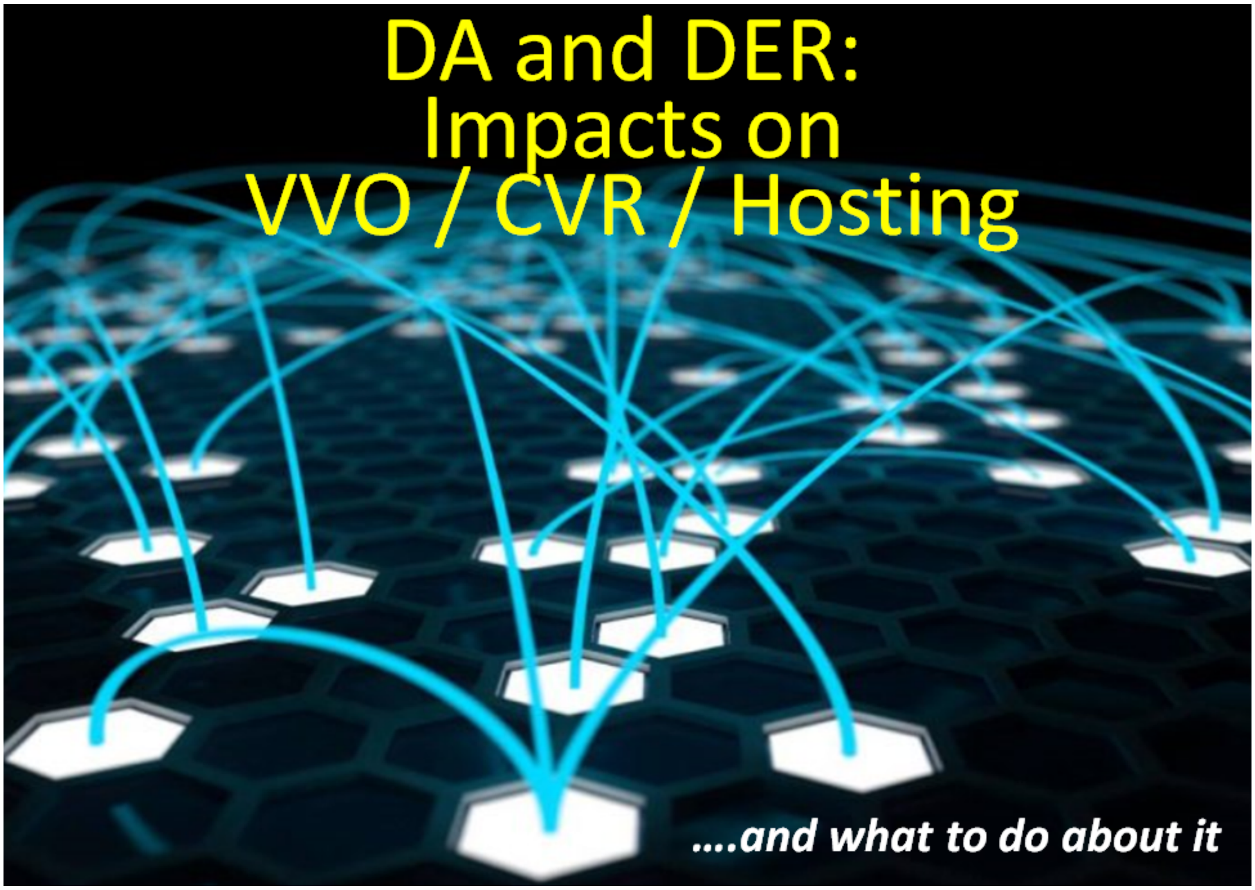

www.BeckwithElectric.com

Speaker Bio

Wayne Hartmann
Senior VP, Customer Excellence

whartmann@beckwithelectric.com
904-238-3844

Beckwith Electric's top strategist for delivering innovative technology messages to the Electric Power Industry through technical forums and industry standard development.

- Before joining Beckwith Electric, performed in Application, Sales and Marketing Management capacities at PowerSecure, General Electric, Siemens Power T&D and Alstom T&D.
- Provides strategies, training and mentoring to Beckwith Electric personnel in Sales, Marketing, Creative Technical Solutions and Engineering.
- Key contributor to product ideation and holds a leadership role in the development of course structure and presentation materials for annual and regional protection & control Seminars.
- Senior Member of IEEE, serving as a Main Committee Member of the Power System Relaying and Control Committee for over 25 years.
- Chair Emeritus of the IEEE PSRCC Rotating Machinery Subcommittee ('07-'10).
- Contributed to numerous IEEE Standards, Guides, Reports, Tutorials and Transactions, delivered Tutorials IEEE Conferences, and authored and presented numerous technical papers at key industry conferences.
- Contributed to McGraw-Hill's "Standard Handbook of Power Plant Engineering."

Acronyms

- CAPC = Capacitor Control (6280A, 6283A)
- REGC = Regulator Control (6200A)
- LTCC = Load Tapchanging Transformer Control (2001D)
- FPF = Forward Power Flow
- RPF = Reverse Power Flow
- DA = Distribution Automation
- OLTC = On Load Tapchanger (REG and PWR XFRM)
- DMS = Distribution Management System
- EOL = End of Line, as in EOL Voltage
- Reconfig = System Reconfiguration
- FLISR= Fault Location, Isolation, System Recovery

2

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Objectives [1]

- Discuss Impact of DA on VVO
- Sample DA Scenarios
- Explore IEEE 1547-2018
  - Active VAr control of DER
- 1547 and Impact on Distribution Protection
  - Bidirectional Load and Fault Currents
  - Effects on Reclosers and Feeder Relaying
- Control of Watts and VAr in DER

3

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Objectives [2]

- Reverse Power Flow (FFP) and Importance of Source Strength Determination
  - Use of OLTC Autodetermination of Source Strength in OLTCs
- RFP OLTC Strategies
- Review of LDC and other Fundamental OLTC Settings

4

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Objectives [3]

- Smart Voltage Reduction
- Use of VAR Bias (instead of LDC) for Better OLTC and Line Cap Coordination
- Use of VAr Bias for DER CVR and Improved CVR_f
- Use Autoadaptive Line Capacitor Control to Cope with DA
- Putting it All Together: Optimization Tactics

5

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VVO

- Adjusting system voltage and pf by properly controlling OLTC and reactive assets. Ideally:
  - OLTC Assets used for Voltage Issues due to *Real* Power Changes
    - Load Tapchanging Transformer Controls (Substation)
    - Voltage Regulator Controls (Substation and Line)
  - Reactive Assets used for VAR regulation (loss minimization)
  - Reactive Assets for Voltage Issues due to *Reactive* Power Changes
    - Capacitors (Line)
    - Active VAR Regulating DER (*new*)

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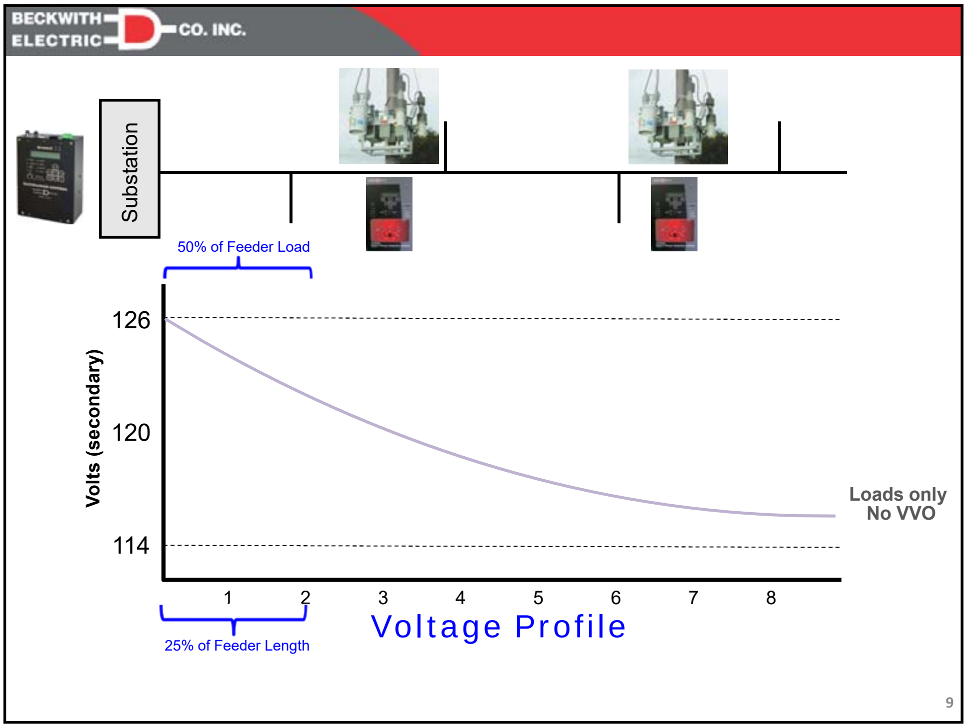
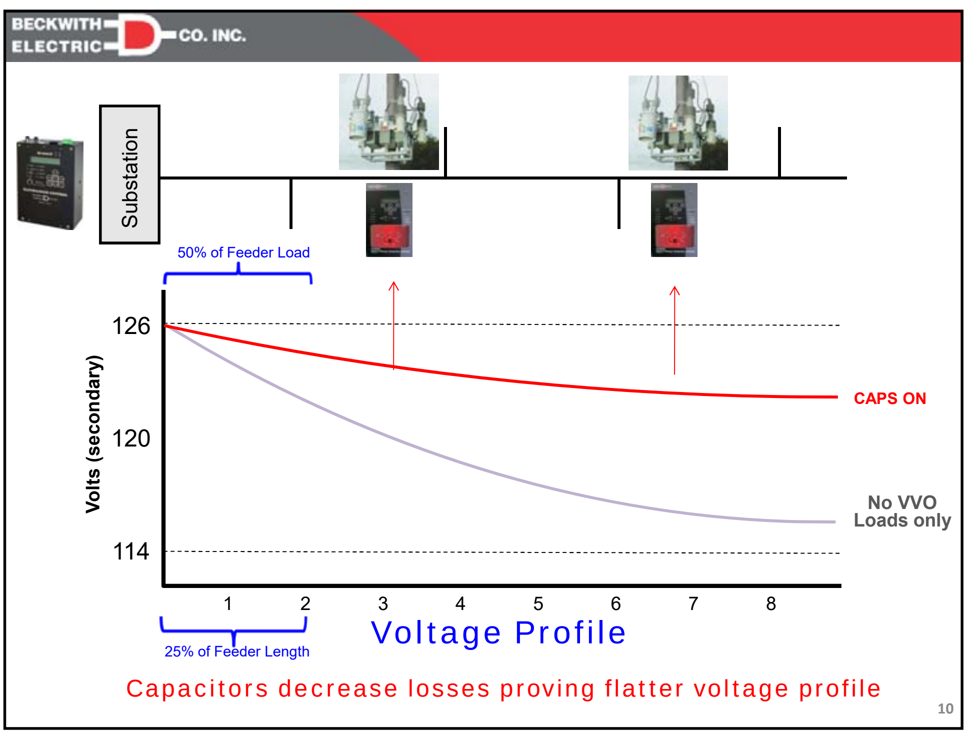
VVO Results

- Reduced losses
  - X_C counters X_L of lines
- Decreased operation of OLTC elements
- Deferred capital expenditures and improved capital asset utilization
- Reduced electricity generation and environmental impacts
- Flatter voltage profile
  - Allows better CVR without low voltage violation at the end-of-line

8


BECKWITH ELECTRIC CO. INC.
Substation
50% of Feeder Load
126
120
114
Volts (secondary)
Loads only
No VVO
1
2
3
4
5
6
7
8
25% of Feeder Length
Voltage Profile
9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1
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4
5
6
7
8
25% of Feeder Length
Voltage Profile
Capacitors decrease losses proving flatter voltage profile
10

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VVO Controllers

- LTC Controls (Load Tapchanger) (M-2001D)
  - Applied on LTC Transformers in Substations
  - Control voltage
- Regulator Controls (6200A)
  - Applied on Regulators
  - Substation and Line
  - Control voltage
- Capacitor Controls (6280A, 1ϕ; 6283A, 3ϕ)
  - Applied on Pole Top Capacitor Banks
  - Provide VARs and influence voltage

We'll explore some advanced applications
Advanced Volt/VAR Optimization Controllers = ADVVOC

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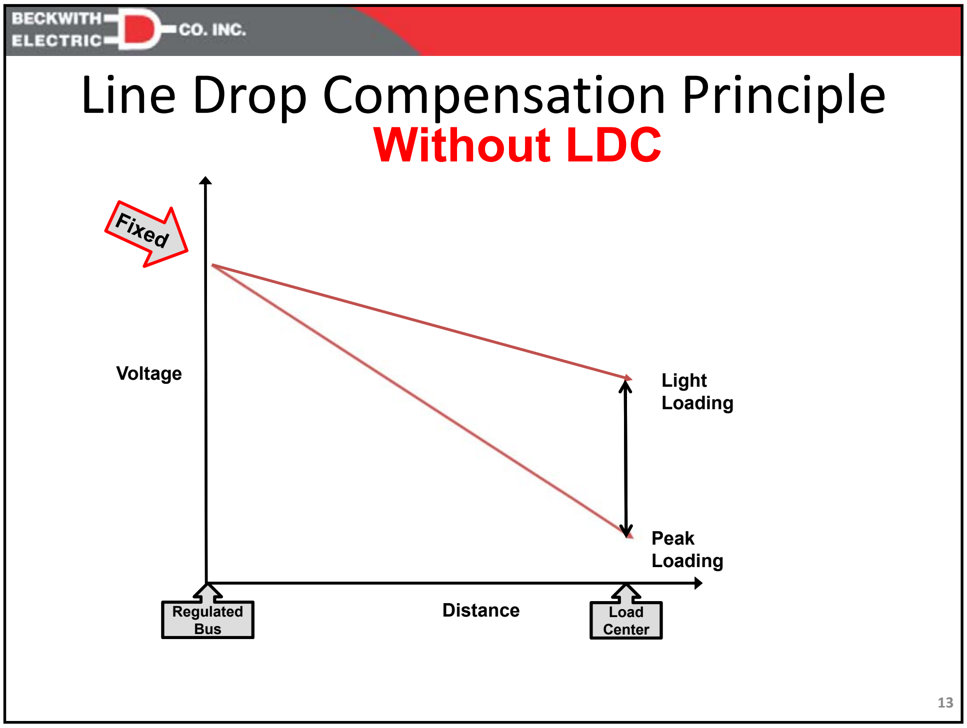
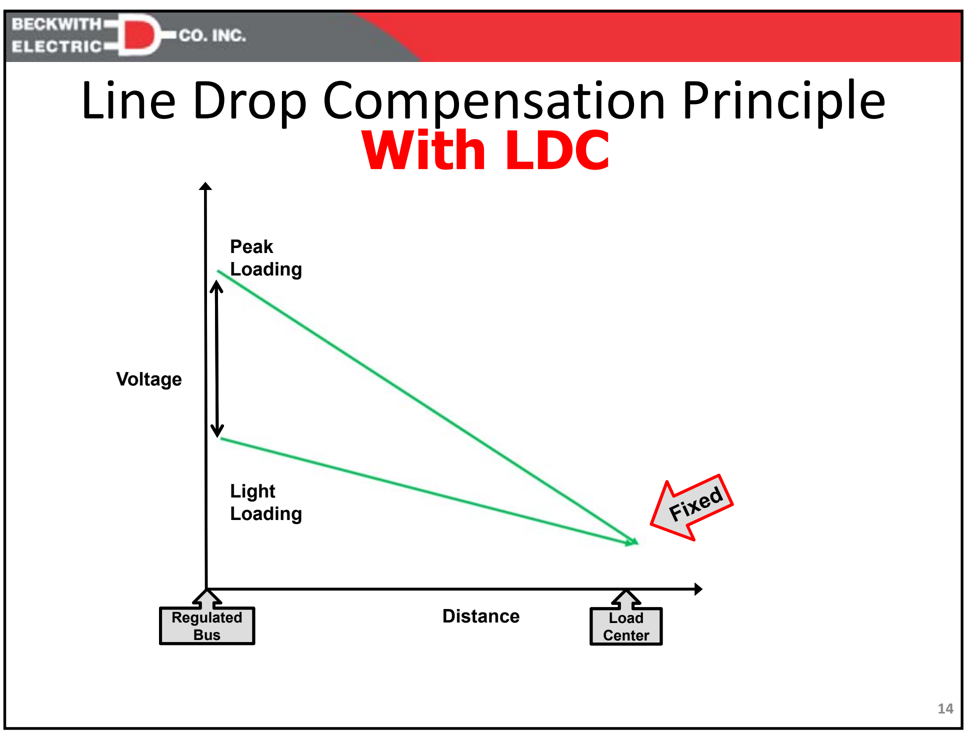
Traditional Methods: Control Based OLTC Elements

- OLTCs use line drop compensation (LDC) to cope with line losses (R/X_L, Z)
  - Only as good as line model
  - May not coordinate with downline capacitors for VAR/pf regulation

- OLTCs use line drop compensation to cope with line losses (X_L)
  - Only as good as line model
  - May not coordinate with downline capacitors for VAR/pf regulation

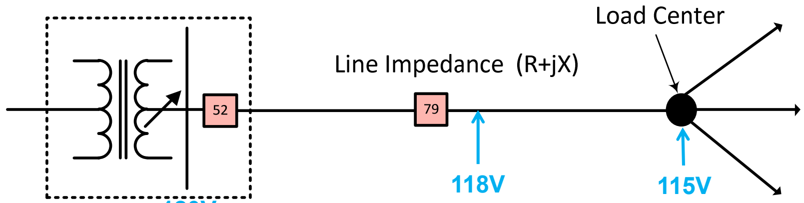
12


BECKWITH ELECTRIC CO. INC.
Line Drop Compensation Principle
Without LDC
Fixed
Voltage
Light Loading
Peak Loading
Regulated Bus
Distance
Load Center
13

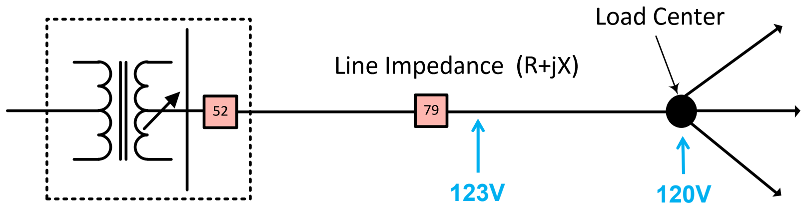

BECKWITH ELECTRIC CO. INC.
Line Drop Compensation Principle
With LDC
Peak Loading
Voltage
Light Loading
Fixed
Regulated Bus
Distance
Load Center
14

LDC – R,X

- Regulates voltage at a point closer to the load as voltage drops due to loss in the line because of line impedance and current



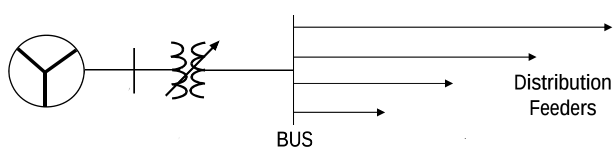
Without LDC at full Load



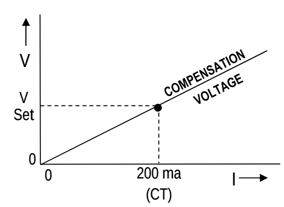
With LDC at full Load and unity power factor(R=5)

LDC - Z

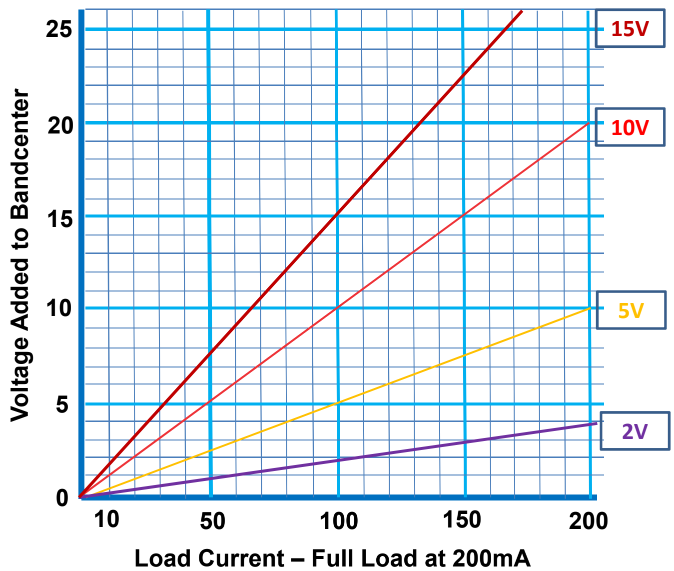
- Application: Distribution bus regulation



- Concept: Increase bus voltage as the load level increases
- No individual line information
- Uses current magnitude ONLY



Forward Power and LDC



Should use high voltage block for 1st house protection!!!

Traditional Methods: Control Based Reactive Support Elements

- Caps use "feedforward" control such as time-of-day, day, temperature, seasonality
  - Feedforward is only as good as your assumptions and correlation factors
- Caps use voltage or VAR w/voltage override
  - Difficult to coordinate with OLTC elements using LDC with voltage or VAR w/voltage override
  - VAR controls not much good near end of line
    - Little load flow
  - VAR controls must be on main line
    - Voltage controls may be on line tap when "real estate" is sparse

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Traditional Methods: DMS-Comms Based

- Costly: Can run millions of dollars $$$$$
- Is DMS *everywhere* on a Utility's system?
- Requires system model
  - Expensive to *create* (needs GIS and live system inputs)
  - Expensive and time intensive to *maintain*
- Requires model dynamic update and near real-time communications to system and system elements

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Traditional Methods: DMS-Comms Based

- Data quality impacts load flow model results
  - Tap position data requirements for model
- Multiple substation and feeder configurations need to be reflected in the model
- Need a DAC regardless if communications between DMS-SCADA-DACs fail

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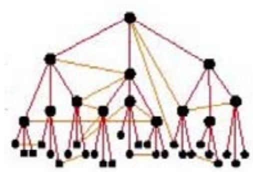
Traditional Methods: Hybrid DMS-Comms to Control Based

- Same CAPEX and OPEX as DMS-Comms Based
- Need an ADVVOC if communications between DMS-SCADA-ADVVOCs fail
- May use less comms bandwidth by employing profile changes and setpoint changes versus “micromanagement” control



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DA and DER Impact on VVO

- DA (DMS) can reconfigure feeders
  - Powerflows and levels change, resulting in voltage changes
  - Placement of VVO equipment changes compounding the issue
- DER is proliferating
  - Powerflows and levels change, resulting in voltage changes
  - Placement of DER can change due to DA
  - 1547-2018 allows *reactive* as well as active powerflow output, compounding the problem

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Sample DA Scenarios

- What does DA do to power flow and source strength on line sections?

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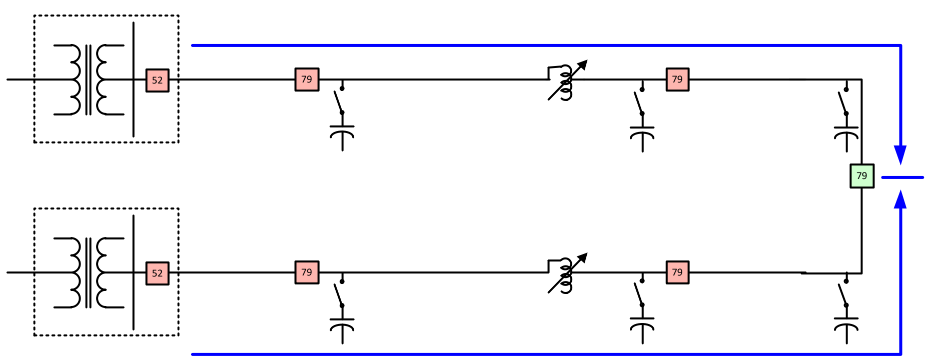
Volt/VAR Control Considerations from DA



- Normal open loop
- Uses recloses to perform FLISR
- V/VAR feeder devices employed: REGC and CAPC

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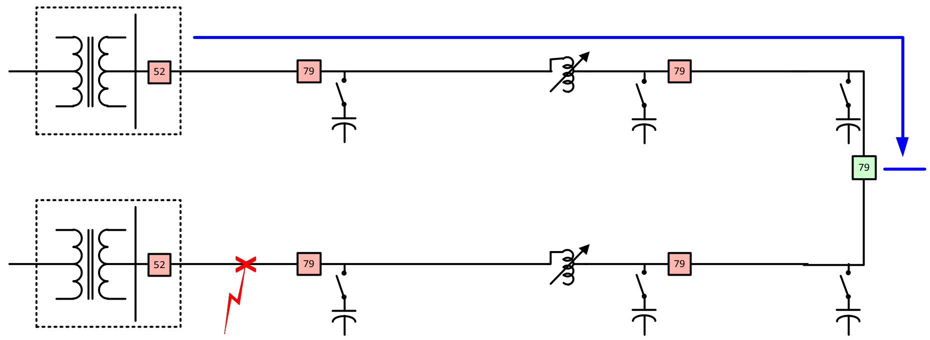
Volt/VAR Control Considerations from DA



- Fault occurs on feeder

25

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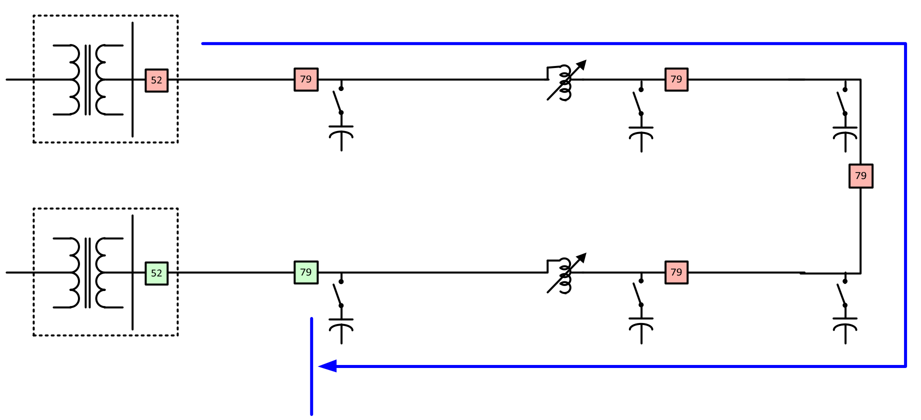
Volt/VAR Control Considerations from DA



- Fault is cleared by 52 (O/C trip and LO) and 79 (27)
- Tie 79 closes (uses H/D logic)
- Power is restored to most of loop system
- Reverse power flow occurs on some section of the newly-configured feeder

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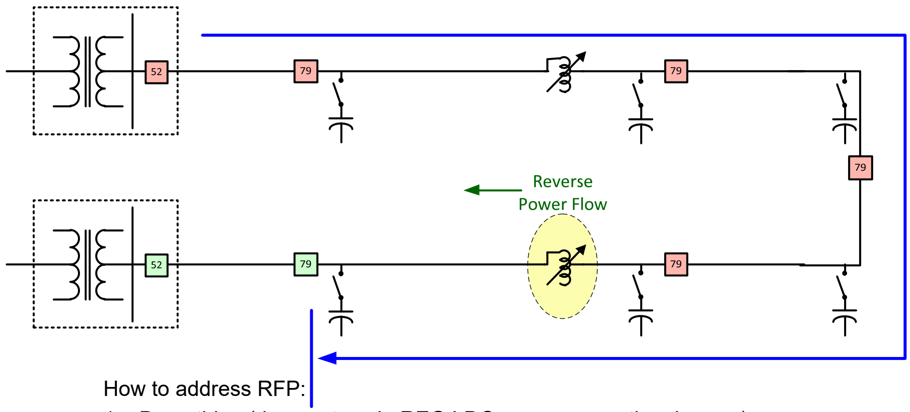
Voltage Control Considerations from DA: REGC



How to address RFP:

1. Do nothing (does not work; REG LDC causes operational errors)
2. Use communications to control by setpoint or setting group
3. Use change of **powerflow direction** to change to a new **predetermined** control mode
4. Use change of **powerflow direction and source strength** (by REGC measurement) to initiate *autodetermination* of **best** control mode

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Reverse Power Flow

- How do VVO elements act after source strength and power flow direction changes?

