FREEDM SYSTEMS CENTER

Distributed Energy Resource (DER) Integration Challenges

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Where Were You in 2008?

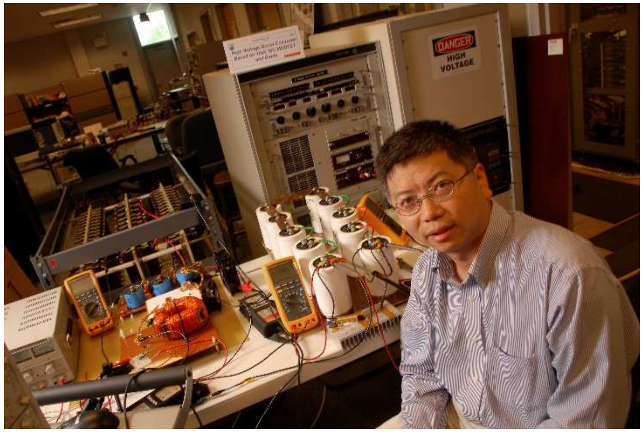
NSF Launches an Engineering Research Center for the Creation of a Green Energy Grid

The National Science Foundation (NSF) announces an award to North Carolina State University and its partners to establish a new NSF Engineering Research Center (ERC). The ERC will develop interdisciplinary research and education programs that address an important energy issue and provide the foundation for new industries through innovation. NSF will invest approximately $18.5 million in the Center over the next five years.

The **NSF ERC for Future Renewable Electric Energy Delivery and Management (FREEDM) Systems** will conduct research to transform the nation's power grid into an efficient network that integrates alternative energy generation and novel storage methods with existing power sources. This new, distributed network would permit any combination and scale of energy sources and storage devices through standard interface modules. The Center's overall goal is to facilitate the use of green energy sources, reduce the environmental impact of carbon emissions, and alleviate the growing energy crisis.

