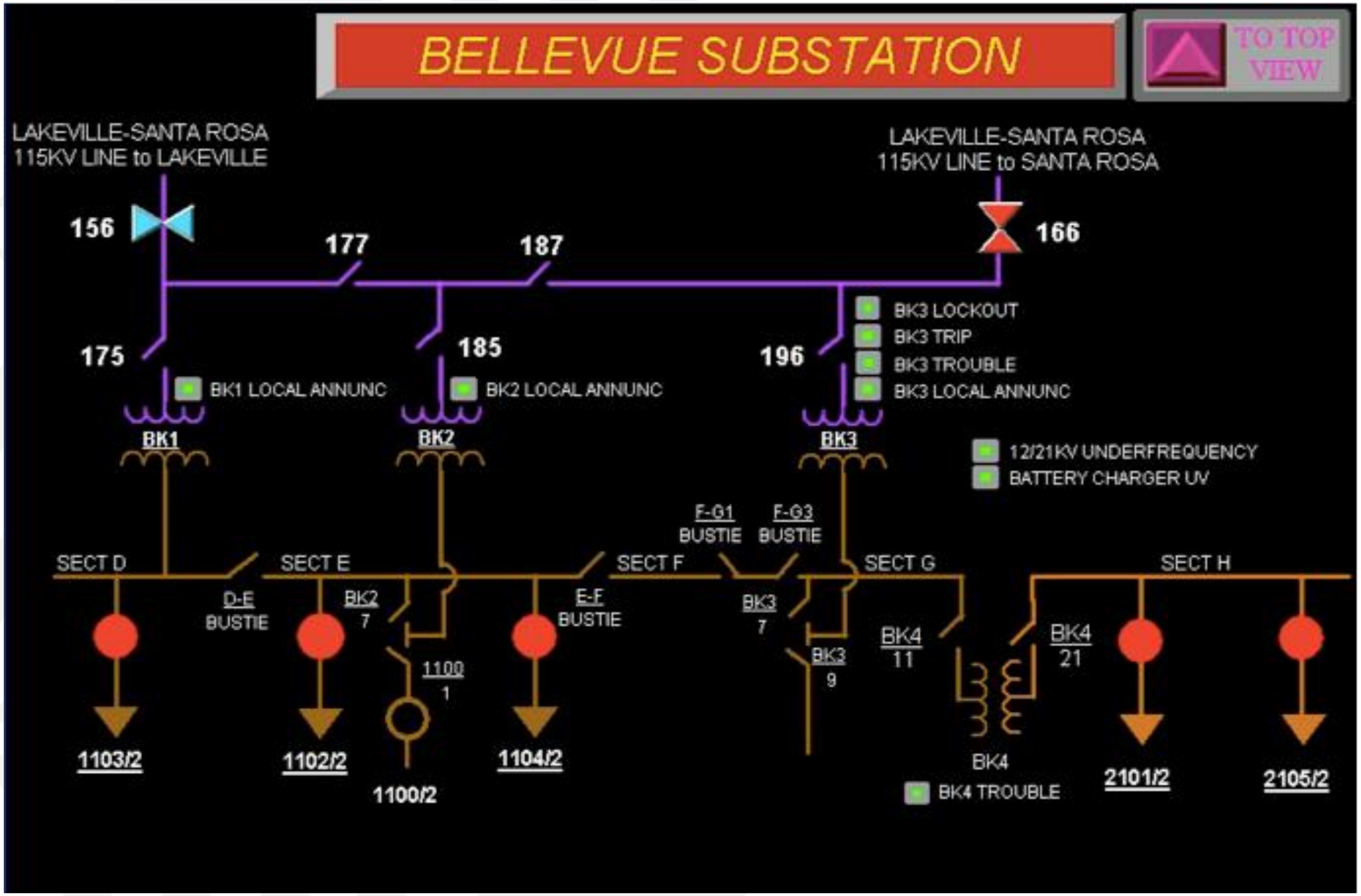
- SCADA* typically available at substation level,
- but not on 100% of distribution circuits

- Many distribution circuits are without 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

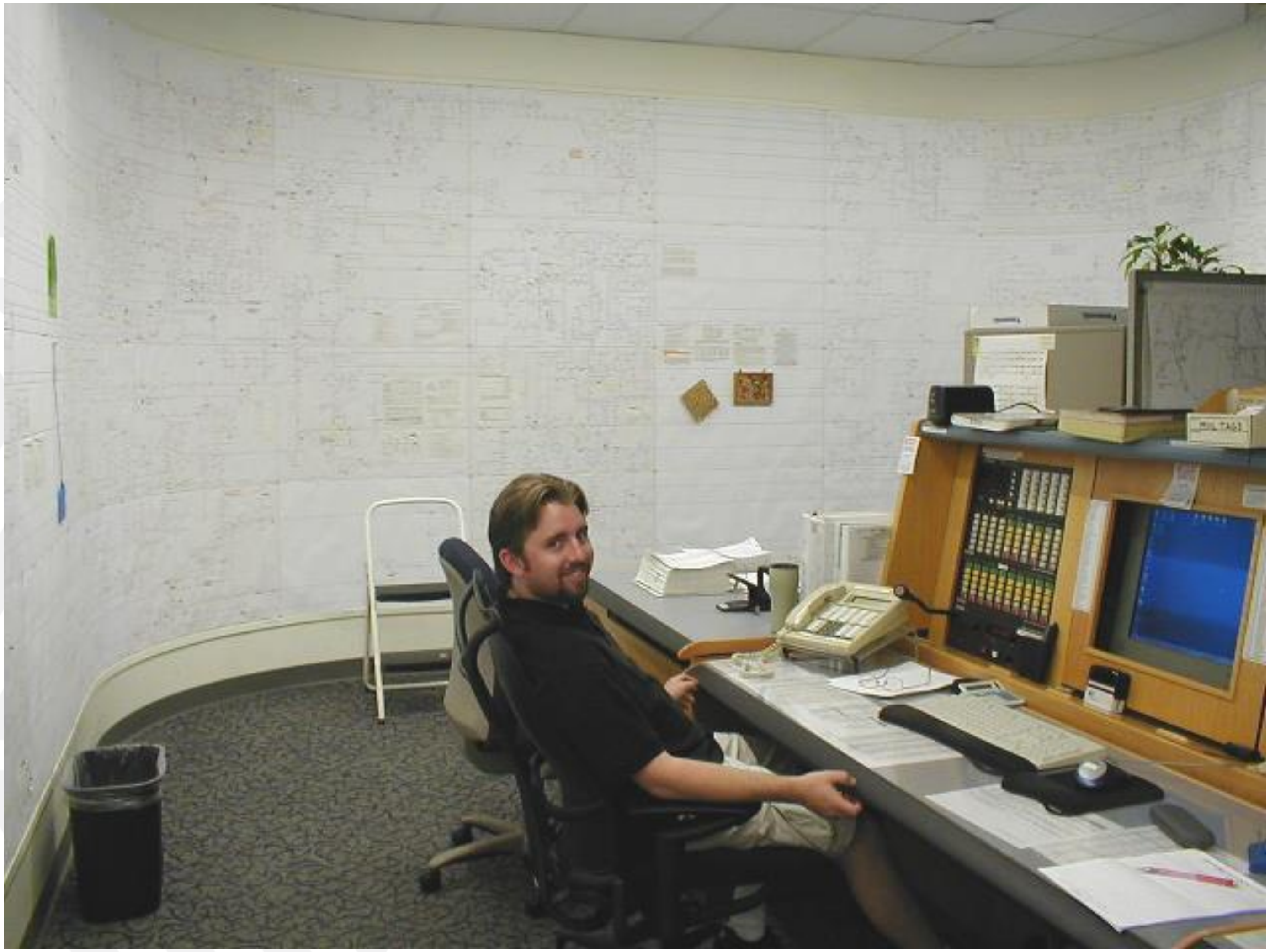
** Supervisory Control and Data Acquisition*

Visibility



BELLEVUE SUBSTATION
TO TOP VIEW
LAKEVILLE-SANTA ROSA 115KV LINE to LAKEVILLE
LAKEVILLE-SANTA ROSA 115KV LINE to SANTA ROSA
156
177
187
166
175
185
196
BK1 LOCAL ANNUNC
BK2 LOCAL ANNUNC
BK3 LOCKOUT
BK3 TRIP
BK3 TROUBLE
BK3 LOCAL ANNUNC
BK1
BK2
BK3
12/21KV UNDERFREQUENCY
BATTERY CHARGER UV
F-G1 BUSTIE
F-G3 BUSTIE
SECT D
SECT E
SECT F
SECT G
SECT H
D-E BUSTIE
BK2 7
E-F BUSTIE
BK3 7
BK3 9
BK4 11
BK4 21
1100 1
BK4
BK4 TROUBLE
1103/2
1102/2
1100/2
1104/2
2101/2
2105/2

Present State: Distribution Operator’s control room, 2003



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Eyes & ears in the field

Substations

Important Equipment

- Transformers
- Conductors
- Protective devices
- Switches
- Voltage control devices
- Sensors and meters

Substation Transformers

Substation Transformers

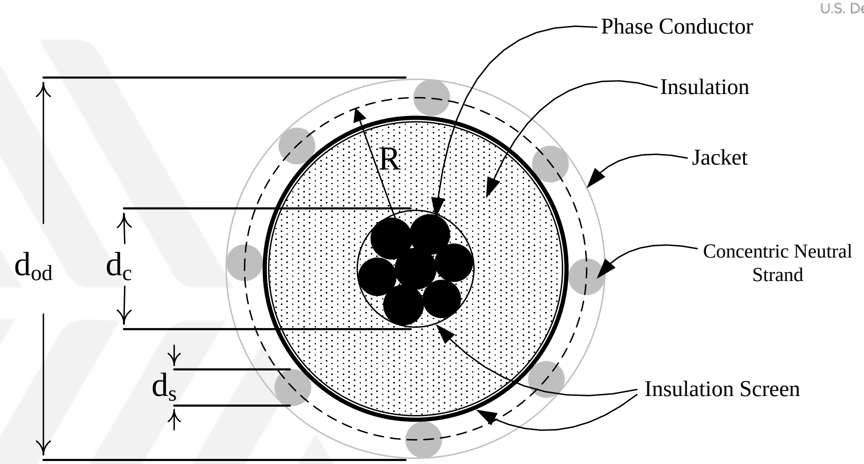
- Substation transformers can perform various functions:
  - Step voltage up from generation to transmission levels
  - Convert between voltages between transmission lines
  - Step voltage down for use at the distribution level
- Power ratings can be from several MVA at the distribution level to greater 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.