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RPF: Why We Care????

- With high penetration levels of DA and/or DER on the distribution system it is becoming more common to have the voltage regulators deal with reverse power situations
- The solution to the OLTC problem gets complicated as the control needs to know (or assume) the source of reverse power.
- It is important to select the correct reverse power mode of operation for voltage regulators otherwise dangerous high or low voltage levels may result causing equipment damage or misoperations

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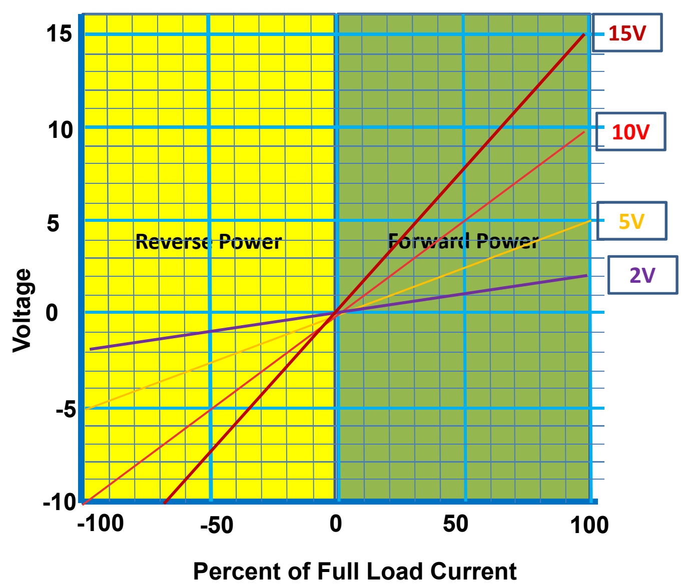
Forward Power and LDC



Notice that if the current is reverse, LDC drops the voltage instead of raising it

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Issues with DA and DER

- Reverse Power Flow (RPF)
- Both a reconfig and DER may cause RPF
  - With *DER* (weaker source than system), *forward regulation* should be employed
  - With *reconfig* (strong source switches), *reverse regulation* should be employed

How do we know weak and strong source if you have mix of DA and DER?

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The Reverse Power Flow (RPF) Problem

- It's all about **source strength**
  - If the source is weak, small impact (most DER)
  - If the source is strong, big impact (reconfiguration)
- Impacts of **strong source** RPF:

  - Drives LDC the wrong way
  - Regulation should be in the now reverse direction
    - The tail *cannot* wag the dog

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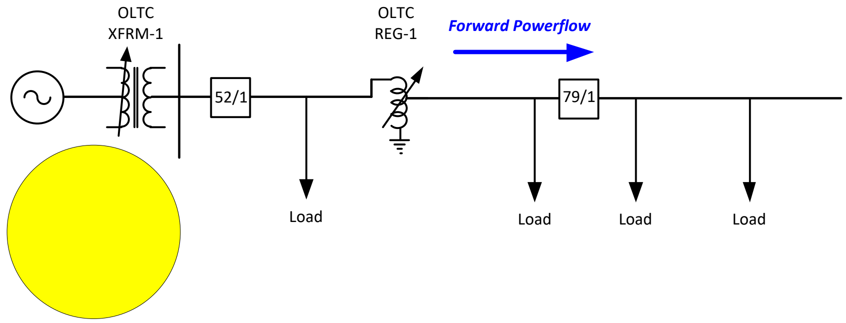
No RPF Source



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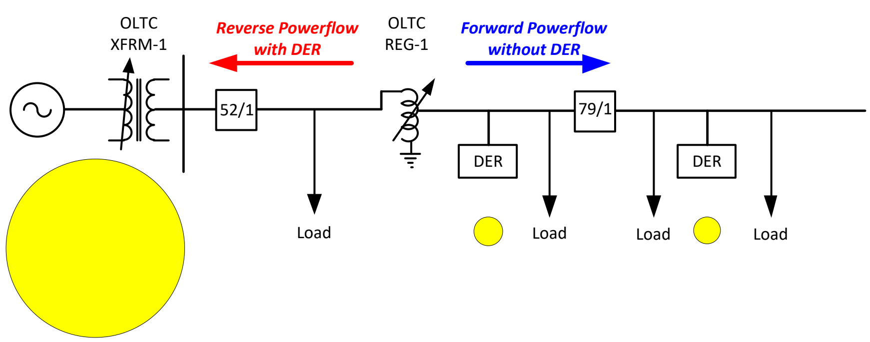
Weak RPF Source



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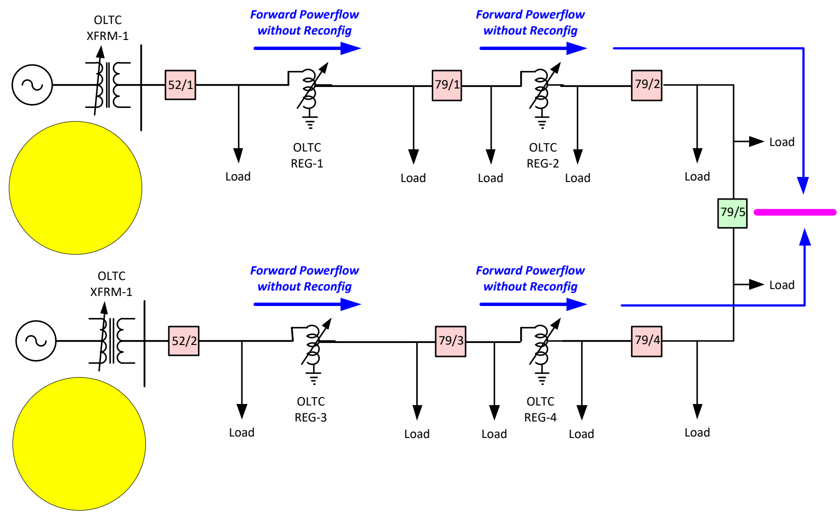
No RPF Source: Open Loop



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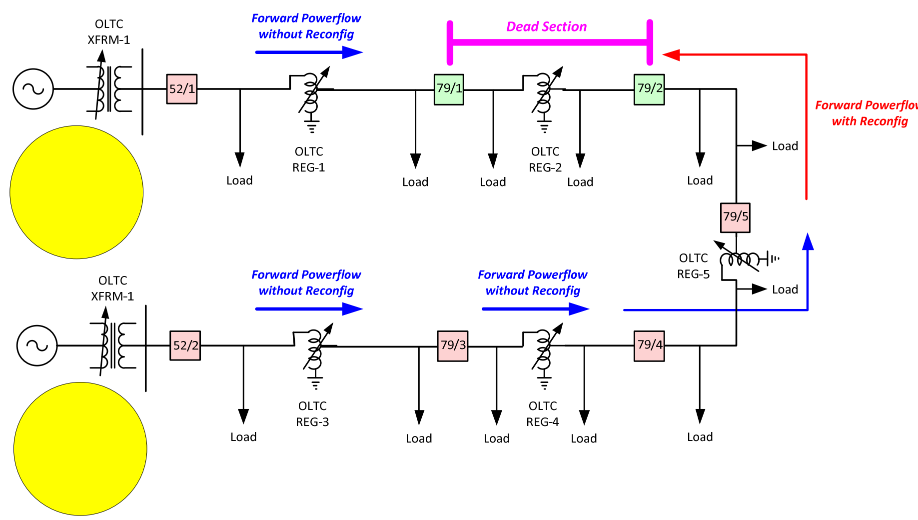
Strong FPF Source: Reconfig



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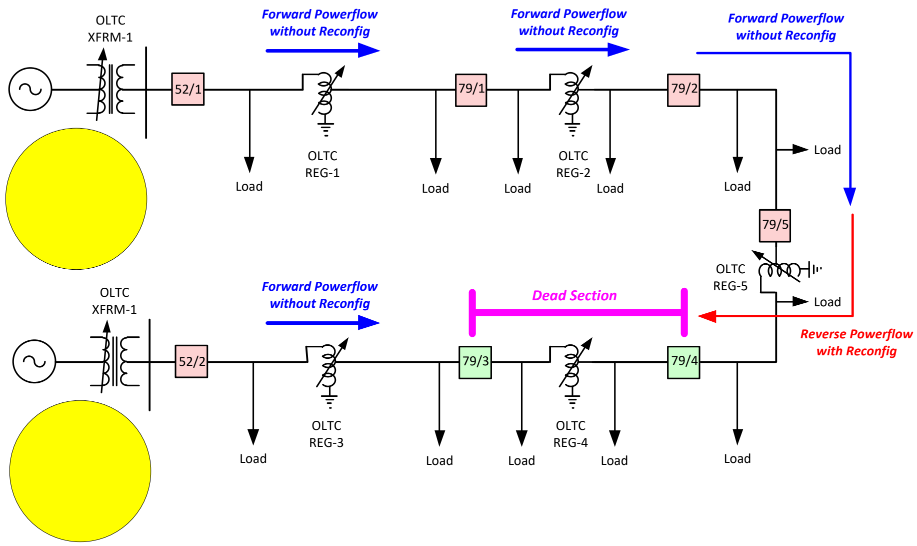
Strong RPF Source: Reconfig



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How Can One Know About Source Strength

- **Guess it, assume it**
- Cheap and easy if one can make assumptions or guess
- LTC or REG makes RPF determination and goes into *predetermined* response mode, either:
  - No DER on line, and the only way you can have RFP is a reconfiguration with a new source direction (assume new strong source)
  - No reconfiguration possible, so only DER can cause RPF

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How Can One Know About Source Strength

- Use **Communications**
- DMS uses information gathered about system elements and configuration
  - DMS determines best control action selection
  - Requires DMS and radios or other comms media
  - Expensive and complex

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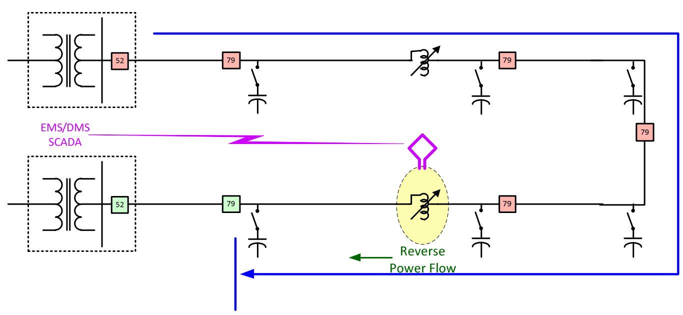
Communications to REGC



1. REGC is able to provide detailed power system information to DMS/DA such as operational data (ex., V, A, W, S, demand, THD, open/closed status) and, and non-operational information such as asset maintenance information, detailed PQ monitoring and event information (DNP)
2. DMS/DA, per modeling or feedback control, sends analog value DNP setpoints to REGCs for new control action. REGCs perform per new setpoints.
3. DMS/DA, per modeling or feedback control, sends DNP profile change command to REGC for new control action. REGC performs per new setting profile. This takes less communication bandwidth and frequency than Solution 1.

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Communications to REGC/LTCC

- Pros:
  - REGC does as commanded, using analog setpoint or profile group
    - Using "Heartbeat," control knows if communications is lost
      - Go to "Plan B;" operation mode with comms
- Cons:
  - Costs of communications infrastructure
  - Requires DMS with either modeling or feedback to properly execute commands
    - *Feedback* requires recloser and switch position status, EOL voltage sensing
    - *Modeling* requires creation, updating and upkeep

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Use of Powerflow Direction Change by REGC/LTCC

- Pros:
  - Communications not needed to detect RPF situation
  - Control is autonomous (no DMS/SCADA required)
  - Autodetermination Mode allows dynamic source stiffness determination and proper regulation based on the dynamic conditions
- Cons:
  - Settings may require adjustment if feeder changes over time
    - Ex.: LDC-R, X_L

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Knowing Relative Source Strength is KEY

- Use "**Autodetermination**"
  - **Reverse Power Flow Source Strength Determination**
    - Control determines relative source strength
  - Why it is important
    - **Weak** source (DER) results in continuing **forward** regulation
      - May employ different LDC or VAR-Bias settings
    - **Strong** source (Reconfig) results in use of **reverse** regulation
      - May employ different Bandcenter, Bandwidth, and LDC or VAR-Bias settings

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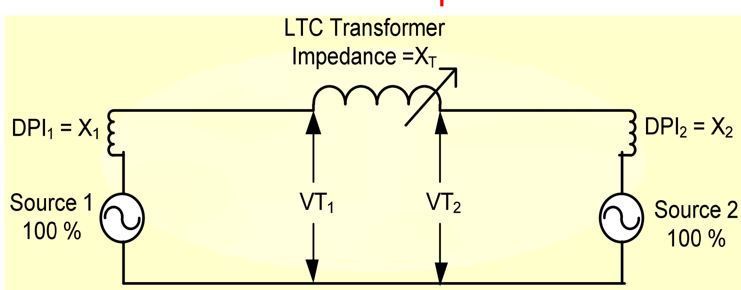
Simulation of LTC Transformer/Regulator with Two sources: Simplified Model



$$VT_1 = 100\% - X_1 . \left(\frac{\Delta V}{X1+XT+X2}\right) \qquad (1)$$

$$VT_2 = 100\% + X_2 . \left(\frac{\Delta V}{X1+XT+X2}\right) \qquad (2)$$

$$\Delta V = 0.625\% \text{ for one tap change}$$

Initial condition: LTC neutral tap position, Source 1 and 2 voltages are each 100%, no reactive current flow (unity power factor)

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Simulation Results

Case #	DPI_1	DPI_2	Reactive Current (I_X) Through the transformer	VT_1	VT_2	ΔV
1	2%	∞	0	100%	100.625%	.625
2	∞	2%	0	99.375%	100%	.625
3	2%	20%	1.953 %	99.96 %	100.4%	.04
4	20%	2%	1.953 %	99.6 %	100.035%	.04
5	2%	2%	7.14 %	99.85%	100.14%	.29

1 & 2: System reconfiguration; one source, radial
3 & 4: DER (weak) vs. System (strong)
5: Two weak sources

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Autodetermination of Source Strength with RPF

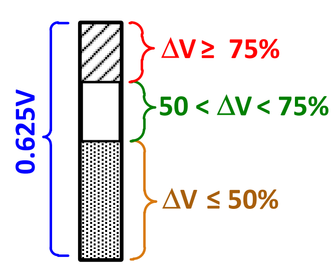
- ❑ When RPF is detected, operation is set initially to "DG Mode"
- ❑ ΔV is measured for two tap operations:

$\Delta V = V_{MBT} - V_{MAT}$

where V_{MBT} = **measured** load side voltage **just before a tap change**
V_{MAT} = **measured** load side voltage one second **after the tap change**

Normally expect 0.625V per tap

- If the measured ΔV is > 0.47 (75%) of the normal expected value (0.625V) for two consecutive tap changes, Autodetermination will maintain "DG Mode" operation
- If the measured ΔV is <= 0.31V (50%) of the normal expected value (0.625V) for two consecutive tap changes, Autodetermination changes to "Regulate Reverse Mode" operation



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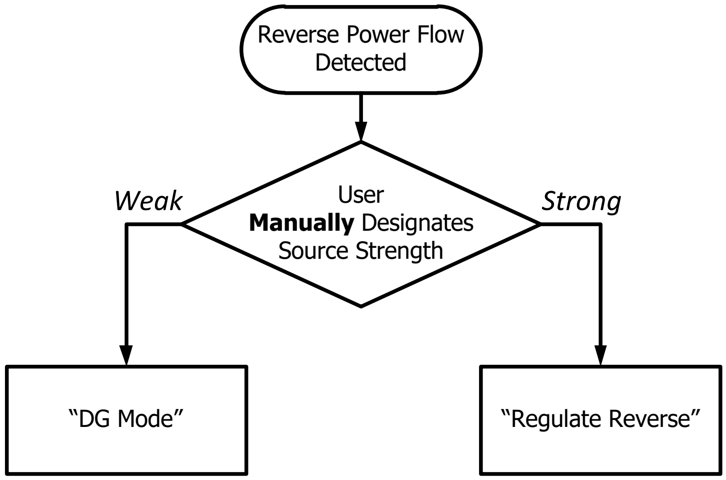
Reverse Power Source Strength Determination: *User Manually Designates*



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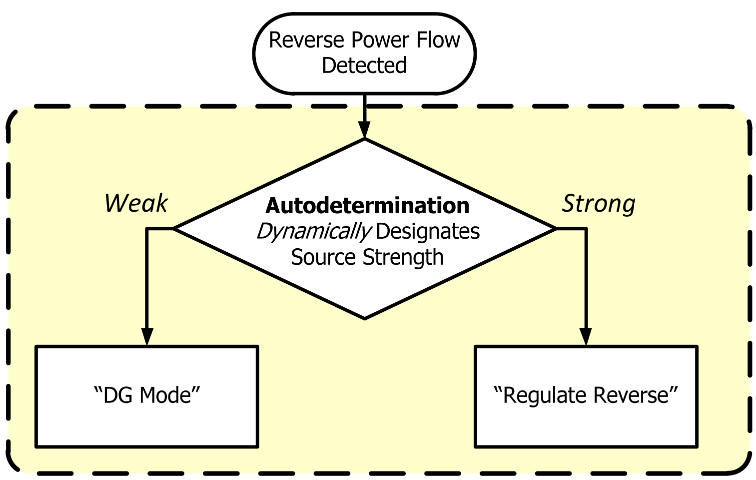
Reverse Power Source Strength Determination: *Autodetermination*



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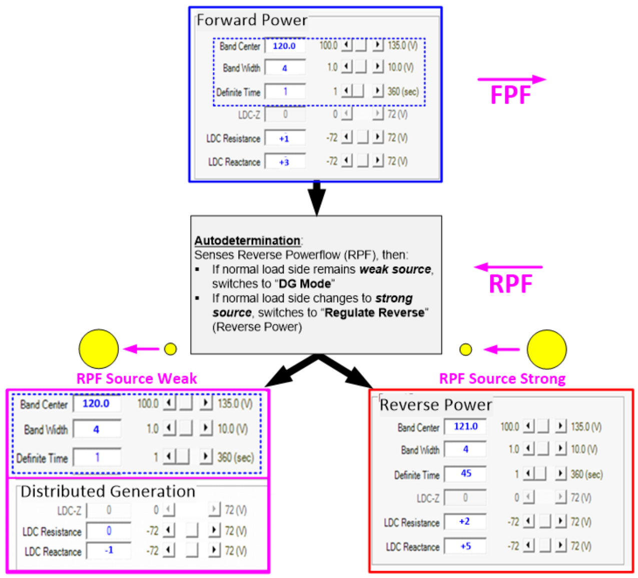
REGC/LTCC: Autodetermination of Operating Mode with Reverse Power



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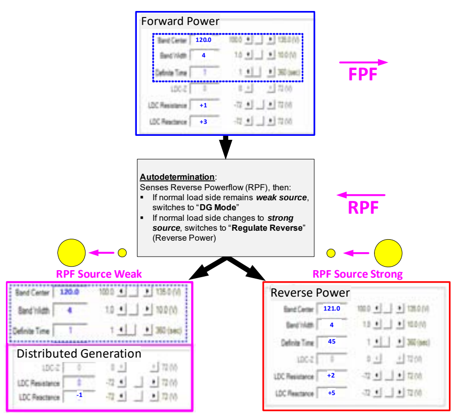
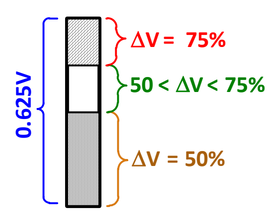


REGC/LTCC: Autodetermination of Operating Mode with Reverse Power



- Once RPF is detected, checks source strength
  - Makes two taps and checks for satisfactory voltage change
  - If voltage change is less than 50% of 0.625V, assumes strong source from RPF direction, uses "Regulate Reverse"
  - If voltage change is greater than 75% of 0.625V, assumes weak source from RPF direction, uses "DG Mode"

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Use of Powerflow Direction Change by REGC/LTCC

Terminology Cross Reference

Beckwith Reverse Power Mode	Cooper/Siemens Reverse Power Mode
Block	Locked Forward Mode
Regulate Forward (Ignore) *	Reverse Idle Mode
Regulate Reverse	Bi- Directional Mode
Return to Neutral *	Neutral Idle Mode
Regulate in Reverse (Measured) *	Bi-Directional Mode
Distributed Generation	Cogeneration Mode
Auto Determination	None
*Low Current block feature must also be enabled to be equivalent to this Cooper Reverse Power Mode.	

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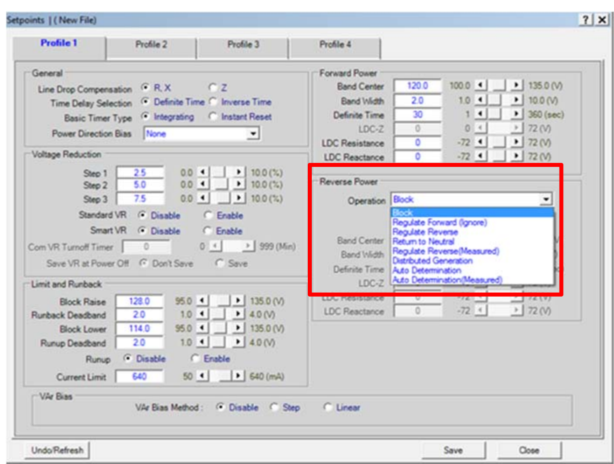
REGC/LTCC: Reverse Power Method Discussion



RPF Selection

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REGC/LTCC: Reverse Power Method Discussion

- **Return to Neutral** – drives tap position to neutral and then stops
  - Use where small unpredictable change in voltage may be encountered on RPF side of REG
  - "Feel safe" strategy when one cannot distinguish the source strength of the RFP
    - Is it DER, and possible weak?
    - Is it DA, and strong?
  - Can be risky as there is no control once at the neutral tap
  - The only control action possible is to have is force lower limit (runback) if voltage becomes too high

- **Block** – inhibits automatic operation, leaving regulator on present tap
  - Use where source of RPF is not expected to change voltage on RPF side of REG
  - Also a "feel safe" strategy when one cannot distinguish the source strength of the RFP.
    - Is it DER, and possible weak?
    - Is it DA, and strong?
  - Can be risky as there is no control and the voltage begins to deviate

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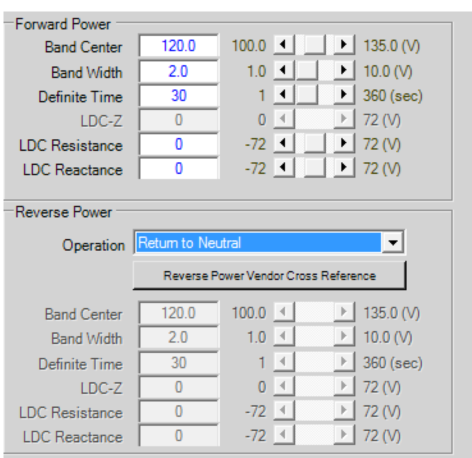
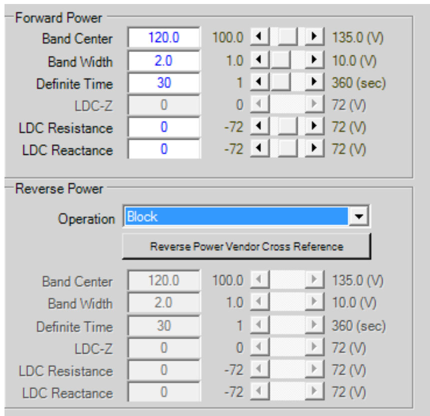
REGC/LTCC: Reverse Power Method Discussion



- "Return to Neutral"
- Operates to neutral position and then freezes there

REGC/LTCC: Reverse Power Method Discussion



- “Block”
- Freezes on present tap
- No control

REGC/LTCC: Reverse Power Method Discussion

- **Regulate Forward (Ignore)** – continues control action as though forward power flow continued to exist.
  - Use where weak DER, without active voltage control, is causing RPF
  - Uses same settings with normal forward power flow
- **Regulate Forward (DG Mode) -** This mode of operation is the same as the Ignore mode, plus provides ability to change line drop compensation (LDC)
  - Use where DER power output is large enough to warrant new LDC settings
    - A separate set of LDC settings can be specified which will be applied during reverse power
      - This can include LDC factor magnitudes, signs and the use of R and X_L , or Z
      - VAR-Bias may also be selected

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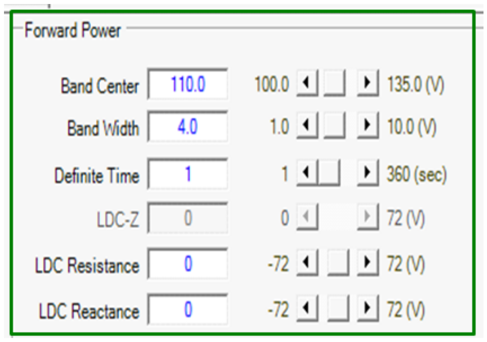
REGC/LTCC: Forward Power



- "Regulate Forward"
- Use for normal forward load
- May use with very weak sources (weak DER only), or when you need to drive down voltage due to DER causing a voltage rise

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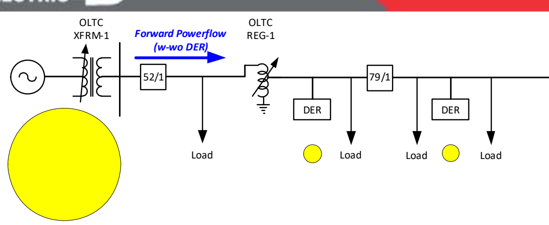
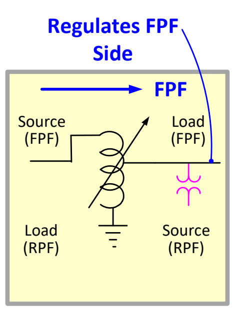
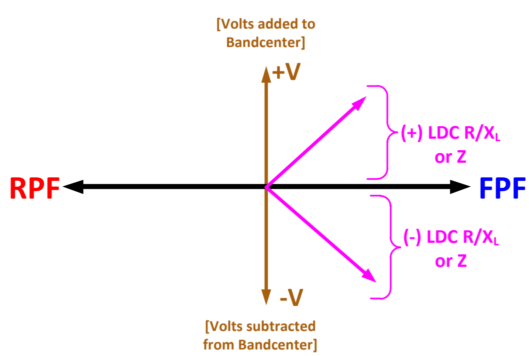
REGC/LTCC: Regulate Forward