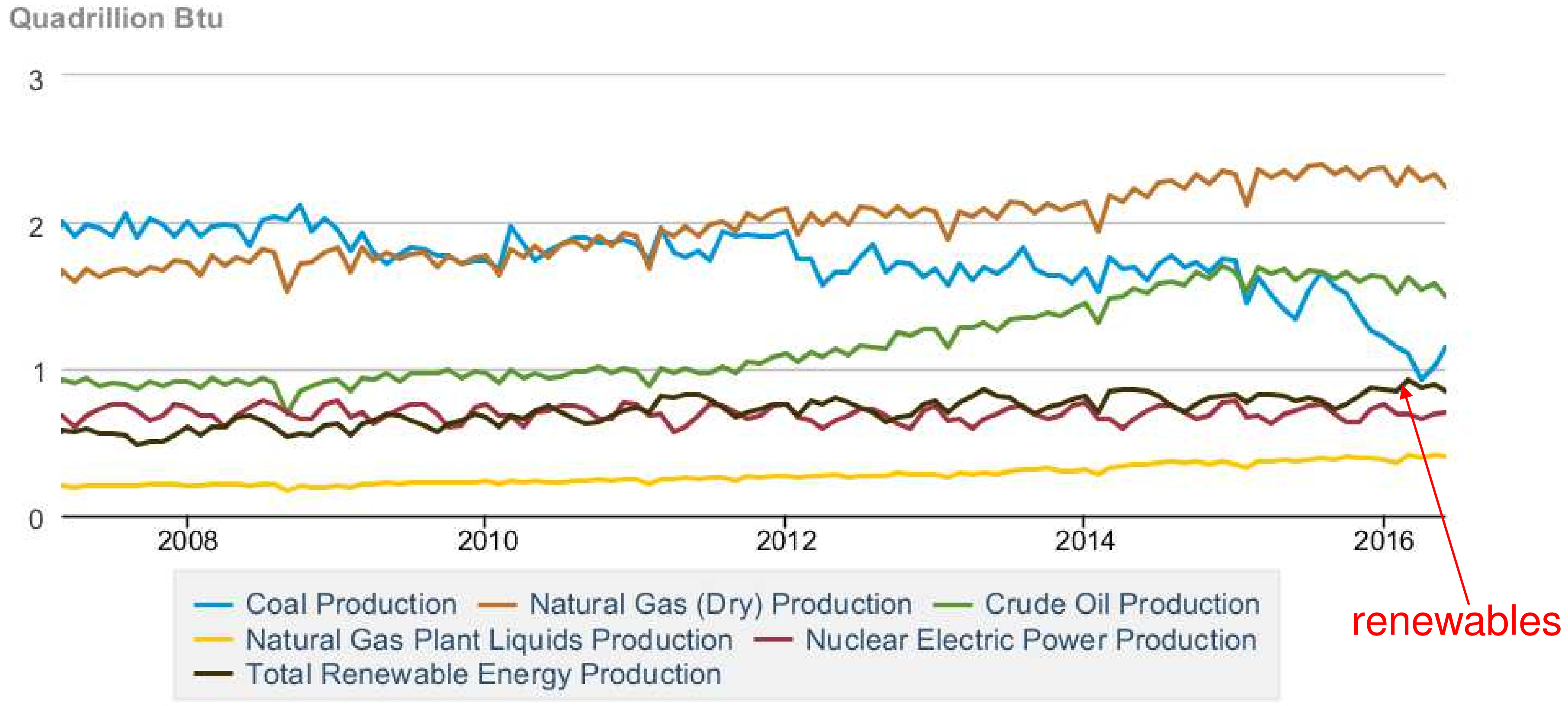
NSF FREEDM Press Release – Sept 8, 2008

https://www.nsf.gov/news/news_summ.jsp?cntn_id=112179



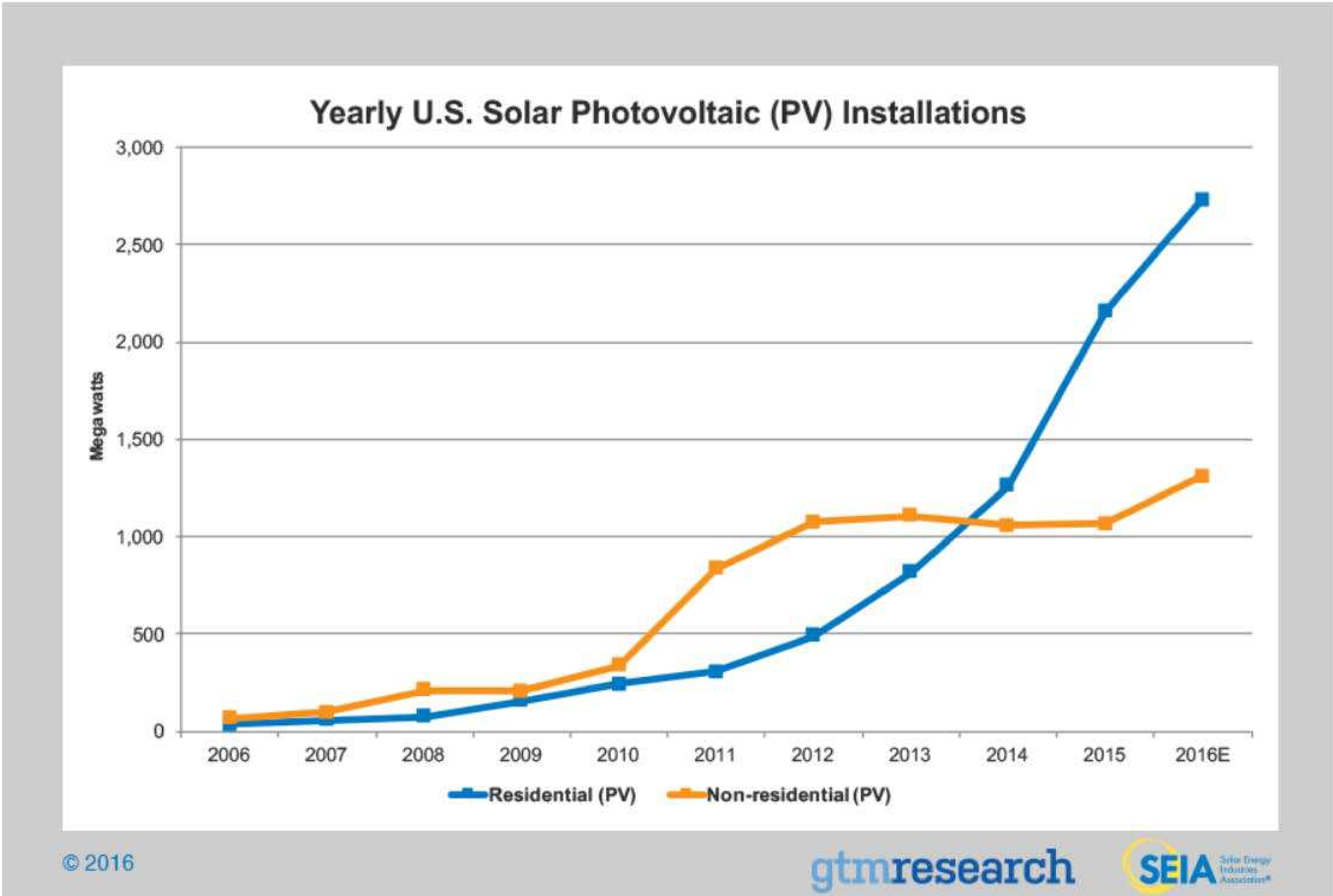
Primary Energy Production by Source

Table 1.2 Primary Energy Production by Source

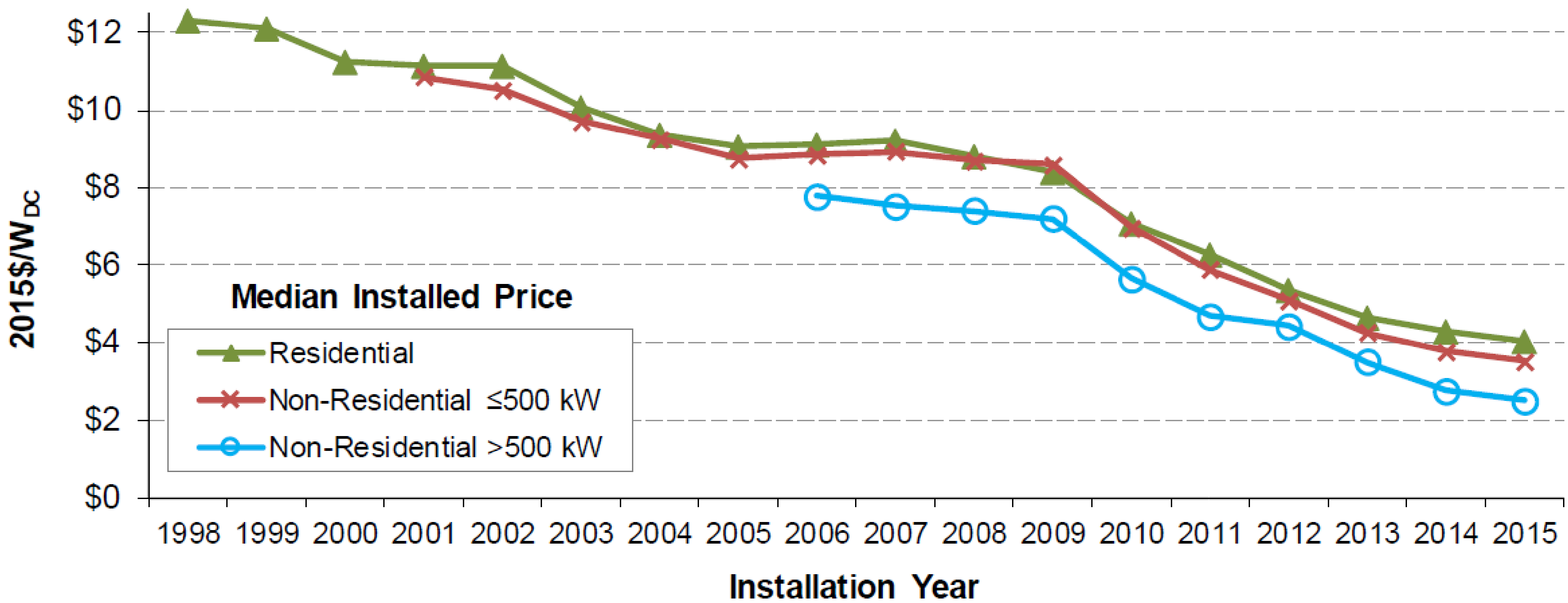


Source: U.S. Energy Information Administration

Number of PV Systems



Installed Price of PV



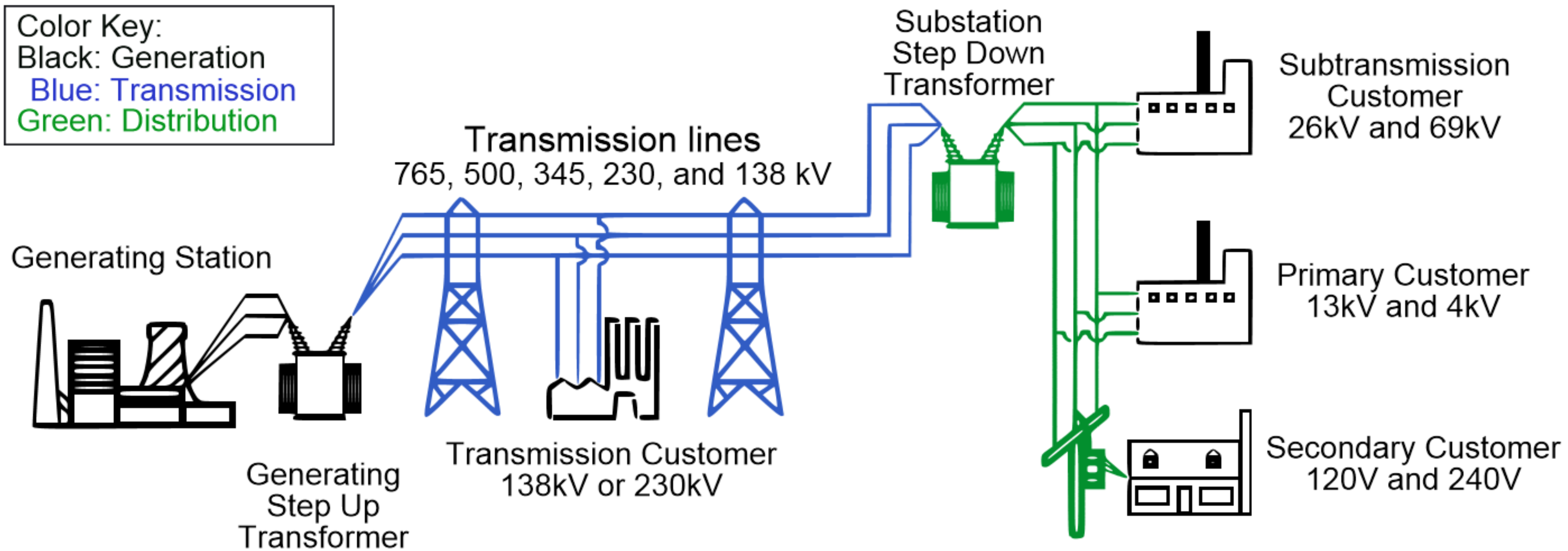
- From Tracking the Sun IX – LBNL report
- In 2007, Residential PV around $9/Watt
- In 2015, Residential PV down to $4/Watt

Presentation Objective

Lay groundwork for following FREEDM webinars on FREEDM technology by discussing:

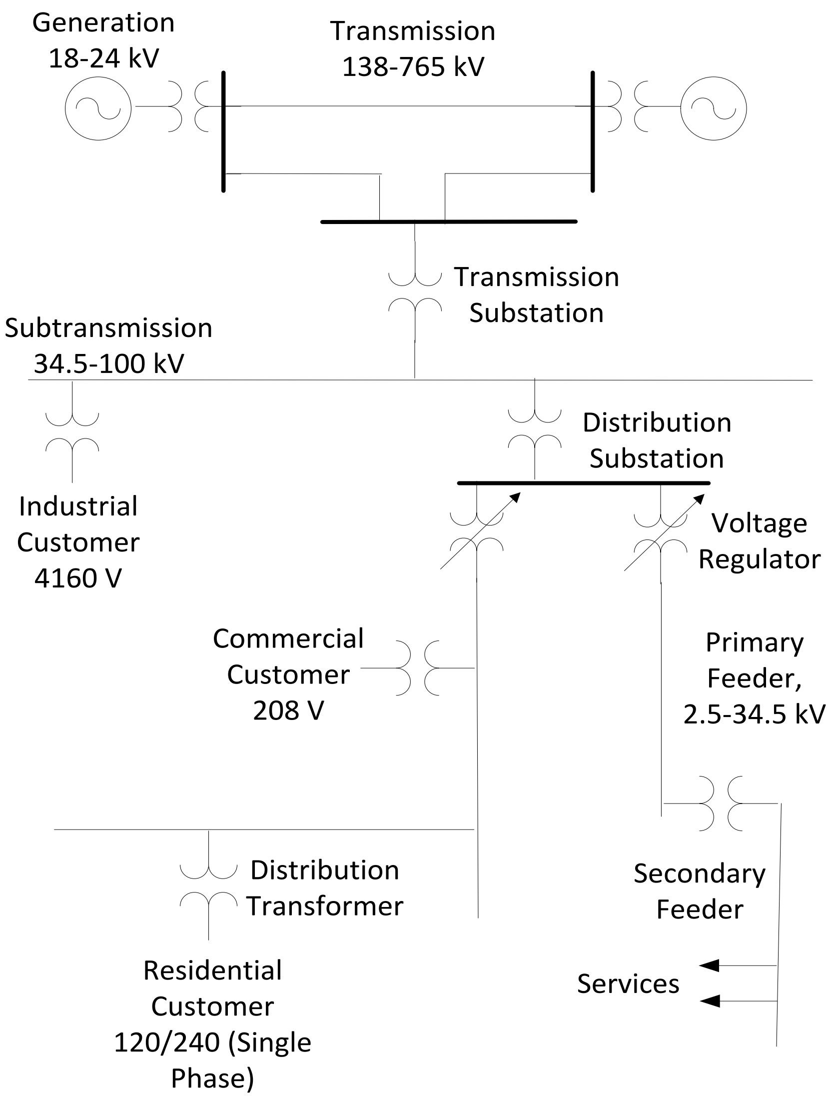
- Overview of traditional distribution circuit operation
- Circuit voltage regulation
- Distributed Generation integration issues, with focus on photovoltaic energy
- Sample Circuit analysis results
- Traditional vs. FREEDM approach

Electric Power System



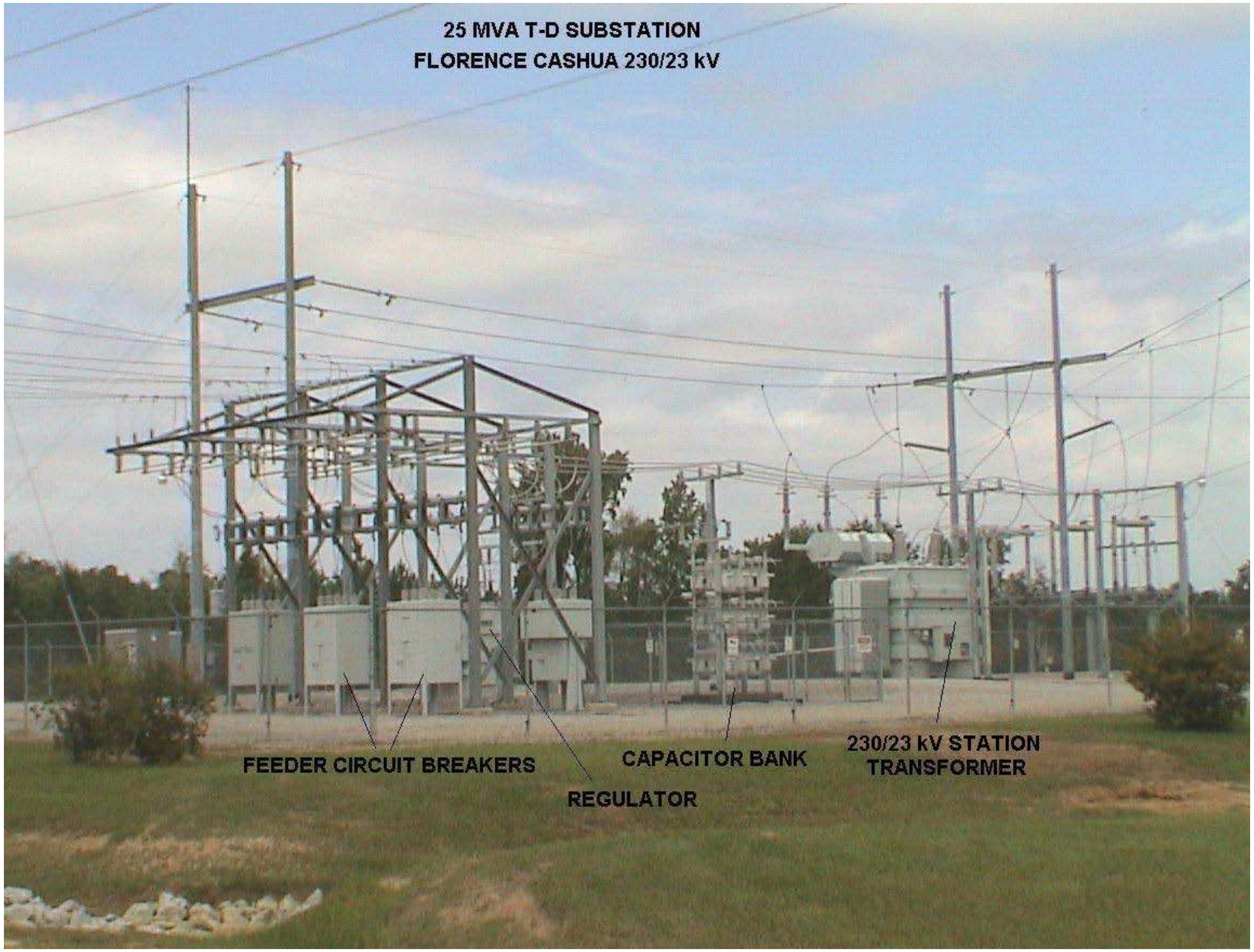
Source: Wikipedia – Electric power distribution

