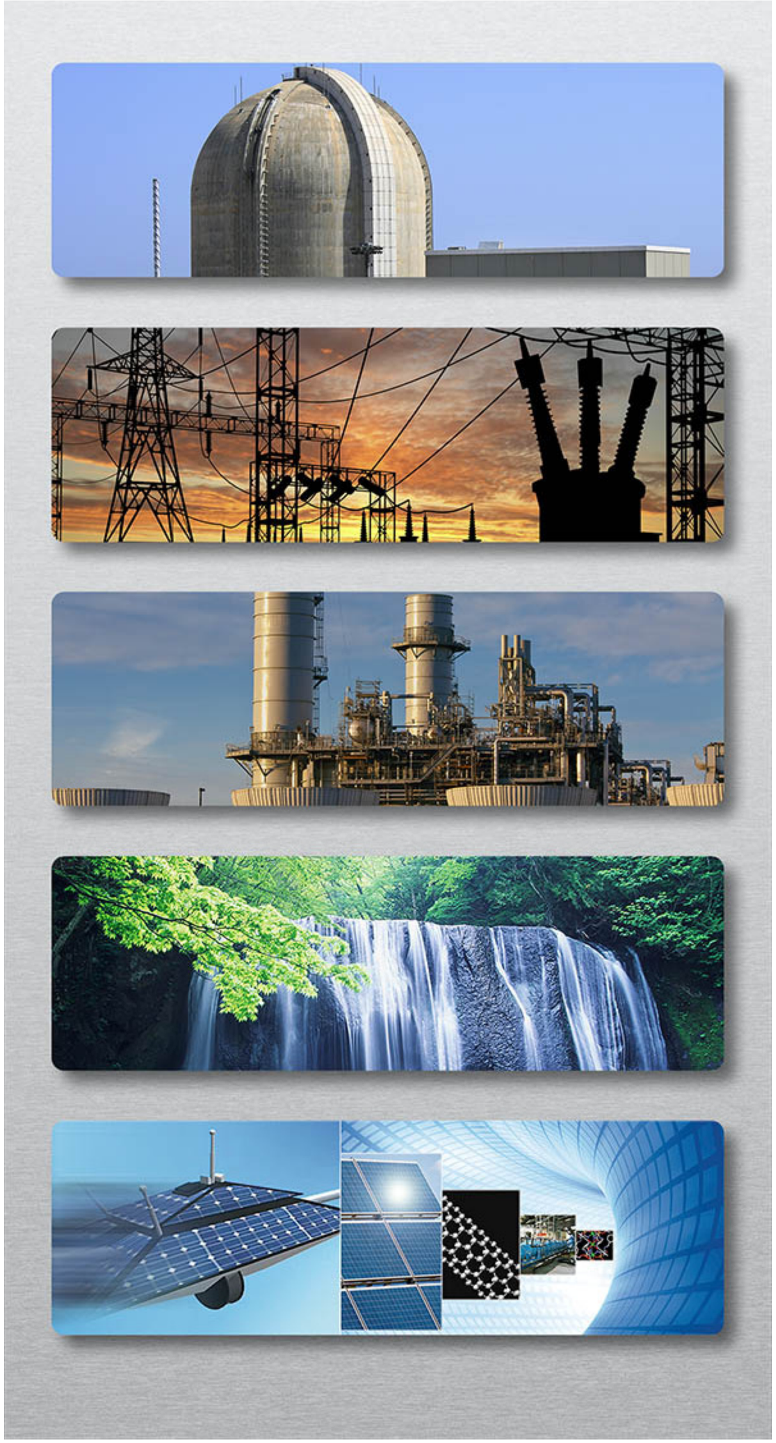

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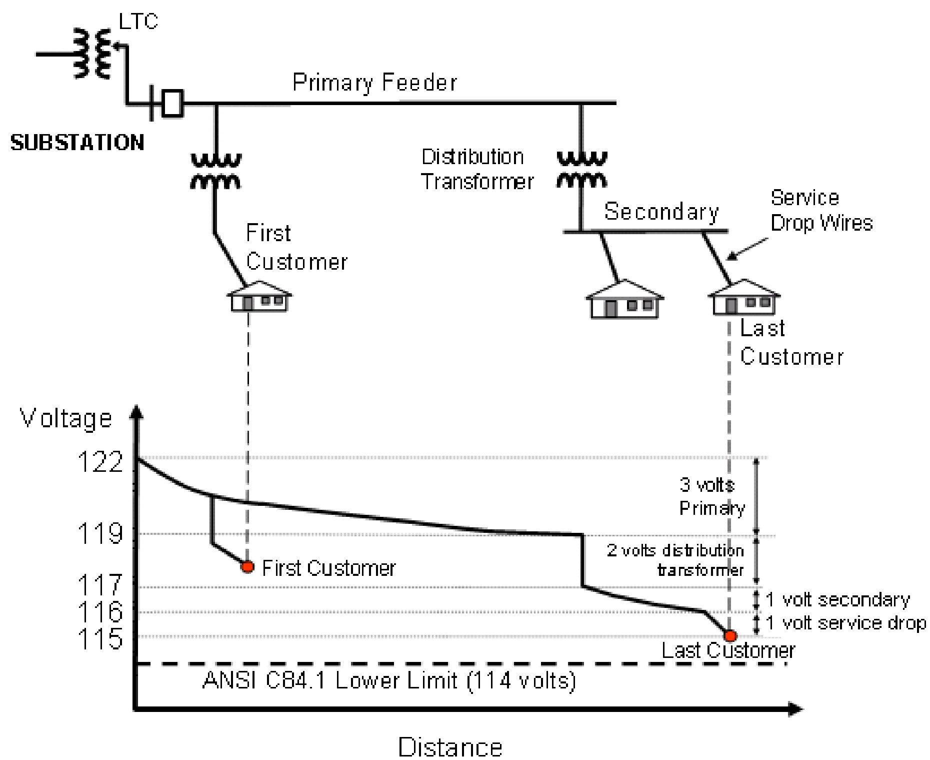
Volt/VAR Control and Optimization Concepts and Issues

Bob Uluski, EPRI
Technical Executive

- Basic concepts of Volt-VAR Control and Optimization
- How these technologies should be assessed ("Proof of Concept")

What is Volt-VAR control?

- Volt-VAR control (VVC) is a fundamental operating requirement of all electric distribution systems
- The prime purpose of VVC is to maintain acceptable voltage at all points along the distribution feeder under all loading conditions



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Volt-VAR Control in a Smart Grid World

- **Expanded** objectives for Volt-VAR control include
  - **Basic requirement – maintain acceptable voltage**
  - **Support major "Smart Grid" objectives:**
    - Improve efficiency (reduce technical losses) through voltage optimization
    - Reduce electrical demand and/or Accomplish energy conservation through voltage reduction
    - Promote a "self healing" grid (VVC plays a role in maintaining voltage after "self healing" has occurred)
    - Enable widespread deployment of Distributed generation, Renewables, Energy storage, and other distributed energy resources (dynamic volt-VAR control)

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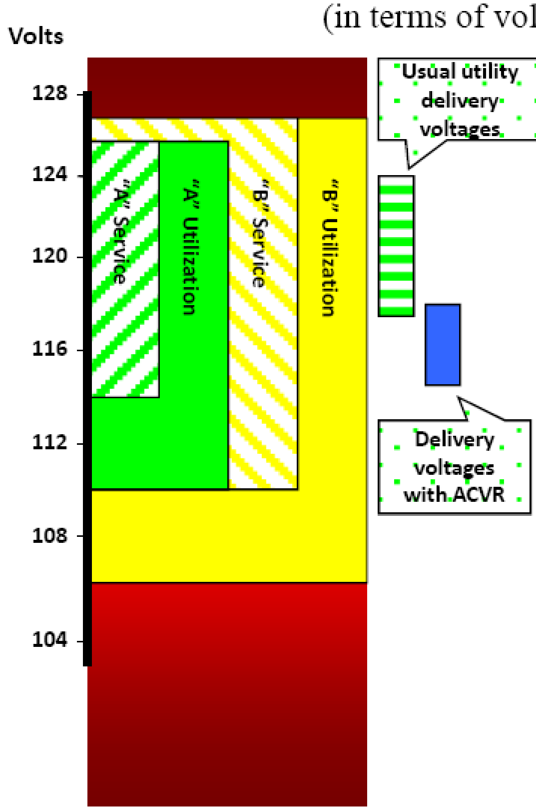
Concept of Conservation Voltage Reduction

- ANSI standards have some flexibility in the allowable delivery voltage
- Distribution utilities typically have delivery voltage in upper portion of the range
- **<u>Concept of CVR:</u> Maintain voltage delivered to the customer in the lower portion of the acceptable range**

Allowable Voltage Range

(in terms of voltages used in homes)



ANSI Standard C 84.1 – 1995 "Electrical Power Systems and Equipment – Voltage Ratings"
[similar to CAN3-C235-83 (R2000)]

Nominal 120 VAC – Range A (Normal Operation

- **Service Voltage 114 v – 126 v**
  - Voltage at which utility delivers power to home
- **Utilization Voltage 110v – 126 v**
  - Voltage at which equipment uses power
  - Most Motors rated at 115 v
  - Incandescent Lamps rated at 120 v

Nominal 120 VAC – Range B (Out of Normal Operation)

- **Service Voltage 110 v – 127 v**
- **Utilization Voltage 106v – 127 v**

Source: ***PCS Utilidata***

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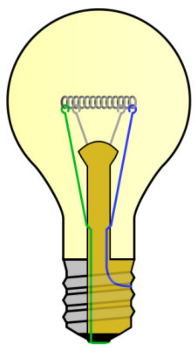
Conservation Voltage Reduction – Why Do It?

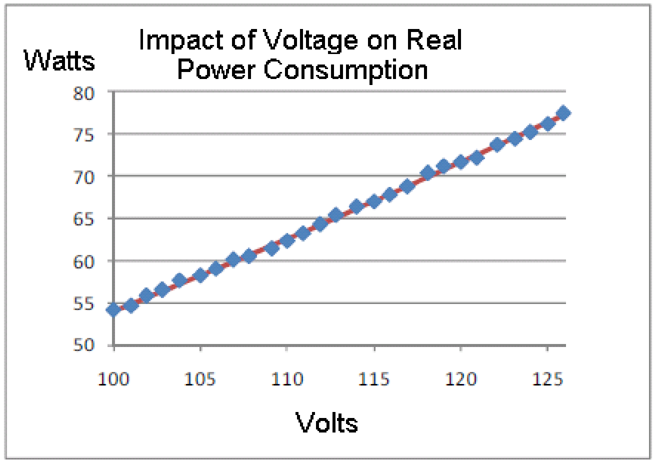
- Many electrical devices operate more efficiently (use less power) with reduced voltage



$$P = V^2 \div R$$

"Constant Impedance" Load

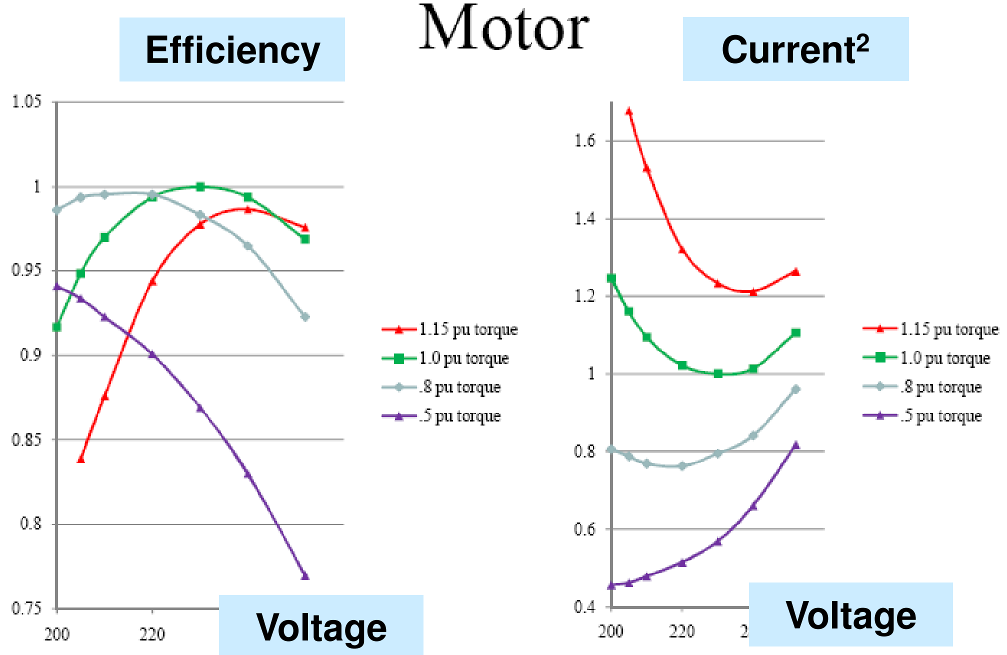
Incandescent Light Bulb (70W)



"Evaluation of Conservation Voltage Reduction (CVR) on a National Level"; PNNL; July 2010

Impact of Voltage Reduction on Electric motors Conservation Voltage Reduction

Voltage effects on ½ Hp, 230 Vac, 1Ø Motor



M.S. Chen, R.R. Shoults and J. Fitzer, *Effects of Reduced Voltage on the Operation and Efficiency of Electric Loads, Volumes 1 & 2,* EPRI, Arlington: University of Texas, 1981, Motor Number 3

Efficiency improve for small voltage reduction

Incremental change in efficiency drops off and then turns negative as voltage is reduced

Negative effect occurs sooner for heavily loaded motors

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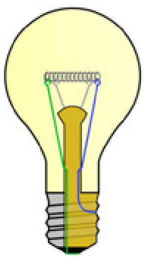
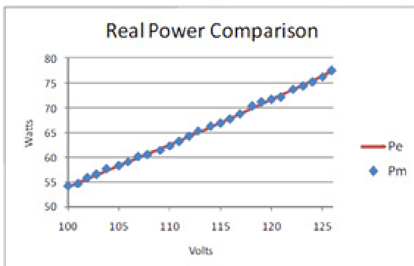
Conservation Voltage Reduction – Why Do It?

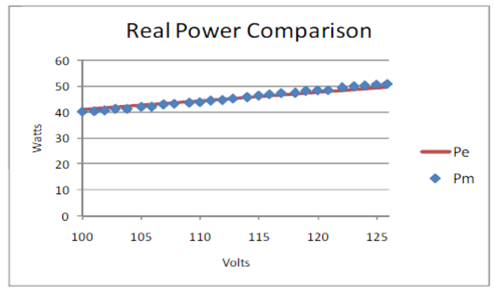
- Some newer devices have exhibit "constant power" behavior to some extent



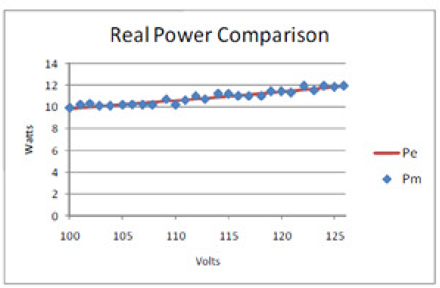
Incandescent Light Bulb (70W)



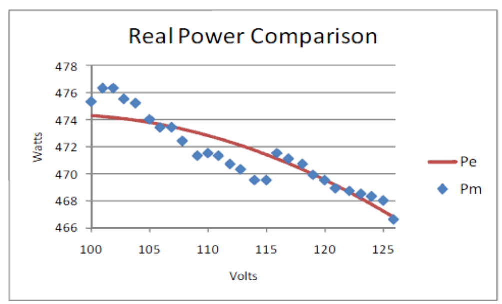
Television (Cathode Ray Tube)



Compact Fluorescent Light (CFL) 13W



Plasma TV



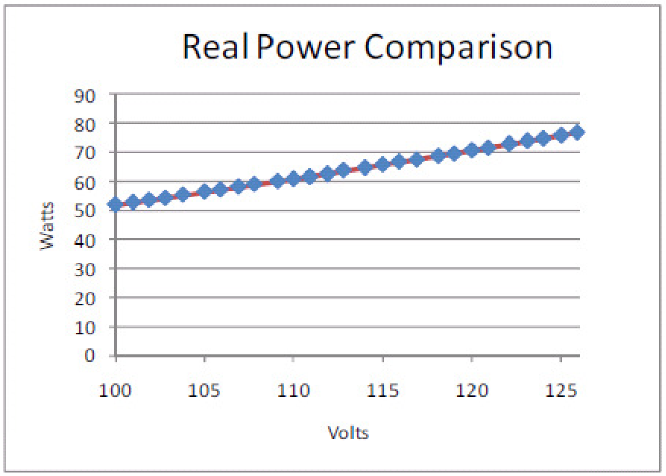
Recent results

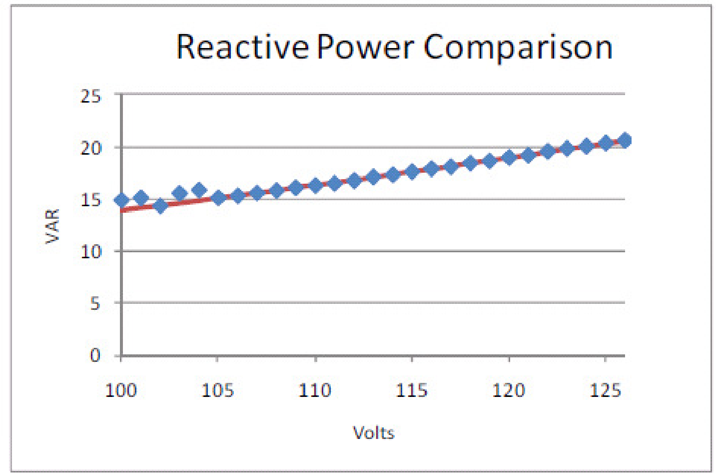
- Despite trend to constant power, reported results are still pretty favorable