- Regulating **forward**, +LDC *raises* bandcenter as **FPF** becomes larger
- Regulating **forward**, -LCD *lowers* bandcenter as **FPF** becomes larger

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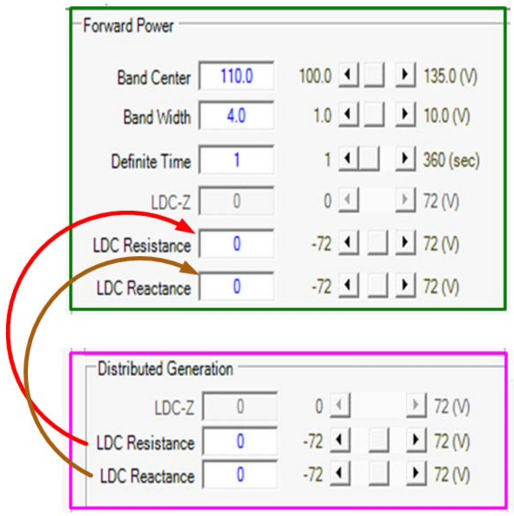
REGC/LTCC: Reverse Power, “DG Mode”



- DG Mode for “Distributed Generation” and “Distributed Energy Resource”
- Regulates **forward** with new LDC values (magnitude and sign)
- Use with weak source (DER)

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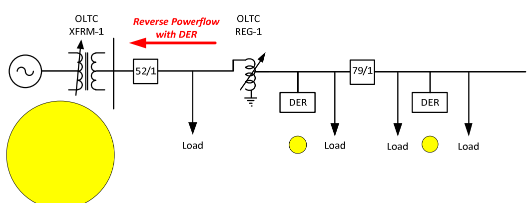
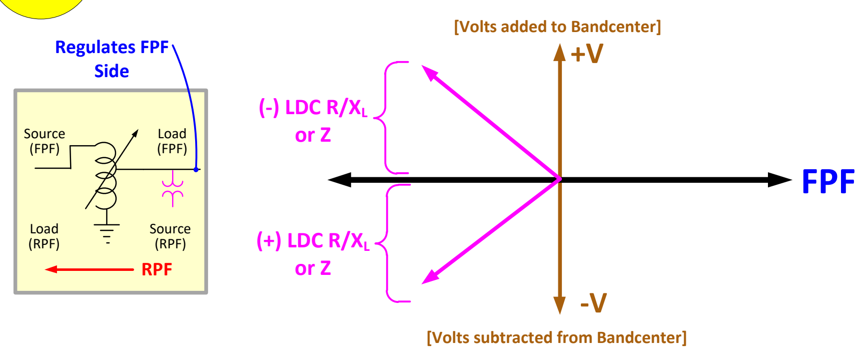
REGC/LTCC: “DG Mode”





- Regulating **forward**, -LDC *raises* bandcenter as **RPF** becomes larger
- Regulating **forward**, +LCD *lowers* bandcenter as **RPF** becomes larger

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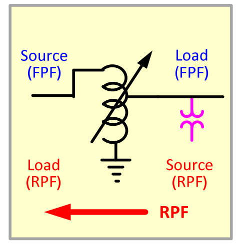
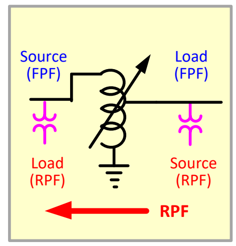
REGC/LTCC: Reverse Power, "Regulate Reverse"

- **Regulate Reverse (Calculated):**
  - Voltage Sensing: With RPF, control uses tap position knowledge and FPF side voltage
  - Regulates according to reverse power settings
    - Use where RPF source to REG is a stronger source
    - Regulate voltage on the RPF side of the REG
      - Typically used for reconfiguration



- **Regulate Reverse (Measured):**
  - Voltage Sensing: With RFP, control switches its voltage sensing input to a RPF side VT
    - RFP side VT must be available
  - Regulates according to reverse power settings
    - Use where RPF source to REG is a stronger source
    - Regulate voltage on the RPF side of the REG
      - Typically use for reconfiguration



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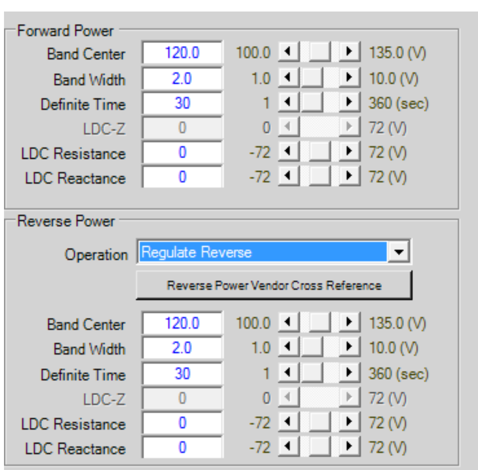
REGC/LTCC: Reverse Power, "Regulate Reverse"



- "Regulate Reverse"
  - Calculated
- Regulates reverse with new voltage settings and LDC values
- Use with strong RPF source (reconfig)
- Uses tap position and calculates voltage on previous source side of regulator
- No additional VT needed

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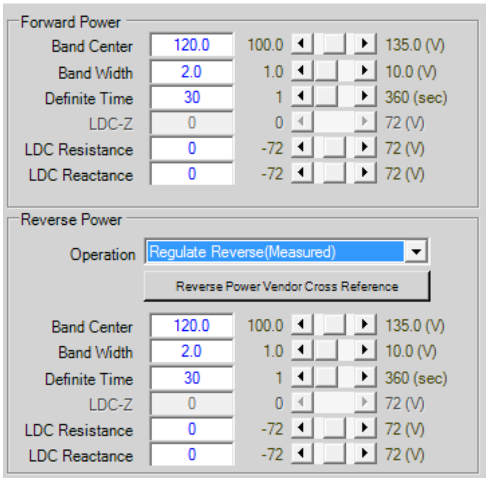
REGC/LTCC: Reverse Power, "Regulate Reverse"



- "Regulate Reverse"
  - Measured
- Regulates reverse with new voltage setpoints and LDC values
- Use with strong RPF source (reconfig)
- Uses additional VT on previous supply side of regulator

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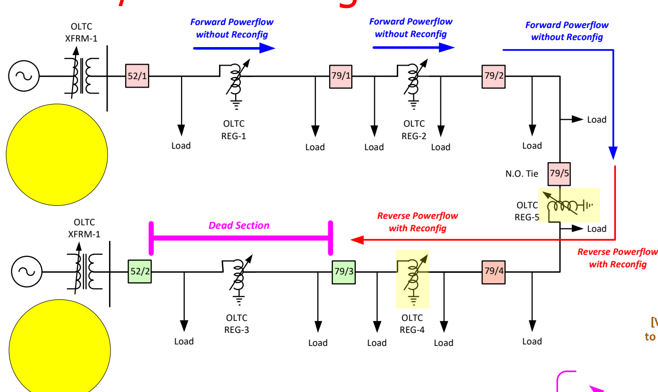
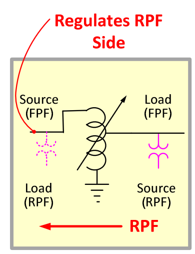
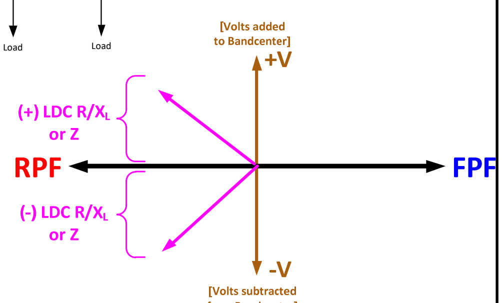
REGC/LTCC: "Regulate Reverse"







- Regulating **reverse**, +LCD *raises* bandcenter as **RPF** becomes larger
- Regulating **reverse**, -LDC *lowers* bandcenter as **RFP** becomes larger

VVO/CVR Concepts

What is VVO?

What is CVR?

How to Optimize Both

65

VVO and CVR - Why

- Lowering distribution voltage levels during peak periods to achieve peak demand reductions
- Reducing voltage levels for longer periods to achieve electricity conservation
- Reducing energy losses in the electric distribution system

Benefits include deferral of capital expenditures, energy savings, and greater operational flexibility and efficiency

Voltage and Reactive Power Management – Initial Results: US DOE, 12/12

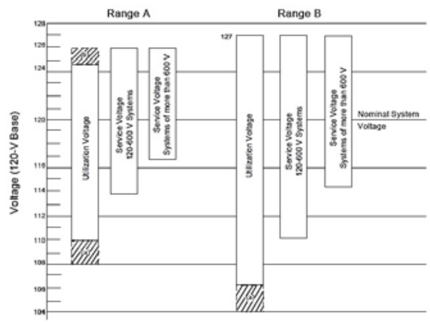
Conservation Voltage Reduction

- Conservation Voltage Reduction (CVR)
  - Part of Voltage/VAr Optimization (VVO)
  - Intentional lowering of distribution circuit voltage within the lower band of the allowed ANSI C84.1 (2006)
    - Standard for Electric Power Systems and Equipment – Voltage Ratings

For 120 V - 600 V Systems				
Nominal Voltage (V)	Service Voltage (V)			
	Range A		Range B	
	Max	Min	Max	Min
120	126	114	127	110
240	252	228	254	220
480	504	456	508	440

ANSI C84.1-2006 Service Voltage Range

- **Range A is the optimal voltage range**
- **Range B is acceptable, but not optimal**



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Conservation Voltage Reduction

- Goal of voltage reduction is to reduce load
  - V= I * R for resistive load
    - The lower the V the lower the I
    - The lower the I, the lower the I^2R = W (constant Z load)
      - Ex., incandescent lights, strip heaters
    - Not true if load is not constant power type (constant PQ load):
      - Ex., motors, power supplies

- Can be deployed at:
  - All times
  - For load reduction periods (peak reduction)
  - During system emergencies when the voltage is collapsing due reactive load exceeding available supply

% VR	pf 1.0 Load Reduction	pf 0.9 Load Reduction
2 %	1.5 %	0.5%
4 %	3.0 %	2.0%

EPRI "Distribution Green Circuits" Report - 2010

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Load Models and CVR Factor

- Load models
  - Constant Power (PQ)
  - Constant Impedance (Z)
  - Constant Current (I)

Load current changes inversely to the change in voltage

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)

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

Evaluating Conservation Voltage Reduction with WindMil® - Milsoft

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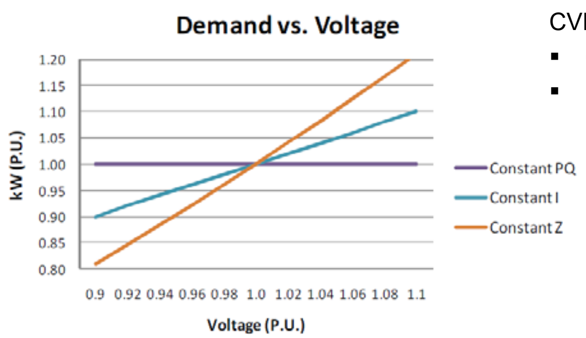
Load Models and CVR Factor



$CVR_f = \Delta P/\Delta V$

- 0.8 to 1 is typical
- Greater than 1 is really good

Constant Power (PQ or kVA)	Constant Impedance (Z)	Constant Current (I)
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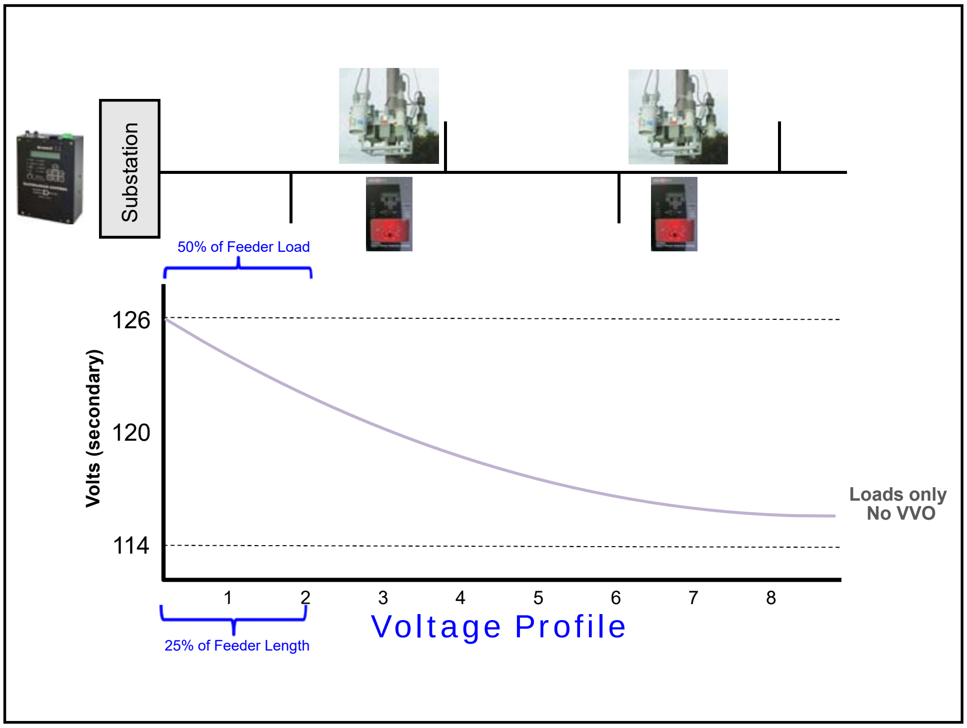
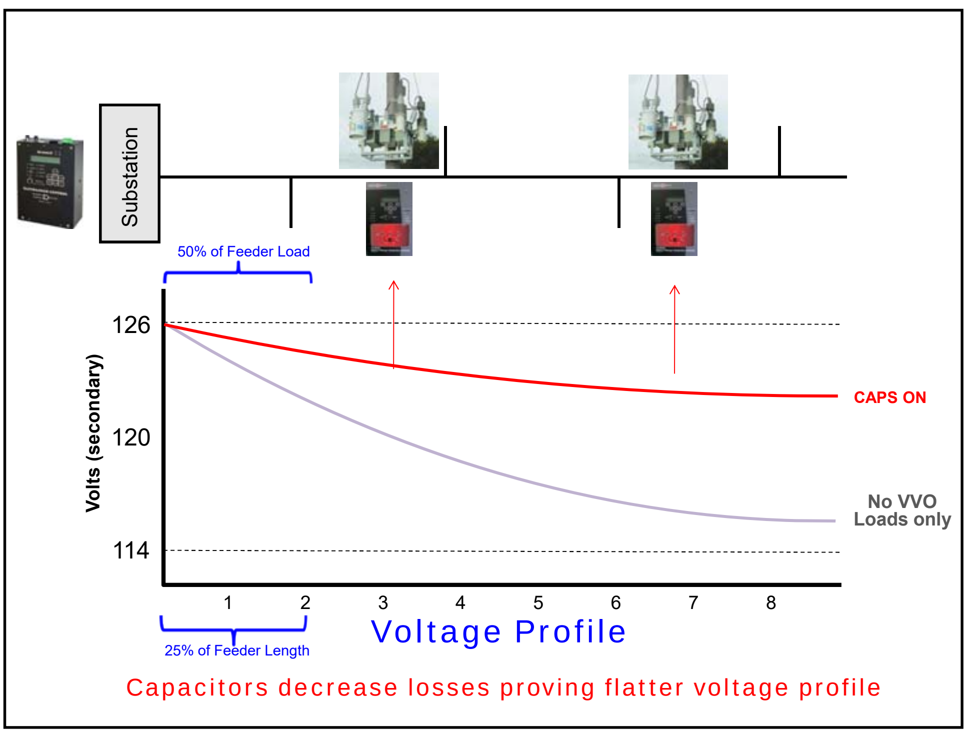
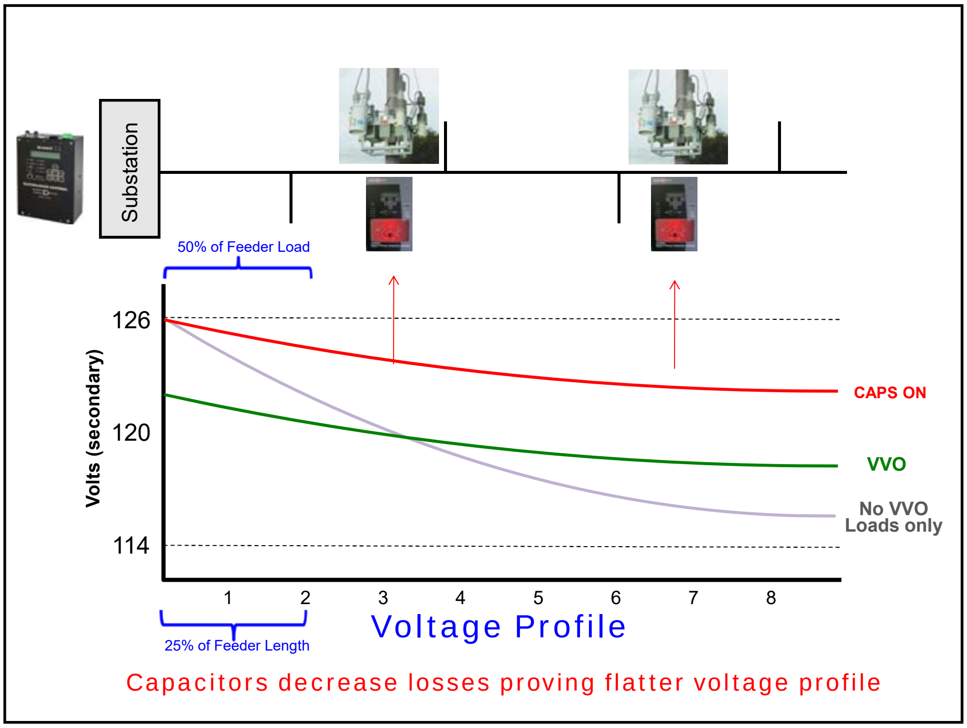
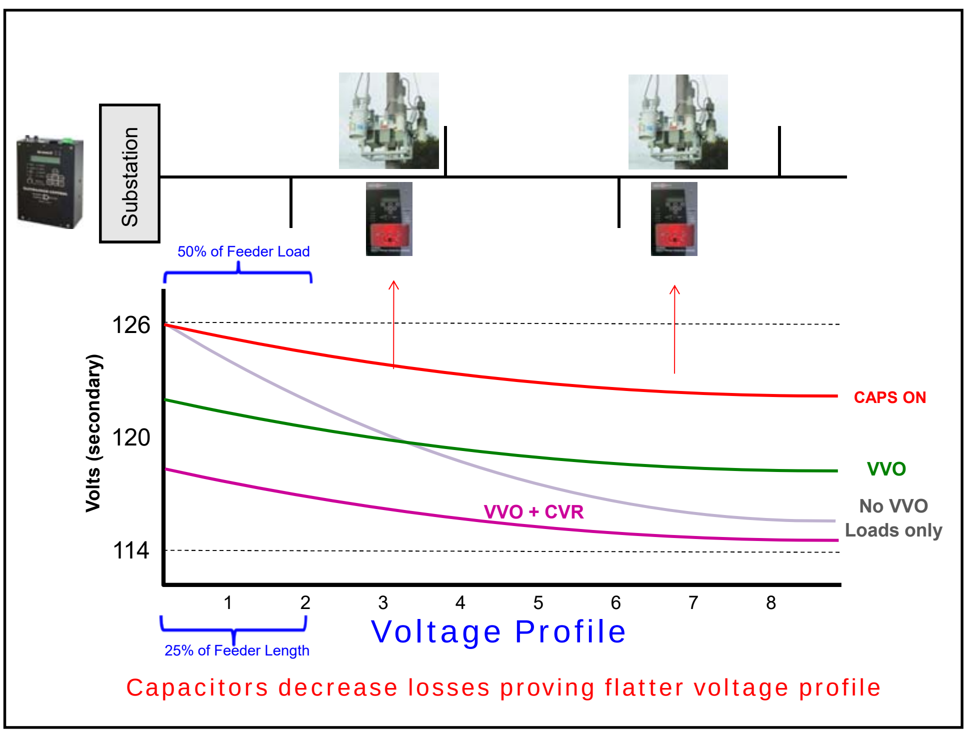
Evaluating Conservation Voltage Reduction with WindMil® - Milsoft


Substation
50% of Feeder Load
126
120
114
Volts (secondary)
Loads only
No VVO
1
2
3
4
5
6
7
8
25% of Feeder Length
Voltage Profile


Substation
50% of Feeder Load
126
120
114
Volts (secondary)
CAPS ON
No VVO
Loads only
1
2
3
4
5
6
7
8
25% of Feeder Length
Voltage Profile
Capacitors decrease losses proving flatter voltage profile


Substation
50% of Feeder Load
126
120
114
Volts (secondary)
CAPS ON
VVO
No VVO
Loads only
1
2
3
4
5
6
7
8
25% of Feeder Length
Voltage Profile
Capacitors decrease losses proving flatter voltage profile


Substation
50% of Feeder Load
126
120
114
Volts (secondary)
CAPS ON
VVO
VVO + CVR
No VVO
Loads only
1
2
3
4
5
6
7
8
25% of Feeder Length
Voltage Profile
Capacitors decrease losses proving flatter voltage profile

Smart Voltage Reduction

Get the Voltage Reduction Called For –

Do you think you always get it????

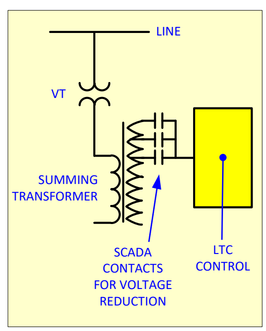
YOU CAN'T ALWAYS GET WHAT YOU WANT

Here is how to get it

75

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**

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

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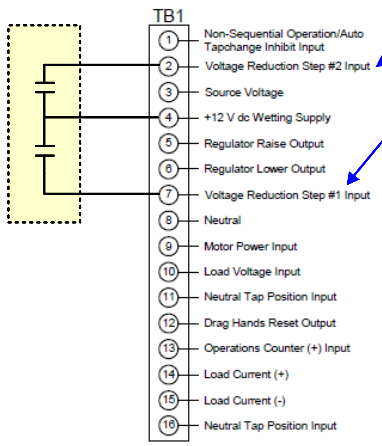
Contacts Used for Voltage Reduction

Digital Voltage Regulator Control

SCADA RTU | **LTC/Regulator Control** | **Voltage Reduction Inputs**



- 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

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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**

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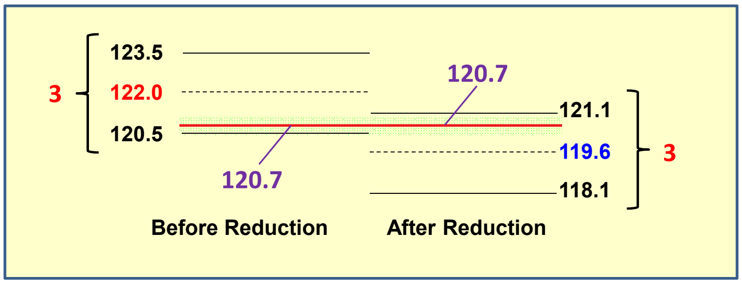
Voltage Reduction

- 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%

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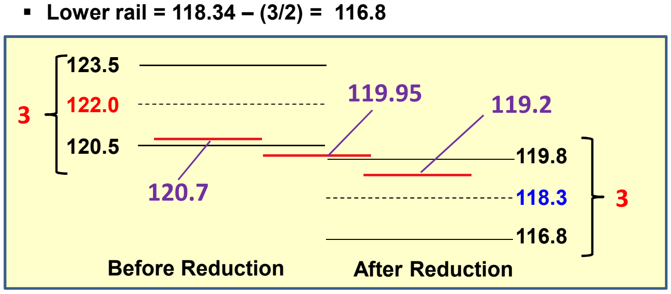
Voltage Reduction

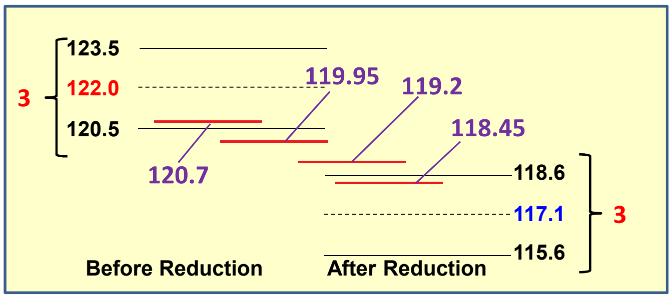
- Bandcenter set to 122V, Bandwidth of 3V
- Apply a 3% reduction of
  - 122 – 122* 0.97 = 118.34 or 118.3
    - Upper rail = 118.34 + (3/2) = 119.8
    - Lower rail = 118.34 – (3/2) = 116.8



- 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

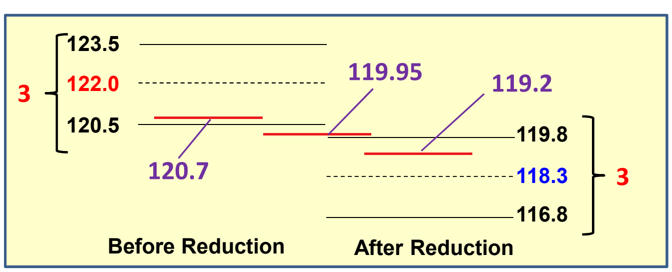
- Bandcenter set to 122V, Bandwidth of 3V
- Apply a 4% reduction of
  - 122 – 122* 0.96 = 117.12 or 117.1
    - Upper rail = 117.1 + (3/2) = 118.6
    - Lower rail = 117.1 – (3/2) = 115.6



- 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

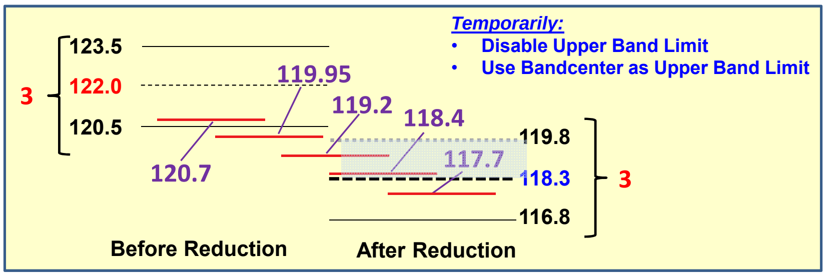
Voltage Reduction – Present Method

- 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



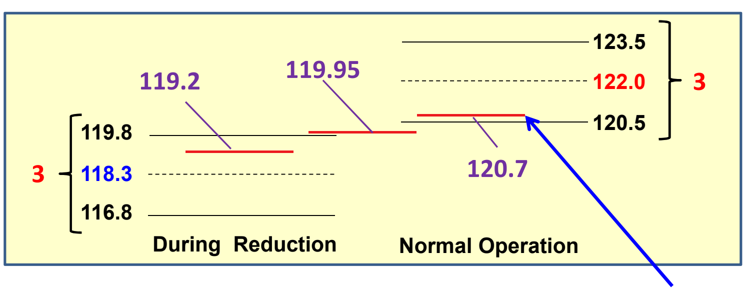
Smart Voltage Reduction

- 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

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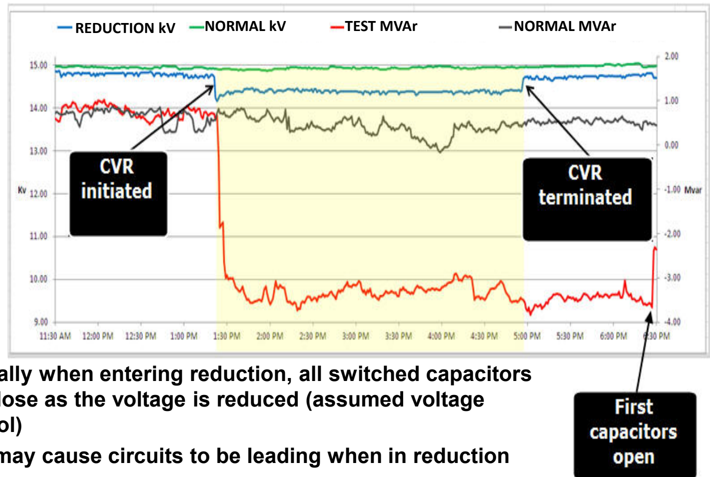
Leaving Voltage Reduction – Present Method