Transmission and Distribution Voltage Levels



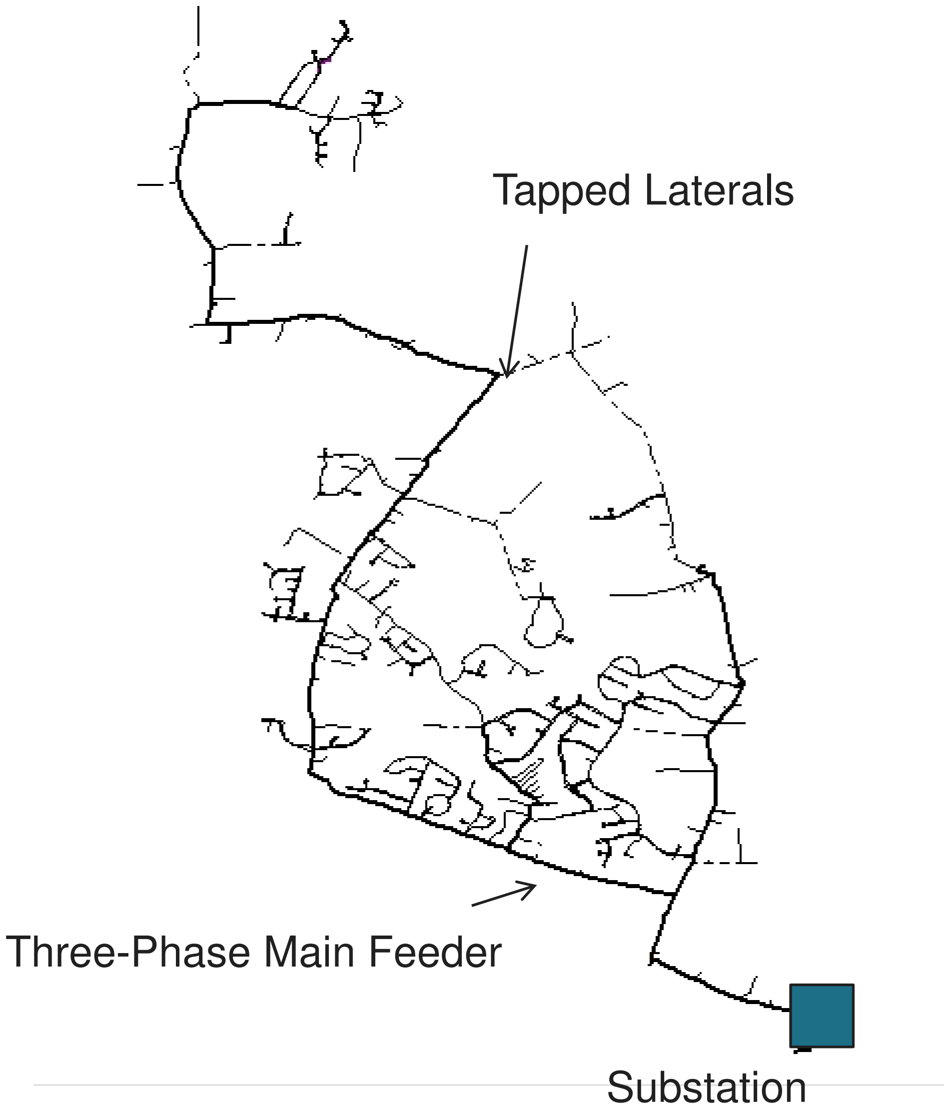
- Levels
  - Bulk Transmission
  - Subtransmission
  - Distribution Substation
  - Primary Feeder
  - Distribution Transformer
  - Secondaries and Services

Distribution Substation



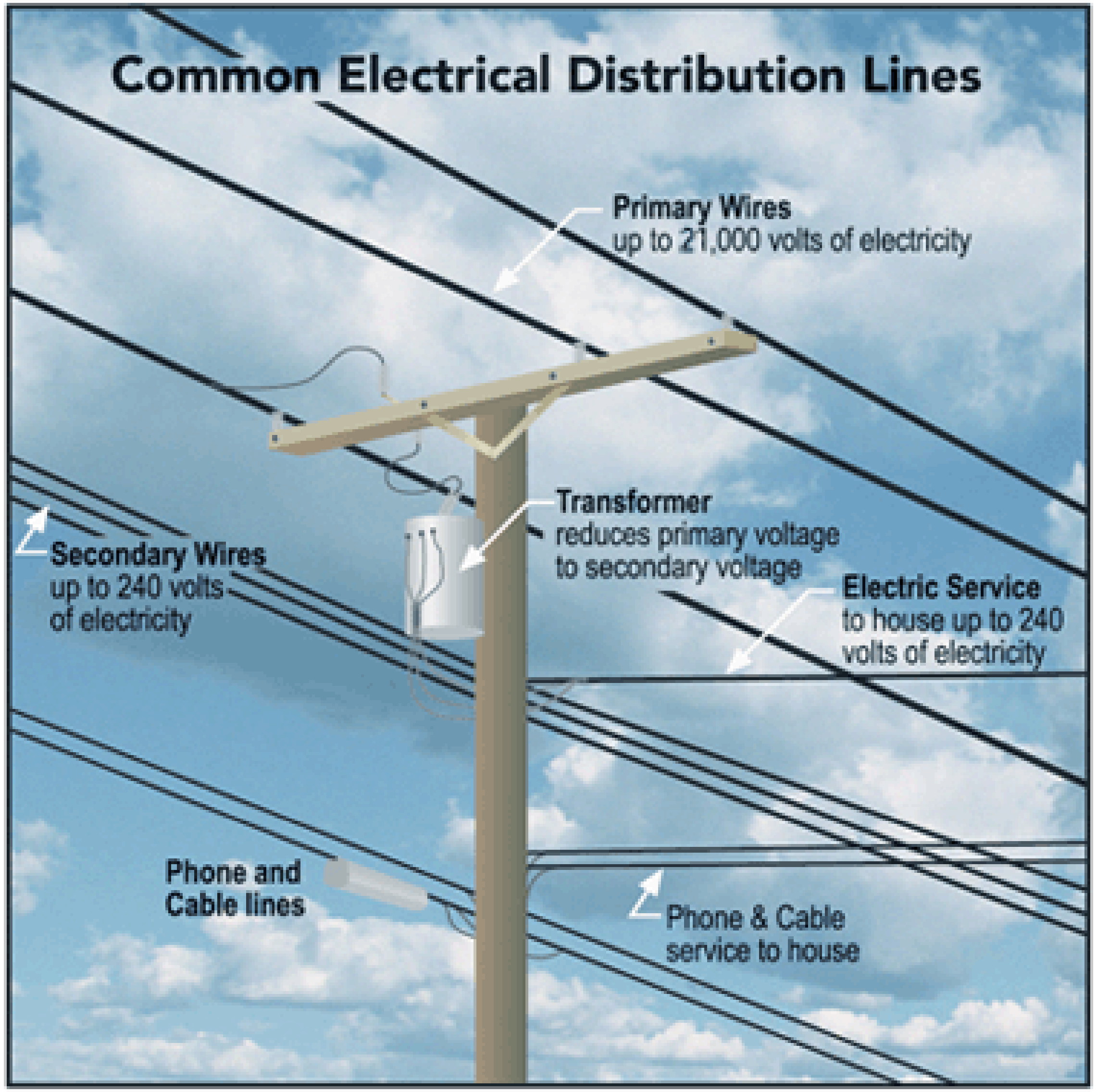
- Connects to a transmission grid
- Transmission to Distribution Primary Voltage Conversion
- Voltage Control
- Feeder Protection
- Switching

Distribution Feeder Layout



- Substations connect to transmission or subtransmission.
- Each Feeder serves an area.
- Main Feeder typically follows main roads.
- Laterals connect to individual businesses or households.
- Laterals can be on streets but can cut through other access paths (alleys).

Primary Overhead Feeder



- Connects substation transformer to customer distribution transformers
- Backbone is three-phase with single or two-phase taps

Overhead Distribution Transformer & Service

Single-phase overhead distribution transformer.

- Converts primary voltage to secondary level
- Secondary service connects to customer meter
- Note: customer voltage related to primary voltage by turns ratio of the transformer

Padmount Distribution Transformer

- Mounted in enclosure on concrete pad
- Primary and secondary both underground

ANSI Voltage Delivery Standards

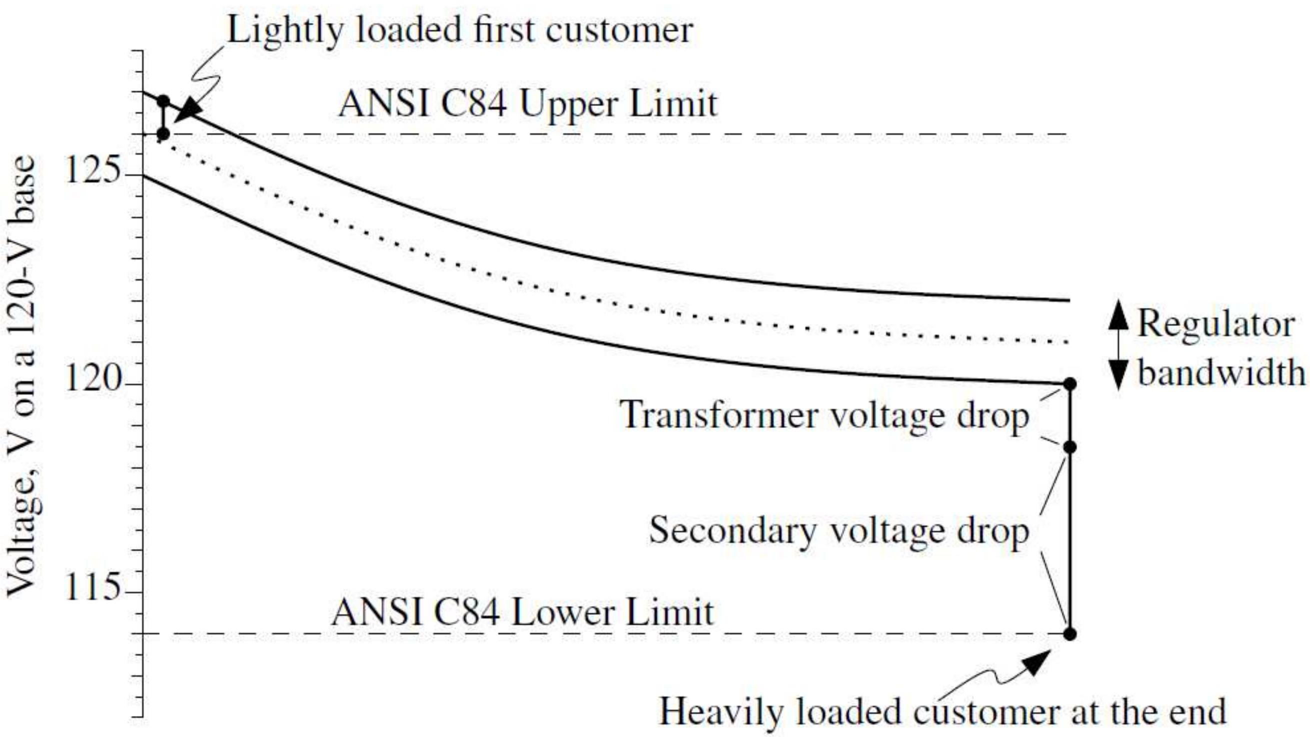
Service voltage — The service voltage is the point where the electrical systems of the supplier and the user are interconnected. This is normally at the meter. Maintaining acceptable voltage at the service entrance is the *utility's* responsibility.