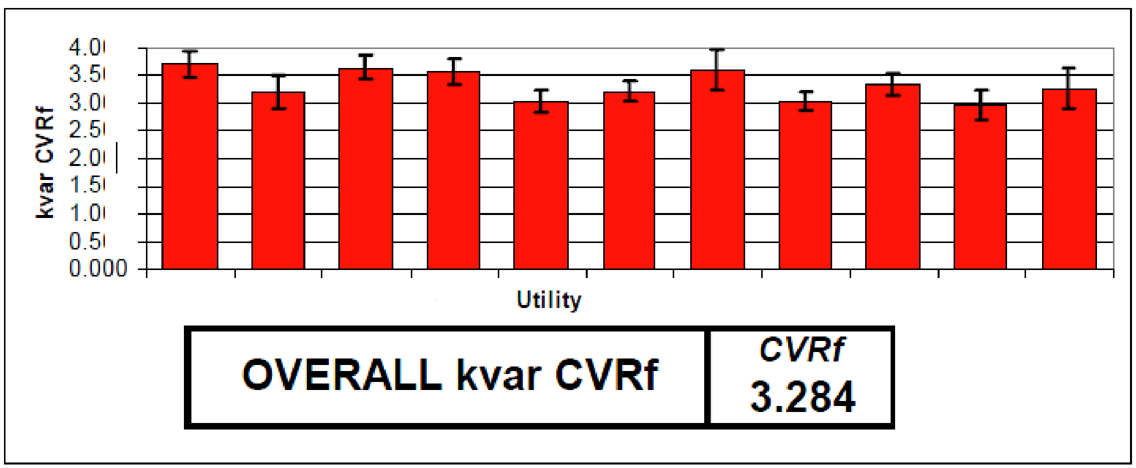
CVRf	Mean Voltage Reduction		Mean Energy Reduction
pu	%	V	%
0.1	3.29%		0.2%
0.2	2.33%	2.86	0.5%
0.3	2.83%	3.47	0.8%
0.7-0.9	1.5% - 2.5%		1.1%-2.2%
0.6	2.00%		1.2%
0.5	2.96%	3.66	1.4%
0.8	2.00%		1.5%
0.6	2.98%		1.7%
0.2-0.7			1.8%
0.6	3.28%		2.0%
0.7	2.98%		2.1%
0.6	3.42%	4.22	2.1%
0.9	2.50%		2.1%
0.7	2.94%	3.61	2.2%
0.7	3.57%		2.4%
0.6	3.95%		2.4%
1.1	2.38%	2.9	2.6%
2.5	1.05%	1.3	2.6%
1.0	2.87%	3.54	2.7%
1.6	1.71%	2.08	2.8%
1.1	2.64%	3.25	3.0%
			3.4%
3.0	1.18%	1.4	3.5%
1.2	3.21%	3.9	3.9%
0.9	4.44%	5.3	4.0%
			4.0%
1.0	4.23%	5.1	4.2%
1.6	2.90%	3.5	4.6%
2.7	1.84%	2.26	4.9%
1.5	3.77%	4.69	5.6%
1.9	3.17%	3.8	6.0%
4.7	1.72%	2.09	8.1%

CVR Also Impacts Reactive Power

Oscillating Fan







kvar CVR factor Results by Utility

Effect of CVR on kVAR is more significant than on kW

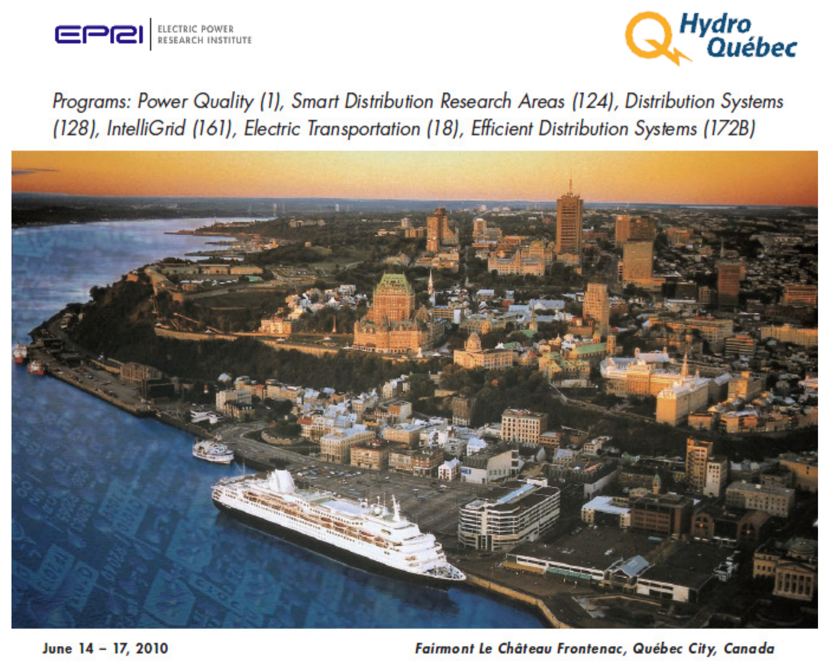
kW CVRf ≈ 0.7

kVAR CVRf ≈ 3.0

Distribution Efficiency Initiative
Northwest Energy Efficiency Alliance

Summary of Voltage Optimization Benefits

- **Voltage optimization is a very effective energy efficiency measure**
  - Demand Reduction - 1.5% to 2.1%; Energy Reduction - 1.3% - 2%
  - “Painless” efficiency measure for utilities and customers
  - Cost effective – Leverage existing equipment
  - Short implementation schedule
- **Reduce number of tap changer operations**
- **Improved voltage profile**
- **Early detection of:**
  - Voltage quality problems
  - Voltage regulator problems



EPRI PQ/Smart Distribution Conference & Expo June 2010

Approaches to Volt VAR Control

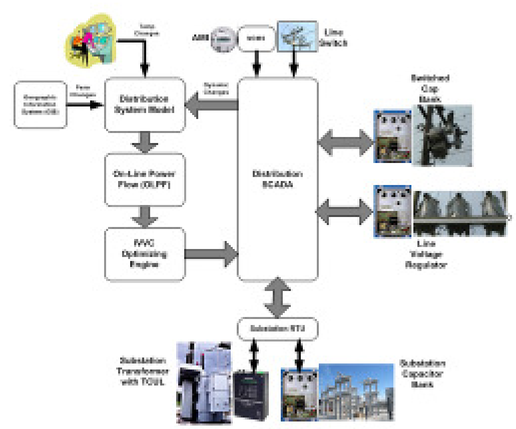
- Standalone Voltage regulator and LTC controls with line drop compensation set to “end-of-line” voltage for CVR

- On-Site Voltage Regulator (OVR) for single location voltage regulation

- “Rule-based” DA control of capacitor banks and voltage regulators for CVR with/without voltage measurement feedback from end of line

- “Heuristic” voltage regulation (e.g. PCS Utilidata “AdaptiVolt”, Cooper Power Systems IVVC)

- “Distribution model based” Volt-VAR Optimization



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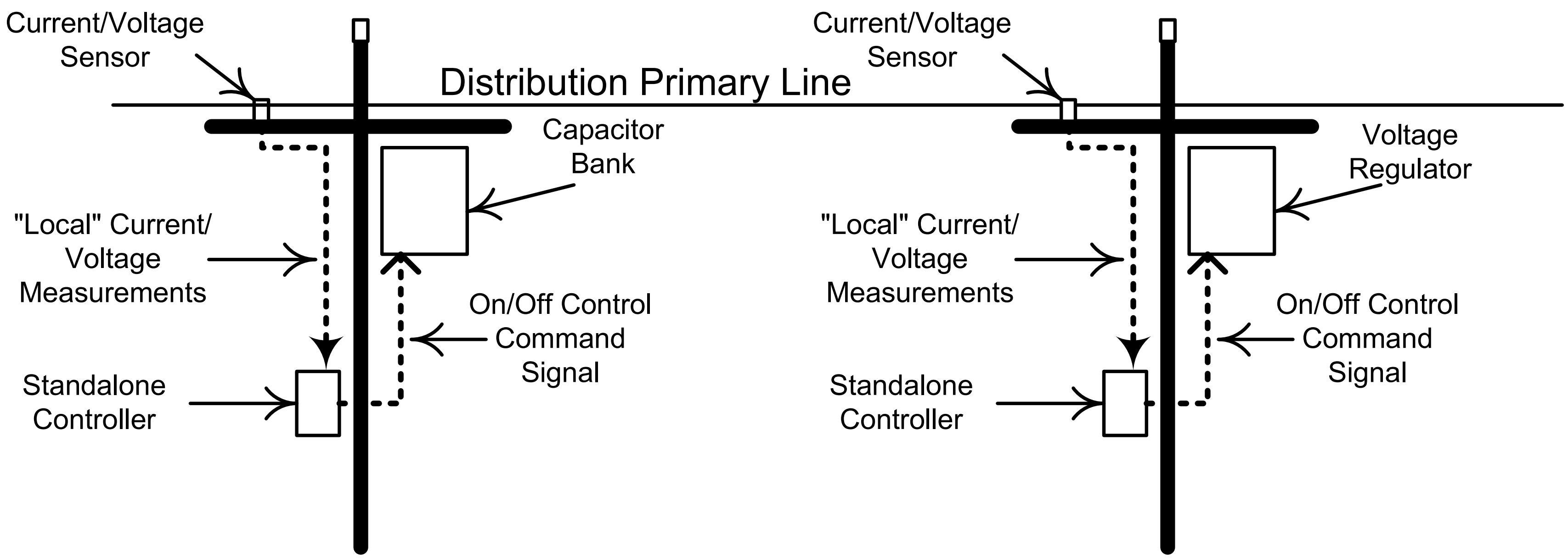
Standalone Controller Approach

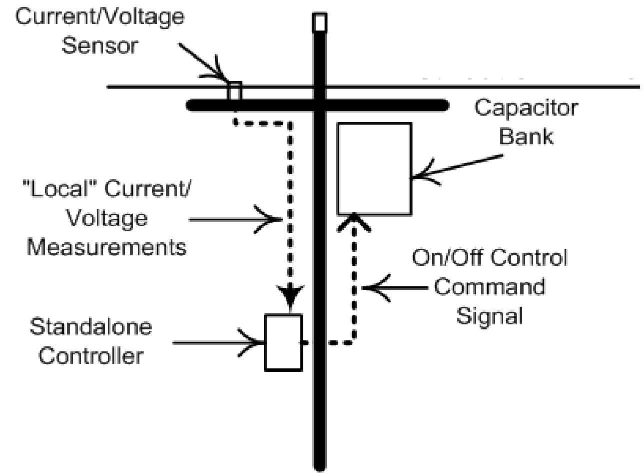
- ***VV Control managed by individual, independent, standalone volt-VAR regulating devices:***
  - Substation transformer load tap changers (LTCs) with voltage regulators
  - Line voltage regulators
  - Fixed and switched capacitor banks



Reactive Power Compensation Using Fixed and Switched Capacitor Banks

- Switch single capacitor bank on or off based on "local" conditions (voltage, load, reactive power, etc.)
- **Control parameters**
  - Power Factor
  - Load Current
  - Voltage
  - Var Flow
  - Temperature
  - Time of day and day of week

Standalone Volt VAR Controllers - Strengths and Weakness



- **Strengths**
  - Low cost – no cost
  - Minimal learning curve
  - Does not rely at all on field communications
  - Very scalable approach – can do one feeder or many

- **Weaknesses**
  - No self monitoring features
  - Lacks coordination between volt and VAR controls – not able to block counter-acting control actions
  - System operation may not be "optimal" under all conditions – need to build in bigger safety margin due to lack of "visibility" of remote conditions
  - Lacks flexibility to respond to changing conditions out on the distribution feeders – can misoperate following automatic reconfiguration
  - May not handle high penetration of DG very effectively
  - Cannot override traditional operation during power system emergencies

"SCADA" Controlled Volt-VAR

- Volt-VAR power apparatus monitored and controlled by Supervisory Control and Data Acquisition (SCADA)
- Volt-VAR Control typically handled by two separate (independent) systems:
  - **VAR Dispatch** – controls capacitor banks to improve power factor, reduce electrical losses, etc
  - **Voltage Control** – controls LTCs and/or voltage regulators to reduce demand and/or energy consumption (aka, **Conservation Voltage Reduction**)
- Operation of these systems is primarily based on a **stored set of predetermined rules** (e.g., *"if power factor is less than 0.95, then switch capacitor bank #1 off")*

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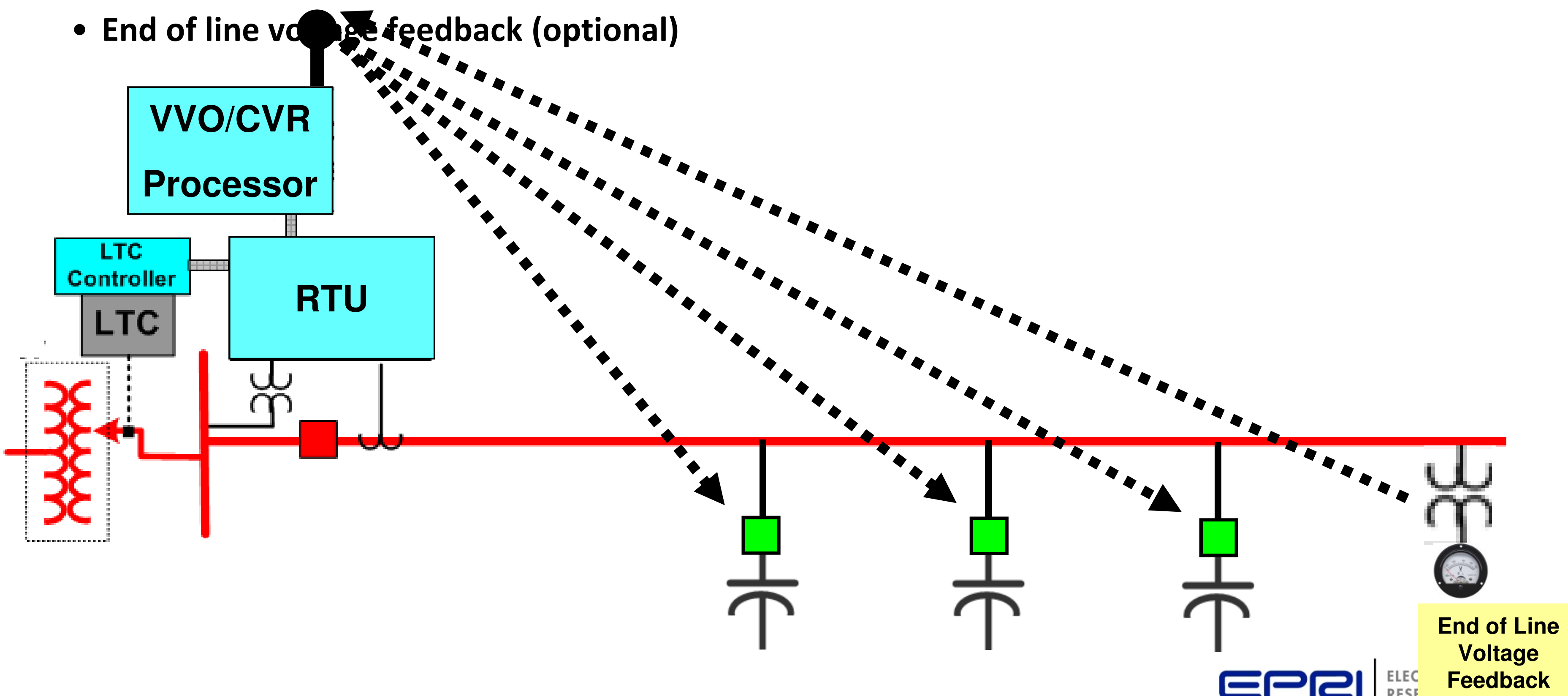
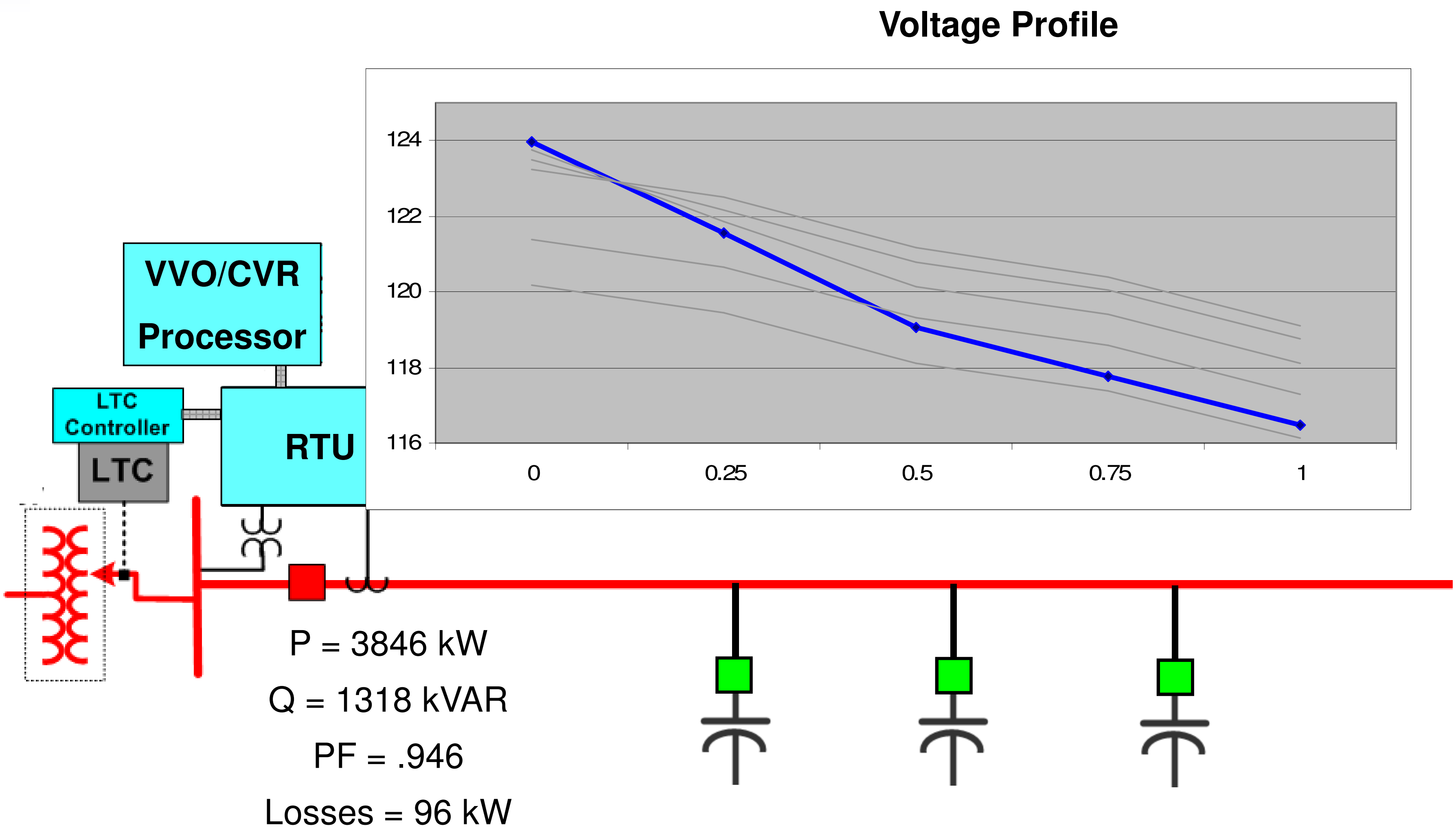
SCADA (Rule Based) Volt-VAR Control System Components

