Implementing Volt/VAR Optimization with DER Penetration

53rd Annual
MINNESOTA POWER SYSTEMS CONFERENCE
November 7–9, 2017

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Wayne Hartmann is VP, Protection and Smart Grid Solutions for Beckwith Electric. He provides Customer and Industry linkage to Beckwith Electric's solutions, as well as contributing expertise for application engineering, training and product development.

Before joining Beckwith Electric, Wayne performed in application, sales and marketing management capacities with PowerSecure, General Electric, Siemens Power T&D and Alstom T&D. During the course of Wayne's participation in the industry, his focus has been on the application of protection and control systems for electrical generation, transmission, distribution, and distributed energy resources.

Wayne is very active in IEEE as a Senior Member serving as a Main Committee Member of the IEEE Power System Relaying Committee for 25 years. His IEEE tenure includes having chaired the Rotating Machinery Protection Subcommittee ('07-'10), contributing to numerous standards, guides, transactions, reports and tutorials, and teaching at the T&D Conference and various local PES and IAS chapters. He has authored and presented numerous technical papers and contributed to McGraw-Hill's "Standard Handbook of Power Plant Engineering, 2nd Ed."

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Definitions

- CAPC = Capacitor Control
- REGC = Regulator Control
- LTCC = Load Tapchanging Transformer Control (2001D)
- OLTC = On Load Tapchanger (REG and PWR XFRM)
- FPF = Forward Power Flow
- RPF = Reverse Power Flow
- VVO= Volt/VAR Optimization
- CVR = Conservation Voltage Reduction
- CVR_{factor} = $\Delta P / \Delta V$ (0.5 typ., >1,0 is excellent)
- DA = Distribution Automation
- EOL = End of Line, as in EOL Voltage
- Reconfig = System Reconfiguration


ADVVOC = Advanced Distribution Volt/VAR Controller

Exploration

- **1547a and the New 1547**
  - Active VAR regulation by DER
- **VVO Issues:**
  - Line drop compensation (LDC), R and X_L, or Z
  - VAR-Bias vs. LDC for control of Active VAR DER
  - LDC issues with reverse power flow
  - Reverse power flow control modes for On-Load tapchanging Elements (OLTC = LTC Transformers and Substation Regulators)
  - Inverse time vs. fixed delay for OLTC Elements

Exploration

- **Substation Protection Issues:**
  - Radial vs. Bidirectional Fault Current Flows
    - Out-of-section (sympathy) trip concerns and mitigation
    - Remote interrupter failure protection
  - Reclosing treatment :
    - Increase of 1st Shot Time Delay (from instantaneous)
    - Adaptive protection with voltage control of reclosing
  - Ferroresonance on load side of feeder CBs
  - Ungrounded fault backfeed into transmission protection
    - High side delta winding issue
- **Summary and Q&A**

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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 1547a, and soon-to-be approved IEEE 1547-2017 (?), allow **reactive** as well as **active powerflow output**, compounding the problem

1547A (2014): Active Voltage/VAR Control

- Coordination and approval of the area EPS and DR operators shall be required for the DR to actively participate to regulate the voltage by changes of real and *reactive* power.

- The DR shall not cause the Area EPS service voltage at other Local EPSs to go outside the requirements of ANSI C84.1-2006, Range A.

IEEE 1547 Addendum: *IEEE 1547a*

- 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

This will be part of IEEE 1547-2017 (?)

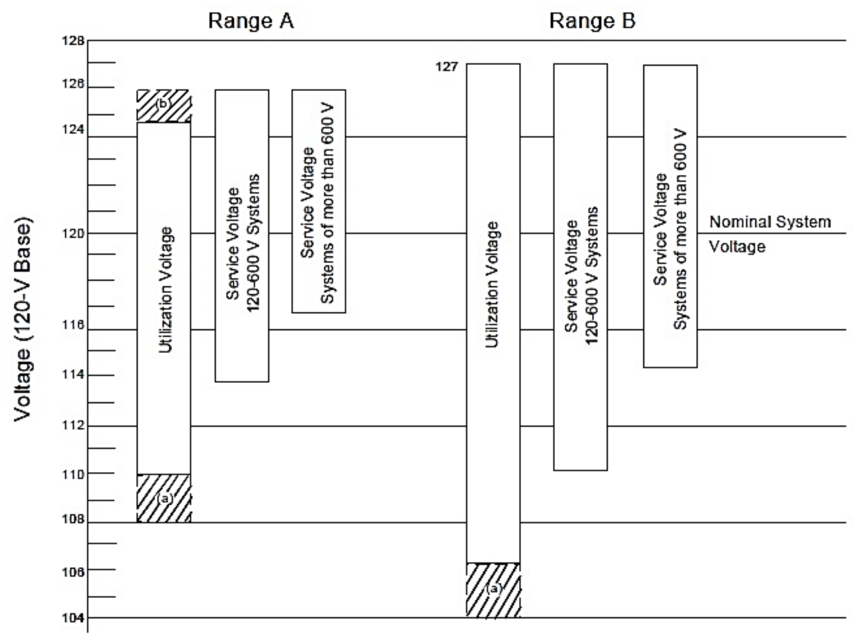
ANSI C84.1-2006

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



VVO Concepts and DER Issues

- ***What is VVO?***
- ***How do you obtain it?***
- ***CVR and what do you get out of it***
- ***How DER can cause control issues with VVO and CVR***
- ***What to do about it***

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VVO

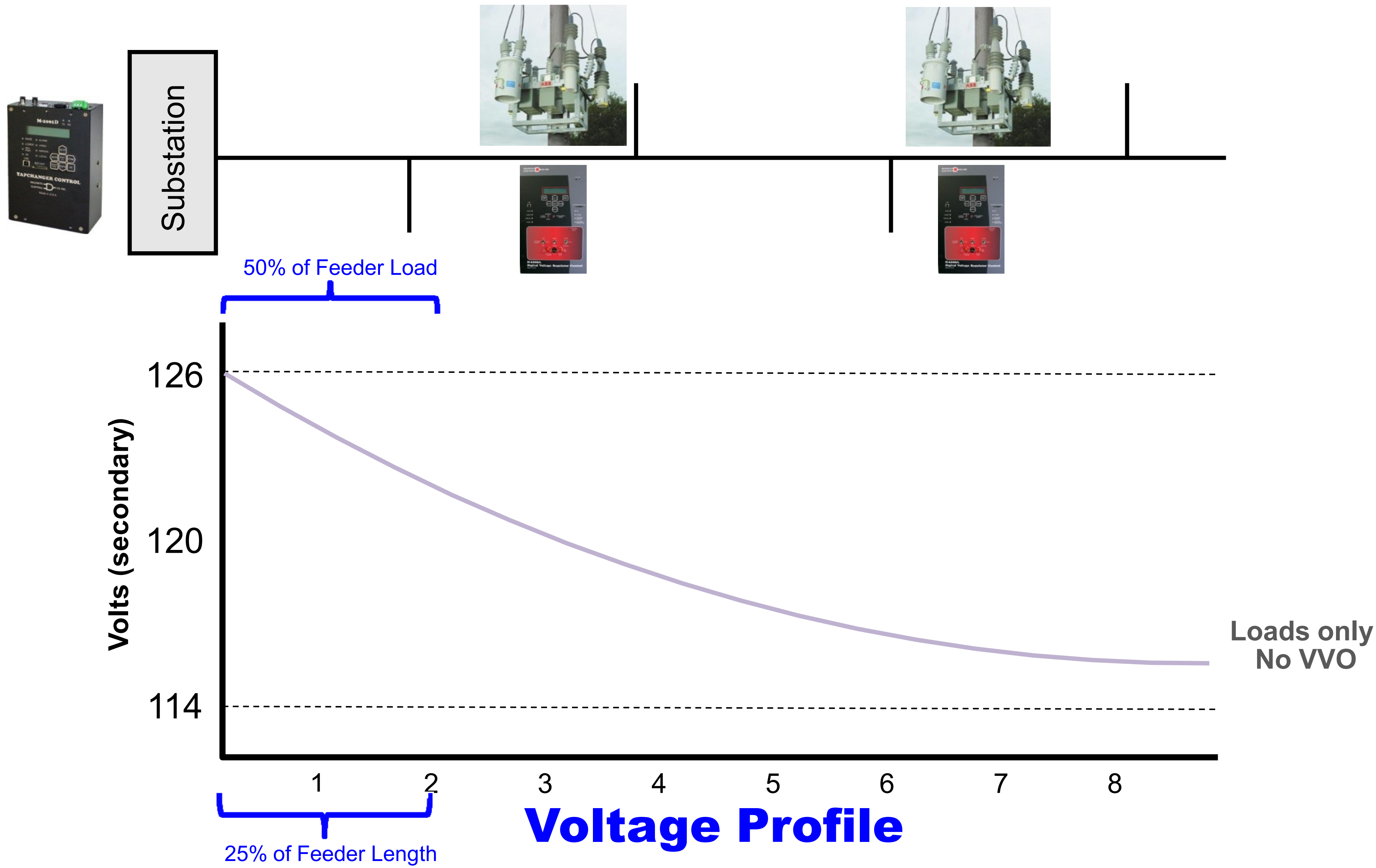
- Adjusting system voltage and pf by properly controlling OLTC and reactive assets. *Ideally*:
  - OLTC Assets used for Voltage Issues due to *Real* Power Changes
    - Load Tapchanging Transformer Controls (Substation)
    - Voltage Regulator Controls (Substation and Line)
  - Reactive Assets used for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

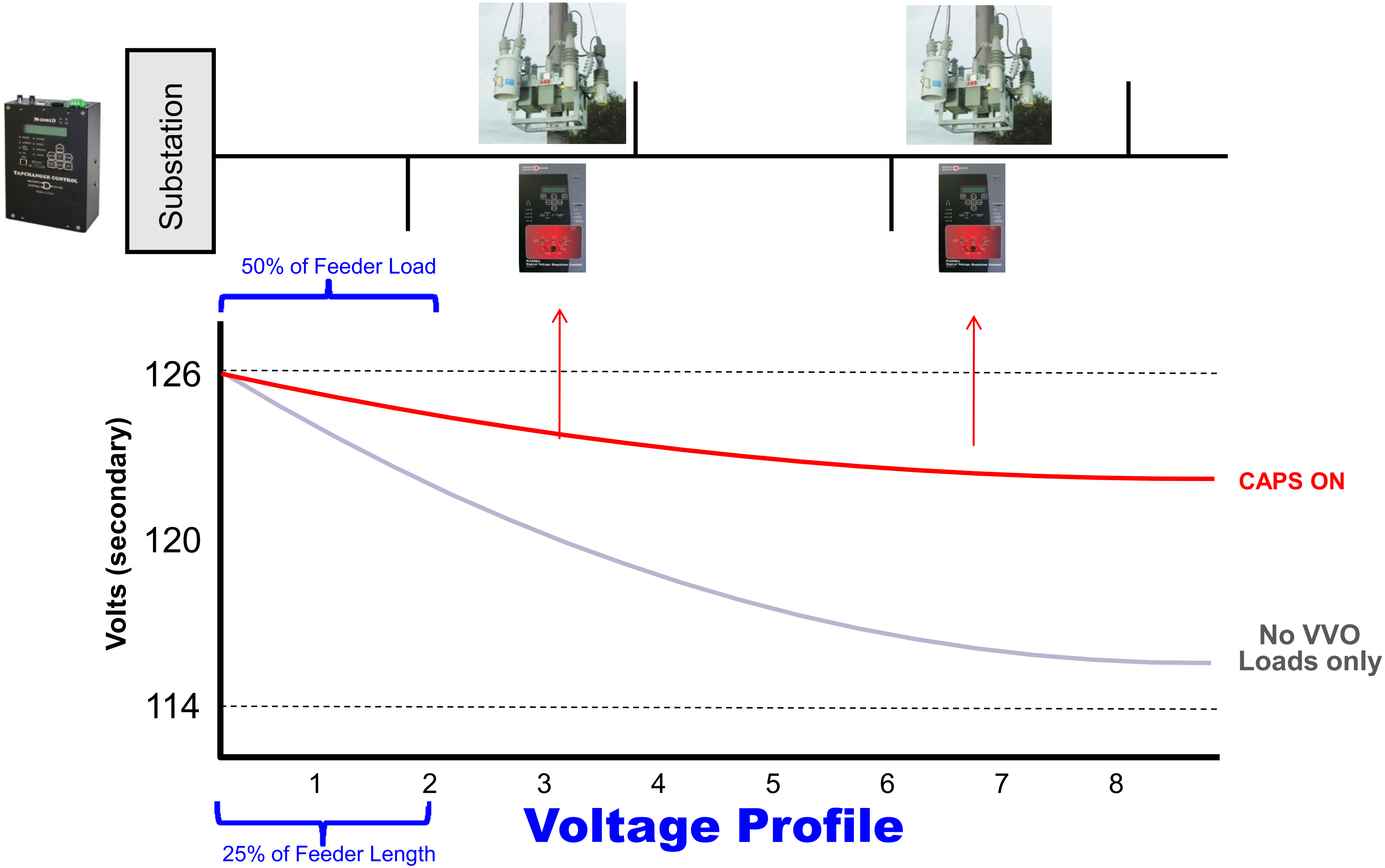
VVO Controllers

- **LTC Controls (Load Tapchanger)**
  - Applied on LTC Transformers in Substations
  - Control voltage
- **Regulator Controls**
  - Applied on Regulators
    - Substation and Line
  - Control voltage
- **Capacitor Controls**
  - Applied on Pole Top Capacitor Banks
  - Provide VARs and influence voltage

