VOLTAGE REGULATION OF THE DISTRIBUTION GRID

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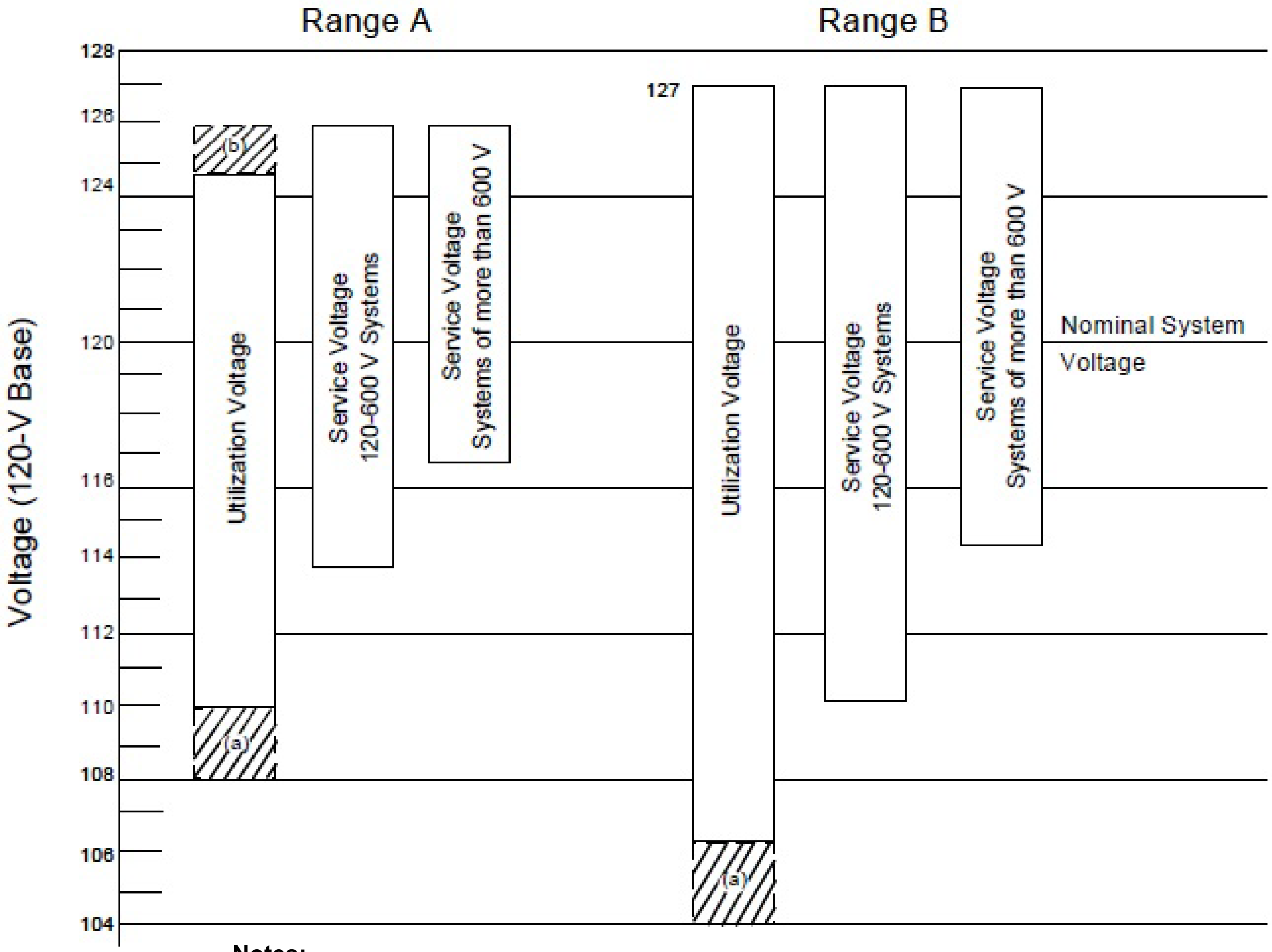
Voltage Regulation and Power Quality Track
Monday and Tuesday Sessions

SESSION 7 –Voltage Reduction and Smart Voltage Reduction.

Voltage Reduction

- Historically, utilities have operated at the high end of the 114V-126 V range permitted by ANSI Std C-84.1.
- Electric utilities have achieved load reductions by reducing the voltage delivered to the load – a technique known as Conservation Voltage Reduction (CVR) – especially during critical peak load periods.
- CVR can be used both for peak demand reduction as well as energy conservation.
- The amount of demand reduction depends on the type of load mix.

Allowable voltage ranges (ANSI C84.1-2011)

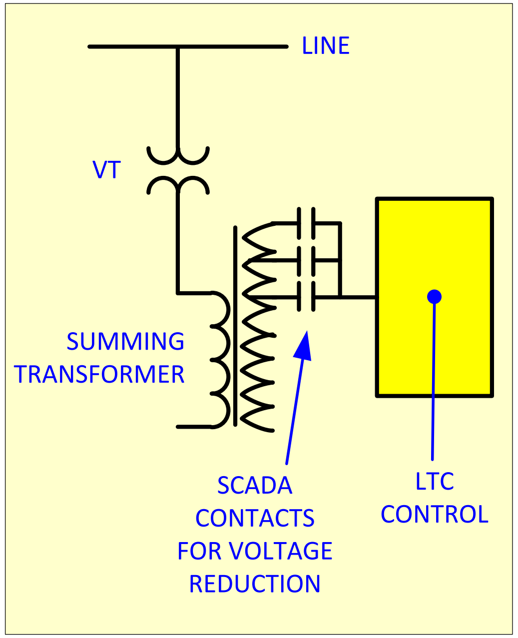


Notes:
a. The shaded portions of the ranges do not apply to circuits supplying lighting load
b. The shaded portion of the range does not apply to 120 V - 600 V systems.

Range A
Service voltage
(120 V Nominal)
114 V – 126 V

Historical Voltage Reduction

- Load Reduction called with Load Management Software.
- Load Reduction Software » SCADA » Output Relay » LTC/Regulator Input.
- Output relays connected to *auxiliary summing transformer* with multiple taps.



- *Auxiliary summing transformer has* taps connected/ disconnected by control relays to create a *higher* sensing voltage the LTC or Regulator Control.
- This higher voltage, sensed by the LTC/Regulator Control, would now cause the control to issue *tap-down* commands to *lower* voltage.
- The control would not know that it is in voltage reduction mode, and would simply react to the sensed voltage change.

Load Models

- Constant Power (PQ):
  - *Load current changes inversely to the change in voltage.*
- Constant Impedance (Z):
  - *Load current changes linearly with the change in delivered voltage, and the demand varies as a squared function of the voltage change.*
- Constant Current (I):
  - *Power delivered to the load varies linearly with the change In voltage delivered to the load.*

Load Models and CVR Factor

- Load models
  - Constant Power (PQ) → Load current changes inversely to the change in voltage.
  - Constant Impedance (Z) → Load current changes linearly with the change in delivered voltage, and the demand varies as a squared function of the voltage change (ex., incandescent bulb).
  - Constant Current (I) → Power delivered to the load varies linearly with the change in voltage delivered to the load.

Constant Power (PQ or kVA)	Constant Impedance (Z)	Constant Current (I)
Motors (at rated load)	Incandescent Lighting	Welding Units
Power Supplies	Resistive (Strip) Water Heaters	Electroplating
Fluorescent Lighting	Electric Stoves	
Washing Machines	Clothes Dryers	

$CVR_f = \Delta P / \Delta V$

0.8 to 1 is typical

Greater than 1 is really good

CVR Factor

CVR_f: CVR Factor = $\Delta E / \Delta V$

% VR	PF 1.0		PF .9	
	ΔE	CVR_f	ΔE	CVR_f
2 %	1.5 %	0.75%	0.5%	0.25%
4 %	3.0 %	0.75%	2.0%	0.5%

EPRI “Distribution Green Circuits” Report - 2010

- As you can see if the power factor is close to unity much higher CVR factors can be obtained. This means using LTC/Regulators alone to correct the circuit voltage will not give high CVR factor.
- Capacitor banks are required to obtain power factor close to unity (or slightly leading) there by giving high CVR factors.

Voltage Reduction

Controls typically support three reduction levels:

- Reduction level range set from (1 -10) %.
- Time delay on reduction skipped.

Typical for static or digital controls:

- Contact sensing inputs -
    - The contacts would be from a SCADA RTU and/or local switches.

Voltage Reduction in Modern Controls

For digital controls, additionally:

- Using the integrated HMI on the control (buttons).
- Using PC software locally.
- Using SCADA interface (ex., DNP from RTU).
- Using Ethernet by radio (ex., DNP TCP/IP).
- Using Cellular or other medium.

Historical Voltage Reduction - Disadvantages

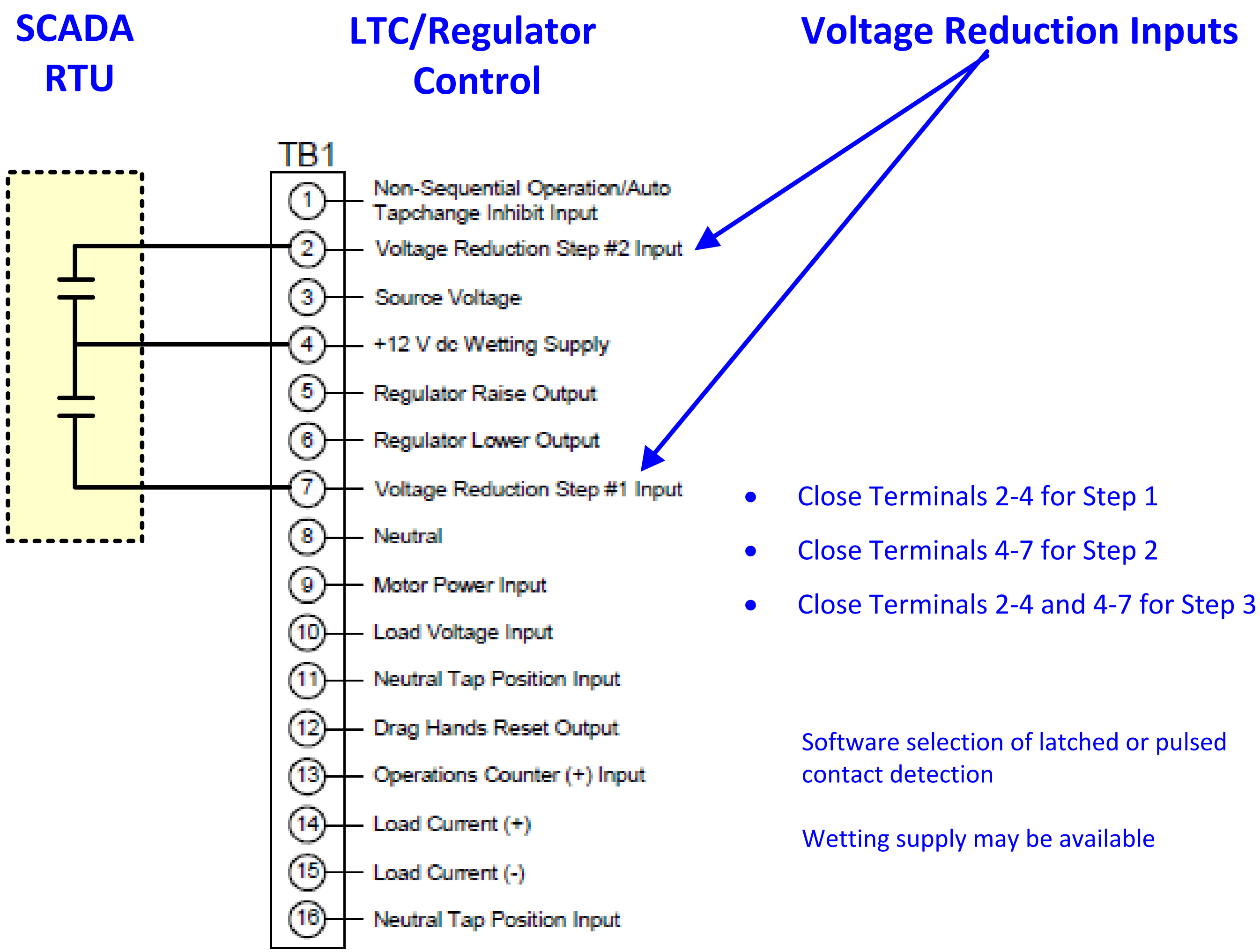
- The *time delay to tap* is still in play.
- The *percentage of reduction* is *fixed* due to the taps on the summing transformer.
- Each percentage reduction point required an auxiliary relay.
- If the communications failed while in reduction, the LTC or Regulator would remain in voltage reduction.