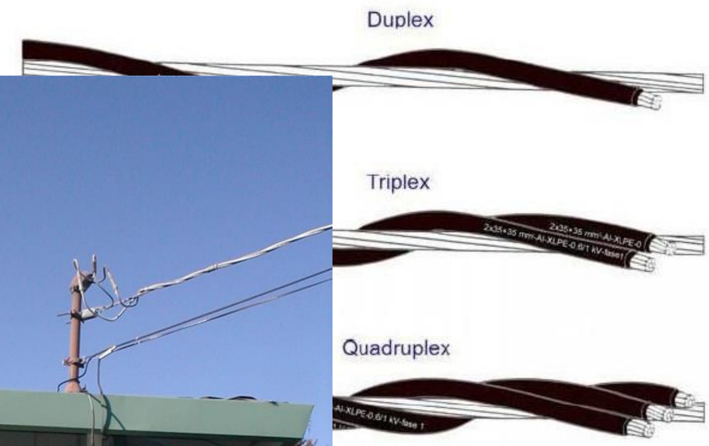
Cables can be directly buried or laid into conduit or a vault.

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.



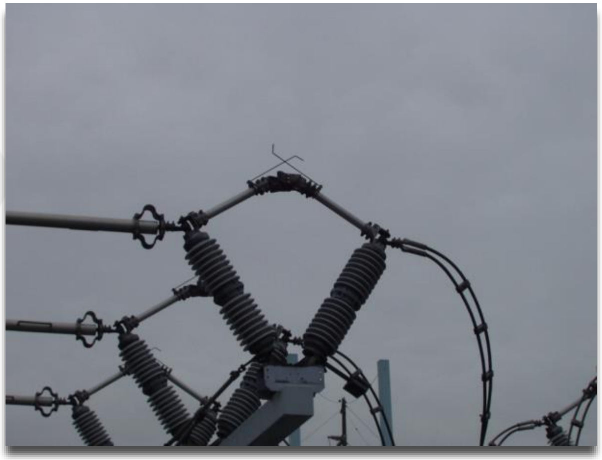
Switchgear

Distinguish:

switches – safe to open under normal load current only

protective devices – safe to open under fault current

- fuses
- circuit breakers
- reclosers



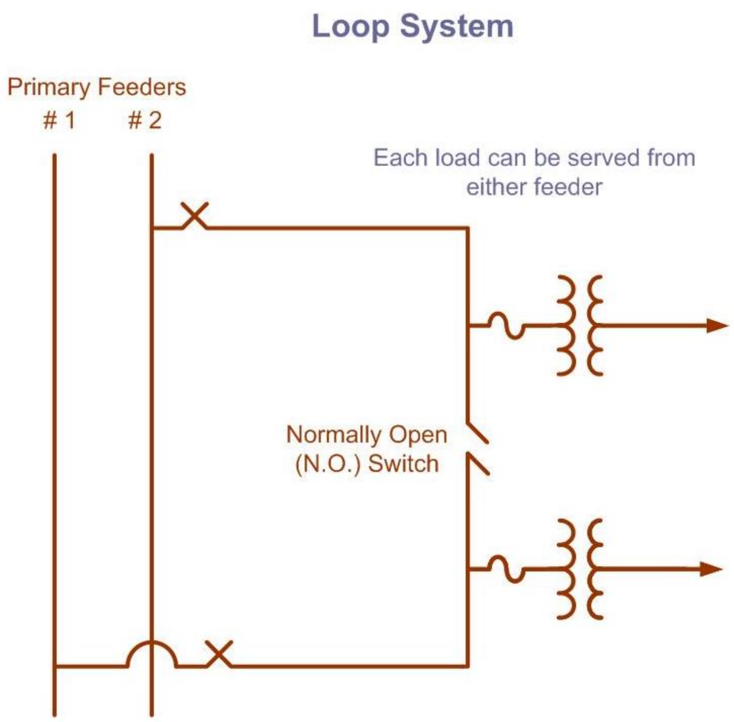
Knife Switch

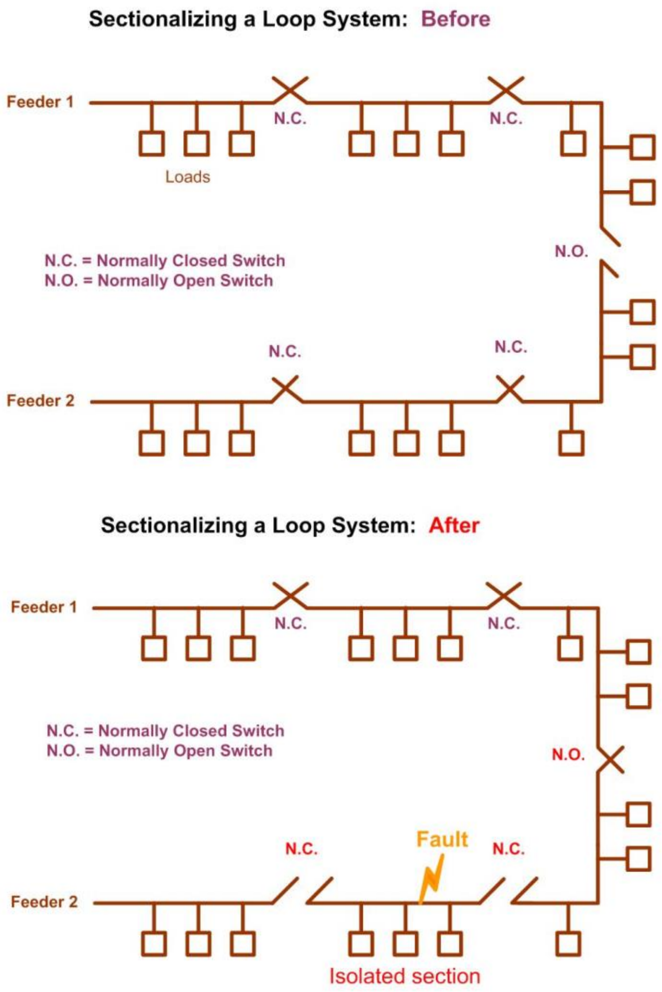

FLORIDA HOSPITAL
Waterman

Distribution System Switches

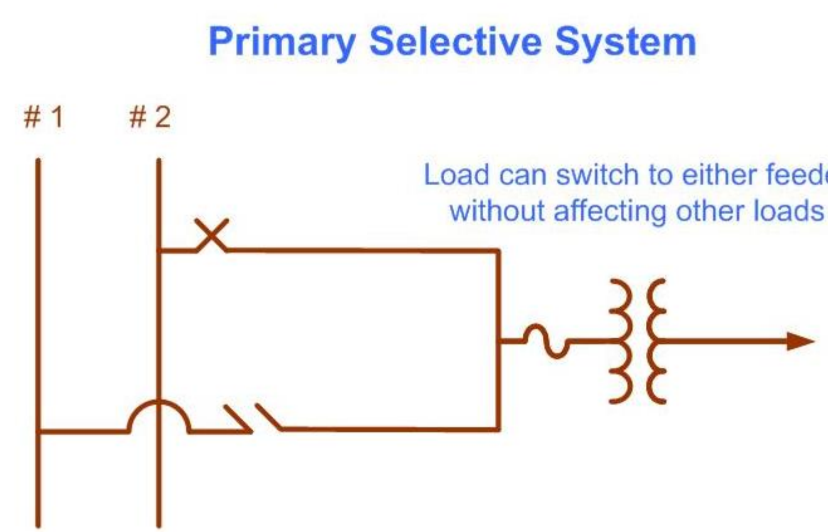
- The primary function of a switch it to provide electrical isolation.
- Switches are not protective devices, unlike breakers they cannot interrupt current.
- Switches at a substation can transfer load between substation transformers.
- At the distribution level switches are used to reconfigure a feeder.
- 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.