We'll explore some advanced applications

Advanced Volt/VAR Optimization Controllers = ADVVOC


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



Voltage Profile

Capacitors decrease losses proving flatter voltage profile

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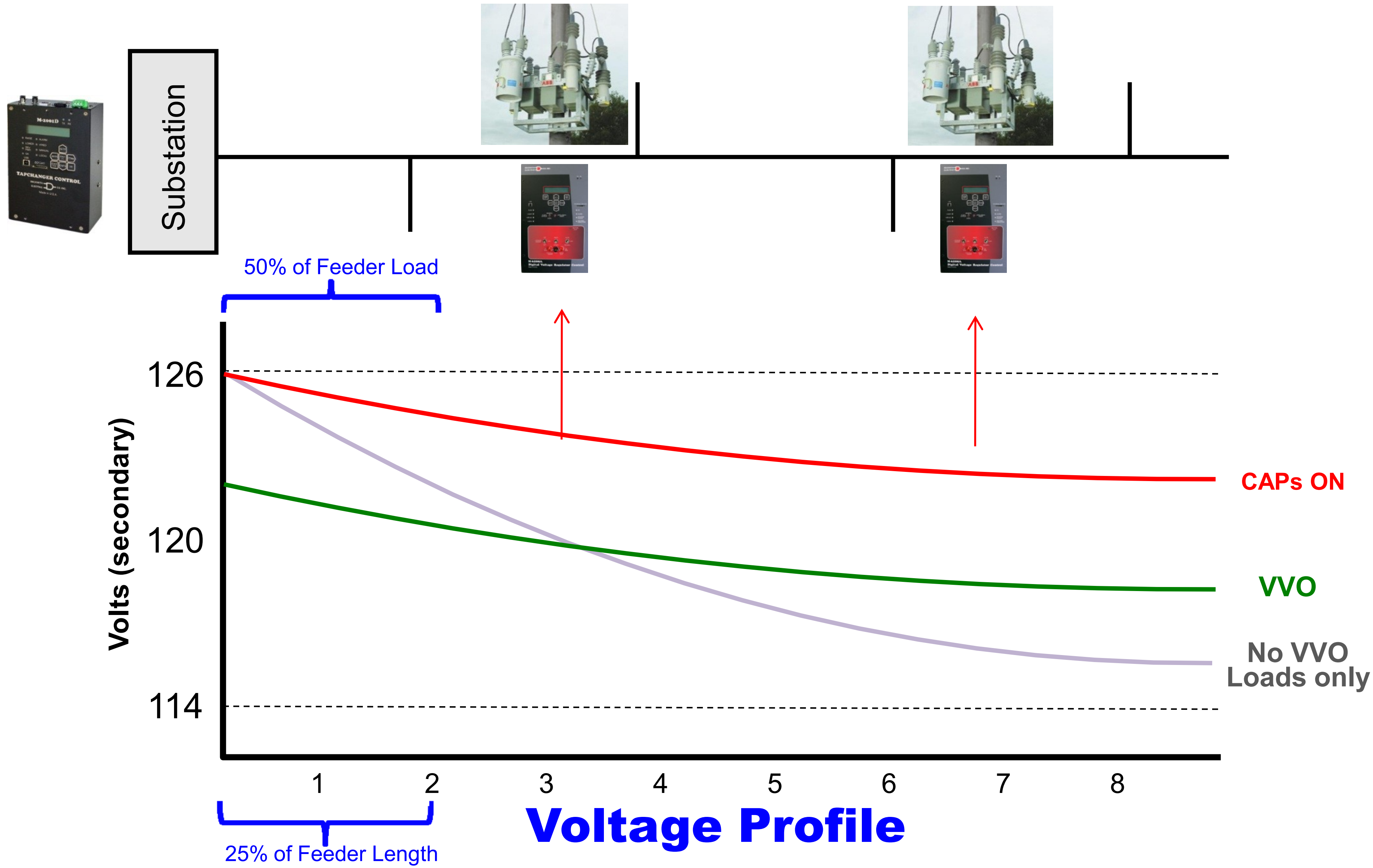

Capacitors decrease losses proving flatter voltage profile

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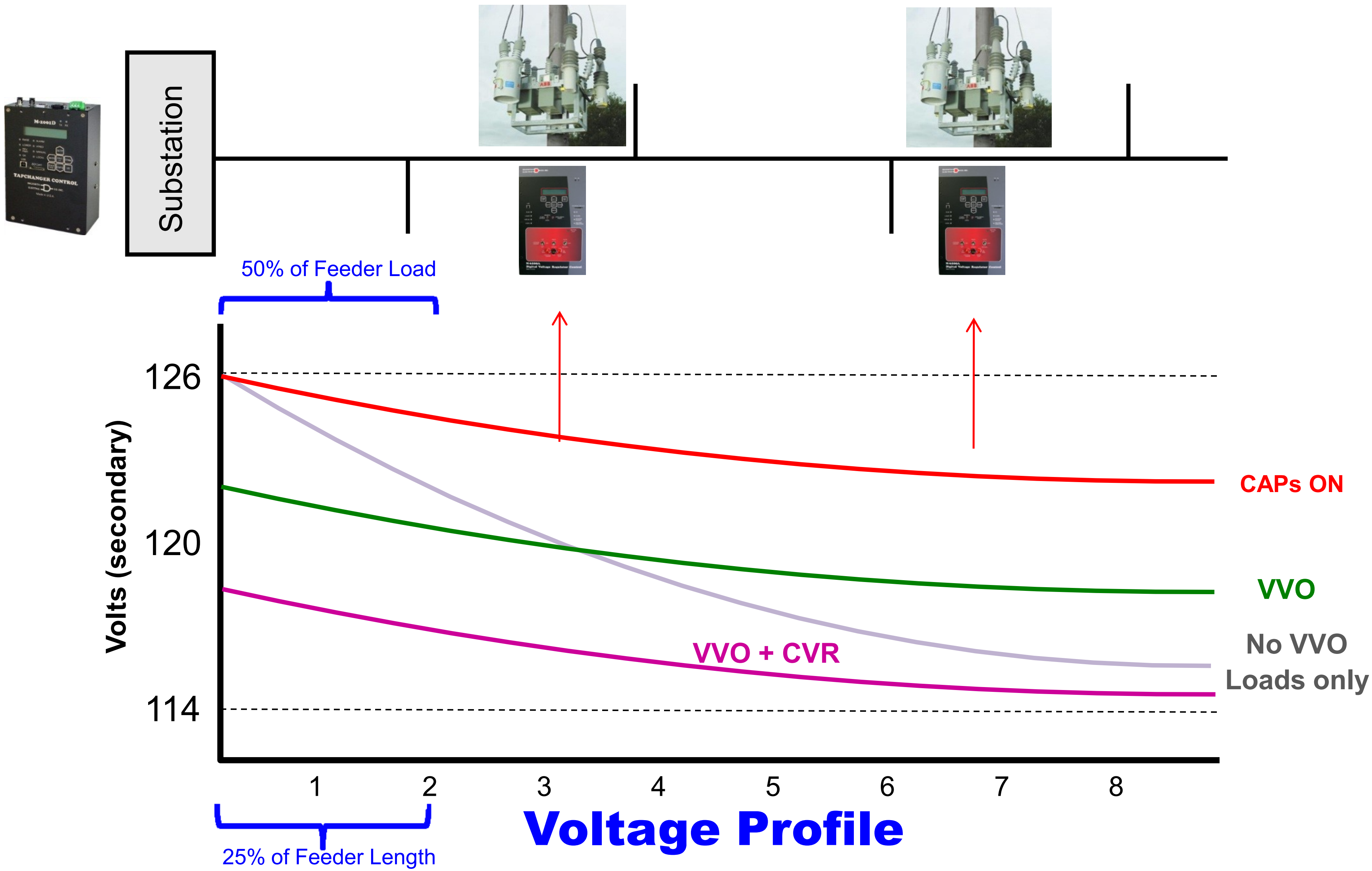
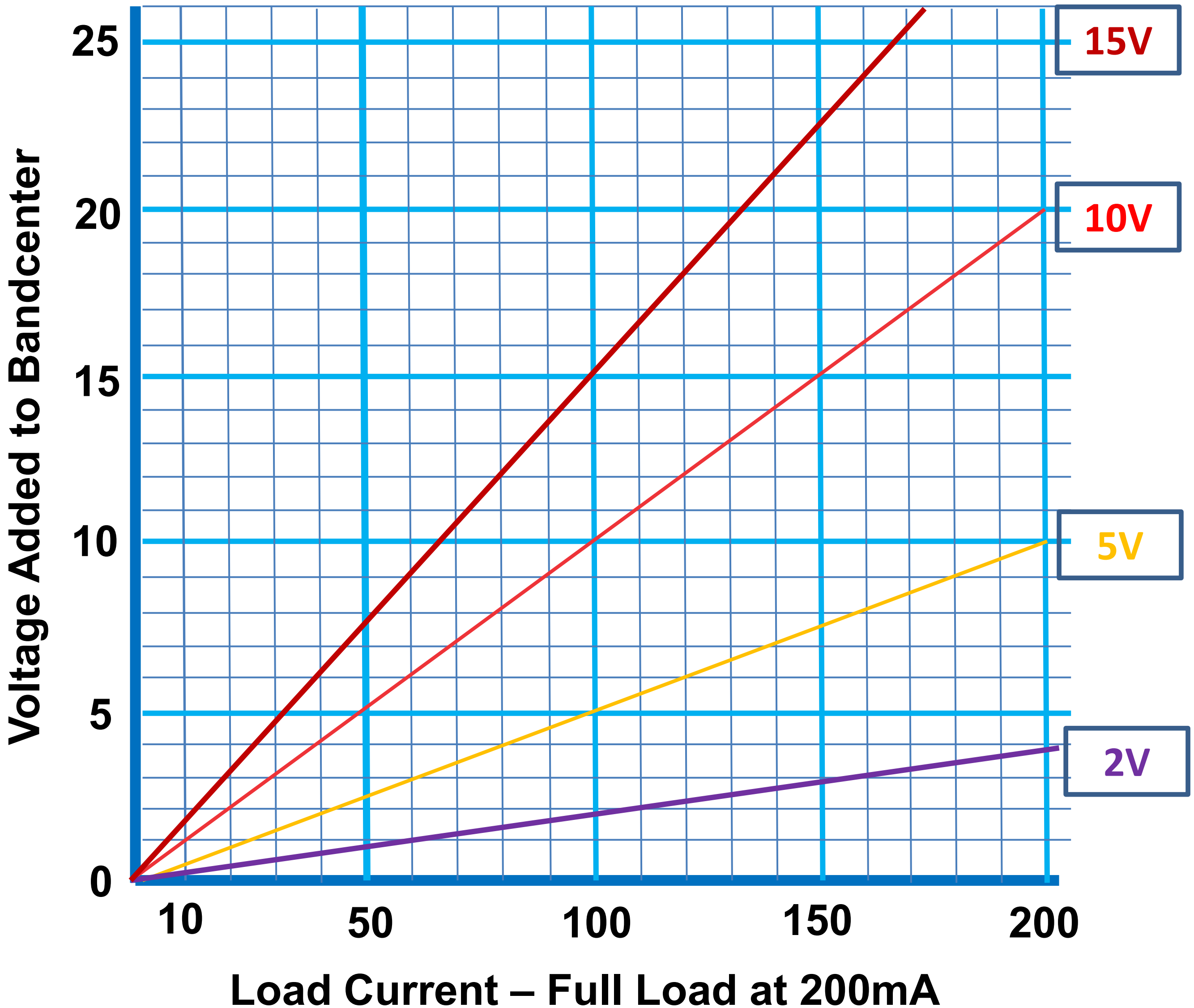