Voltage Reduction in Modern Controls

- Controls typically support three reduction levels.
  - Reduction level range set from 1 -10 %.
- Typical for static *or* digital controls:
  - Contact sensing inputs.
  - The contacts would be from a SCADA RTU and/or local switches.
- For digital controls, additionally:
  - Using the integrated HMI on the control (buttons).
  - Using PC software locally.
  - Using SCADA interface (ex., DNP from RTU).
  - Using Ethernet by radio (ex., DNP TCP/IP).
  - Using Cellular or other medium.

Contacts Used for Voltage Reduction

Digital Voltage Regulator Control



- Close Terminals 2-4 for Step 1
- Close Terminals 4-7 for Step 2
- Close Terminals 2-4 and 4-7 for Step 3

Software selection of latched or pulsed contact detection

Wetting supply may be available

Voltage Reduction in Modern Controls

- Voltage Reduction changes the bandcenter to induce the controls to lower the voltage instead of increasing the sensed voltage.

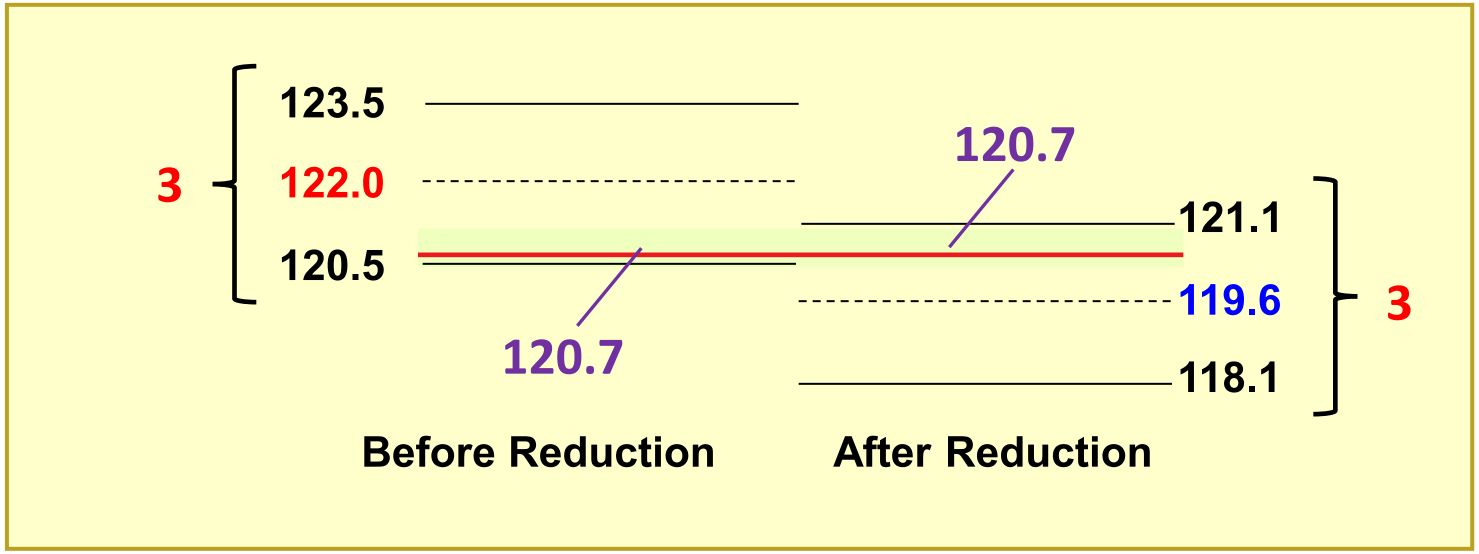
- Signal to control can be:
  - SCADA to contacts, contacts to control.
  - Direct SCADA DNP write to control.

- Time delay skipped on initial voltage reduction command.

- Because the bandcenter is being altered, entering reduction does not always reduce the voltage, or reduce near the amount of requested reduction.

Voltage Reduction - Example

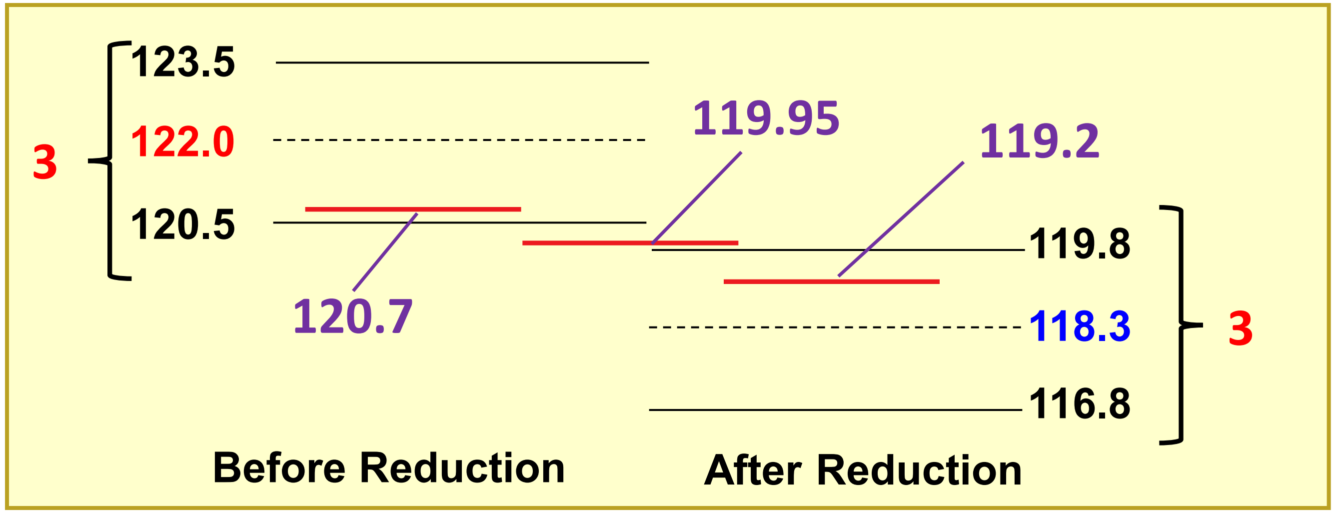
- Bandcenter set to 122V, Bandwidth of 3V.
- Apply a 2% reduction:
  - 122 – 122* 0.98 = 119.56 or 119.6 -
    - Upper rail = 119.6 + (3/2) = 121.1.
    - Lower rail = 119.6 – (3/2) = 118.1.



- Assume 0.75V/tap (10V/16 taps = 0.75V/tap).
- 120.7V before reduction, after reduction that value is still in-band.
- Results in no voltage reduction, 0%.

Voltage Reduction - Examples

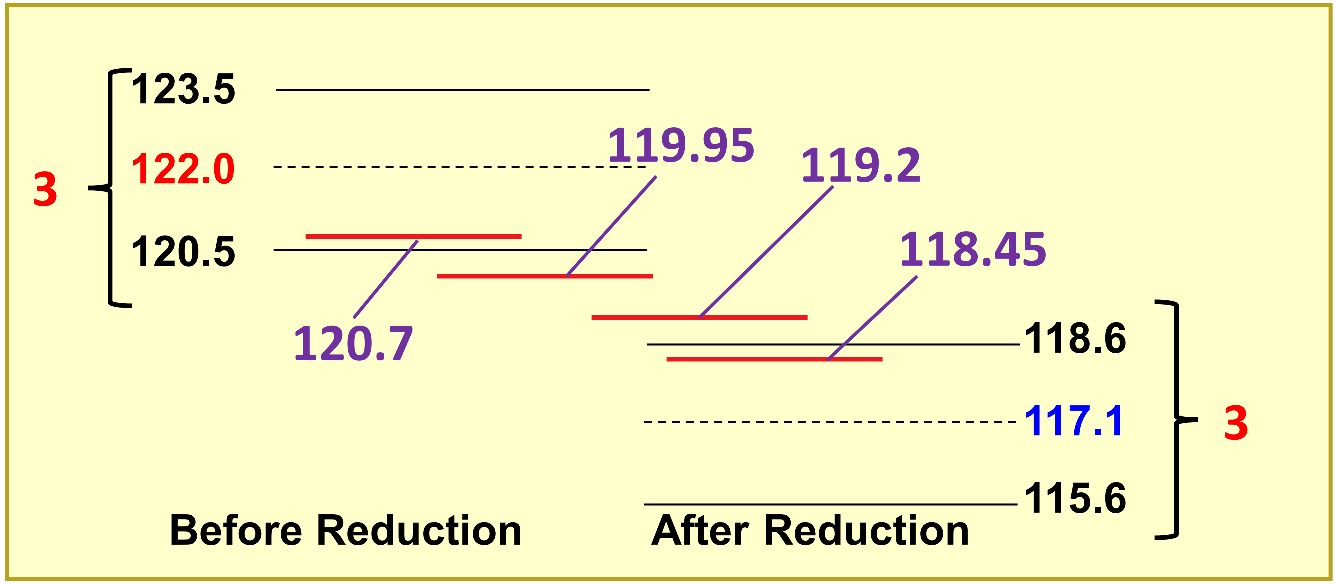
- Bandcenter set to 122V, Bandwidth of 3V.
- Apply a **3%** reduction of:
  - 122 – 122* 0.97 = 118.34 or 118.3 -
    - Upper rail = 118.34 + (3/2) = 119.8.
    - Lower rail = 118.34 – (3/2) = 116.8.



- Assume 0.75V/tap (120*10%=12V; 12V/16 taps = 0.75V/tap)
- 120.7V before reduction, 2 Taps Down Taken
- Tap 1 = 119.95, Tap 2 = 119.2
- % = (| V1 - V2 | / ((V1 + V2)/2)) * 100
- = (| 120.7 - 119.2 | / ((120.7 + 119.2)/2)) * 100 = **1.25%** reduction

Voltage Reduction - Examples

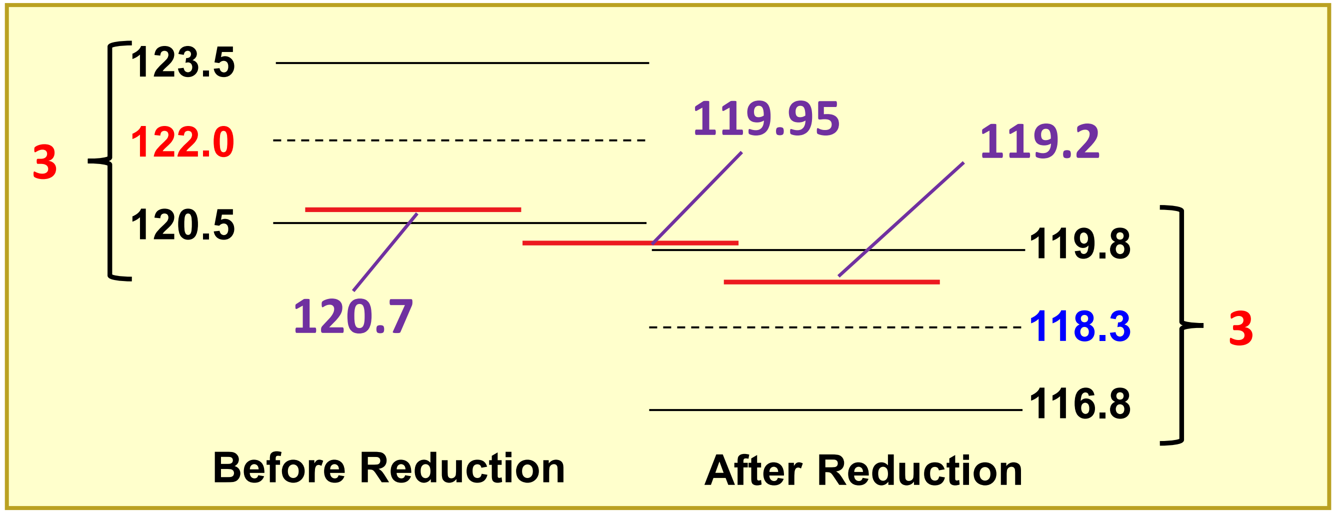
- Bandcenter set to 122V, Bandwidth of 3V.
- Apply a **4%** reduction of:
  - 122 – 122* 0.96 = 117.12 or 117.1 -
    - Upper rail = 117.1 + (3/2) = 118.6.
    - Lower rail = 117.1 – (3/2) = 115.6.