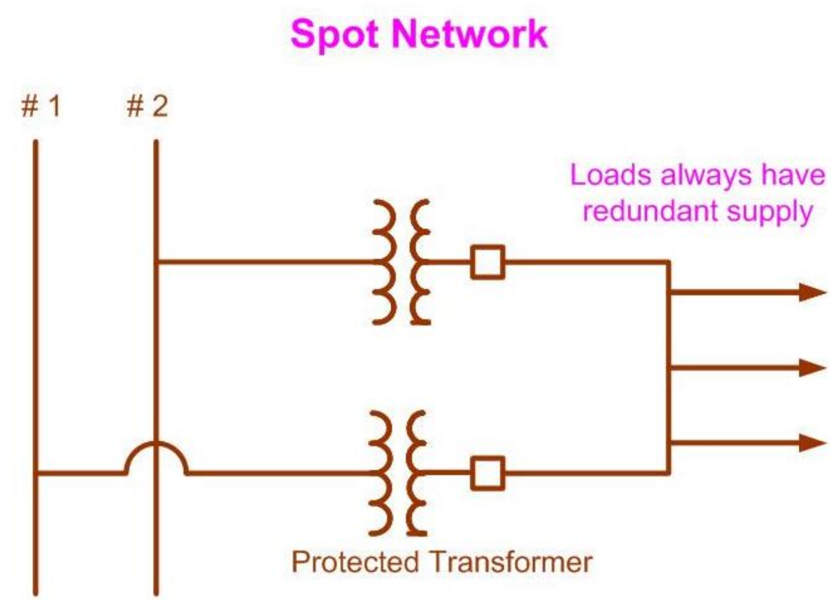
Distribution configurations





Distribution Configurations





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

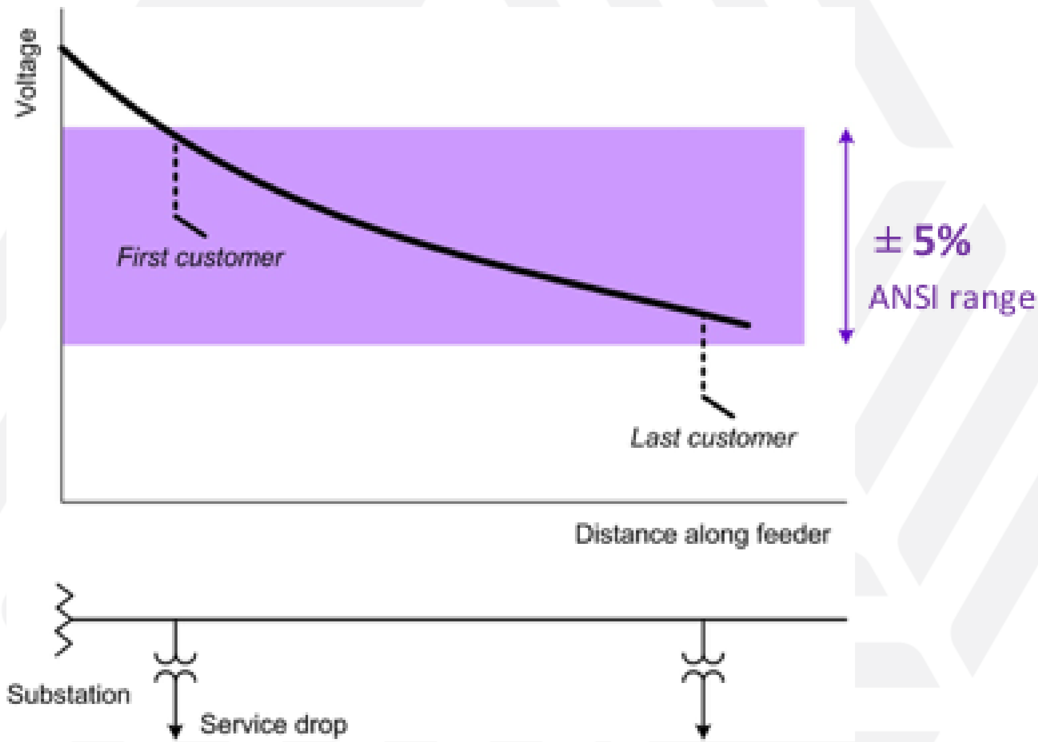
Voltage Control Devices

- Present State
  - Cap Banks
  - In line regulators
  - On Load Tap Changers

- What does not control voltage…
  - Small DG at the POC

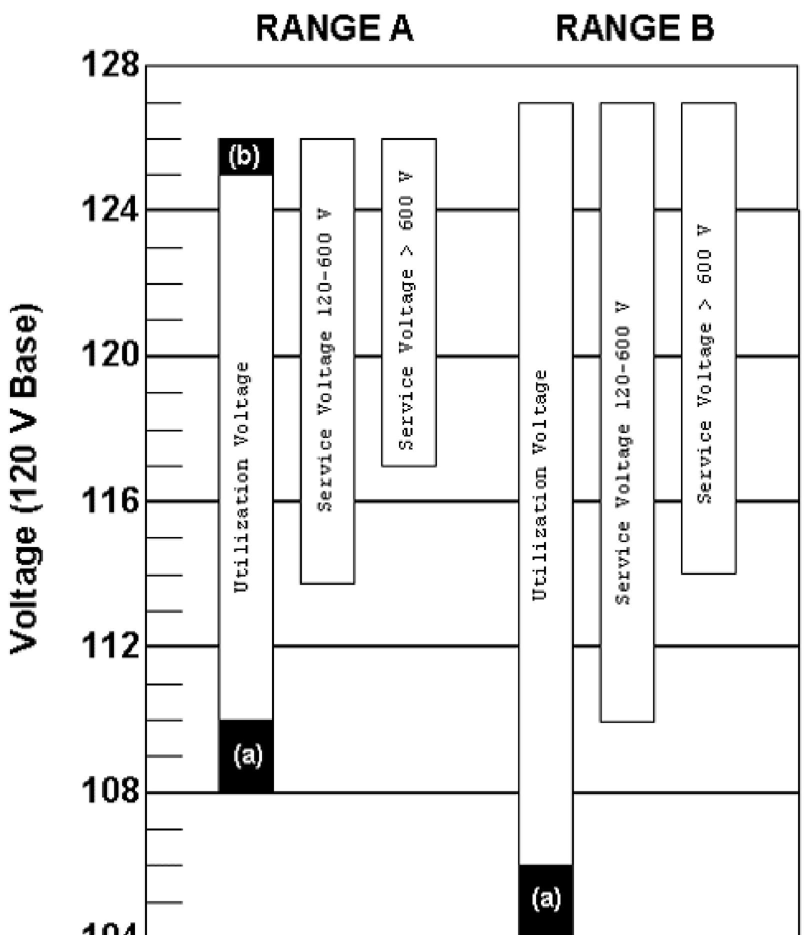
- New state
  - CVR
  - VVO
  - Distributed var devices

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 ±10%

RANGE B: "for short duration or unusual conditions"

Current State of Distribution Voltage Regulation

Traditional voltage regulation

- load tap changer
- voltage regulator
- capacitors

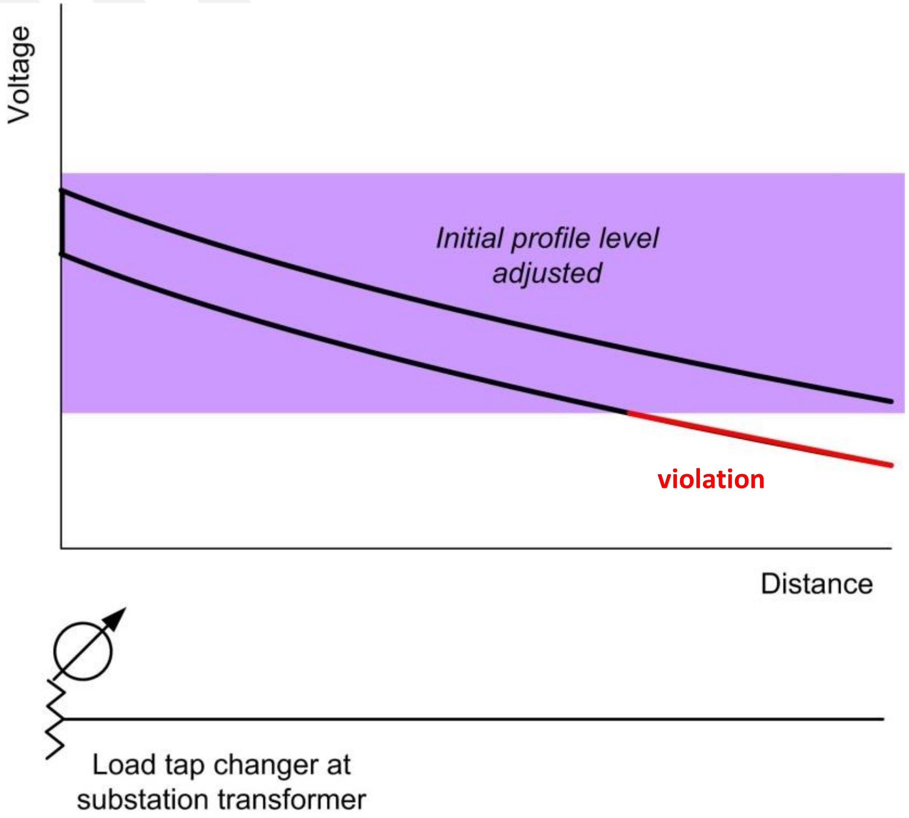
Newer technologies (Discussed in future presentations)

- four-quadrant (± P, Q) inverters
- solid-state transformers
- static VAR compensators for distribution

•Volt Var/Volt-Watt/CVR

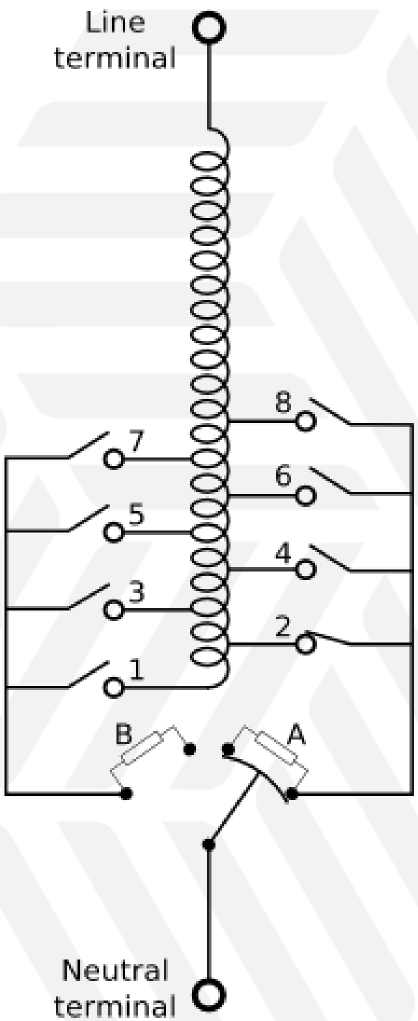
Traditional Voltage Regulation: Load tap changers