Capacitors decrease losses proving flatter voltage profile

VVO Results

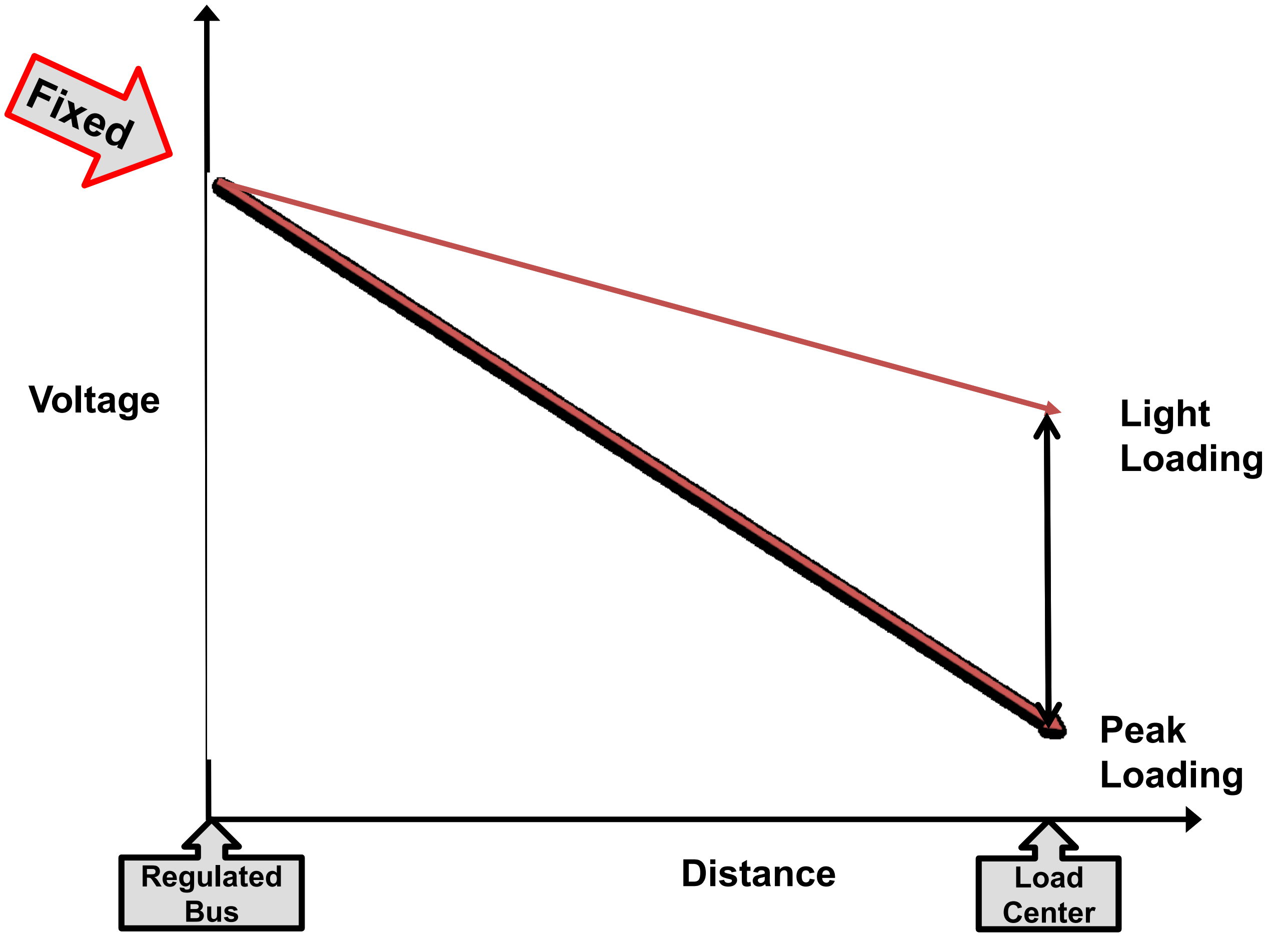
- Reduce losses
  - X_C counters X_L of lines
- Decreased operation of OLTC elements
- Deferred capital expenditures and improved capital asset utilization
- Reduced electricity generation and environmental impacts
- Flatter voltage profile
  - Allows better CVR without low voltage violation at the end-of-line

Forward Power and LDC

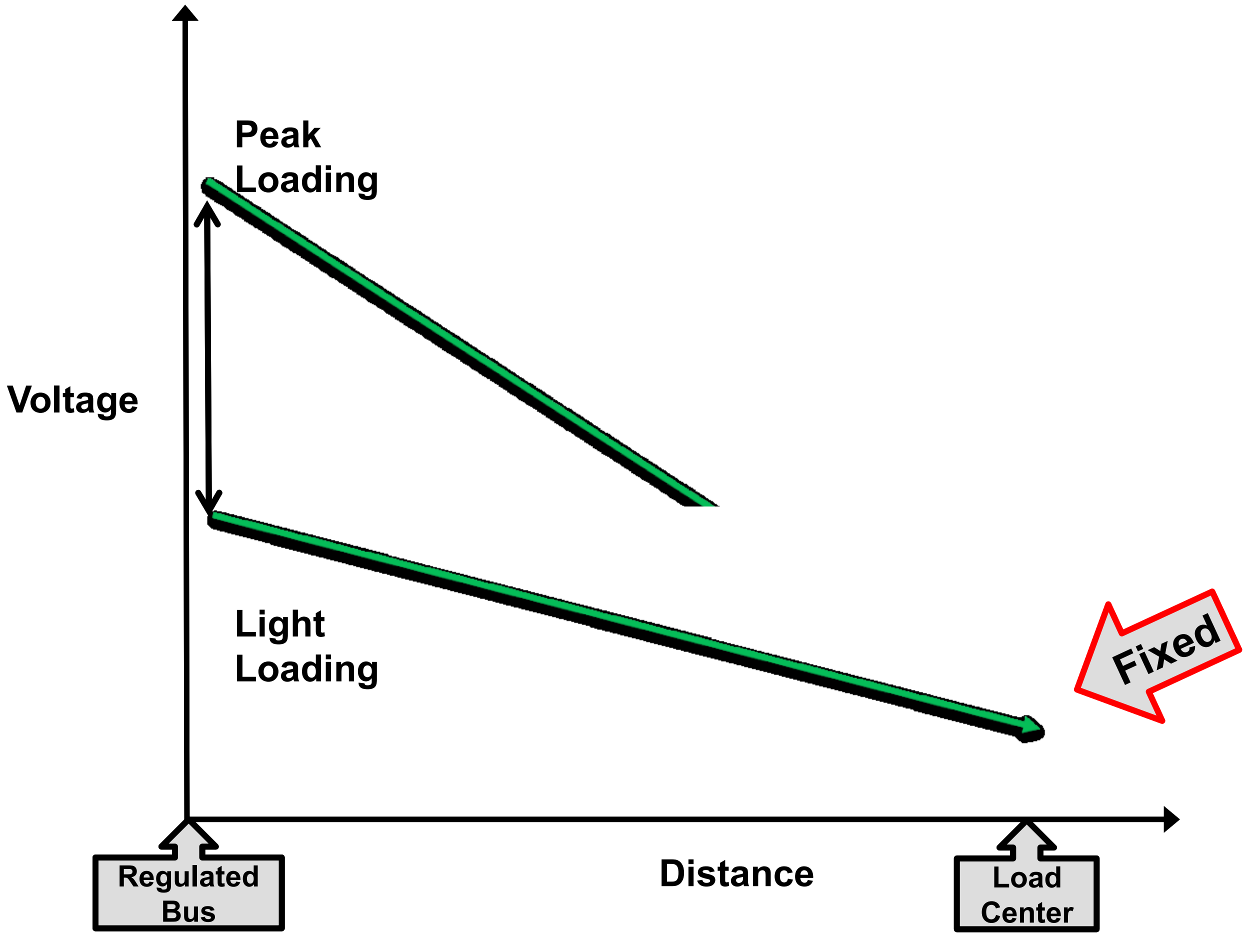


Should use high voltage block for 1st house protection!!!