- Assume 0.75V/tap (120*10%=12V; 12V/16 taps = 0.75V/tap).
- 120.7V before reduction, 3 Taps Down Taken.
- Tap 1 = 119.95, Tap 2 = 119.2, tap 3 = 118.45.
- % = (| V1 - V2 | / ((V1 + V2)/2)) * 100.
- = (| 120.7 - 118.45 | / ((120.7 + 118.45)/2)) * 100 = **1.88%** reduction.

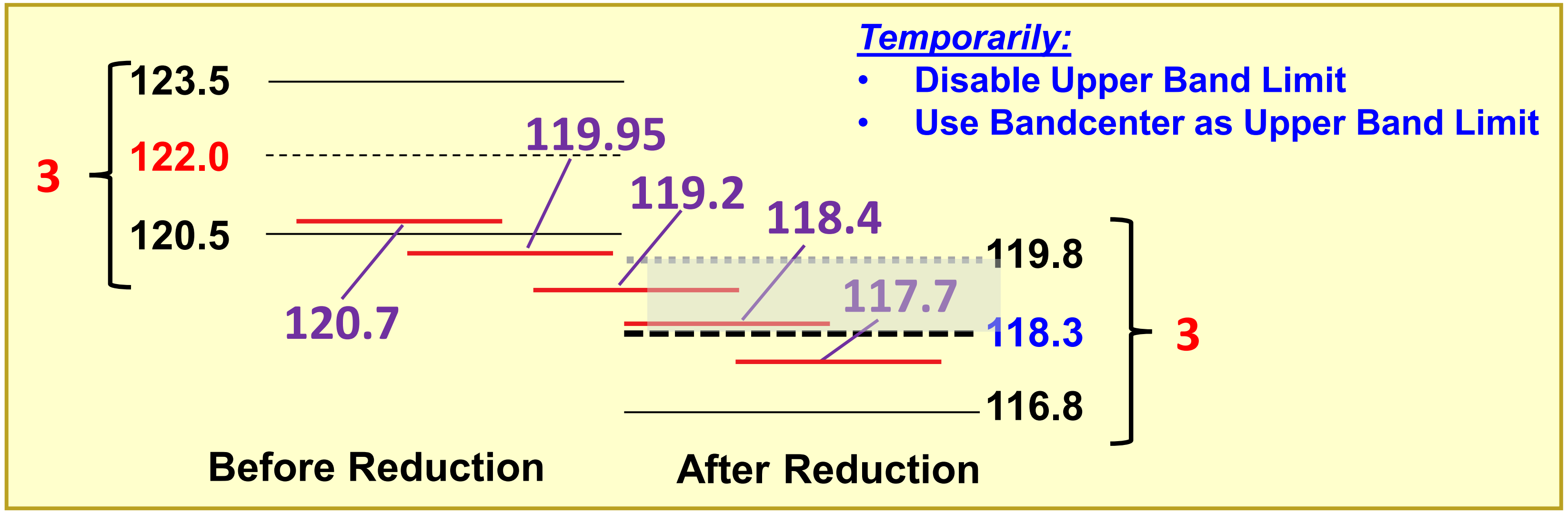
Voltage Reduction – Traditional Method

- If the goal of voltage reduction is to reduce voltage, we want to finish the reduction on the lower end of the band, not the higher end.
- Previous example: **3%** request, **1.25%** delivered.



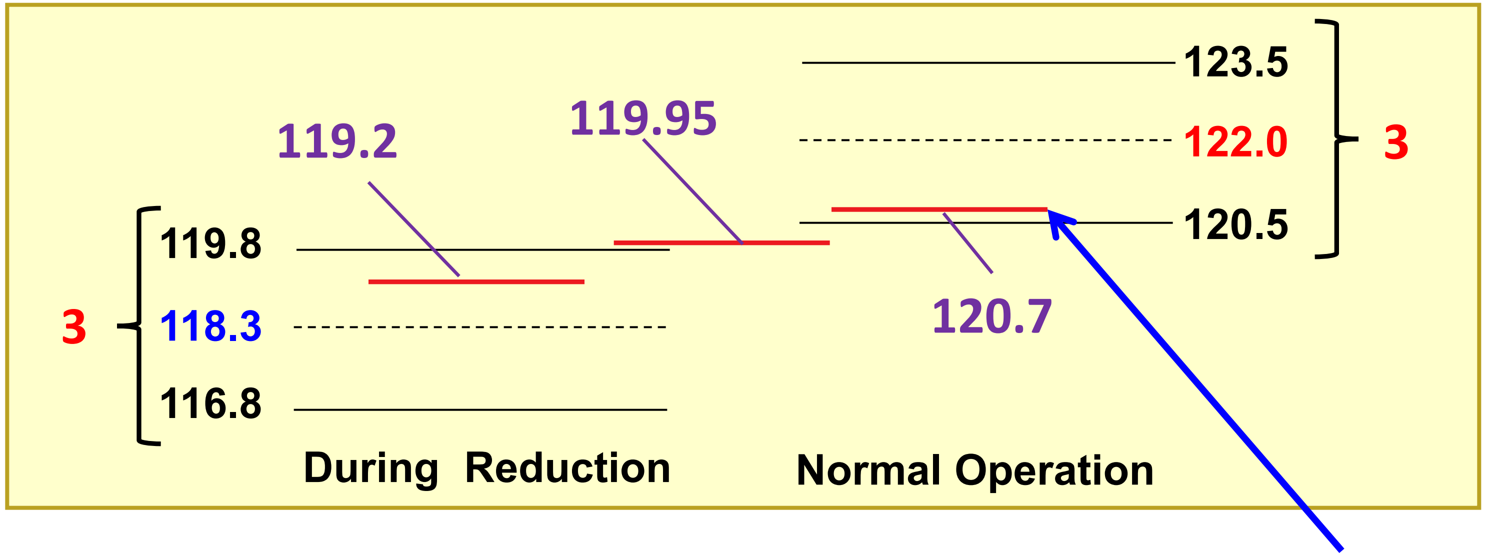
Smart Voltage Reduction

- Apply a 3% reduction of:
  - 122 – 122* 0.97 = 118.34 or 118.3 -
    - Upper rail = 118.34 + (3/2) = 119.8.
    - Lower rail = 118.34 – (3/2) = 116.8.



- Assume 0.75V/tap (120*10%=12V; 12V/16 taps = 0.75V/tap).
- 120.7V before reduction, 4 Taps Down Taken.
- Tap 1 = 119.95, Tap 2 = 119.2, Tap 3 = 118.4, Tap 4 = 117.7.
- % = (| V1 - V2 | / ((V1 + V2)/2)) * 100.
- = (| 120.7 - 117.7 | / ((120.7 + 117.7)/2)) * 100 = 2.52% reduction.

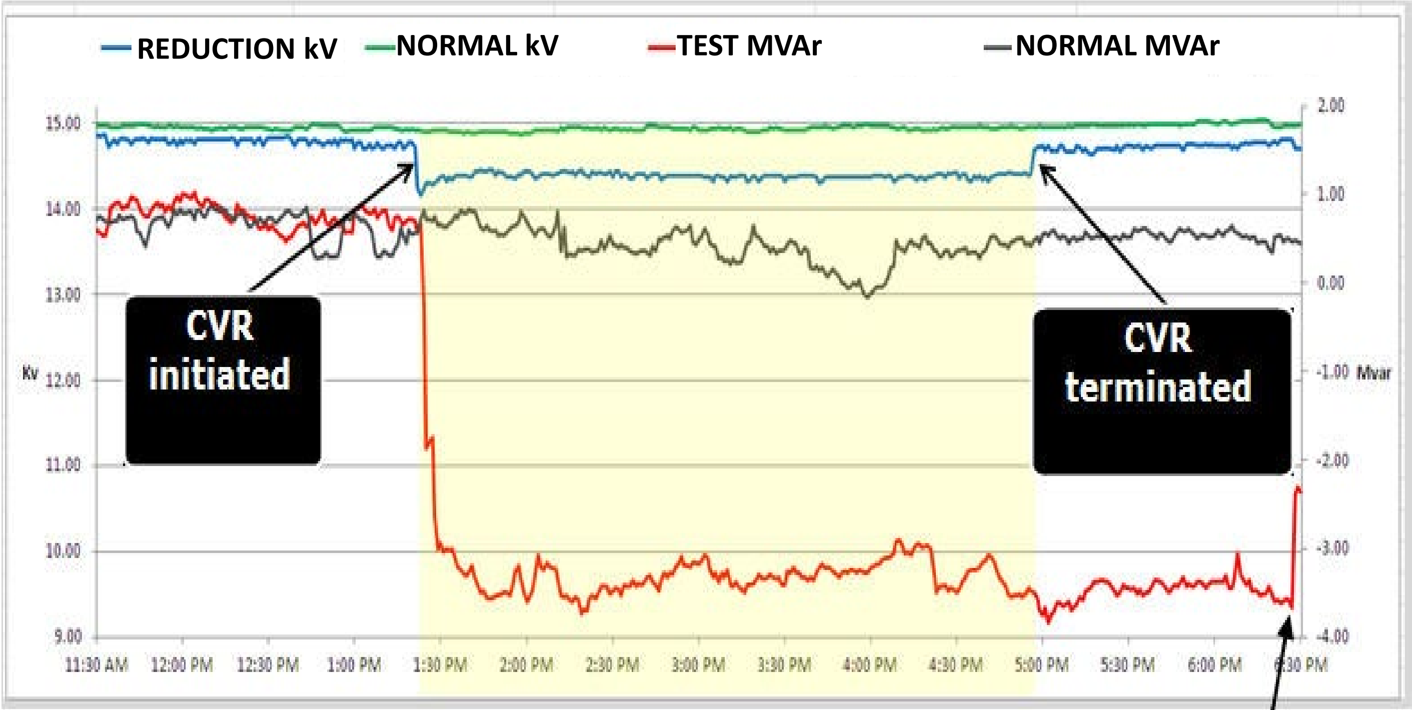
Leaving Voltage Reduction - Present Method



This may not be a high enough voltage to cause voltage-controlled capacitors to switch off.