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

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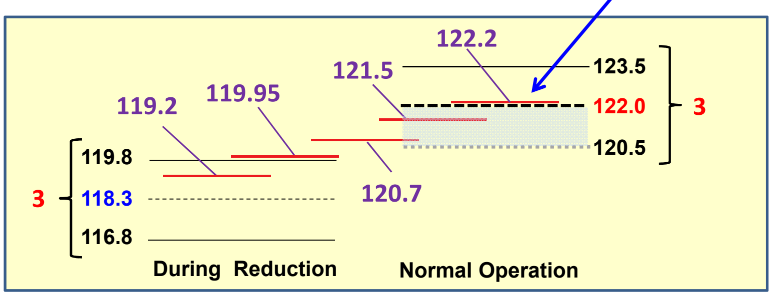
Leaving Voltage Reduction: Smart Voltage Reduction Method

The extra voltage will now allow the capacitors to start timing to an open



- 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

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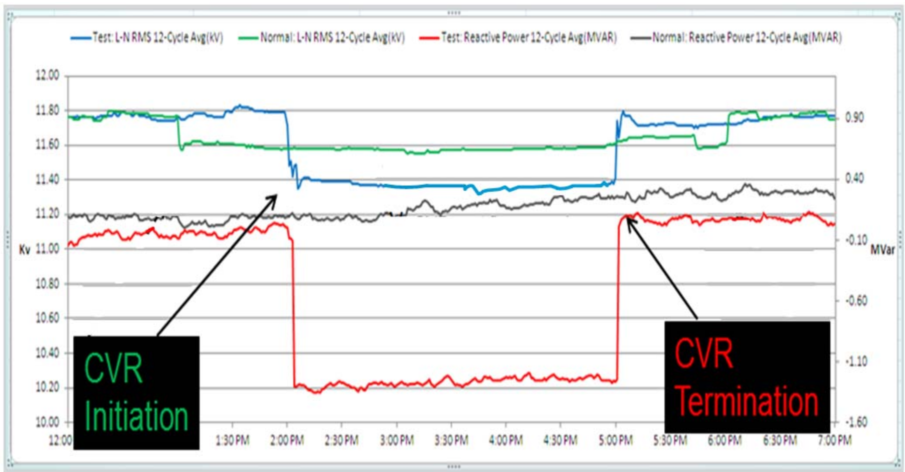
Cap Banks Opening After Leaving Reduction

Smart Voltage Reduction Employed



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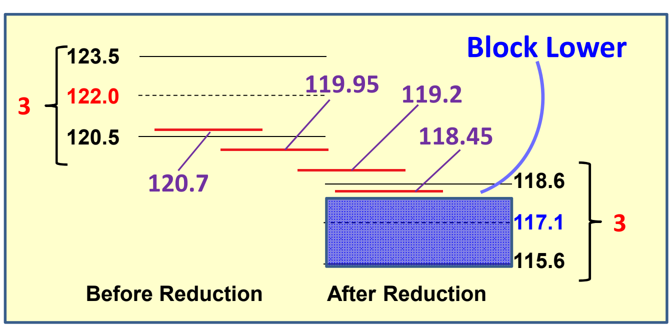
Voltage Reduction: Block Lower

- 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



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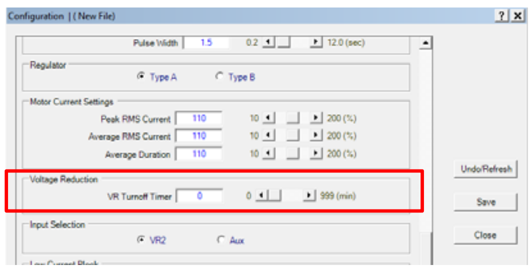
Voltage Reduction Turnoff Timer

- 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



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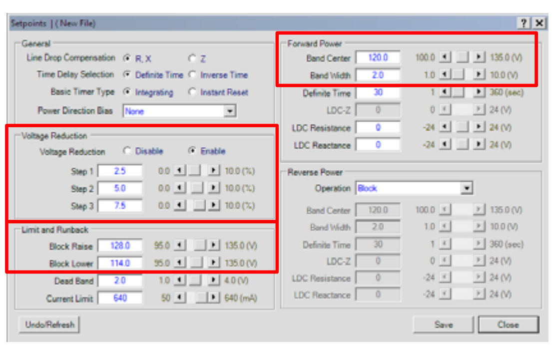
Voltage Reduction - Summary

- The control will never reduce the actual voltage by the percentage requested
- The larger the bandwidth, the less actual reduction
- The "Block Lower" setting:
  - Does not block voltage reduction
  - Does block a tap down command from occurring if the measure voltage is less than setpoint
- There is no time delay when entering or exiting voltage reduction



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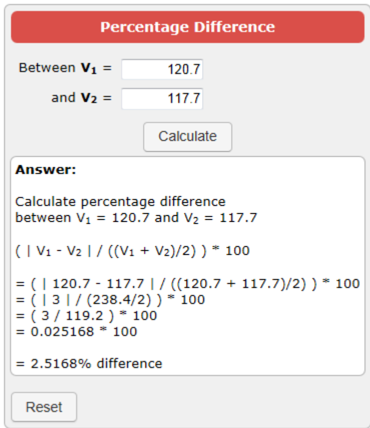
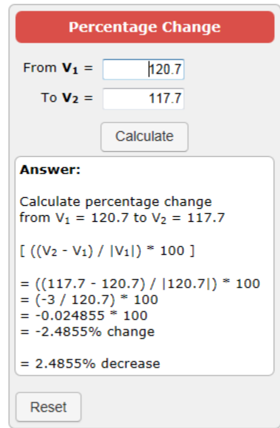
Annex: Percent Calculations





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Voltage Reduction: New Application DER Hosting Improvement

- With high penetration of DER, perfect X_L/X_C compensation still leaves R
- Heavy power flows from DER back to feeder source cause voltage rise on feeder
  - Exasperated at near the end of the feeder as R to the source increases
- High voltage rise can minimize hosting ability
- Concept: Drop voltage at the feeder original to have a wider voltage rise band along feeder to the end of the line

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Voltage Reduction: Increase DER Hosting Ability

- At times of high feeder DER output, enter voltage reduction
  - Voltage at head end lowers
  - Voltage at end of line lowers
- DER picks up voltage from end of line back to head end
- Use either negative LDC or positive VAR-Bias
  - Negative LDC lowers voltage bandcenter as reverser power flow increases
  - Positive VAR-Bias discussed later section

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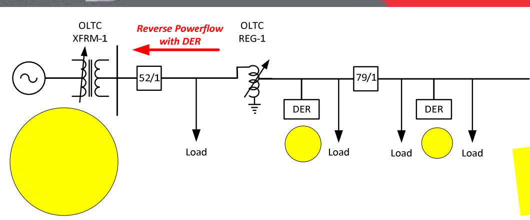
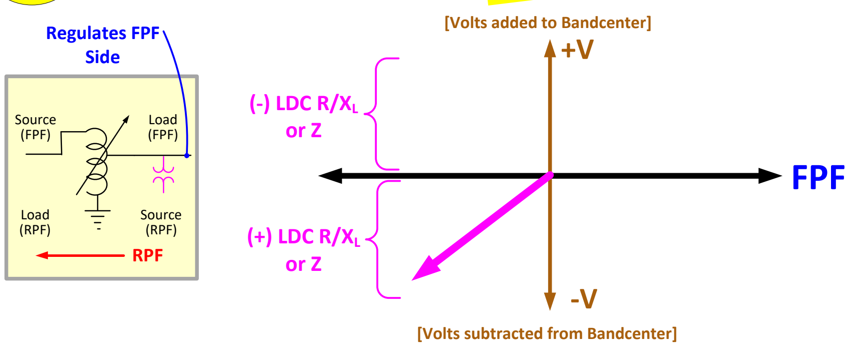
REGC/LTCC: "DG Mode"

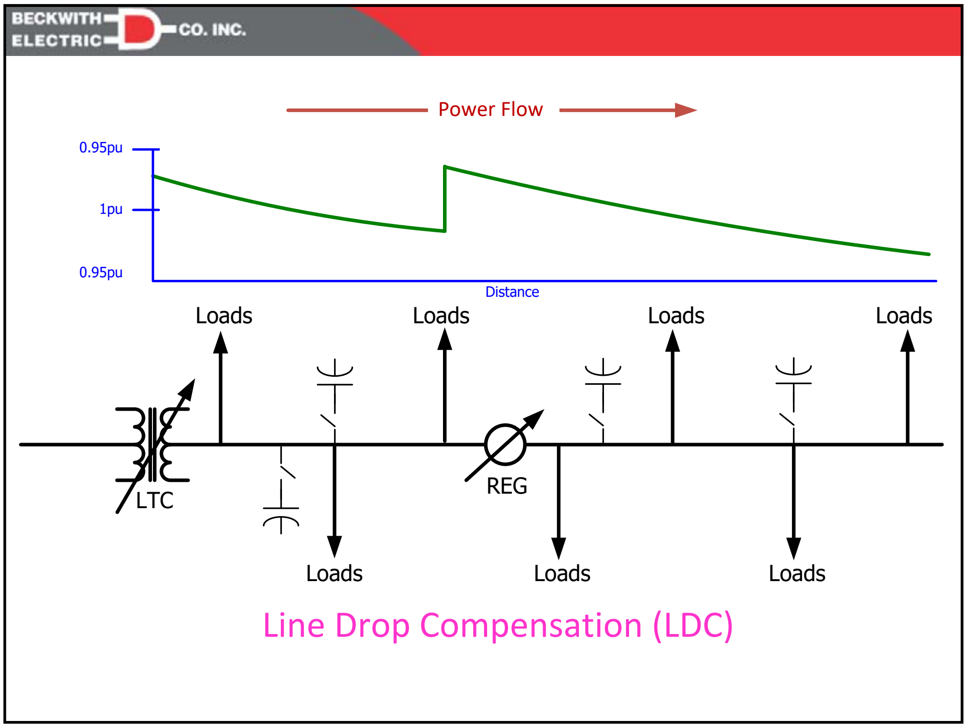


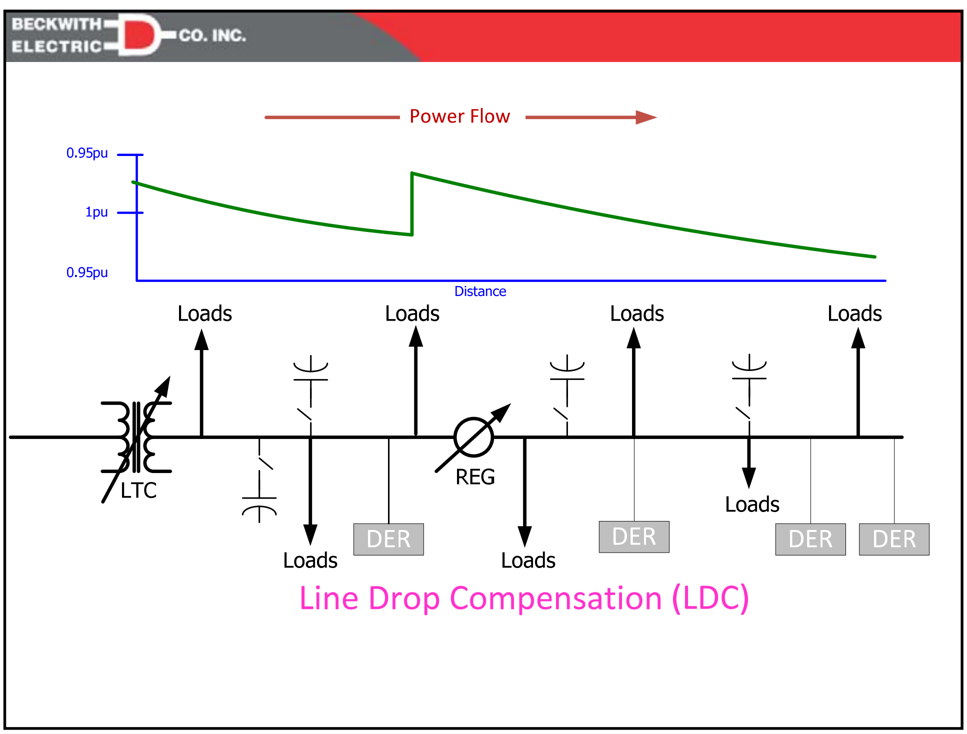
Reduce Voltage at high DER Output to Improve Hosting



- Regulating **forward**, -LDC *raises* bandcenter as **RPF** becomes larger
- Regulating **forward**, +LCD *lowers* bandcenter as **RPF** becomes larger

96


BECKWITH ELECTRIC CO. INC.
Power Flow
0.95pu
1pu
0.95pu
Distance
Loads
Loads
Loads
Loads
LTC
REG
Loads
Loads
Loads
Line Drop Compensation (LDC)


BECKWITH ELECTRIC CO. INC.
Power Flow
0.95pu
1pu
0.95pu
Distance
Loads
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LTC
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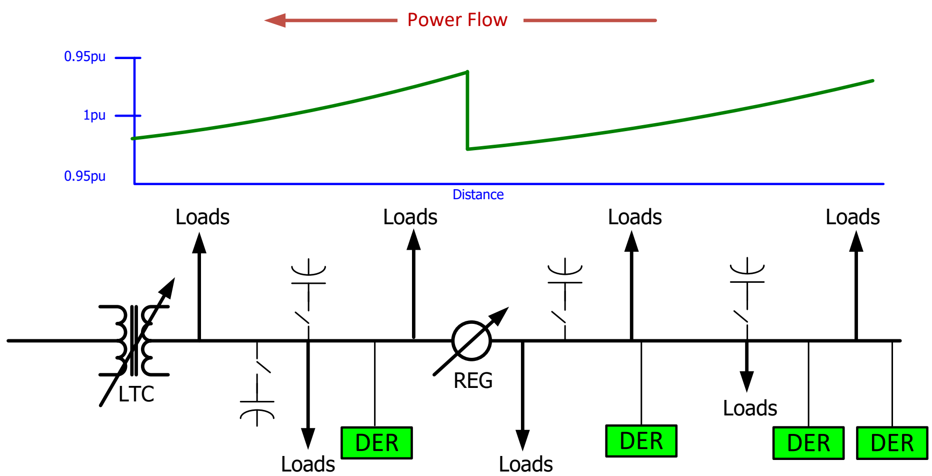
Loads
Loads
Line Drop Compensation (LDC)



Line Rise Compensation (LRC)

Use of VAR Bias (instead of LDC) for Better OLTC and Line Cap Coordination

- Using LDC to Coordinate can be less than optimal
- VAR-Bias as a new concept to unify VVO with OLTCs and CAPs

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Improved Volt/VAR Coordination between DERs/CAPCs and REGCs/LTCCs

- REGCs and/or LTCCs:
  - Typically use LDC-RX or LDC-Z
  - No direct feedback mechanism using LDC-RX or LDC-Z for PF or VAR control
- Voltage-control based CAPCs:
  - VAR measurement not available
  - Switch on voltage
    - Less expensive than VAR control and sensors
    - May be used at end of line

How do we coordinate to obtain optimum VVO/IVVC?

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Use of VAR-Bias to Coordinate DERs/CAPs with REGs and LTCs

- REGC and LTCC use information on VAR flow
  - Is the VAR flow out to the line (load)?
  - Is the VAR flow into the source?
- The above indicate if you **are** *or* **are not** at/near **unity power factor**
- VAR flow **into the REG or LTC** indicate the voltage downline is higher than the voltage at the REG or LTC

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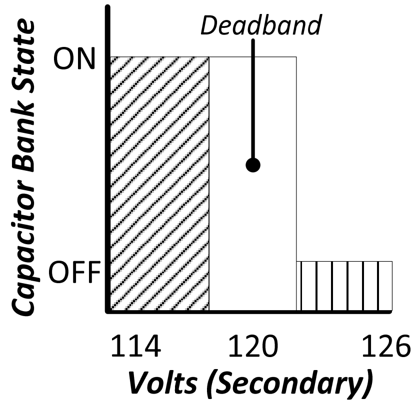
CAP Voltage Control

- Setting with Deadband
- Deadband avoids hunting



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Use of VAR-Bias to Coordinate DERs/CAPs with REGs and LTCs

- Use a "VAR-Bias" characteristic to change the response of the REGC or LTCC
- The VAR-Bias characteristic can be tailored for normal operation (non-CVR) and CVR operation
  - Normal (non-CVR) Operation: Negative VAR Bias
  - CVR Operation: Positive VAR Bias

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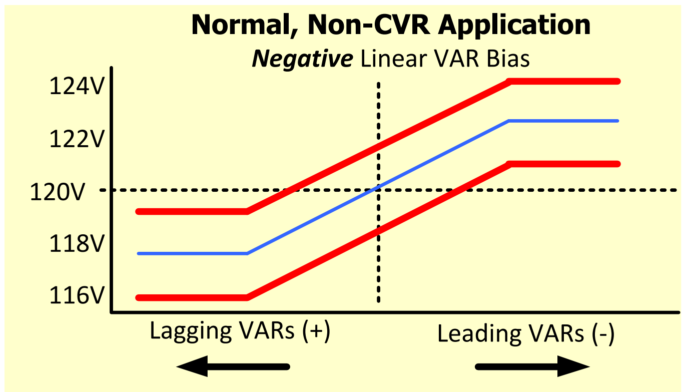
Use of VAR Bias in OLTC Devices (instead of LDC)

- Use VAR-Bias control to modify behavior of the voltage adjustment with regard to *real* and *reactive* power flows to properly manipulate voltage bandcenter



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VAR Bias (LTCC and REGC)

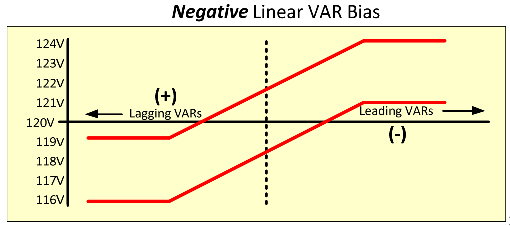
- In the **Negative Mode (Normal)**, as:
  - VARs flow toward source (leading VAR at LTCC/REGC)
    - Voltage bandcenter ***rises***, allowing line voltage to ***rise***, causing voltage-controlled CAPCs to switch banks ***off***, stopping VAR output and ***lowering line voltage***
  - VARs flow toward load (lagging VAR at LTCC/REGC)
    - Voltage bandcenter ***lowers***, allowing line voltage to ***drop***, causing voltage-controlled CAPCs to switch banks ***on***, outputting VAR, and ***raising line voltage***

➢ This action creates unity power factor and flattens the voltage profile

➢ The OLTC device does <u>not</u> take a tap

Normal, Non-CVR Application

Negative Linear VAR Bias



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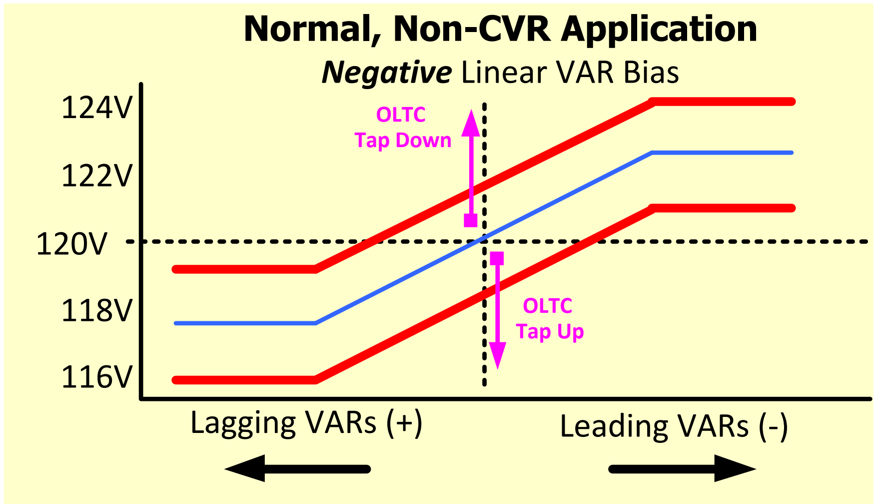
VAR-Bias: Near or at Unity PF



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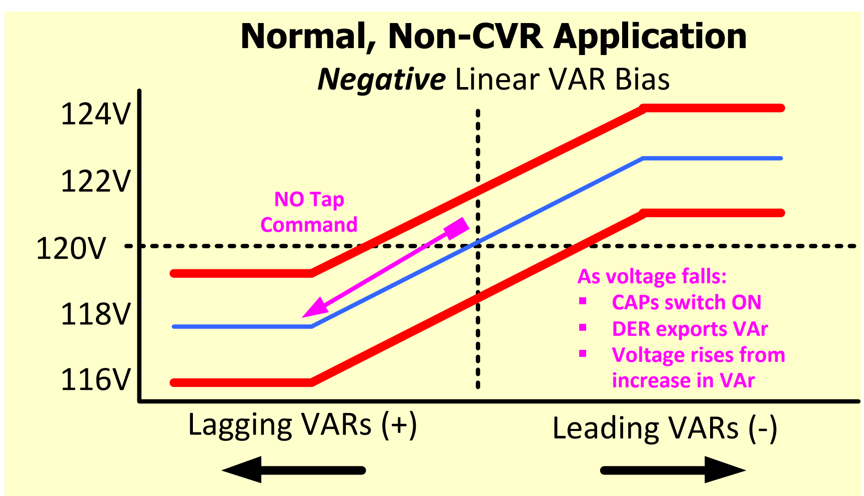
VAR-Bias:

Bandcenter Decreases with Lagging VAR



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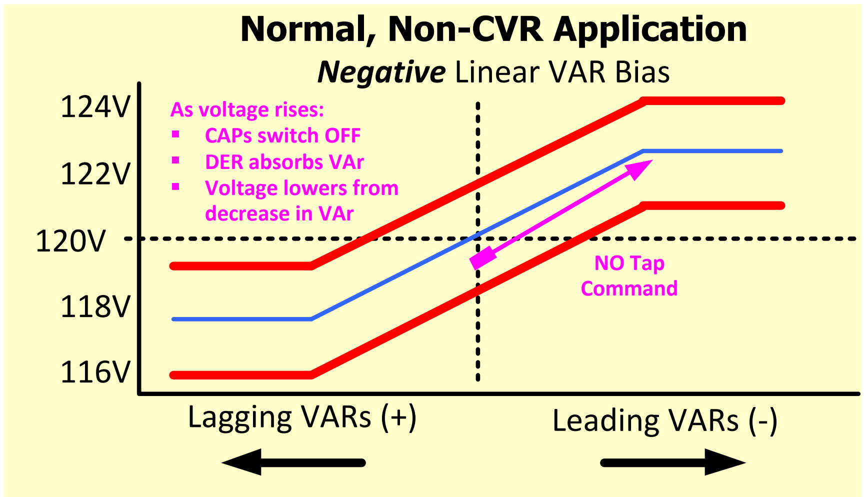
VAR-Bias:

Bandcenter Increases with Leading VAR



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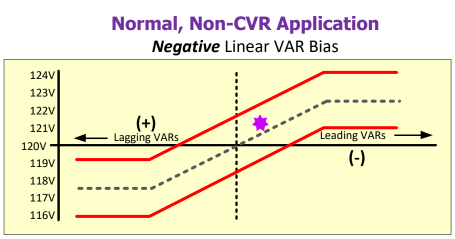
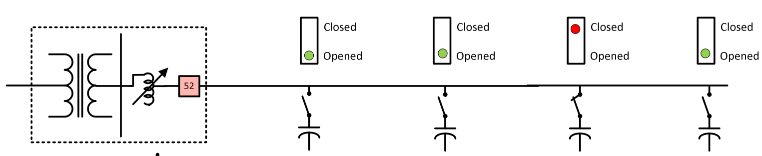
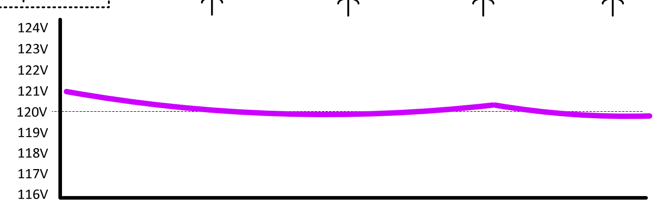
Normal Operation: Negative VAR-Bias



NORMAL OPERATION (non-CVR)



- Voltage near center of band
- Near unity power factor



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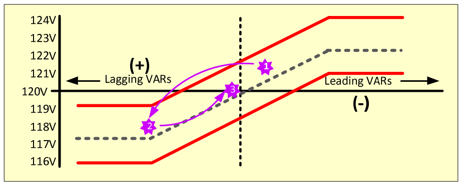
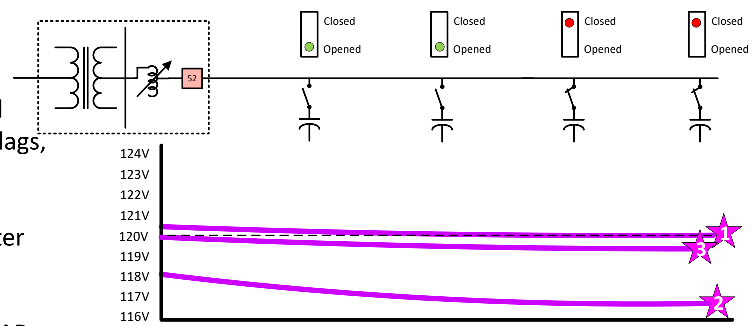
Normal Operation: Negative VAR-Bias

Normal, Non-CVR Application
Negative Linear VAR Bias



NORMAL OPERATION (non-CVR)

- Inductive load increases, pf lags, voltage decreases.
- REG bandcenter lowers.
- Caps come on
- Voltage and VAR normalize



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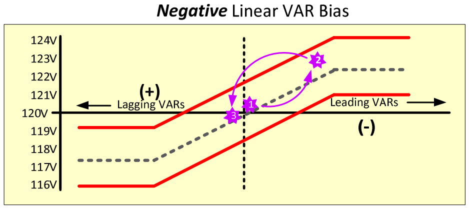
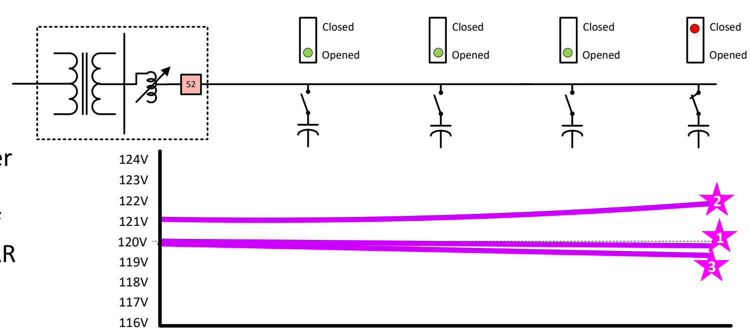
Normal Operation: Negative VAR-Bias