Line Drop Compensation Principle
Without LDC

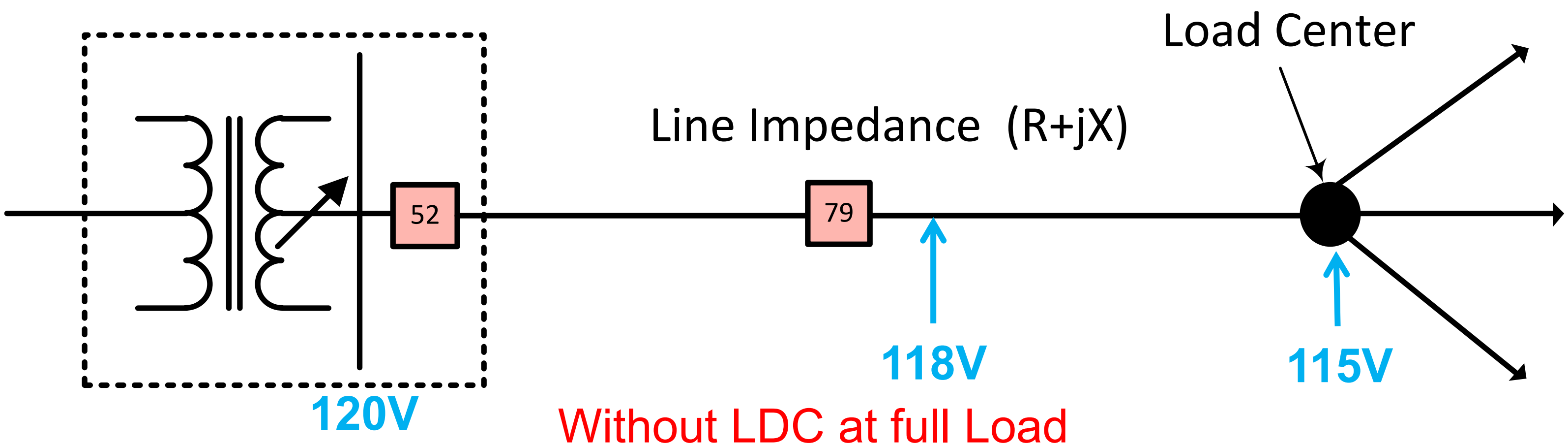


Line Drop Compensation Principle
With LDC

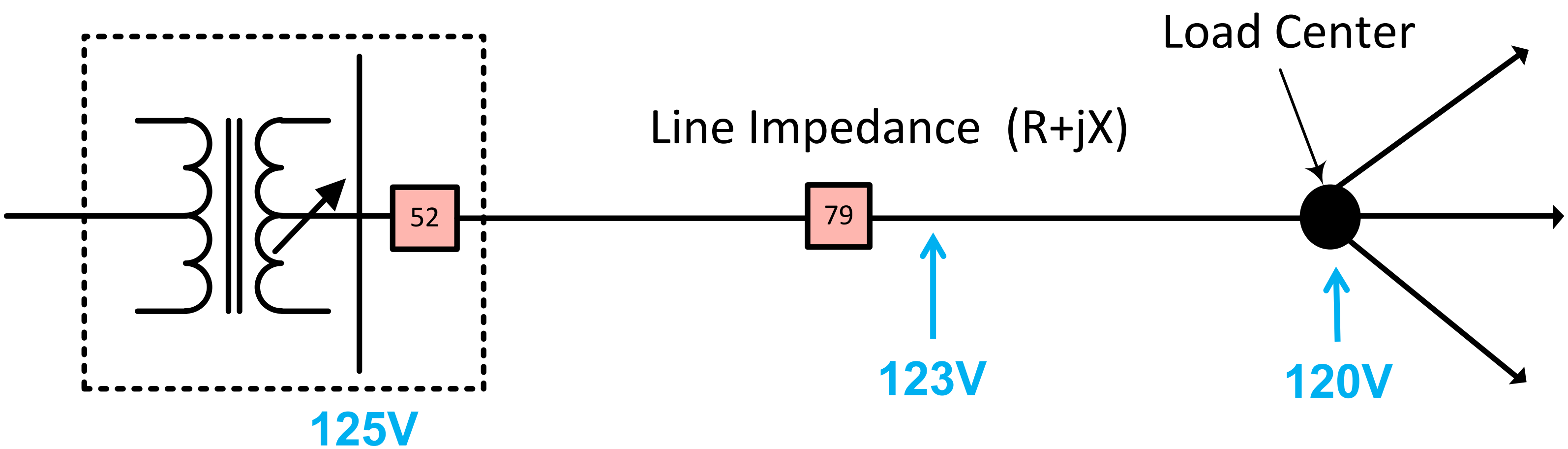


LDC – R,X

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



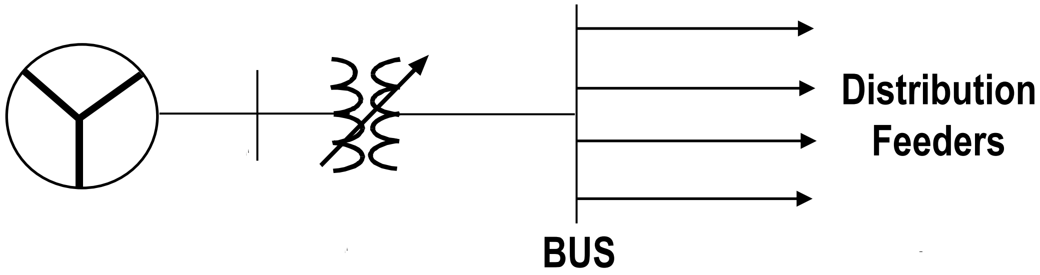
Without LDC at full Load



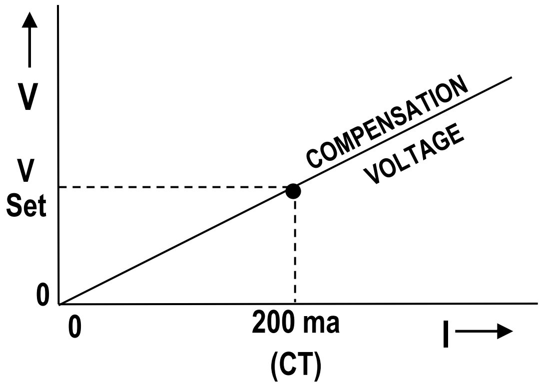
With LDC at full Load and unity power factor(X=5)

LDC - Z

- Application: Distribution bus regulation



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

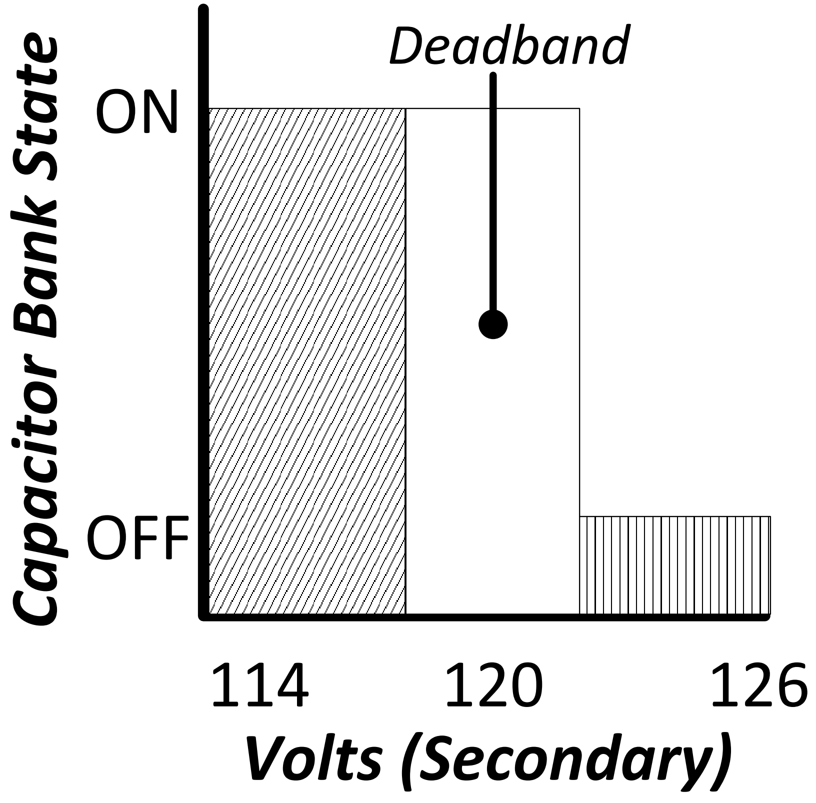


Traditional Methods: Control Based Reactive Support Elements

- 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

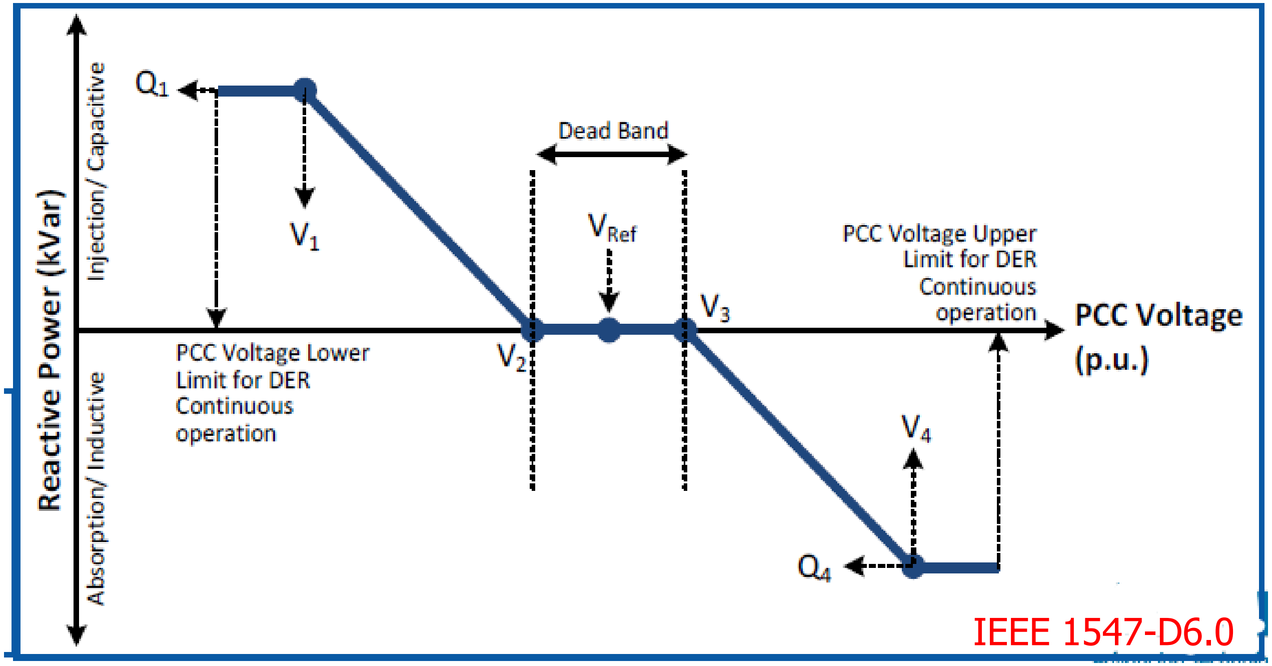
CAP Voltage Control

- Setting with Deadband
- Deadband avoids hunting



DER Actively Controlling VAR

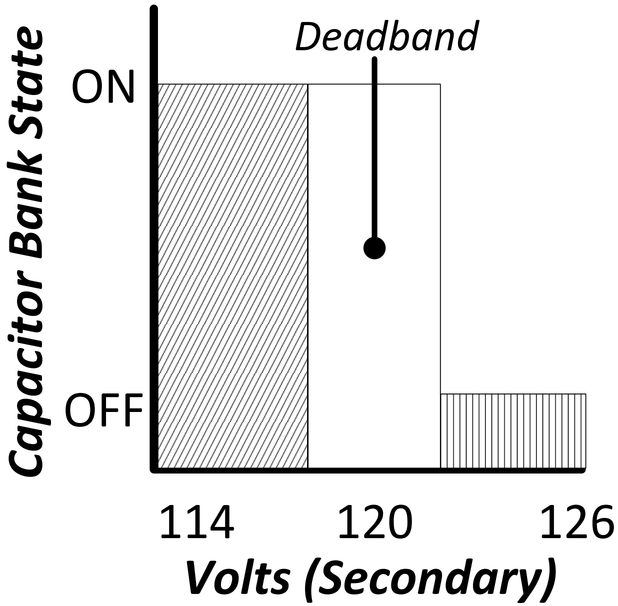
Volt-VAr

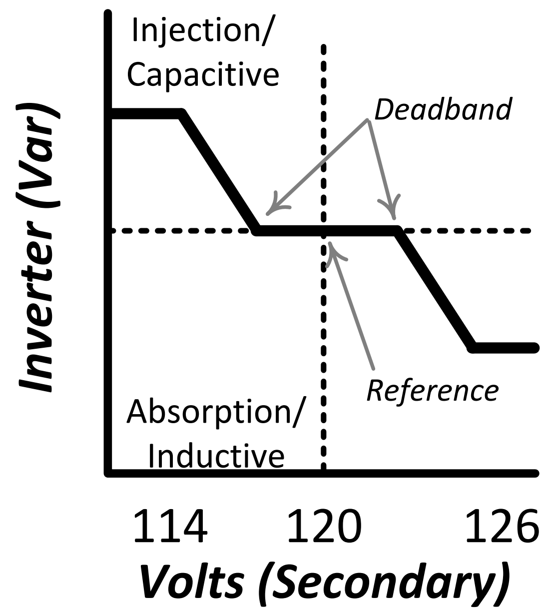


- ***Why?*** As voltage rises, counter with absorbing VAr
- Uses droop characteristic
- Based on **power and voltage sensing** at PCC
- If inverter based, a “Smart” Inverter

CAPs and DER

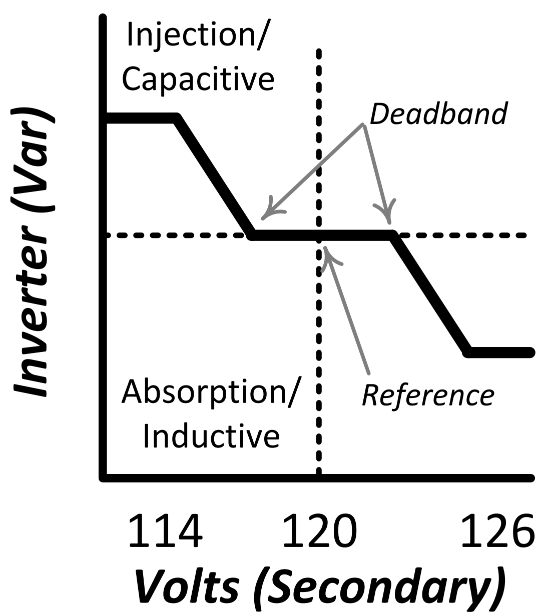
- As power flows and assumed reactive voltage drops can change as DER proliferates, consider changing fixed CAPs to switched to avoid overvoltage (from excessive VAR support) under high DER output conditions
- Consider active voltage (VAR) control of DER as proliferation increases

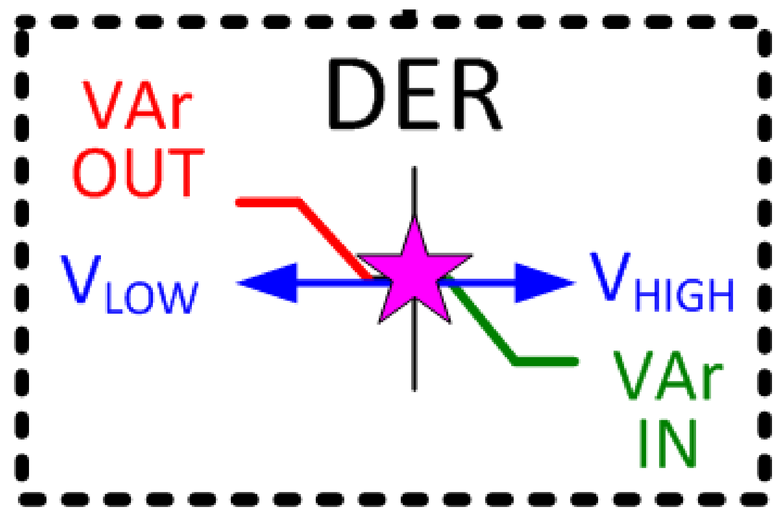




Representation in Application Sequences

- Voltage Low = Provide VARS
- Voltage High = Consume VARS





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 reactive elements for VAR/pf regulation
    - How can LDC control voltage sensing CAPs?
    - How can LDC control DER VAR output?