Utilization voltage — The voltage at the line terminals of utilization equipment. This voltage is the *facility's* responsibility. Equipment manufacturers should design equipment which operates satisfactorily within the given limits.

ANSI C84.1 Voltage Ranges for 120 V

	Service Voltage		Utilization Voltage	
	Minimum	Maximum	Minimum	Maximum
Range A	114 (–5%)	126 (+5%)	110 (–8.3%)	125 (+4.2%)
Range B	110 (–8.3%)	127 (+5.8%)	106 (–11.7%)	127 (+5.8%)

Typical Voltage Profile



- Substation LTC or bus regulator controls voltage at top of circuit.
- Limit voltage at top of feeder to 127 V, assuming secondary has 1 V drop.
- Slope of curve changes as load increases or decreases.
- Utilities typically want voltage to stay above 117-118 V.

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Approximate Voltage Drop Relationship

We can approximate the voltage drop along a circuit as

$$V_{drop} = |V_s| - |V_r| \approx I_R \cdot R + I_X \cdot X$$

where

V_{drop} = voltage drop along the feeder, V

R = line resistance, Ω

X = line reactance, Ω

I_R = line current due to real power flow (in phase with the voltage), A

I_X = line current due to reactive power flow (90° out of phase with the voltage), A

In terms of the load power factor, *pf*, the real and reactive line currents are

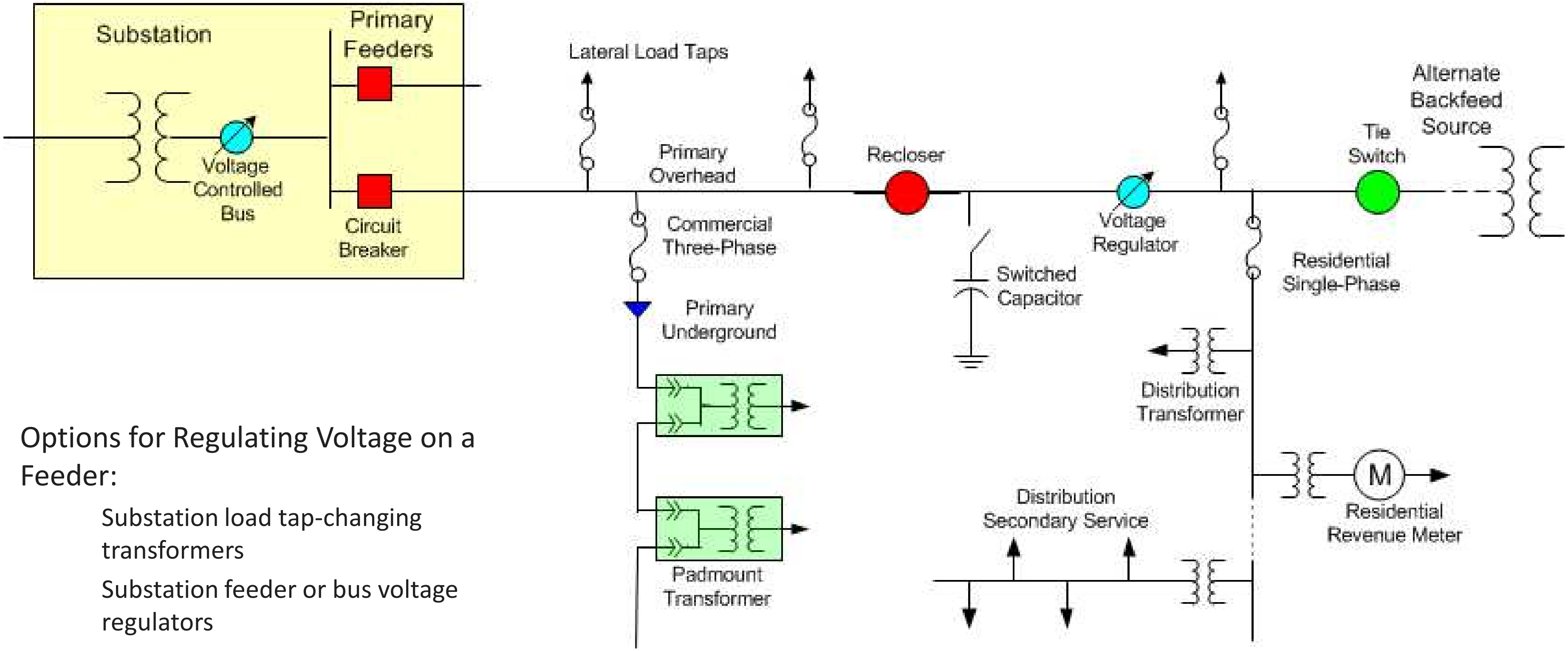
$$I_R = I \cdot pf = I \cos\theta$$

$$I_X = I \cdot qf = I \sin\theta = I \sin(\cos^{-1}(pf))$$

Notes about this Voltage Drop Relationship

- Resistive Load – for high power factor, voltage drop highly correlated to the resistance of the conductors.
- Reactive Load – for lower power factor, voltage drop highly correlated to reactance of conductors.
- Reactive power injection (negative VARs) due to capacitors will boost voltage.
- Real power injection (negative load) due to distributed generation will boost voltage.

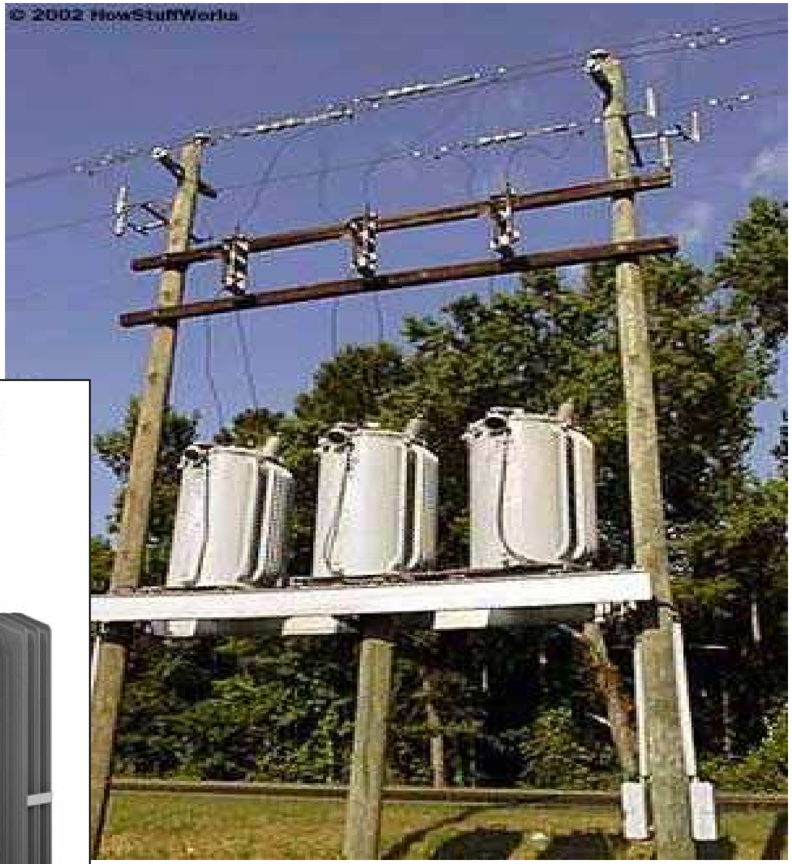
Primary Distribution Voltage Controls



Options for Regulating Voltage on a Feeder:

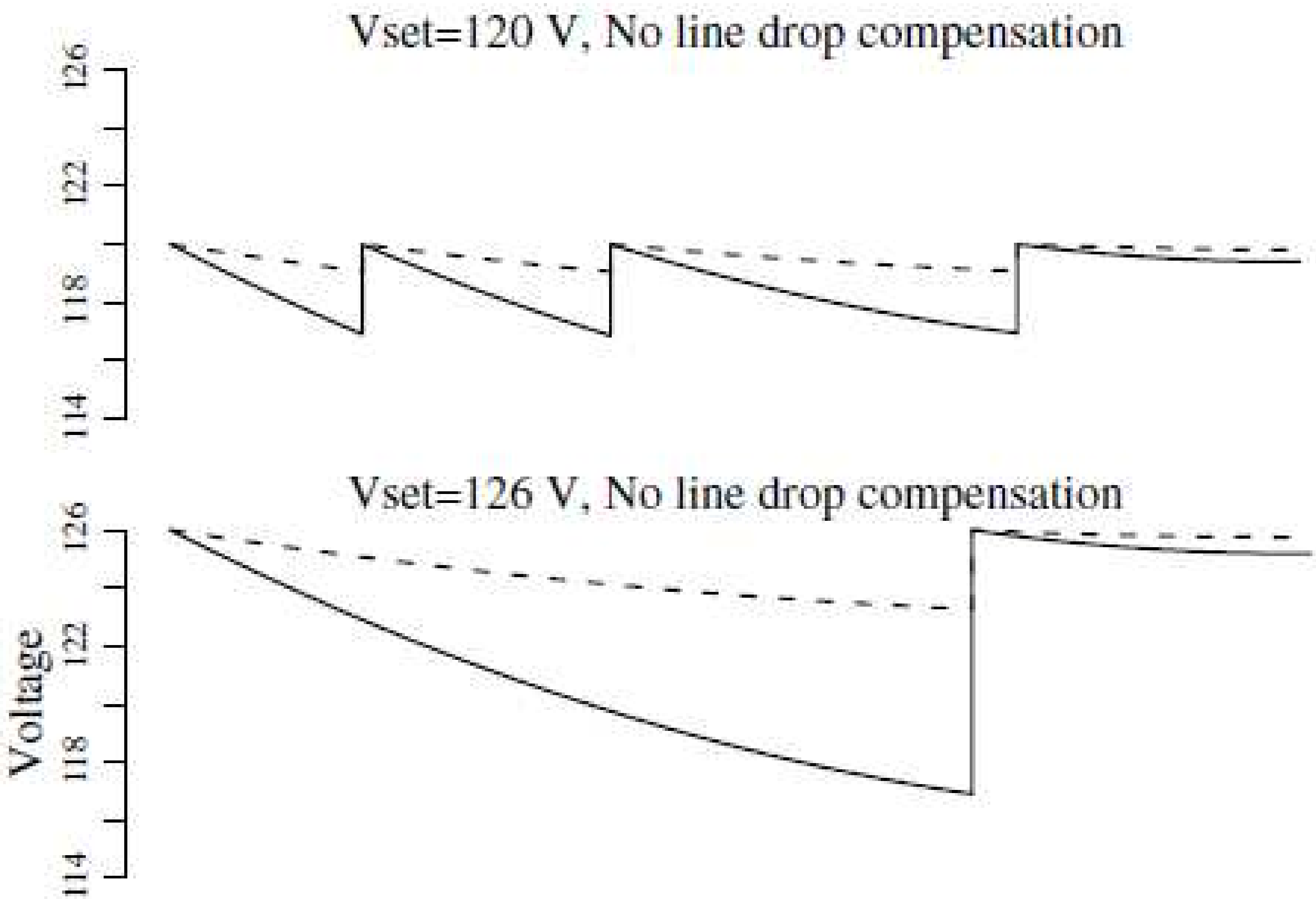
- Substation load tap-changing transformers
- Substation feeder or bus voltage regulators
- Line voltage regulators
- Fixed and switched capacitors