- Substation Remote Terminal Unit (RTU) – handles device monitoring and control
- VVO/CVR processor – contains "rules" for volt and VAR control
- Switched Cap banks & local measurement facilities
- Voltage regulators (LTCs) & local measurement facilities
- Communication facilities
- End of line voltage feedback (optional)



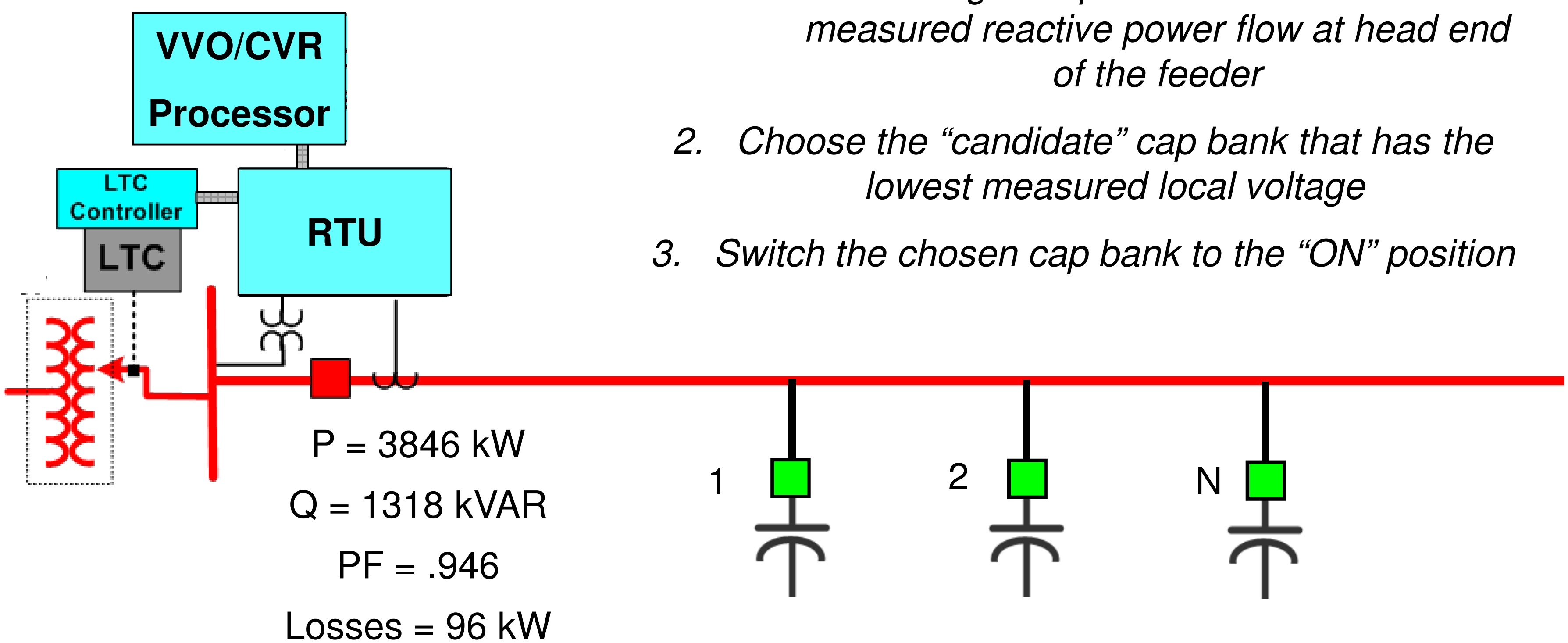
SCADA (Rule Based) Volt-VAR Control
Part 1: VAR Control (Power Factor Correction)



SCADA (Rule Based) Volt-VAR Control
Part 1: VAR Control (Power Factor Correction)

Sample Rules:

1. *Identify "candidate" cap banks for switching*
   - *Cap bank "i" is currently "off"*
   - *Rating of cap bank "i" is less than measured reactive power flow at head end of the feeder*
2. *Choose the "candidate" cap bank that has the lowest measured local voltage*
3. *Switch the chosen cap bank to the "ON" position*



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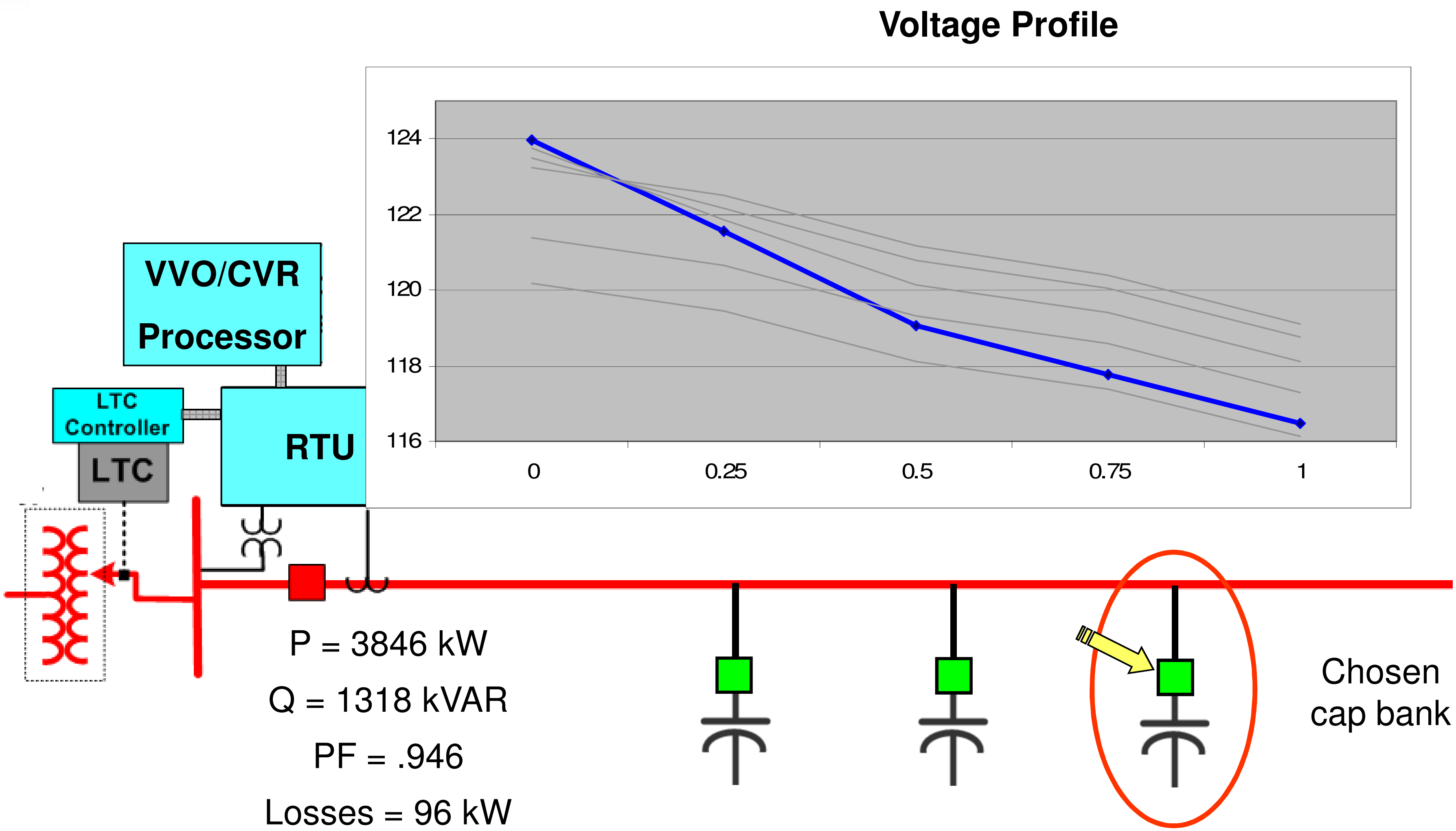

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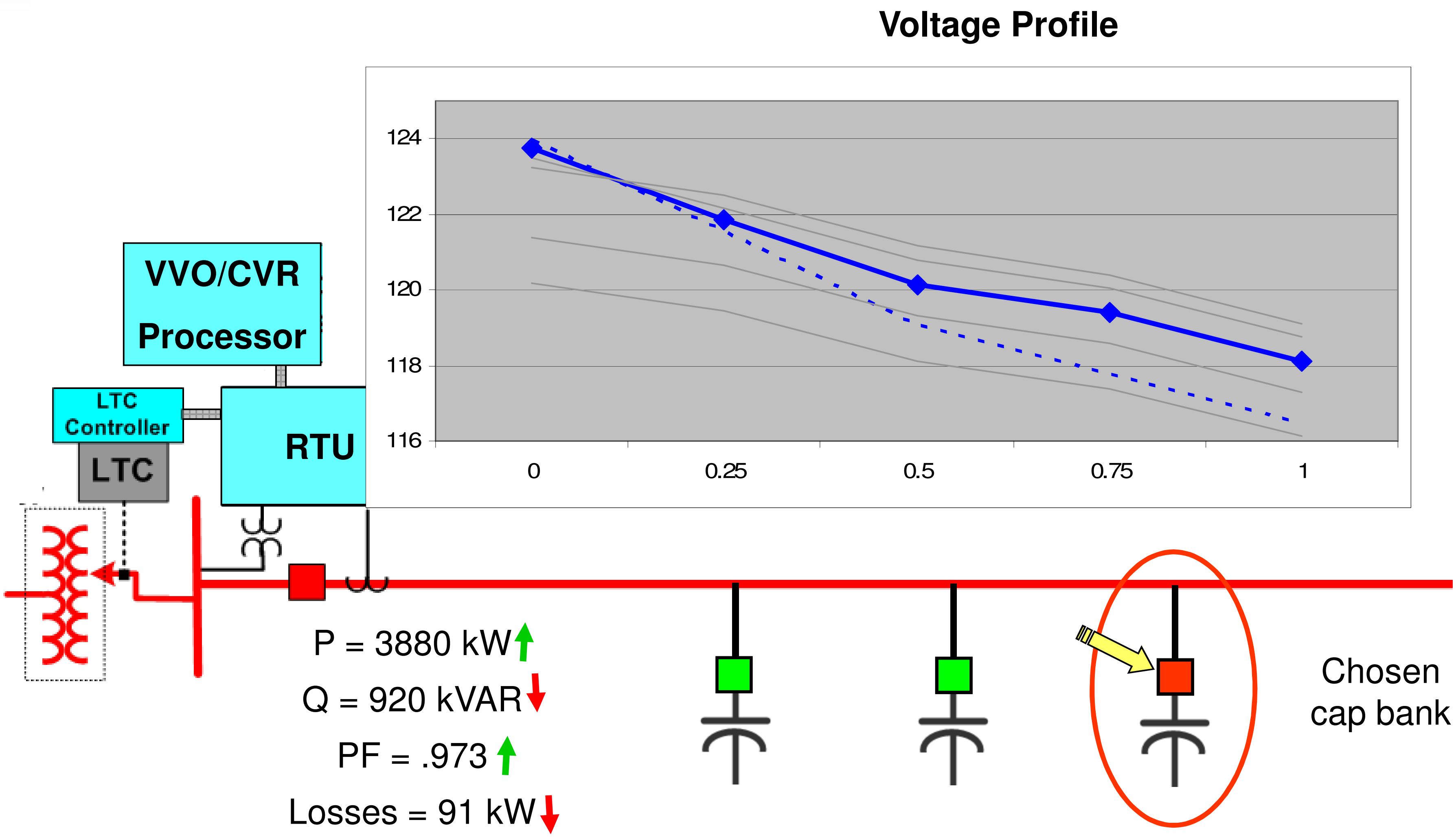

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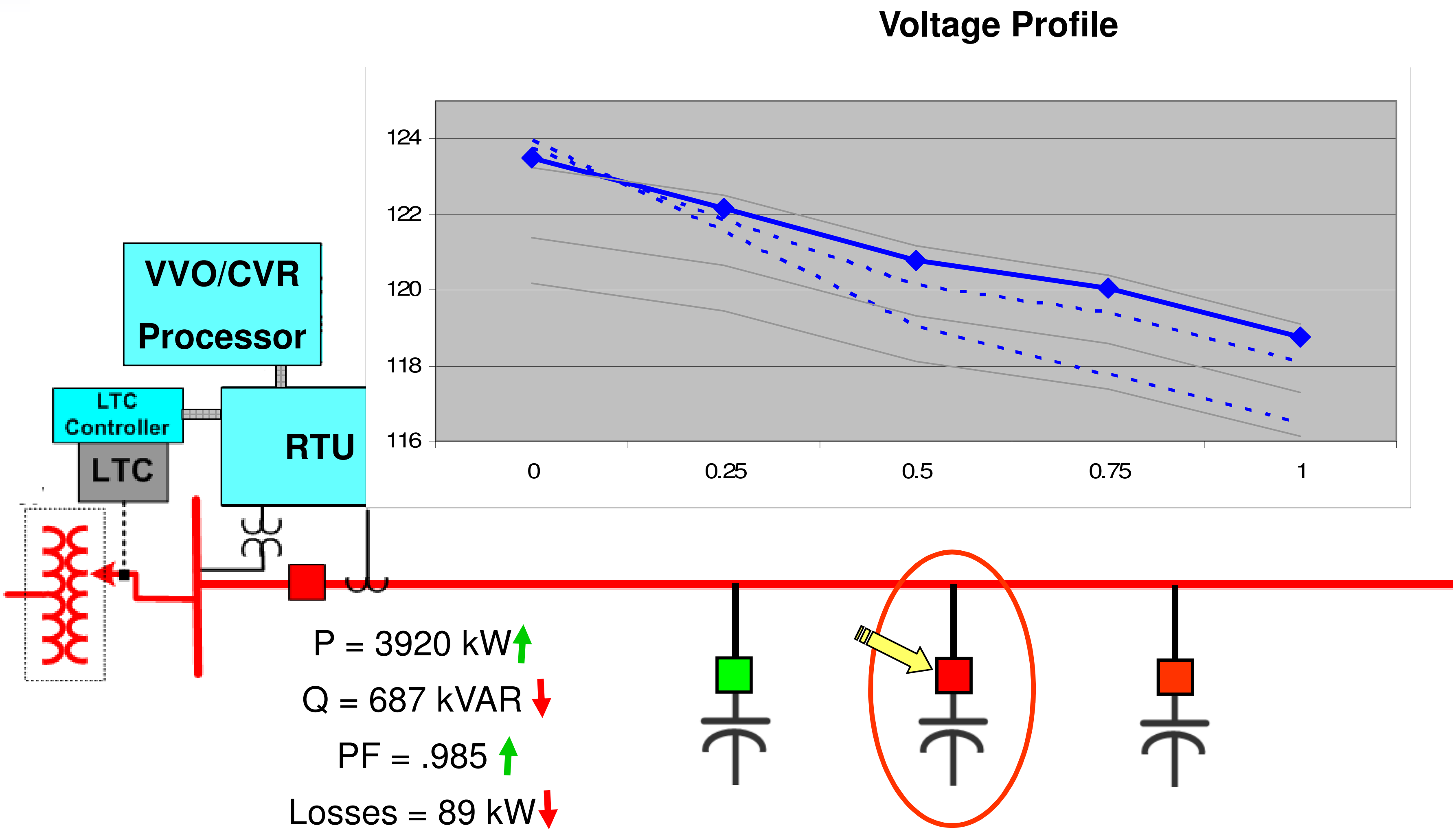