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

- VAR-Bias as a new concept to unify VVO with OLTCs and CAPs
- Use a "VAR-Bias" characteristic to change the response of the OLTC (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 to Coordinate DERs/CAPs with REGs and LTCs

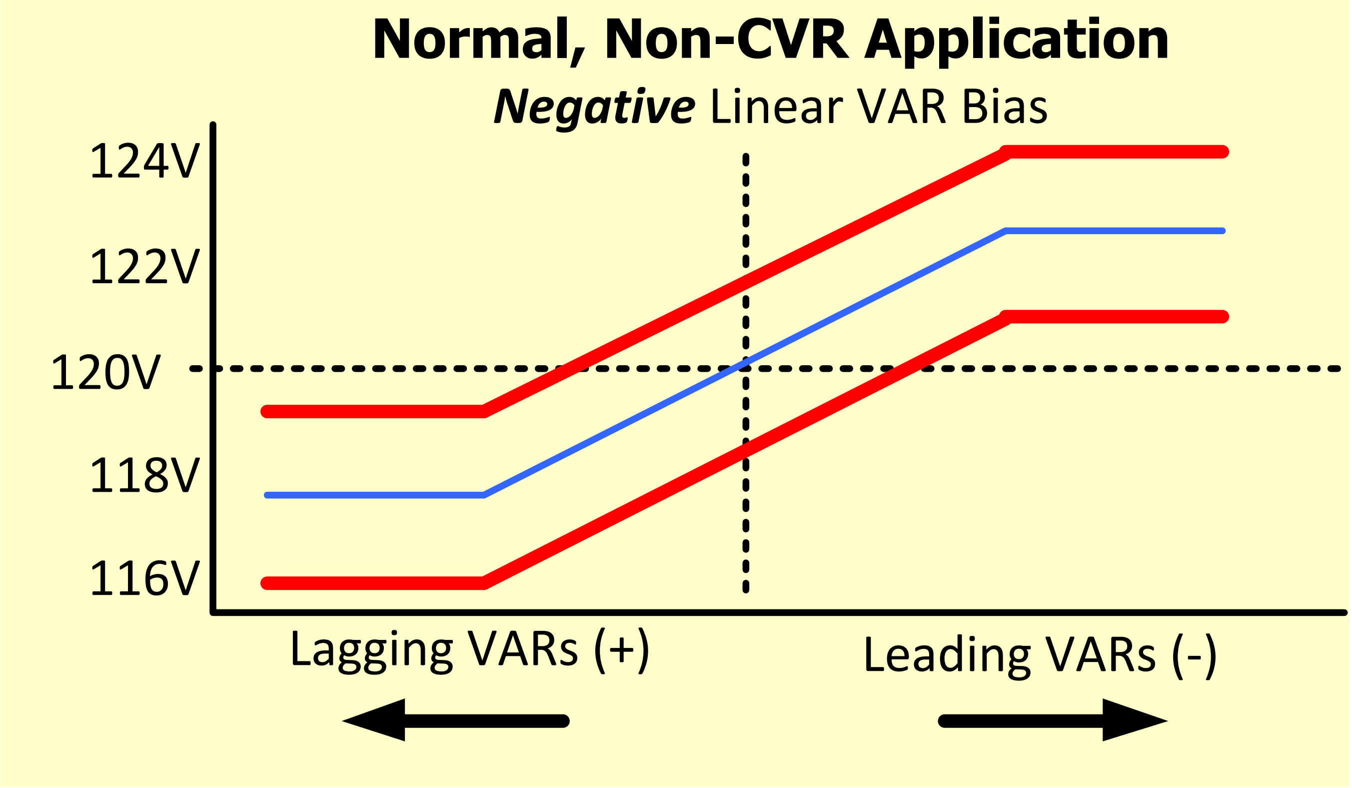
- REGC and LTCC use information on VAR flow
  - Is the VAR flow out to the line (load)?
  - Is the VAR flow into the source?

- 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

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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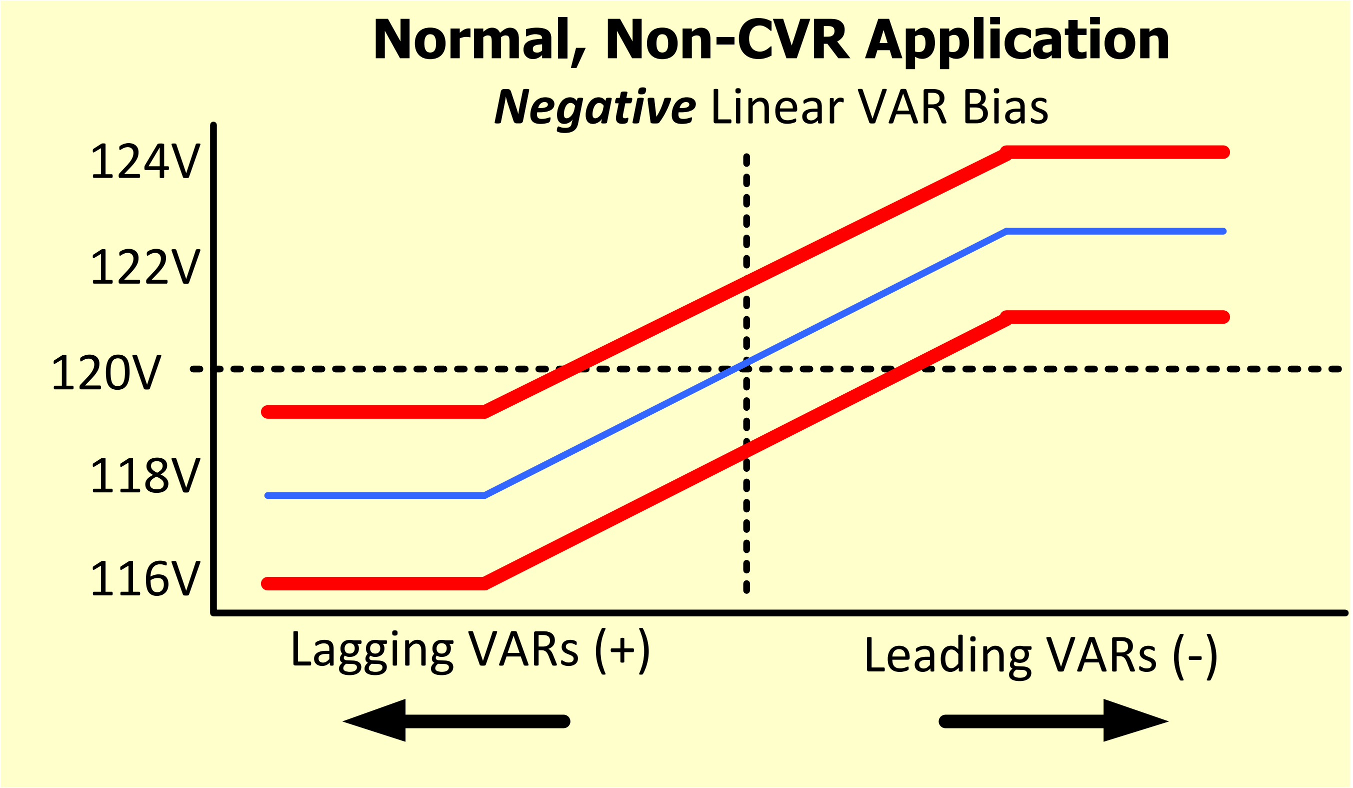
Negative VAR-Bias

- Called "negative" as lagging VAR causes voltage band to be lowered
- Designed to maintain unity pf and coax proper voltage asset, OLTC or reactive asset, to act depending on the cause of the voltage change
  - ✓ Voltage change from real power change, use OLTC asset
  - ✓ Voltage change by reactive power change, use VAR asset



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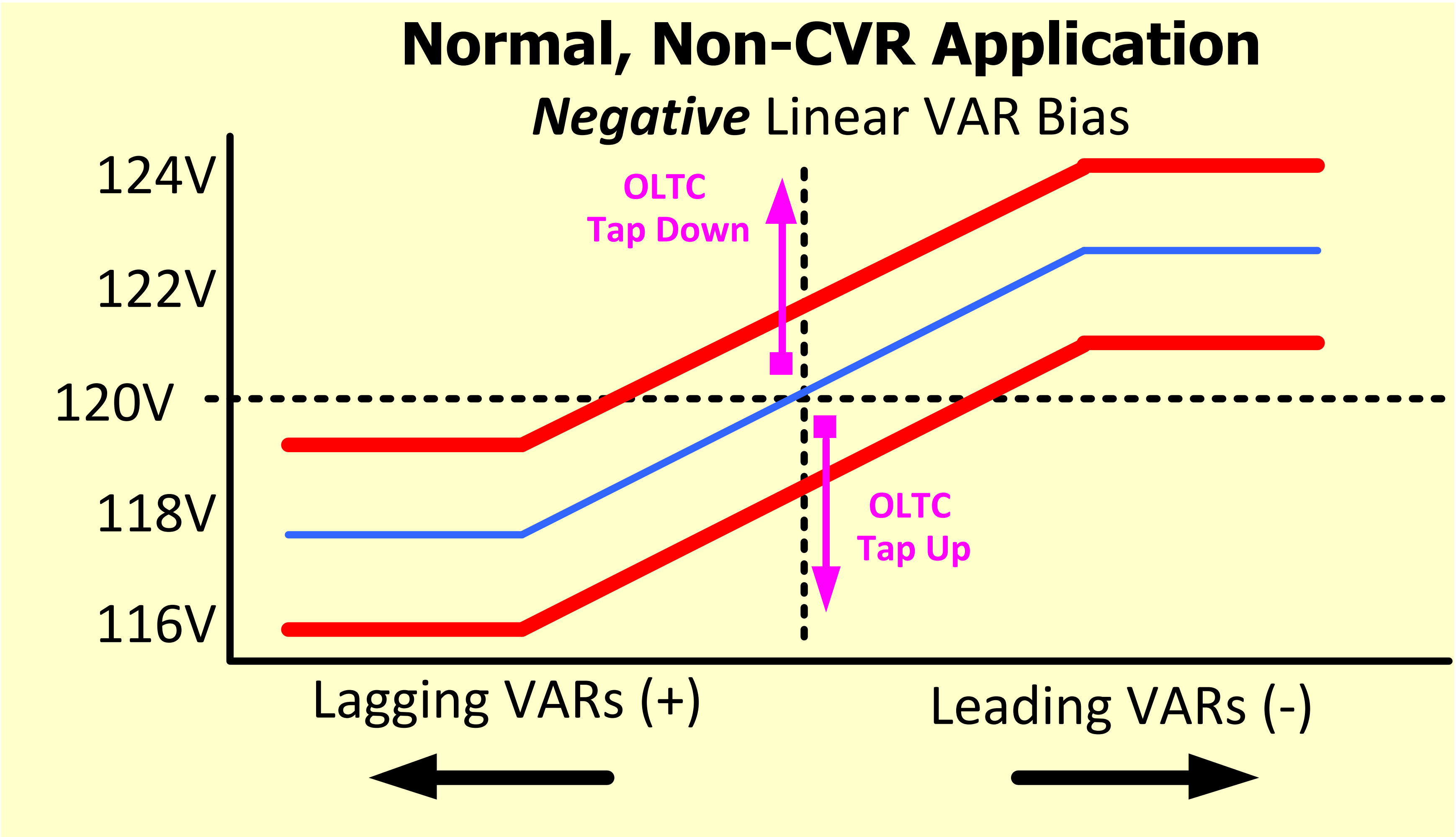
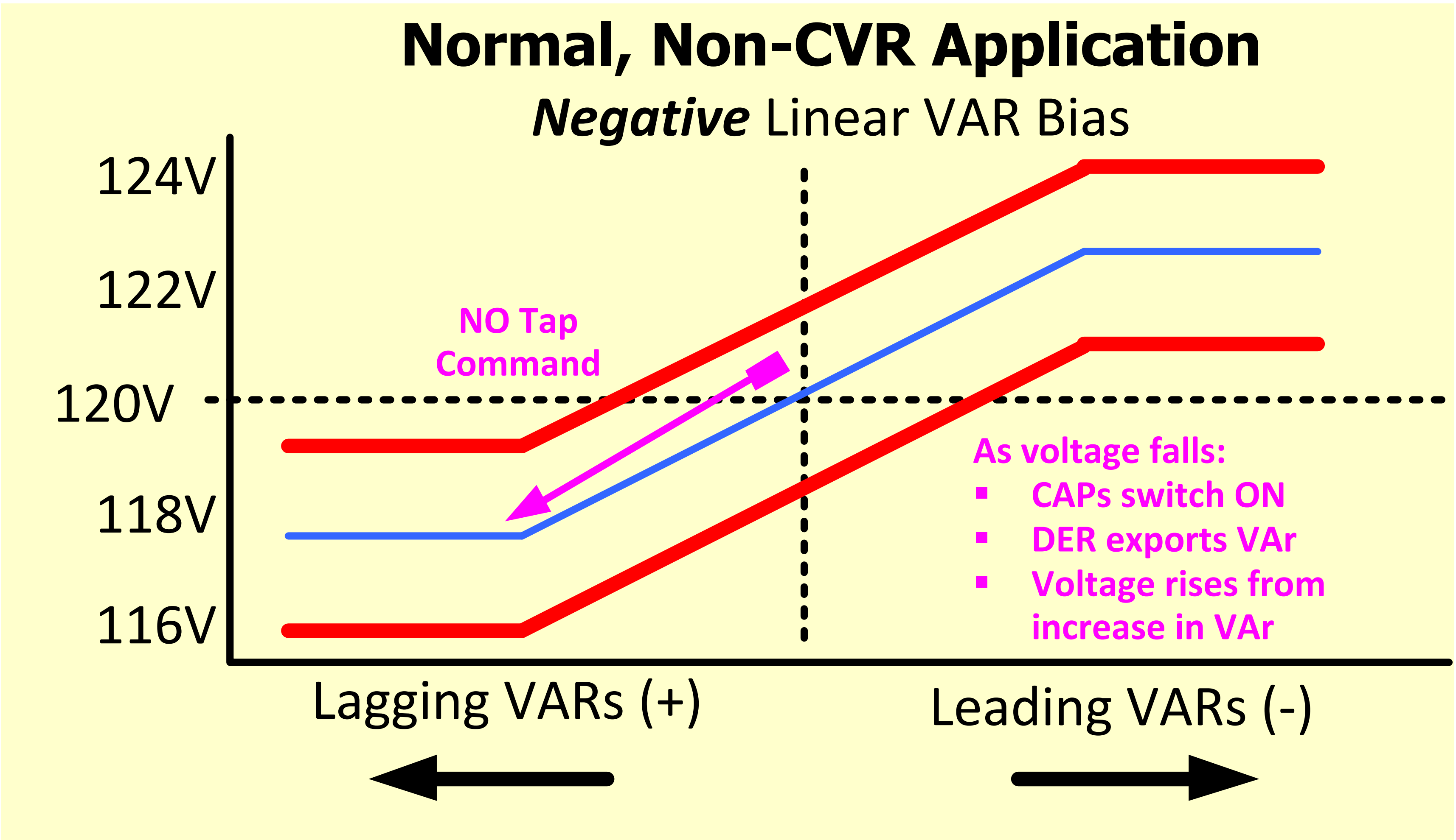
VAR-Bias: Near or at Unity PF



