Distributed Solar T&D Grid Impacts: Engineering Concepts

Kevin Schneider

Pacific Northwest National Laboratory

Utah Public Service Commission - Docket No. 17-035-61
National Lab Technical Workshop on Distributed Solar Grid Impacts
July 11, 2019 1-5 PM

Slide credits: Sascha von Meier, UCB

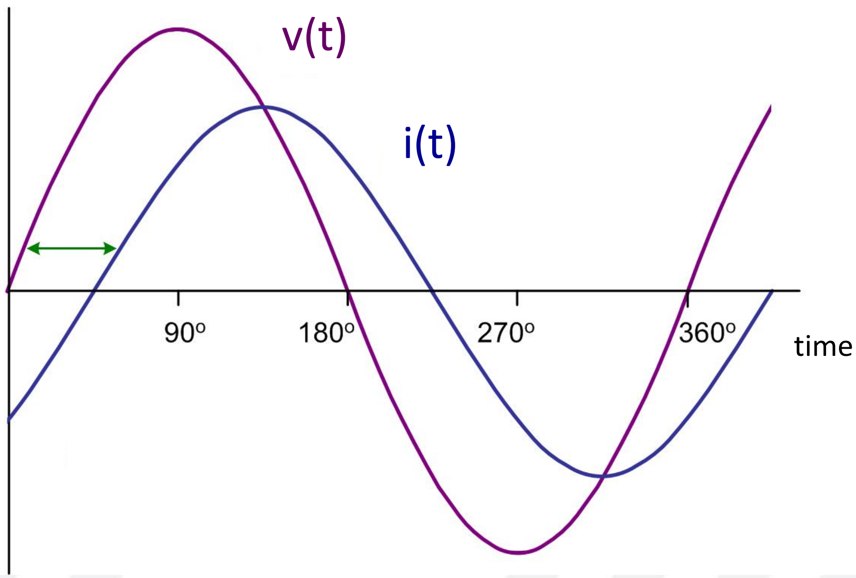
What we'll cover – Part 1

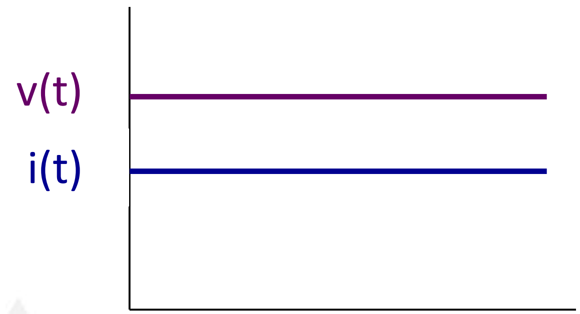
- Part 1 - **<u>Distribution system attributes</u>** important to assessing impacts of distributed solar
  - AC power
  - Reactive Power
  - Key characteristics of distribution systems
  - Components and functionality
  - Voltage regulation
  - Protection
  - Smart meters
  - Questions and discussion

What we'll cover – Part 2

- Part 2 - **Planning the distribution system** with solar PV
  - Basics
  - Load forecasting
  - Modeling tools
  - Advances in distribution system planning – PV example
  - Hosting capacity
  - T&D voltage impacts
  - Questions and discussion

Alternating Current (AC) fundamentals





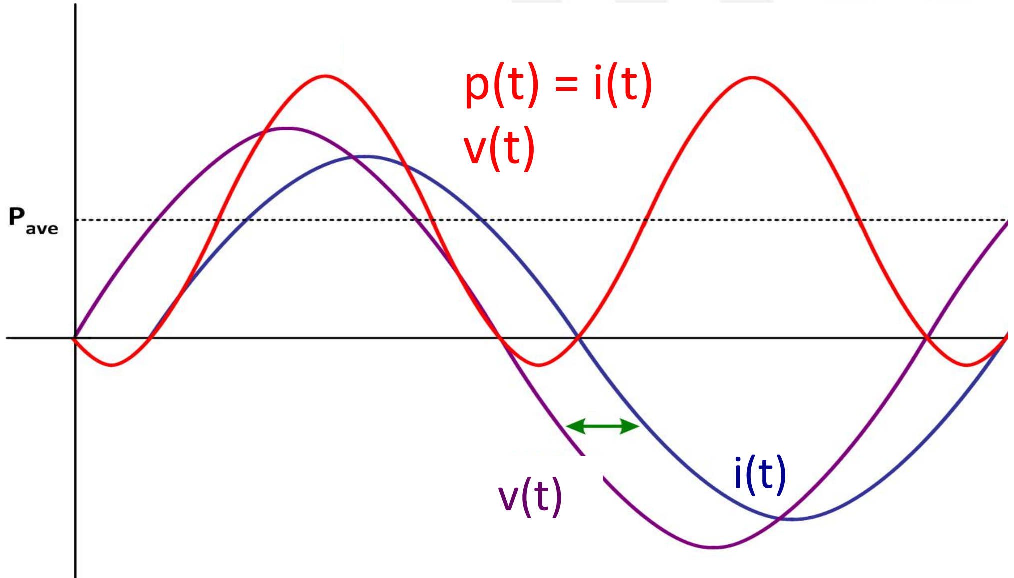
AC voltage and current waveforms are time varying with a 60 Hz fundamental frequency:

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:

$S = P + j\,Q$

active power $P = S \cos \theta$ (W)

reactive power $Q = S \sin \theta$ (VAR)

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

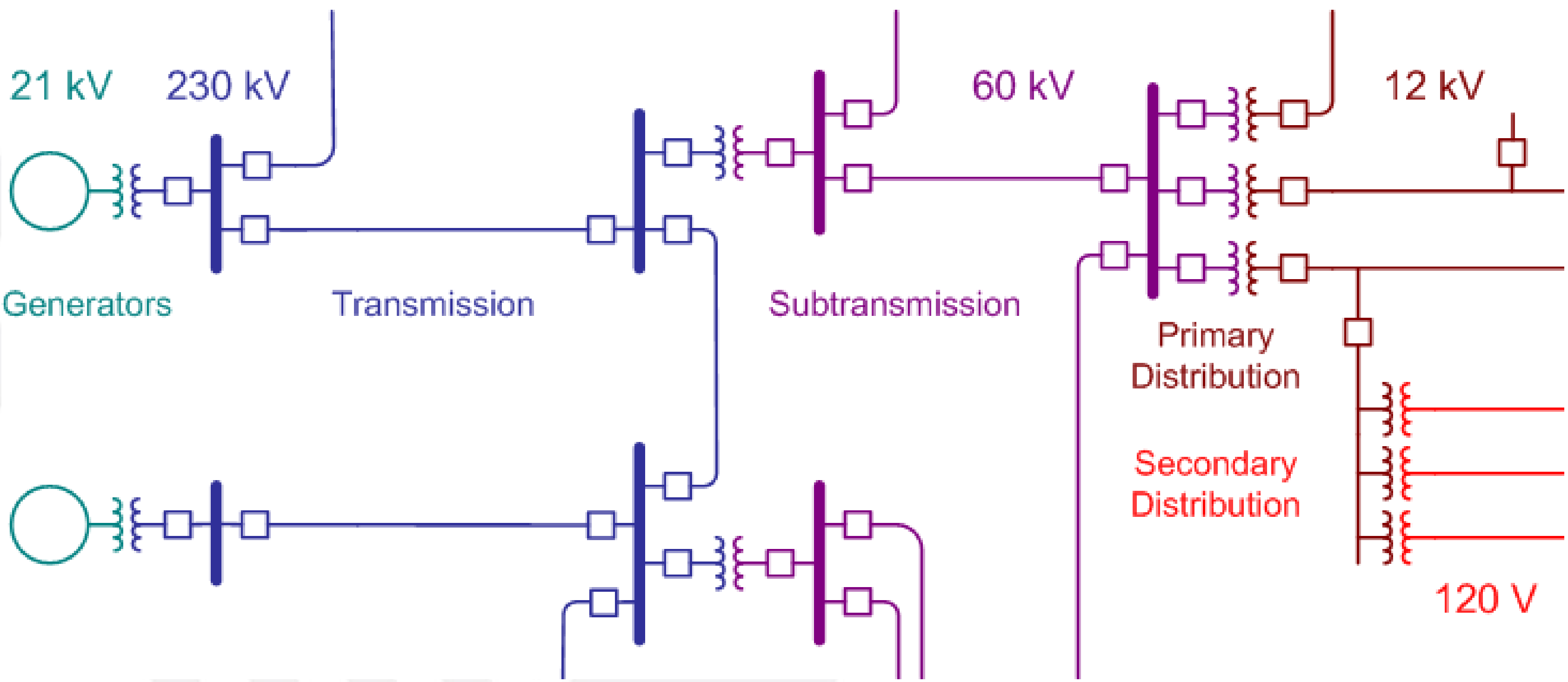
Components and Functionality – a basic introduction to the distribution system “as is”

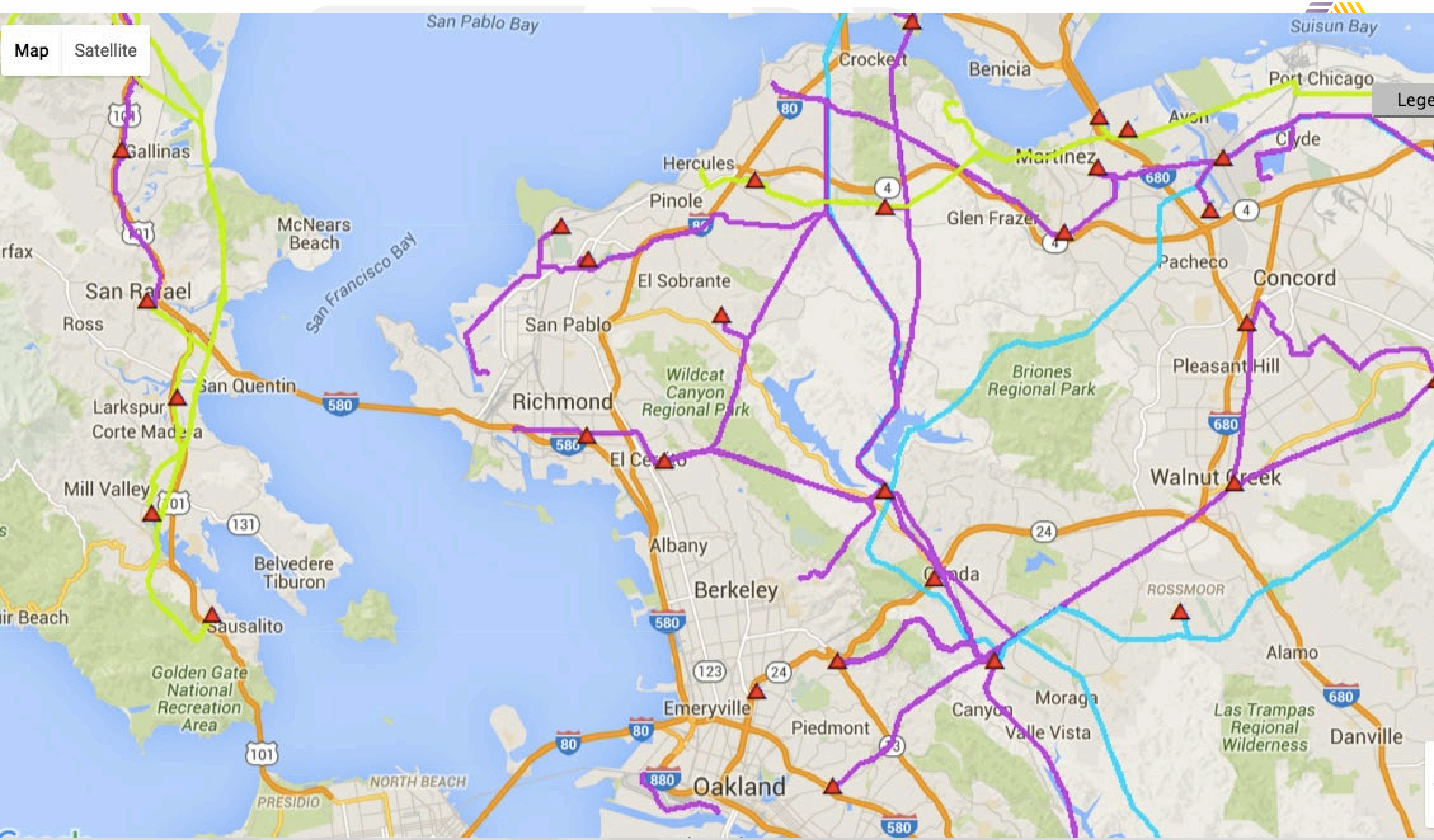
How distribution systems are different than transmission systems

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

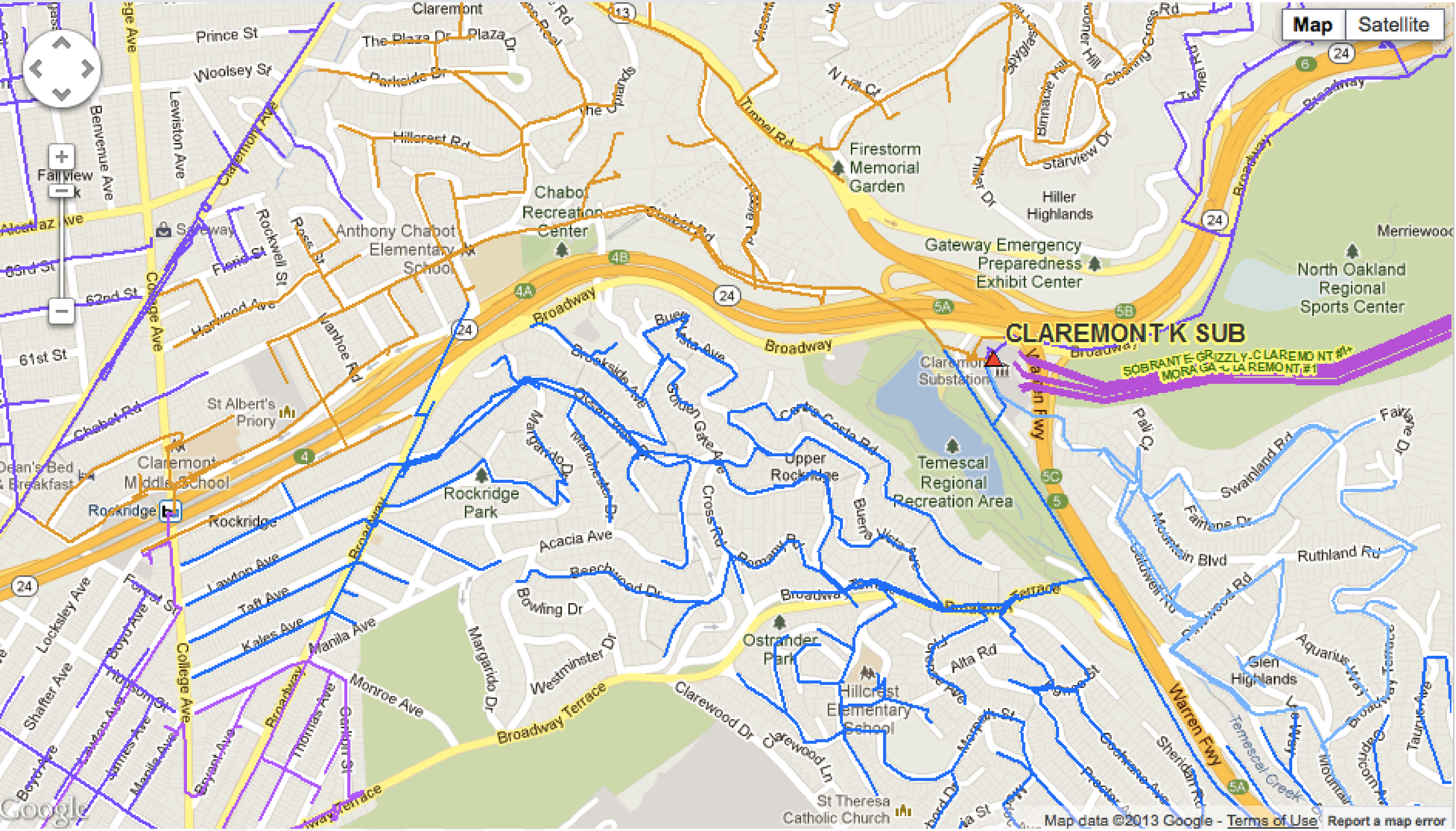




115kV Transmission network

Distribution substations

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


Map
Satellite
CLAREMONT K SUB
Claremont Substation
Firestorm Memorial Garden
Hiller Highlands
Gateway Emergency Preparedness Exhibit Center
North Oakland Regional Sports Center
Merriewood
Temescal Regional Recreation Area
Upper Rockridge
Rockridge Park
Chabot Recreation Center
Anthony Chabot Elementary School
St Albert's Priory
Claremont Middle School
Rockridge
Ostrander Park
Hillcrest Elementary School
St Theresa Catholic Church
Glen Highlands
Broadway
Broadway Terrace
Warren Fwy
Tunnel Rd
Claremont Ave
College Ave
Prince St
Woolsey St
Alcatraz Ave
Chabot Rd
Acacia Ave
Manila Ave
Monroe Ave
Kales Ave
Taft Ave
Lawton Ave
Margarido Dr
Westminster Dr
Bowling Dr
Beechwood Dr
Clarewood Dr
Alta Rd
Cross Rd
Golden Gate Ave
Buena Vista Ave
Contra Costa Rd
Swainland Rd
Fairlane Dr
Ruthland Rd
Aquarius Way
Starview Dr
Hillcrest Rd
Sheridan Rd
Temescal Creek
Map data ©2013 Google - Terms of Use
Report a map error

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

► **Some distribution feeder attributes:**

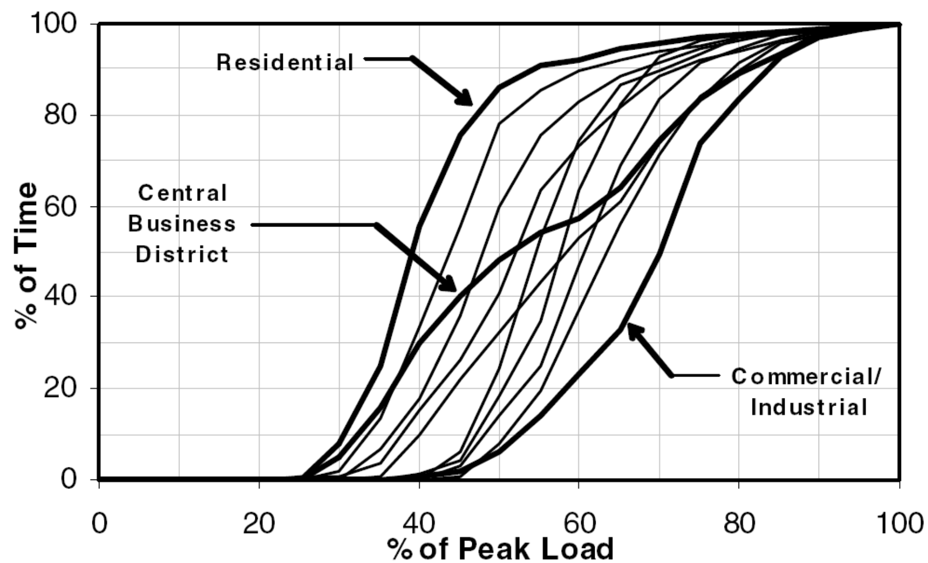
- underground vs. overhead
- topology (e.g. radial, loop, network), sectionalizing options
- circuit length, load density
- load characteristics (time profile, load factor, predictability)
- anticipated load growth, EV, DG
- sensitivity of loads to power quality
- phase imbalance
- extent of SCADA capabilities 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

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

External influences are always nearby:

- weather
- vegetation
- animals
- vehicles
- people
- …?