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SCADA (Rule Based) Volt-VAR Control
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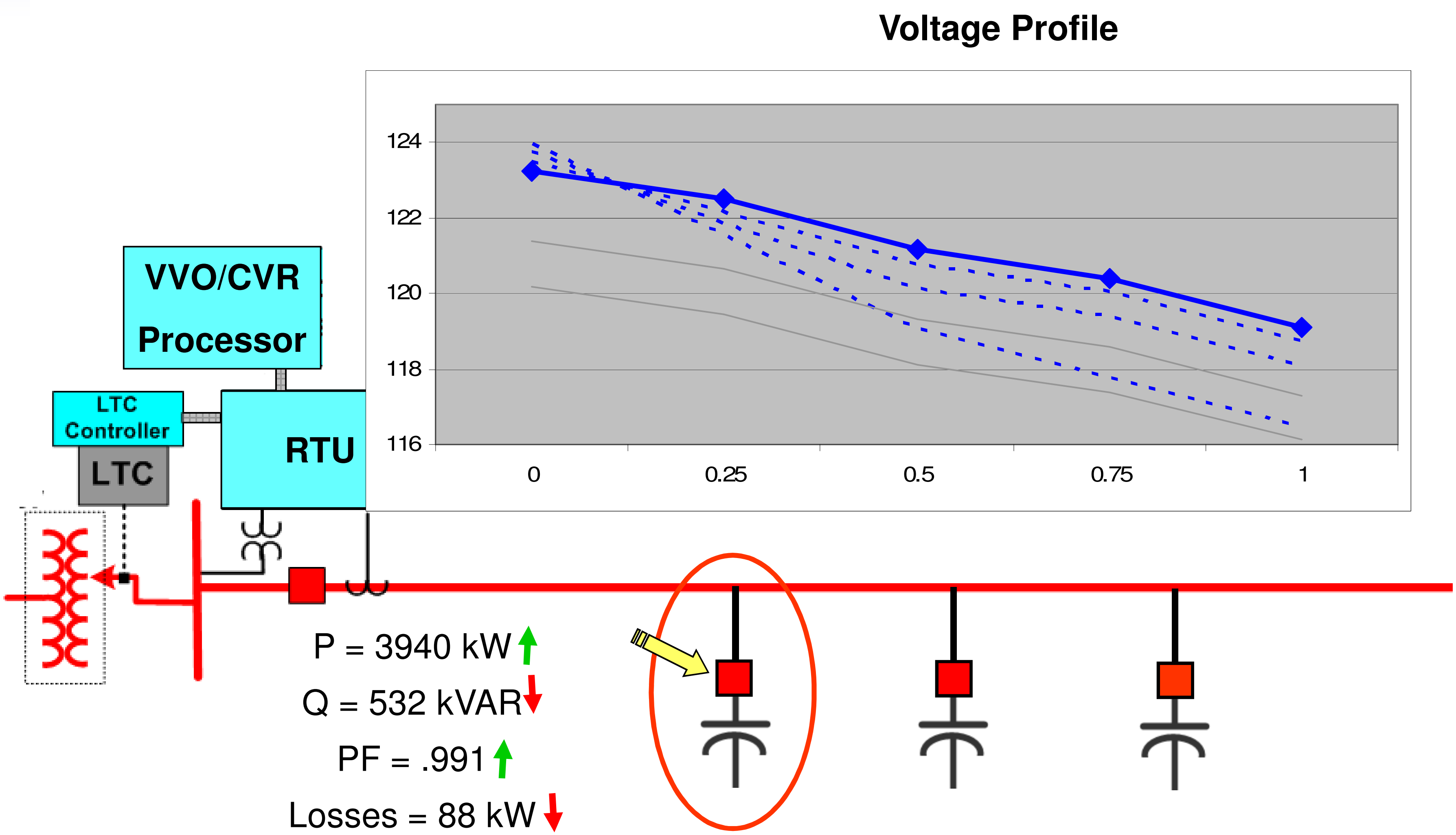
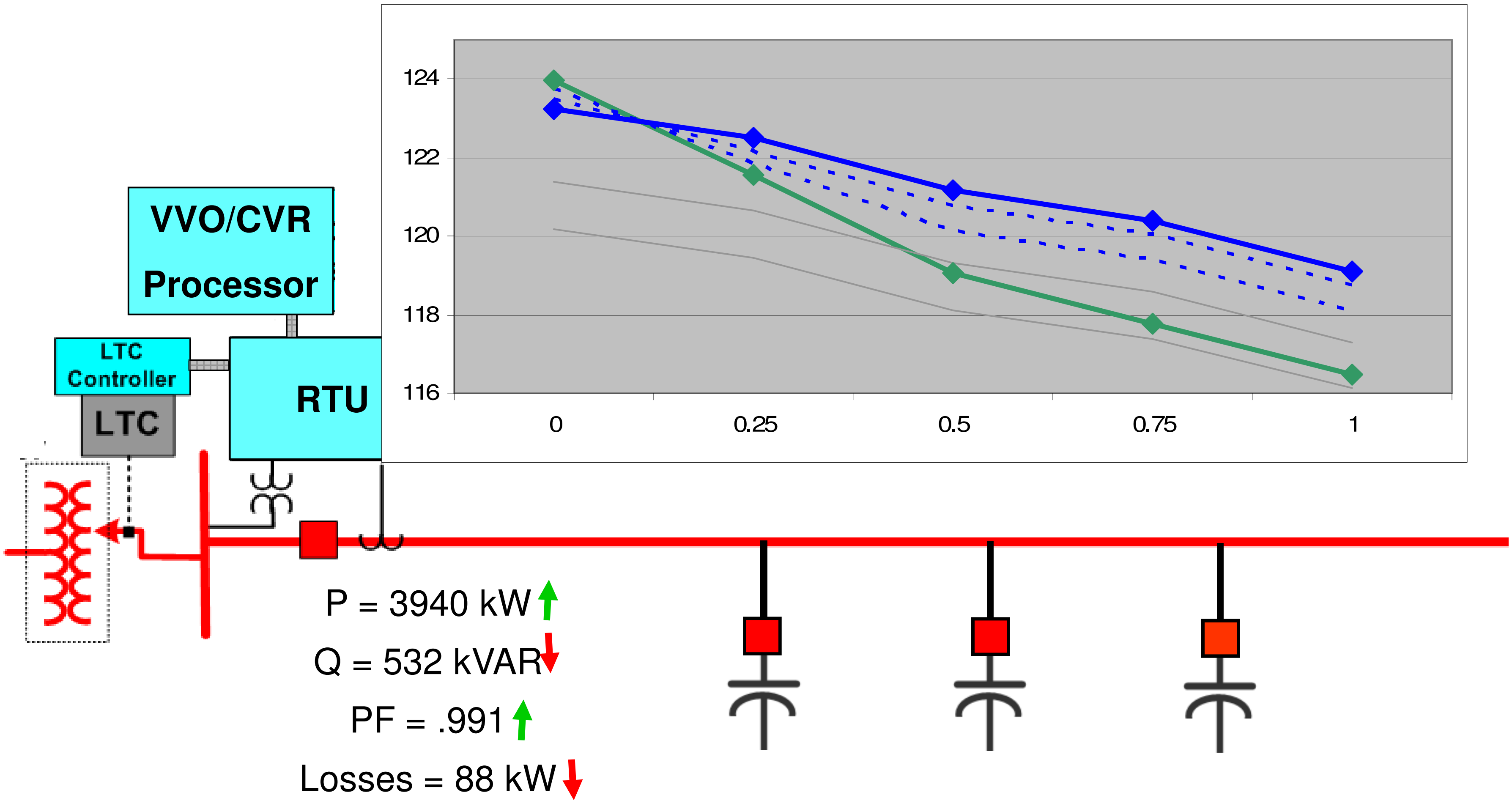
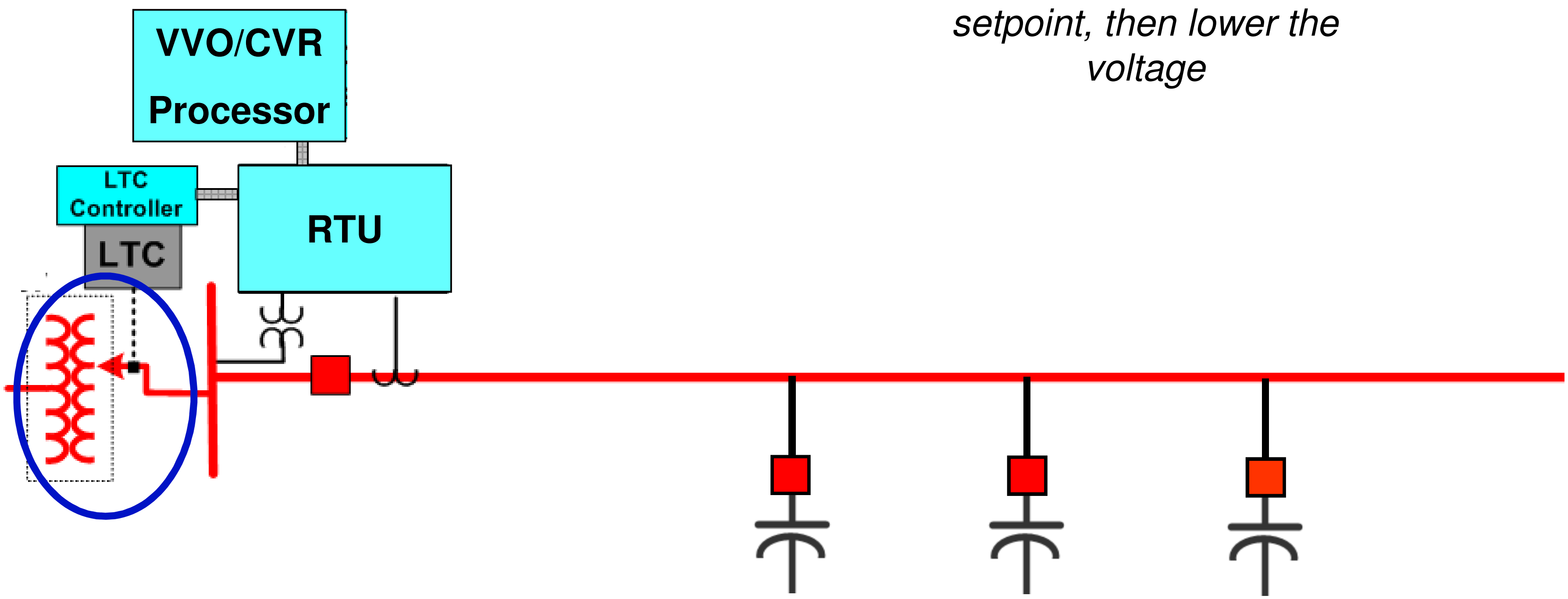


SCADA (Rule Based) Volt-VAR Control
Part 1: VAR Control (Power Factor Correction)

Voltage Profile *Before and After*



SCADA (Rule Based) Volt-VAR Control
Part 2: Voltage Control (CVR)



<u>Sample rule for voltage reduction:</u>

1. *If voltage at head end of the feeder exceeds LTC setpoint, then lower the voltage*

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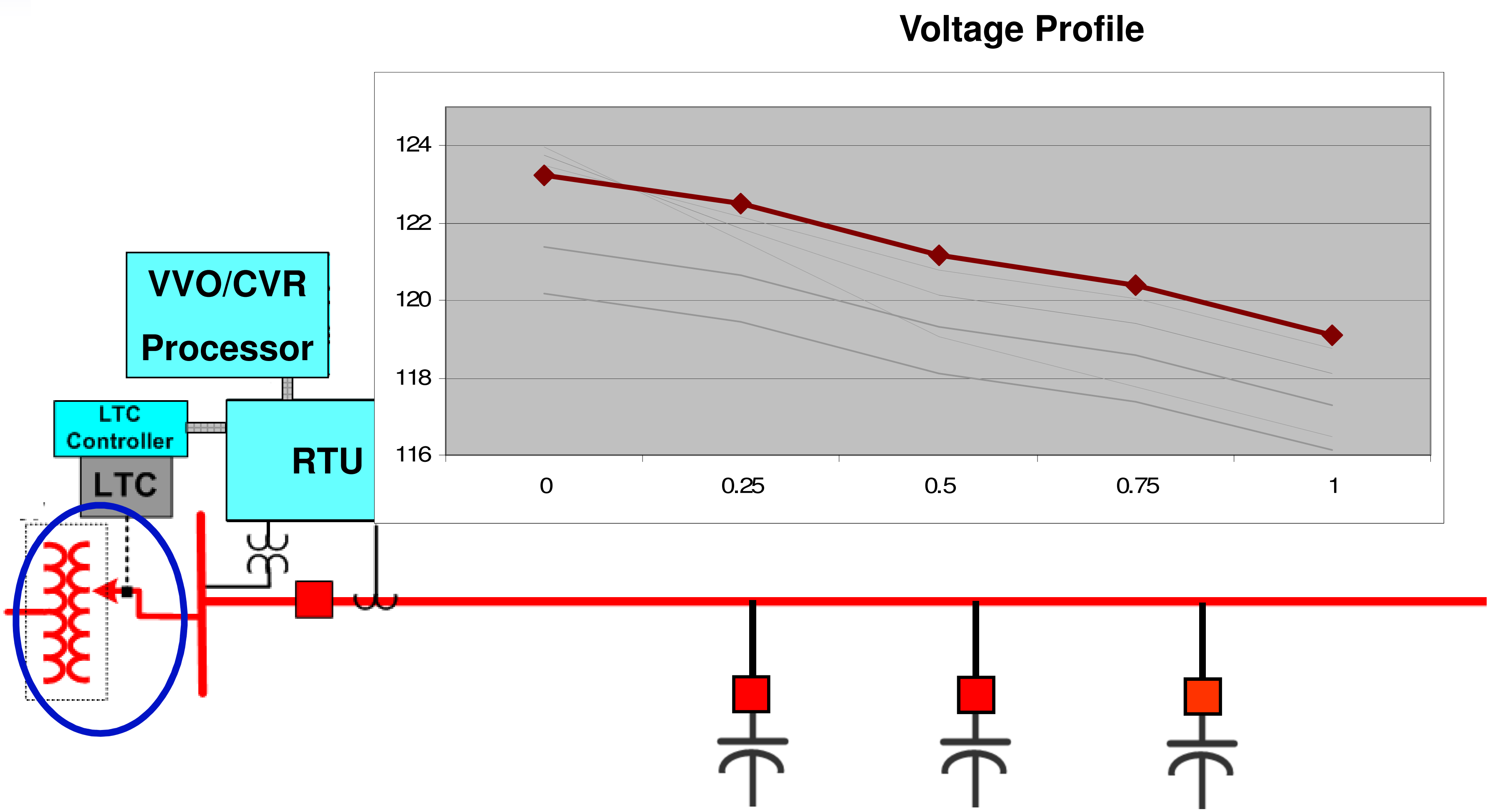
SCADA (Rule Based) Volt-VAR Control
Part 2: Voltage Control (CVR)



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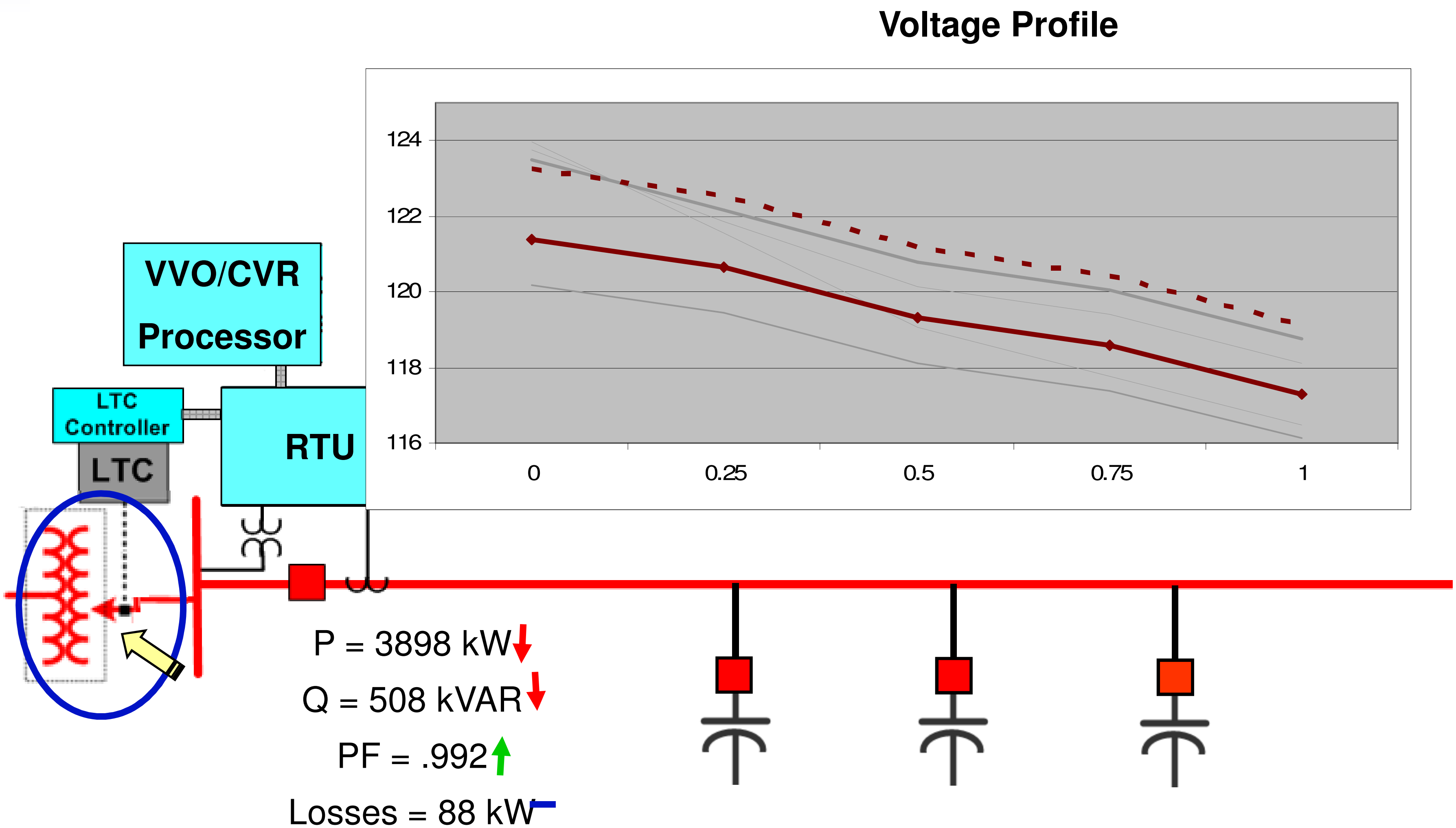