VAR-Bias:

Bandcenter Decreases with Lagging VAR



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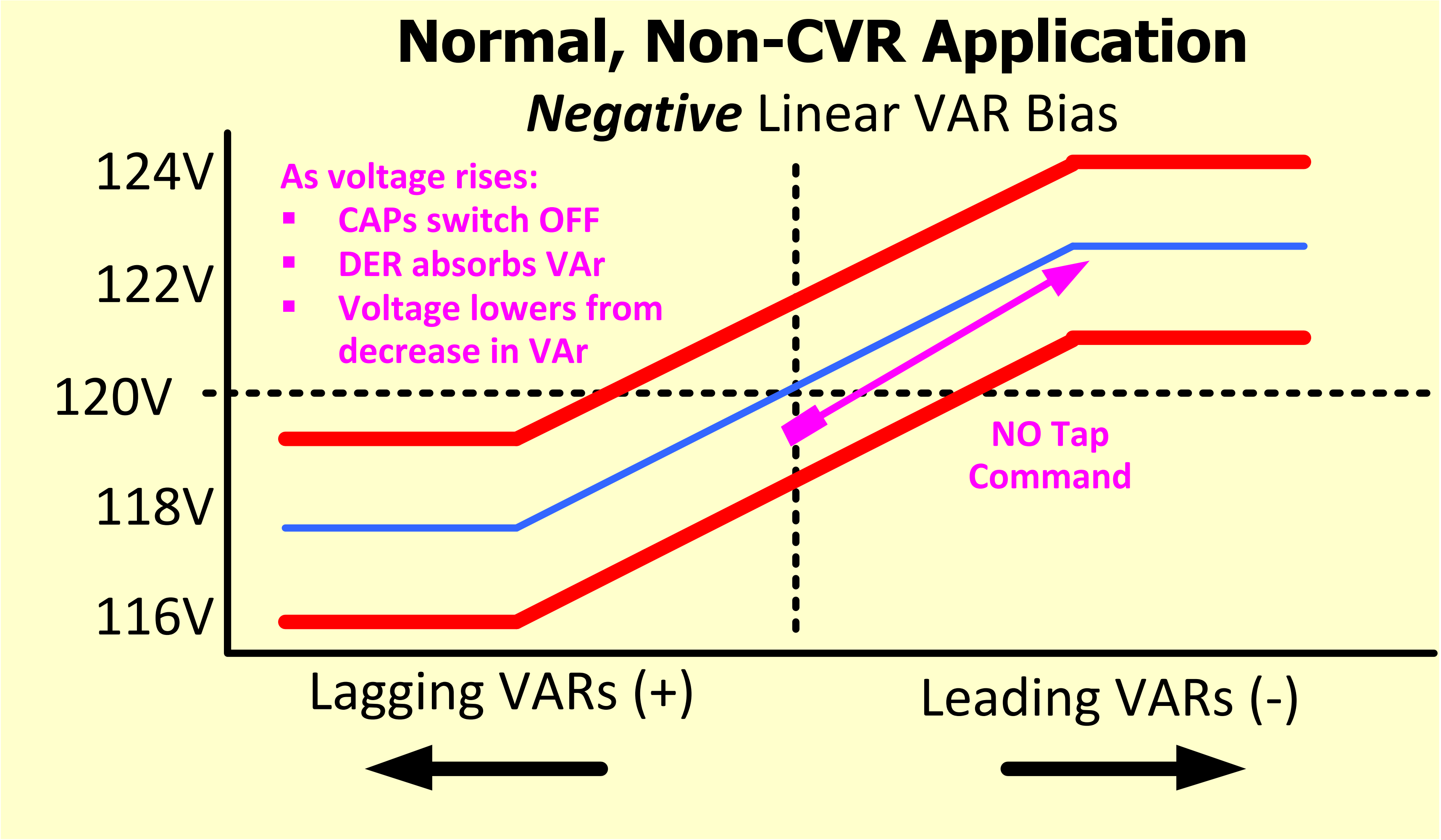
VAR-Bias:

Bandcenter Increases with Leading VAR



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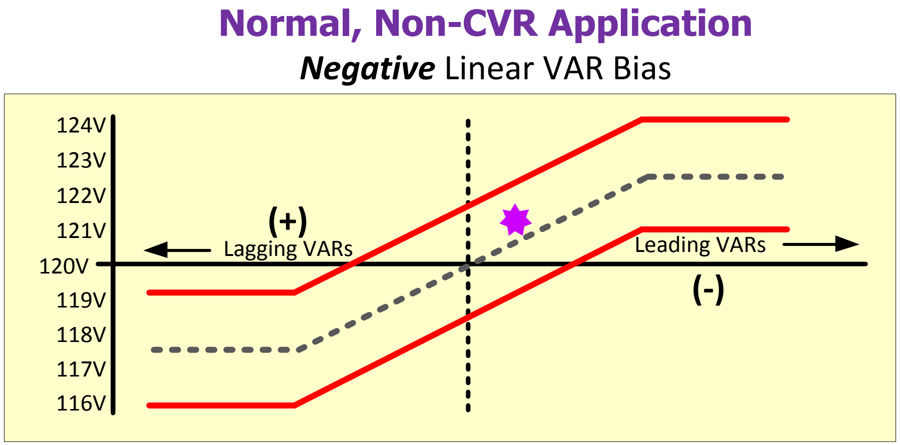
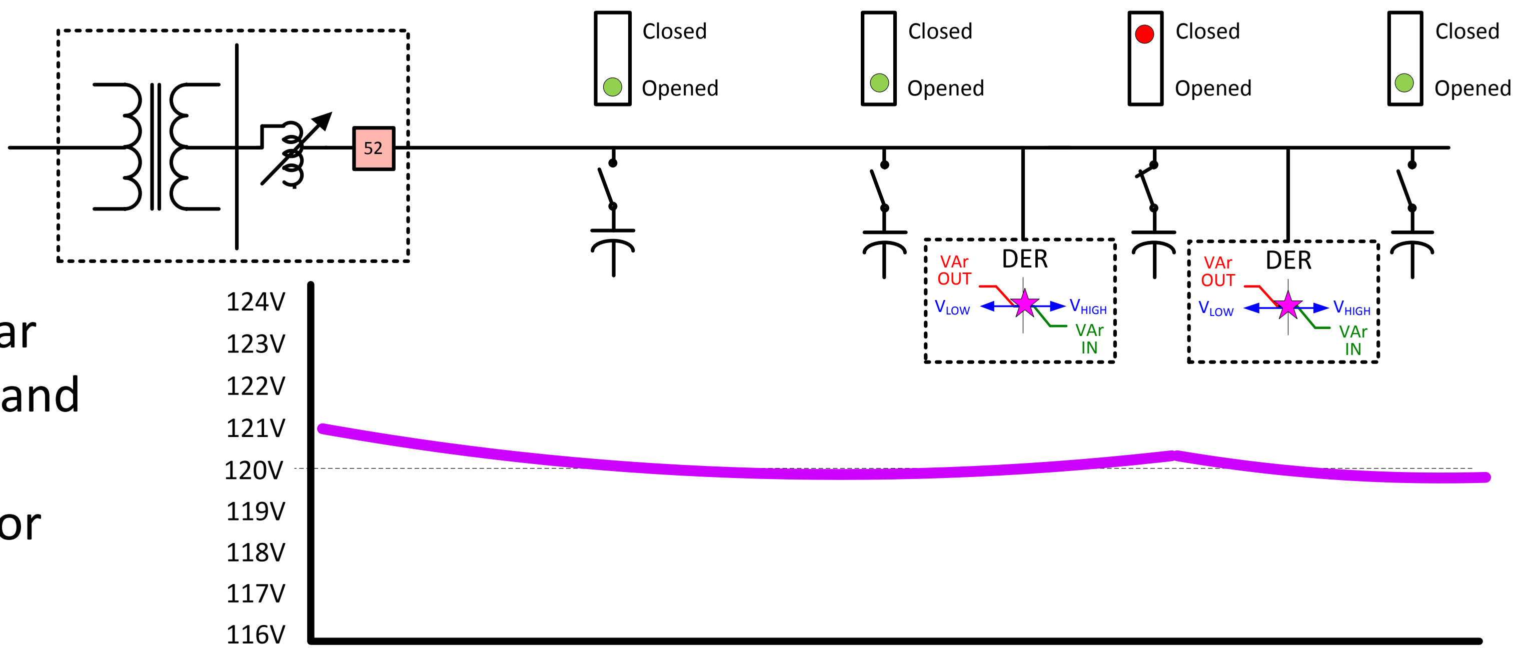
Normal Operation: Negative VAR-Bias



NORMAL OPERATION (non-CVR)