Line Voltage Regulator Banks

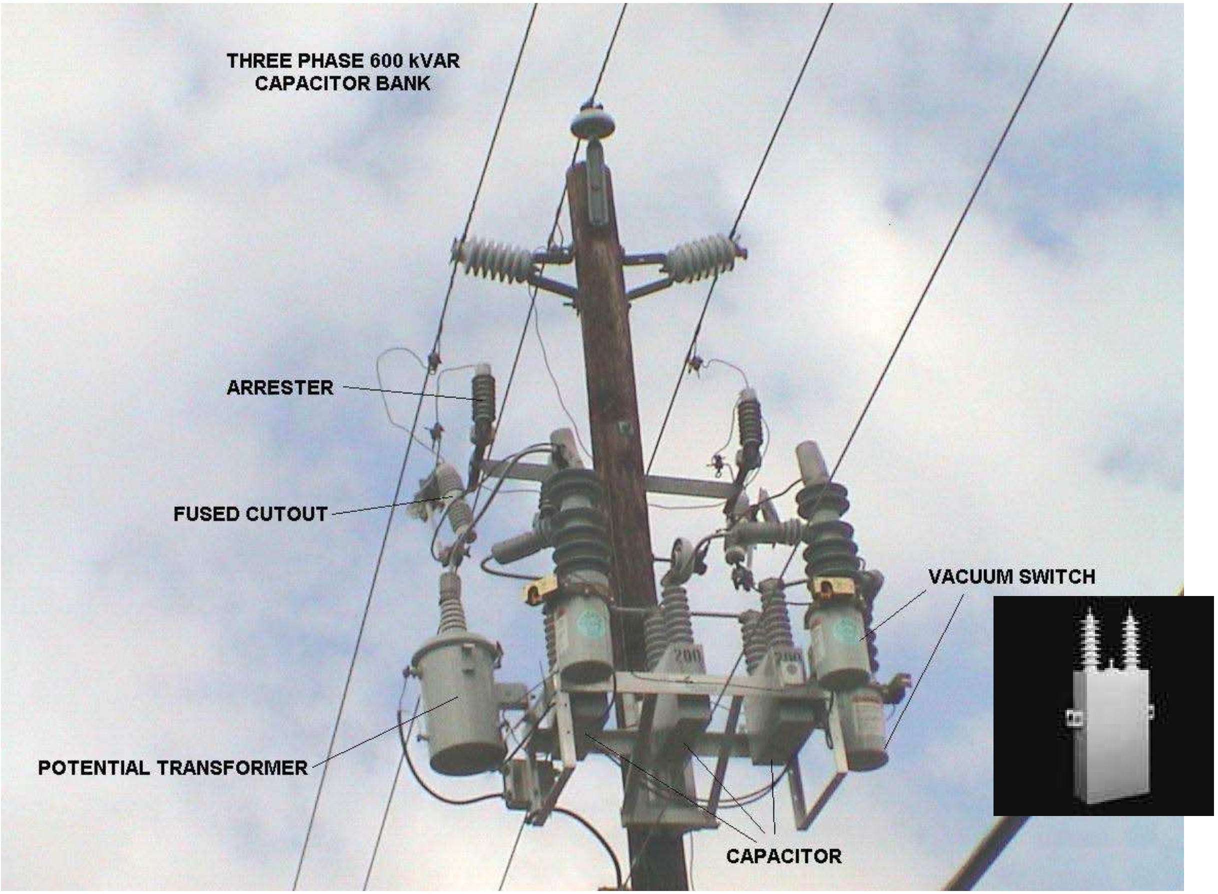


- Regulate voltage at points downstream from substation.
- Essentially an autotransformer with many taps in the series winding.
- Common distribution regulator:
  - ✓ +/- 10%, 32 taps
  - ✓ ⅝ % (.75 volts on 120 volt base) per tap
- Feedback control keeps load side voltage within proper range.

Voltage Regulator Impact

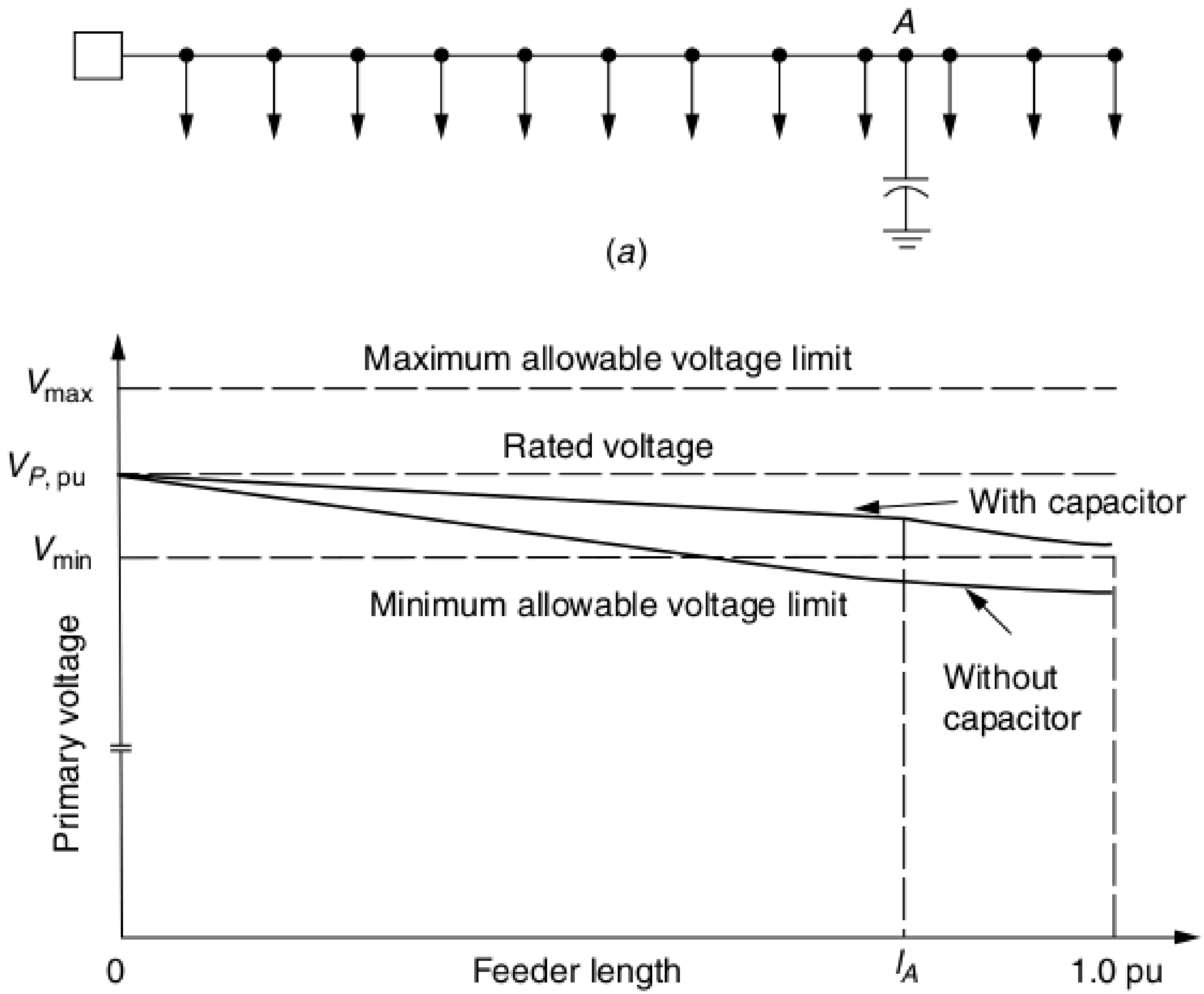


Line Capacitors



- Fixed or Switched Capacitor Banks
- Benefits:
  - Power Factor Improvement
  - Voltage Improvement
  - Loss Reduction

Capacitor Impact on Voltage Profile



Distributed Energy Resource (DER)

- A device that produces electricity, and is connected to the electrical system, either "behind the meter" in the customer's premise, or on the utility's primary distribution system.

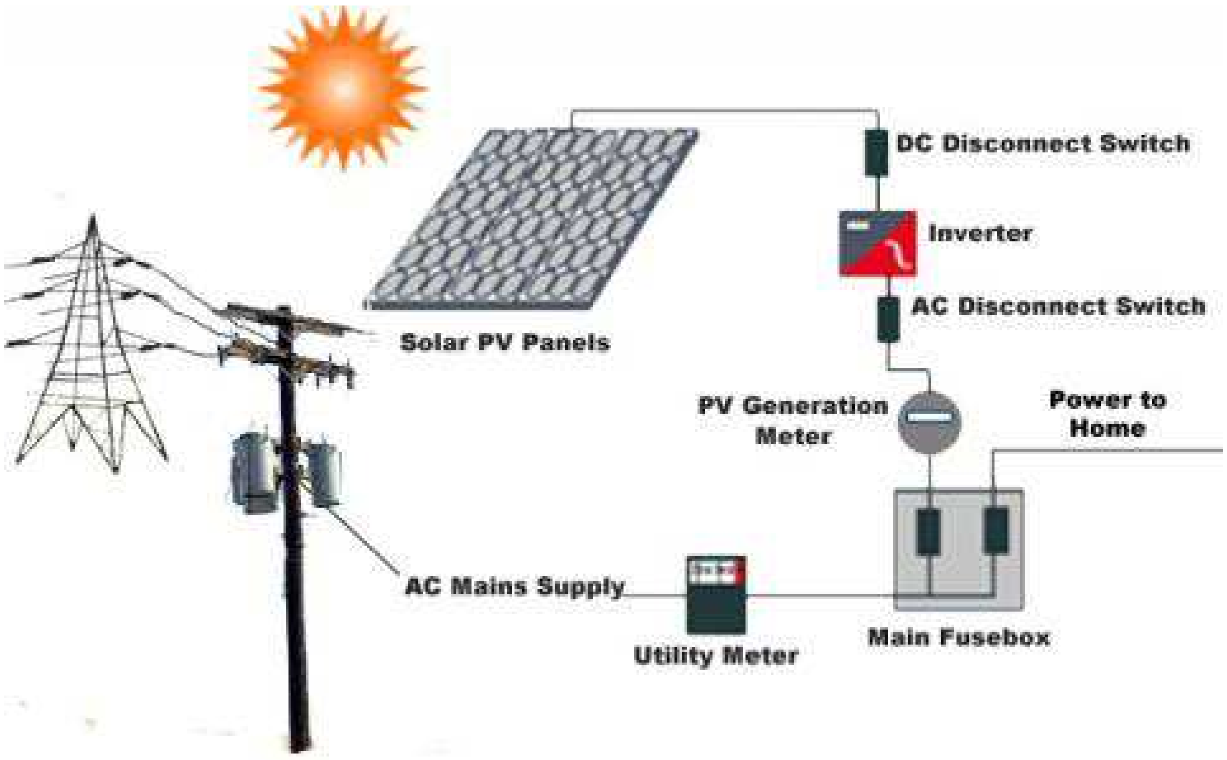
- A Distributed Energy Resource (DER) can utilize a variety of energy inputs including:
  - Natural Gas
  - Biofuel
  - Solar
  - Wind
  - Batteries

- In this presentation, will focus on impact of Photovoltaic (solar) Systems.