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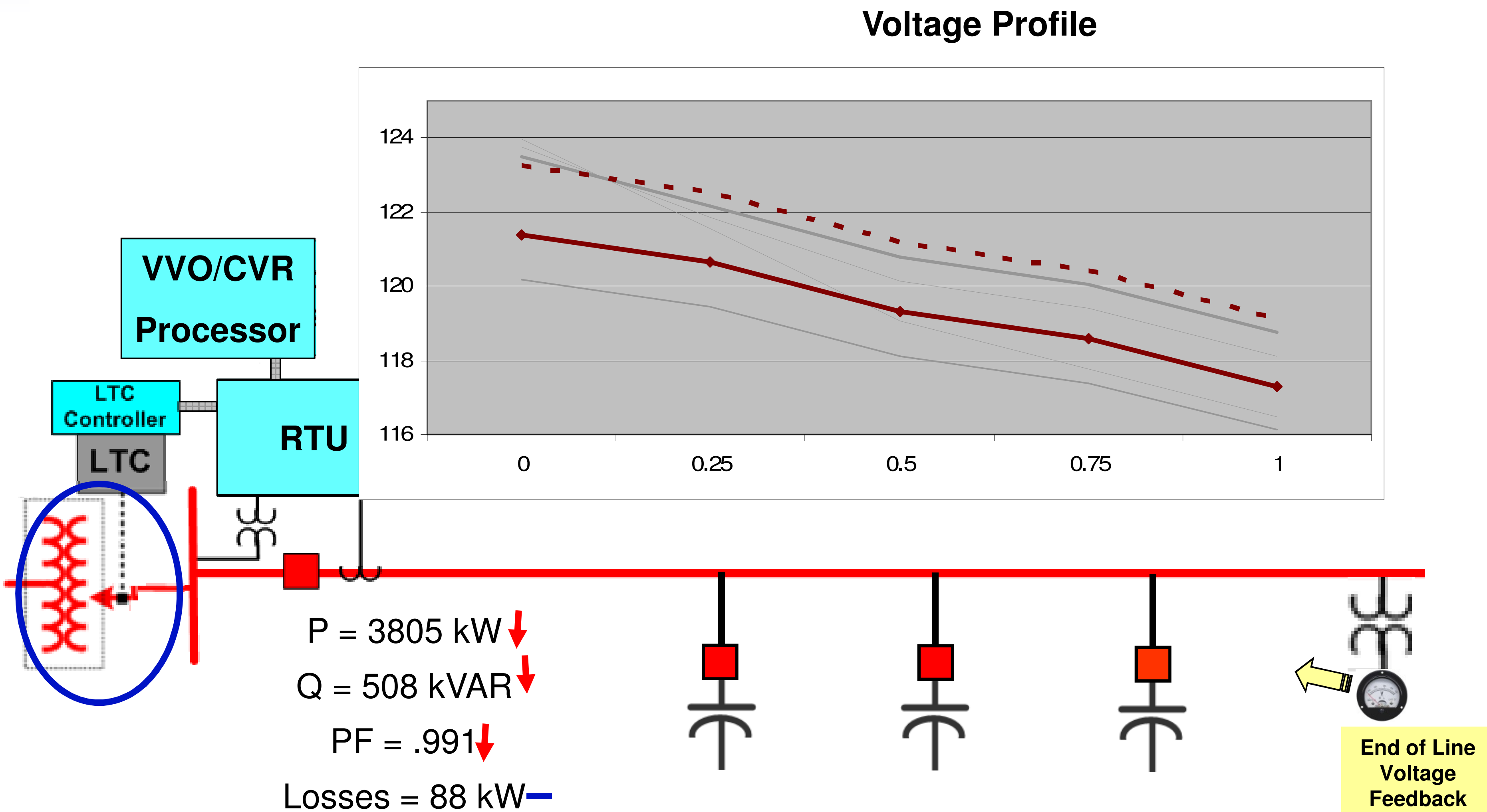

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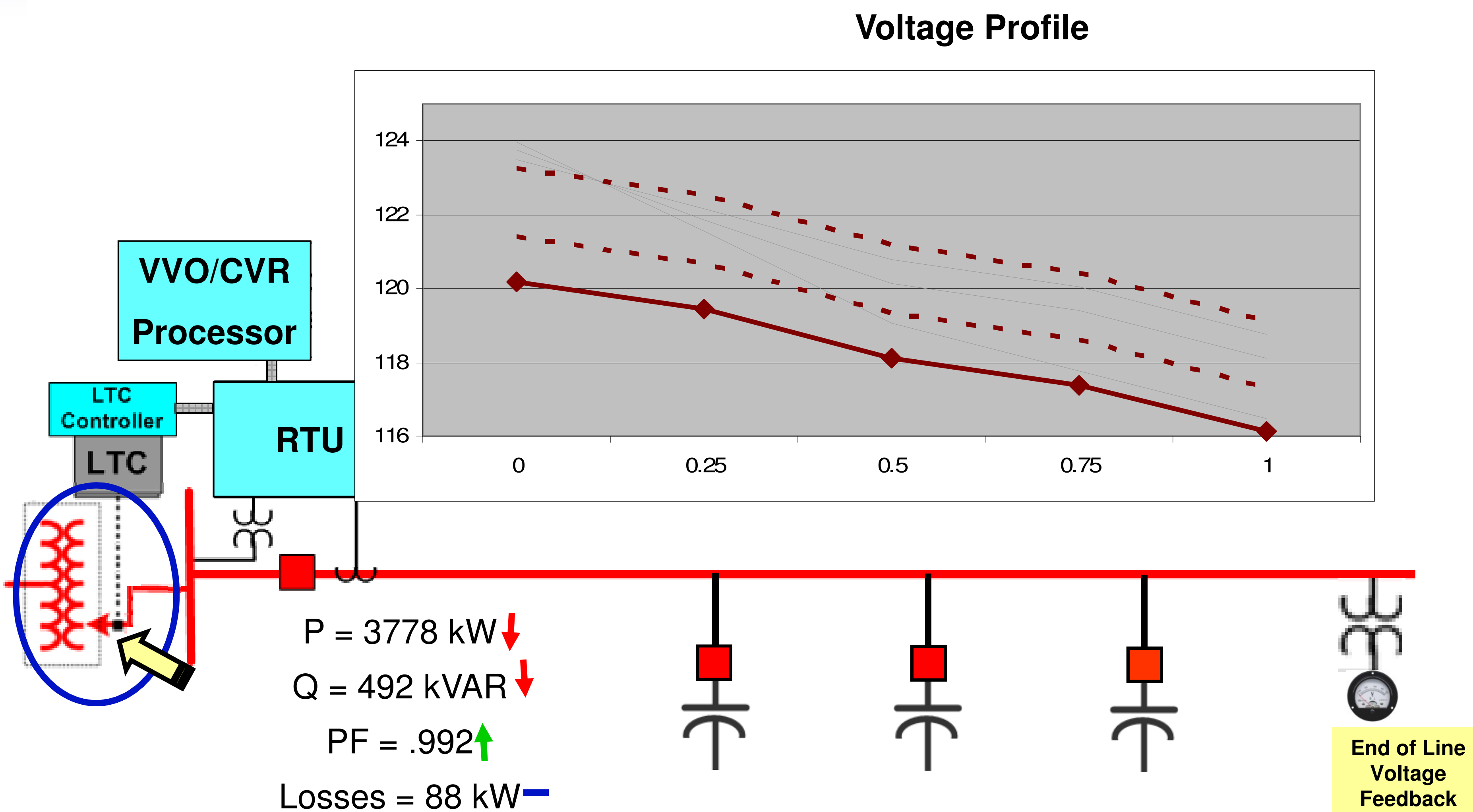

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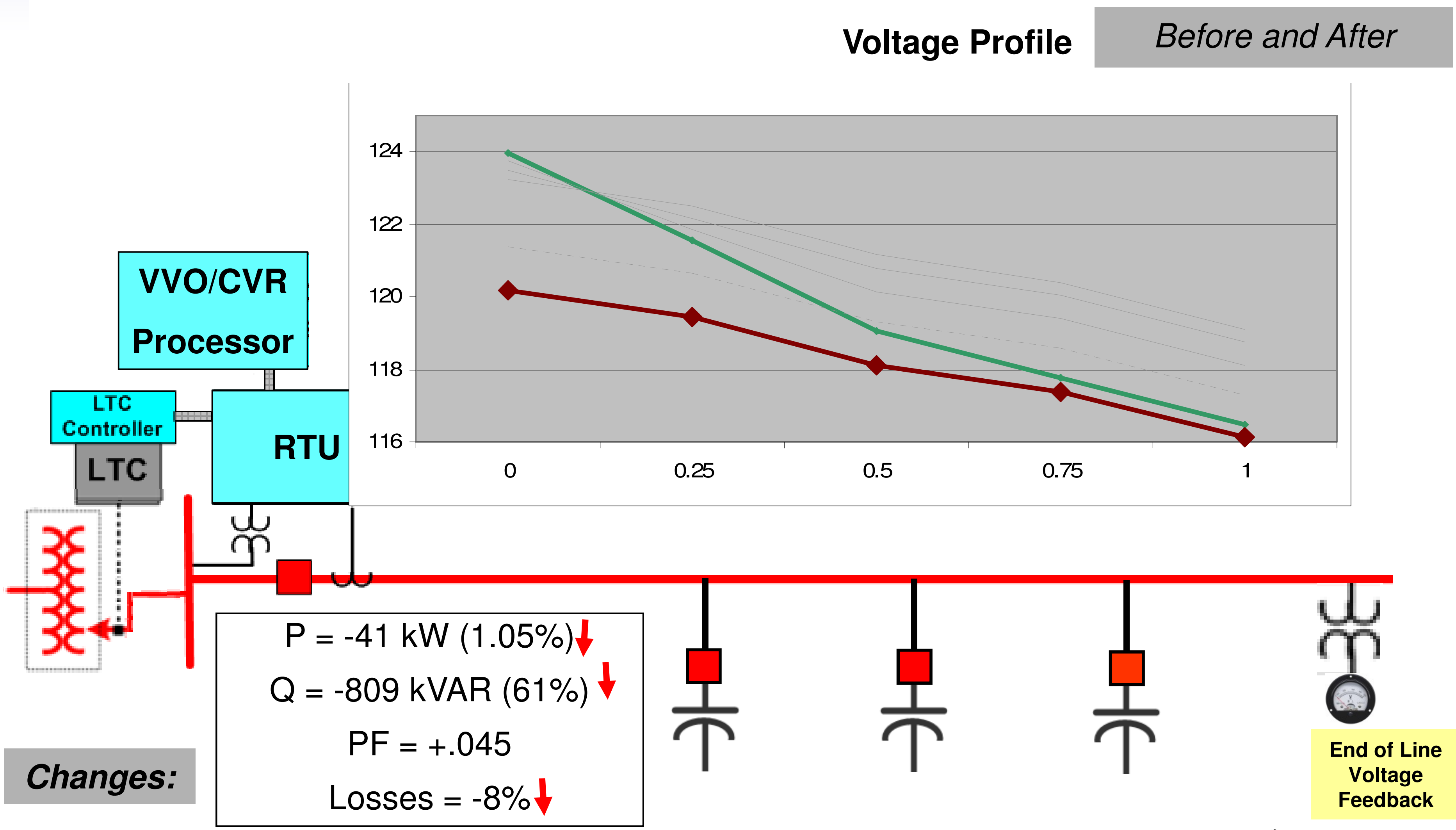

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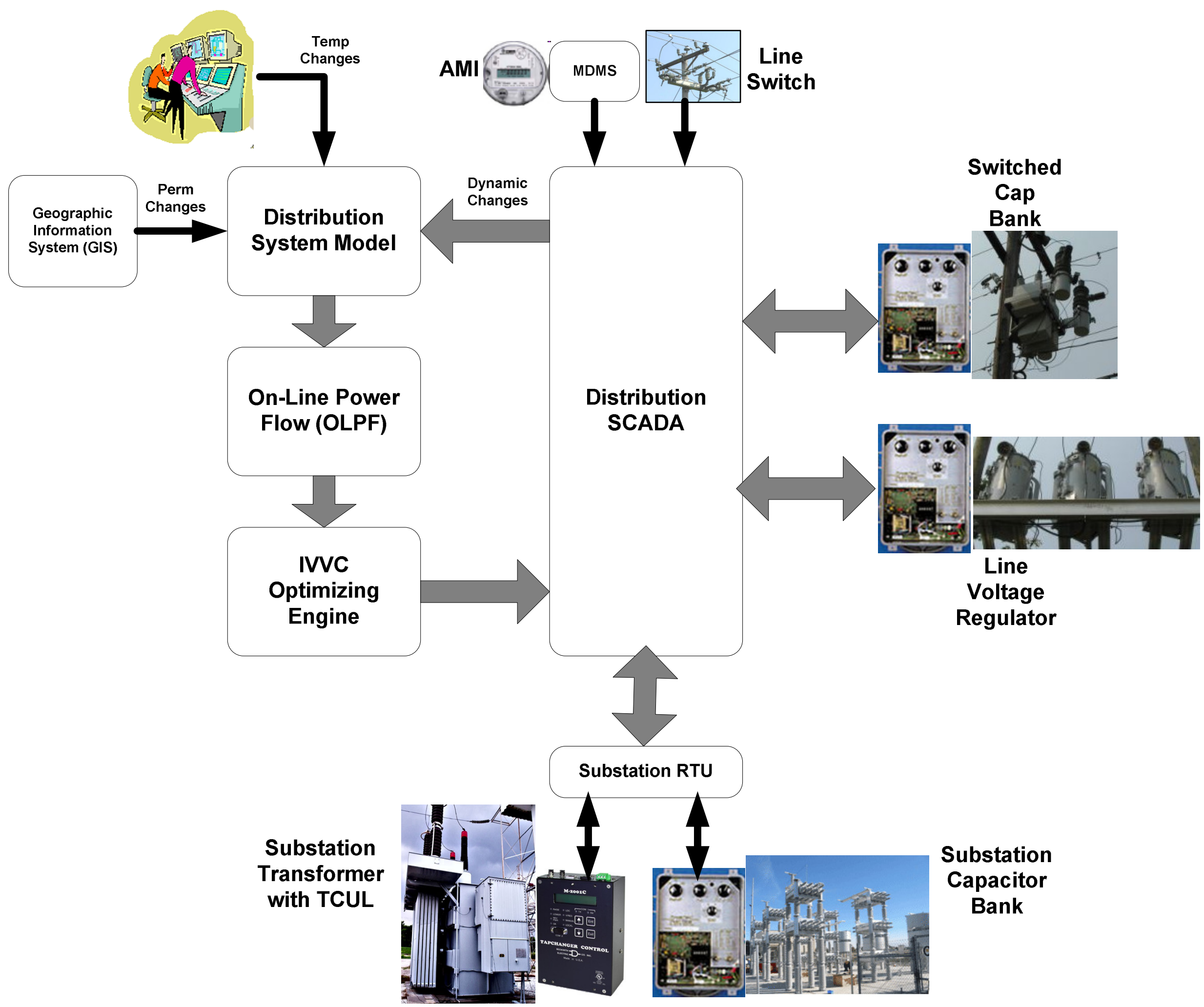
SCADA Controlled Volt VAR Summary

- **Strengths:**
  - Usually **some efficiency improvement** versus standalone controllers
  - **Self monitoring**
  - **Can override operation** during system emergencies
  - Can include remote measurements in the "rules" – smaller margin of safety needed
- **Weaknesses:**
  - **Somewhat less scalable** that standalone controllers (minimum deployment is one substation)
  - More complicated – requires extensive communication facilities
  - Does **not** adapt to **changing feeder configuration** (rules are fixed in advance)
  - Does **not** adapt well to **varying operating needs** (rules are fixed in advance)
  - Overall efficiency is improved versus traditional approach, but is **not necessarily optimal under all conditions**
  - Operation of VAR and Volt devices usually not **coordinated (separate rules for cap banks & Vregs)**
  - Does **not** adapt well to **presence of high DG penetration**

Distribution Model Driven Volt-VAR Control and Optimization

- Develops and executes a coordinated "optimal" switching plan for all voltage control devices to achieve utility-specified objective functions:
  - Minimize energy consumption
  - Minimize losses
  - Minimize power demand
  - Combination of the above
- Can bias the results to minimize tap changer movement and other equipment control actions that put additional "wear and tear" on the physical equipment