- Voltage near center of band
- Near unity power factor

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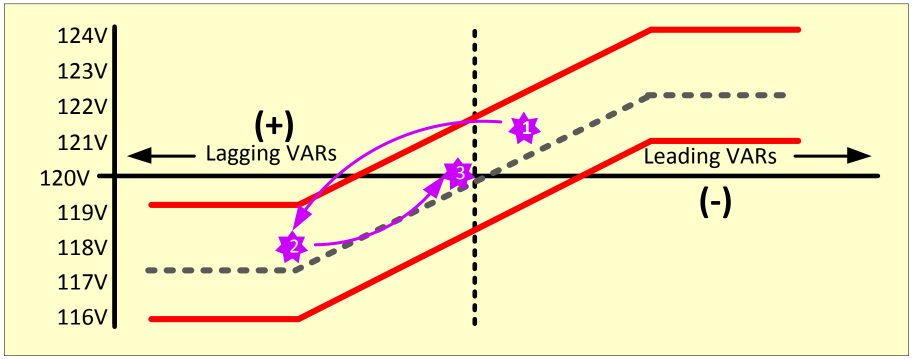
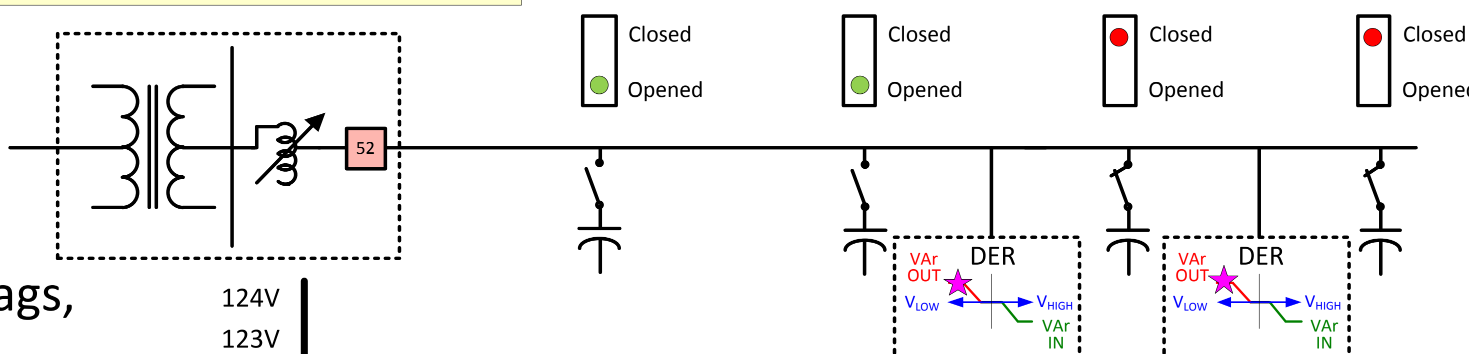
Normal Operation: Negative VAR-Bias

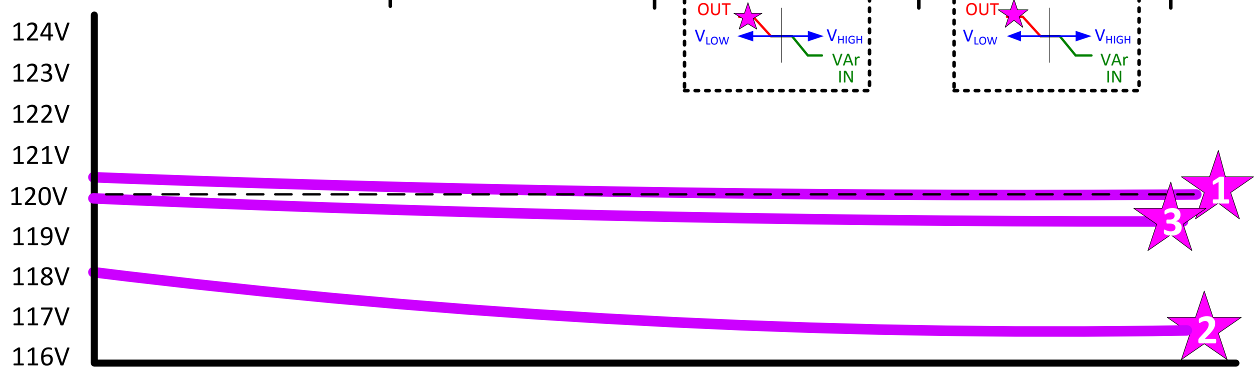
Normal, Non-CVR Application

Negative Linear VAR Bias



NORMAL OPERATION (non-CVR)



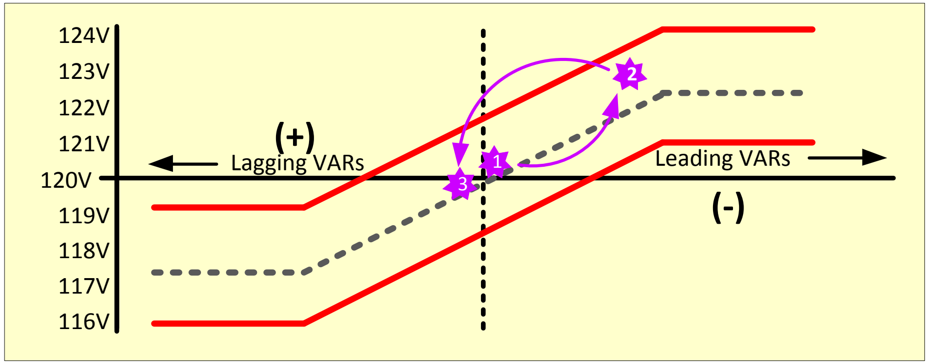


- Inductive load increases, pf lags, voltage decreases.
- REG bandcenter lowers.
- CAPs come on, DER outputs VAr
- Voltage and VAr normalize

Normal Operation: Negative VAR-Bias

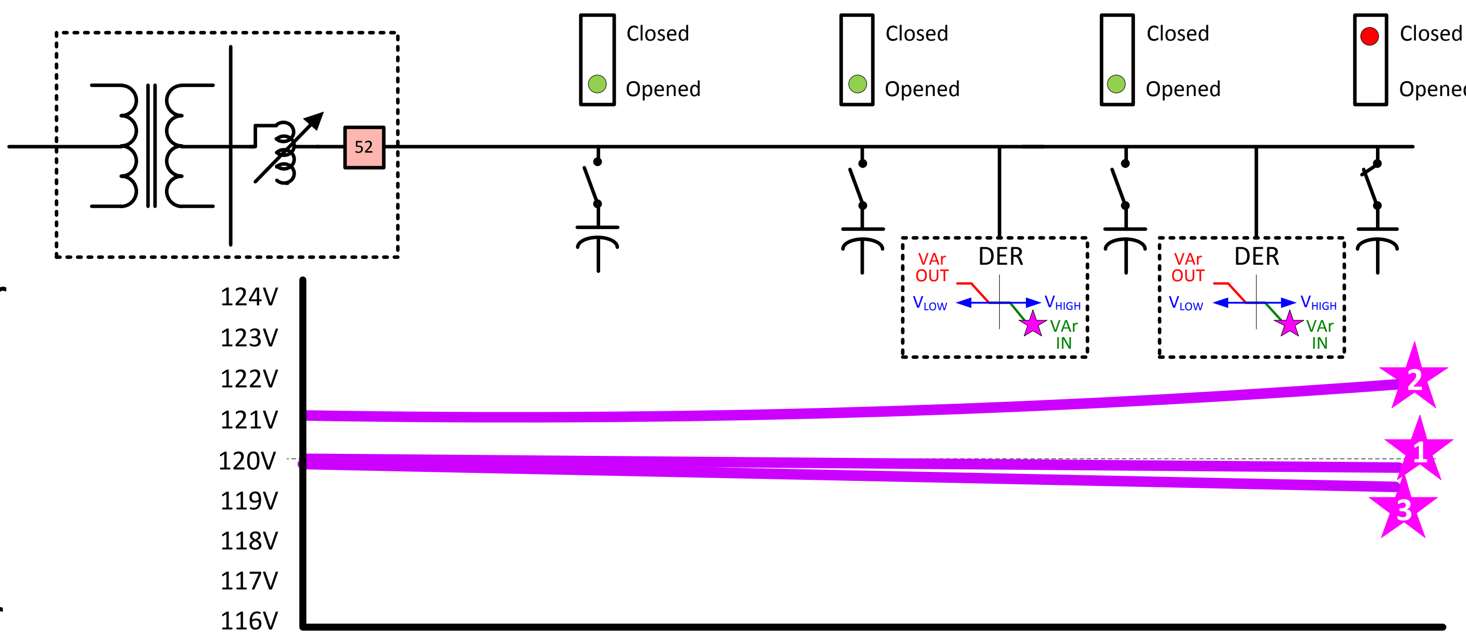
Normal, Non-CVR Application

Negative Linear VAR Bias

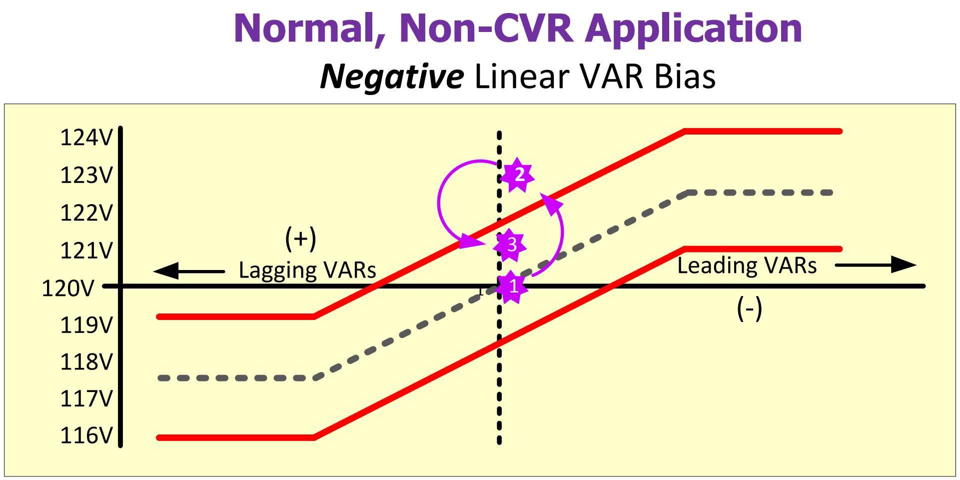


NORMAL OPERATION (non-CVR)

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

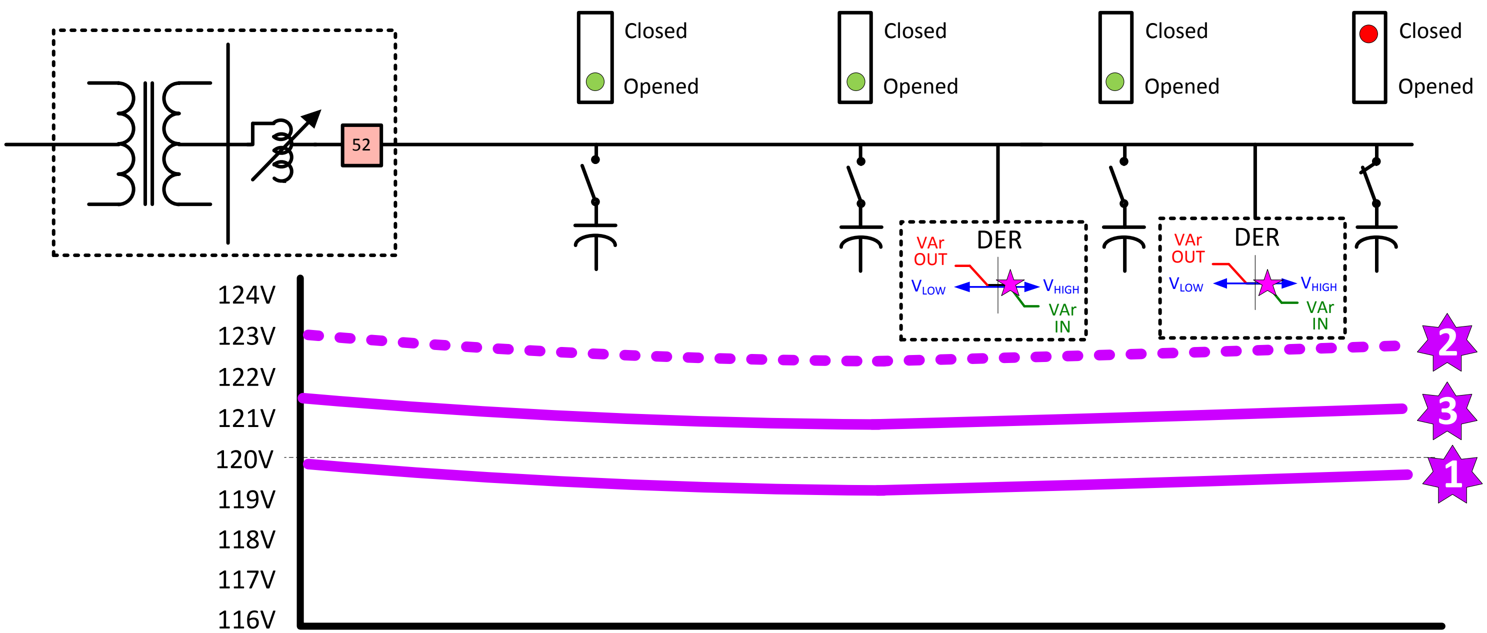


Normal Operation: Negative VAR-Bias



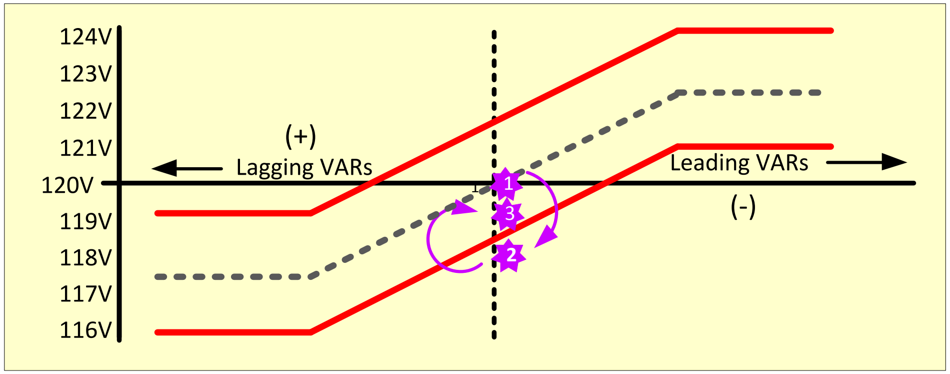
NORMAL OPERATION (non-CVR)