PV System - Residential

- Residential Scale Systems.
- Typically 5 kW for houses, but that is trending up.
- String-Inverter vs. Micro-Inverter Technology.

Residential Interconnection



- Excess power backfeeds into the utility distribution system.
- Utility has no direct control of inverter on customer side of meter.
- Injected power can be variable.
- PV generation can impact other customers connected to distribution grid.

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Basic Issue: Changes in Radial Feeder Power Flows

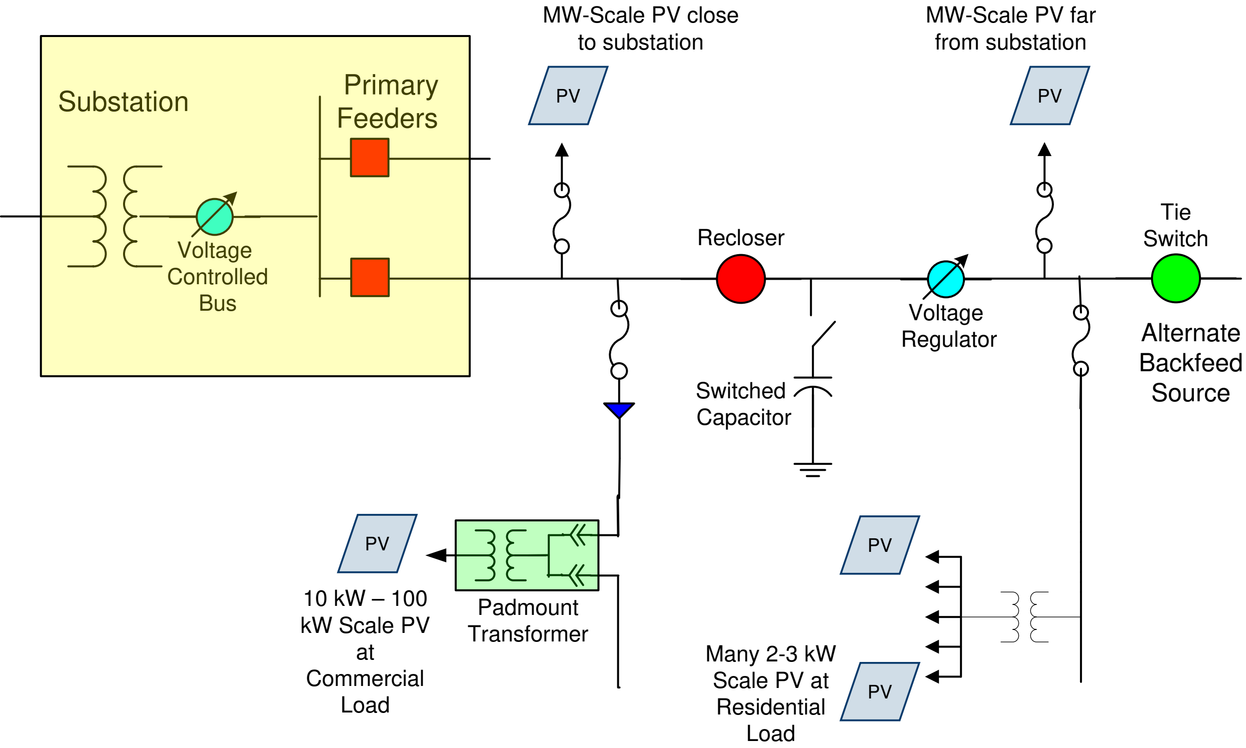
- DER invalidates historical assumption of unidirectional power flow, which will perturb typical distribution system operations.

- System typically optimized for decreasing load density, with wire sizes dropping as we go further from the substation.

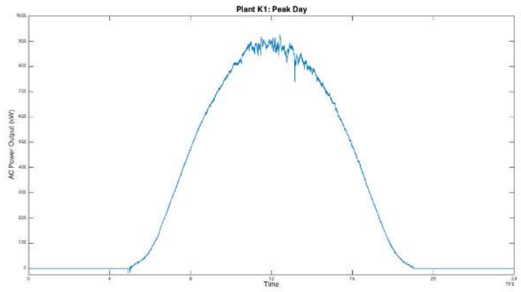
- System voltage regulation originally designed for voltage drop further from substation.

- Impact varies as we go from a few 5 kW residential systems to one or more 5 MW systems.

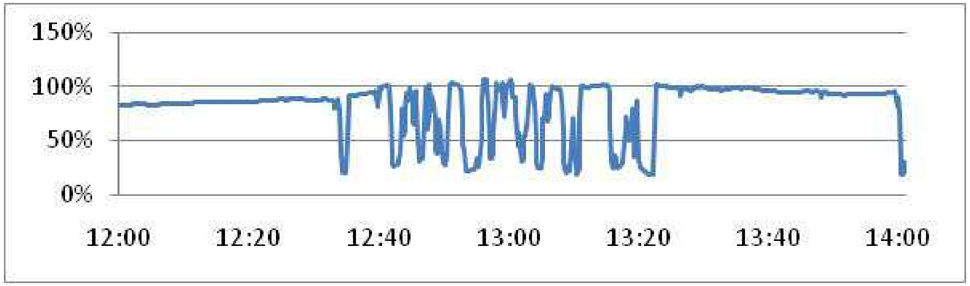
Distribution-Level PV Concerns



- Ability to properly Control Voltage during Reverse Power Flow
- Additional Wear on Voltage Control Devices
- Voltage Flicker at Customer Loads
- Coordination of Protection Relays
- Constraints on Recloser Operation



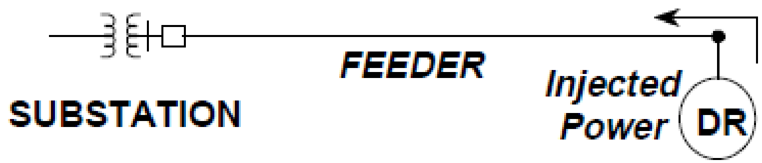
Sunny Day

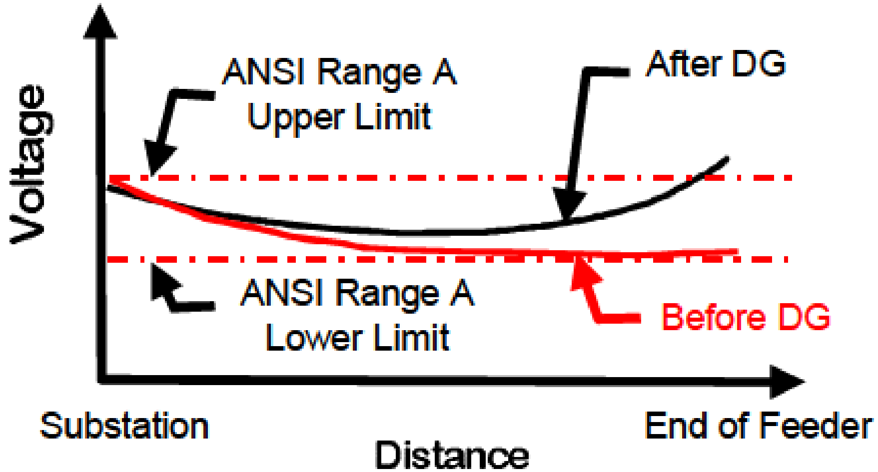


Impact of Cloud Cover

High Voltage due to DER

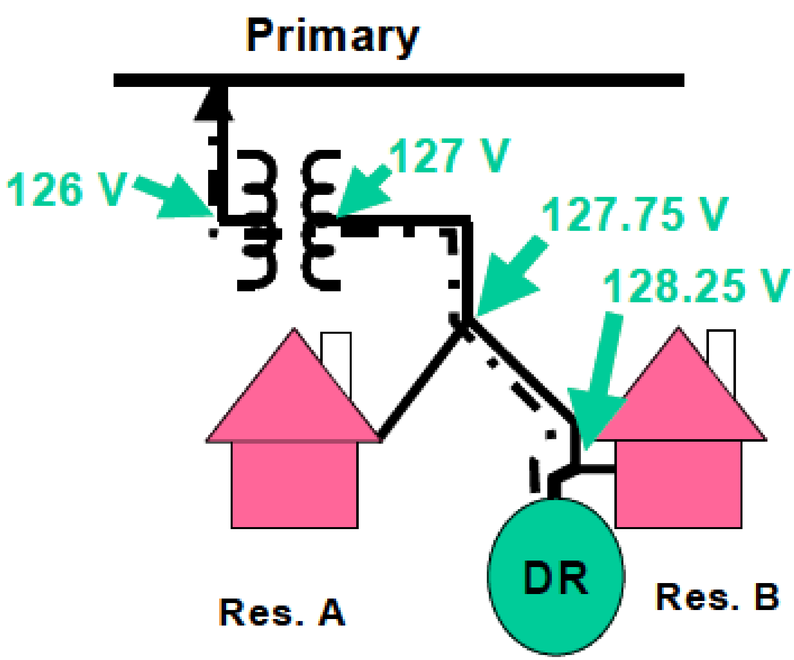
- Reverse power flow will cause voltage rise (negative voltage drop).
- Under light load conditions when primary voltage is high, voltage rise can push voltage over ANSI voltage limits.



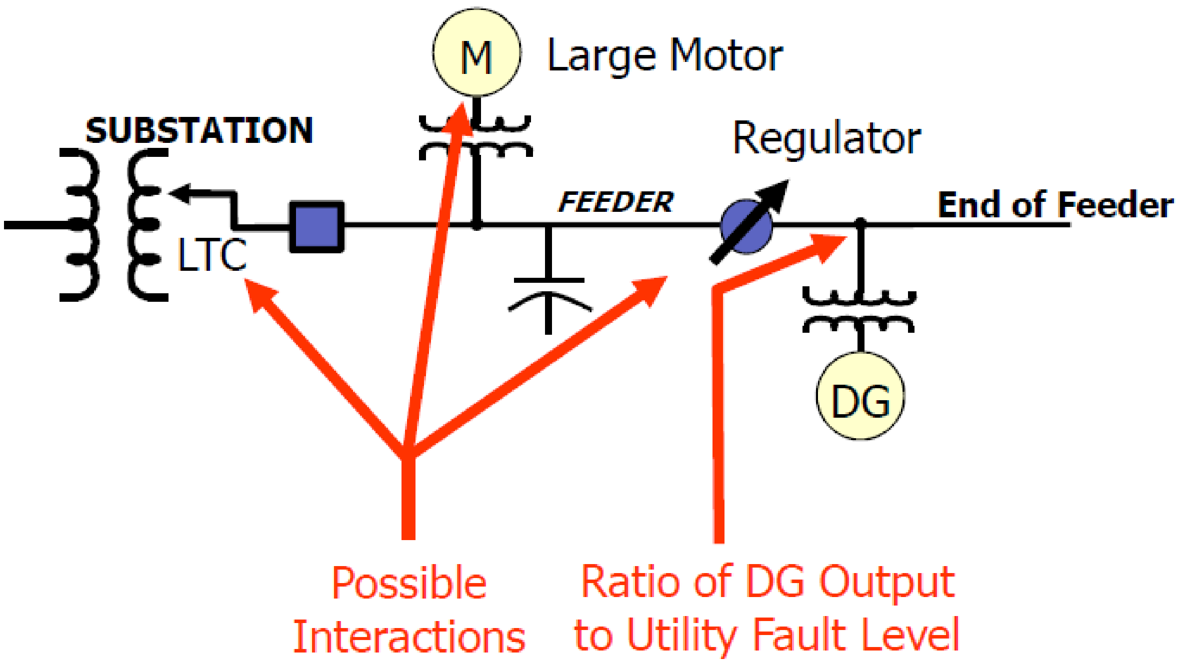


Voltage Rise on Secondary Circuit

- Even small amounts of DER can impact voltage, if there is injected power flow under light load conditions.
- Distribution models typically do not include customer transformer and secondary, so need to make sure additional secondary voltage rise is not an issue.