DMS Volt-VAR Optimization



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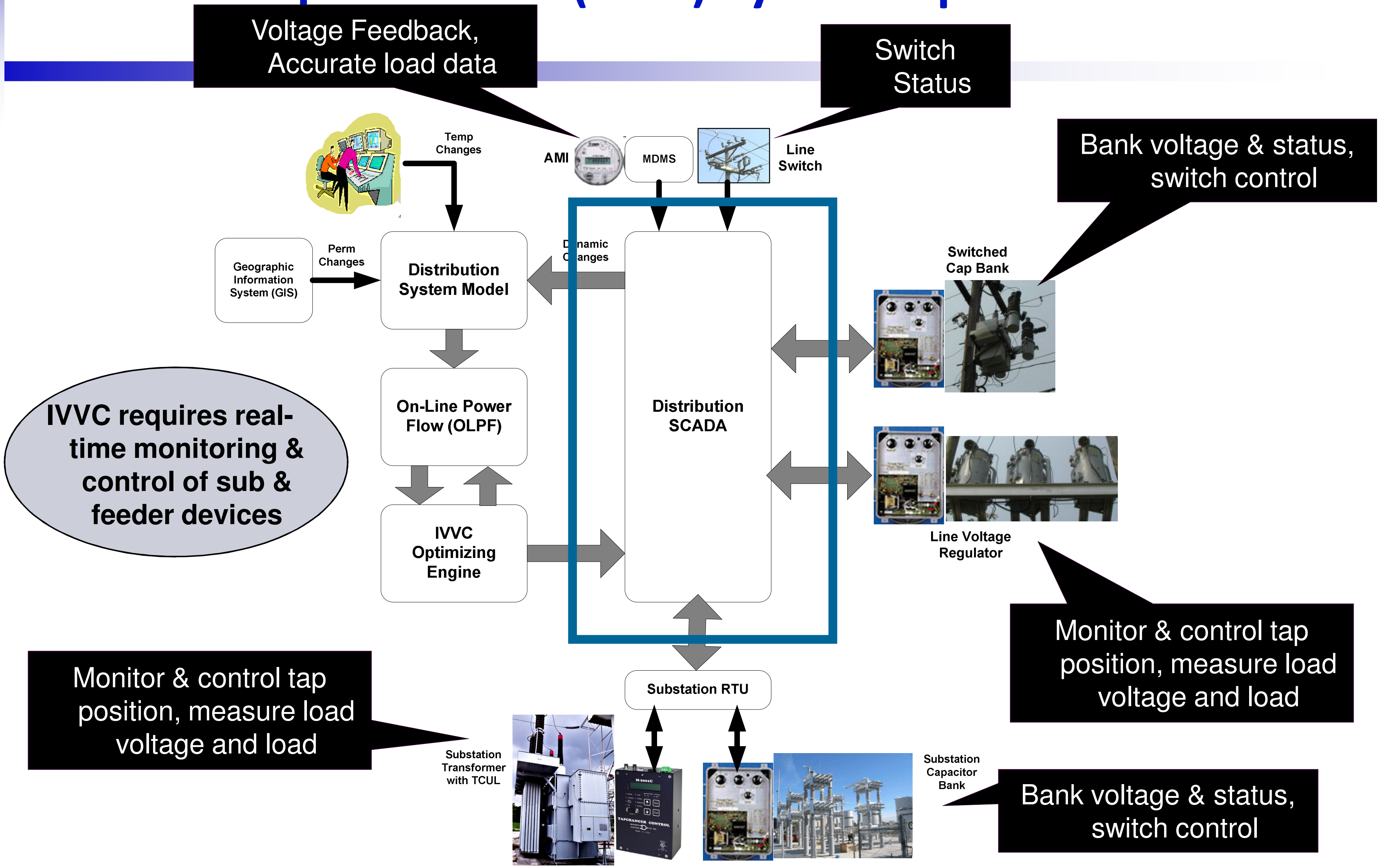
Volt VAR Optimization (VVO) System Operation



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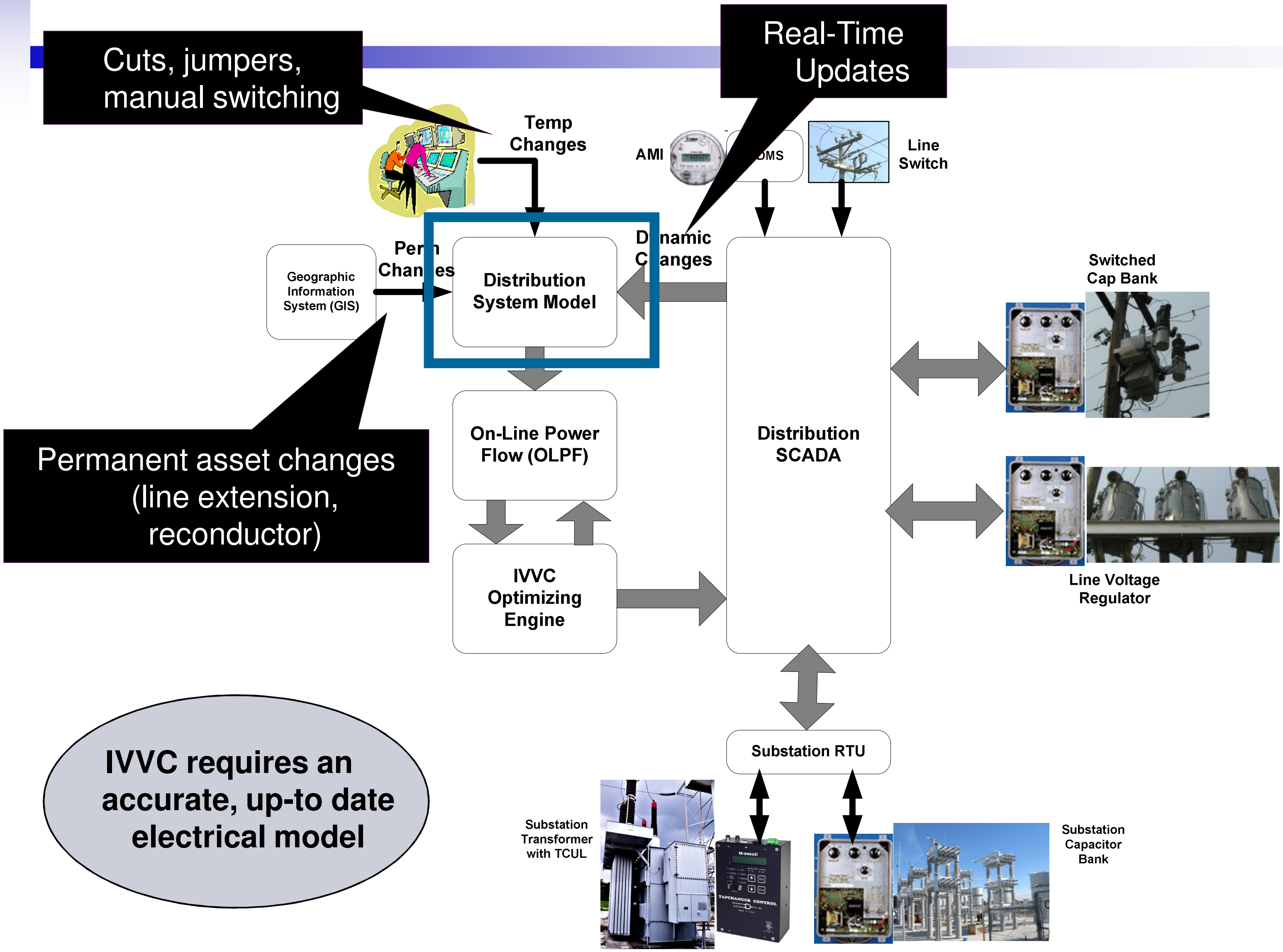
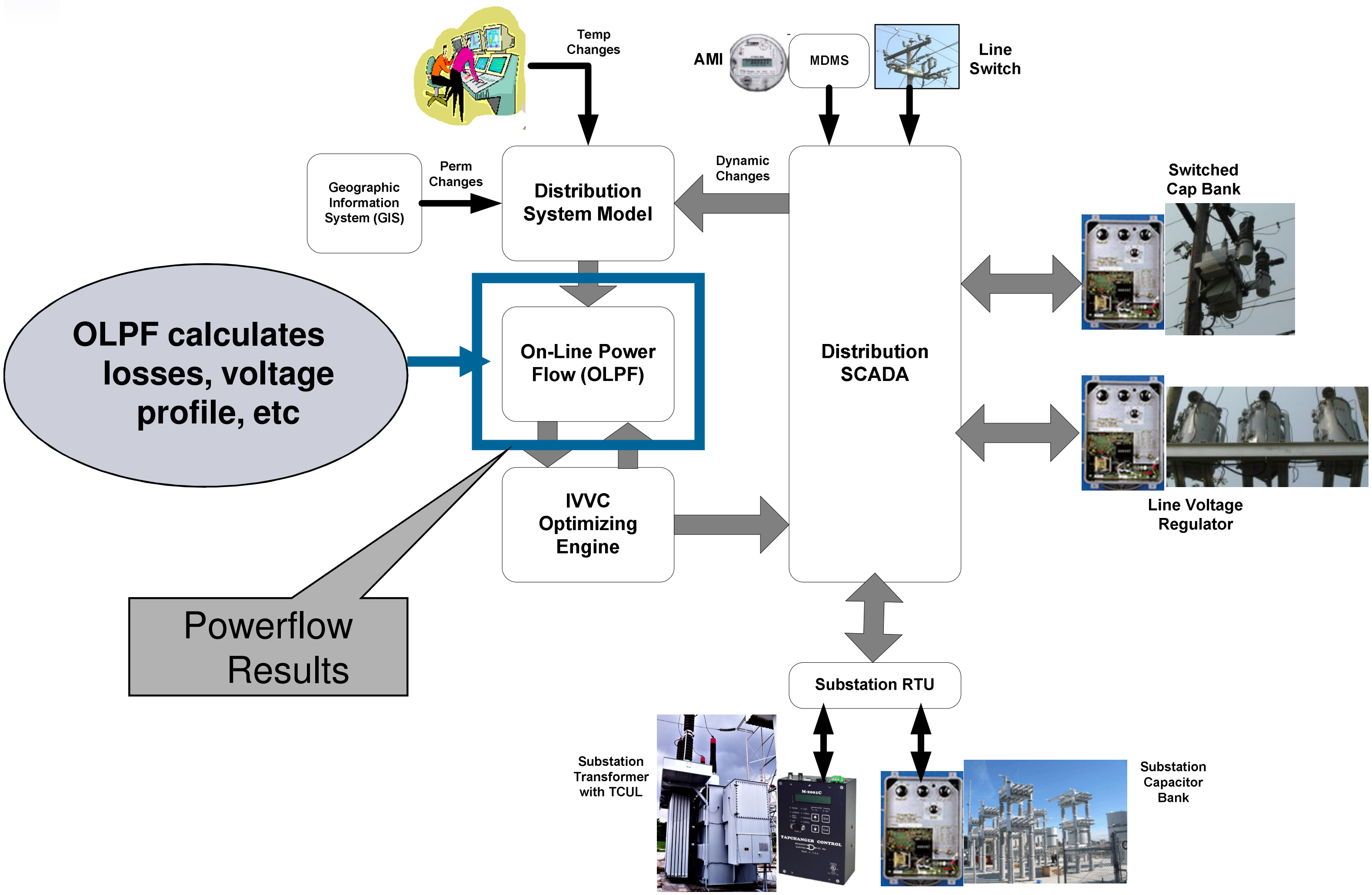
Volt VAR Optimization (VVO) System Operation



Volt VAR Optimization (VVO) System Operation



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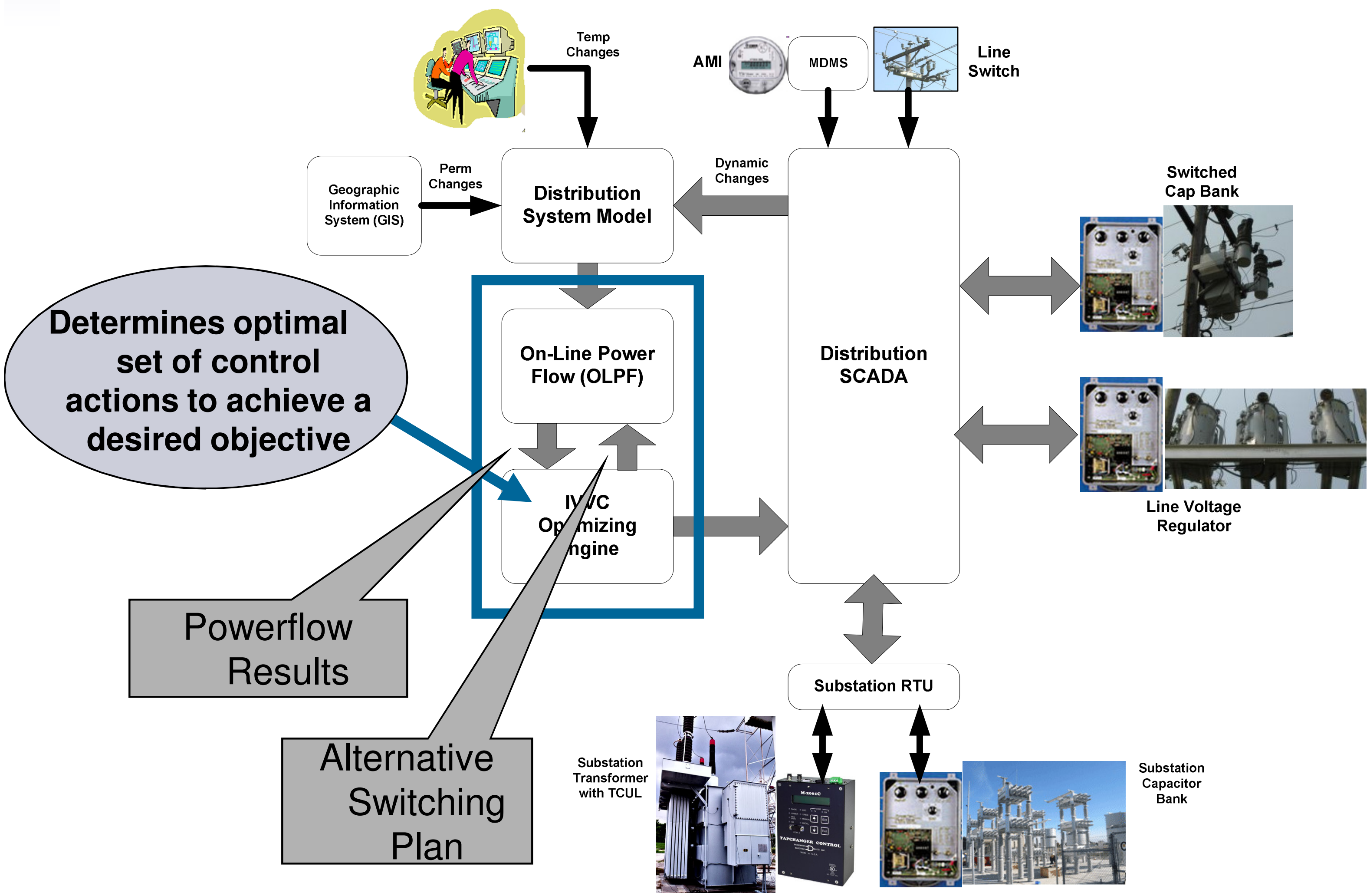
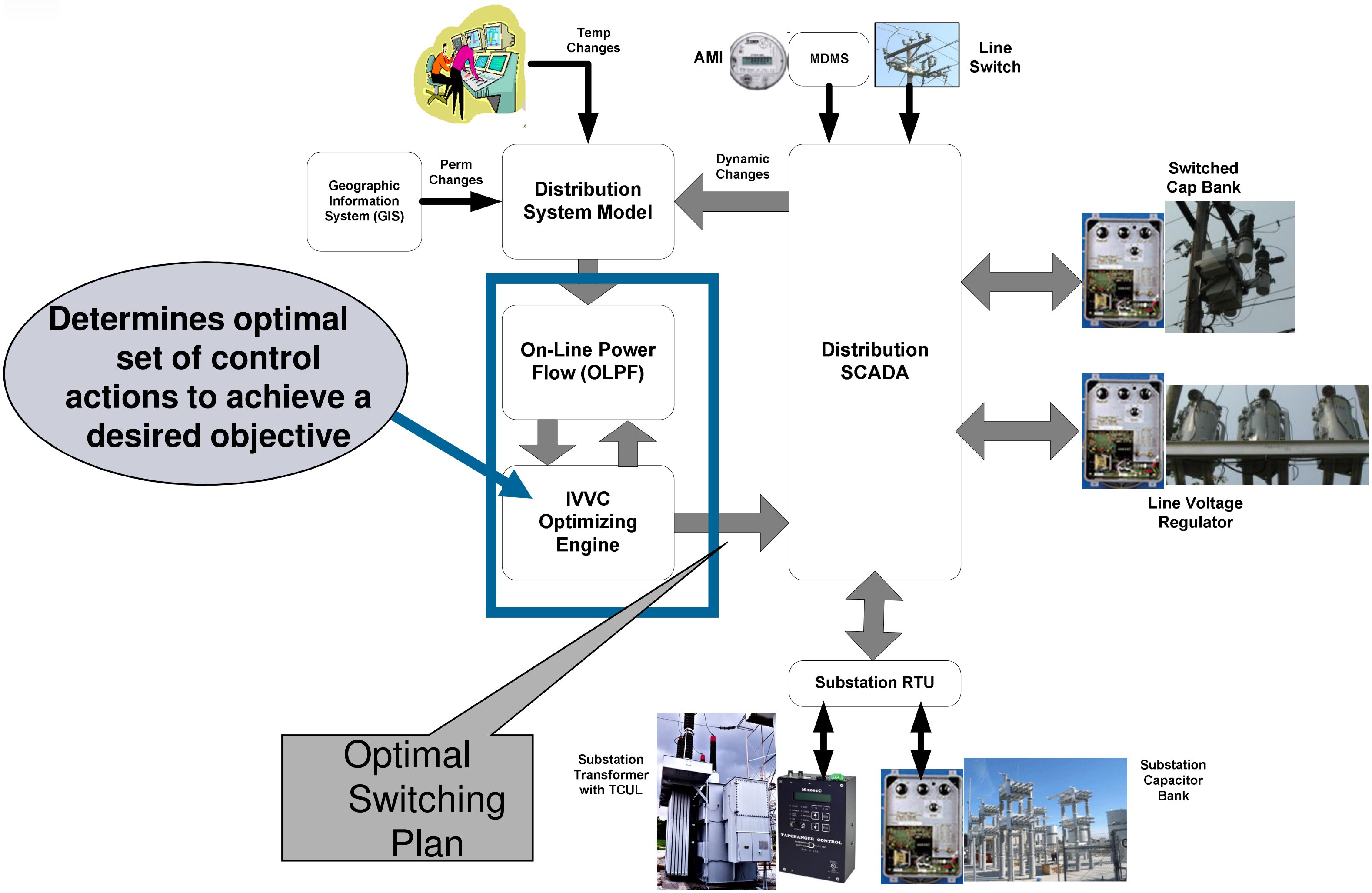
Volt VAR Optimization (VVO) System Operation