Normal, Non-CVR Application
Negative Linear VAR Bias



NORMAL OPERATION (non-CVR)

- Inductive load decreases, pf leads, voltage rises.
- REG bandcenter rises.
- Caps switch off
- Voltage and VAR normalize



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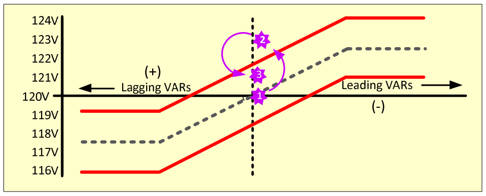
Normal Operation: Negative VAR-Bias

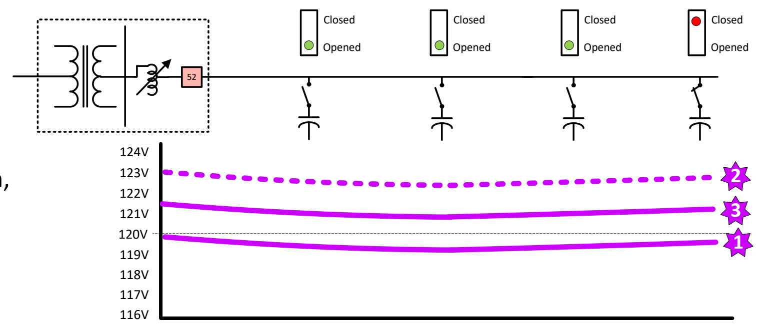
Normal, Non-CVR Application

Negative Linear VAR Bias



NORMAL OPERATION (non-CVR)

- Resistive load decreases, pf remains the same, voltage rises
- REG taps down, voltage normalizes
- CAPs do not change VAR output



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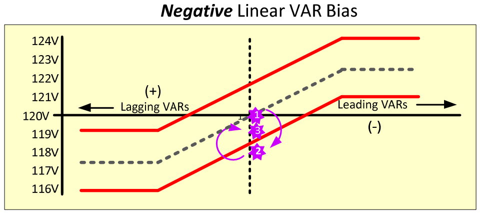
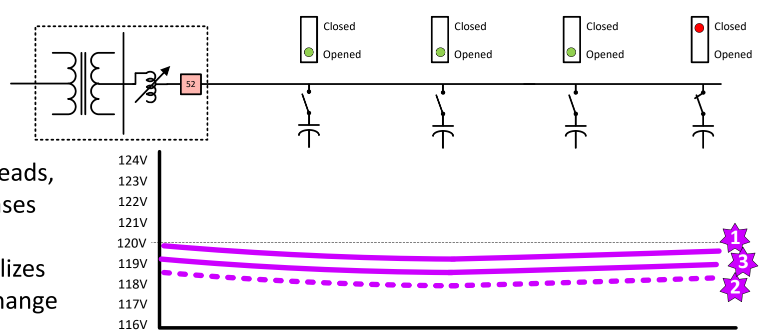
Normal Operation: Negative VAR-Bias

Normal, Non-CVR Application

Negative Linear VAR Bias

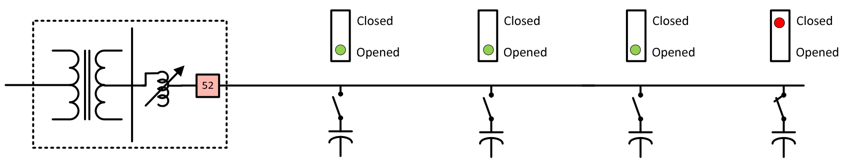


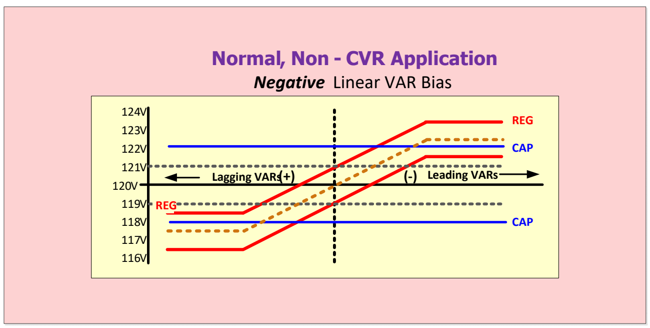
NORMAL OPERATION (non-CVR)



- Resistive load increases, pf leads, voltage decreases
- REG taps up, voltage normalizes
- CAPs do not change VAR output

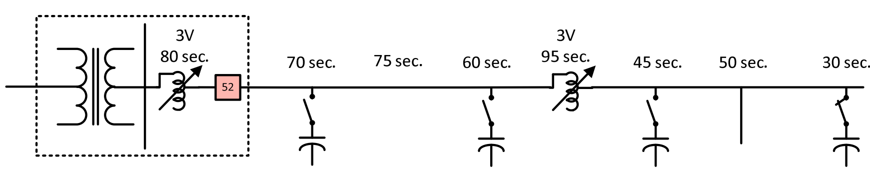
Voltage Bandcenter and Bandwidth: LTC/REG, CAP, DER



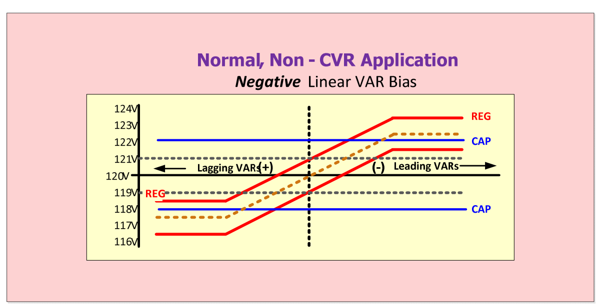


- CAPS furthest away from source have shorter time delay than upline CAPs

Voltage Settings and Timings: LTC/REG, CAP, DER



- CAPS furthest away from source have shorter time delay than upline CAPS
- REGs use VAR-Bias with larger bandwidth and longer time delays than CAPs



VAR-Bias and Deep CVR

- How low can you go?
  - ✓ *Lower than you may think!*

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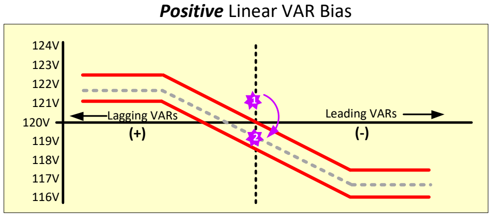
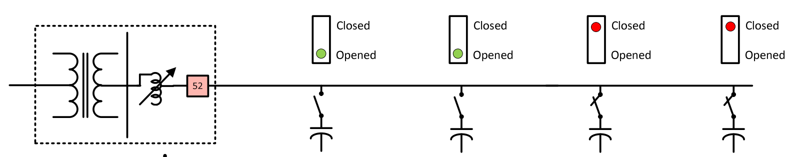
CVR Application

Positive Linear VAR Bias

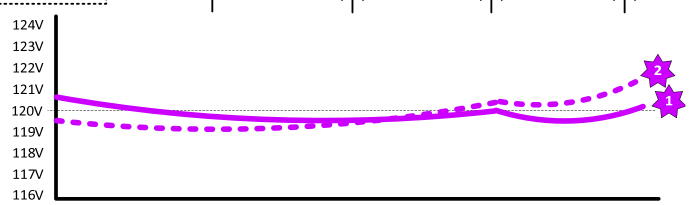


CVR Operation: Positive VAR-Bias

CVR OPERATION



- REG forces voltage lower
- CAPs begin to switch on and DER outputs VAR



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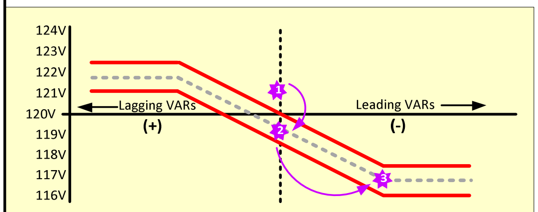
CVR Operation: Positive VAR-Bias

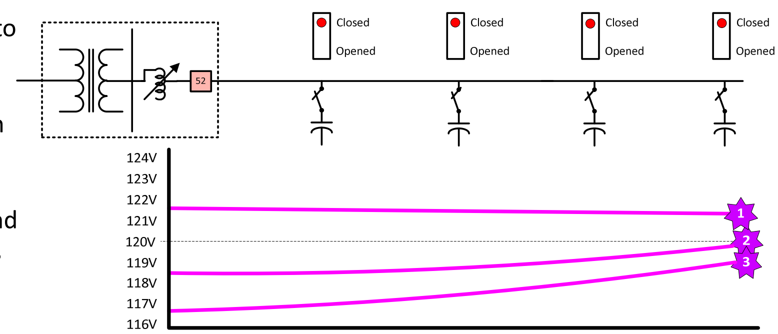
CVR Application

Positive **Linear VAR Bias**



CVR OPERATION

- VARs begin to lead.
- REG forces voltage even lower.
- More CAPs switch on and DER outputs VAR



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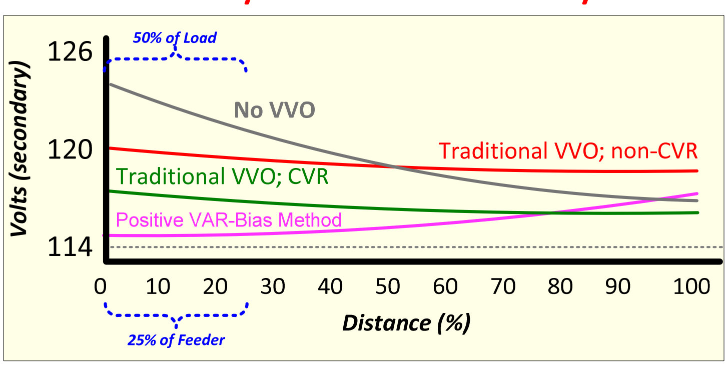
CVR: REGs/LTC with DERs/CAPs



- For CVR, forcing overVAr on feeder causes end of line voltage to rise
- You can have a deeper voltage reduction at the beginning of the line where most of the load is located (EPRI Green Circuits)

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VAR-Bias

Take Away

- The cost is ADVVOCs, which you need anyway

- No extensive comms system
- NO DMS required
- Feedback loop from CAPs to OLTCs is made from VAR flow/direction

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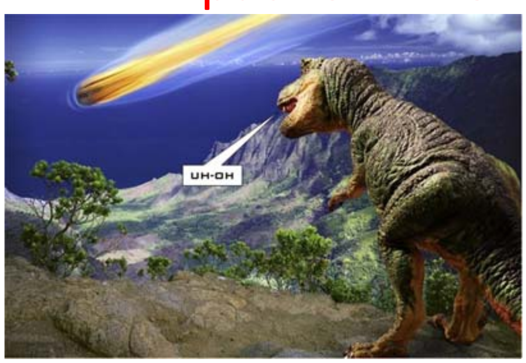
DER Impact on VVO



- DER is proliferating
  - Powerflows and levels change, resulting in voltage changes
  - Placement of DER can change due to DA
  - IEEE 1547-2018, allows ***reactive*** as well as **active powerflow output**, compounding the problem

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IEEE 1547-2018

- If large amounts of DER are easily “shaken off” for transient out-of-section faults, voltage and power flow upset can occur in:
  - Feeders
  - Substations
  - Transmission
- Fault ride-through capability makes the system more stable
  - Distribution: Having large amounts of DER “shaken off” for transient events suddenly upsets loadflow and attendant voltage drops.
    - Impacts include unnecessary LTC, regulator and capacitor control switching
    - If amount of DER shaken off is large enough, voltage limits may be violated
  - Transmission: Having large amounts of DER “shaken off” for transient events may upset loadflow into transmission impacting voltage, VAR flow and stability

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1547-2018: Active Voltage/VAR Control

- Coordination with and approval of, the area EPS and DR operators, shall be required for the DR to <u>actively participate to regulate the voltage</u> by <u>changes of real and reactive power</u>.
- The DR shall not cause the Area EPS service voltage at other Local EPSs to go outside the requirements of ANSI C84.1-2006 1 1995, Range A.

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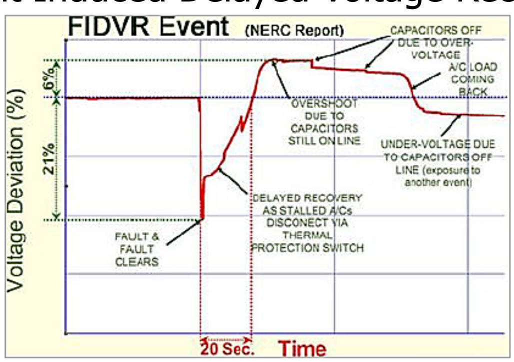
IEEE 1547-2018

❑ Fault Ride-Through

- Categories I, II, III
  - **Category I**: based on essential bulk electric system (BES) stability/reliability needs and reasonably attainable by all DER technologies that are in common usage today
  - **Category II**: covers all BES stability/reliability needs and coordinated with existing reliability standards to avoid tripping for a wider range of faults
  - **Category III**: based on both BES stability/reliability and distribution system reliability/power quality needs and coordinated with existing interconnection requirements for very high DER penetration

FIDVR Event

Fault Induced Delayed Voltage Recovery



- Power system event in which the voltage remains at low levels for several seconds after a transmission, sub-transmission, or distribution fault has been cleared
- FIDVR is caused by stalling of induction motors driving constant torque loads

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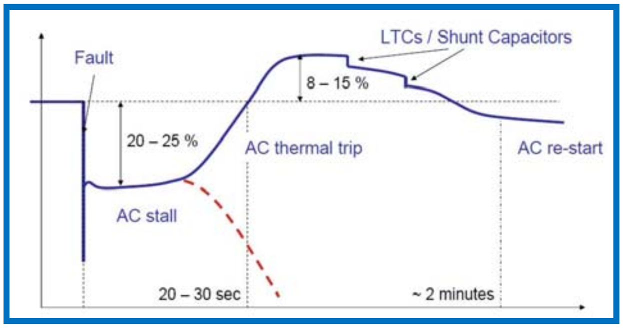
FIDVR Event

Fault Induced Delayed Voltage Recovery



- Power system event in which the voltage remains at low levels for several seconds after a transmission, sub-transmission, or distribution fault has been cleared
- FIDVR is caused by stalling of induction motors driving constant torque loads

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IEEE 1547-2018

Voltage Trip Limits: CAT I

DER response to abnormal voltages for DER of Category I

Shall trip – Category I				
Shall trip function	Ranges of adjustability[a]		Default settings[b]	
	Voltage (% of nominal voltage)	Clearing time (s)	Voltage (% of nominal voltage)	Clearing time (s)
OV2	N/A	N/A	120	0.16
OV1	110 – 120	1 – 13	115	10
N/A	N/A	N/A	N/A	N/A
UV1	0 – 88	2 – 21	70	2[c]
UV2	0 – 50	0.16 – 2	30	0.5

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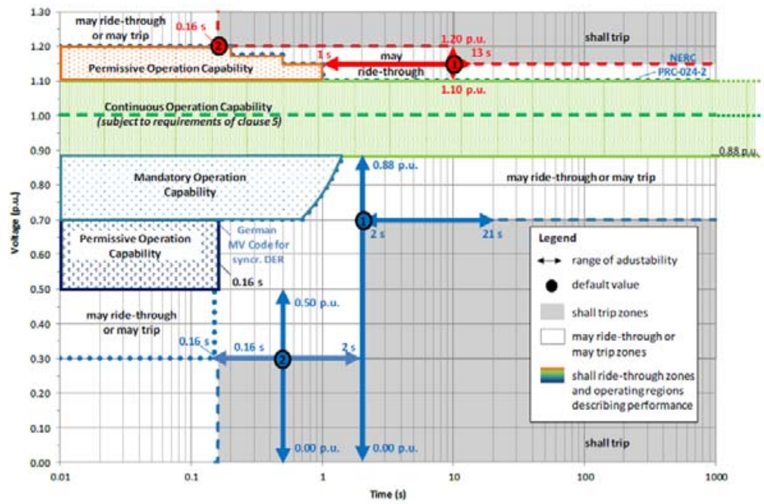
IEEE 1547-2018

Voltage Trip Limits: CAT I



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Voltage Trip Limits: CAT II

Voltage ride-through requirements for DER of Category II

Voltage range (% of nominal voltage)	Operating Mode / Response	Voltage Ride-Through – Category II Minimum ride-through time (s) (design criteria)	Maximum response time (s) (design criteria)
$V > 120$	Cease to Energize[30]	N/A	0.16
$117.5 < V \leq 120$	Permissive Operation	0.2	N/A
$115 < V \leq 117.5$	Permissive Operation	0.5	N/A
$110 < V \leq 115$	Permissive Operation	1	N/A
$88 \leq V \leq 110$	Continuous Operation	infinite	N/A
$65 \leq V < 88$	Mandatory Operation	Linear slope of 8.7 sec./1 p.u. voltage starting at 3 sec. @ 0.65 p.u.: $T_{VRT} = 3\text{ s} + \frac{8.7\text{ s}}{1\text{ p.u.}}(V - 0.65\text{ p.u.})$	N/A
$45 \leq V < 65$	Permissive Operation	0.32	N/A
$30 \leq V < 45$	Permissive Operation	0.16	N/A
$V < 30$	Cease to Energize[30]	N/A	0.16

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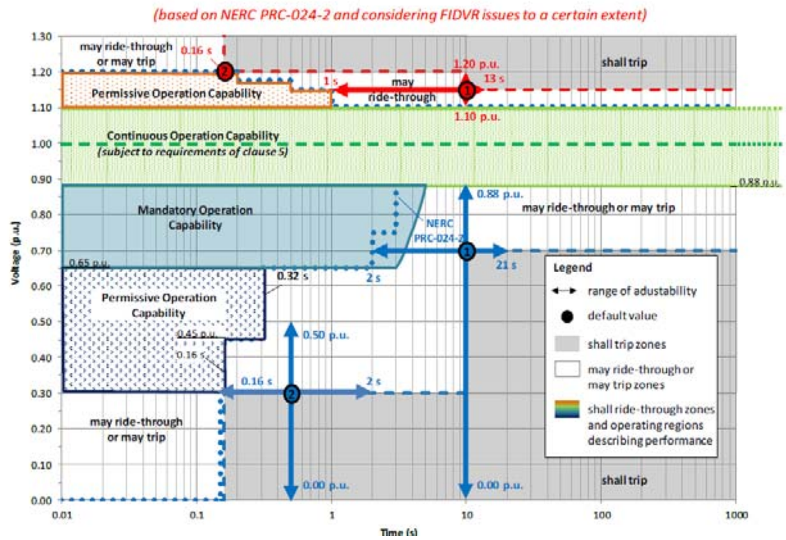
Voltage Trip Limits: CAT II



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IEEE 1547-2018

Voltage Trip Limits: CAT III

Voltage ride-through requirements for DER of Category III

Voltage range (% of nominal voltage)	Voltage Ride-Through – Category III Operating Mode / Response	Minimum ride-through time (s) (design criteria)	Maximum response time (s) (design criteria)
V > 120	Cease to Energize[30]	N/A	0.16
110 < V ≤ 120	[Momentary Cessation][31]	12	0.083
88 ≤ V ≤ 110	Continuous Operation	infinite	N/A
70 ≤ V < 88	Mandatory Operation	20	N/A
50 ≤ V < 70	Mandatory Operation	10	N/A
V < 50	Momentary Cessation[31]	1	0.083

IEEE 1547-D6.0

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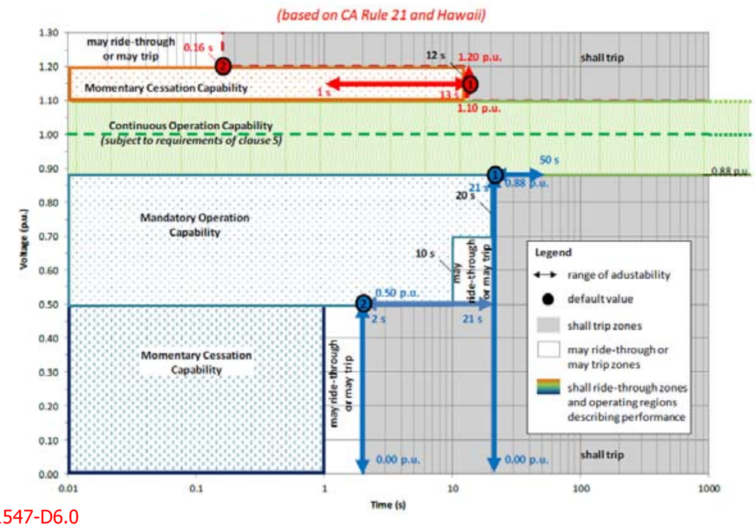
IEEE 1547-2018

Voltage Trip Limits: CAT III

(based on CA Rule 21 and Hawaii)



IEEE 1547-D6.0

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IEEE 1547-2018

- ❑ Voltage Regulation Performance
- ❑ Reactive Power Capability
  - ➢ Categories A, B

- **Category A**
  - Covers minimum performance capabilities needed for Area EPS voltage regulation that are reasonably attainable by all state-of-the-art DER technologies
  - Performance is deemed adequate for applications where the DER penetration in the distribution system is lower, and where the DER power output is not subject to frequent large variations

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- Voltage Regulation Performance
- Reactive Power Capability
  - Categories A, B

- **Category B**
  - Covers all requirements within Category A and specifies supplemental capabilities needed to adequately integrate the DER in local Area EPS where the DER penetration is higher or where the DER power output is subject to frequent large variations.

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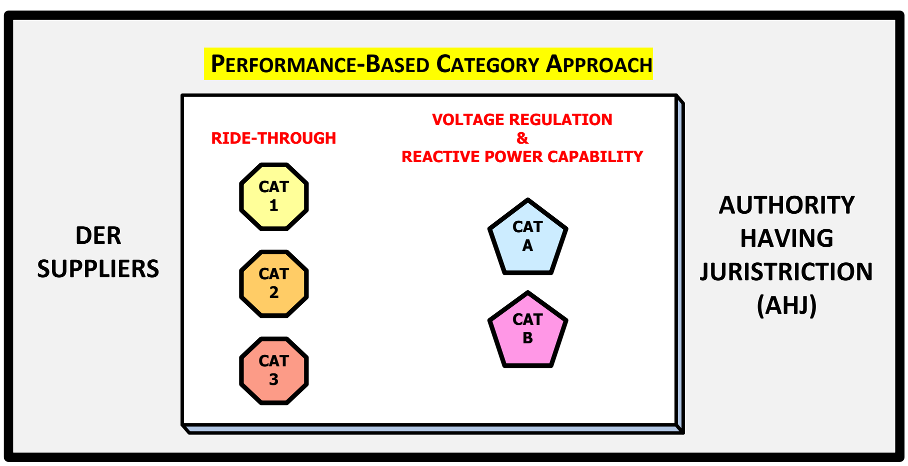

Recommended:

- **Use CATS I and A together**
- **Use CATS II, III and B together**

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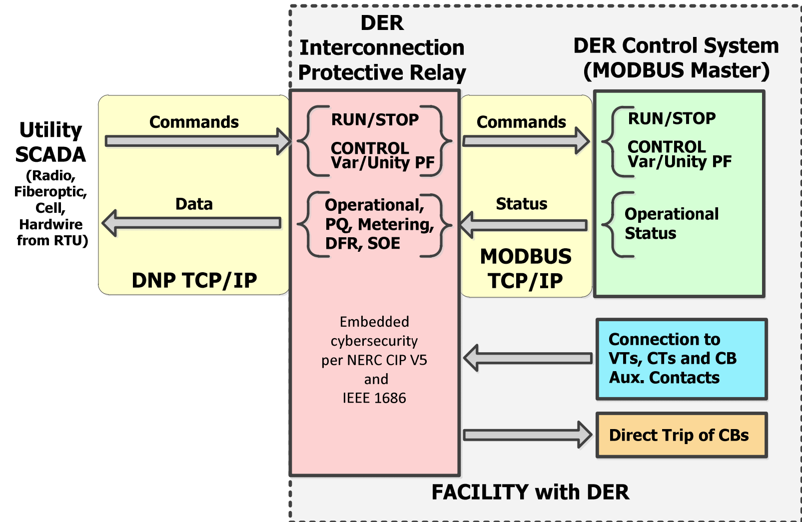
DER Interconnection Relay as the Utility Interface Point



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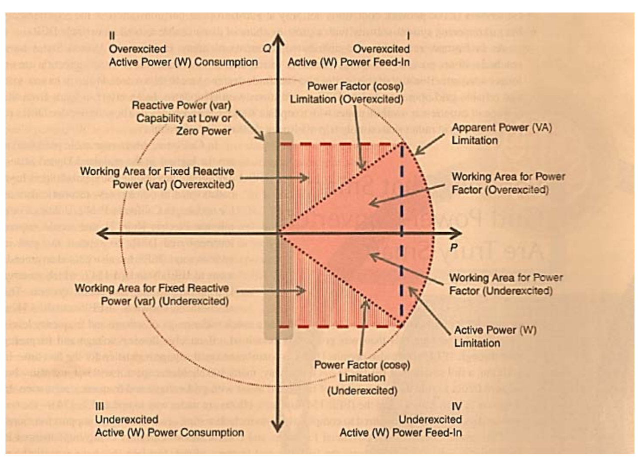
Example of Inverter P & Q Output Capability



Graph from Mar/Apr 2014 IEEE PES Magazine Article "Lab Tests" by Roland Brundlinger, Thomas Straaser, Georg Lauss, Andy Hoke, Sudipta Chakraborty, Greg Martin, Benjamin Kropotkin, Jay Johnson and Eric de Jong

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Inverter Control Modes

- ❑Constant Power factor mode (adjustable)
- ❑Reactive power mode (adjustable)
- ❑Voltage-reactive power (Volt-VAr) mode
- ❑Active power-reactive power mode (Watt-VAr)
- ❑Volt-active power (Volt-Watt)

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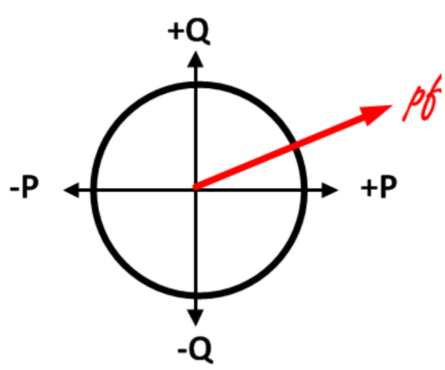
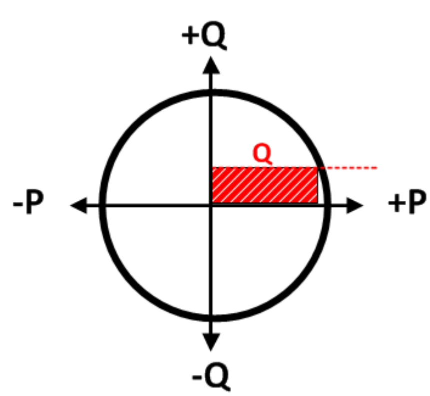
DER Actively Controlling VAR