load tap changer



± 5%

LTC's cont



Mechanical load tap changer

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

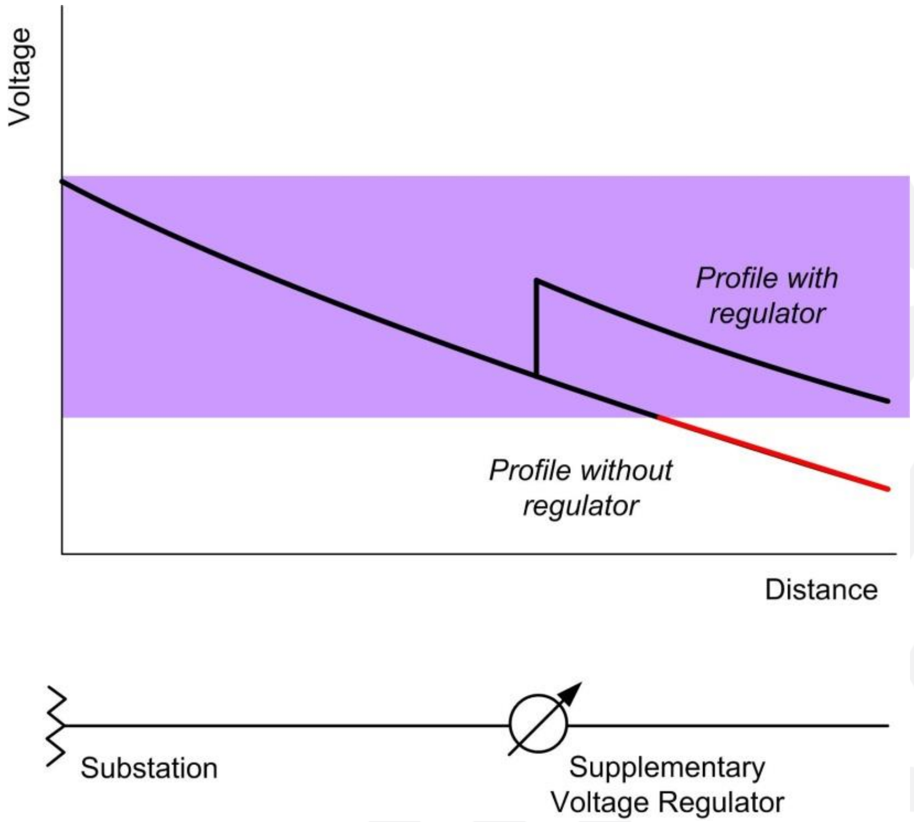
A and B are "diverter" resistors

but some arcing and wear is unavoidable

thus frequent operation is not desirable

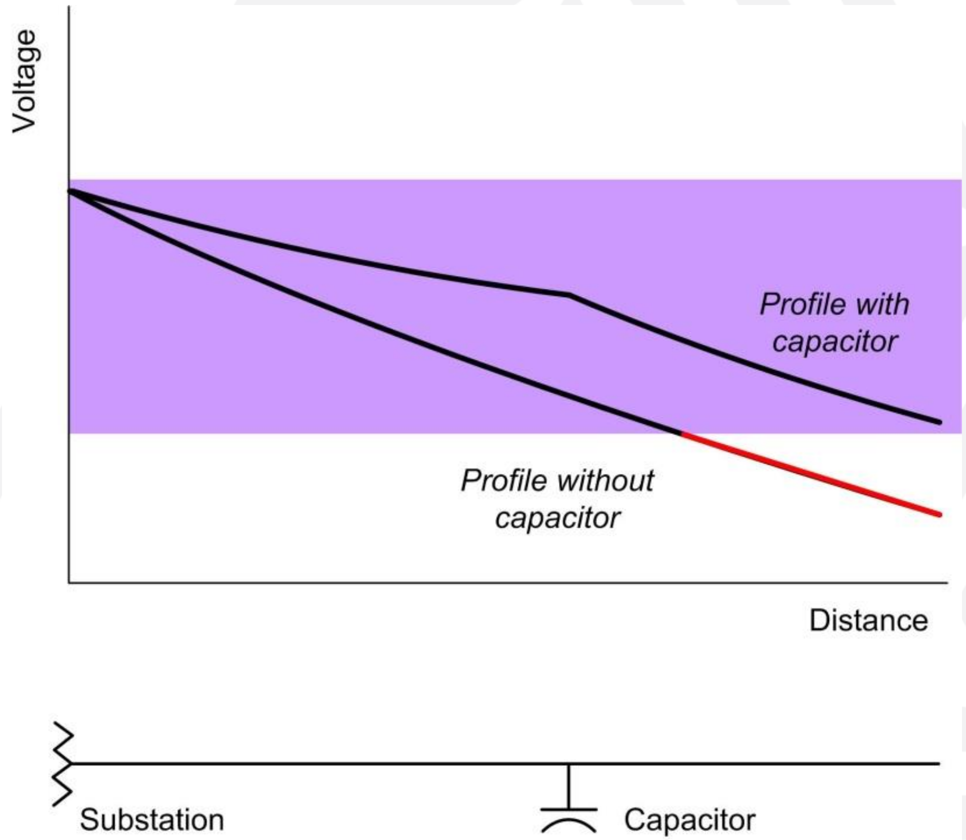
(lifetime is 1M+ operations normally)

Traditional Voltage Regulation: in line voltage regulators



voltage regulator

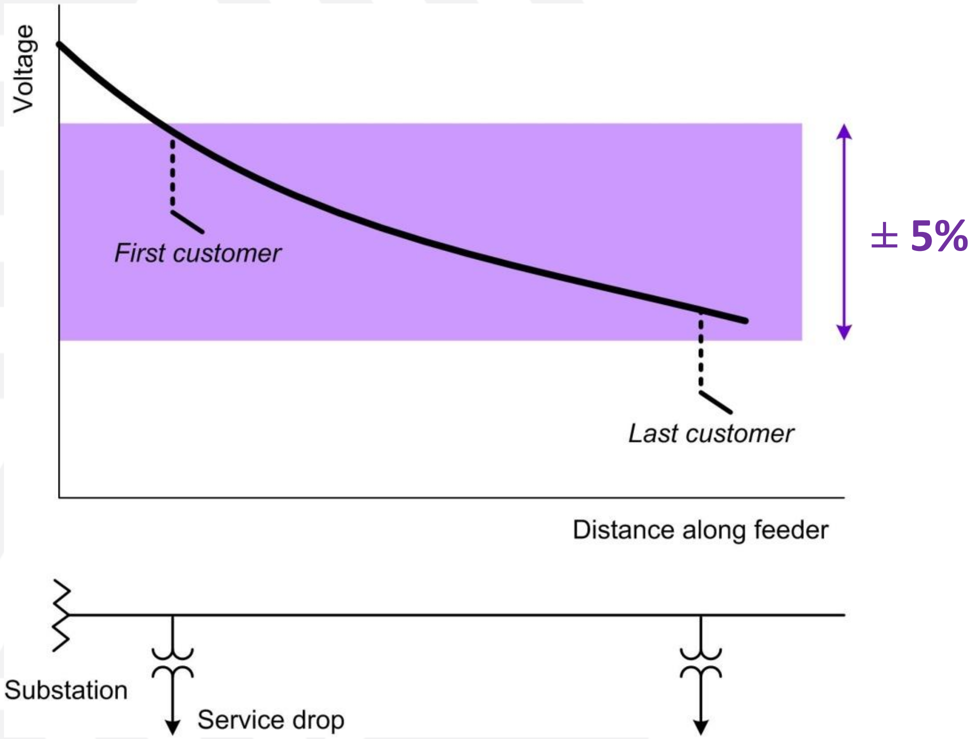
Traditional Regulation: Capacitor Banks



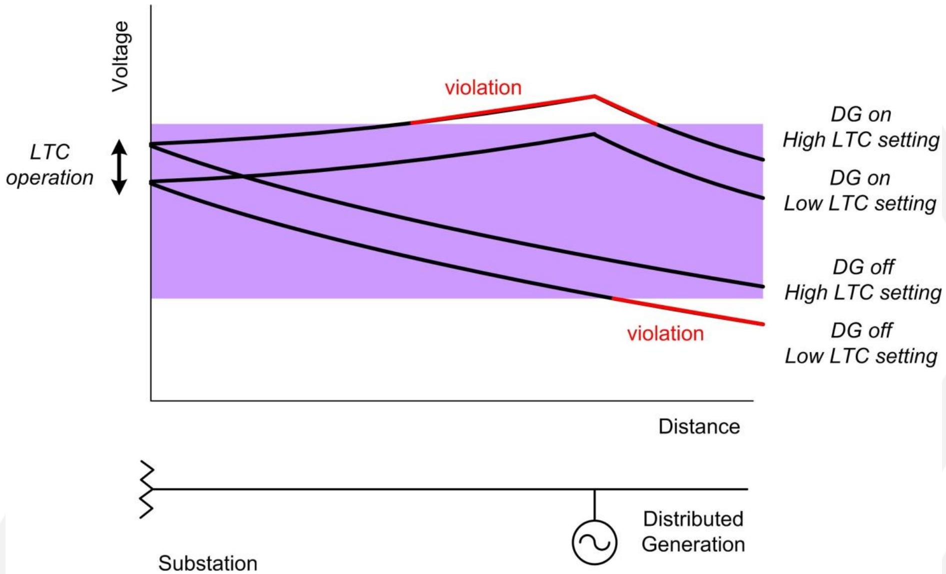
capacitor bank

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

The legacy approach assumes one-directional power flow.