Leaving Voltage Reduction – Present Method

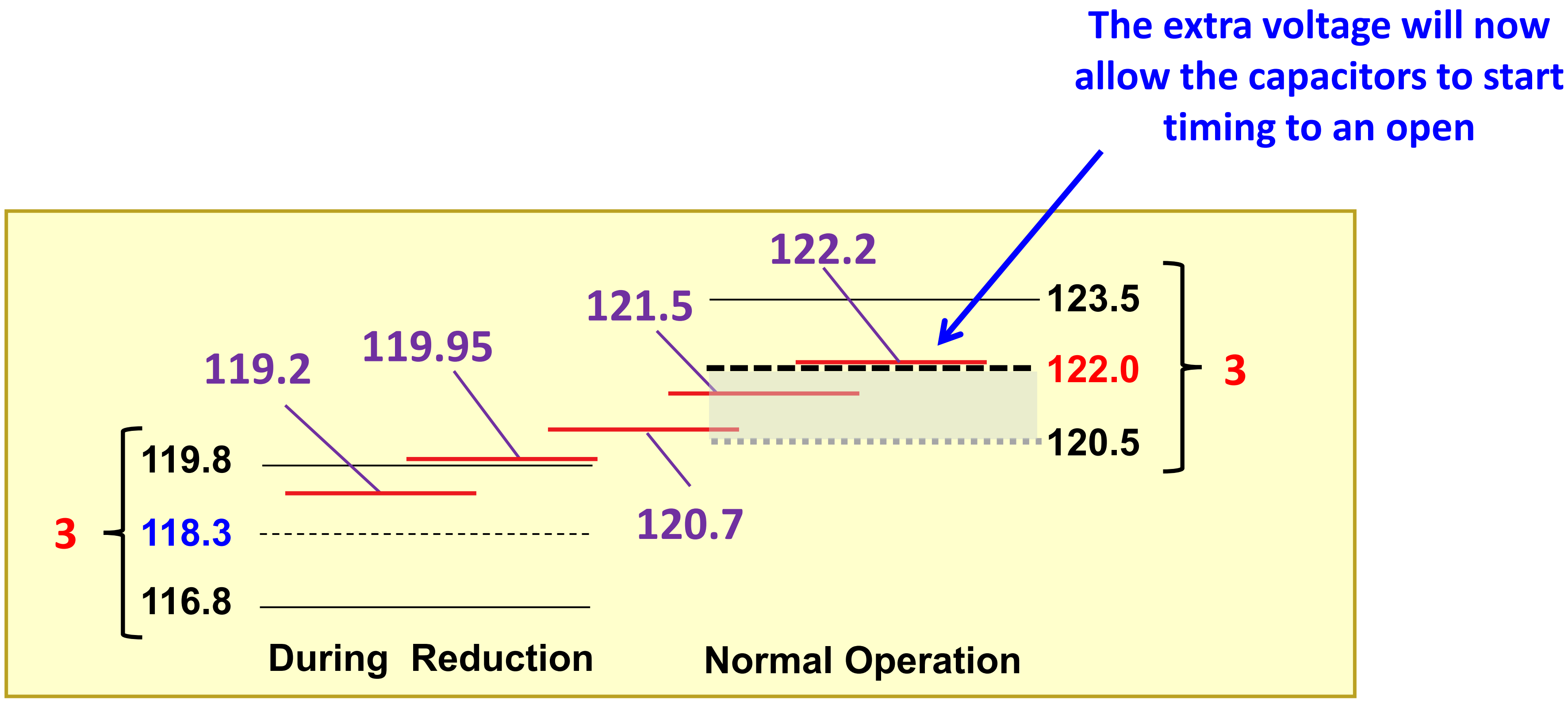
Unintended Results: Cap Banks May Stay On Too Long



- Typically, when entering reduction, all switched capacitors will close as the voltage is reduced (assumed voltage control).
- This may cause circuits to be leading when in reduction.
- When leaving reduction, some of the capacitors need to be switched off to get back to unity power factor.

Leaving Voltage Reduction

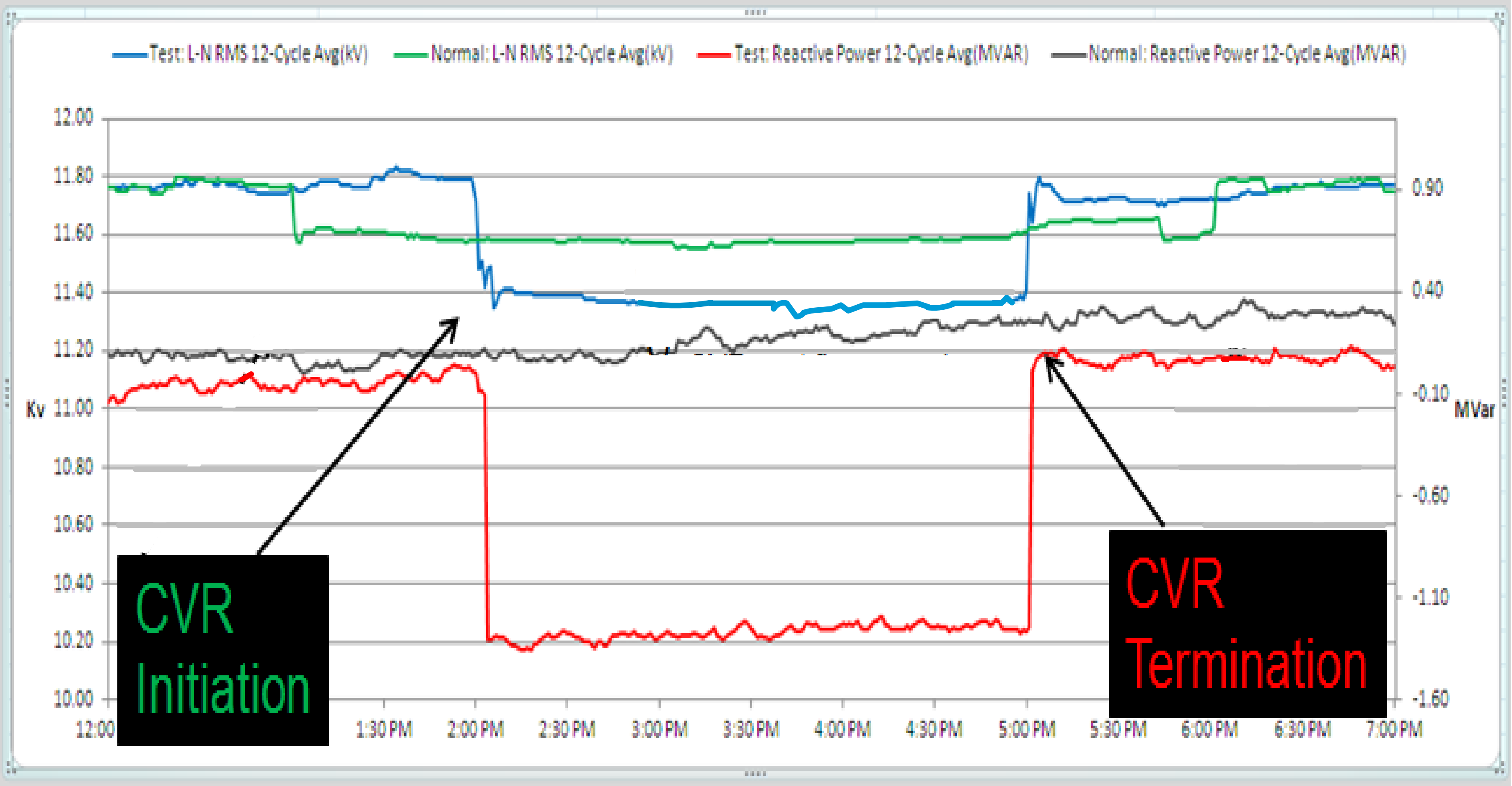
Smart Voltage Reduction Method



- The lower band is temporarily disabled to force the voltage to finish between the bandcenter and the high band edge.
- Once the voltage crosses the bandcenter, the lower band edge becomes active again.

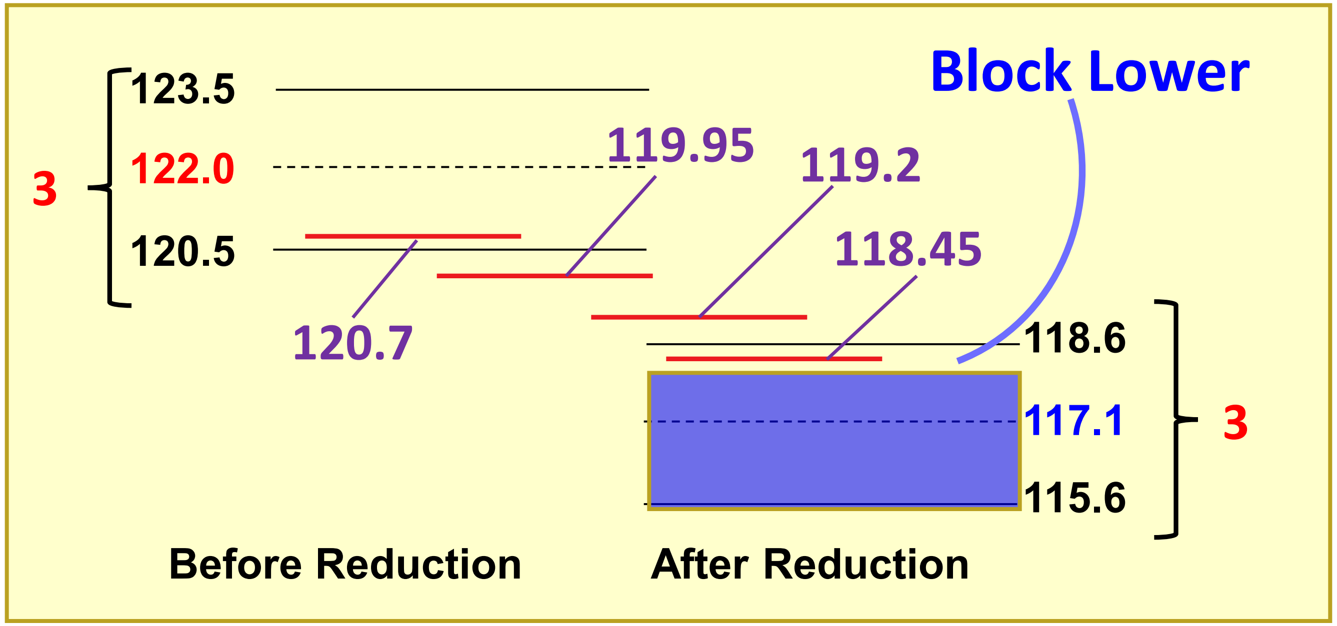
Cap Banks Opening After Leaving Reduction

Smart Voltage Reduction Employed



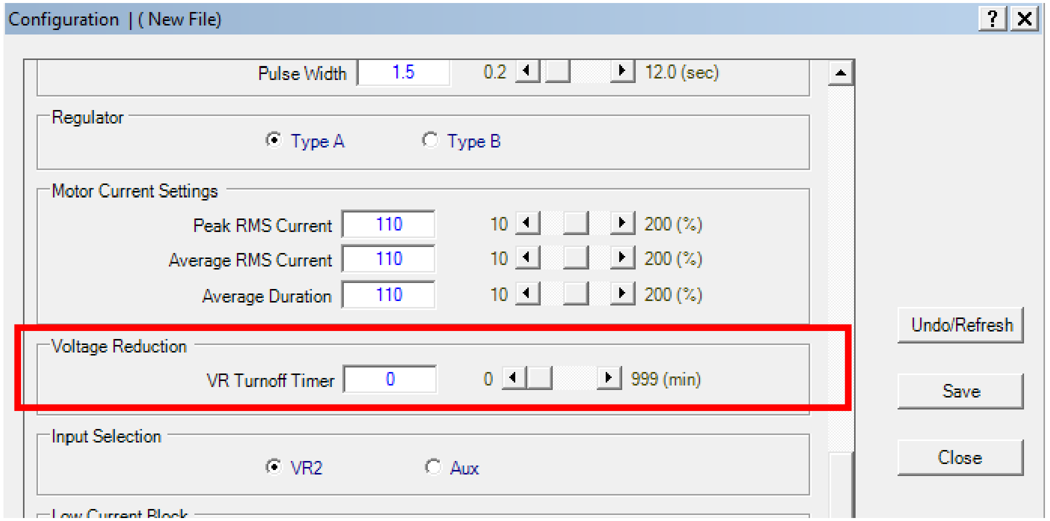
Voltage Reduction: Block Lower

- A “Block Lower” setting of 118 will stop the control from performing voltage reduction if low limit setpoint is violated.
- Be sure the “Block Lower” setting does not interfere with voltage reduction settings.