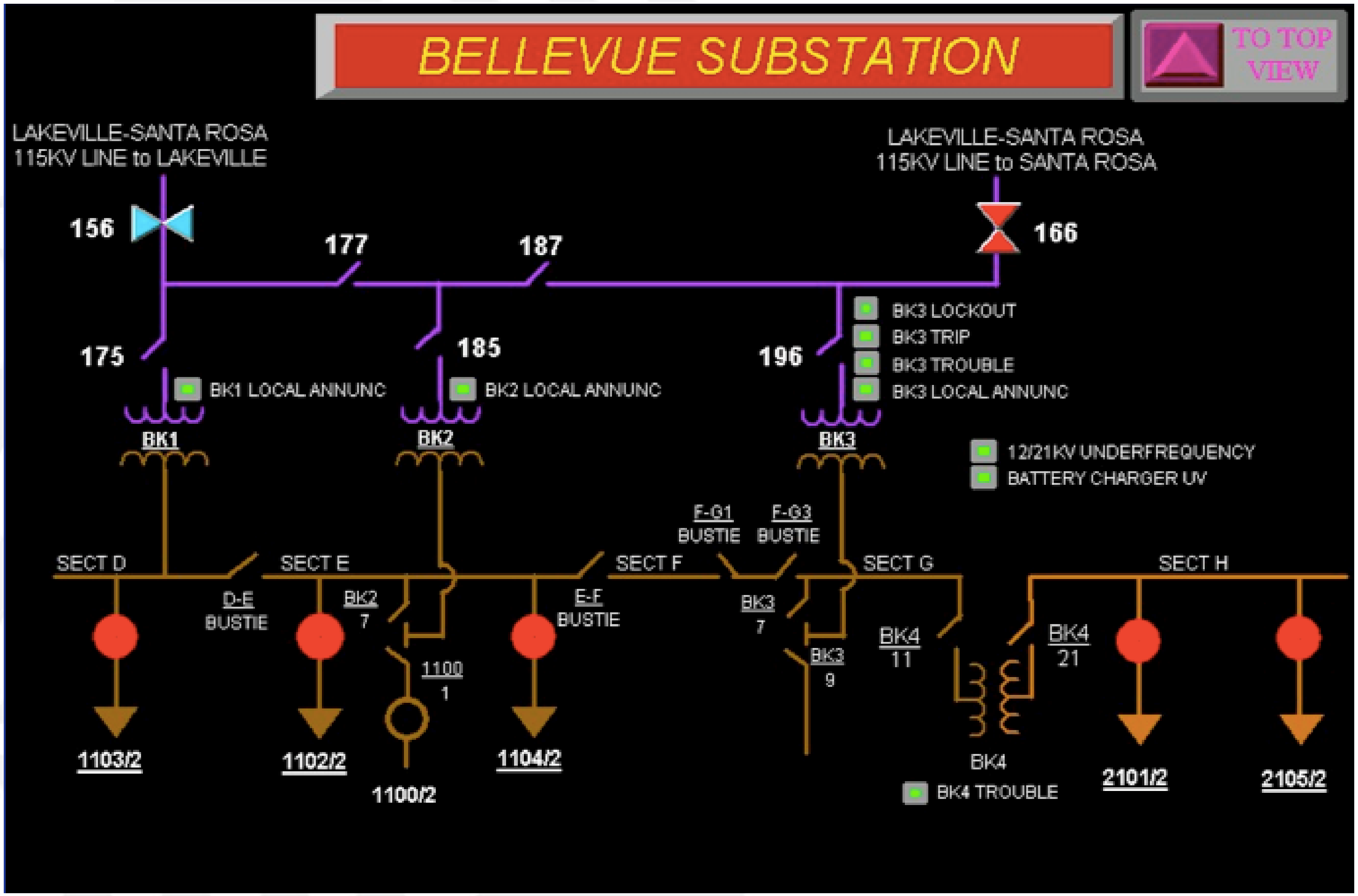
Note: 80-90% of customer outages originate in the distribution system


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 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

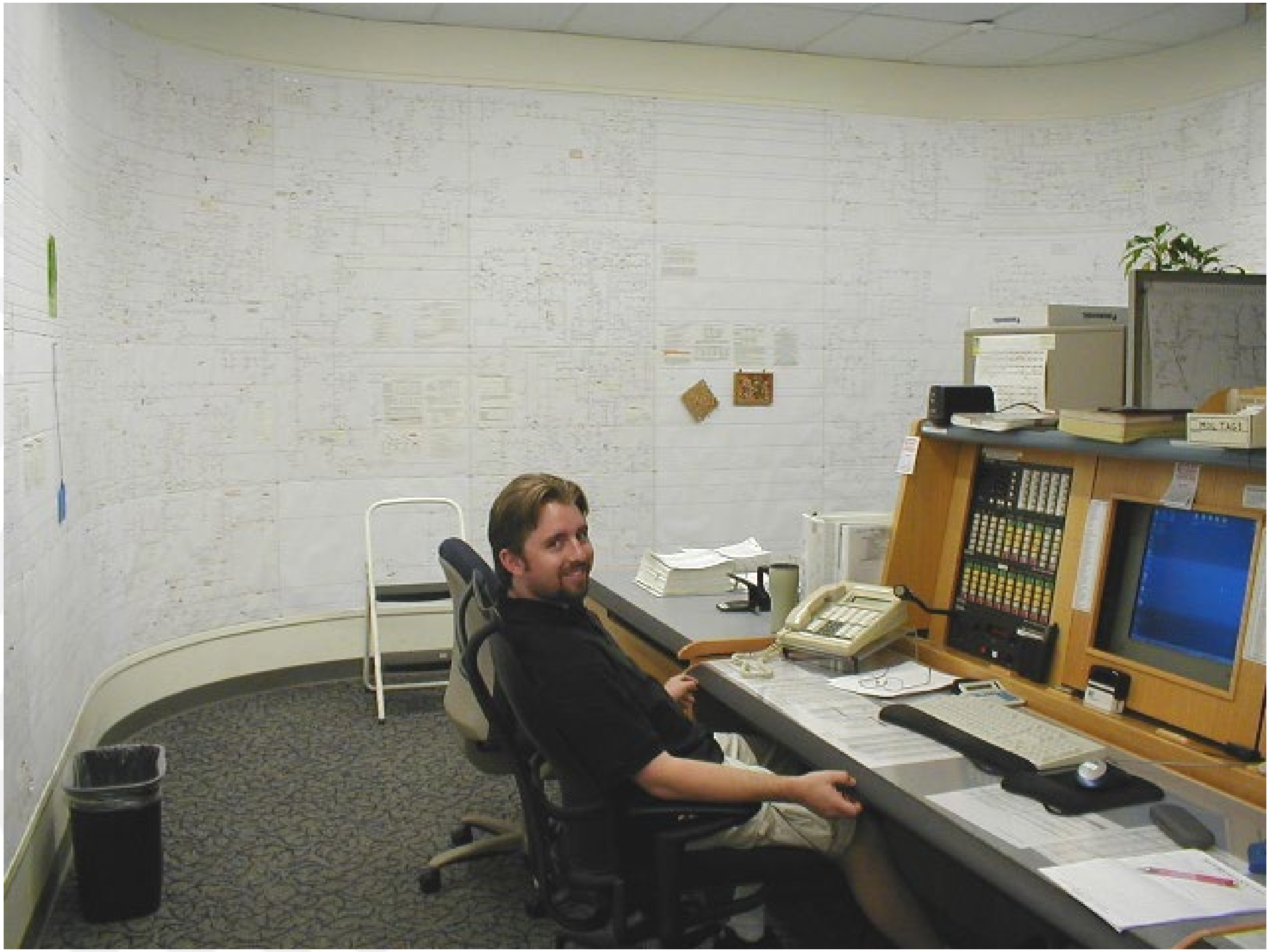
** Supervisory Control and Data Acquisition*

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
1103/2
1102/2
1100/2
1104/2
BK4
BK4 TROUBLE
2101/2
2105/2

Present State: Distribution Operator's control room, 2003

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy



Eyes and Ears in the Field

Substations

Important Equipment

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

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

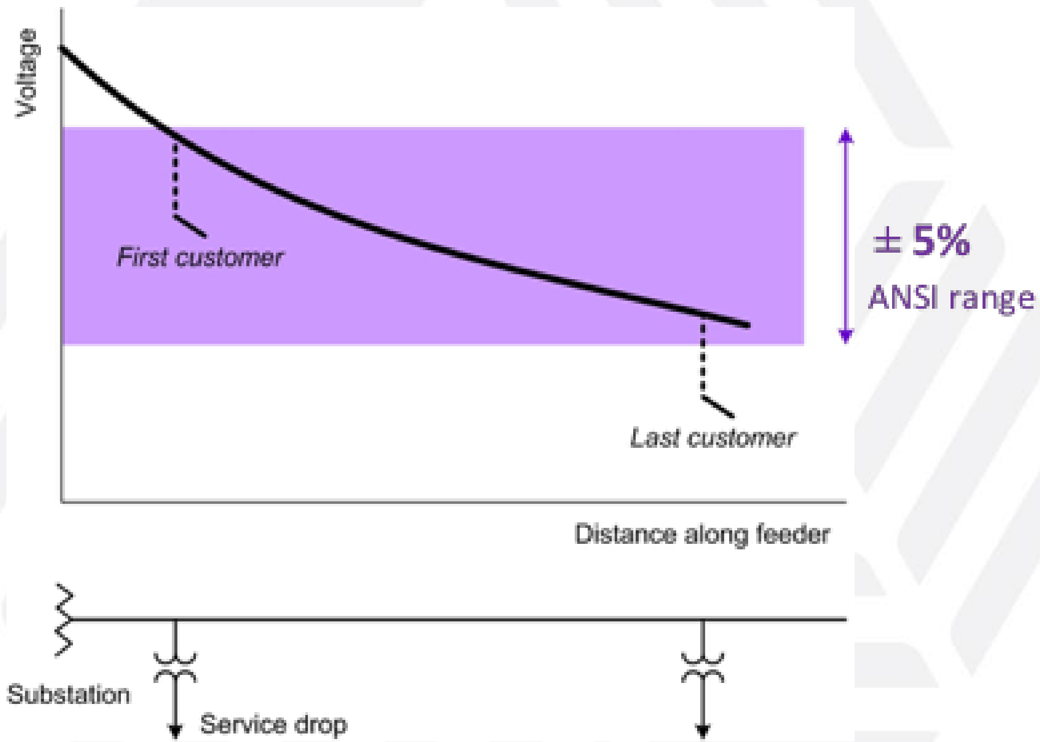
Voltage Control Devices

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

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

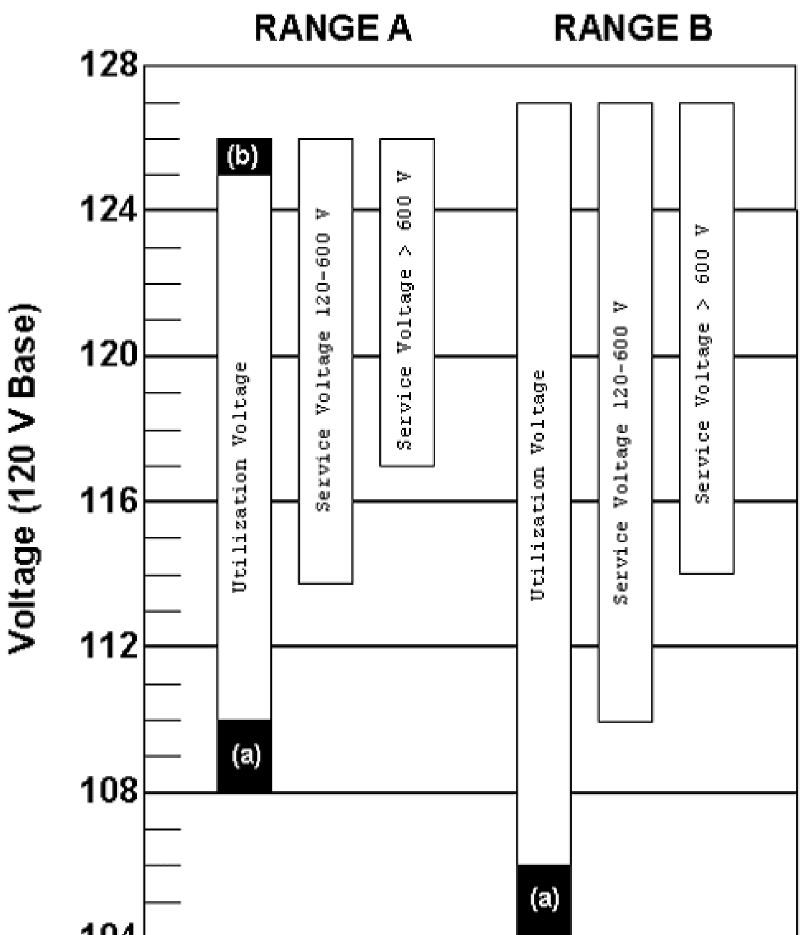
- New state
  - Conservation Voltage Reduction (CVR)
  - Volt-var Optimization (VVO)
  - Distributed var devices

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

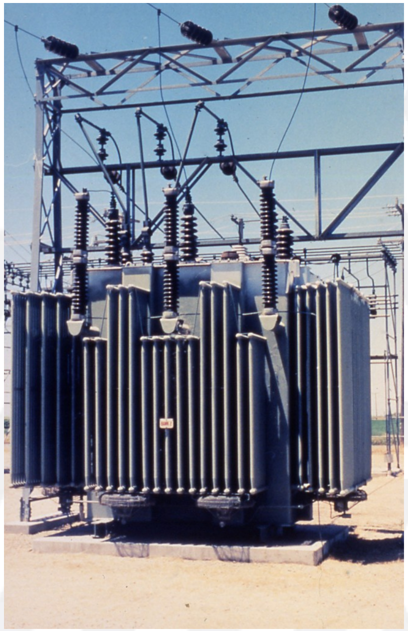
Traditional voltage regulation

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

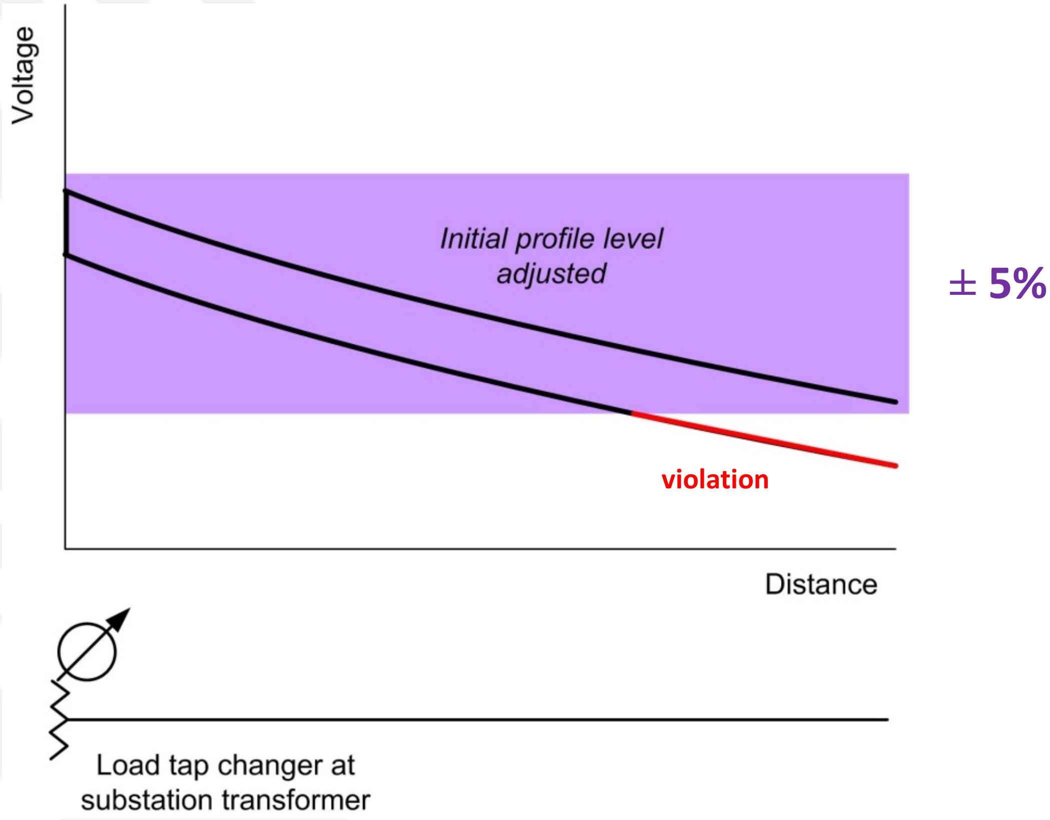
Emerging technologies (Discussed in future presentations)

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

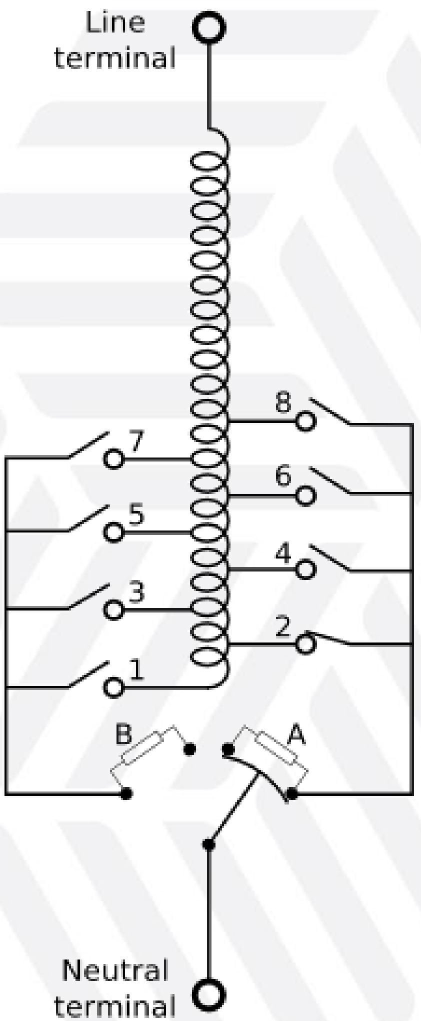
Traditional Voltage Regulation: Load tap changers (LTCs)