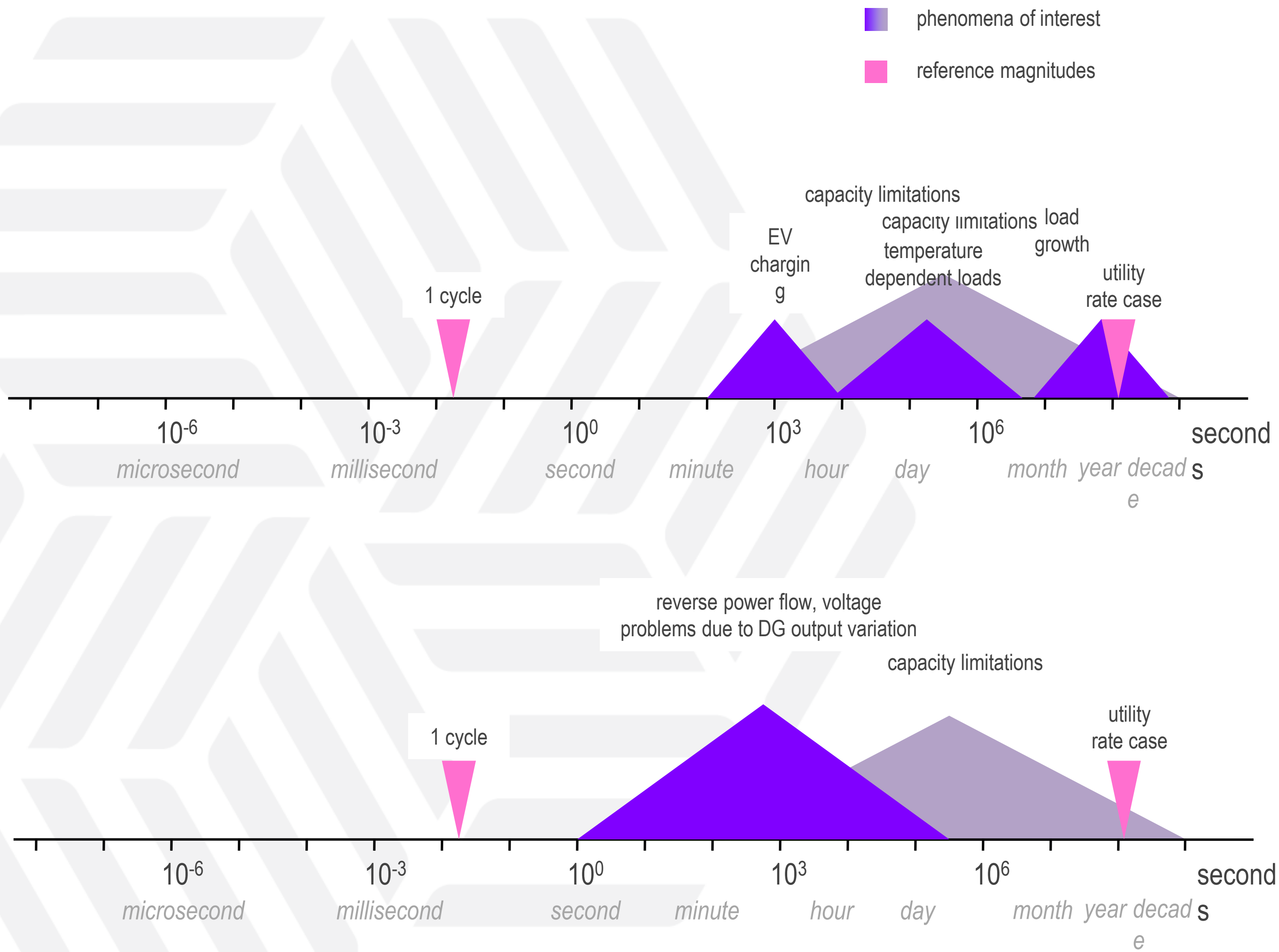
Moving towards smart voltage control: Coordination issues with uncontrolled DG



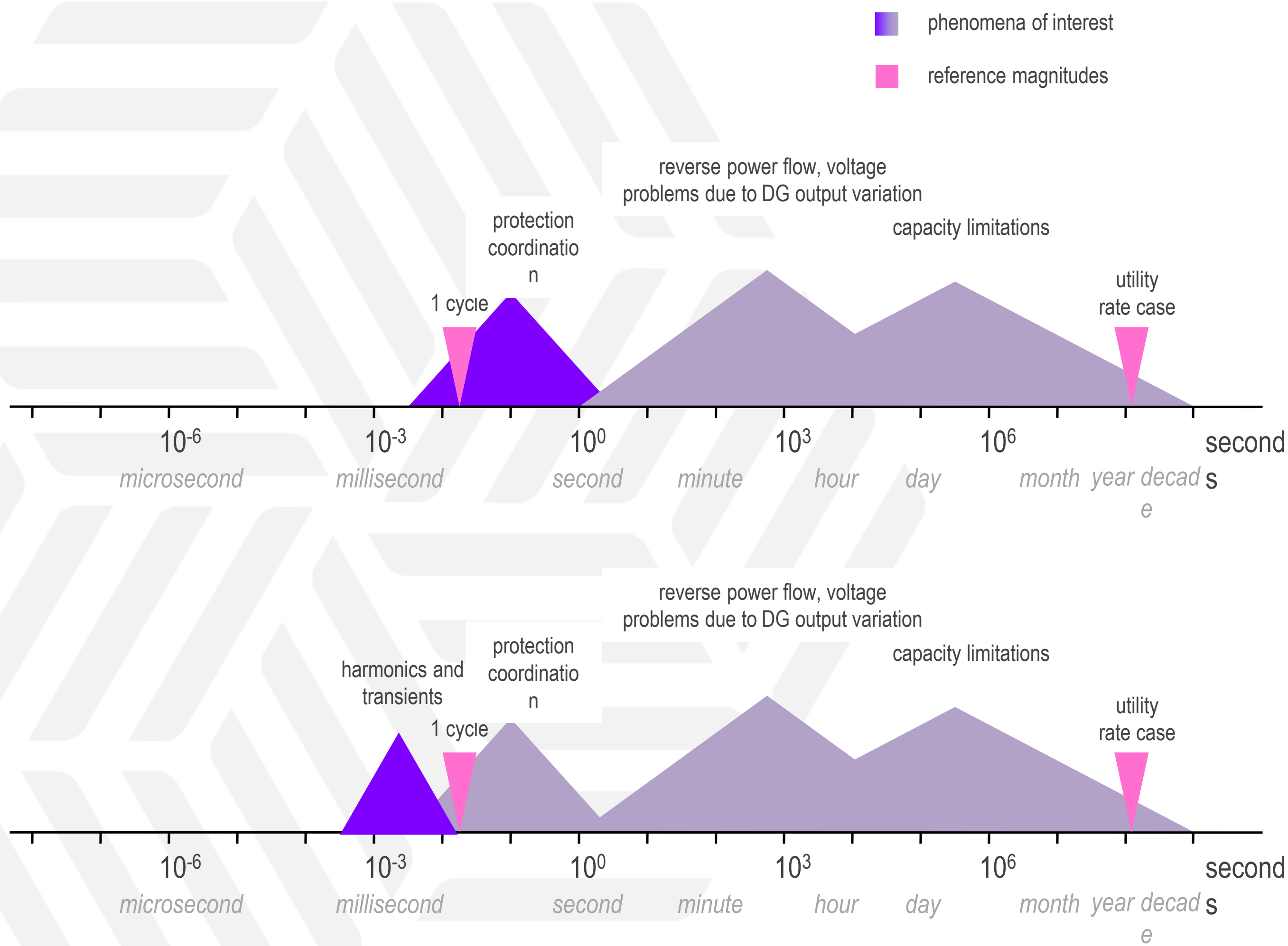
- Distributed generation (DG) may drive voltage out of range
- DG may wear out legacy equipment “hunting” the voltage
- inverted voltage profile may confuse controls
- voltage status may become even less transparent to operators
- this will all be presented later!

Introduction to Sensing and Measurement for the Distribution System

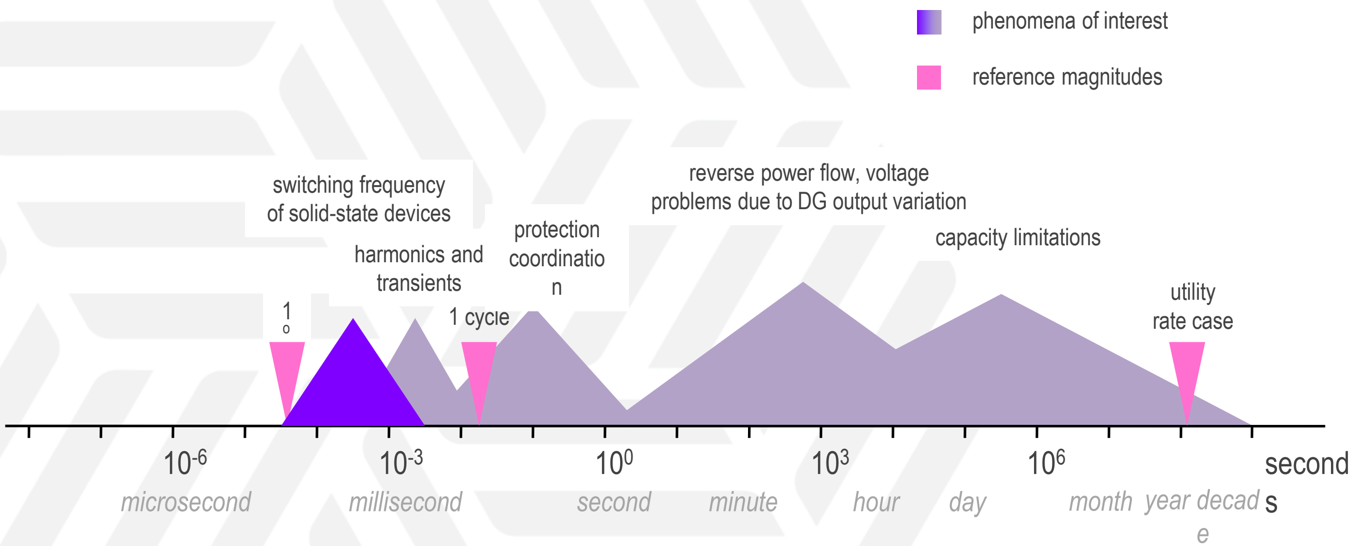
Distribution System Issues on Different Time Scale