Constant pf



Constant VAR



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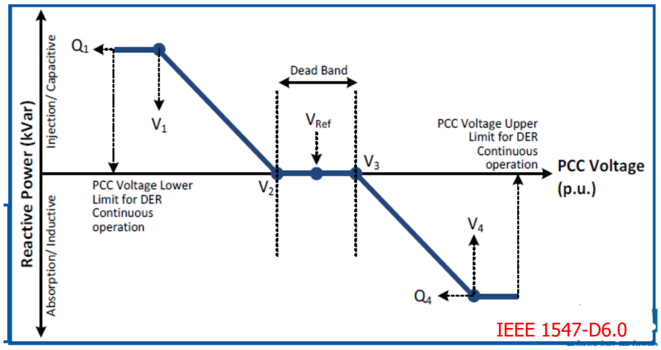
DER Actively Controlling VAR

Volt-VAr



- ***Why?*** As voltage rises, counter with absorbing VAR
- Uses droop characteristic
- Based on **power and voltage sensing** at PCC
- If inverter based, a "Smart" Inverter

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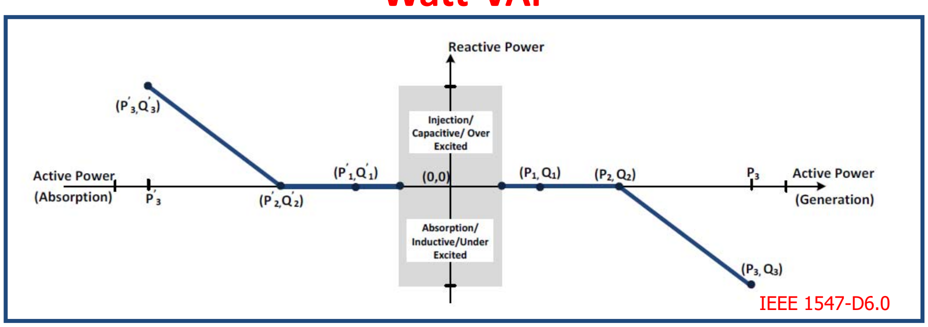
DER Actively Controlling VAR

Watt-VAr



- ***Why?*** As real power output increases, counter voltage rise by absorbing VAR
- Uses droop characteristic
- Based on **power and voltage sensing** at PCC
- If inverter based, a "Smart" Inverter

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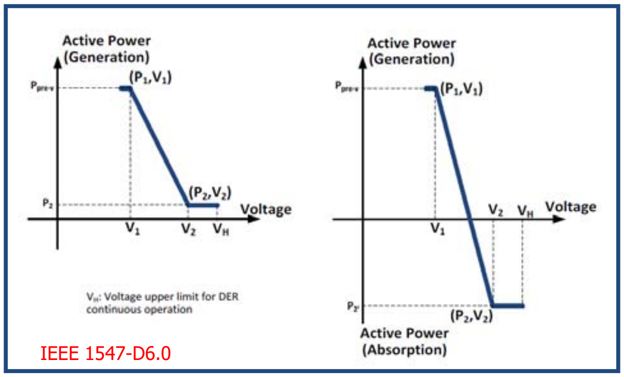
DER Actively Controlling VAR

Volt-Watt



- ***Why?*** As real power output increases, area voltage can increase due to line losses (R and X_L)
- Uses droop characteristic
- Based on **power and voltage sensing** at PCC
- If inverter based, a “Smart” Inverter

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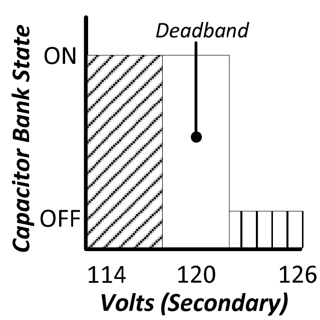
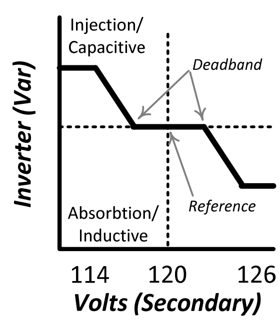
CAPs and DER

- As power flows and assumed reactive voltage drops can change as DER proliferates, consider changing fixed CAPs to switched to avoid overvoltage (from excessive VAR support) under high DER output conditions
- Consider active voltage (VAR) control of DER as proliferation increases





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Use of VAR Bias (instead of LDC) for Better OLTC and Line Cap Coordination

- Using LDC to Coordinate can be less than optimal
- VAR-Bias as a new concept to unify VVO with OLTCs and CAPs

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Improved Volt/VAR Coordination between DERs/CAPCs and REGCs/LTCCs

- REGCs and/or LTCCs:
  - Typically use LDC-RX or LDC-Z
  - No direct feedback mechanism using LDC-RX or LDC-Z for PF or VAR control
- Voltage-control based CAPCs:
  - VAR measurement not available
  - Switch on voltage
    - Less expensive than VAR control and sensors
    - May be used at end of line

How do we coordinate to obtain optimum VVO/IVVC?

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Use of VAR-Bias to Coordinate DERs/CAPs with REGs and LTCs

- REGC and LTCC use information on VAR flow
  - Is the flow out to the line (load)?
  - Is the flow into the source?

- The above indicate if you **are** *or* **are not** at/near **unity power factor**

- VAR flow **into the REG or LTC** indicate the voltage downline is higher than the voltage at the REG or LTC

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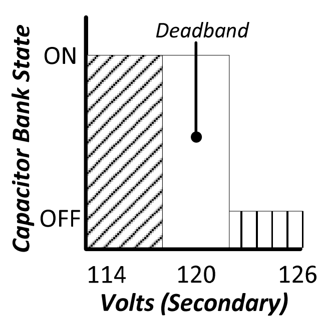
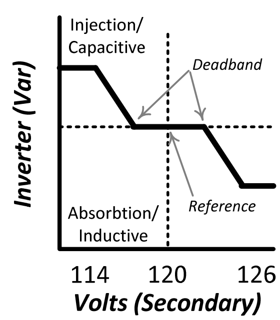
CAPs and DER

- As power flows and assumed reactive voltage drops can change as DER proliferates, consider changing fixed CAPs to switched to avoid overvoltage (from excessive VAR support) under high DER output conditions
- Consider active voltage (VAR) control of DER as proliferation increases





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Use of VAR-Bias to Coordinate DERs/CAPs with REGs and LTCs

- Use a “VAR-Bias” characteristic to change the response of the REGC or LTCC
- The VAR-Bias characteristic can be tailored for normal operation (non-CVR) and CVR operation
  - Normal (non-CVR) Operation: Negative VAR Bias
  - CVR Operation: Positive VAR Bias

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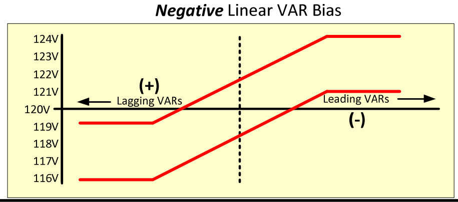
VAR Bias (LTCC and REGC)

- In the **Negative Mode (Normal)**, as:
  - VARs flow toward source (leading VAR at LTCC/REGC)
    - Voltage bandcenter rises, causing voltage-controlled:
      - DERs to decrease VAR output
      - CAPCs to switch banks off, stopping VAR output
  - VARs flow toward load (lagging VAR at LTCC/REGC)
    - Voltage bandcenter lowers, causing voltage-controlled:
      - DERs to decrease VAR output
      - CAPCs to switch banks on, outputting VAR

➢ This action tends to create unity power factor and flatten voltage profile

Normal, Non-CVR Application

Negative Linear VAR Bias



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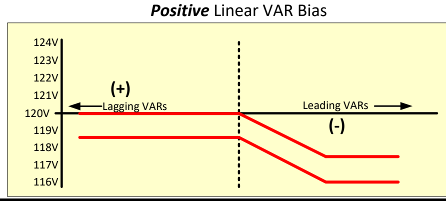
VAR Bias (LTCC and RECC)

- In the **Positive Mode (CVR)**, as:
  - VARs flow toward source (leading VAR at LTCC/REGC)
    - Voltage bandcenter lowers, causing voltage-controlled:
      - DERs to decrease VAR output
      - CAPCs to switch banks on, outputting VAR
  - VARs flow toward load (lagging VAR at LTCC/REGC)
    - Voltage bandcenter rises, causing voltage-controlled:
      - DERs to decrease VAR output
      - CAPCs to switch banks off, stopping VAR output

➢ This action tends to allow deep voltage reduction at the feeder origin as end of line voltage is higher than at REG or LTC output

CVR Application

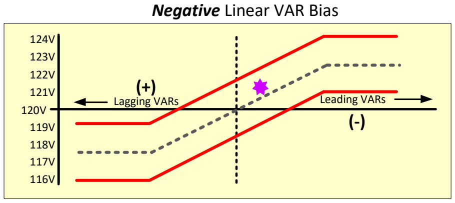
Positive Linear VAR Bias



151

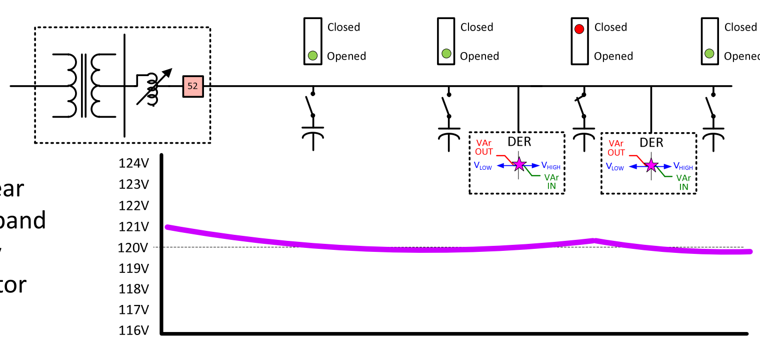
Normal, Non-CVR Application

Negative Linear VAR Bias



Normal Operation: Negative VAR-Bias

NORMAL OPERATION (non-CVR)



- Voltage near center of band
- Near unity power factor

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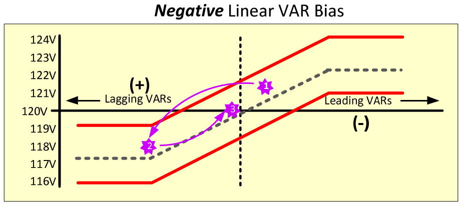
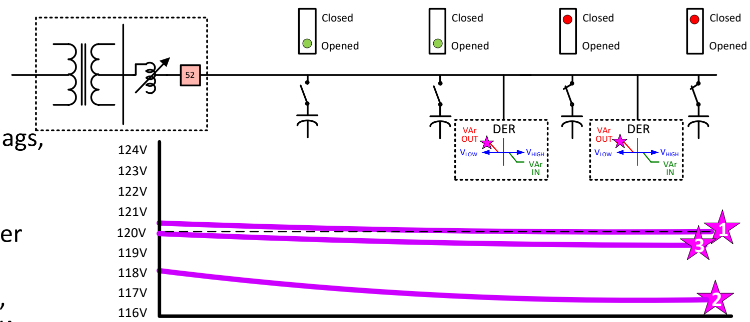
Normal Operation: Negative VAR-Bias

Normal, Non-CVR Application

Negative Linear VAR Bias



NORMAL OPERATION (non-CVR)



- Inductive load increases, pf lags, voltage decreases.
- REG bandcenter lowers.
- Caps come on, DER outputs VAr
- Voltage and VAr normalize

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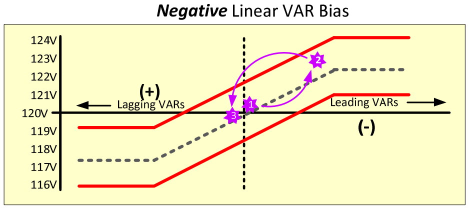
Normal Operation: Negative VAR-Bias

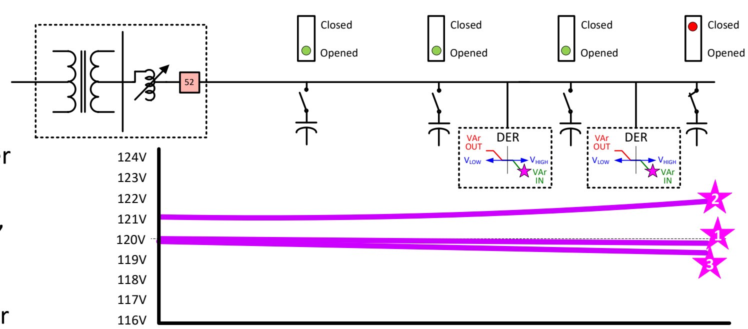
Normal, Non-CVR Application

Negative Linear VAR Bias



NORMAL OPERATION (non-CVR)

- Inductive load decreases, pf leads, voltage rises.
- REG bandcenter rises.
- Caps switch off, DER consumes VAr
- Voltage and VAr normalize



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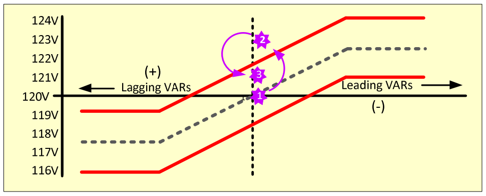
Normal, Non-CVR Application

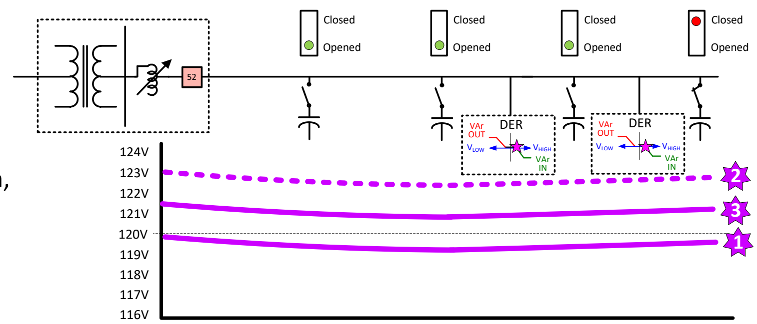
Negative Linear VAR Bias



Normal Operation: Negative VAR-Bias

NORMAL OPERATION (non-CVR)

- Resistive load decreases, pf remains the same, voltage rises
- REG taps down, voltage normalizes
- CAPs and DER do not change VAr output



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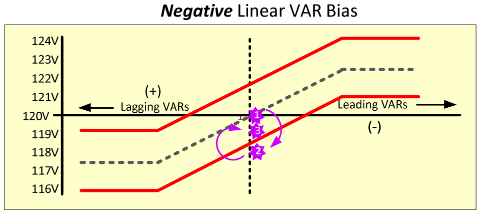
Normal, Non-CVR Application

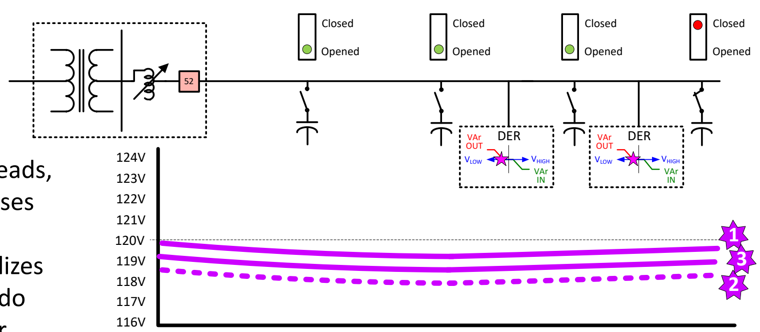
Negative Linear VAR Bias



Normal Operation: Negative VAR-Bias

NORMAL OPERATION (non-CVR)

- Resistive load increases, pf leads, voltage decreases
- REG taps up, voltage normalizes
- CAPs and DER do not change VAr output



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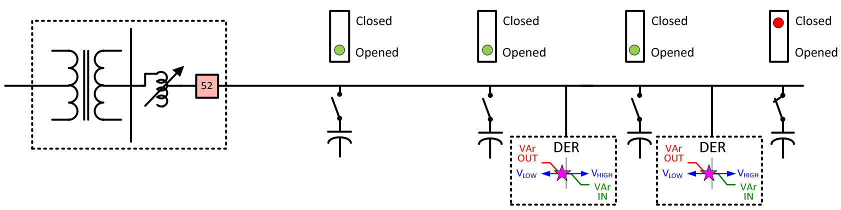
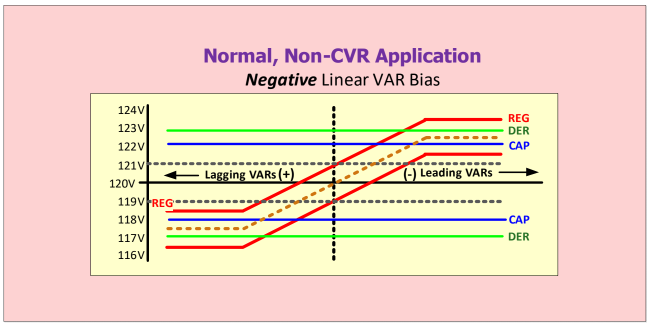
Voltage Bandcenter and Bandwidth: LTC/REG, CAP, DER





- CAPS and DER furthest away from source have shorter time delay than upline similar devices
- This examples uses CAPs before DER
  - Assuming DER charges for reactive support

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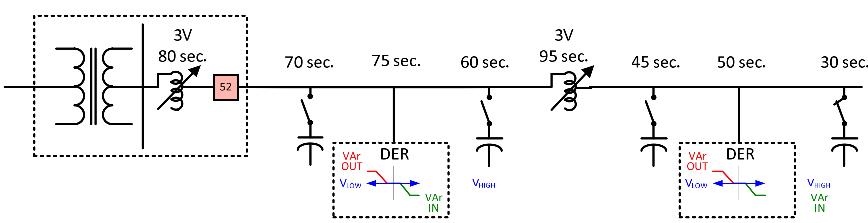
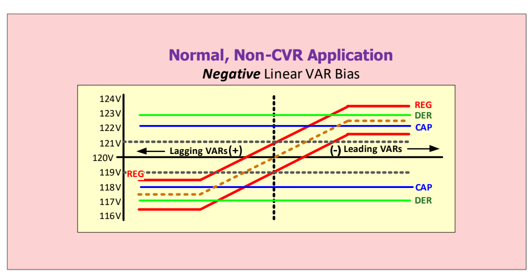
Voltage Settings and Timings: LTC/REG, CAP, DER

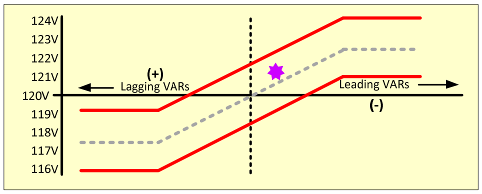


- CAPS and DER furthest away from source have shorter time delay than upline similar devices
- This examples uses CAPs switching before DER, assuming DER charges for reactive support
- REGs use VAR-Bias with larger bandwidth and longer time delays than CAPs or DER



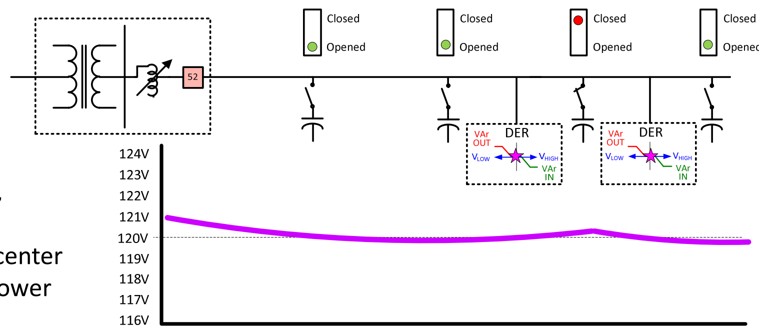
Normal, Non-CVR Application

Negative Linear VAR Bias



Before CVR Operation: Negative VAR-Bias

NORMAL OPERATION (non-CVR)



- Normal load, voltage near center bandcenter
- Near unity power factor

VAR-Bias and Deep CVR

- How low can you go?
  - *Lower than you may think!*

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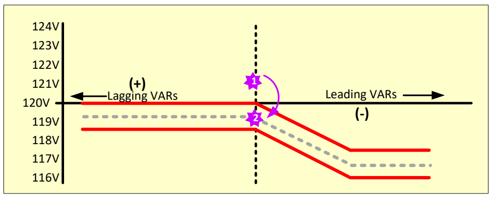
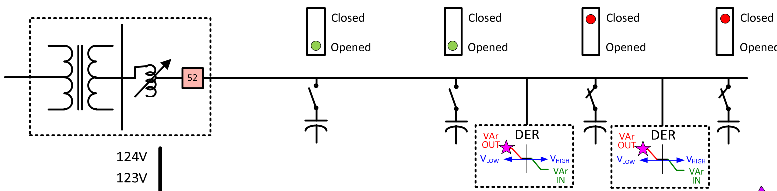
CVR Operation: Positive VAR-Bias

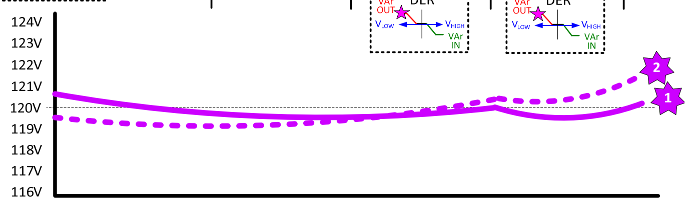
CVR Application

Positive Linear VAR Bias



CVR OPERATION





- REG forces voltage lower
- CAPs begin to switch on and DER outputs VAr

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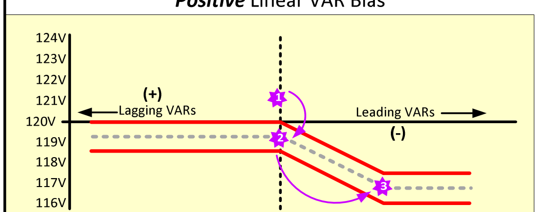
CVR Operation: Positive VAR-Bias

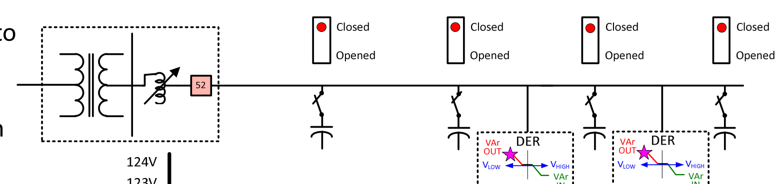
CVR Application

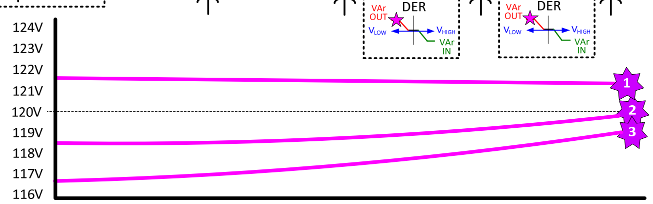
Positive Linear VAR Bias



CVR OPERATION

- VARs begin to lead.
- REG forces voltage even lower.
- More CAPs switch on and DER outputs VAr





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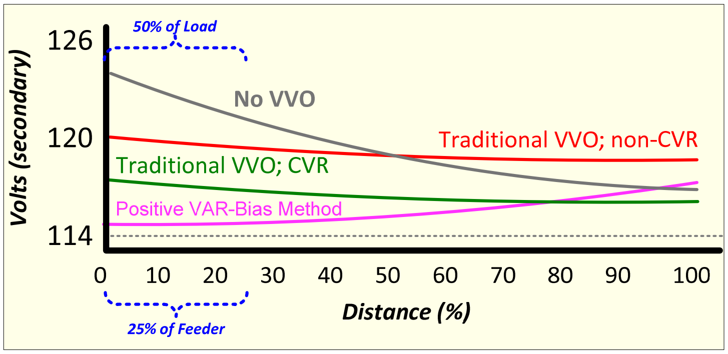
CVR: REGs/LTC with DERs/CAPs



- For CVR, forcing overVAr on feeder causes end of line voltage to rise
- You can have a deeper voltage reduction at the beginning of the line where most of the load is located (EPRI Green Circuits)

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Voltage Reduction: Increase DER Hosting Ability

- At times of high feeder DER output, enter voltage reduction
  - Voltage at head end lowers
  - Voltage at end of line lowers
- DER picks up voltage from end of line back to head end
- Use either negative LDC or positive VAR-Bias
  - Negative LDC lowers voltage bandcenter as reverser power flow increases
  - Positive VAR-Bias discussed later section

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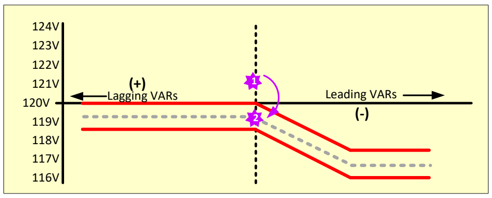
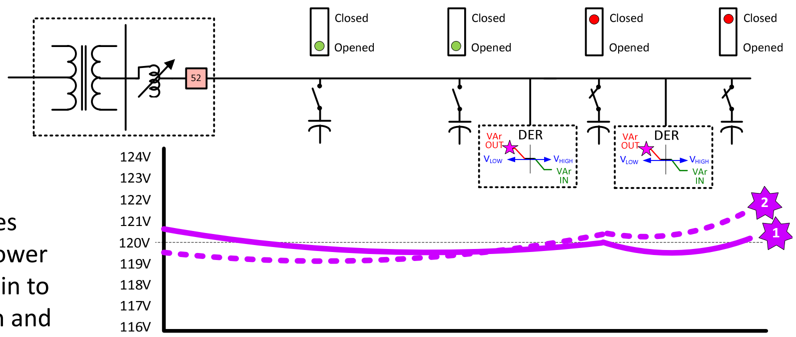
CVR Operation: Positive VAR-Bias



CVR OPERATION



- REG forces voltage lower
- CAPs begin to switch on and DER outputs VAr

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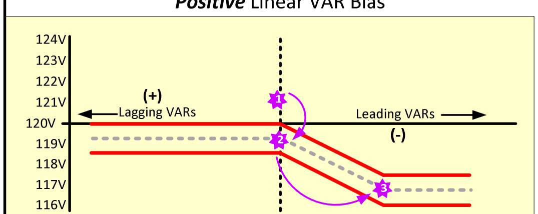
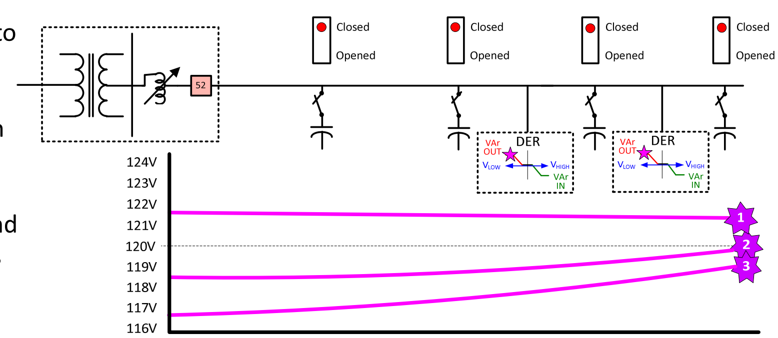
CVR Operation: Positive VAR-Bias



CVR OPERATION

- VARs begin to lead.
- REG forces voltage even lower.
- More CAPs switch on and DER outputs VAr