Volt VAR Optimization (VVO) System Operation



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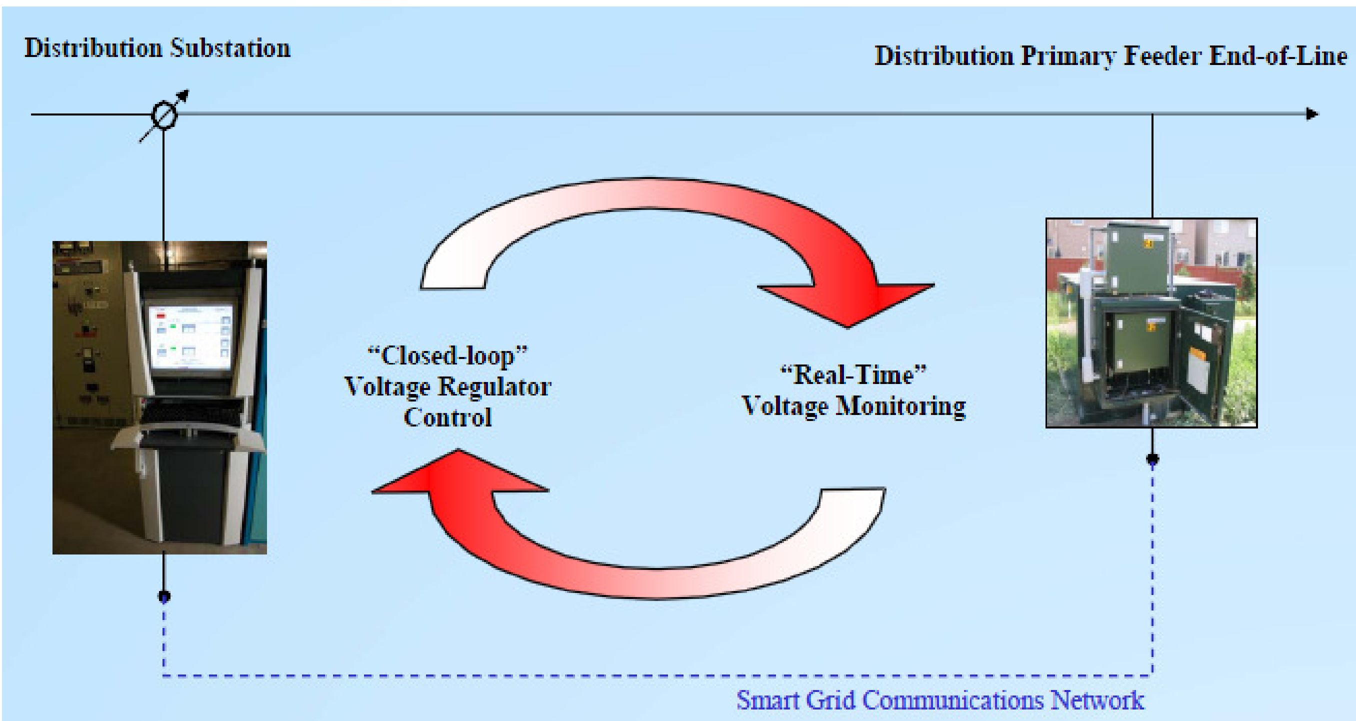
DMS-Based Volt VAR Optimization Strengths and Weaknesses

- **Strengths**
  - Fully coordinated, optimal solution
  - Flexible operating objectives - Accommodates varying operating objectives depending on present need
  - Able to handle complex feeder arrangements - Dynamic model updates automatically when reconfiguration occurs
  - Works correctly following feeder reconfiguration
  - System can model the effects of Distributed Generation and other modern grid elements - Handles high penetration of DER properly, including proper handling of reverse power flows
- **Weaknesses**
  - Not very scalable – would not use this approach for one feeder or substation due to high control center
  - High cost to implement, operate and sustain
  - Learning curve for control room personnel
  - Lack of field proven products

Auto-Adaptive Volt VAR Optimization

- processes real-time distribution system information to determine appropriate volt-VAR control actions and provide closed-loop feedback to accomplish electric utility specified objectives
- uses advanced signal processing techniques to determine what control actions are needed



Courtesy of PCS Utilidata

Auto-Adaptive Approach

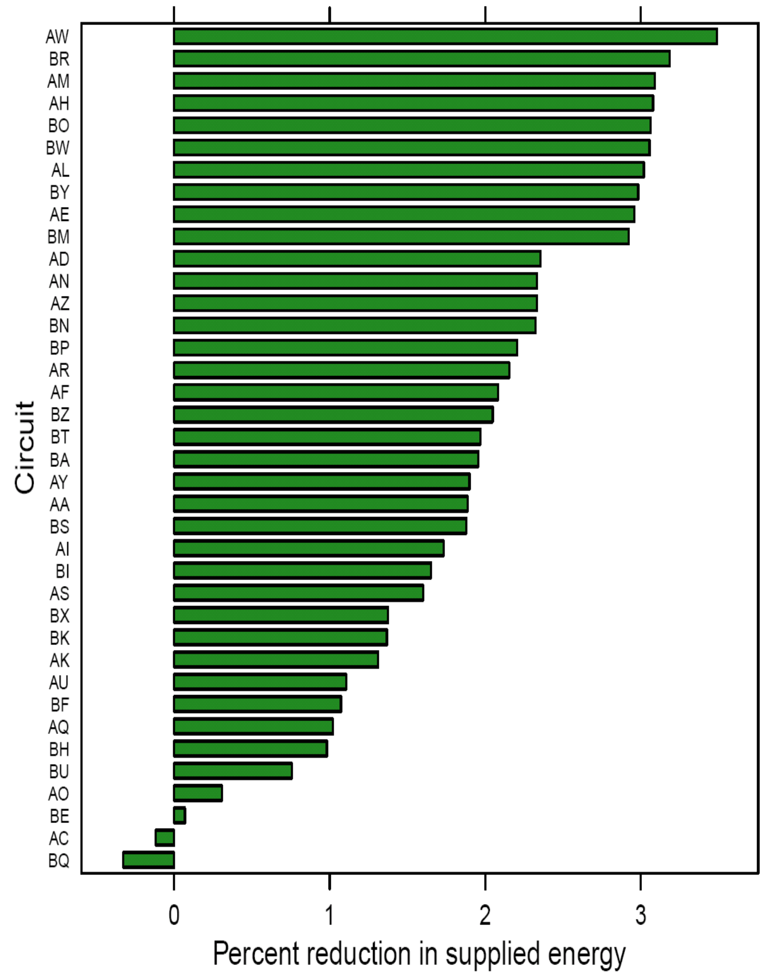
- Strengths
  - Does not require models or predetermined rules
  - Highly scalable (one substation or many)
- Weaknesses
  - (Presenter's opinion) → How it works is a bit of a mystery

Proving the Concept

Proof of Concept: What is it? and Why Do it?

- What is it?:
  - Typically a small-scale CVR demonstration on a few representative substations
    - Live operation on real feeders
    - Close observation of the results that are achieved
- Why Do It?
  - Not all feeders are created equal
  - Will CVR work as well on my distribution system?

From EPRI "Green Circuits"



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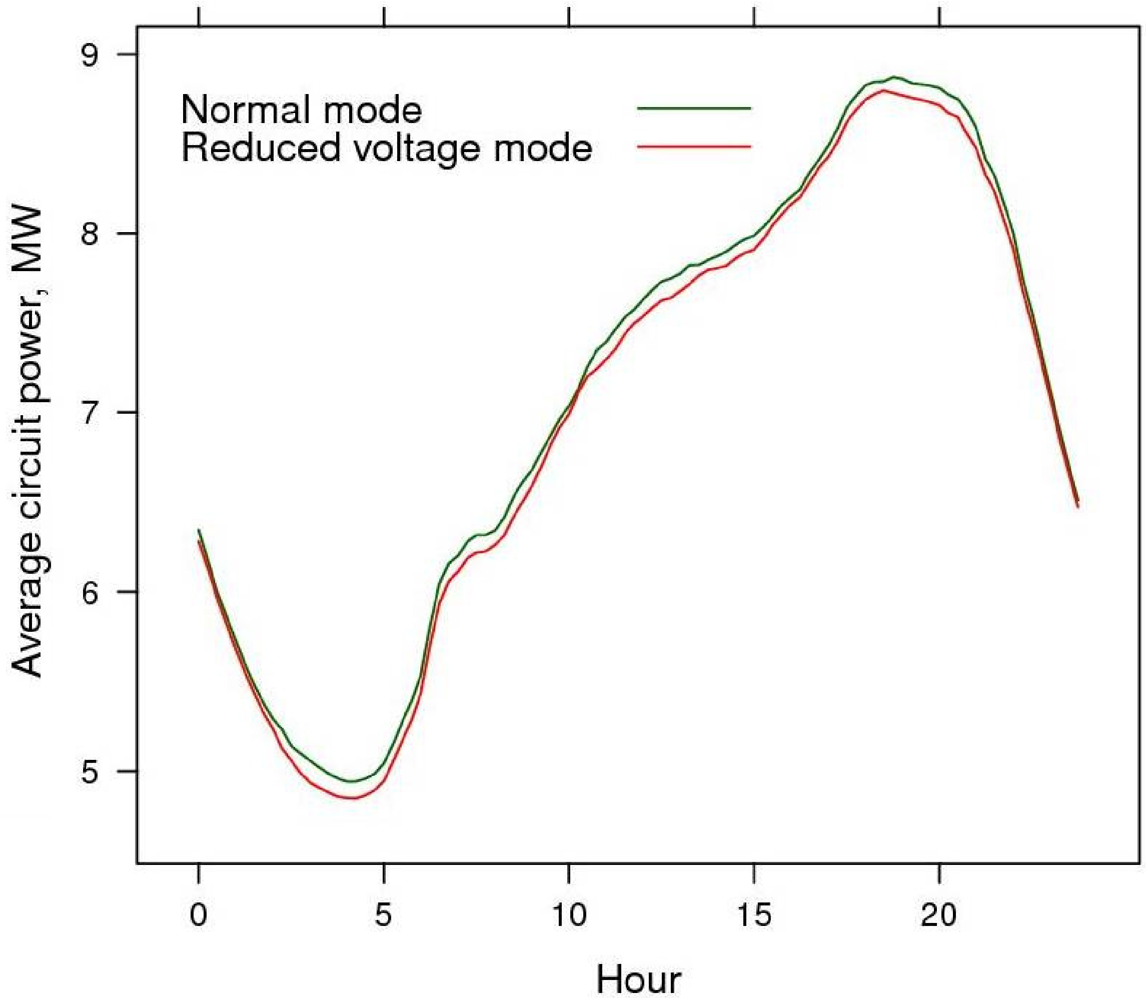
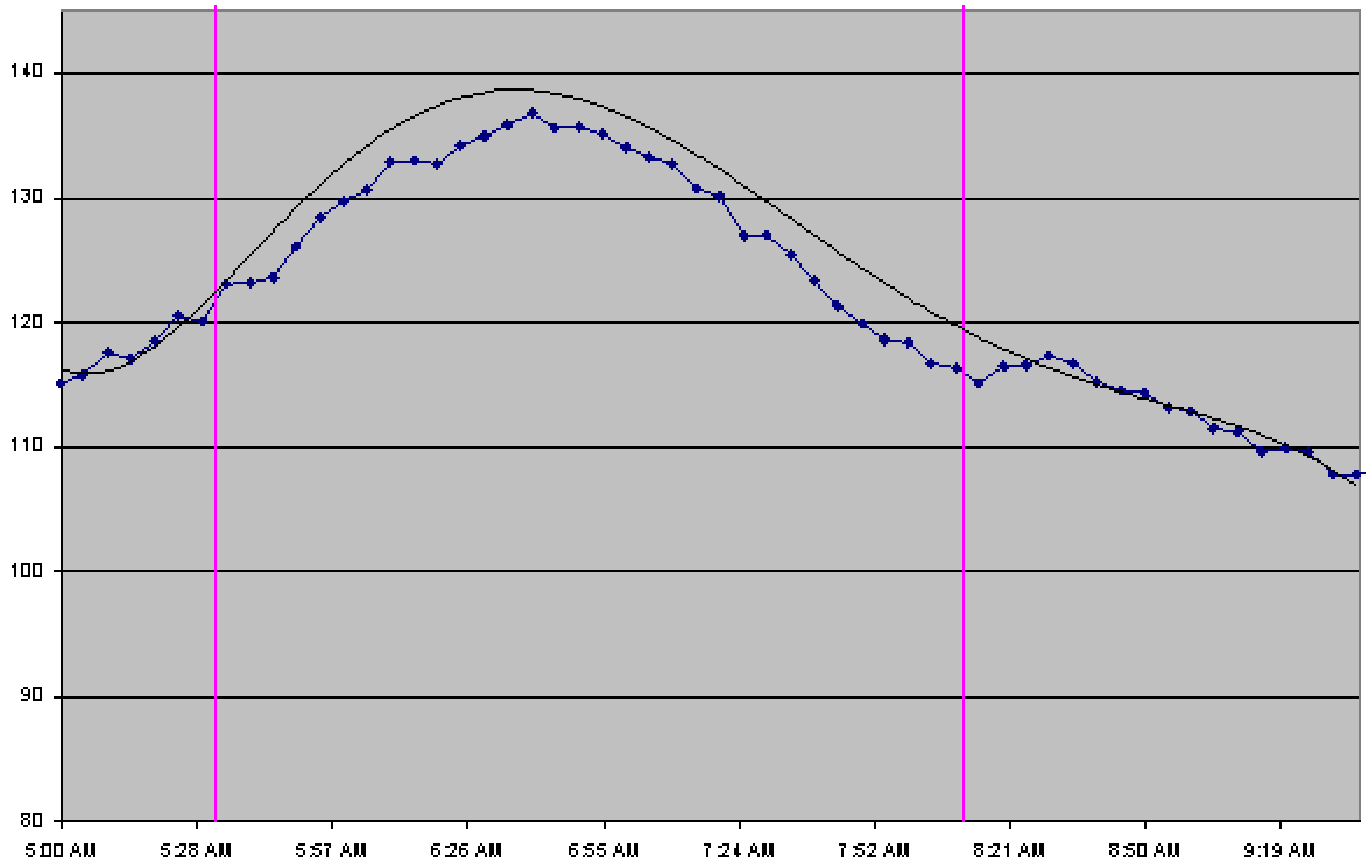
Objectives for Proof of Concept

- **Primary Objectives:**
  - Show that CVR produces benefits without customer complaints
  - Show that it works before “making the plunge”
- **Secondary Objectives:**
  - gain valuable implementation and operating experience
  - compare vendor solutions

Measurement and Verification
CVR Impact on Energy



Measurement and Verification
CVR Impact on Demand



PEE DEE ELECTRIC COOPERATIVE

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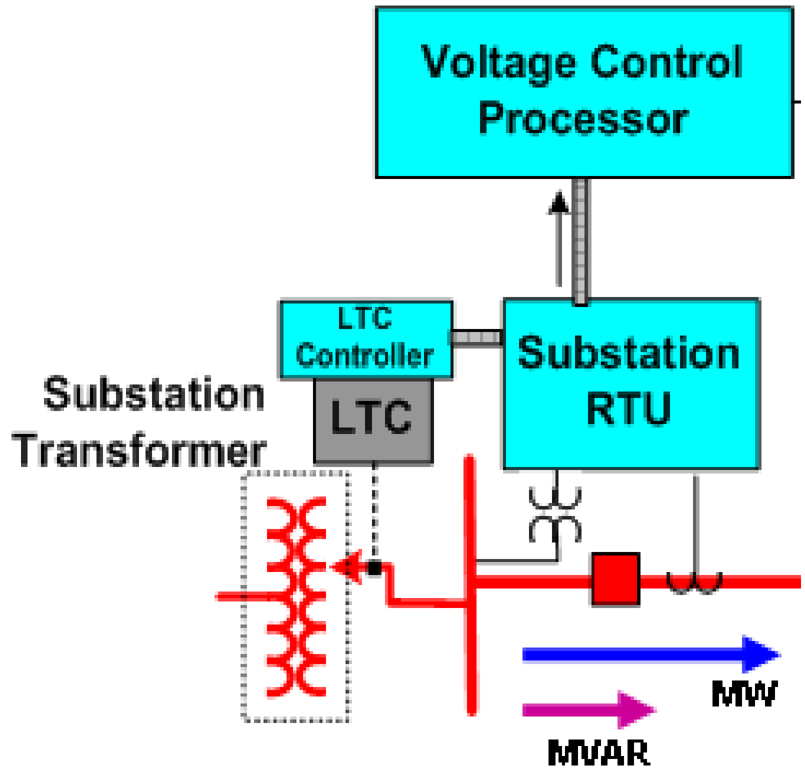
A simple approach – "flip the switch", measure "instantaneous" response

- **Basic approach to determine CVR/VVO benefit**
  - Lower tap setting by one position on LTC or Voltage regulator….
  - Measure the change in load
- **Problem with this approach**
  - Initial response to voltage reduction is significant drop in load
  - Load reduction benefit usually drops off with time
    - Devices that run off a thermostat just run longer
    - Loss of load diversity