Distribution System Issues on Different Time Scale

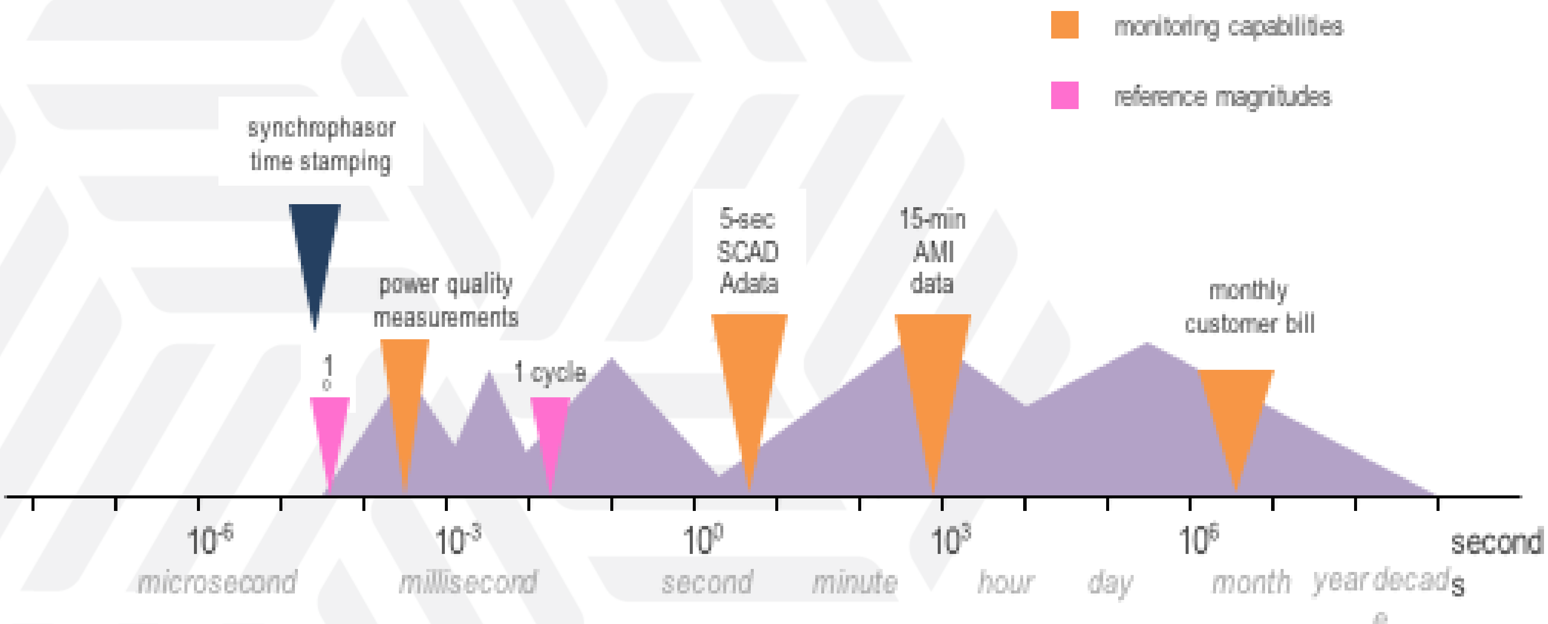


Distribution System Issues on Different Time Scale



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

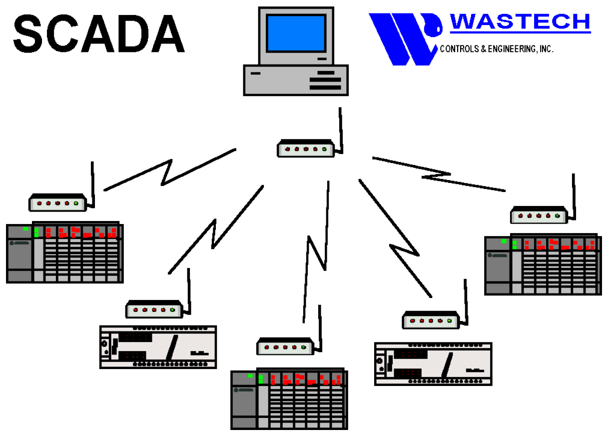
Programmable Logic Controllers (**PLCs**): similar to RTUs, more sophisticated controls

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

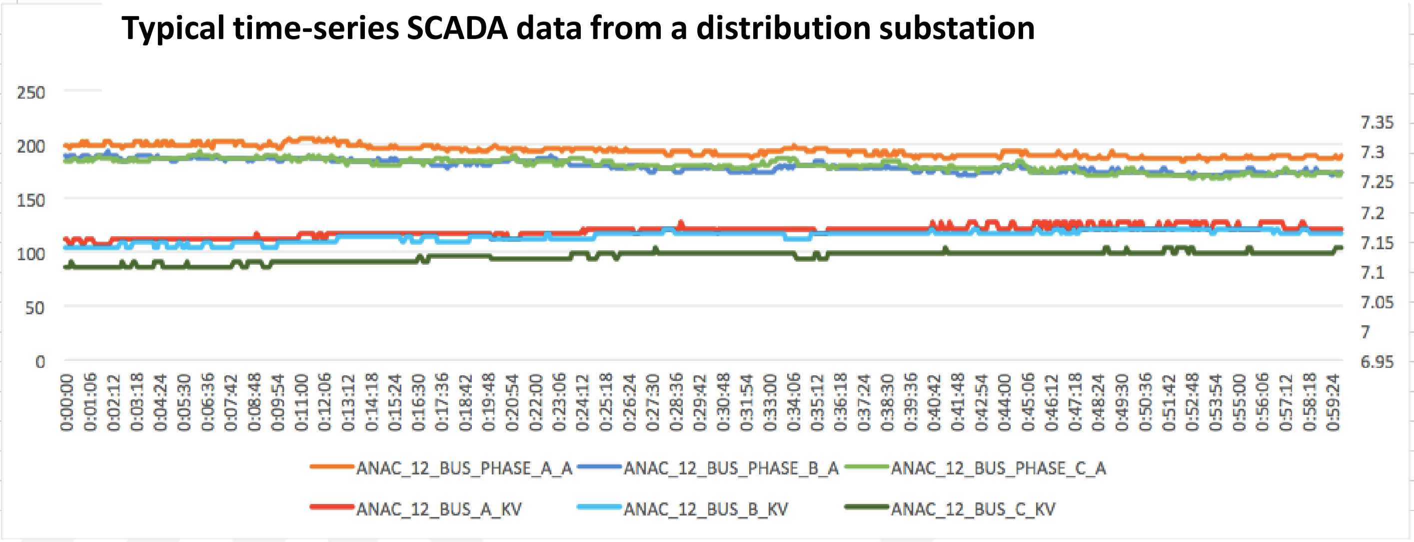
Data Acquisition Server: manages data from field devices

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 mechnical
- 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

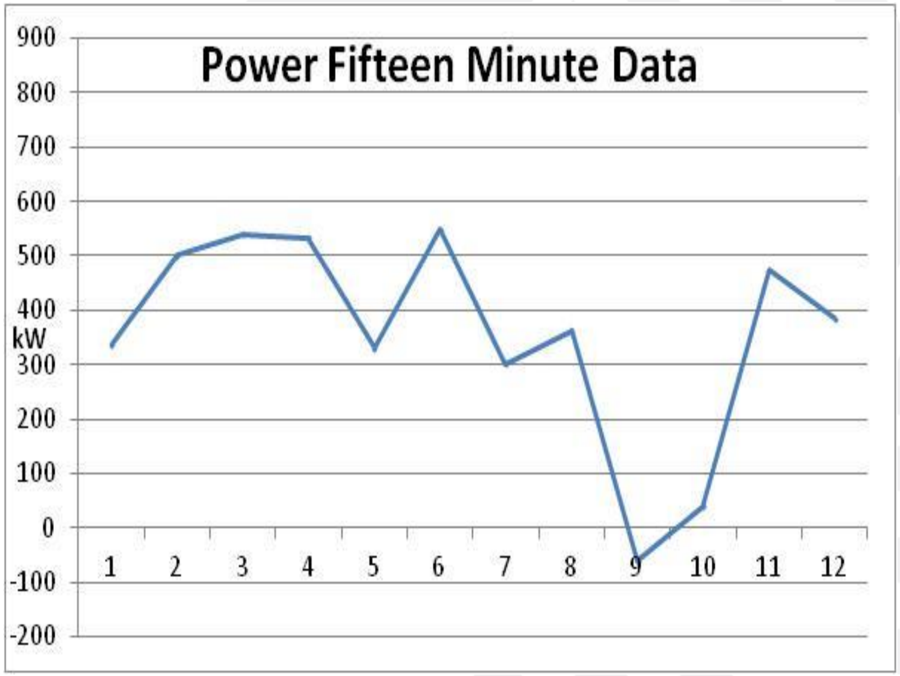
Present State in Normal Deployment

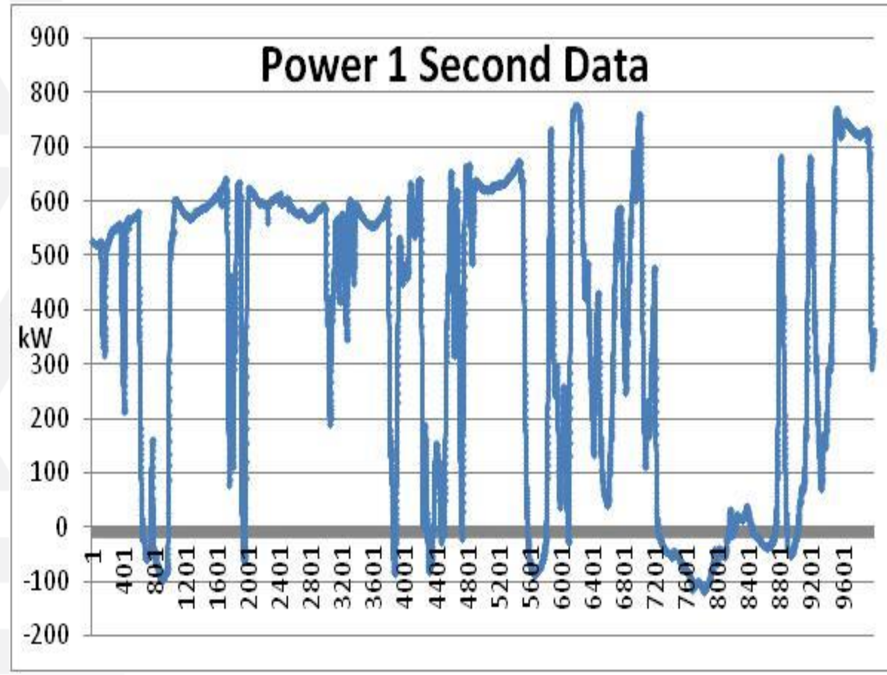
- not enough resolution to observe short-term power variations
- typically do not report voltage (although it is sensed)
- data may not be provided in real-time
- data may be provided only to billing department, not operations
- most likely early operational application: fault location, isolation and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