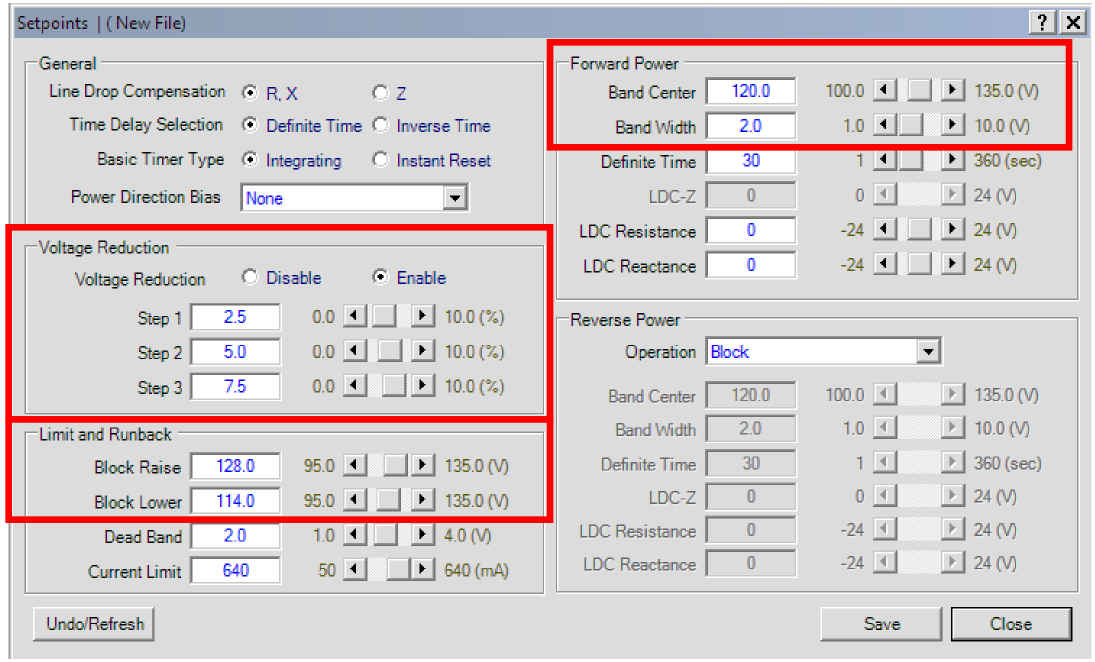
Voltage Reduction Turnoff Timer

- Used to turn off Voltage Reduction (VR) if entered via SCADA or pulsed contacts.
- Intent is to remove voltage reduction mode if SCADA is lost, and communications goes down.
- Control will automatically remove VR once the timer expires, even if SCADA is still communicating:
  - New signal during timing interval would keep VR going.



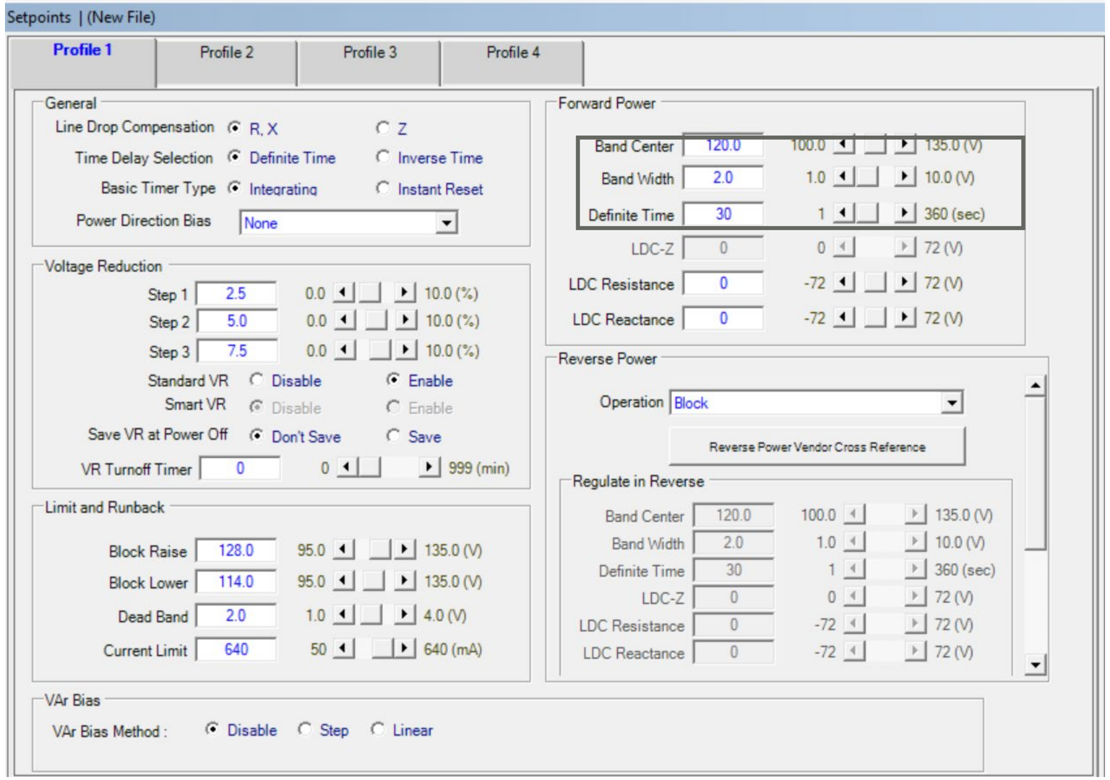
Voltage Reduction - Summary

- The control will never reduce the actual voltage by the percentage requested.
- The larger the bandwidth, the less actual reduction.
- The “Block Lower” setting:



Voltage Reduction - Summary

- The control will never reduce the actual voltage by the percentage requested.
- The larger the bandwidth, the less actual reduction.
- The “Block Lower” setting will block voltage reduction.



Line Drop Compensation

- Voltage Drop is due to current through the resistive and reactive network of distribution system and customer loads.
- As current increases, voltage drop increases.
- Reactive current increases cause 3 – 4 times more voltage drop as majority of impedance is reactive:
  - Typical X/R ratios 3:1 to 6:1.
- LDC allows the voltage to be operated at lower voltages at light loads.

Line Drop Compensation

- The Regulator or LTC control can apply compensation to correct for the voltage drop.

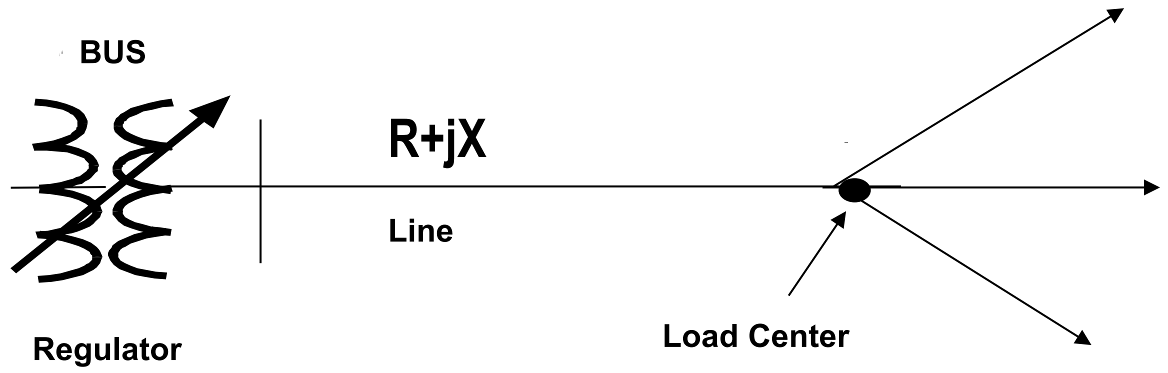
- The settings are:
  - R (using the real or resistive portion of the load).
  - X_L (using the reactive portion of the load).

- Settings are entered as voltages.

- The settings entered will be applied at full scale and are linear:
  - Settings may be calculated from the impedance of the system.

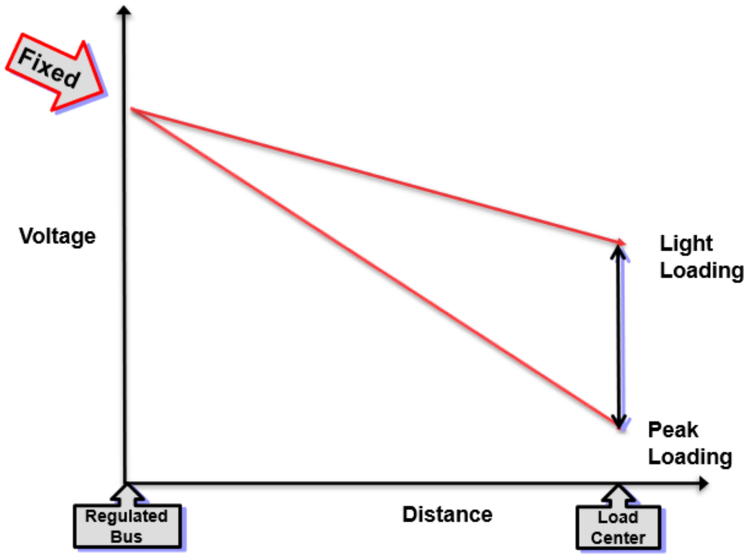
Line Drop Compensation

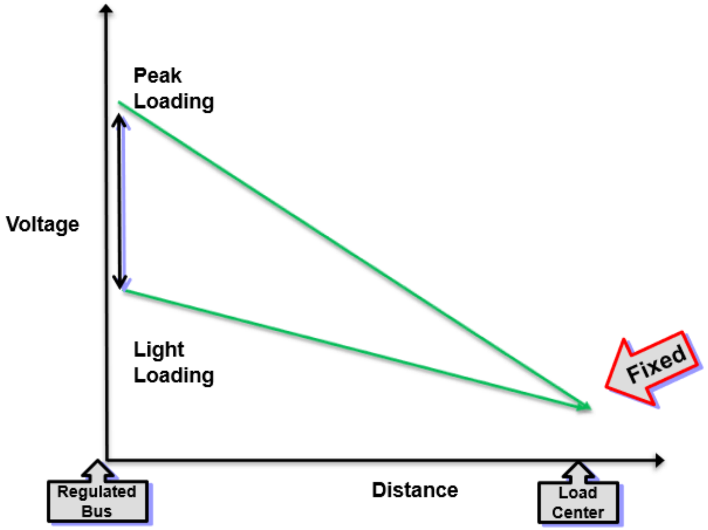
- LDC allows voltage regulation closer to the load accounting for line impedance, load and associated voltage drop.
- Used to maintain voltage at a remote load center.
- Use R only as X should be regulated with Cap Banks not LTCs/Regulators.



Line Drop Compensation

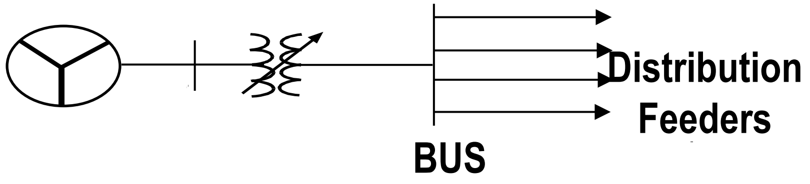
- As can be seen the left has no LDC and the voltage is held constant at the source.
- The right has LDC so the voltage is held constant at the load center.