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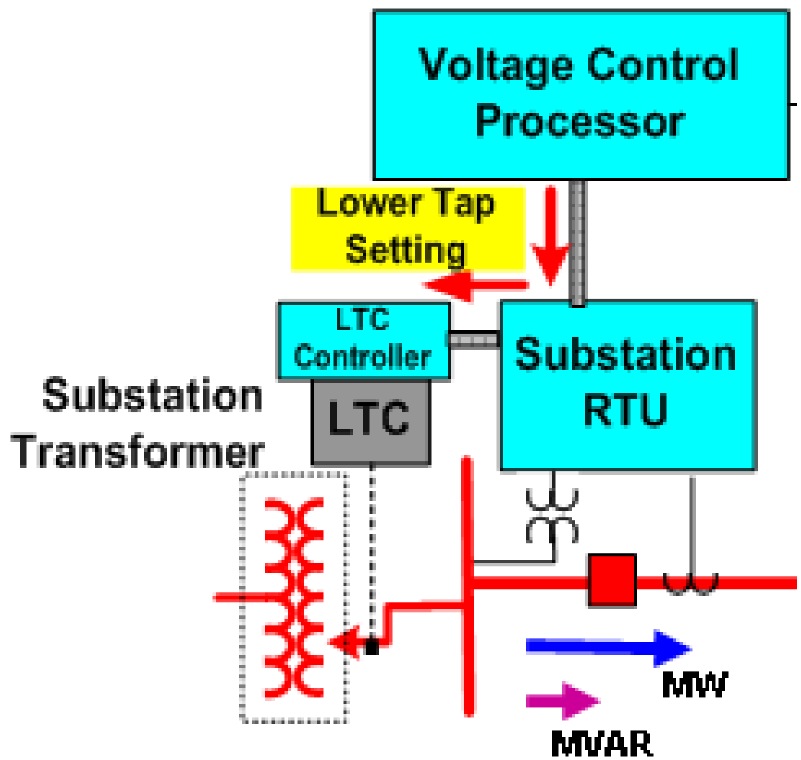
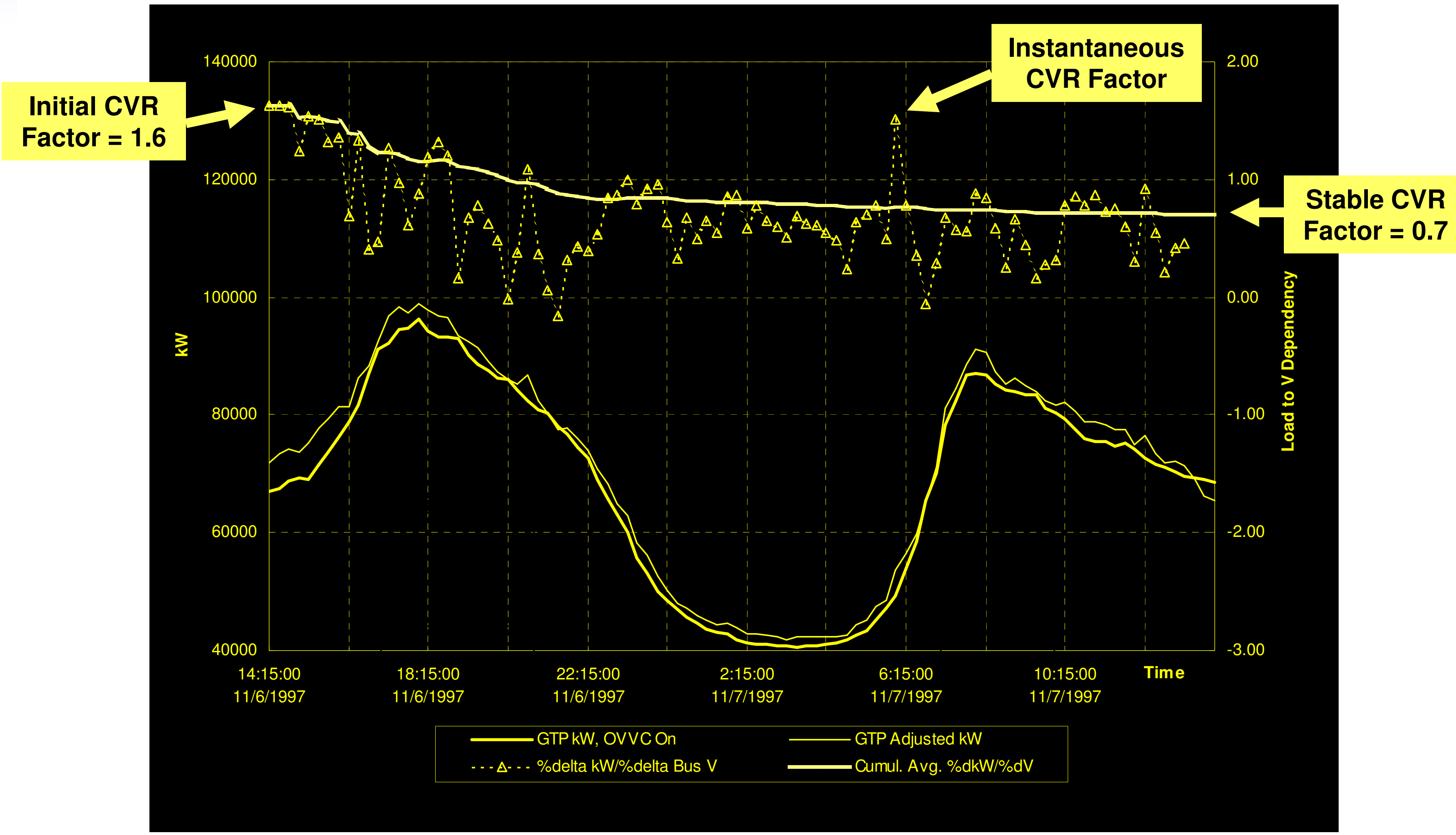


A simple approach – measure instantaneous response (CVR response drops off with time)



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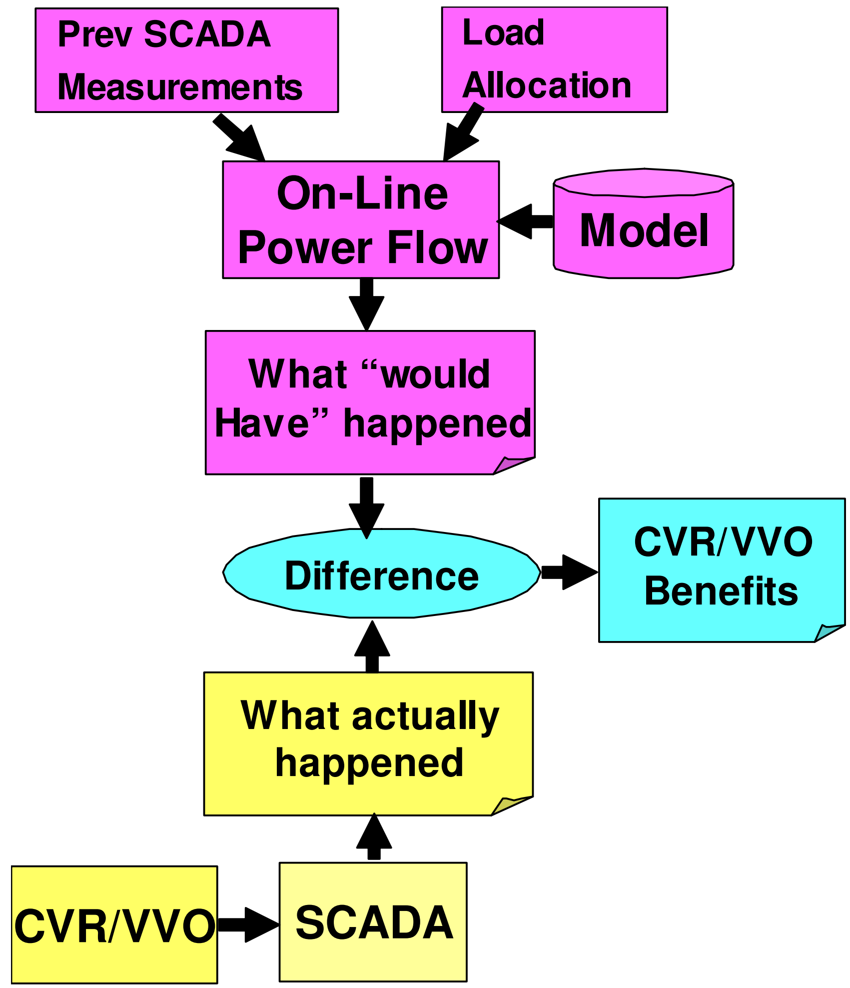
Determining the benefits over time

- To overcome this issue, should observe CVR/VVO operation over time
- **Benefit** is difference between **electrical conditions when CVR/VVO is running** minus **electrical conditions if CVR/VVO was not running**
- For example:
  - Reduction in energy consumption = **energy consumed** when running CVR/VVO – **energy that would have been consumed** if CVR/VVO was not running
- **Trick is determining what would have happened if CVR/VVO was not running!**

S&C/Current Group approach to CVR/VVO M&V

- Use **Powerflow** program to determine what would have happened if CVR/VVO was not running
  - Most recent SCADA real/reactive power measurements
  - Load allocated from standard load profiles for each customer class
  - Voltage regulators and switched capacitor banks use standard controls
  - Compare power flow output with actual measures while running CVR/VVO



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CVR/VVO "Time On – Time Off" Demonstrations

- Approach summary:
  - Turn CVR/VVO **ON** for period of time and record results
  - Turn CVR/VVO **OFF** for similar time period and record results
  - CVR/VVO Benefit is difference between the two

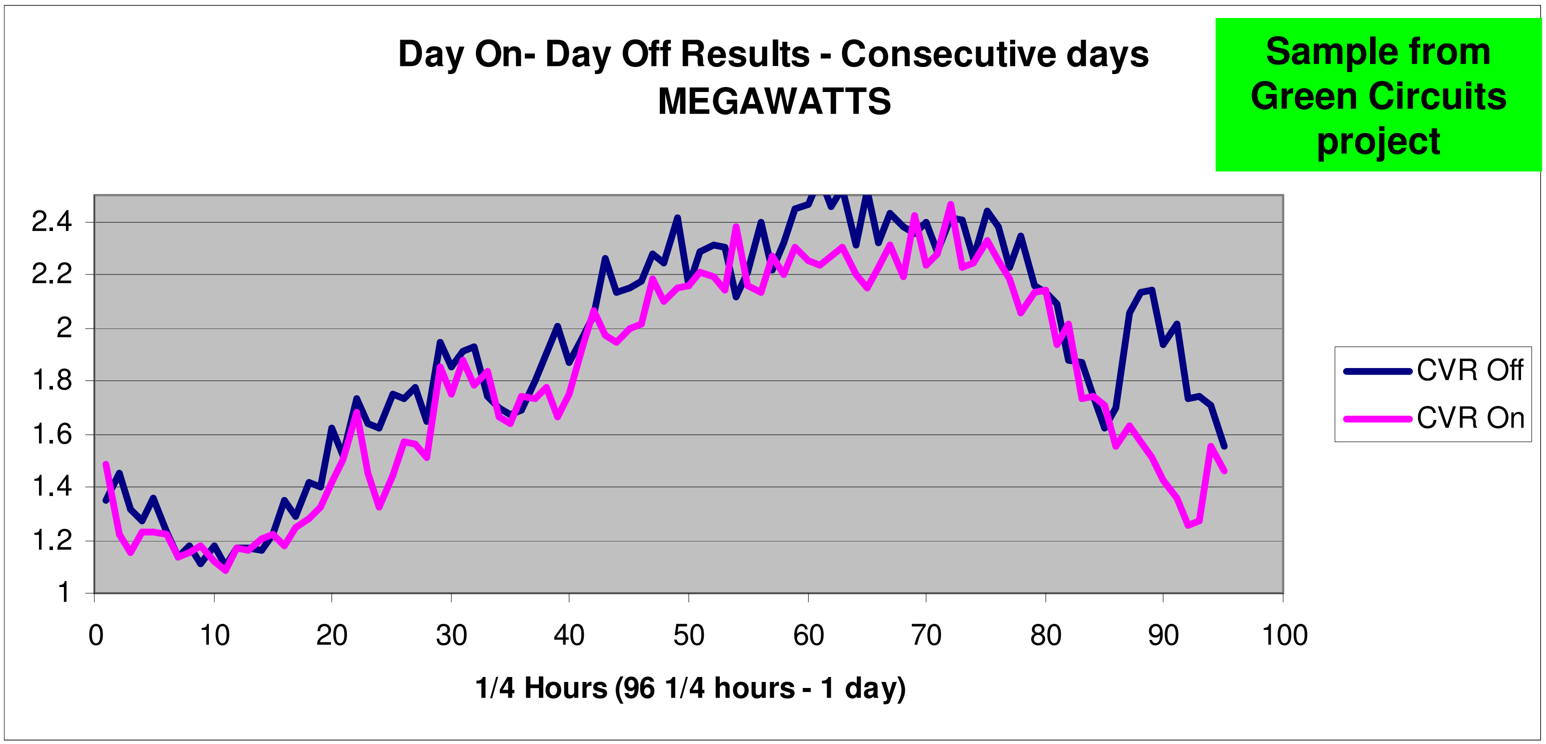
TIME	MW	MVAR	VOLTAGE	CVR On/Off
01:30:00	1.5351	-0.6036	123.9707634	Off
01:45:00	1.626	-0.6147	123.9192437	Off
02:00:00	1.7889	-0.6281	123.7390301	Off
02:15:00	1.6447	-0.649	118.846097	On
02:30:00	1.7859	-0.6947	119.0263457	On
02:45:00	1.5786	-0.6539	118.8975816	On
03:00:00	1.8166	-0.7025	118.9490662	On

CVR/VVO OFF

CVR/VVO ON

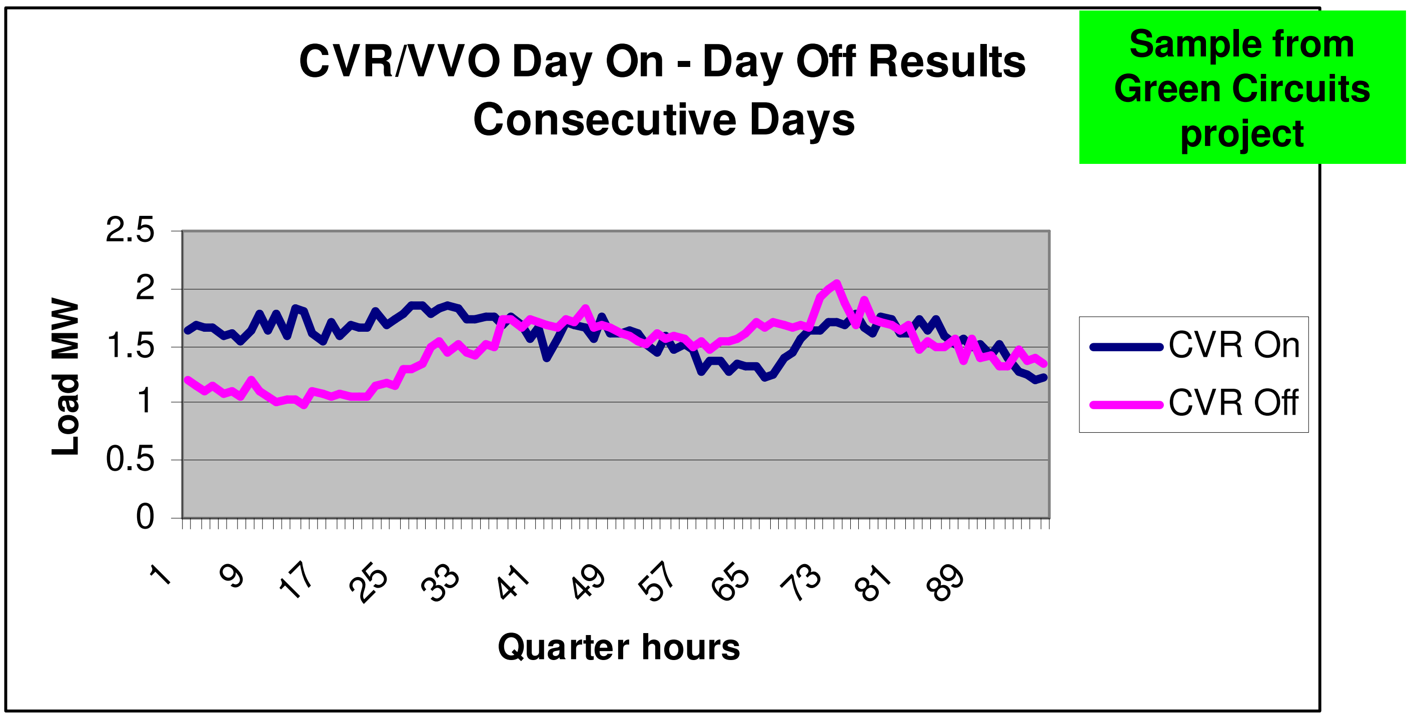
CVR/VVO "Time On – Time Off" Demonstrations

- Issues:
  - Easy to see benefits if load is nearly the same for the 2 time periods



CVR/VVO "Time On – Time Off" Demonstrations

– If natural load fluctuations occur, results are corrupted:
  - Load variation due to temperature
  - Random (stochastic) customer behavior
  - Feeder outages, load transfers
  - Weekday/weekend, holidays
– Need to exclude "outlier" data (missing data, bad data) that can distort results



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Techniques for dealing with fluctuations

- Exclude all missing and obviously bad data
- Exclude all data for weekends and special days (holidays)

- Normalize load to adjust for day to day variations due to:
  - Temperature/weather changes
  - Random (stochastic) customer behavior

- Two strategies
  - CVR Protocol Number 1 (developed by David Bell of PCS Utilidata) – used by Northwest Energy Efficiency Alliance (NEEA)
  - EPRI "Green Circuits" analysis (developed in cooperation with Dr Bobby Mee of Univ Tenn.)

Techniques for dealing with fluctuations

- **Exclude bad/missing data** and data for special days
- Perform statistical analysis to **identify and eliminate potential outliers** data. (Minimum Covariance Determinant (MCD) Robust Regression)
- **Normalize the load:**
  - **NEEA**
    - Adjust for temperature variations
  - **EPRI Green Circuits**
    - Adjust based on another circuit with a similar load composition
    - Similar circuit cannot be affected by voltage reduction on CVR fdr

NEEA

$$kW = \beta_0 + \beta_1 * hdh + \beta_2 * cdh$$

Where: hdh = heating-degree hours

cdh = cooling-degree hours

2 methods for determining what load "would have been" without CVR

EPRI GREEN CIRCUITS

$$kW = k_1 * kW_{comparable} + k2 * V_{state}$$

Where: kW_{comp} = avg power measured at a comparable circuit

V_{state} = 1 for normal voltage, 0 for reduced voltage

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Some other points about POC

- Should pick substations that include representative feeder designs and customer mix
- POC time period should be long enough to capture seasonal variations
- CVR control system used for POC doesn’t necessarily have to be the final vendor solution

Together…Shaping the Future of Electricity

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