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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
• Remote meter reading • Remote service connections/disconnections	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
• Tamper detection and notification	Enables potential recovery of ~1% of revenues that may be lost from meter tampering
• Outage detection and notification	Enables faster restoration (e.g., PECO avoided 6,000 truck rolls following Superstorm Sandy and accelerated restoration by 2-3 days)
• Voltage and power quality monitoring	Enables more effective management of voltages for conservation voltage reductions and other VVO applications

Transformer Project Background

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- 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

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: 1-10-2013 End: 03-08-2013 Premise/Address/TLN: [2114607] 19755 SW 302ND ST,33030 **Load Data**

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

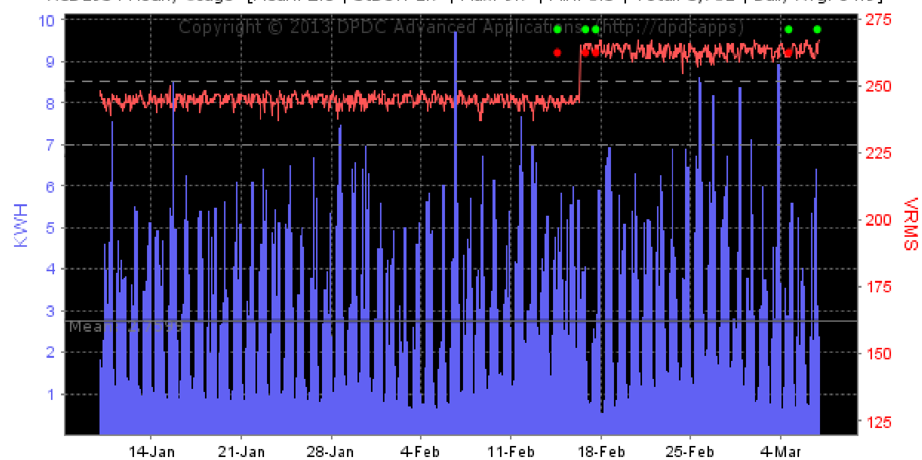
Event Summary: 2114607 | View All

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

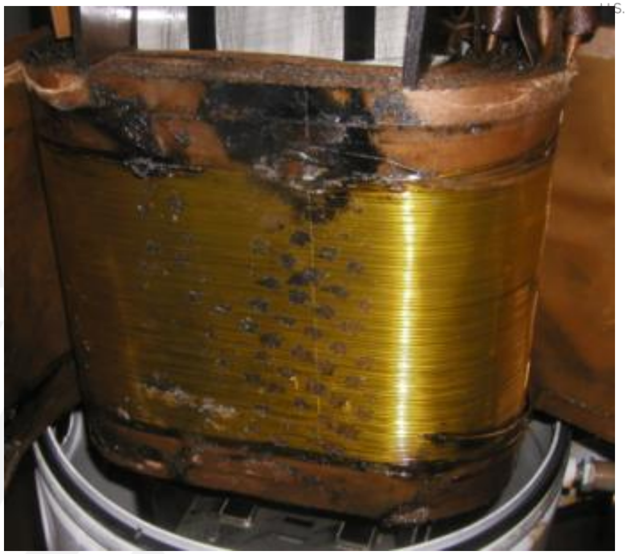
ACD1934 Hourly Usage [Mean: 2.8 | StDev: 1.7 | Max: 9.7 | Min: 0.5 | Total: 3,701 | Daily Avg: 64.9]



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

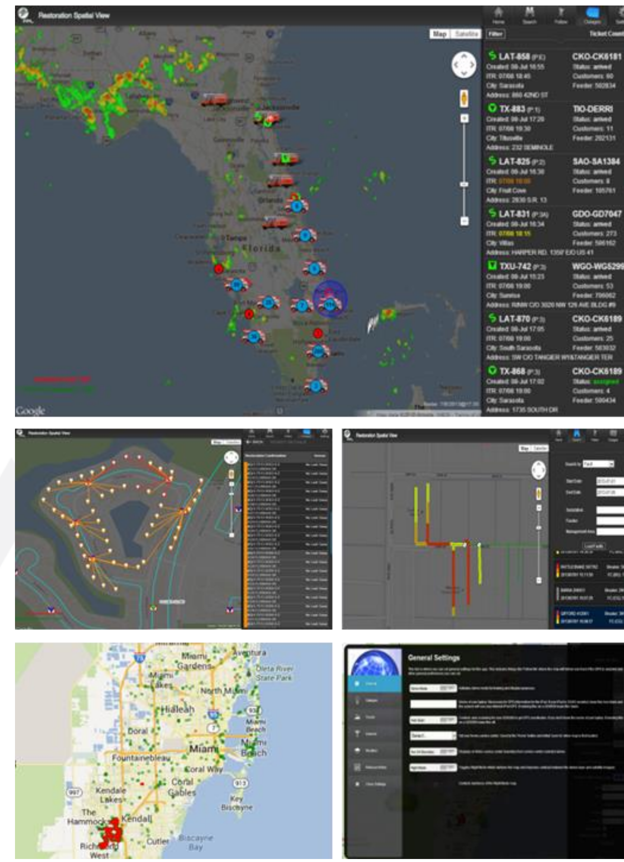
Using voltage information, FPL can proactively identify and replace transformers before they cause an outage

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

- All to be covered in later sessions
- DER
- ADMS
- Data & analytics
- Automation
- Modeling
- Communications

Summary

- Intention of first session: give the background to the present state of the distribution grid – how did we get here

- Information Covered:
  - Present State
  - What is a smart grid
  - Equipment and controls

- Future reading (included in extra slides)

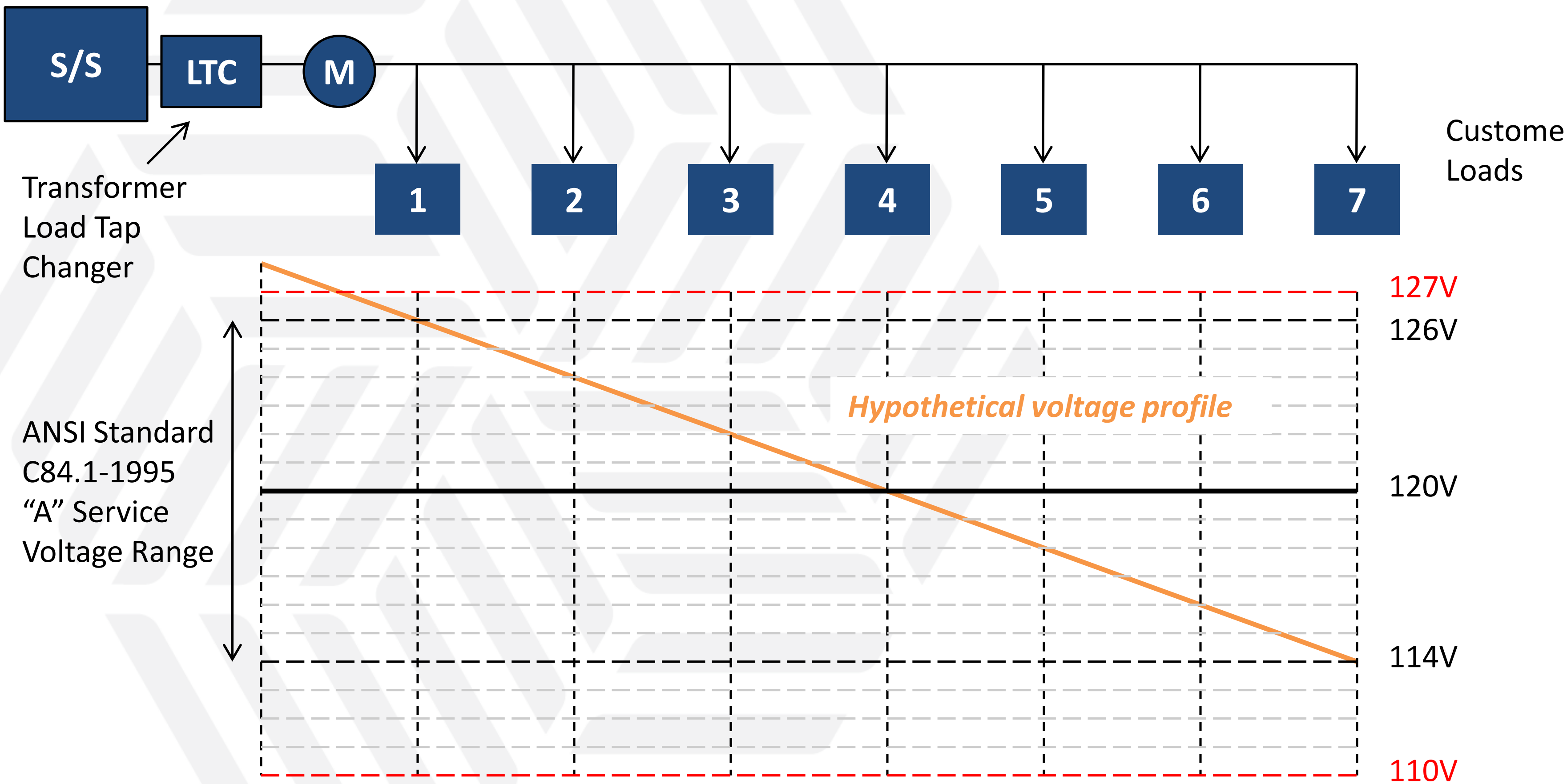
Extra Slides

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_Integrated%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://pubarchive.lbl.gov/islandora/object/ir%3A186035/