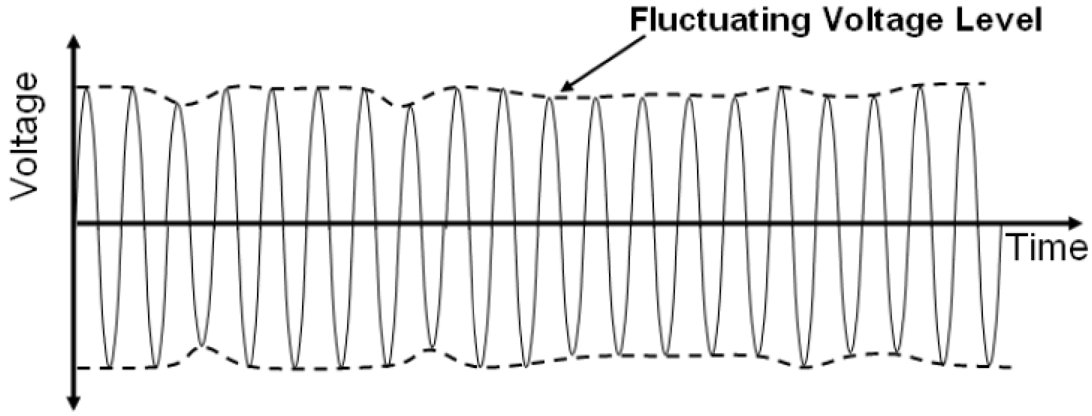


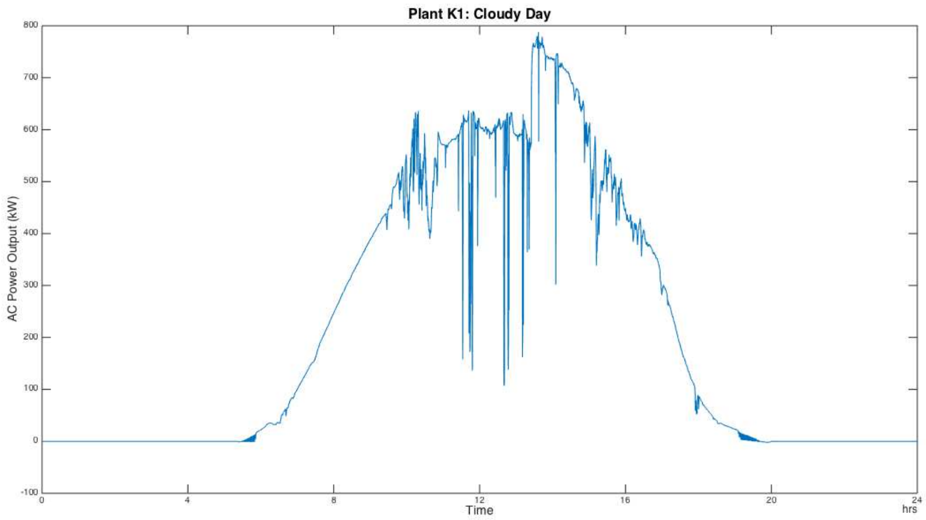
Interaction with Voltage Regulating Equipment



- If DER has time-varying output, will change system current flow enough to cause a regulator tap change or operation of a switched capacitor bank.
- Also DER with voltage control may not work well with utility regulation equipment.
- This leads to undesirable cycling of voltage regulators and voltage power quality degradation.

Voltage Flicker



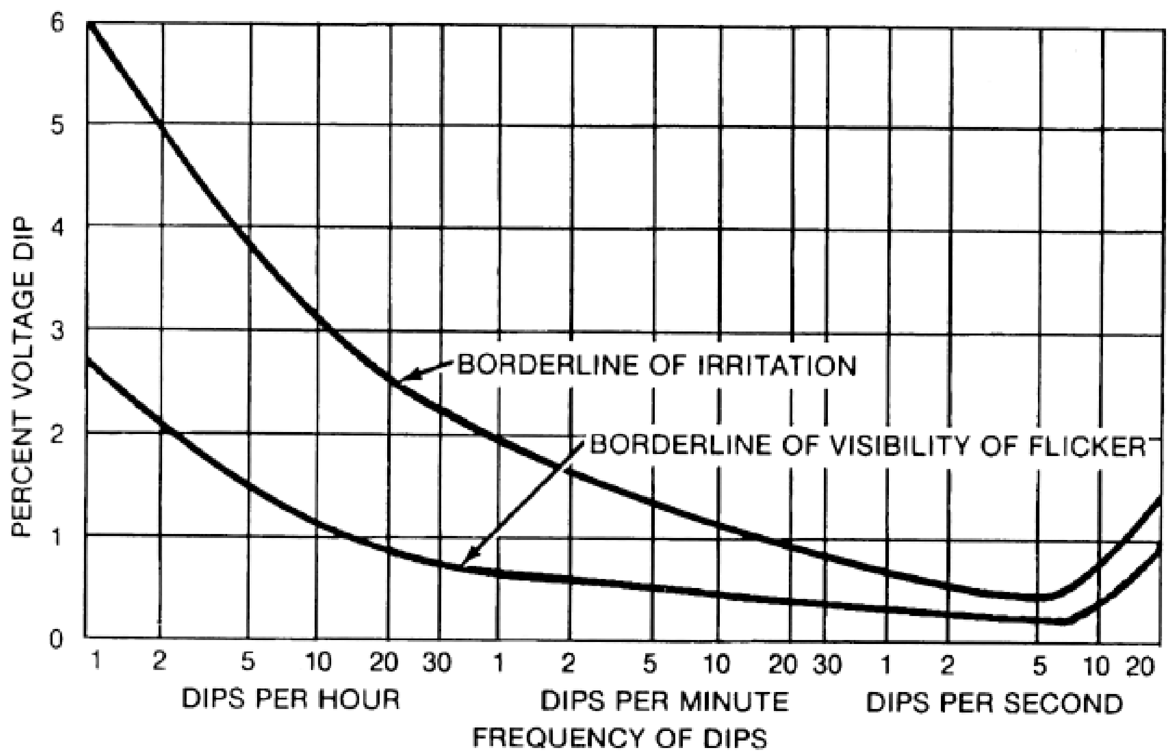


Cloudy Day Profile

- Intermittent DER output is reflected in both load current and load voltage.
- Rapid fluctuations in voltage referred to as Voltage Flicker.
- Can measure this with a Flicker Meter (IEC Standard).

Voltage Fluctuations and Light Flicker

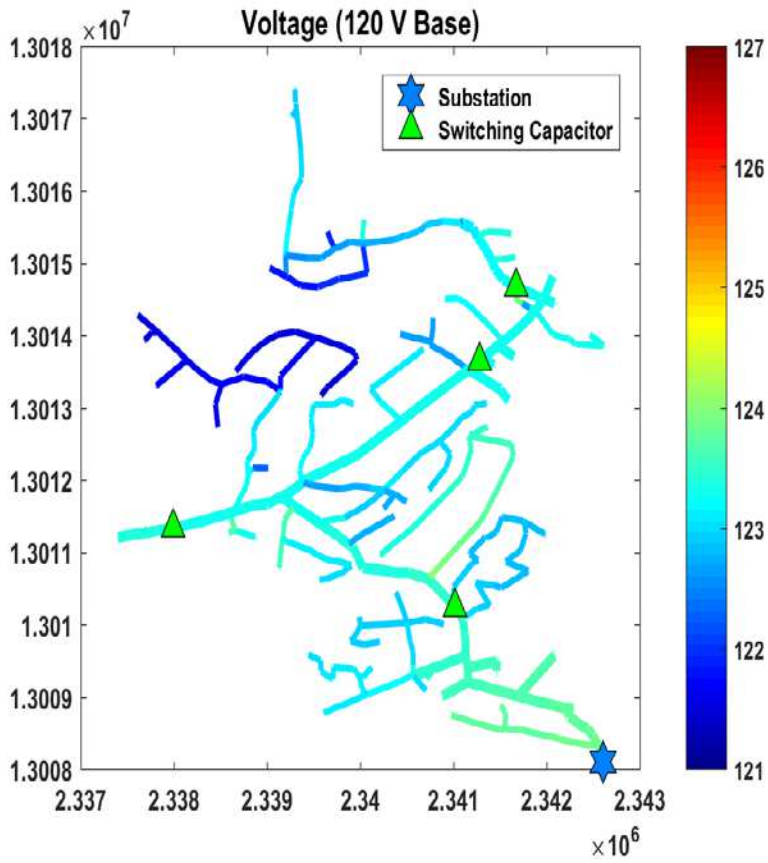
- Light flicker created by fast changing loads and generation that cause fluctuation in the voltage.
- Amount of irritation depends on both the frequency and magnitude of these fluctuations, characterized by a flicker curve.



Sample Circuit Study

- Circuit Characteristic
  - System Voltage: 12.47 kV
  - Peak Load (year): 6.7 MW
  - Feeder Length: 3 miles
- Baseline Simulation Results

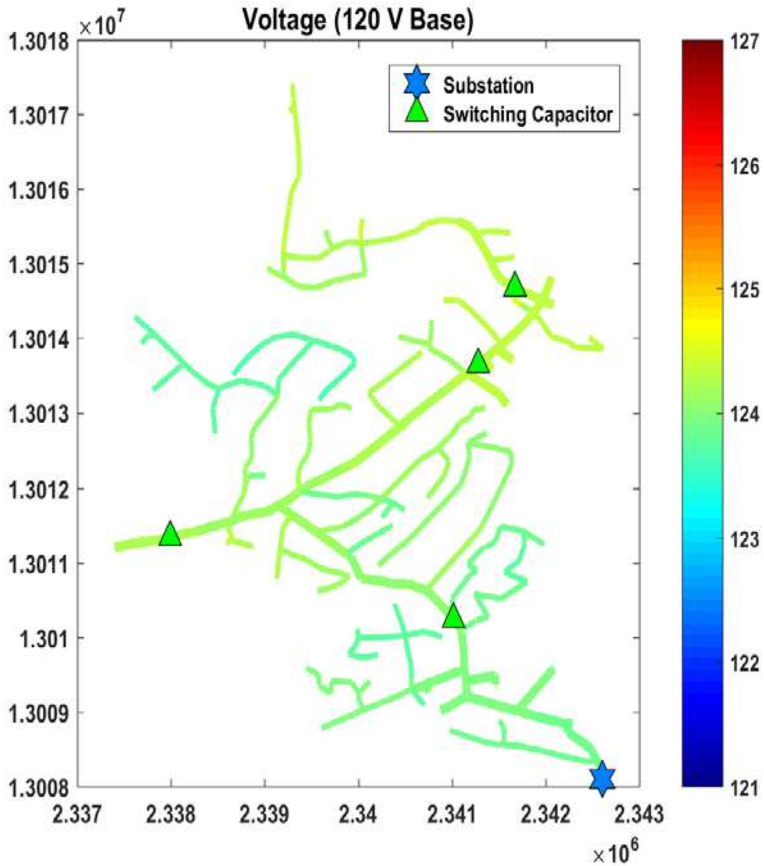
Top of the Feeder	6.8 MW
High Customer Voltage	124.1 V
Low Customer Voltage	117.3 V
Losses	170 kW