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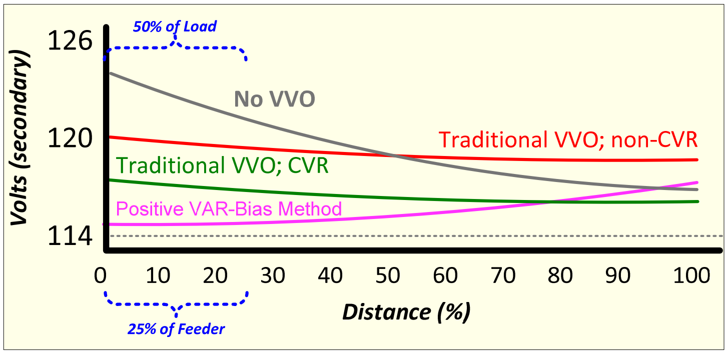
CVR: REGs/LTC with DERs/CAPs



- For CVR or DER Hosting VR, forcing overVAr on feeder causes end-of-line voltage to rise
- You can have a deeper voltage reduction at the beginning of the line where most of the load is located (EPRI Green Circuits)

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Voltage Reduction: Increase DER Hosting Ability

- At times of high feeder DER output, enter voltage reduction
  - Voltage at head end lowers
  - Voltage at end of line lowers
- DER picks up voltage from end of line back to head end
- Use either negative LDC or positive VAR-Bias
  - Negative LDC lowers voltage bandcenter as reverse power flow increases
  - Positive VAR-Bias plus negative LDC lowers voltage as either/both reverse real and reactive power flow increase

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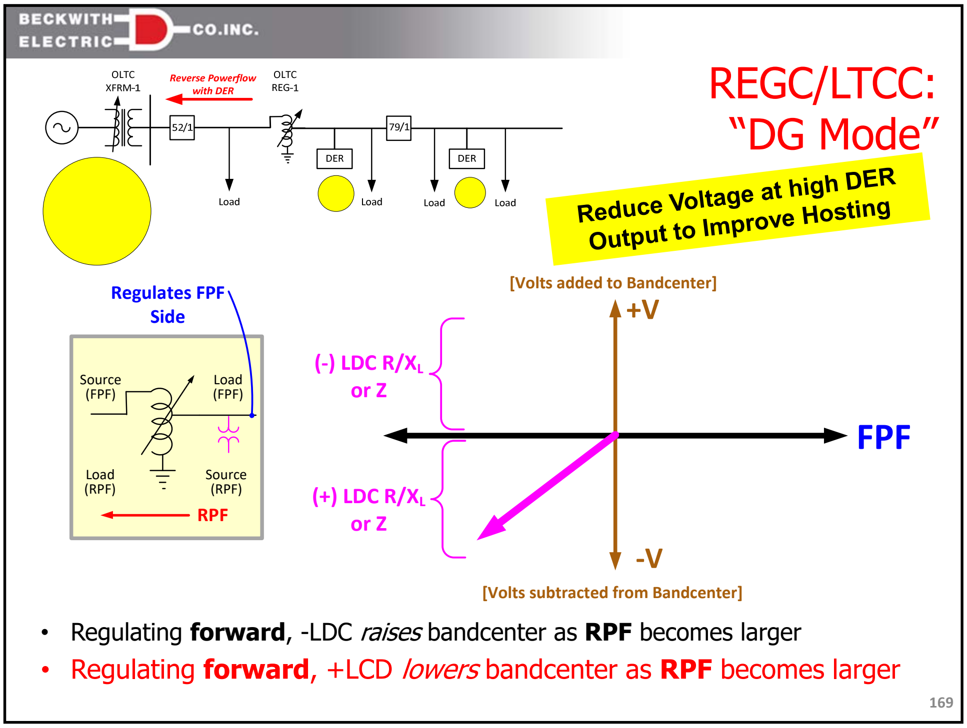
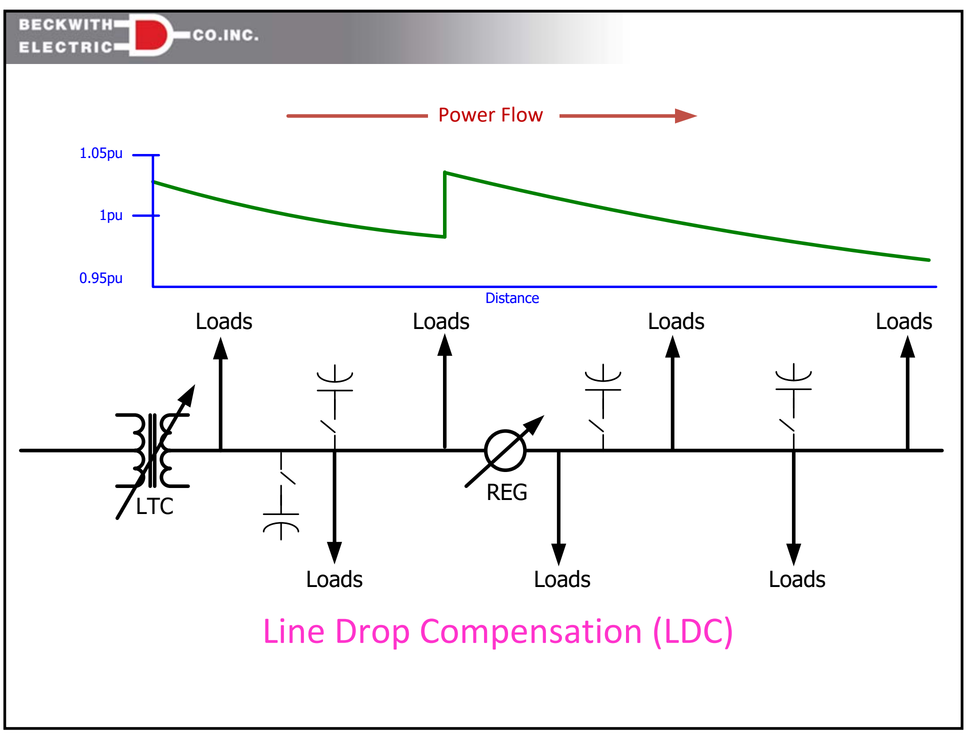
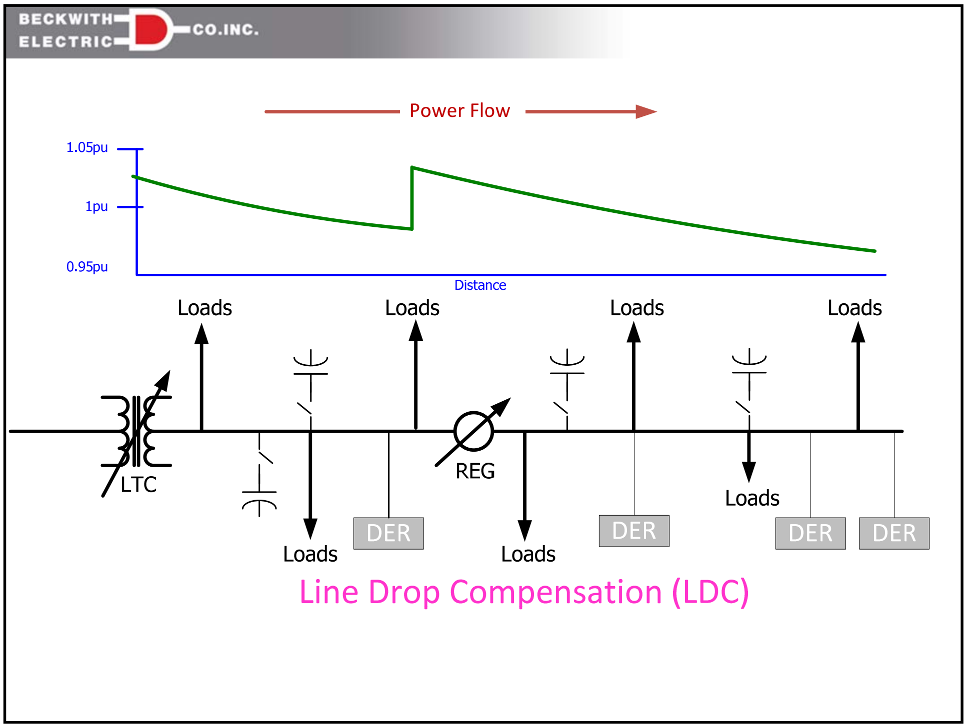
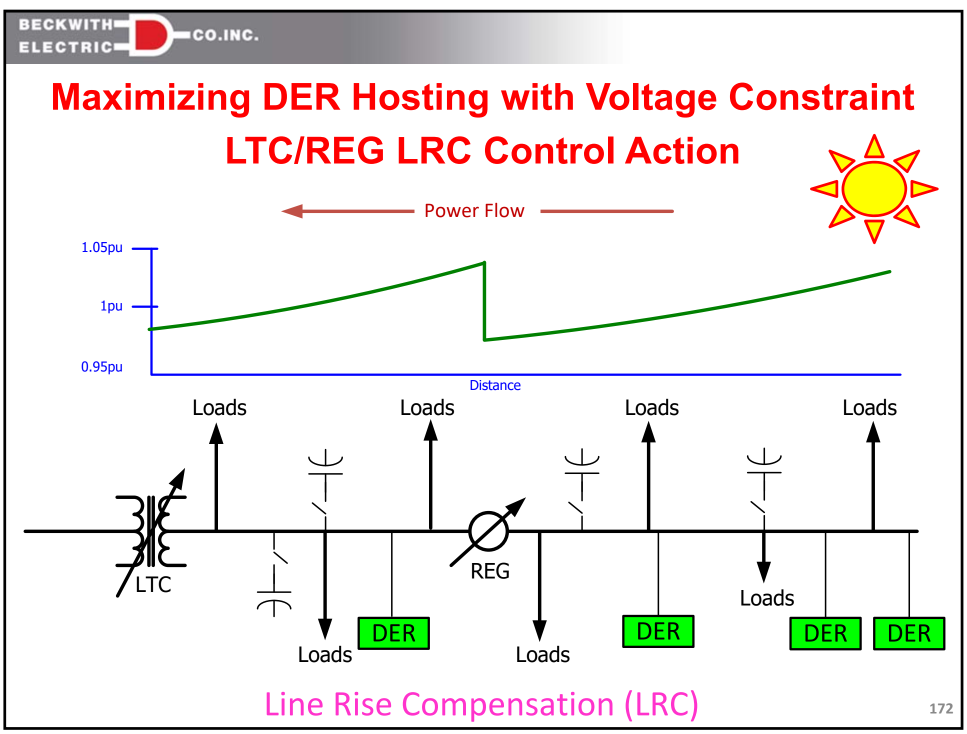

BECKWITH ELECTRIC CO. INC.
REGC/LTCC:
"DG Mode"
OLTC
XFRM-1
Reverse Powerflow
with DER
OLTC
REG-1
52/1
79/1
DER
DER
Load
Load
Load
Load
Reduce Voltage at high DER
Output to Improve Hosting
Regulates FPF
Side
Source
(FPF)
Load
(FPF)
Load
(RPF)
Source
(RPF)
RPF
[Volts added to Bandcenter]
+V
(-) LDC R/X_L
or Z
FPF
(+) LDC R/X_L
or Z
-V
[Volts subtracted from Bandcenter]
• Regulating **forward**, -LDC *raises* bandcenter as **RPF** becomes larger
• Regulating **forward**, +LCD *lowers* bandcenter as **RPF** becomes larger
169

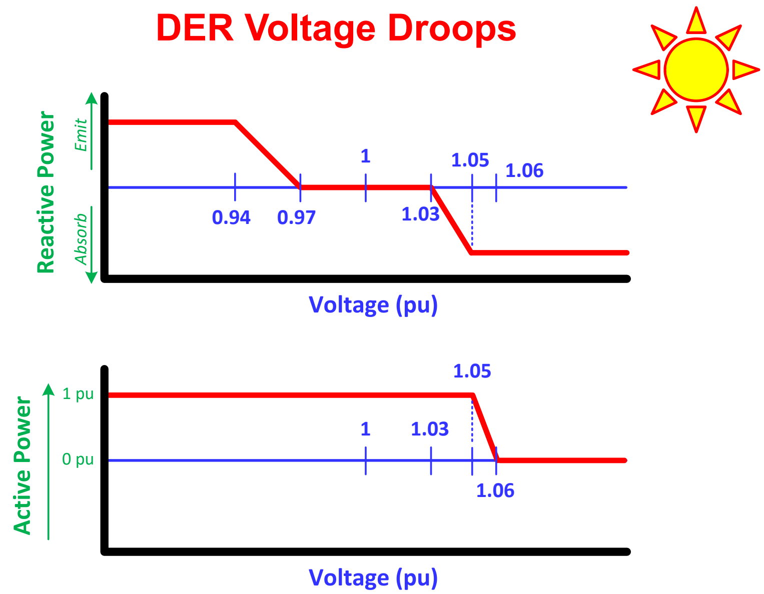

BECKWITH ELECTRIC CO. INC.
Power Flow
1.05pu
1pu
0.95pu
Distance
Loads
Loads
Loads
Loads
LTC
REG
Loads
Loads
Loads
Line Drop Compensation (LDC)


BECKWITH ELECTRIC CO.INC.
Power Flow
1.05pu
1pu
0.95pu
Distance
Loads
Loads
Loads
Loads
LTC
REG
Loads
DER
DER
DER
DER
Loads
Loads
Line Drop Compensation (LDC)


BECKWITH ELECTRIC CO.INC.
Maximizing DER Hosting with Voltage Constraint
LTC/REG LRC Control Action
Power Flow
1.05pu
1pu
0.95pu
Distance
Loads
Loads
Loads
Loads
LTC
REG
Loads
DER
DER
DER
DER
Loads
Loads
Line Rise Compensation (LRC)
172

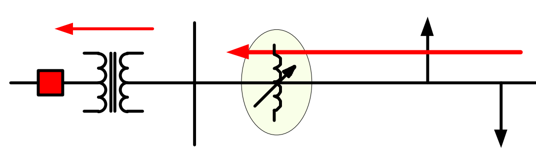
Maximizing DER Hosting with Voltage Constraint

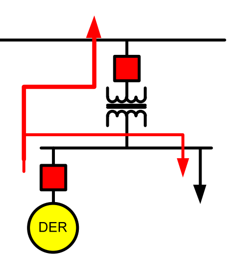
DER Voltage Droops



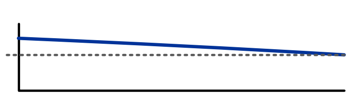
173

Effects of Reverse Power from DER on Line Drop Compensation (LDC)

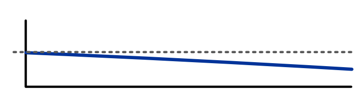




- If RPF is large enough to cause reverse power flow, the REGC will operate to lower voltage
- Using to “DG Mode” allows change to the polarity of the LDC (and factors if desired) under reverse power conditions to prevent this from occurring



Normal LDC with FPF



Improper LDC with RPF

174

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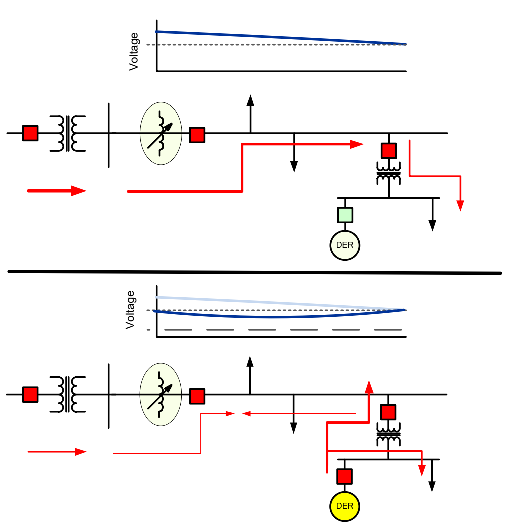
Effect of DER on Regulator Line Drop Compensation (LDC)



- LDC is reduced when DER contributes power
- More DER power = less load = less LDC = voltage setpoint lowers
- If DER is in PF mode, it maintains a VAR output to not import or export any VARs, so it cannot control voltage
- Voltage profile can change depending on:
  - o R and X_L of the line
  - o Reactive compensation to counter the X_L
  - o Power output of the DER

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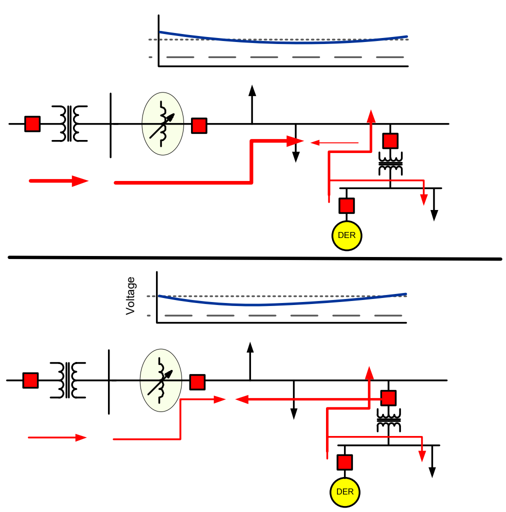
Effect of DER on Regulator Line Drop Compensation (LDC)



- Assume line R and X_L drops are low
- Assume REGC in DG Mode
- Assume variable DER power output per the graphic
- Line voltage assumes "smile" profile
- Curve of smile (flat or very arced) not the severe
  - o Arc more severe with higher R and XL, more DER output

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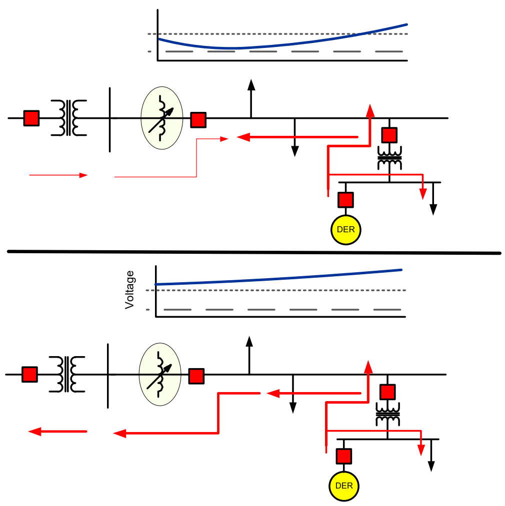
Effect of DER on Regulator Line Drop Compensation (LDC)



- Assume line R and X_L drops are low
- Assume REGC in DG Mode
- Assume variable DER power output per the graphic
- Line voltage assumes “smile” profile
- Curve of smile (flat or very arced)
  - Arc more severe with higher R and X_L, more DER output

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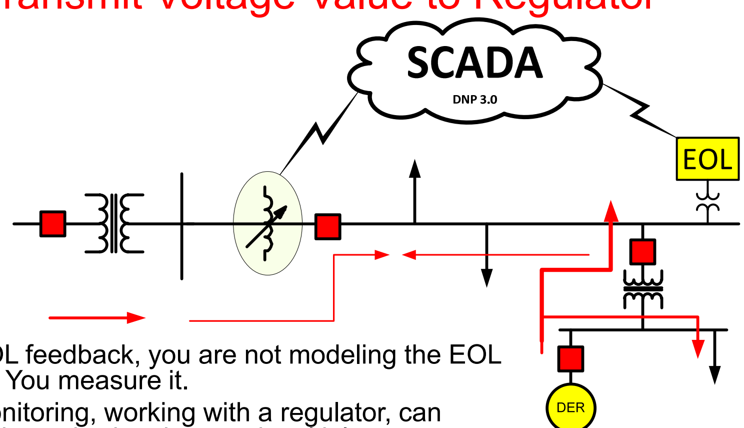
Use of an End-of-Line Monitor (EOL) to Transmit Voltage Value to Regulator



- With EOL feedback, you are not modeling the EOL voltage. You measure it.
- EOL monitoring, working with a regulator, can handle dynamic situations and multiple sources to adjust line voltage
- Works when DG Mode where unfavorable line/DER output characteristics exist
  - o “Smile arc” too severe or DER EOL voltage too high

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Line Caps and DA

- How do we get proper VAr support after a reconfiguration?

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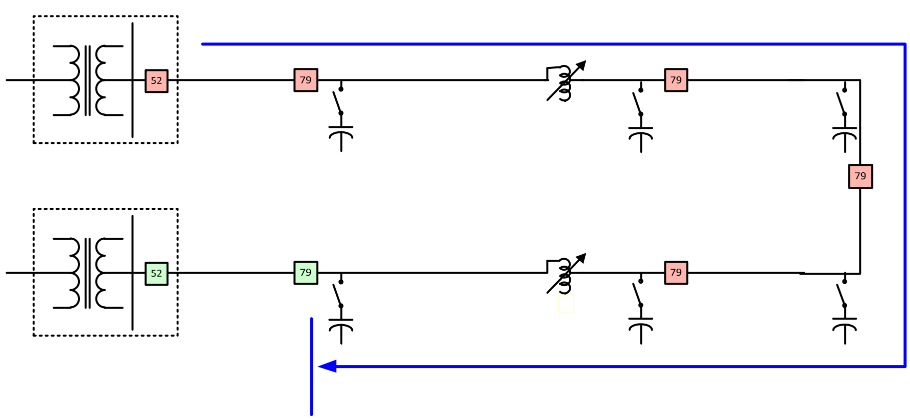
Volt/VAR Control Considerations from DA: CAPC



How to address reconfiguration:

1. Do nothing (resulting control may be suboptimal)
2. Use communications to control by setpoint or setting group
3. Use autoadaptive methodology to retune switch timing per relative position on newly configured feeder

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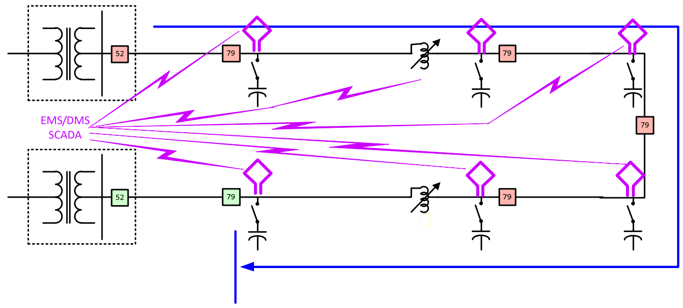
Communications to CAPC



1. CAPC is able to provide detailed power system information to DMS/DA such as operational data (ex., V, A, W, S, demand, THD, open/closed status) and, and non-operational information such as asset maintenance information, detailed PQ monitoring and event information (DNP)
2. DMS/DA, per modeling or feedback control, sends analog value DNP setpoints to CAPCs for new control action. CAPCs perform per new setpoints.
3. DMS/DA, per modeling or feedback control, sends DNP profile change command to CAPC for new control action. CAPC performs per new setting profile. This takes less communication bandwidth and frequency than Solution 1.

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Communications to CAPC

- Pros:
  - CAPC does as commanded, using analog setpoint or profile group
    - Using "Heartbeat," control knows if communications is lost
      - Go to "Plan B;" operation mode with comms
- Cons:
  - Costs of communications infrastructure
  - Requires DMS with either modeling or feedback to properly execute commands
    - Feedback requires recloser position status, EOL voltage sensing; may require VAR sensing at substation
    - Modeling requires creation, updating and upkeep

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Use of Autoadaptive Methodology by CAPC

- CAPCs, using Autoadaptive ΔV based control, alter their *timing* to properly switch per control's (new) location from source on feeder (furthest from source switches on first, off last).
  - This implementation maintains better multi-capacitor control action on a given feeder regardless of configuration
  - Uses ΔV observed on switching to change timing. Example:
    - ΔV_{factor} = 90 sec. / 1 volt = 90 sec/V.
    - Sec. = ΔV_{factor} / $\Delta V_{(MEASURED)}$
    - Increasing $\Delta V_{(MEASURED)}$ = further distance (more impedance) from source
    - Decreasing $\Delta V_{(MEASURED)}$ = closer distance (less impedance) from source

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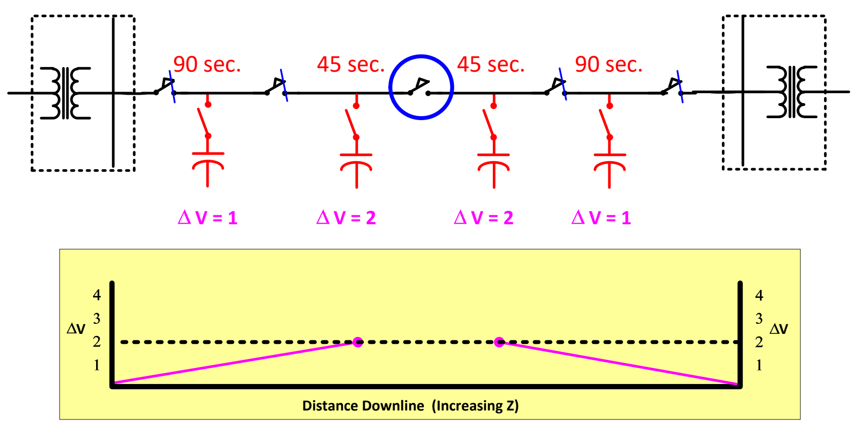
Use of Autoadaptive Methodology by CAPC



- ΔV_{factor} = 90 sec. / 1 volt = 90 sec/V.
- Sec. = ΔV_{factor} / ΔV

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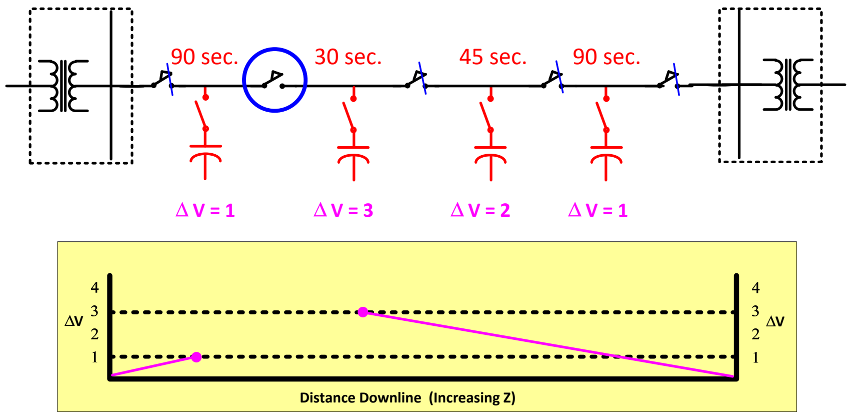
Use of Autoadaptive Methodology by CAPC



- ΔV_{factor} = 90 sec. / 1 volt = 90 sec/V.
- Sec. = ΔV_{factor} / ΔV

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Use of Autoadaptive Methodology by CAPC

- Pros:
  - Communications not needed to retune CAPC time settings
  - Control is autonomous (no DMS/SCADA required)
  - Upon another reconfiguration, CAPC will learn new time setting depending on its position form the source
- Cons:
  - None

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Putting it All Together: Optimization Tactics

- Adapting to DA and DER to Optimize VVO/CVR

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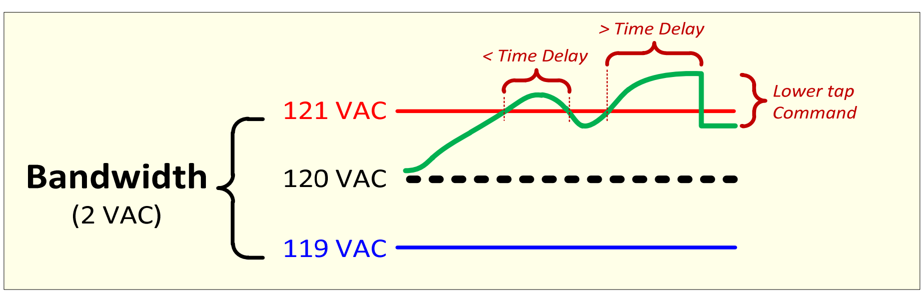
Time Delay

Definite Time



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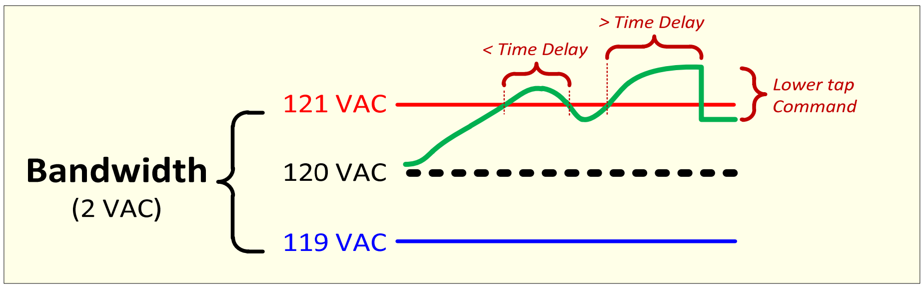
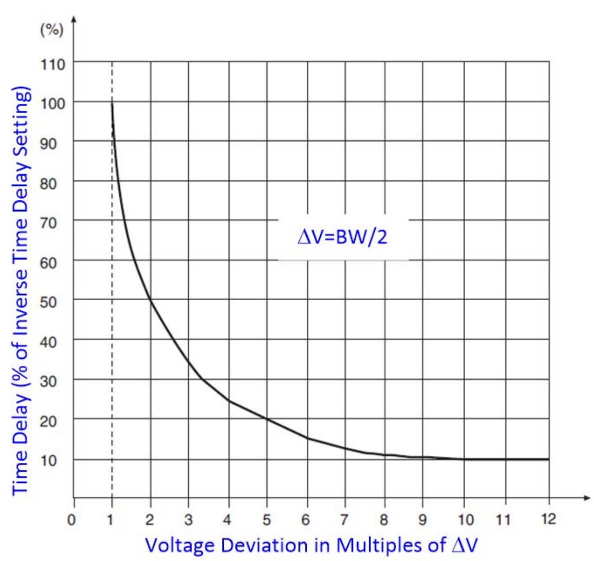
Time Delay

Definite Time



Inverse Time Characteristic



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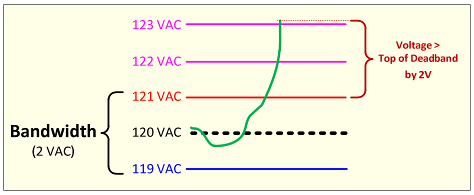
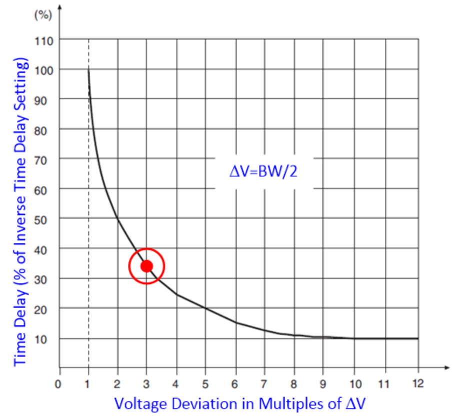
Inverse TD Example





<u>Example</u>

Bandcenter = 120 V

Bandwidth = 2 V

Inverse Time Delay = 120 V

Sensed Voltage = 123 V

Time Delay Factor = (V_{sense} - $V_{bandcenter}$)/(BW/2)

Time Delay Factor =(123-120)/(2/2) = 3/1 = 3

From Graph, % Factor = 34%

Time = Setting * % Factor

Time = 120 sec. * 0.34 = 40.8 = 41 sec.