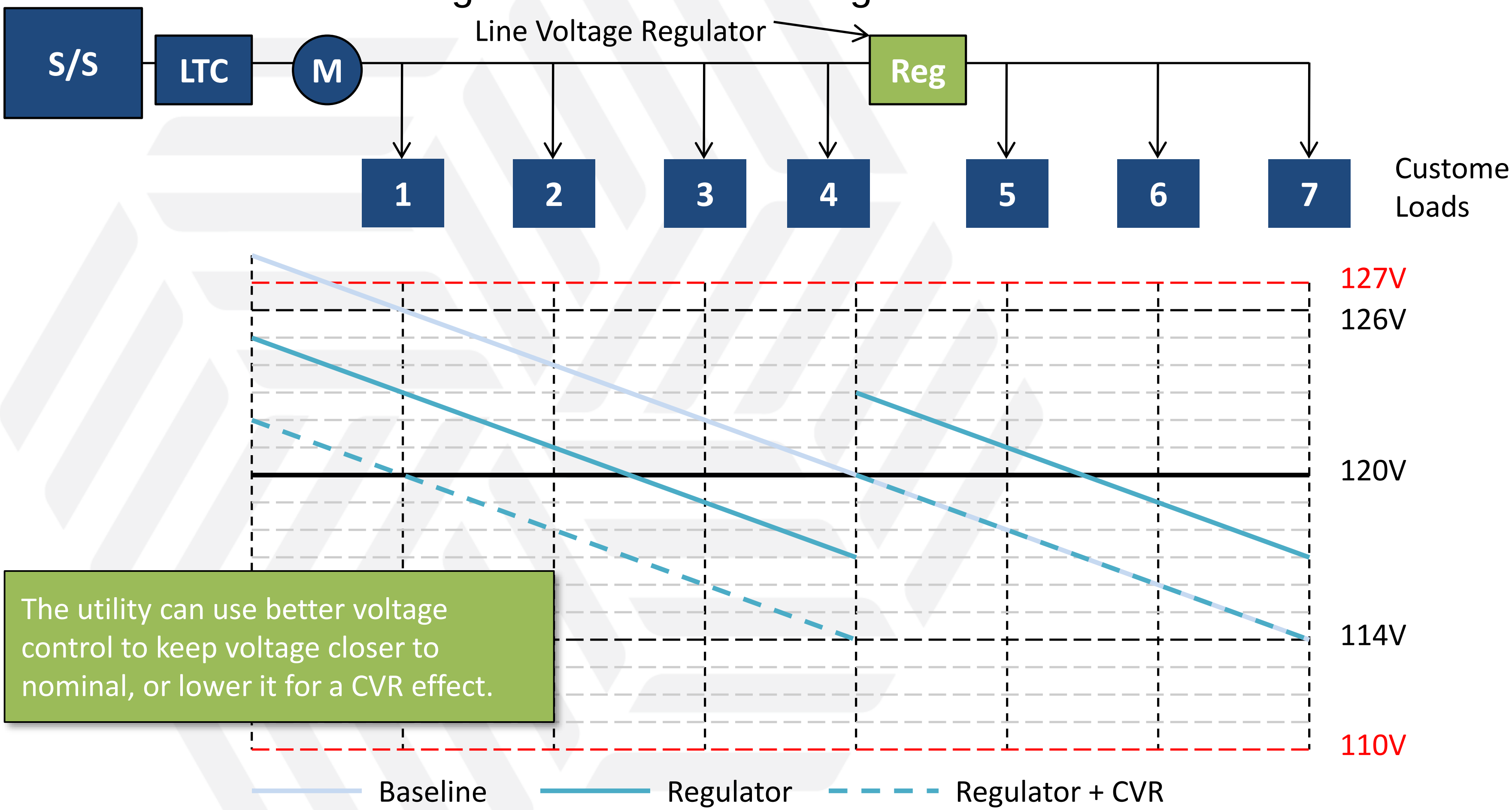
Voltage Profile

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



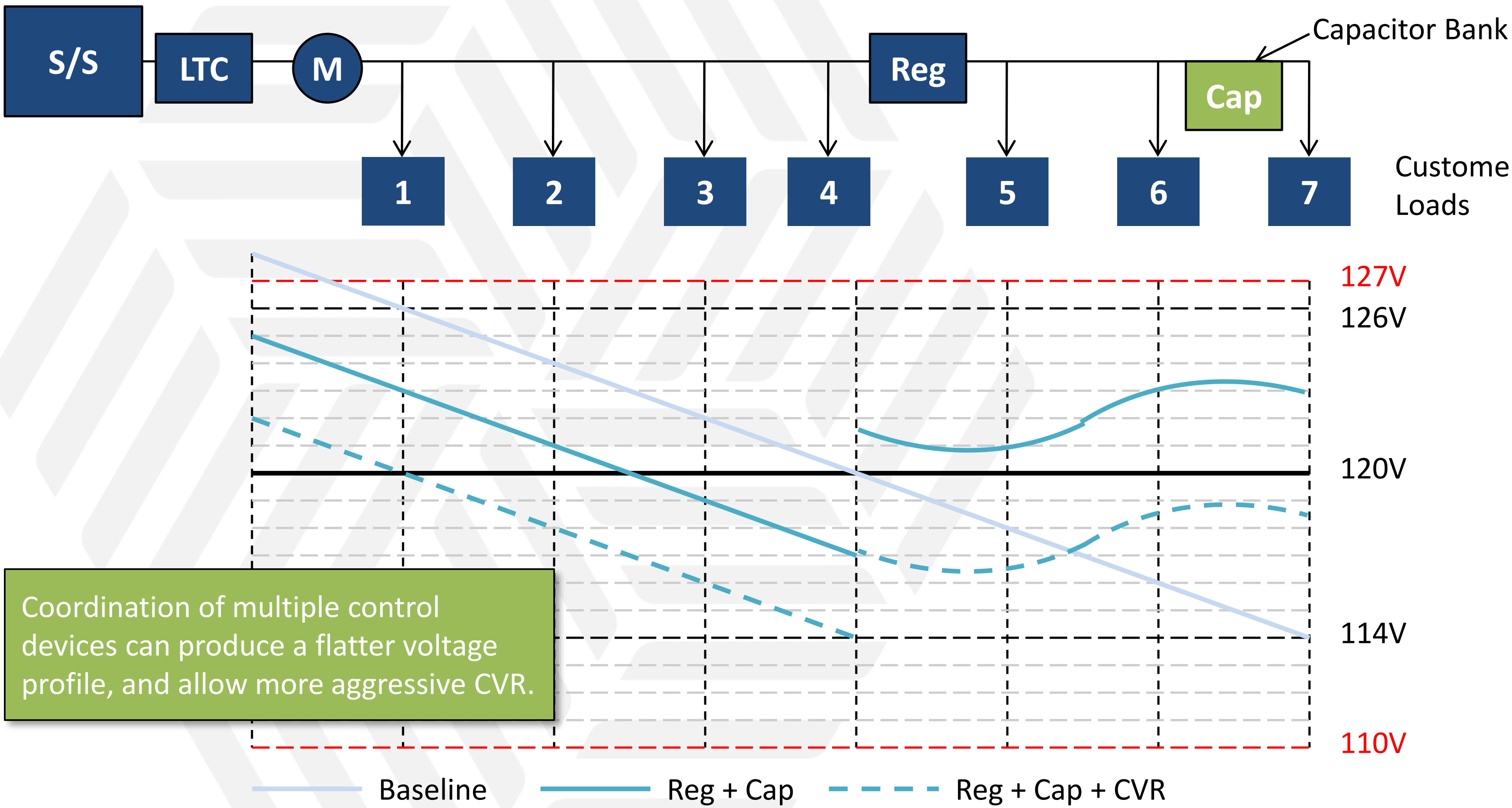
Voltage Optimization

- 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

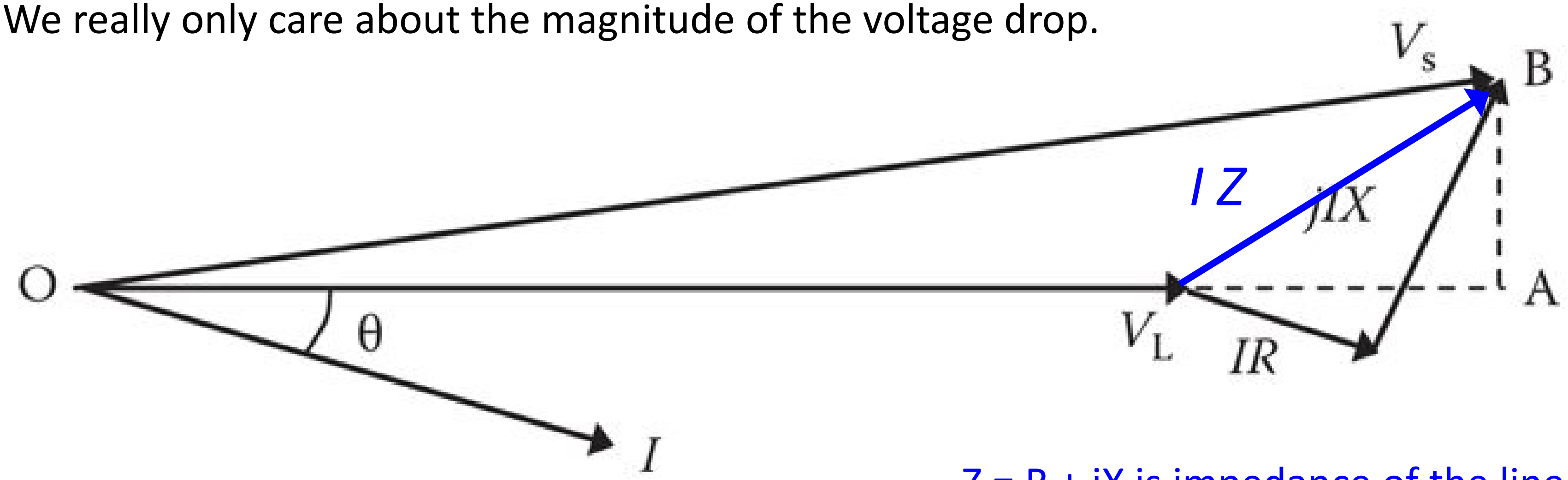
- A capacitor bank can help regulation by compensating for the lagging power factor of load and the line itself.



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

Geometry problem: is the voltage drop IZ 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.



Z = R + jX is impedance of the line

multiplied by load current

I Z gives voltage drop

Bottom line:

Changing the phase angle θ of current by introducing capacitance changes the direction of IZ and therefore the sensitivity of voltage drop to load current.

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

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 **(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