Substation transformer with load tap changer



LTCs cont



Mechanical load tap changer

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

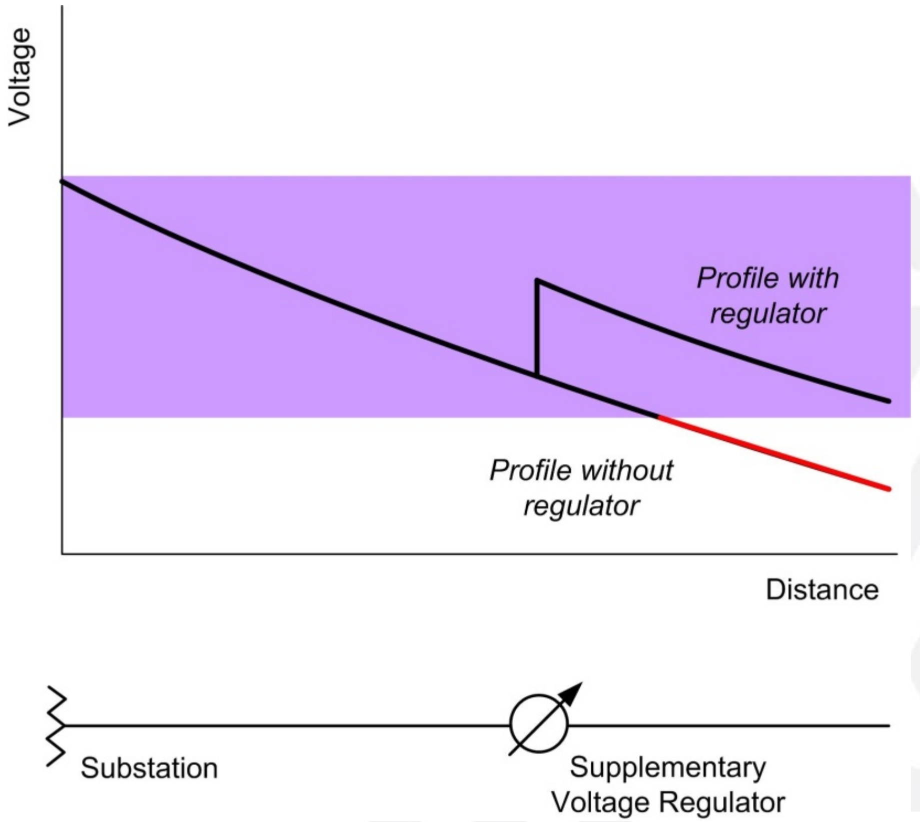
A and B are "diverter" resistors

but some arcing and wear is unavoidable

thus frequent operation is not desirable

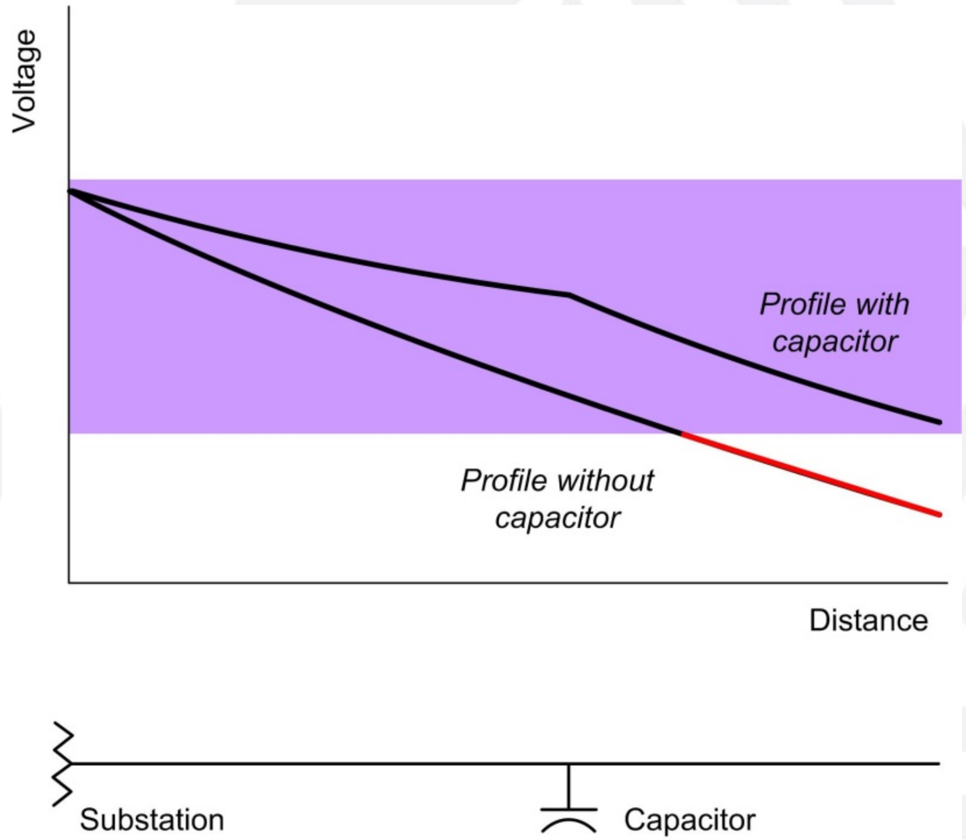
(25K-50K operations between maintenance)

Traditional Voltage Regulation: in line voltage regulators



2 Single Phase Voltage Regulators

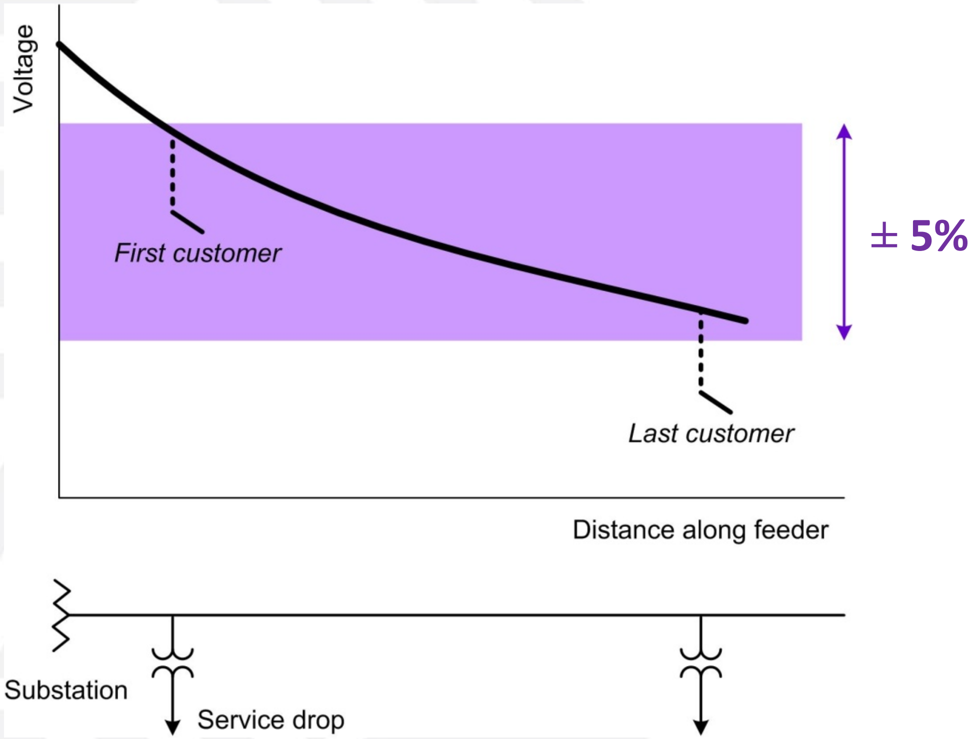
Traditional Regulation: Capacitor Banks



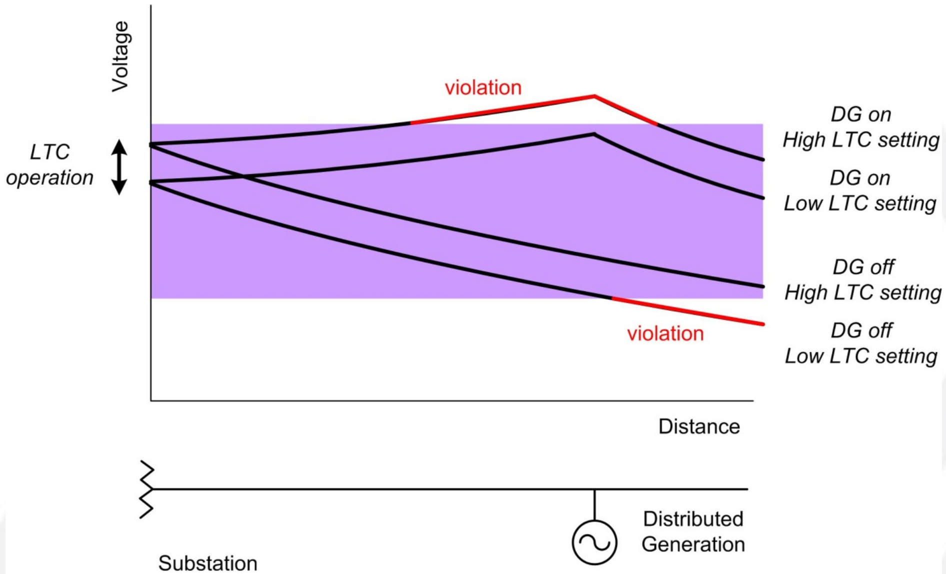
Capacitor Bank

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

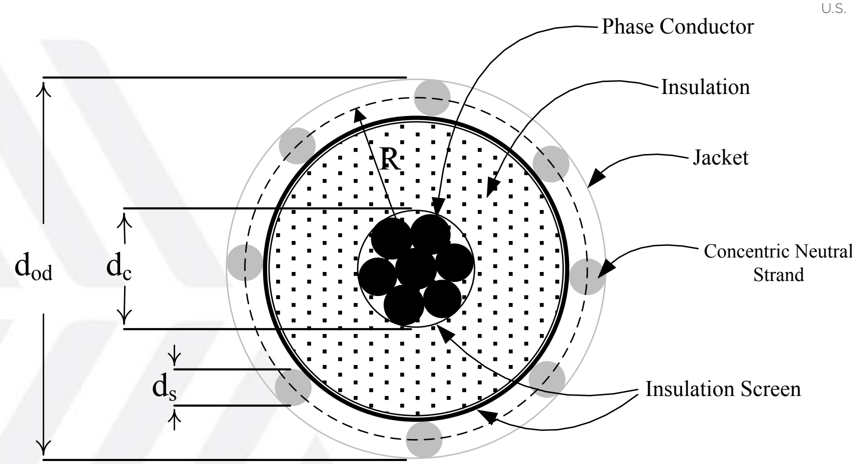
GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

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.

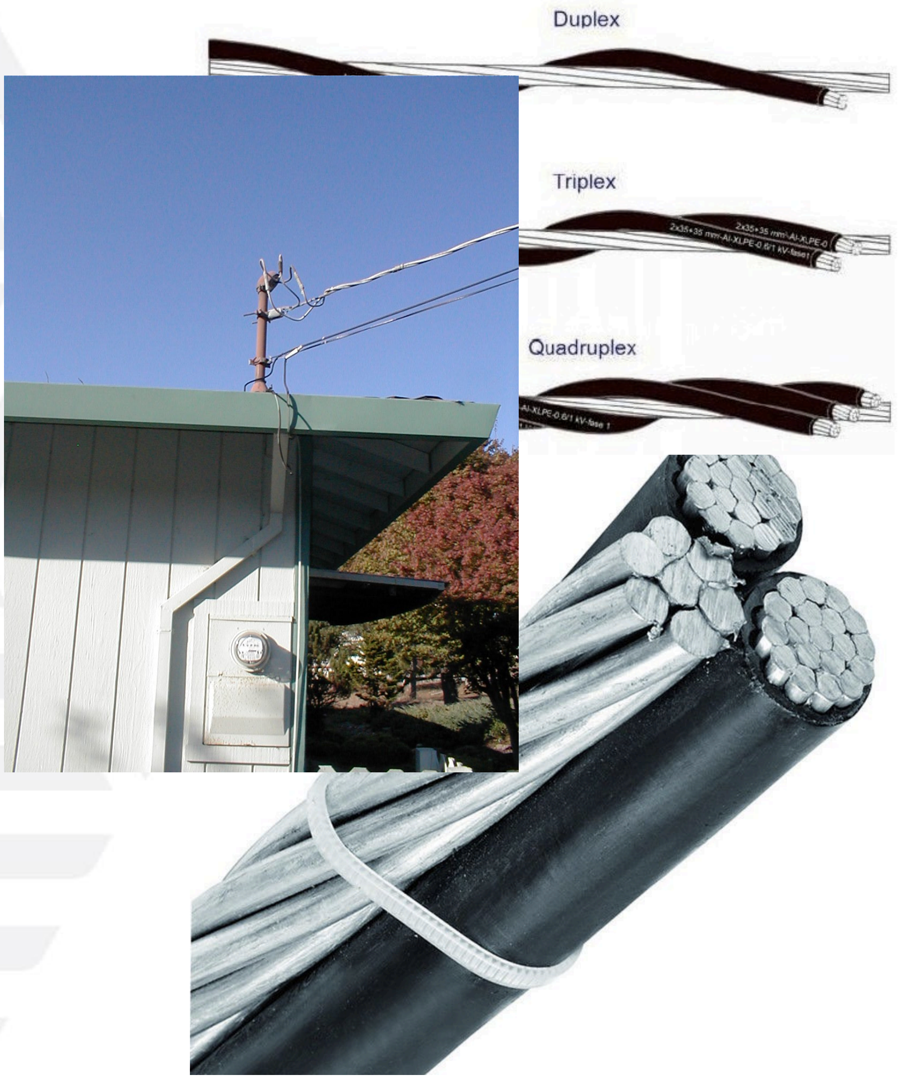
Cables can be directly buried or laid into conduit and vaults.

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.



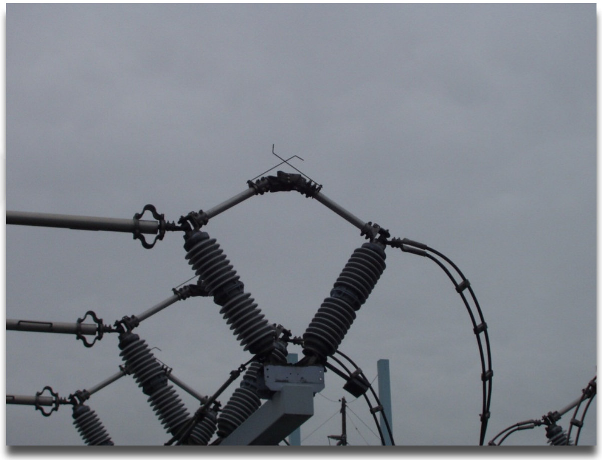
Switchgear

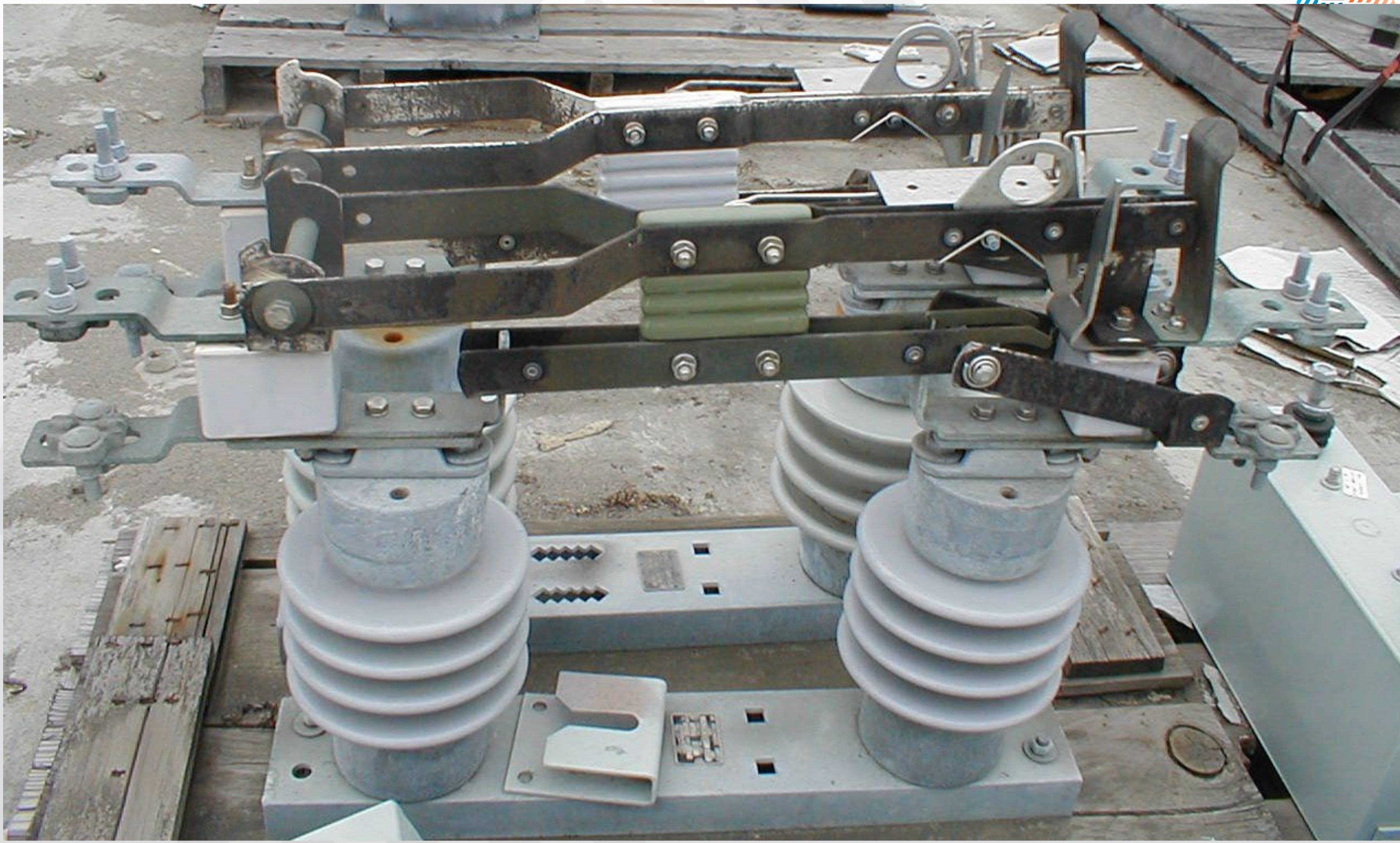
Distinguish:

Switches vs Protective Devices

protective devices

- fuses
- circuit breakers
- reclosers





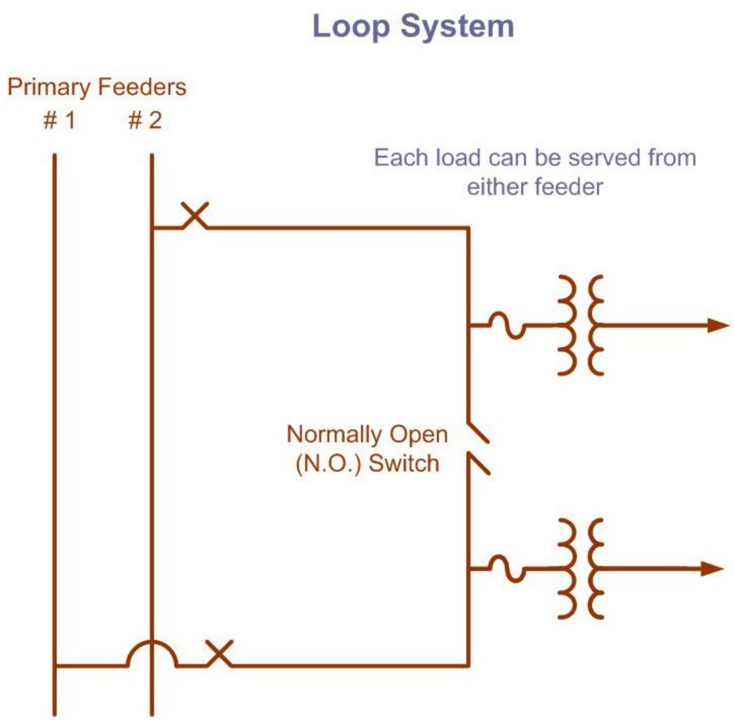
Knife Switch

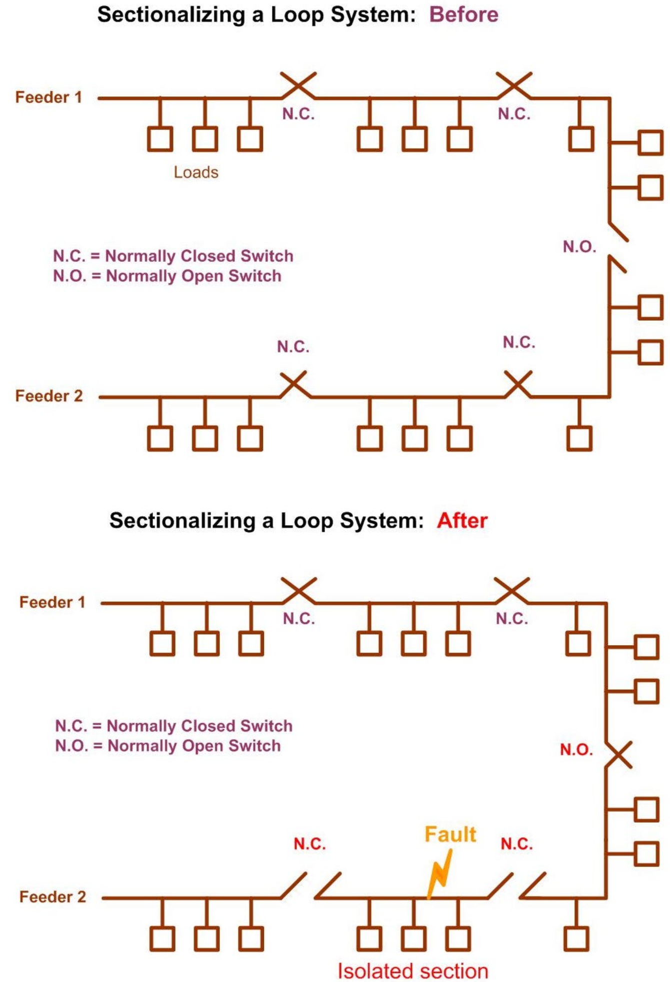
GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

Distribution System Switches

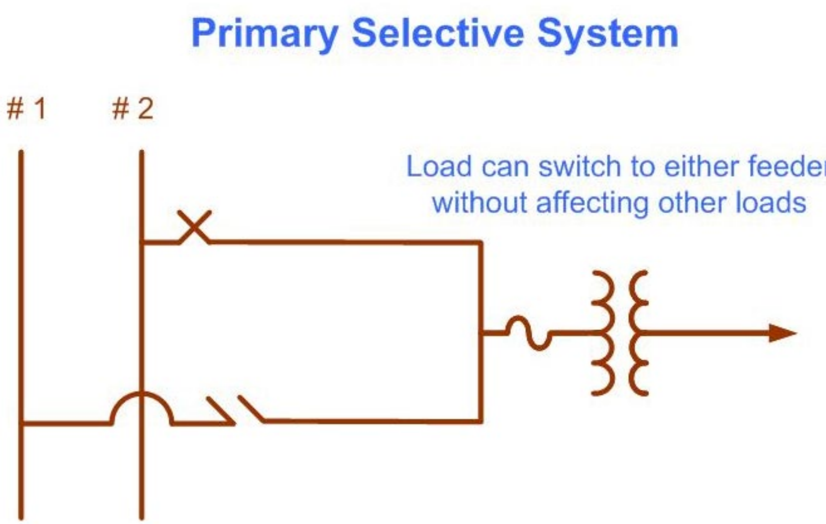
- The primary function of a switch is to provide electrical isolation.
- Switches are not protective devices, unlike breakers they cannot interrupt current.
- Switches at a substation can transfer load between substation transformers.
- At the distribution level switches are used to reconfigure a feeder.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

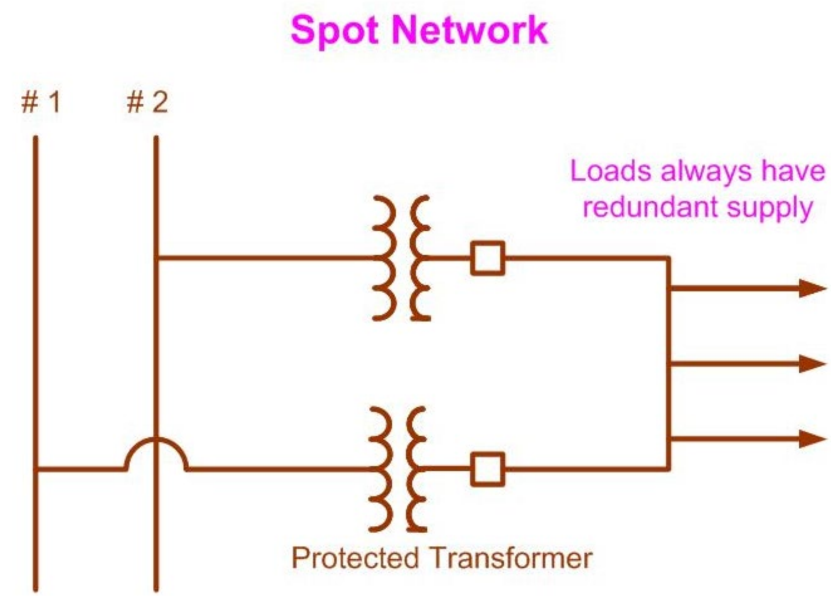
Distribution configurations





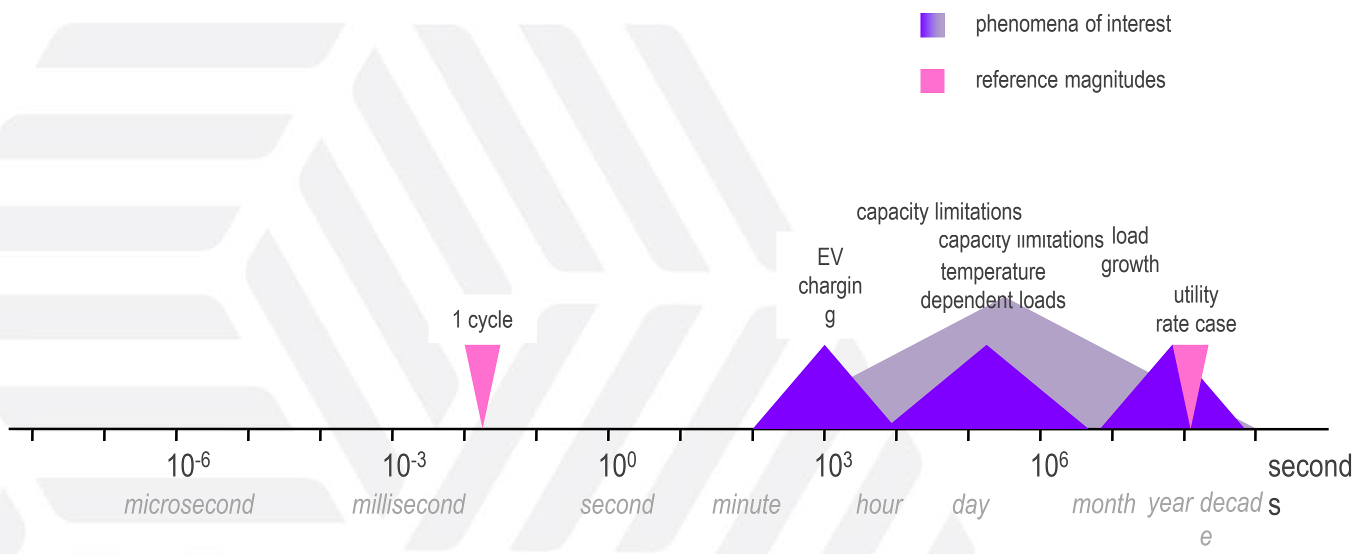
Distribution Configurations

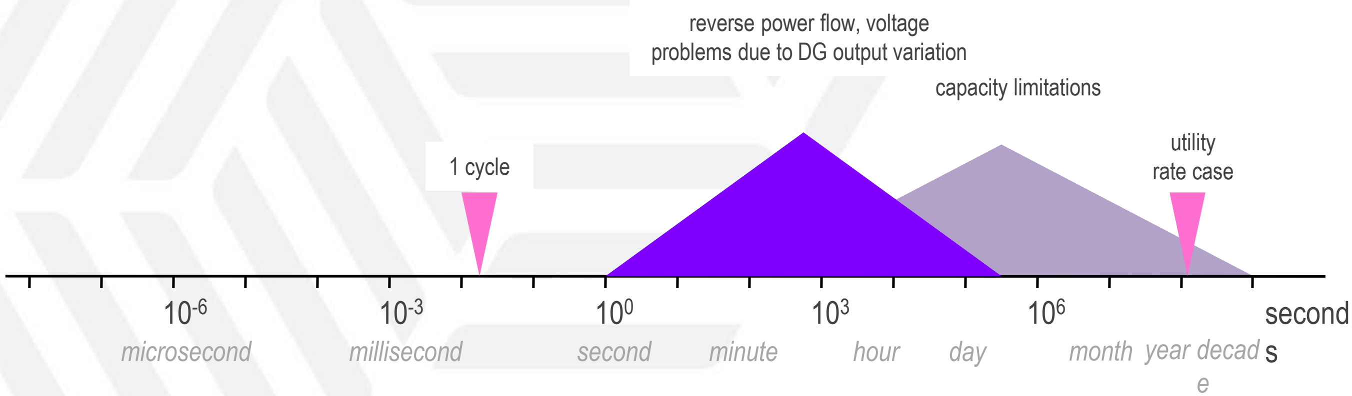




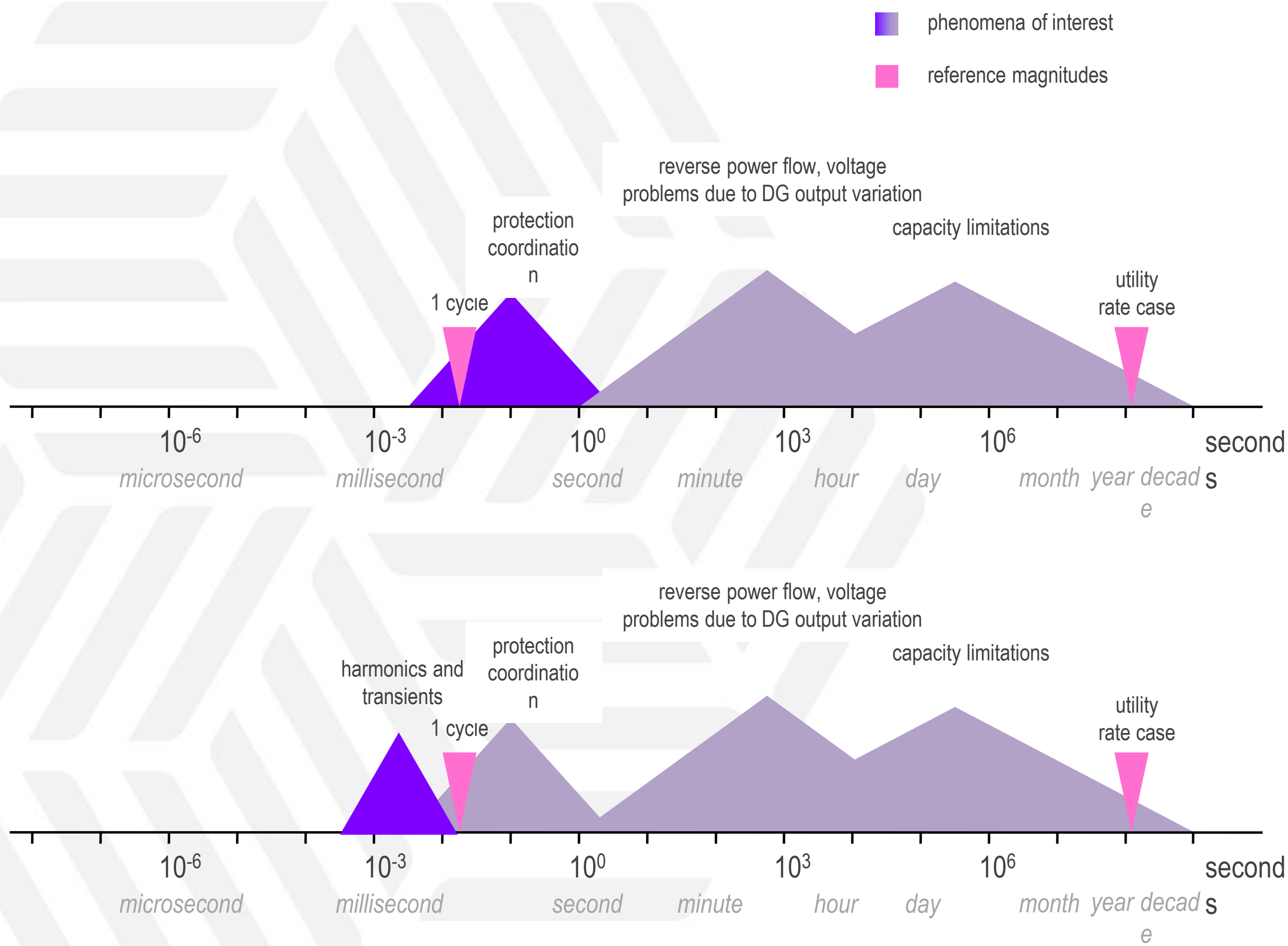
Spot networks are much more expensive and used only in high-stakes settings such as downtown business districts of big cities

Distribution System Issues on Different Time Scale

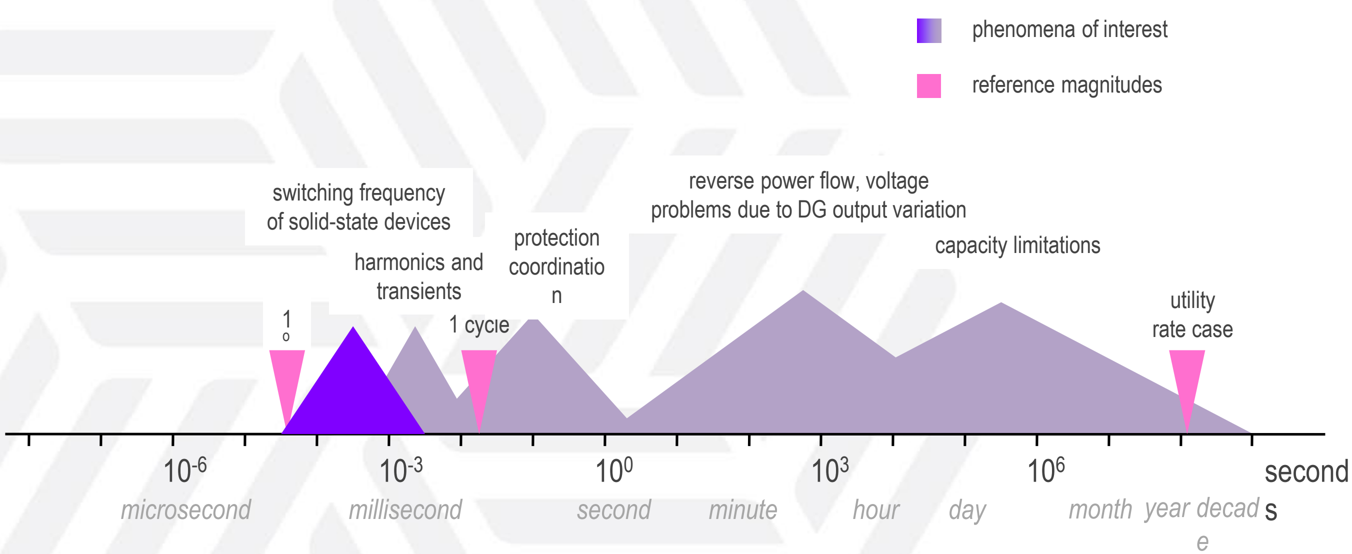




Distribution System Issues on Different Time Scale

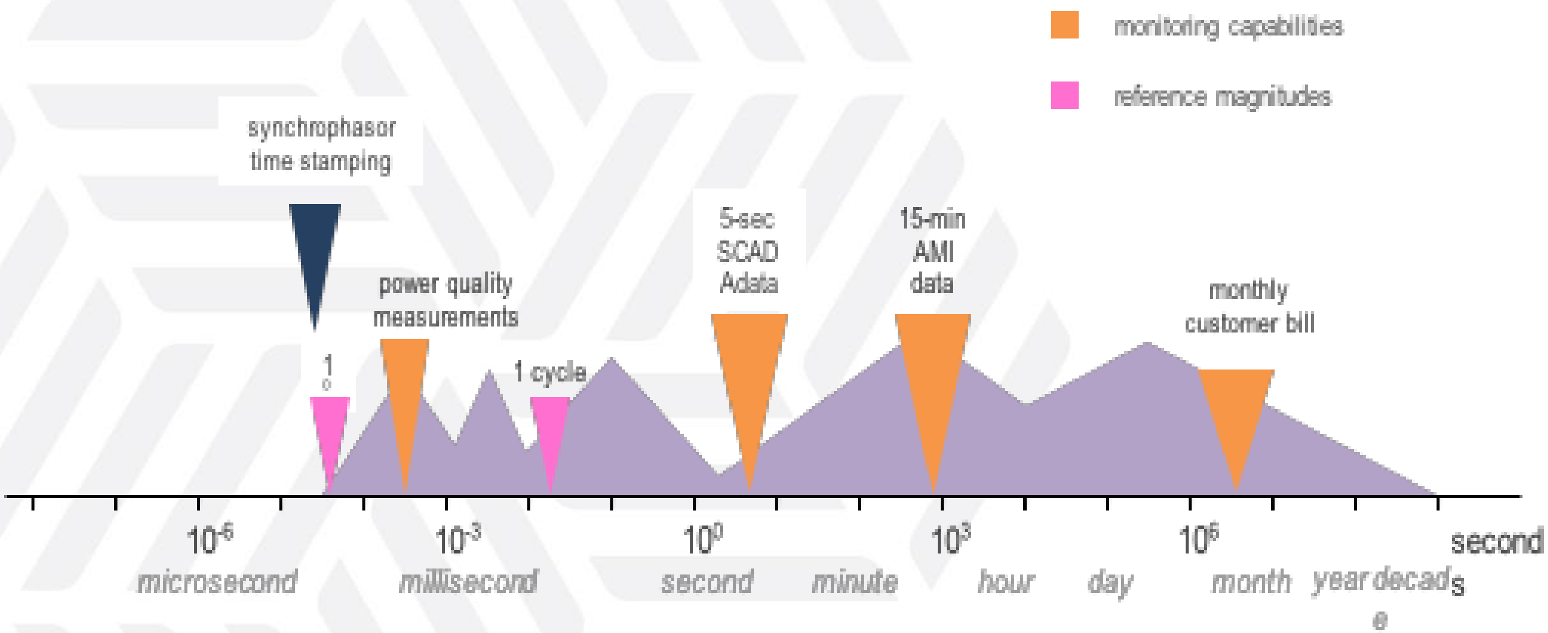


Distribution System Issues on Different Time Scale



Monitoring capabilities on different time scales

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



Smart Meters

Primary purpose: Settlement
(time-differentiated meter reading)