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When to Use Inverse Time

1. When voltage is just outside of band, regulating device will wait a longer time before tapping which may reduce operations
   - Asset preservation

2. When voltage undergoes a rapid excursion, regulating device will tap quickly to maintain voltage quality
   - Large load rejection (fault clearing, reconfig)
   - Large load pickup (restoration, reconfig)
   - DER VAR regulation issues (poor coordination with Utility VVO assets)
   - DER power output issues (irradiance, unpredictability)

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Time Delay Reset

- Two types of timers
  - When voltage goes out of bandwidth and then returns to normal before tap is taken, there are two ways to reset the timer

    1. Integrating:
       1. Increments timer 1 second voltage is out of range and decrements timer 1 second when voltage is within range
          » Tends to allow tap change
    2. Instantaneously:
       1. Increments timer 1 second every second voltage is out of range and resets timer to zero immediately when voltage is within range
          » Tends to inhibit tap change

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VVO Elements

- Consider use of reactive controlling DER
  - Compliment and fine tune LTCC, REGC and CAPC
  - Save LTC and REG operations
- Consider substation caps be controlled on VAR/pf with high voltage and low voltage override
- Consider line caps use CAPC that employ voltage measurement
- Consider REGCs using Autodetermination for selection of RFP control mode

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VVO Elements

- Use of VAR-Bias avoids LDC issues as DER power output increases
- If DER can control VAR output, coordinating DER voltage output setting with REGC/LTCC bandcenter will keep voltage at the setting
  - VAR-Bias reacts to VAR to maintain unity PF
  - REGC/LTCC, CAPs and active DERs maintain voltage
  - If DERs charge for reactive support, use CAPs first
    - Employ narrower bandwidth on CAPs

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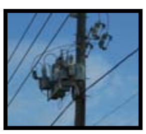

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Extended Capabilities of Advanced Volt/VAR Distribution Automation Controllers (ADVVOCs) for Data Acquisition and Use Into Higher Power SCADA/DMS Applications

3rd Annual Smart Grid Conference

October 2-3, 2018

Anaheim, CA

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Our Exploration
ADVVOCS & DMS for Enhanced:

1) Asset Maintenance

- Push unsolicited messages to SCADA/DMS regarding asset health of controlled elements
- Allow drill down to logging for additional information

2) System Monitoring

- Push unsolicited messages on high THD% to monitor effects of DER, caps and resonance
- Allow drill down to individual harmonic levels for precise analysis

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Our Exploration
ADVVOCS & DMS for Enhanced:

3) Distributed Intelligence

- Perform min/max calculations for monthly updates
- Eliminates need for constant polling, storage and data crunching in the DMS
- Low bandwidth requirements and leased comms costs

4) Alarm, Limit and Runback Functions

- Alarms, Limit and Runback Functions to supervise DMS actions and issues beyond DMS immediate control
- Eliminates need for the DMS to execute these functions, and also corrective action taken without latency
- Low bandwidth requirements and leased comms costs

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Asset Maintenance: Feeder Capacitor Banks

- Feeder Capacitor Banks
  - Applied in distribution for VAR support
  - Applied in distribution for voltage control
    - Supplied VARs raise voltage and change pf
    - VARs switched off lower voltage and change pf
- Bank Construction Details
  - Switches are used on each phase
  - Fuses protected switches, banks and interconnected wiring form faults
  - Some capacitor cans have fuses internal to component capacitors within cans (packs)

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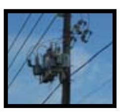

Asset Maintenance: Feeder Capacitor Banks

- Single Phase Sensing, Simultaneous Phase Switching
  - Voltage sensed on one phase
  - All phases switched on or off at one time
  - May employ :
    - 3-single phase switches, or
    - 1 ganged switch
- Three phase sensing, independent phase switching
  - Voltage sensed on all 3 phases
    - For switching decision, can sense each phase, can switch on highest, lowest or average
  - Phases may be switched independently or simultaneously
  - Employs 3-single phase switches

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Capacitor Bank Components

Voltage Transformer

Arrestor

Oil Switch

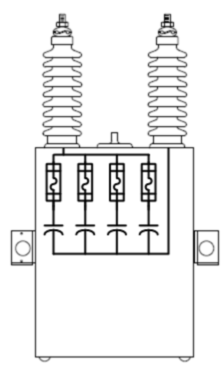
Vacuum Switch

Fuse

Credit: Cooper Power Systems

Capacitor Bank Components

Capacitor



Cut-Away of Capacitor w/Internal Fuses

Credit: Cooper Power Systems

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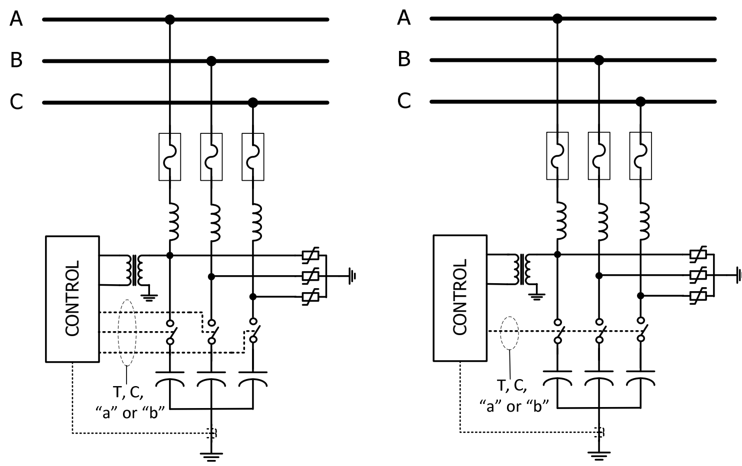
Asset Maintenance: Feeder Capacitor Banks



Grounded Bank, 1∅ Voltage Sensing

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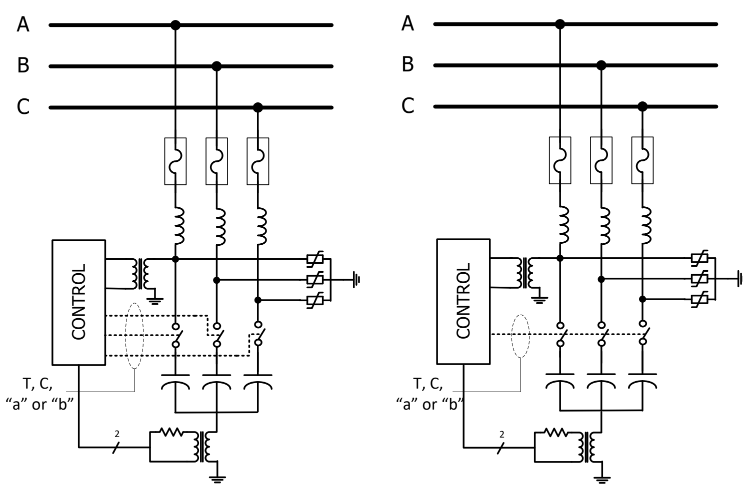
Asset Maintenance: Feeder Capacitor Banks



Ungrounded Bank, 1∅ Voltage Sensing

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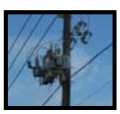
Asset Maintenance: Feeder Capacitor Banks

Failure Modes

- Switch or Switches Failure
  - Stuck open or stuck closed
- Phase Fuses
  - Blown
- Fuses for Packs in Cans
  - Blown
- Connecting Wiring
  - Open circuits
  - Shorts (Fuse)
- Arrestors
  - Shorts (Fuse)

205



Asset Maintenance: Feeder Capacitor Banks

Failure Frequency

- At any given moment, over 30% of distribution feeder cap banks may have failures
- Often only detected by feeder patrolling at time intervals
- Reactive support is compromised with bank failures
  - Lack of VAR causing poor power factor
    - May negatively impact CVR
  - OLTC elements may have to operate much more than they should with failed banks
    - Becomes maintenance issue for OLTC elements

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Asset Maintenance:
ADVVOC Failure Detection Methods

BANK FAILURE SCENARIO

- ✓ Fuse Blown, Open Connecting Wire, Open Switch
- ✓ Assuming Battery Backup to Control

Failed Phase(s)

A	A, B	A, C	B	B,C	A,B,C
1	1	1	2	2	1

Alarm Action

- ➢ Alarm 1: Control Power Phase Open
  - Indicates Bank Power Down
- ➢ Alarm 2: Bank Failure Alarm
  - Indicates Bad Fuse, Conductor or Switch

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Asset Maintenance:
ADVVOC Failure Detection Methods

BANK FAILURE SCENARIO

- ✓ Switch Failure to Close on Close Command
- ✓ Switch Failure to Open on Trip Command

- ➢ Alarm 3: Switch Fail to Open
  - Detectable by monitoring switch auxiliary contacts, *or*,
  - Detectable by examining open command against lack of level neutral current
- ➢ Alarm 4: Switch Fail to Close
  - Detectable by monitoring switch auxiliary contacts, *or*,
  - Detectable by examining open command against low level of level neutral current

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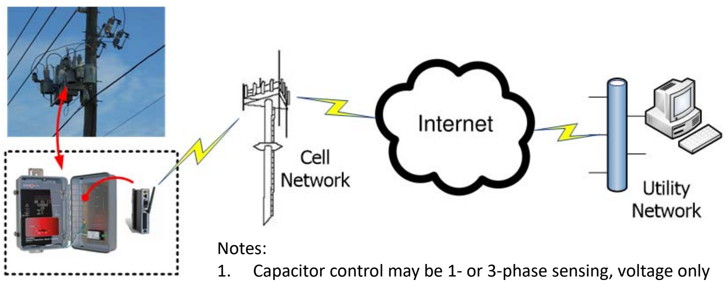
Asset Maintenance: Feeder Capacitor Banks

- Treatment of Alarms at ADVVOC
  - Push unsolicited messages to SCADA/DMS regarding asset health of controlled elements
  - Allow drill down to logging for additional information



Notes:
1. Capacitor control may be 1- or 3-phase sensing, voltage only or voltage and current

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System Monitoring: Feeder Capacitor Banks & Voltage Regulators

- Feeder Capacitor Banks
  - For monitoring, controls with three-phase sensing may be applied
    - Current monitoring dependent on if current is sensed
  - "Usual Suspects" available: V, I, W, VAR, S
  - Capable of monitoring THD% voltage and THD% current

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System Monitoring:
Feedback Capacitor Banks & Voltage Regulators

- Line Voltage Regulators
  - Applied in distribution for voltage regulation
  - OLTC autotransformer used to tap to raise and lower voltage
  - For monitoring, controls sense voltage and current
  - Each regulator uses a control, therefore 3-phase voltage and current measurement is available
  - “Usual Suspects” available: V, I, W, VAR, S
  - ADVVOCs capable of monitoring THD% voltage and THD% current

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System Monitoring:
Feeder Capacitor Banks & Voltage Regulators

- Distribution System Loads
  - Load types have changed
  - Proliferation of Electronic Loads
    - Power Electronics
      - Variable Speed Drives
      - DER (Inverter Based)
    - Switching Power Supplies for Lighting and Other Loads
  - Proliferation of Capacitors and Harmonic Filter Banks

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System Monitoring:
Feeder Capacitor Banks & Voltage Regulators

- Rise in Harmonics
  - Harmonics can interfere with operation of sensitive loads
  - Harmonics can overload transformers and conductors
  - Harmonics can raise motor heating
  - Resonance can sometimes develop between harmonic sources and capacitor/filter banks
  - Harmonics are strongest at the source and decrease as they travel through system impedances
    - Strong sources absorb harmonics better than weak sources

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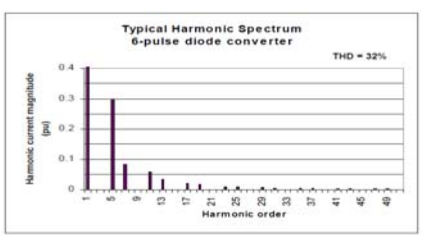
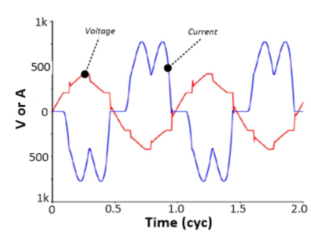
System Monitoring:
Feeder Capacitor Banks & Voltage Regulators



6 Pulse Converter
ASD Harmonic Order



Note: Current inverted to ease of viewing

6 Pulse Converter
ASD Harmonics

Credit: TMEIC
Medium Voltage Application School

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System Monitoring:
Feeder Capacitor Banks & Voltage Regulators

Typical values of harmonic current (% of fundamental current) of different types of front end configurations (% I_h/I_1)

Harmonic order (h)	5	7	11	13	17	19	23	25	*THD*
6-pulse without line reactor (Stiff source)	80.0%	58.0%	18.0%	10.0%	7.0%	6.0%	5.0%	2.5%	**101.5%**
6-pulse with 2-3% line reactor	40.0%	15.0%	5.0%	4.0%	4.0%	3.0%	2.0%	2.0%	**43.6%**
6-pulse with 5% line reactor	32.0%	9.0%	4.0%	3.0%	3.0%	2.0%	1.5%	1.0%	**33.9%**
6-pulse with line harmonic filter (LHF)	2.5%	2.5%	2.0%	2.0%	1.5%	1.0%	0.5%	0.5%	**4.9%**
12-pulse	3.7%	1.2%	6.9%	3.2%	0.3%	0.2%	1.4%	1.3%	**8.8%**
18-pulse	0.6%	0.8%	0.5%	0.4%	3.0%	2.2%	0.5%	0.3%	**3.9%**

Credit: Siemens Whitepaper
Harmonics in Power Systems; Causes, Effects and Control

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System Monitoring:
Feeder Capacitor Banks & Voltage Regulators

- IEEE has Guidelines for Harmonic Levels
  - **IEEE 519**, Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

Table 2—Current distortion limits for systems rated 120 V through 69 kV

Maximum harmonic current distortion in percent of I_L						
	Individual harmonic order (odd harmonics)[a, b]					
I_{SC}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a]Even harmonics are limited to 25% of the odd harmonic limits above.

Credit: IEEE 519

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System Monitoring:
Feedeer Capacitor Banks & Voltage Regulators

- IEEE has Guidelines for Harmonic Levels
  - **IEEE 519**, Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV $< V \leq 69$ kV	3.0	5.0
69 kV $< V \leq 161$ kV	1.5	2.5
161 kV $< V$	1.0	1.5[a]

Credit: IEEE 519

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System Monitoring:
Feeder Capacitor Banks & Voltage Regulators

- IEEE has Guidelines for Harmonic Levels
  - **IEEE 1547**, Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces

Table 26—Maximum odd harmonic current distortion in percent of rated current (I_{rated})[a]

Individual odd harmonic order h	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h < 50$[109]	Total rated current distortion (TRD)
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

[a] I_{rated} = the DER unit rated current capacity (transformed to the RPA when a transformer exists between the DER unit and the RPA).

Table 27—Maximum even harmonic current distortion in percent of rated current (I_{rated})[a]

Individual even harmonic order h	$h = 2$	$h = 4$	$h = 6$	$8 \leq h < 50$
Percent (%)	1.0	2.0	3.0	Associated range specified in Table 26

[a] I_{rated} = the DER unit rated current capacity (transformed to the RPA when a transformer exists between the DER unit and the RPA).

Credit: IEEE 1547

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System Monitoring:
Feedeer Capacitor Banks & Voltage Regulators

- If THD% limits as set are exceeded, push unsolicited alarm to SCADA/DMS
- Once alarm received, an *integrity poll* can be made by DMS/SCADA and the harmonic levels (THD and individual harmonics) can be read.
- Alternatives:
  - If the communication infrastructure allows, a remote connection can be made between the control using its software to examine THD and individual levels in CSV and graphic formats, or,
  - Connect to the control directly using its software to examine THD and individual levels in CSV and graphic formats

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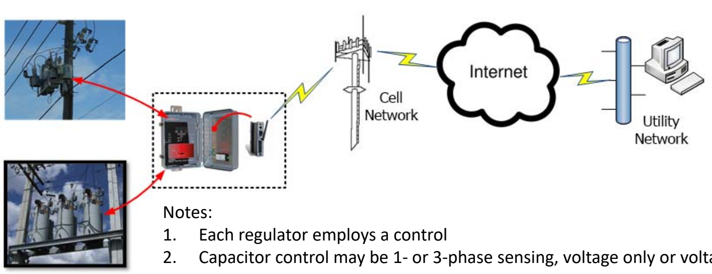
System Monitoring:
Feeder Capacitor Banks & Voltage Regulators

- Treatment of Alarms at ADVVOC
  - Push unsolicited messages to SCADA/DMS regarding asset health of controlled elements
  - Allow drill down for additional information



Notes:
1. Each regulator employs a control
2. Capacitor control may be 1- or 3-phase sensing, voltage only or voltage and current

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Distributed Intelligence: Voltage Regulators

- Planners use information such as Energy and Demand:
  - Current Demand
  - Watt Demand
  - VAR Demand
  - VA Demand
  - W-Hrs Forward
  - W-Hrs Reverse
  - VAR-Hrs Forward
  - VAR-Hrs Reverse
- One can use SCADA/DMS to constantly poll, or let the ADVVOC measure the quantities and calculate
- SCADA/DMS polls once per month, obtains values
- SCADA/DMS resets all values to zero, and the ADVVOC measure and calculates for the next and ensuing months
- Greatly decrease bandwidth and DMS programming

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Distributed Intelligence: Feeder Capacitor Banks & Voltage Regulators

- Instead of SCADA/DMS "micromanaging" the ADVOC to control the element, let the SCADA/DMS select setting profiles (setting groups) to match operational conditions
- Examples:
  - Normal Mode
  - Voltage Reduction Mode for CVR
  - Voltage Reduction Mode for DER Hosting
  - DA Switching with new line/load characteristics
- Greatly decrease bandwidth and DMS programming

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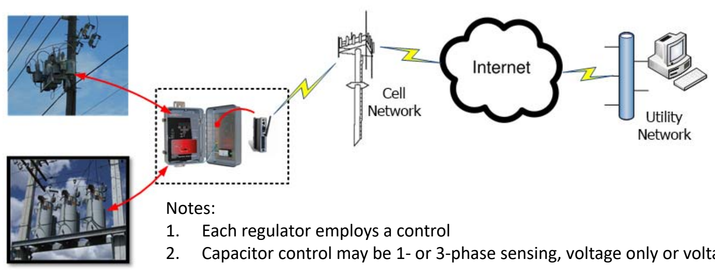
Distributed Intelligence:
Feeder Capacitor Banks & Voltage Regulators

- Data Polling from ADVVOC
  - Request data at widely separated intervals
- Select Setting Profile to Match System Conditions
  - Simple binary data command



Notes:
1. Each regulator employs a control
2. Capacitor control may be 1- or 3-phase sensing, voltage only or voltage and current

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Alarm, Limit and Runback Functions:
Voltage Regulators

- If a DMS model has an error, and erroneous command may be given to a ADVVOC, resulting in a voltage violation
- If the system changes and the DSM does not have visibility, or the change cannot be quickly sensed due to communication latency, an voltage violation may occur
  - Fast block load removal due to a fault
  - Fast power output change in highly penetrated DER
    - PV in local area with rapid cloud cover

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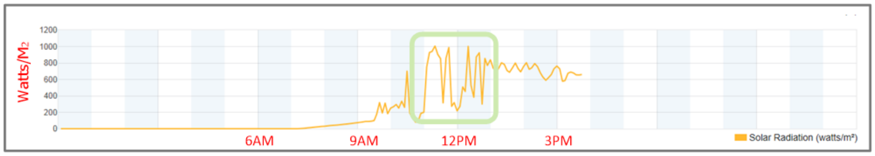
Alarm, Limit and Runback Functions: Voltage Regulators



- Weather data from Tampa, FL (9/14/18)
- Irradiance is rapidly fluctuating from 200-1000 W/M^2; 11AM to 1PM
- With significant PV DER penetration, those power swings would manifest as rapid voltage changes.
- What happens if DMS model or polling feedback from sensors is not quick enough?
- Use Alarms, Limits and Runback on the ADVVOCs

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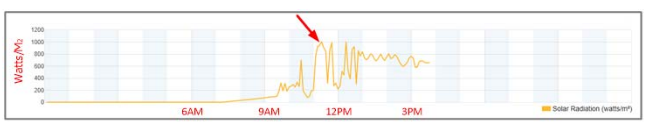
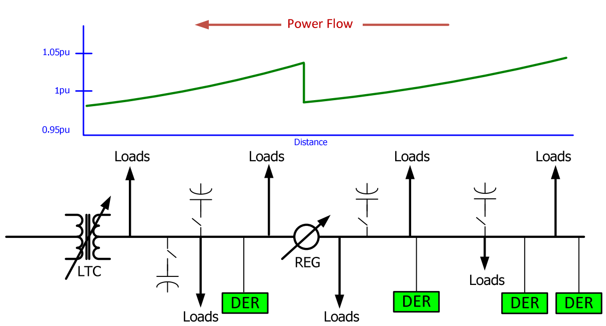
Alarm, Limit and Runback Functions: Voltage Regulators



- Fluctuating Voltage from Fluctuating Irradiance
  - Regulators adjusted for DER Hosting with High DER Output



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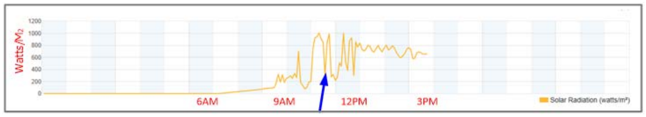
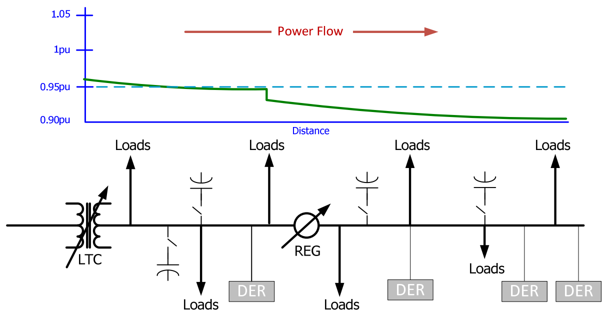
Alarm, Limit and Runback Functions: Voltage Regulators



- Fluctuating Voltage from Fluctuating Irradiance
  - Sudden cloud cover resulting in loss of DER output
  - DMS does not control before violation occurs



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Alarm, Limit and Runback Functions: Voltage Regulators

- Alarm: Push unsolicited message to SCADA/DMS that the voltage is close to violating
- Limit: Do not allow the control, on its own or from DMS command, to move voltage in eth direction of the violation
- Runback: If voltage continues to move to violation, control issues tap command to move voltage away from violation

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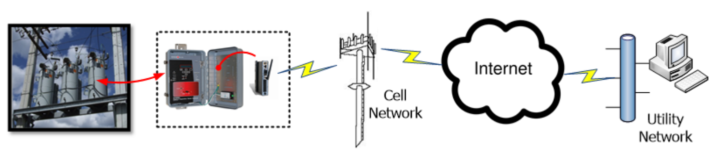
System Monitoring:
Voltage Regulators

- Treatment of Alarms at ADVVOC
  - Push unsolicited messages to SCADA/DMS regarding asset health of controlled elements
  - Allow drill down for additional information



Notes:
1. Each regulator employs a control

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Summary

- ADVVOCs and DMS can work together to make a better combined system
- In this exploration we shared application buckets where the combined ADVVOC and DMS :
  - Providing asset maintenance functions
  - Improving visibility to the power system
  - Decreased communication bandwidth requirements
  - Decreased programming in the DMS
  - Improving final control action

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