Peak Loading With PV

- PV Systems
  - Size: 100% of the load peak
  - Number of PV: 299
  - 6.7 MW in total
- Simulation Results

Top of the Feeder	0.07 MW
High Customer Voltage	124.5 V
Low Customer Voltage	122.8 V
Losses	68 kW



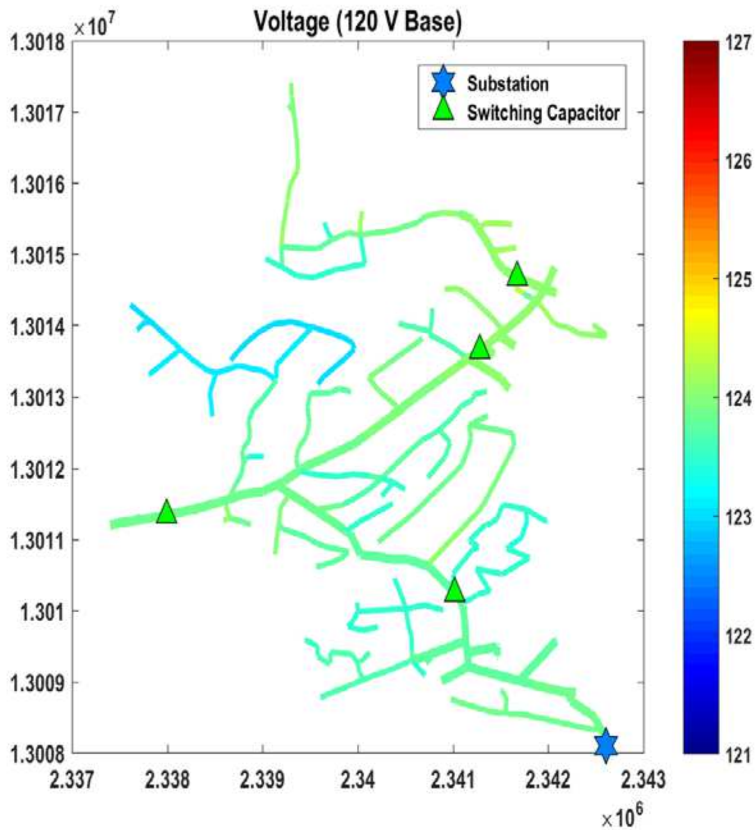
Loads are compensated by PV.
Dramatically drop in losses.
Voltage rises to 122-124 V range.

Light Loading

- Light Loading Condition
  - 40% of the Peak Load
  - Load: 2.8 MW

- Simulation Results

Top of the Feeder	2.8 MW
High Customer Voltage	124.3 V
Low Customer Voltage	121.5 V
Losses	76 kW

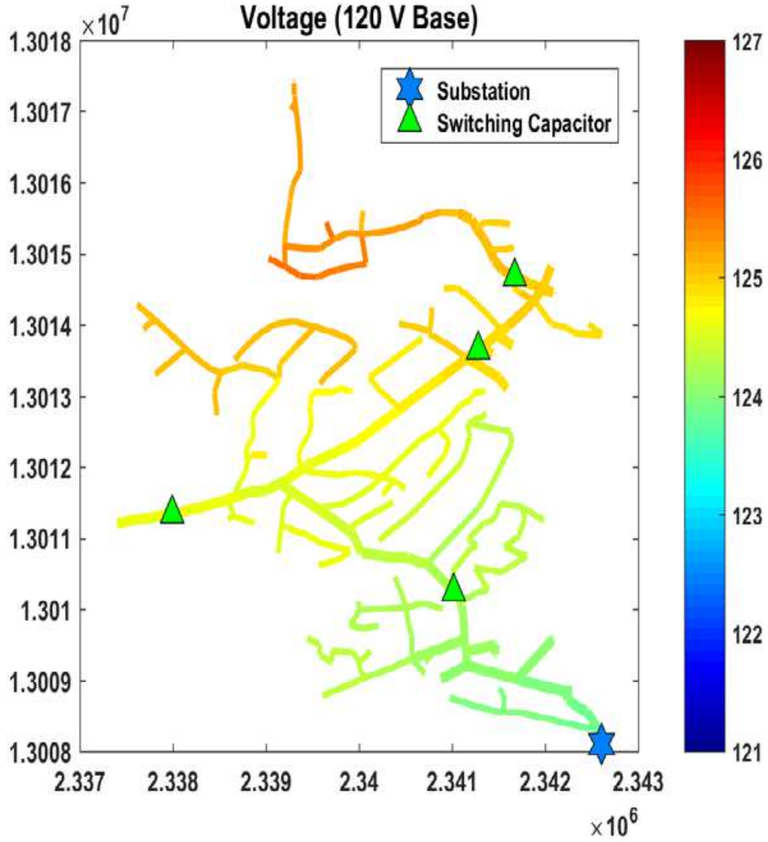


Light Loading With PV

- Light Loading Condition
  - Load: 2.8 MW
  - PV: 6.7 MW

- Simulation Results

Top of the Feeder	-3.9 MW
High Customer Voltage	126.7 V
Low Customer Voltage	123.9 V
Losses	97 kW



PV is back feeding into the grid.
A little bit increase in losses.
Overvoltage issues!

Possible Mitigation Options with Today's Technology

Distribution Circuit Upgrades ($$$ - Expensive to overbuild circuit)

- Reconductor to lower voltage drop and increase ampacity
- Relocate/Add line voltage regulators and capacitor banks

Feeder Device Controls ($ - Limit to simple changes that can be made)

- Modify reference voltages, line drop compensation, bandwidth and delays

DER Inverter Control ($$ - Stability issues for high penetration levels)

- Operate leading power factor to help control voltage
- Deploy active reactive power control (smart inverter)

Battery Energy Storage System compensation ($$$$ - Too Expensive for power management only)

Today's technology won't get us to the very high-penetration scenarios being proposed for future grid systems.

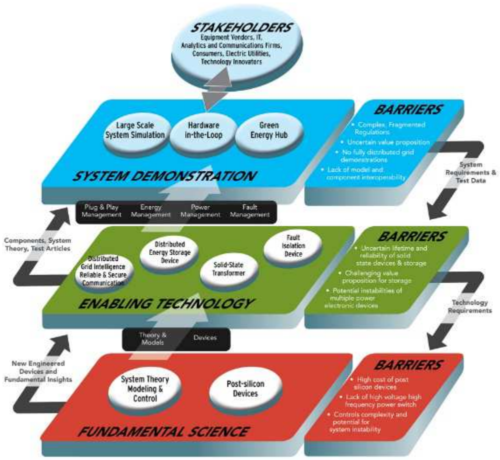
Where does the FREEDM Center come in?

We need new enabling technology for high-penetrations of DER.

Vision is to build an internet for energy: a network of distributed energy resources that intelligently manages power using secure communications and advanced power electronics.

Research priorities:

- Power electronics packaging
- Solid state transformers
- Fault isolation devices
- Controls theory
- Power systems simulation and demonstration

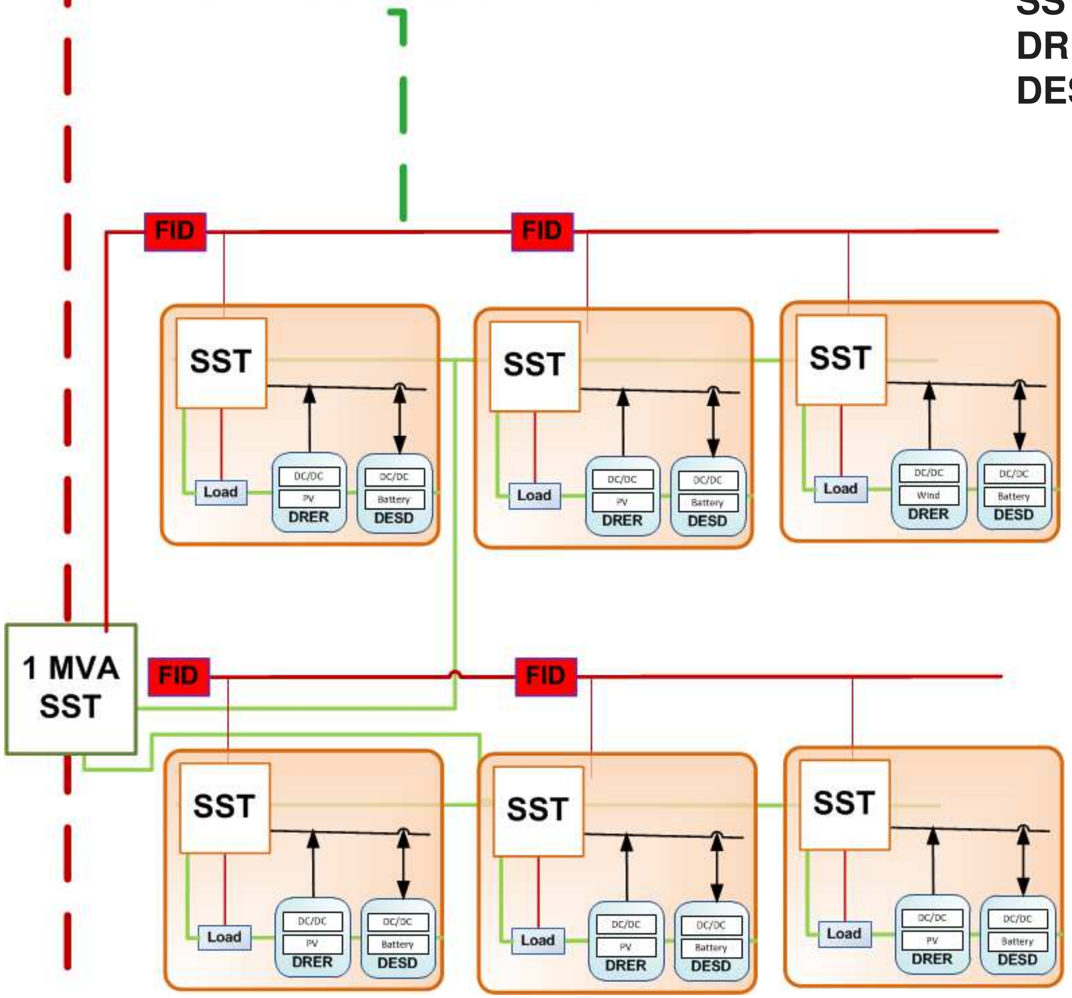


Many other technologies will play a supporting role including battery storage, smart thermostats, real-time use monitors and apps.

FREEDM System Concept

Estimated primary distribution services: 1.0 MVA / 25 kVA = 40 sites. About 3 households per site/25kVA SST. Local controls per site: about 3 – 6.

FID = Fault Interruption Device
SST = Solid State Transformer
DRER = Distributed Renewable Energy Device
DESD = Distributed Energy Storage Device



Capable of operation with energy from the grid supply, or in islanded mode using only stored energy and distributed resources.