Secondary purpose:
identify outages
other operations support

Typical activity:

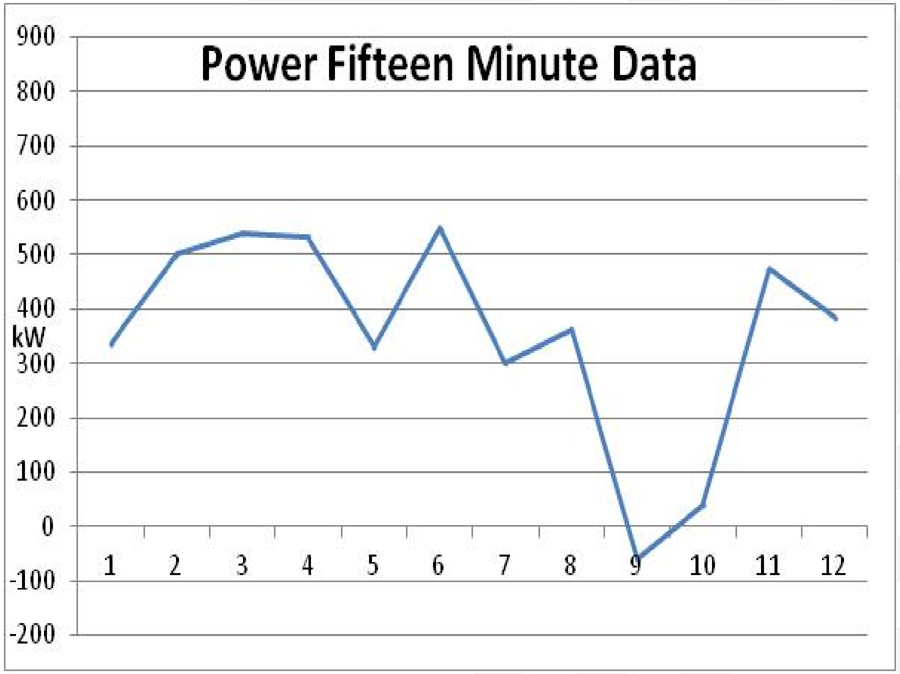
- record kWh usage, voltage at 15-min intervals
- report 8 hrs worth of 15-min kWh data to access point 3x per day
- send "death chirp" in case of outage
- Headroom on communications network allows querying subset of meters for some additional data, reported within minutes
- Automated Meter Reading (AMR): one-way communication
- Advanced Metering Infrastructure (AMI): two-way communication

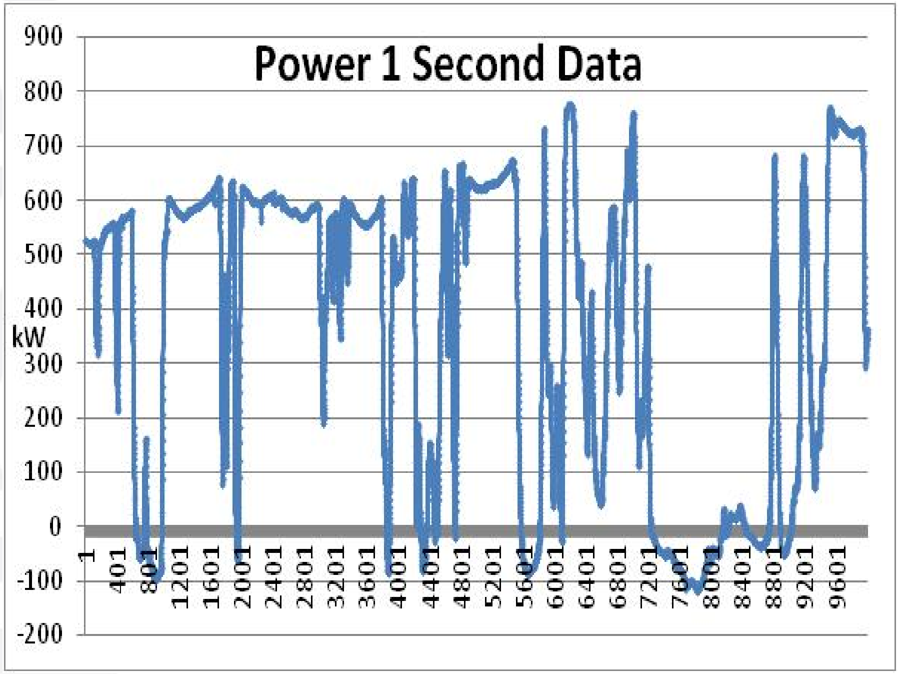
Present State in Normal Deployment
- not enough resolution to observe short-term power variations
- typically do not report voltage (although it is sensed)
- data may not be provided in real-time
- data may be provided only to billing department, not operations
- most likely early operational application: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





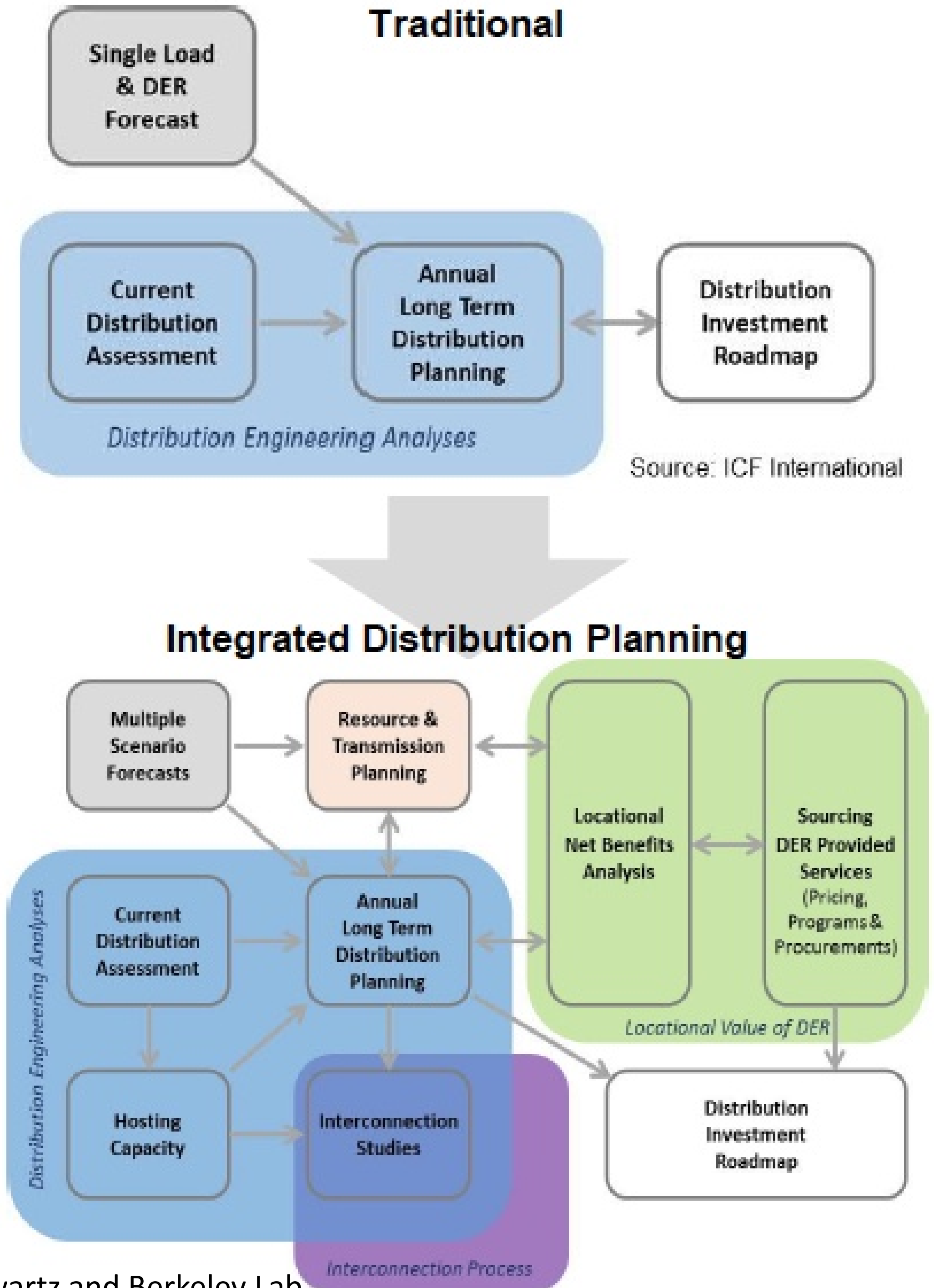
Questions about distribution systems?

Distribution System Planning - Context

- Distribution planning has traditionally been focused on maintaining:
  - Safety
  - Reliability
  - At reasonable cost
- At the core distribution planning supports investment decisions
- As the grid and resource mix are changing, distribution systems are changing and distribution planning is changing
  - In many places, a lot of new gen is connected to the distribution system
  - Distribution system has least amount of utility visibility/control
- In some states, more detailed distribution plans are being required :
  - Hosting capacity
  - Locational benefits and non-wires alternatives
- New skill sets may be required as well as coordination across entities within the utility

Planning enhancements: "Integrated distribution planning"

- Develop multiple scenarios to address uncertainty in customer loads and DER growth and types
- Identify distribution hosting capacity
- Identify potential to use services from DER providers and the grid investments required to enable these services
- Evaluate alternatives to grid upgrades (e.g., for load relief)
- Engage stakeholders
- Coordinate distribution planning with other processes



[DOE's Modern Distribution Grid initiative](#)
I. Customer and State Policy Driven Functionality
II. Advanced Technology Market Assessment
III. Decision Guide

Slide from Lisa Schwartz and Berkeley Lab

Electric Distribution System Planning – An Overview

Electric Distribution Planning is a key utility strategy/function that is used to forecast changes on the grid and modify the system accordingly, all with a focus on;

Safety

- Design and maintain an electric system that does not place the general public nor utility workers at risk

Reliability

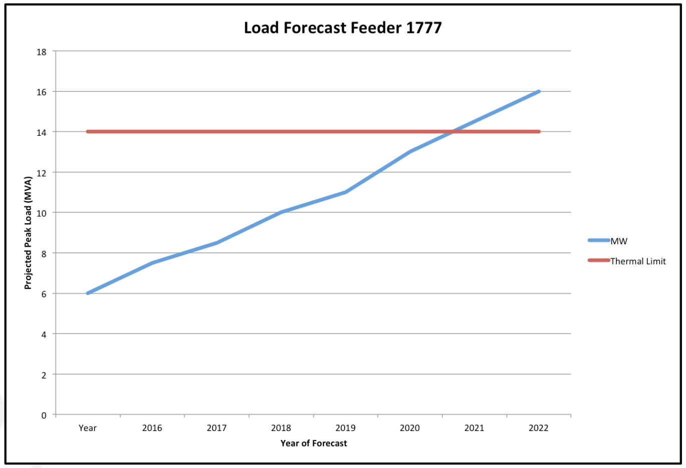
- Provide the power that the consumers need
- Maintain power quality
  - Maintain stable voltage at point of delivery
  - Support a stable frequency
- Reduce number of outages
  - Frequency (SAIFI) and Duration (SAIDI/CAIDI) are tracked

Cost

- Supply power and energy at a fair and acceptable price

Traditional Areas of Focus for Larger Utilities**

Load Forecasting



- Track peak loads (using SCADA data)
- Publish annual long-range forecast
- Evaluate each distribution feeder for annual growth, new loads
- Feeder load forecasts aggregate to show substation status, need for expansion
- Substations may require upgraded transformers, new transformer banks, transmission, distribution equipment
- System Planning (transmission) use this to plan line upgrades (new lines, larger lines, higher voltages)
- Substation departments evaluate the need for larger transformers or additional transformer banks

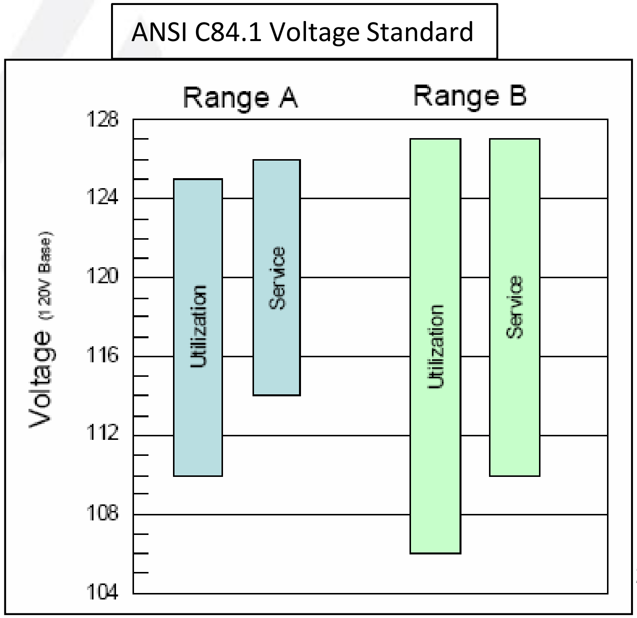
** Larger utilities often have groups of engineers that focus entirely on distribution planning functions

Traditional Areas of Focus for Larger Utilities - Continued

- Reliability (SAIDI, SAIFI)
  - Feeder-Level protection
  - Under Frequency Load Shedding (UFLS) schedules
  - PUC/customer complaint resolution
- Power quality support
- Voltage support (ANSI C84.1)
  - Capacitor placement
  - Voltage regulator placement
- Evaluation of “special projects” such as large DER systems
- Large distribution project design

- These traditional functions remain, while new challenges and opportunities are emerging

Image: NREL Pix 03207



Question:

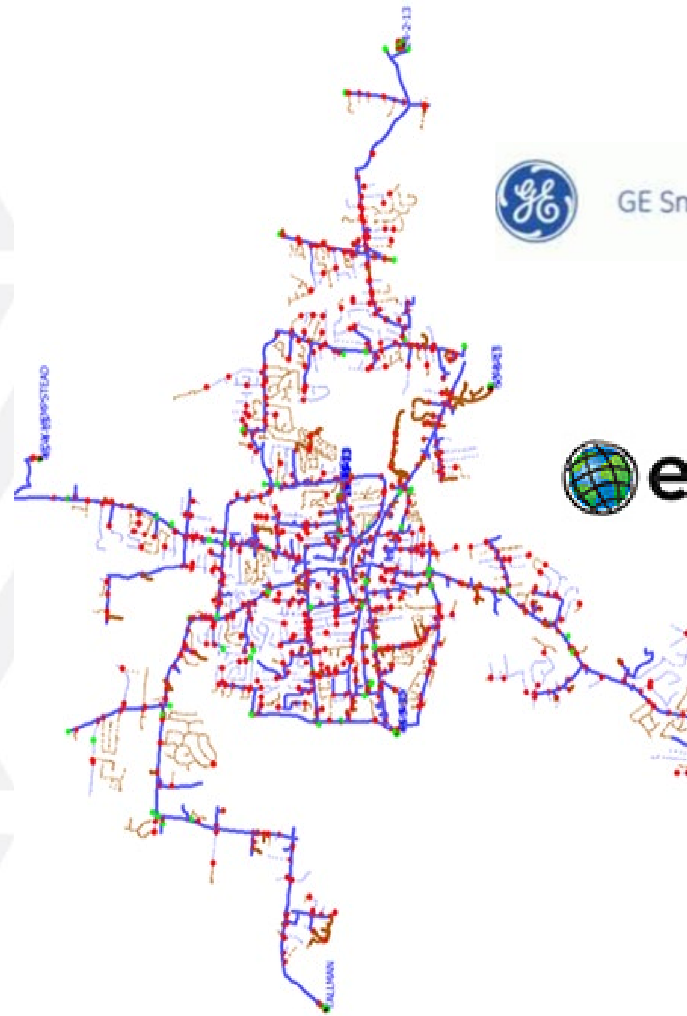
How do utility engineers plan their system changes and upgrades?

Answer:

Sophisticated computerized tools are often utilized by utility engineers, but there are many types of tools available.

The Foundation for Computer Models - GIS

- Most utilities have a Geospatial Information System (GIS) in place, where they track their distribution lines, transformers, customers, substations, and sometimes the DER (like PV) systems.
- GIS departments only update GIS systems to track any system changes
- Modeling platform users “Extract” the GIS data and then run the model
- Thus, it is critical to have a high-quality GIS system which is accurate



GE Smallworld

esri

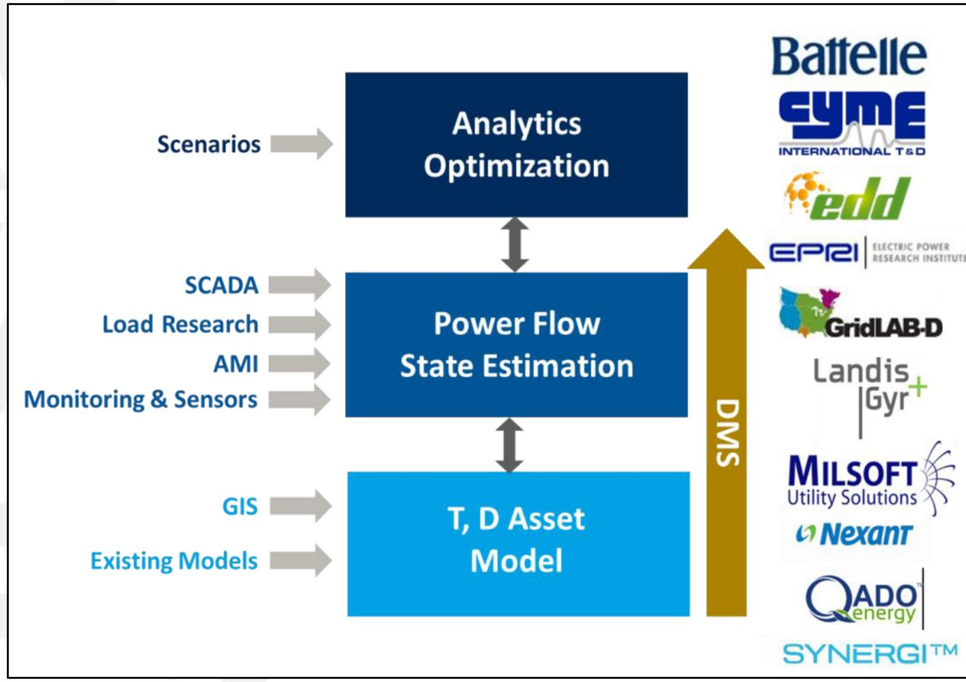
Distribution Modeling Tools - Observations

Larger utilities typically use the following (with exceptions):

- ☐ CYMDIST (power flow)
- ☐ Synergi (power flow)
- ☐ ASPEN (protection)
- ☐ DEW (power flow)
- ☐ Others….