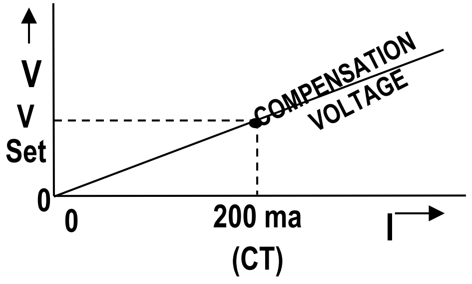




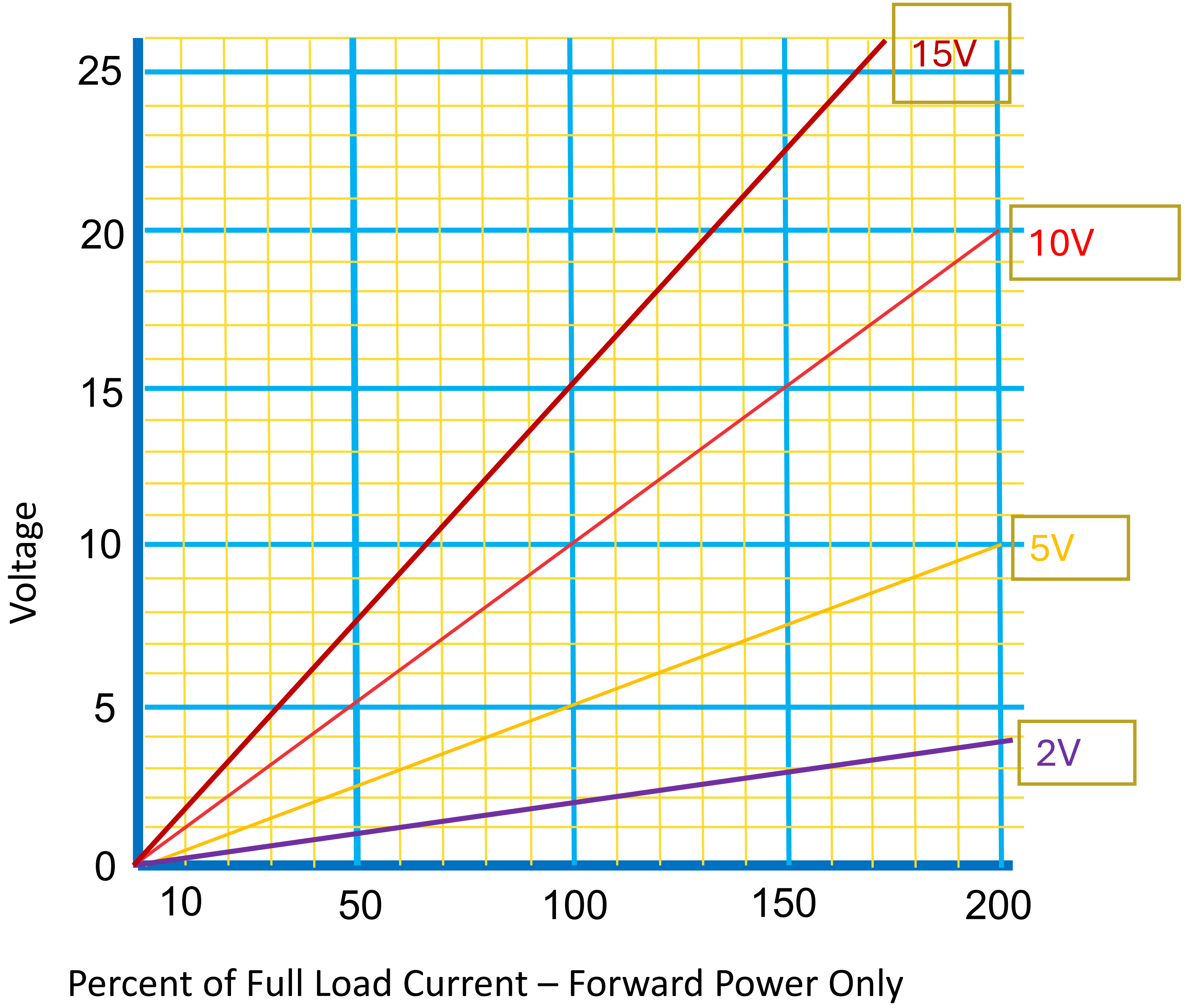
Line Drop Compensation for LTCs

- Application: Distribution bus regulation.
- Multiple circuits that have different impedances and loads.
- Use LDC Z and set the Z value to the largest voltage drop in the Zone.

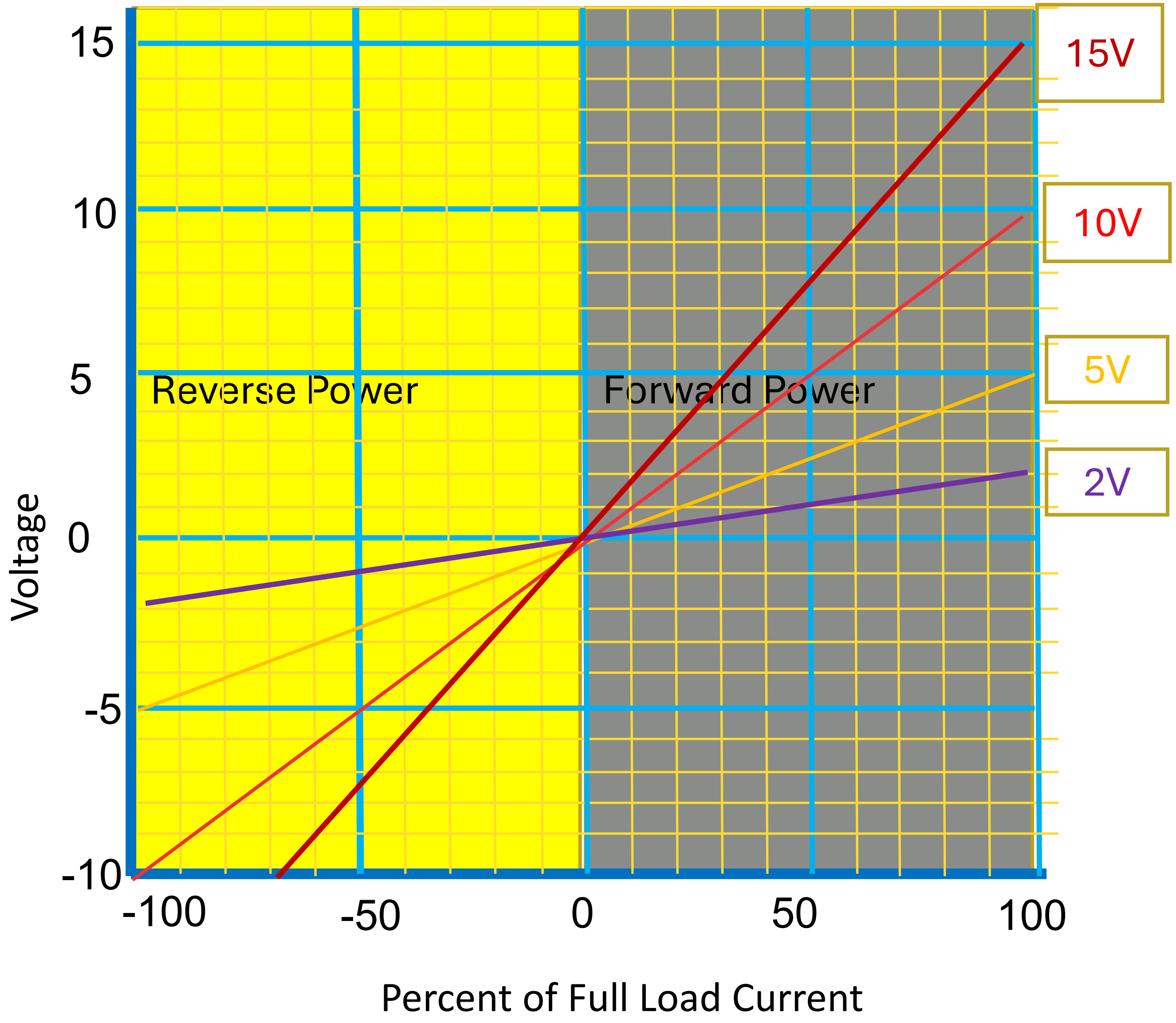




LDC Voltage vs. Load Current – Forward Power Only

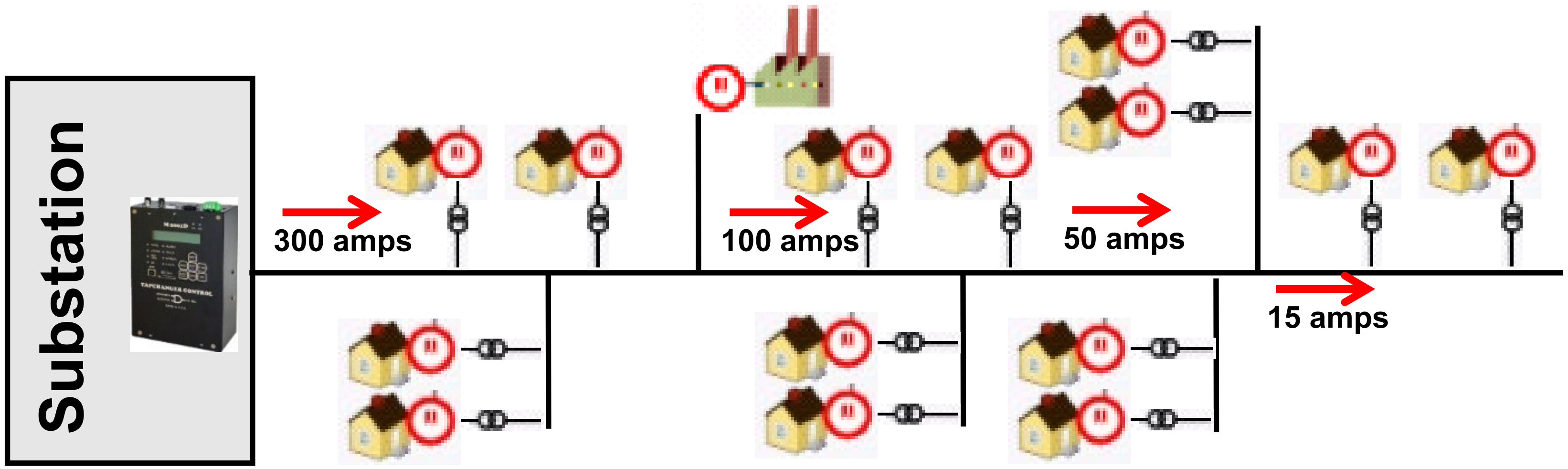


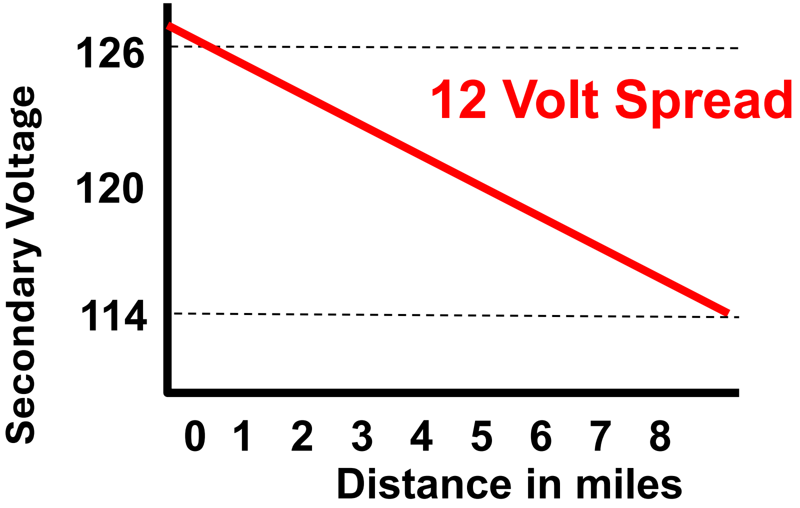
LDC voltage vs load current – with Reverse Power



Notice that if the current is in reverse direction, the voltage is dropped instead of raised. The block lower voltage setting will limit low voltage in reverse direction due to line drop compensation.