Small-Medium utilities typically use

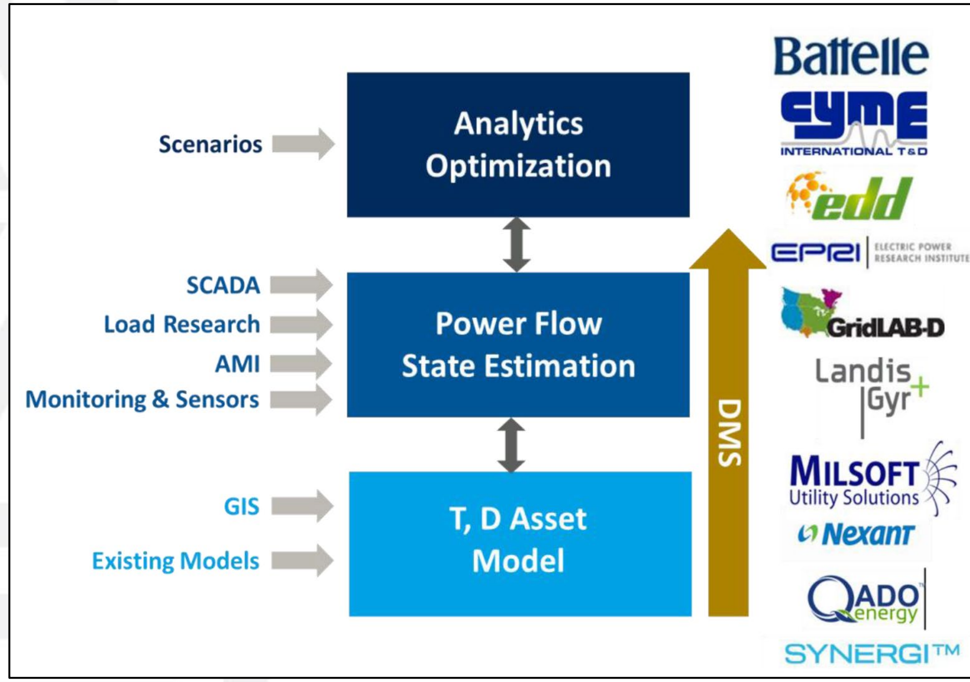
- ☐ Milsoft Windmil (power flow)
- ☐ Milsoft Light Table (protection)
- ☐ Others….
- ☐ Consultants



Modeling software is generally a large investment, as is trained staff, thus utilities are quite hesitant to change platforms!

Larger utilities have teams of model experts, while smaller utilities rely on institutional knowledge or third parties

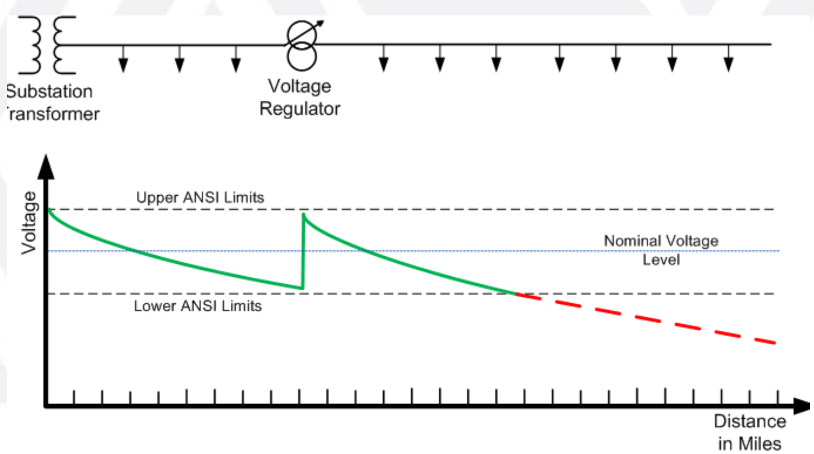
- Typically Used Tools
  - CymDist
  - Milsoft Windmil
  - Synergi
  - ASPEN

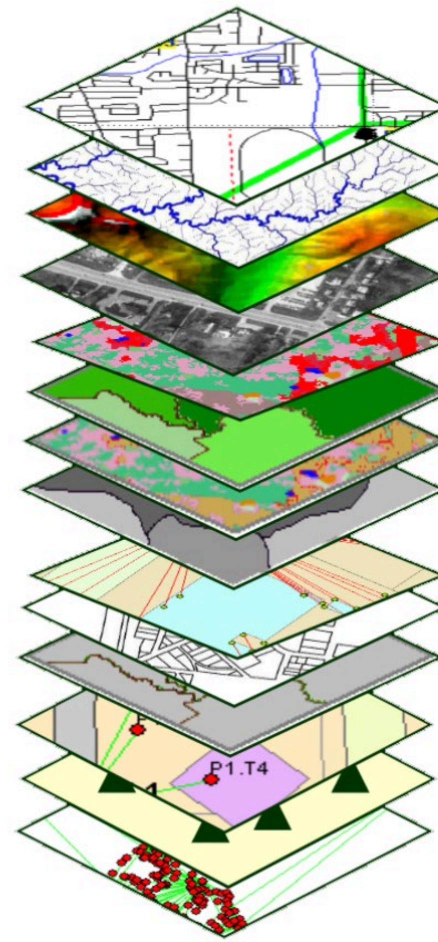


- Research Centric Tools
  - OpenDSS
  - GridLab-D

Utility Distribution Mapping & Modeling – Importance of getting the models right

- ► GIS mapping
- ► Power flow modeling platform
- ► Importance of updating and cleaning GIS models
- ► Updates and system accuracy
  - Phases
  - Secondary wires
  - Load points
  - DERs
- ► Modeling for protection





Source: EPRI GIS Interest Group

Advances in Electric Distribution System Planning (example PV analysis)

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

- Traditional planning studies have focused on:
  - Capacity planning
  - Cost
  - Safety

- Because of newer technologies being deployed at the distribution level, the planning process must change. Capacity is not the only factor to consider.

- As an example, the future deployment of small scale residential solar cannot be predicted, the planning process must take into account this uncertainty.

- 15 prototypical circuits were used to examine the larger parent population of SCE circuits.

- The following is an example process that was developed of Southern California Edison as part of California Solar Initiative #4.

Classes of Distribution Planning Tools

- Forecasting
  - DER forecasting
  - Load forecasting
- Power flow analysis
  - Peak Capacity Power Flow Study
  - Voltage drop study
  - Ampacity study
  - Contingency and restoration study
  - Reliability study
  - Load profile study
  - Stochastic power flow study
  - Volt/Var study
  - Real-time performance study
  - Time series power flow analysis
- Power quality analysis
  - Voltage sag and swell study
  - Harmonics study
- Fault analysis
  - Arc flash hazard study
  - Protection coordination study
  - Fault location identification study
- Dynamic analysis
  - Long-term dynamics study
  - Electromechanical dynamics study
  - Electromagnetic transients study
- Advanced optimization

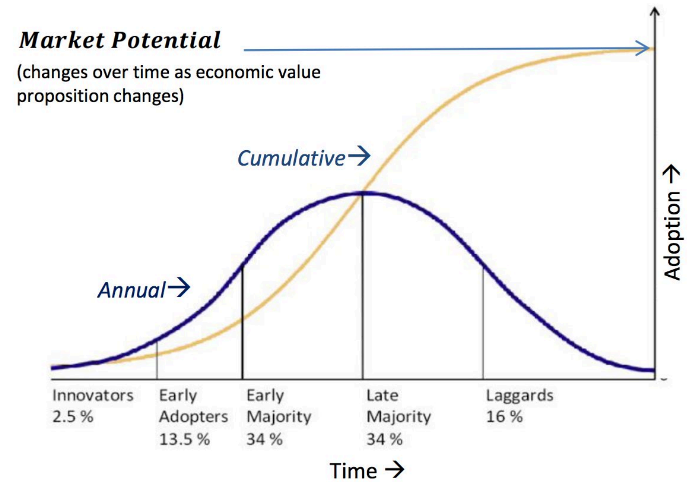
Load forecasting tools

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

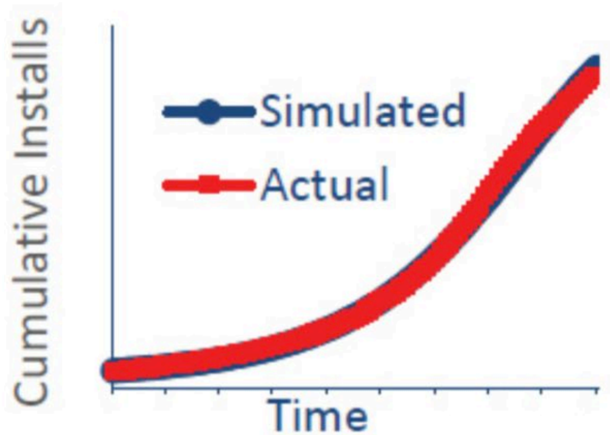
- Inputs to load forecasting tools
  - Weather, geographic, economic, demographic, DER and demand response data
- Forecasting DER growth requires
  - DER type, quantity, location, timing and other attributes
- Factors that that impact DER forecasting:
  - Historical adoption rates
  - Economic return for the customer
  - Available DER incentives
  - Procurement programs
- Output of load forecasting tools:
  - Load profiles across circuits, banks and subsections of the circuit
  - Necessary temporal and spatial granularity to considering impacts
- Inputs for DER forecasting:
  - Market information (e.g., fuel prices, existing electricity tariff)
  - Customer load information (hourly end use loads), and
  - DER technology information (e.g. capital costs, operating and maintenance costs, performance data
  - Other customer decision factors

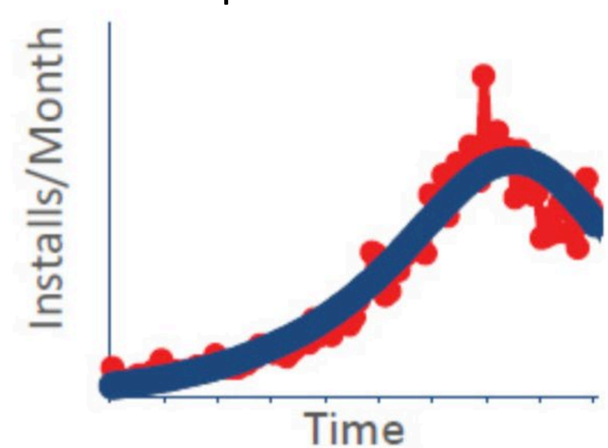
Load forecasting - Best practice method for PV

1. Identify adoption characteristics
2. Develop S-curve model based on adoption characteristics (e.g., by zip code)
3. Forecast adoption by zip code
4. Allocate DPV to zip codes proportional to zip code adoption forecast
5. Allocate DPV to circuits proportional to load or proportional to number of customers



SDG&E example of PV adoption model





Top: PG&E, DRP DER Growth Scenarios Workshop Distributed Generation, May 3, 2017
Bottom: Itron, Distribution Forecasting Working Group Final report June 28, 2018

Slide courtesy of Debbie Lew – GE Consulting

Determining Native PV Limits of a Circuit

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

► Step 1 -Define key metrics: What is, and what is not an operational limit that would prevent the deployment of additional solar. (utility dependent)

► Step 2 -Clear base case models of violations: Time-series models of representative circuits were developed and the base condition must be free of violations.

► Step 3 - Deploy Monte-Carlo PV adoption models: A socio-economic PV adoption model provides different "likely" future scenarios for each circuit.

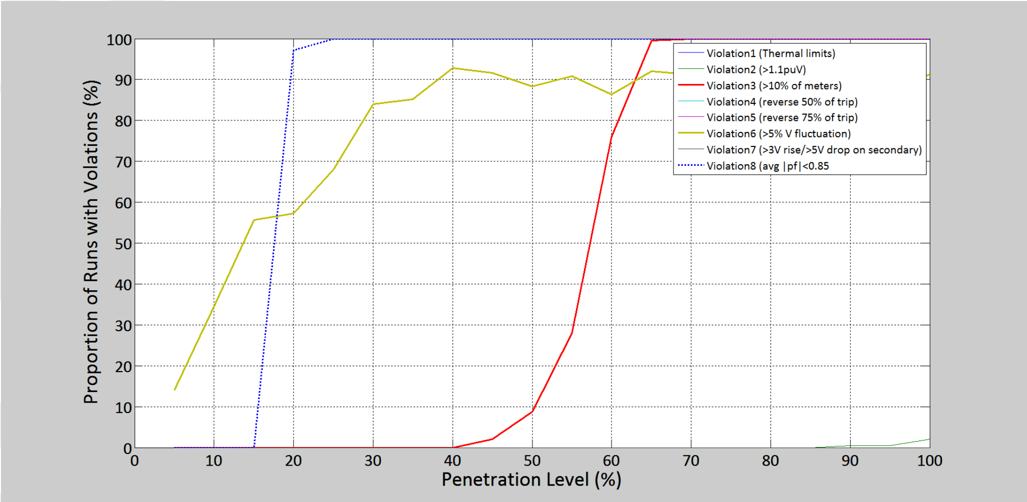
► Step 4 - Run simulations on various scenarios to determine the native PV limit for the circuit. In this case, 50 simulations were conducted at each penetration level.

Table 4.1 - Circuit Operational Limits and Thresholds For determining Native Limits

Violation #	Violation	Violation Description
1	Thermal Overloads	Limit: Exceeding any device thermal limit, 100% rating (200% for secondary service transformers)
2	High Instant Voltage	Limit: Any instantaneous voltage over 1.10 p.u. at any point in the system.
3	5 min ANSI Violation	Limit: ANSI C84.1: 0.95>V>1.05 p.u. for 5 minutes at >10% of meters in the system.
4	Moderate Reverse Power	Warning: Any reverse power that exceeds 50% of the minimum trip setting of the substation breaker or a recloser. (Requires analysis of protection coordination)
5	High Reverse Power	Limit: Any reverse power that exceeds 75% of the minimum trip setting of the substation breaker or a recloser.
6	Voltage Flicker	Limit: any voltage change at a PV point of common coupling that is greater than 5% between two one-minute simulation time-steps. (Adapted from the Voltage fluctuation design limits, May 1994)
7	Voltage Drop/Rise on Secondary	Limit: 3V drop or 5V rise across the secondary distribution system (Defined as the high side of the service transformer to the customer meter)
8	Low Average PF	Warning: Average circuit power factor <0.85 (Measured at substation)
9	Circuit Plan Loading Limit	Warning: Nameplate solar exceeds 10MVA for a 12 kV circuit, 13 MVA for a 16 kV circuit, or 32 MVA for a 33 kV circuit.
10	High Short Circuit Contribution	Warning: Total short circuit contribution from downstream generation not to exceed 87.5% of substation circuit breaker rating

Determining Native PV Limits of a Circuit (Hosting Capacity Determination)

- For each circuit, 4,000 time-series simulations are conducted.
  - At each penetration level there are 50 simulations conducted
  - Penetration levels at 5% are examined
  - Each simulation is a different adoption scenario of solar
- The results of these simulations are distilled into a single plot for each circuit. Example shown at the right.
- The plot can then be used to determine the native limit, and to identify what the limiting factors are.
- The plot forms a basis to determine how to support higher penetration levels of PV, and which technologies might enable this.



Determining Native PV Limits of a Circuit (Mitigation for PV Limits)

- Each of the native limits can be avoided through circuit upgrades.
- Traditional methods:
  - Adjustment of existing voltage regulators
  - Installation of voltage regulators
  - Adjustment of existing capacitors
  - Reconductoring secondary segment
  - Reconductoring primary segment
- Advanced technologies
  - Fixed pf PV inverters
  - Advanced inverter control (CES Rule 21)
  - Centralized battery storage
  - Behind the meter battery storage
- The simulation provide the basis for selecting the best mitigating technologies, but there are many

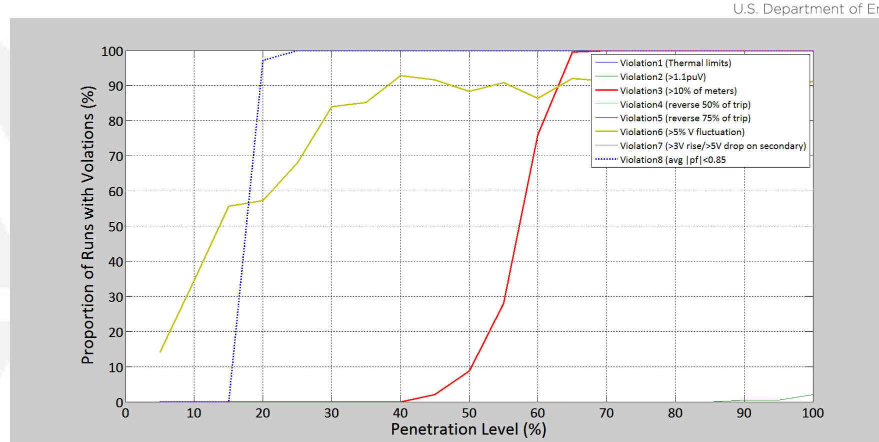


Table 5.1 - Summary of Mitigation Types and Strategies

Traditional Upgrade Strategies		Non-Traditional Mitigation Strategies	
T1	Adjustment of existing shunt capacitor set points	NT1	Fixed power factor on solar inverters
T2	Removal of existing shunt capacitors	NT2	Advanced Controls on PV Inverters
T3	Addition of shunt capacitors	NT3	Centratlized Energy Storage (utiltity)
T4	Installation of voltage regulators (regulating their output voltage magnitude)	NT4	Commercial Behind Meter Energy Storage
T5	Reconductoring of a primary line/cable segment		
T6	Reconductoring of a secondary line/cable segment		
T7	Upgrade of secondary service transformer		

Determining Native PV Limits of a Circuit (Key Lessons Learned)

- Most SCE circuits could support 100% penetration of PV once the proper mitigation strategies have been applied.
- Nearly 50% of SCE circuits can host less than 50% PV, where approx. 40% can host less than 25% PV
- Determining how to achieve 100% penetration on legacy circuits can be challenging, with a mitigation leading to new violations. (domino effect)
- The most common violations experienced were power factor and voltage based.
- Proper sizing of secondary drops when new solar is installed is essential.

Summary of practices at advanced utilities

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

- Performing detailed load and DER forecasts, by location
- Conducting hosting capacity studies for some or all feeders and making information publicly available via online maps
- Systematically considering non-wires alternatives (NWA) to traditional distribution system investments – developing NWA suitability criteria
- Investing in automation, communication and information technology improvements to provide greater visibility and flexibility and enable greater levels of DERs
- Looking at value components of DERs by location and incorporating into tariffs. Value components include:*
  - Energy
  - Capacity
  - Environmental
  - Demand reduction and system relief

* From New York REV Value Stack tariff

What are potential impacts to transmission?

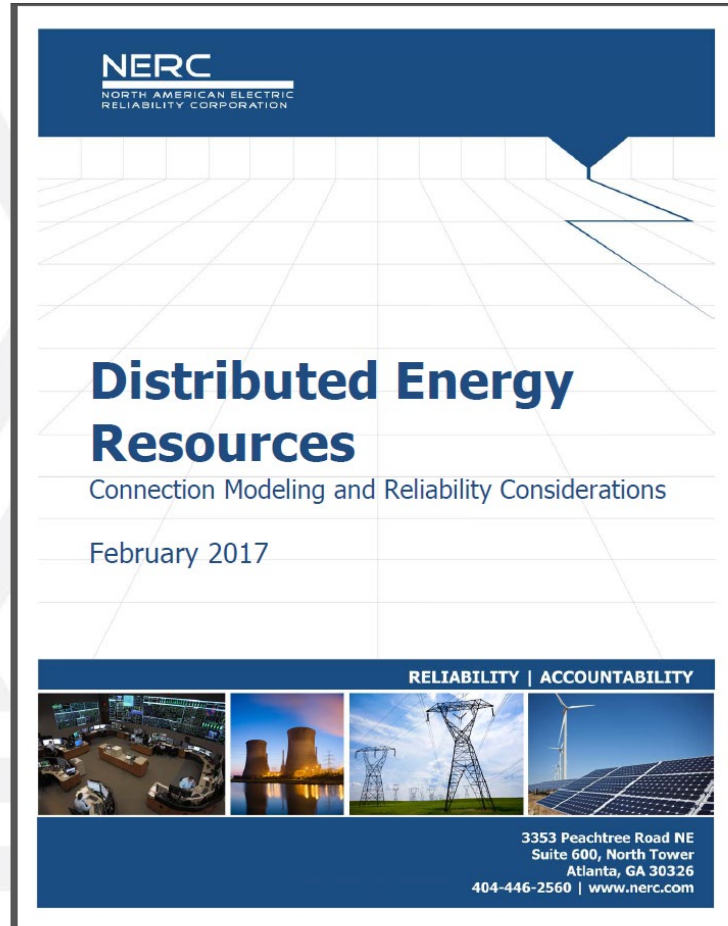
GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

- Distributed PV impacts on transmission include potential synchronized actions taken by DPV which result in a transmission operational or reliability impact:
- Examples:
  - Loss of generation impacts due to frequency tripping
  - Loss of generation impacts due to high/low voltage tripping
  - Ramping impacts in the morning and evening (PV)
  - …

Slide courtesy of Barry Mather from NREL

NERC DER Task Force

- Report released in February 2017 outlines potential impacts of DER on the bulk system reliability
- Recommends specific modeling methods and data requirements for DER
- Work of this group continues…



http://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/Distributed_Energy_Resources_Report.pdf

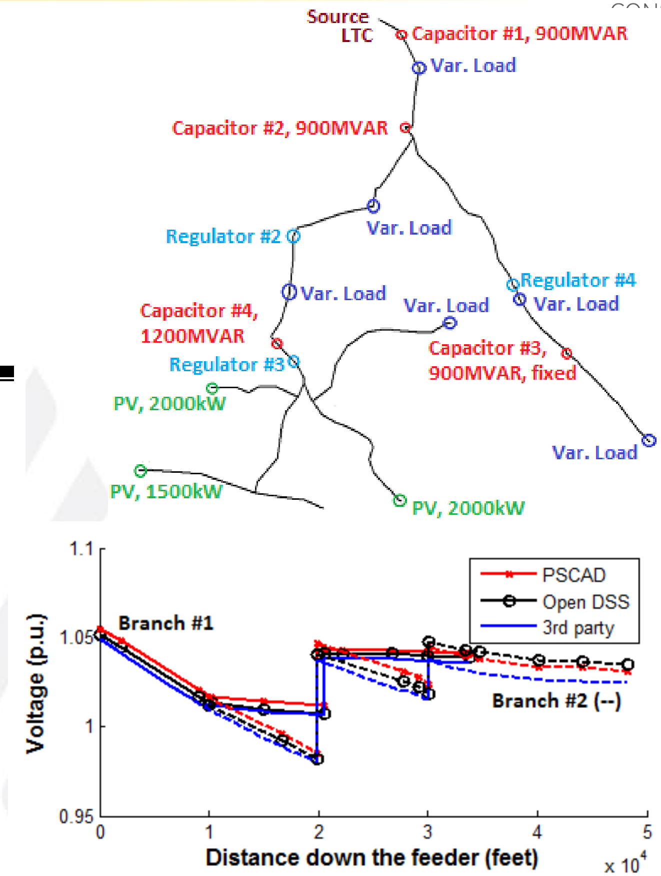
Slide courtesy of Barry Mather from NREL

What about the distribution part of the discussion? – voltage matters

- Most distribution-connected PV drops off-line at 0.88 pu

Voltage range (% voltage)	DG Operation
V < 88	disconnect
88 < V < 110	may operate
V > 110	disconnect

From: IEEE 1547:2003 – default voltage trip settings for DG (i.e. PV).

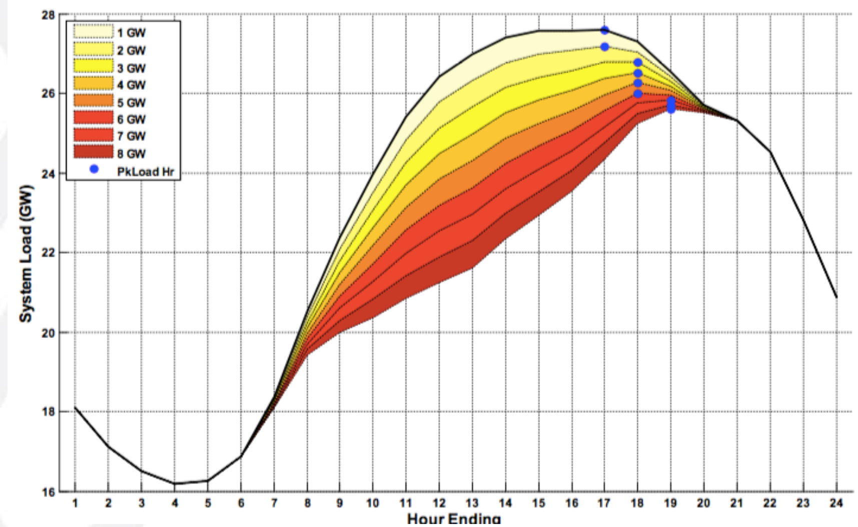


Voltage diversity on the distribution system will impact DERs voltage-related response

Slide courtesy of Barry Mather from NREL

Load profiles/shapes are important

- ► Traditional generation offered fixed capability at all times
  - Resource adequacy could be determined by peak
- ► However, DERs may offer variable output
  - Resource adequacy needs to be based on hourly profile for peak day
- ► "Peak" is moving because of a changing grid
  - As we move to time-varying rates, as solar penetrations increase, as EVs proliferate, it becomes harder to predict when peak will be
- ► System peak may be different from circuit peak



Graphic: W. Henson, ISONE, 2016

Slide courtesy of Debbie Lew – GE Consulting

Summary

- Basics of power and distribution systems
- Important equipment
- Distribution system planning
- Load forecasting
- Modeling tools
- Advances in distribution system planning
- Hosting capacity
- Voltage impacts

Questions and Discussion

Extra Slides

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

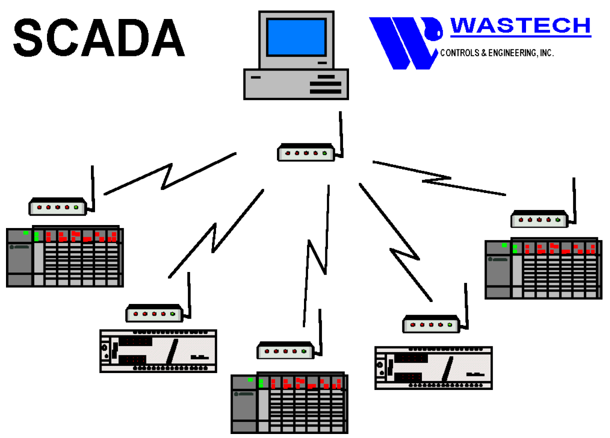
Programmable Logic Controllers (**PLCs**): similar to RTUs, more sophisticated controls

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

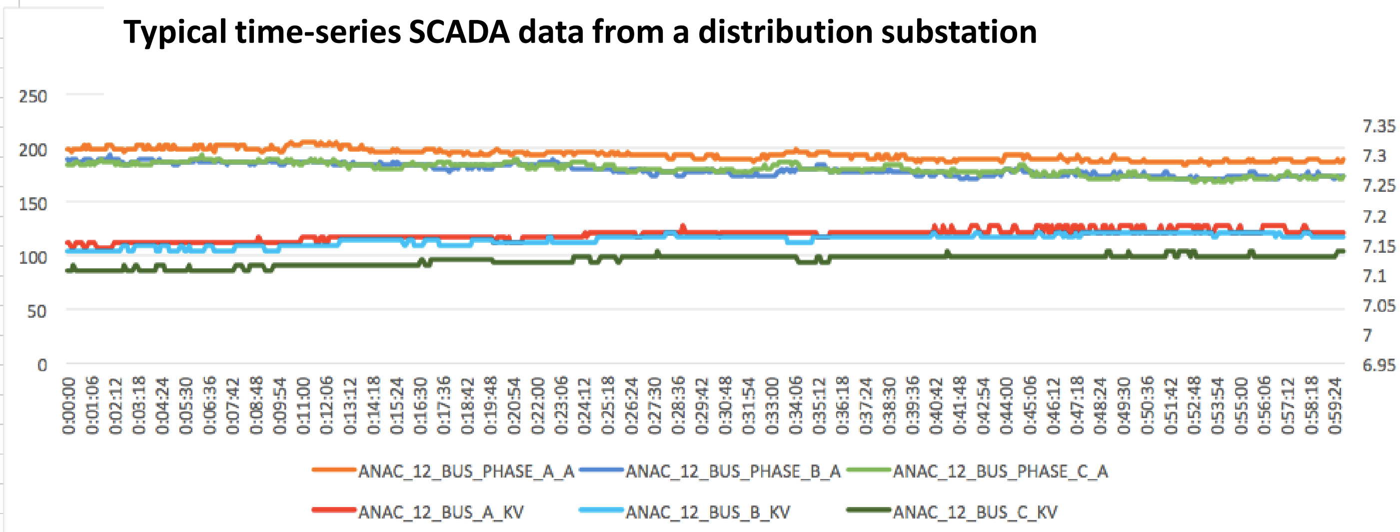
Data Acquisition Server: manages data from field devices

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

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

- 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 home area networks, thermostats and smart appliances

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

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

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

GRID MODERNIZATION LABORATORY CONSORTIUM
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."

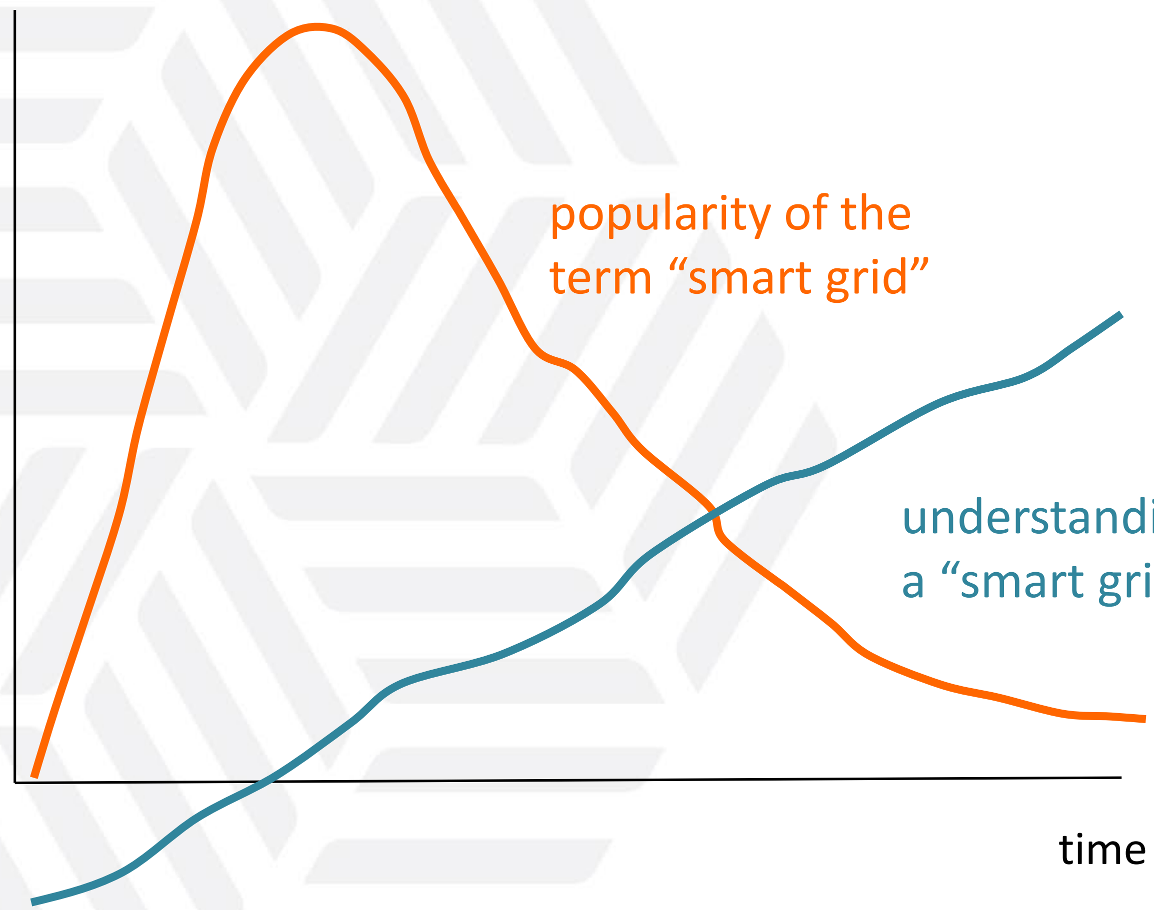
http://energy.gov/oe/technology-development/smart-grid

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

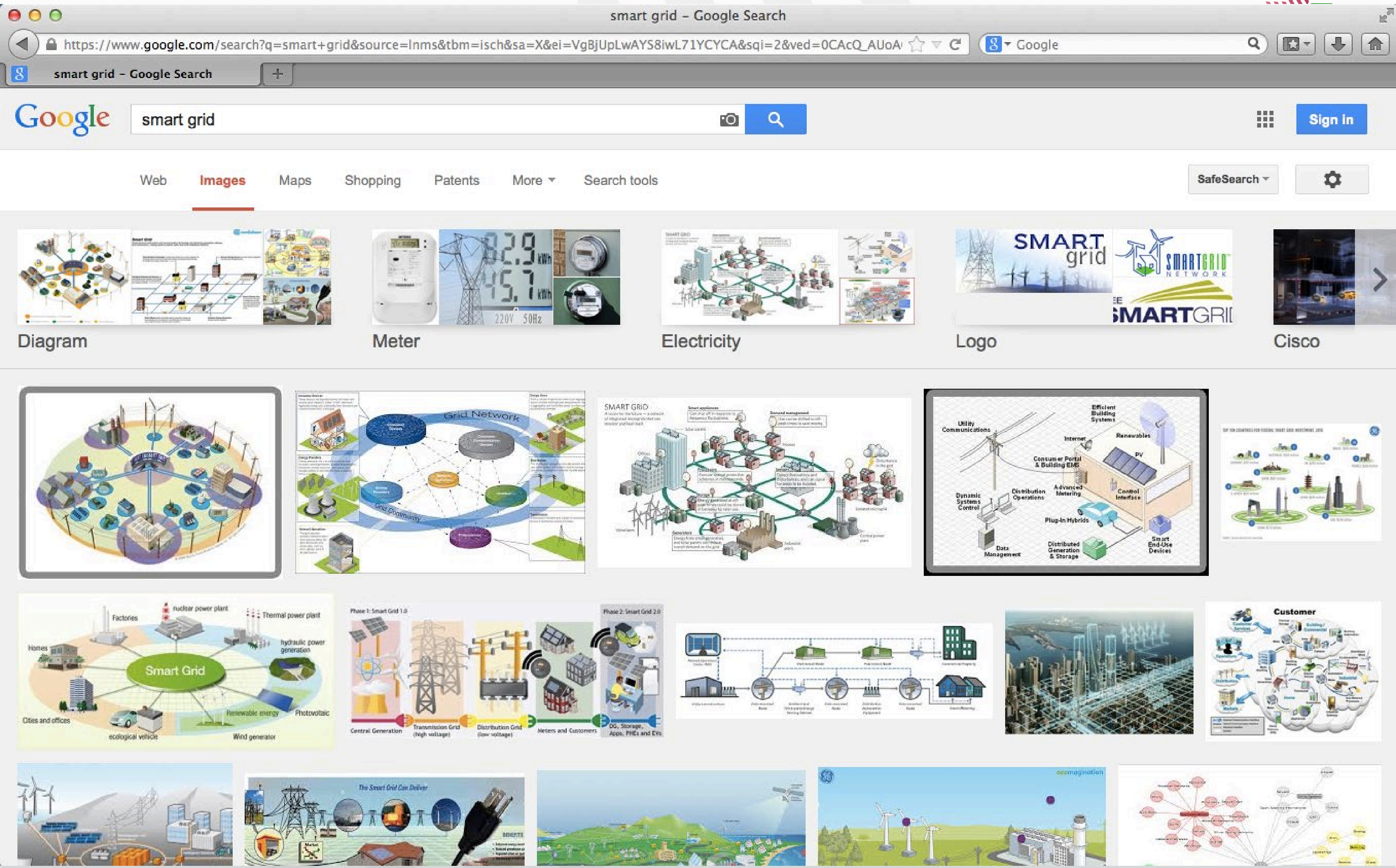
GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