Traditional Circuit Design

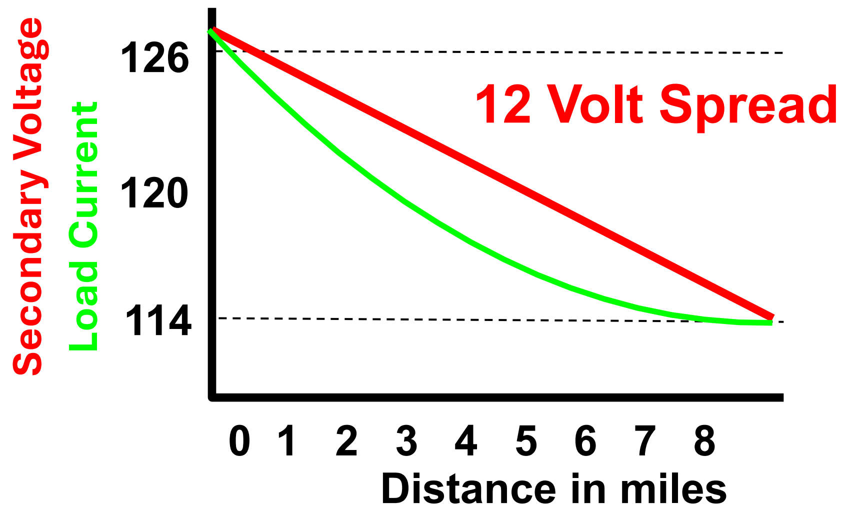




Voltage Profile – Loads Only Feeder Regulated

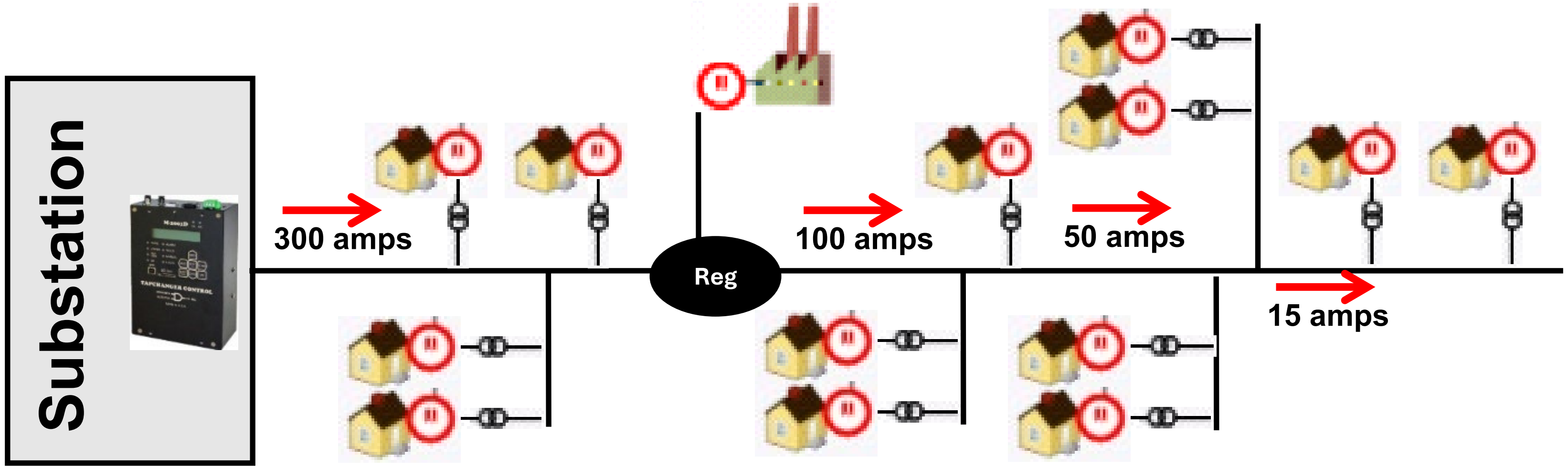
Traditional Circuit Design

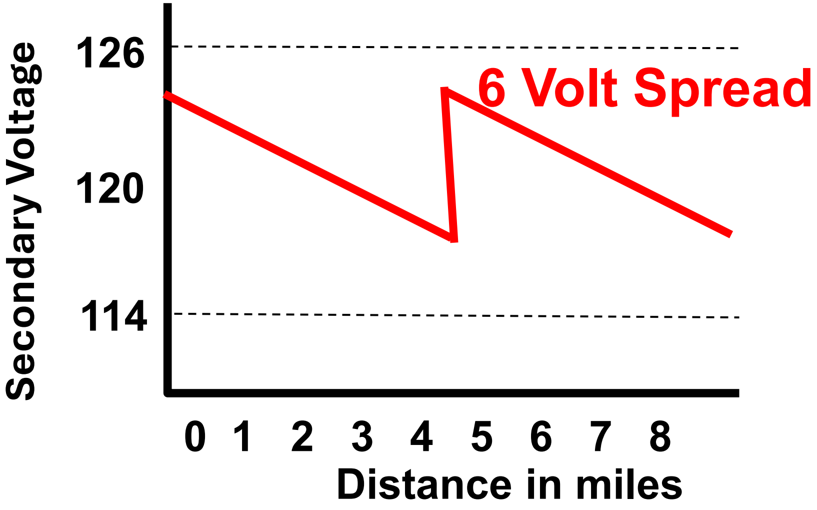
- One can see on a traditional circuit that voltage reduction is not optimized.
- Voltage is highest where the load is highest and lowest where the load is lowest.
- This means that the load will not be reduced as much as desired.

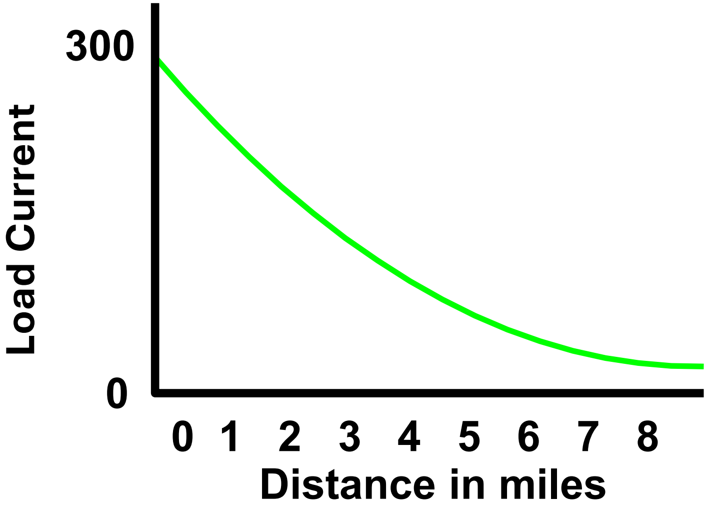


Voltage Profile – Loads Only, Feeder Regulated

Traditional Circuit Design with Regulators





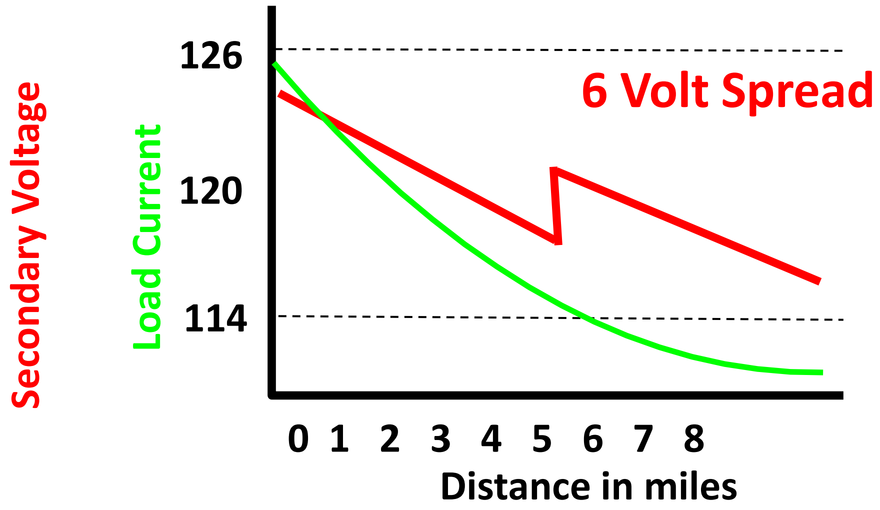


Voltage Profile – Loads Only, Feeder and Line Regulated

Traditional Circuit Design with Regulators

- As we can see adding regulators helps slightly by allowing the substation bus to be regulated at a slightly lower voltage.

- But the Voltage at the source is still at the highest where the load is at the highest and the same is true at the regulators.