- 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

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

- …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

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

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

- 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

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

FPL

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**

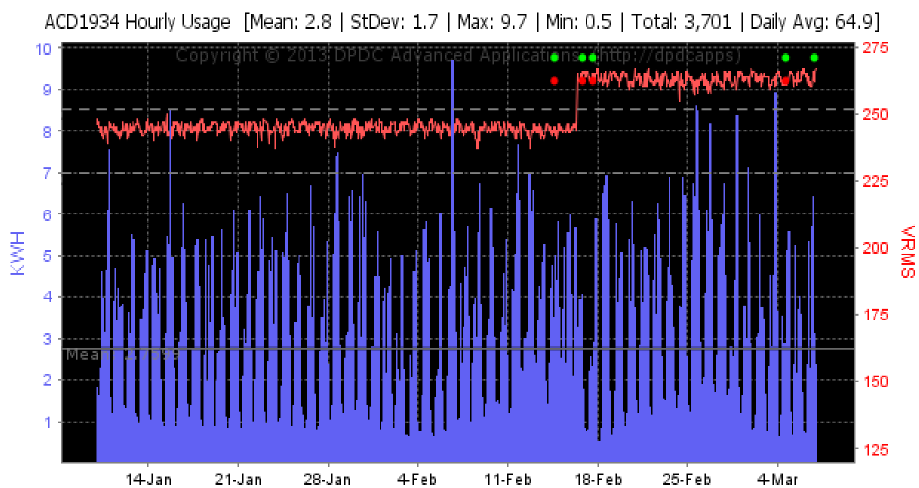
Premise	Meter	Transformer	Lateral	Feeder	Phase	Substation	Address
2114607	[ACD1934] G0205461934 - Ping	85233278401	85233317406	811361	A	ANHINGA	19755 SW 302ND ST HOMESTEAD,33030

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



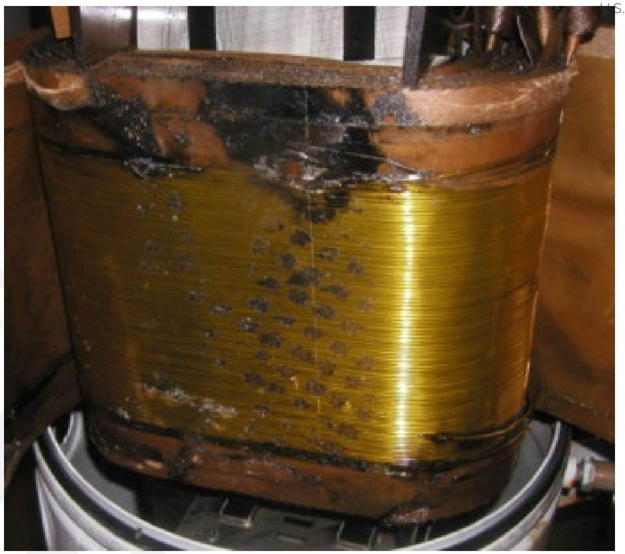
Smart meter voltage data can proactively identify transformers that need to be replaced

High-voltage Transformer Replacement Program

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

FPL

- 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

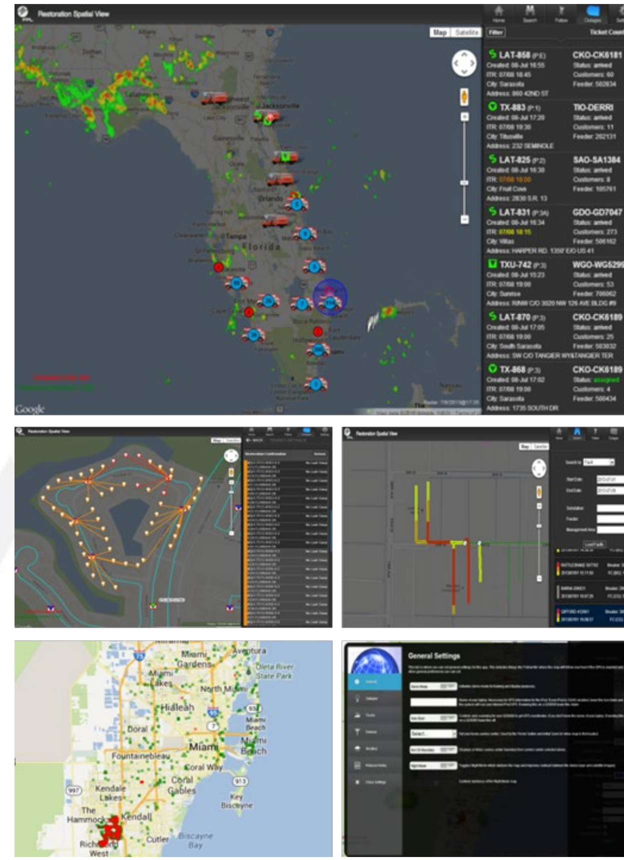
Using voltage information, FPL can proactively identify and replace transformers before they cause an outage

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

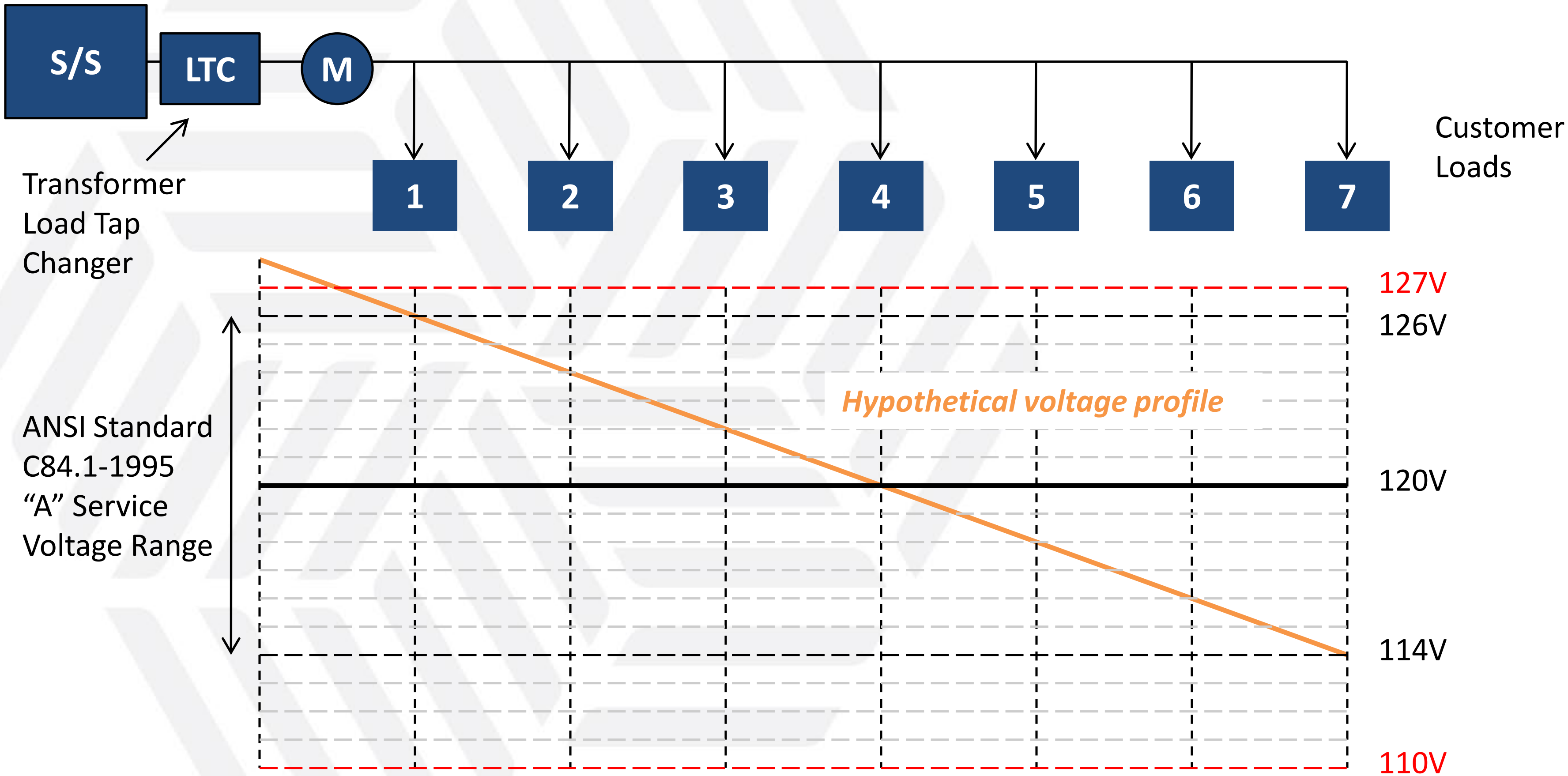
- DER
- ADMS
- Data & analytics
- Automation
- Modeling
- Communications

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/

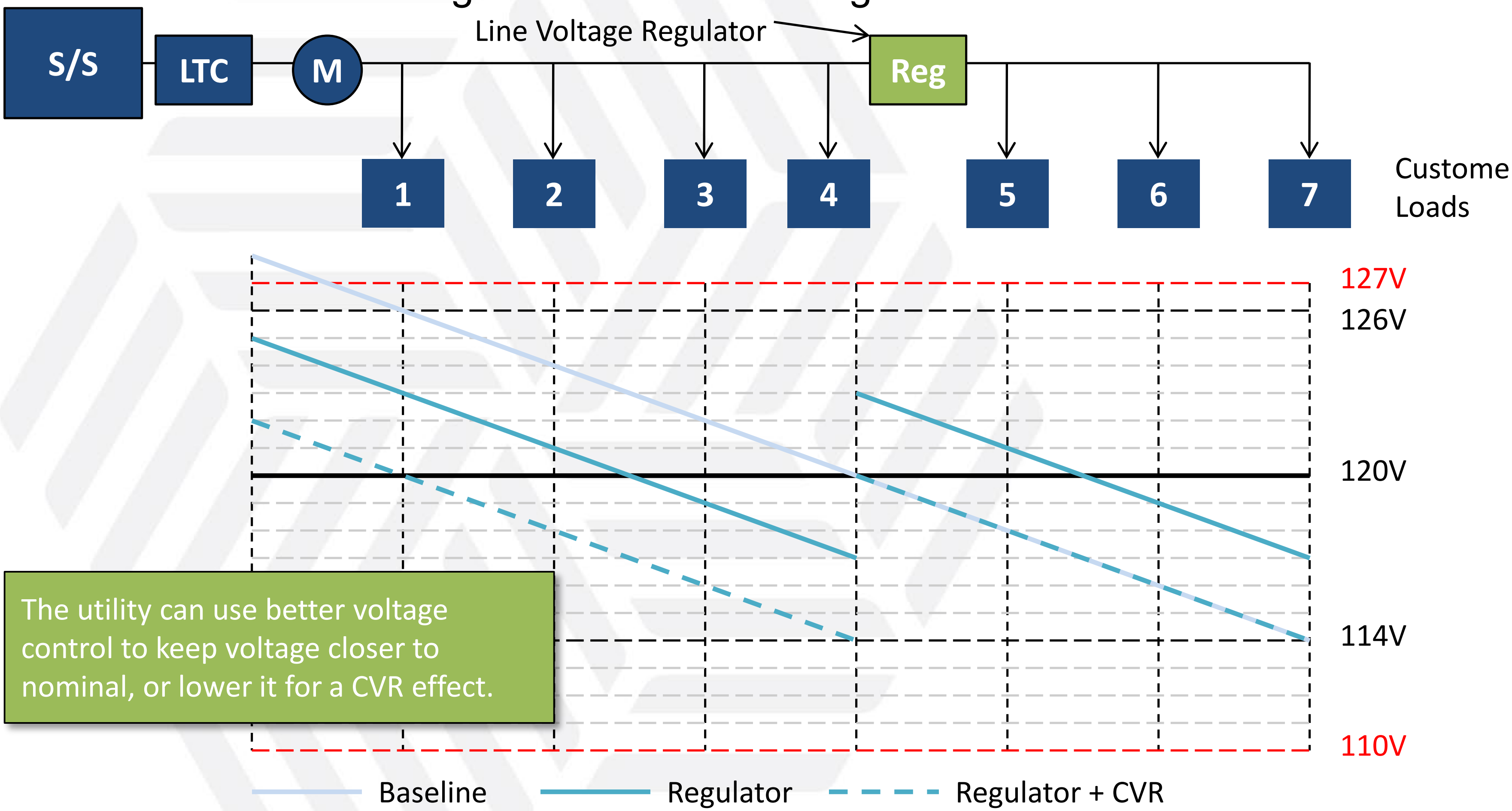
Voltage Profile

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



Voltage Optimization

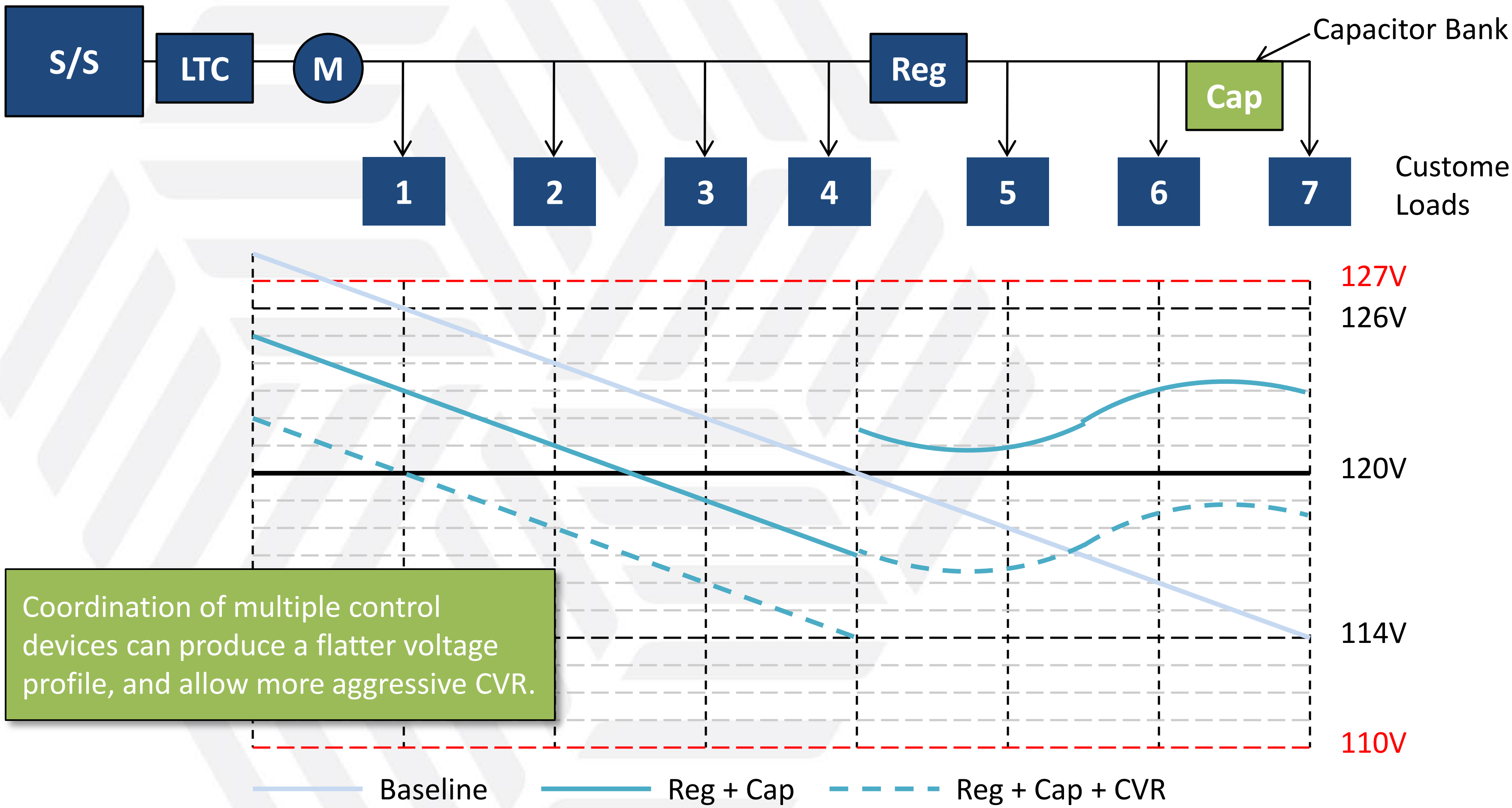
- A voltage regulator can boost (raise) or buck (lower) voltage at a point on the distribution line and regulate down-line voltage.



The utility can use better voltage control to keep voltage closer to nominal, or lower it for a CVR effect.

Coordinated LTC, Regulator and Capacitor Bank

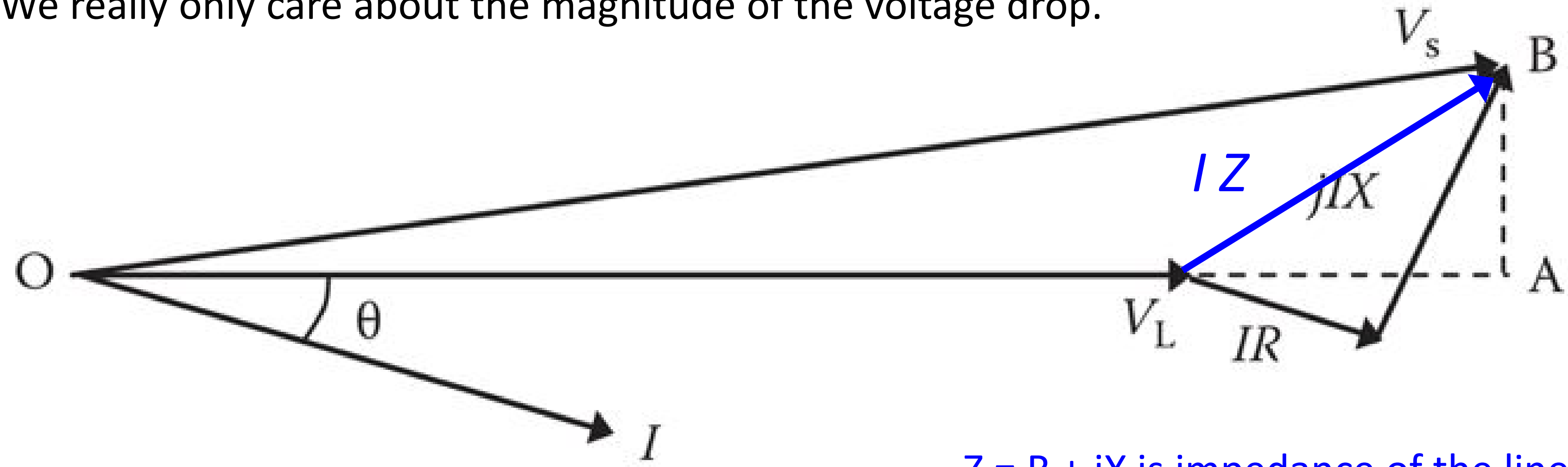
► A capacitor bank can help regulation by compensating for the lagging power factor of load and the line itself.



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

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

FPL

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