Voltage Profile – Loads Only, Feeder and Line Regulated

Traditional Circuit versus Smart Grid

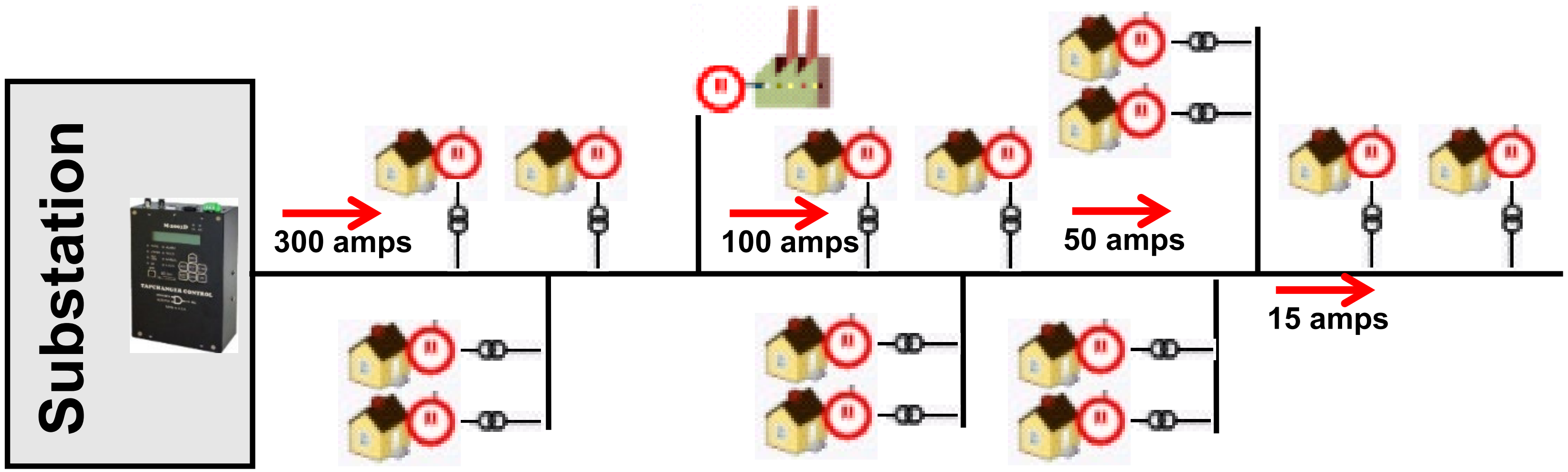
The traditional circuit design has

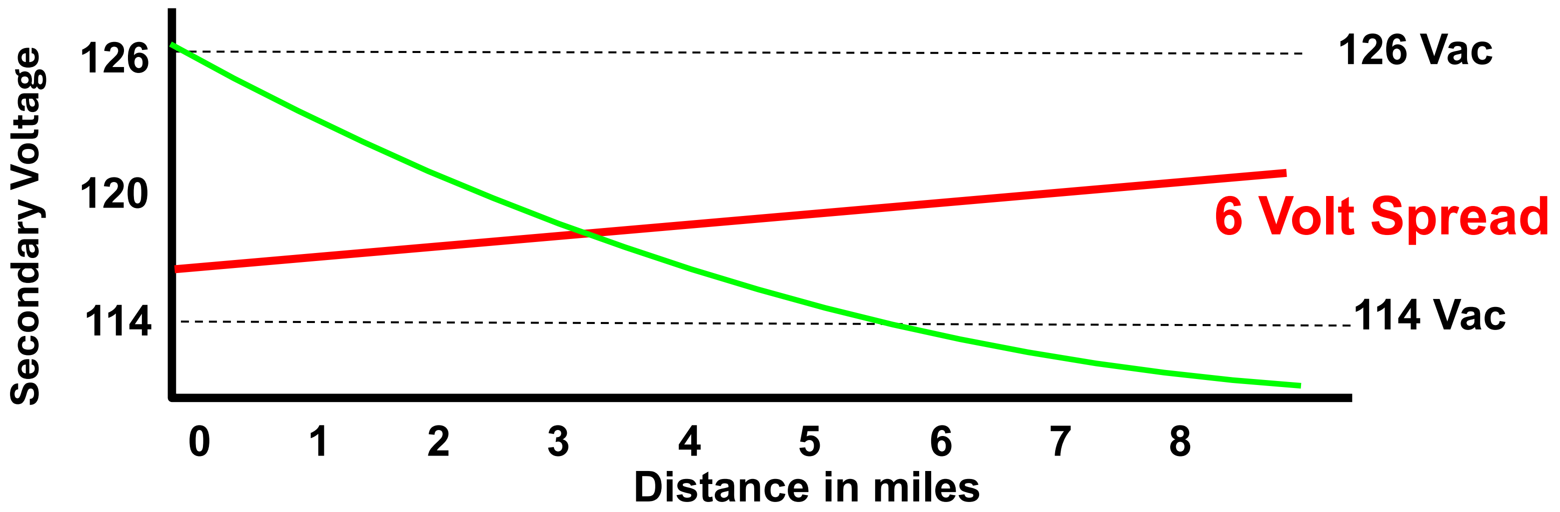
- The voltage at the highest point where the load is also at the highest point
- Keep the first customer below 126 (First House Protection) and the last customer above 114 (EOL monitoring)
- Spins the meter faster, good for utility bottom line
- No longer politically correct

BecoGrid– Flip the Circuit

- The voltage is lowest where the load is greatest
- This means having the lowest voltage at the source and having the downline voltage higher
- Reduces load and line losses

Smart Grid Circuit





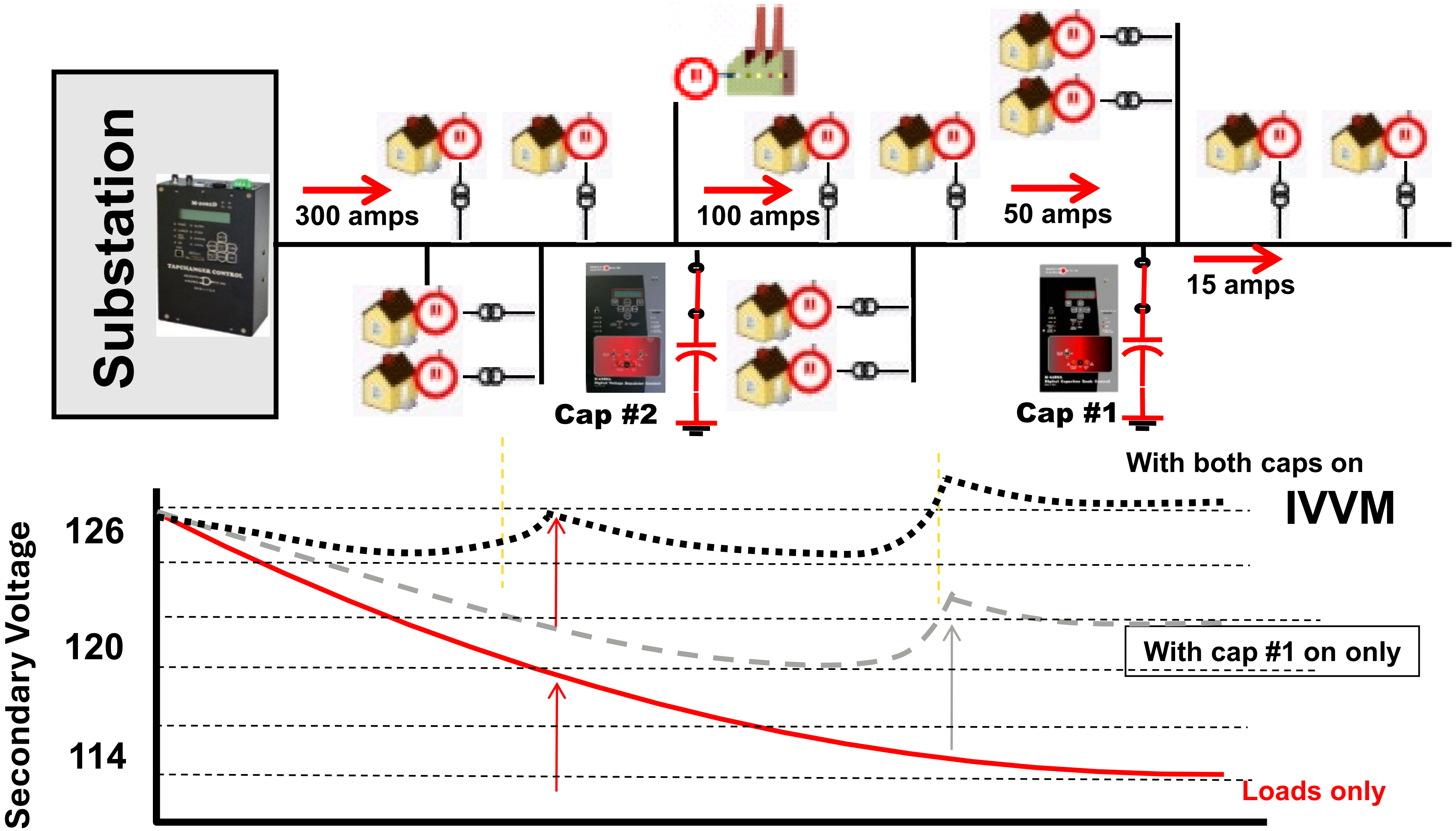
Voltage Profile – Voltage Lowest, where Load is Highest

Traditional Circuit and BecoGrid Circuit

Primary goals of BecoGrid Circuit Design:

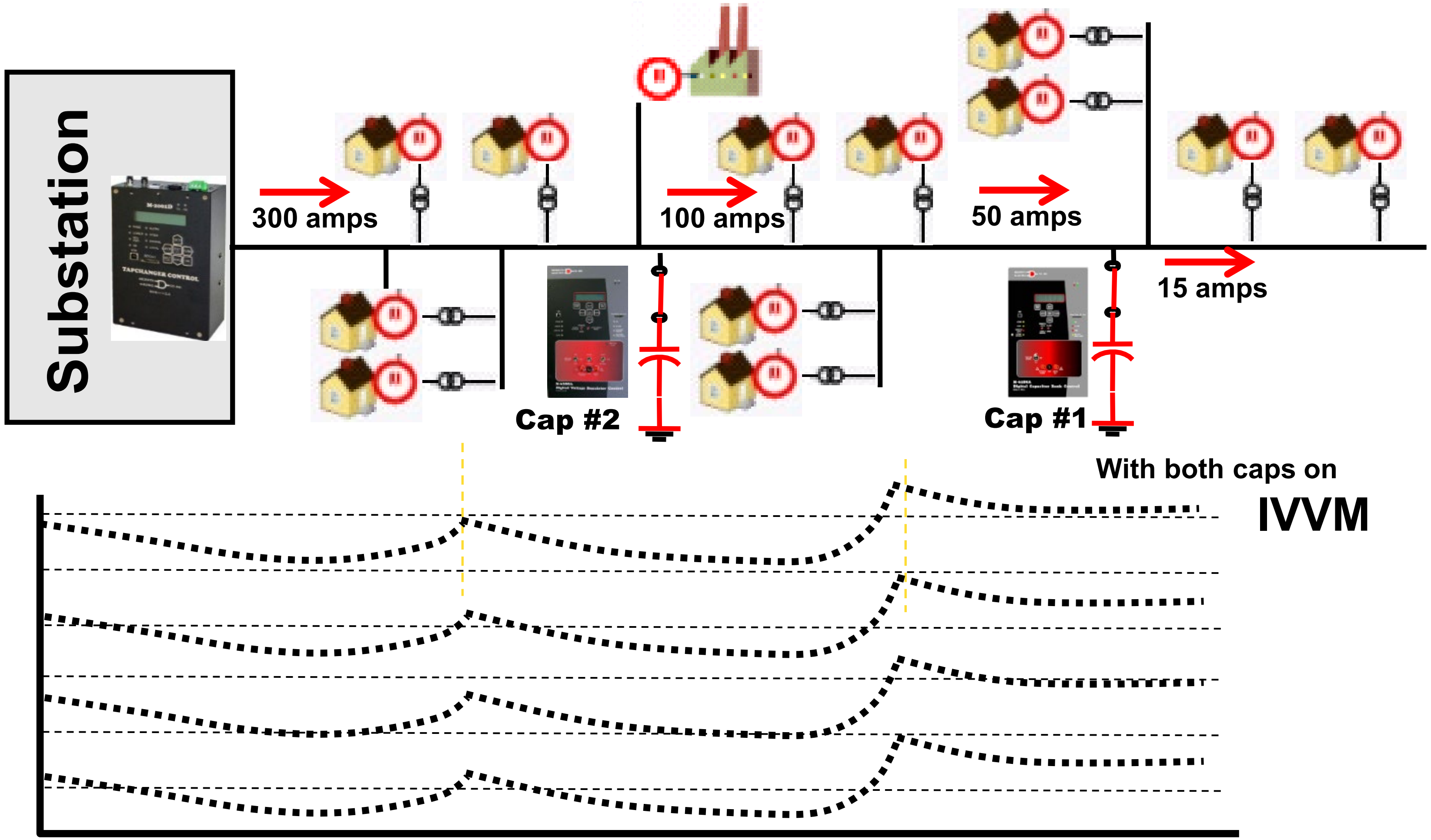
- Reduce operations on higher priced equipment (LTCs and Regulators).
- Reduce Line losses and free up capacity to transport more real power. To free up capacity we must eliminate the need to transmit Vars from the substation to the load.
- Minimize the voltage spread to allow more reduction in voltage when needed. Since reactive current causes 3-4 times more line losses than real current , this means get to unity power factor .
- Flip the circuit to obtain maximum amount of voltage reduction.
- But how?

Traditional Circuit With Cap Banks



Voltage Profile – With Capacitors Added

Capacitors affect voltage level, losses, capacity, etc.



Voltage Profile – With Capacitors Added

Regulator can now shift the voltage up or down

Traditional Circuit and BecoGrid Circuit

Primary goals of BecoGrid Circuit Design:

- Flip the circuit with Cap Banks in voltage control mode raising the voltage at the back end of the circuit.
- This will flatten the profile.
- Use the regulators/LTCs to move the voltage up and down.
- This creates flexibility for CVR as well as increased solar hosting capacity.

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