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



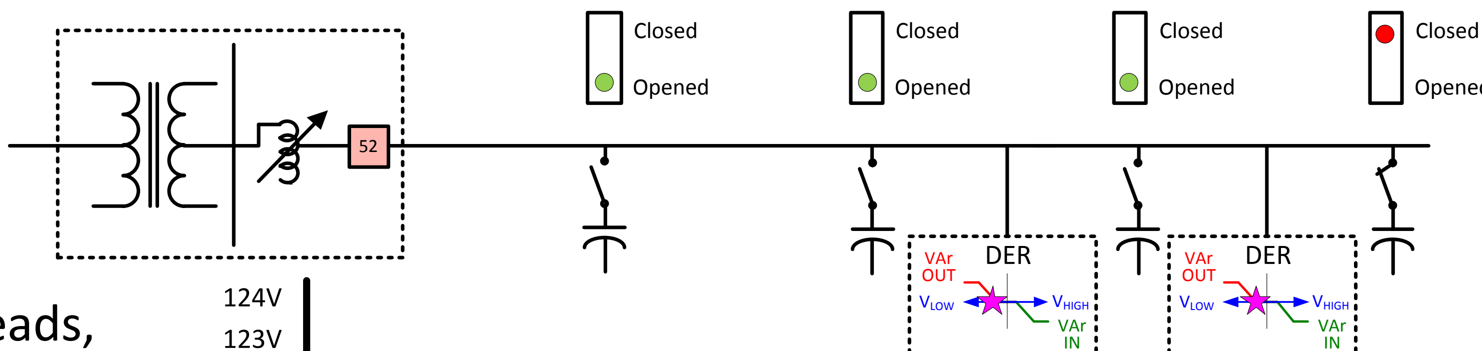
Normal, Non-CVR Application

Negative Linear VAR Bias

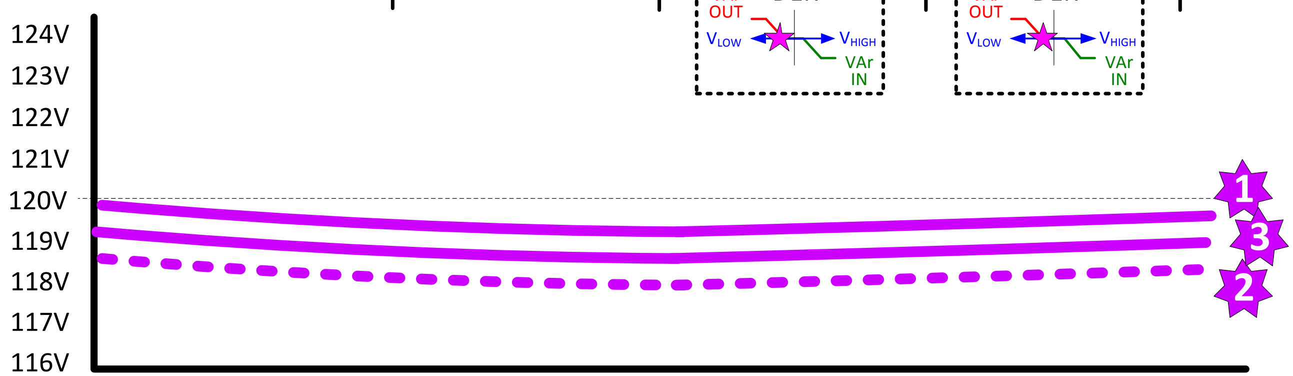


Normal Operation: Negative VAR-Bias

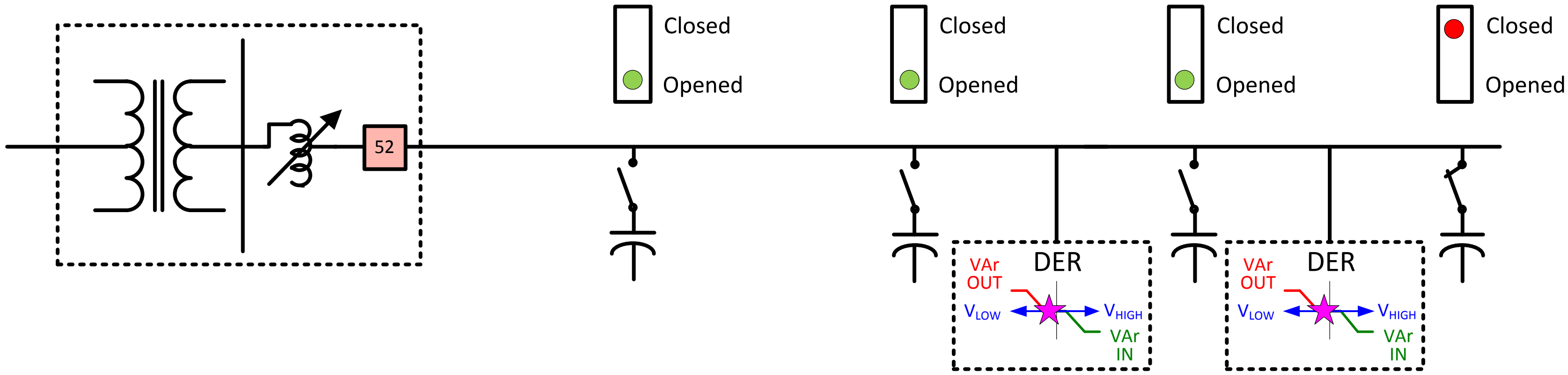
NORMAL OPERATION (non-CVR)



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

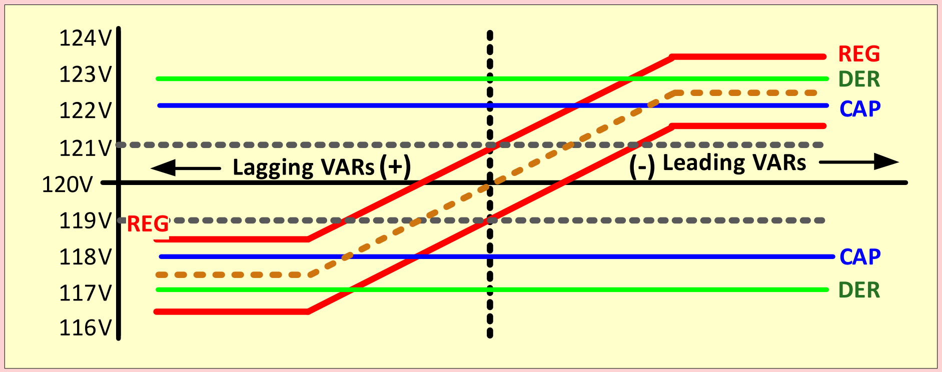


Voltage Bandcenter and Bandwidth: LTC/REG, CAP, DER



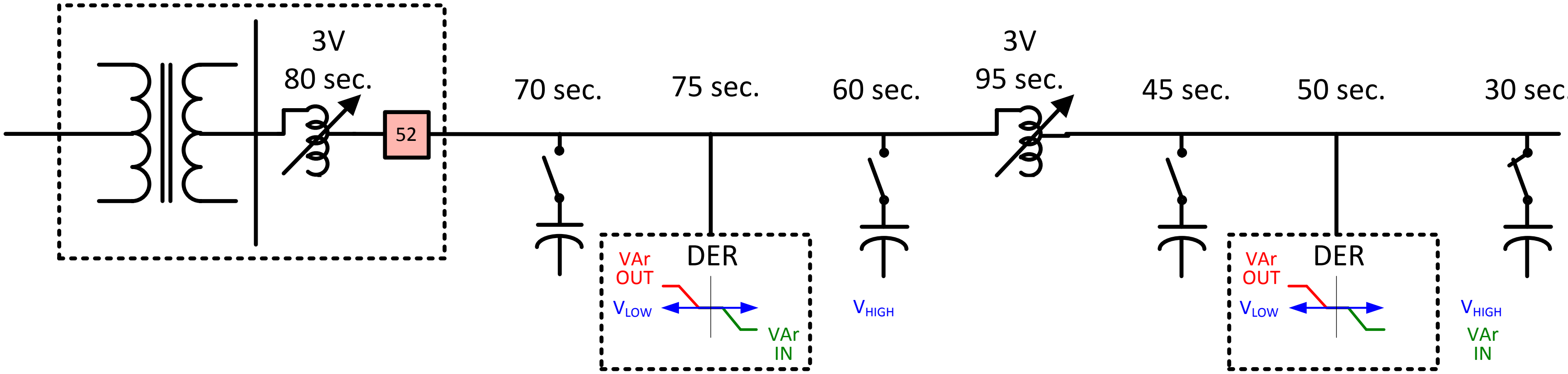
Normal, Non-CVR Application

Negative Linear VAR Bias

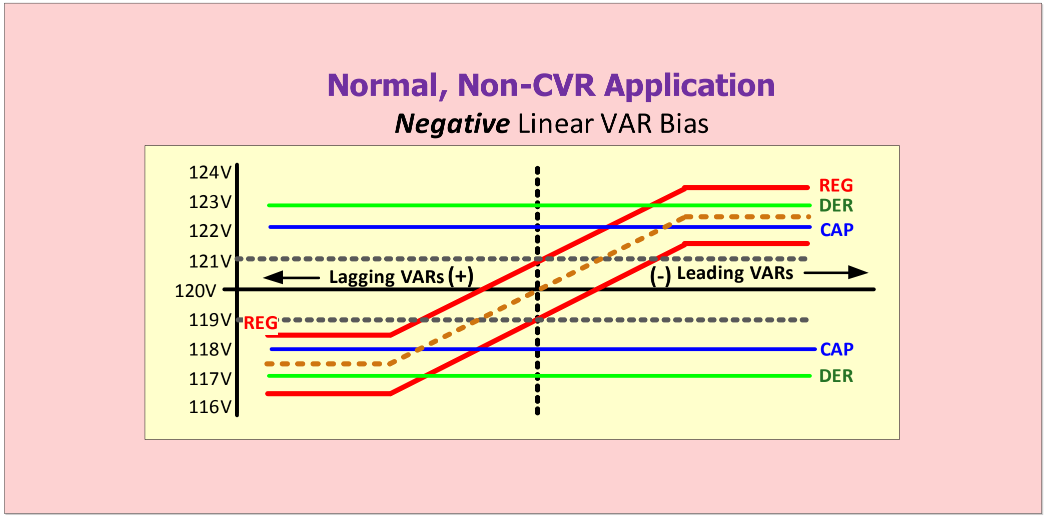


- CAPS and DER furthest away from source have shorter time delay than upline similar devices
- This examples uses CAPs before DER
  - Assuming DER charges for reactive support

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



VAR-Bias and Deep CVR

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

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

- Goal of voltage reduction is to reduce load
  - V= I * R for constant Z 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

Load Models and CVR Factor

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

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

$CVR_f = \Delta P / \Delta V$

- 0.5 to 0.7 is typical
- Greater than 1 is really good

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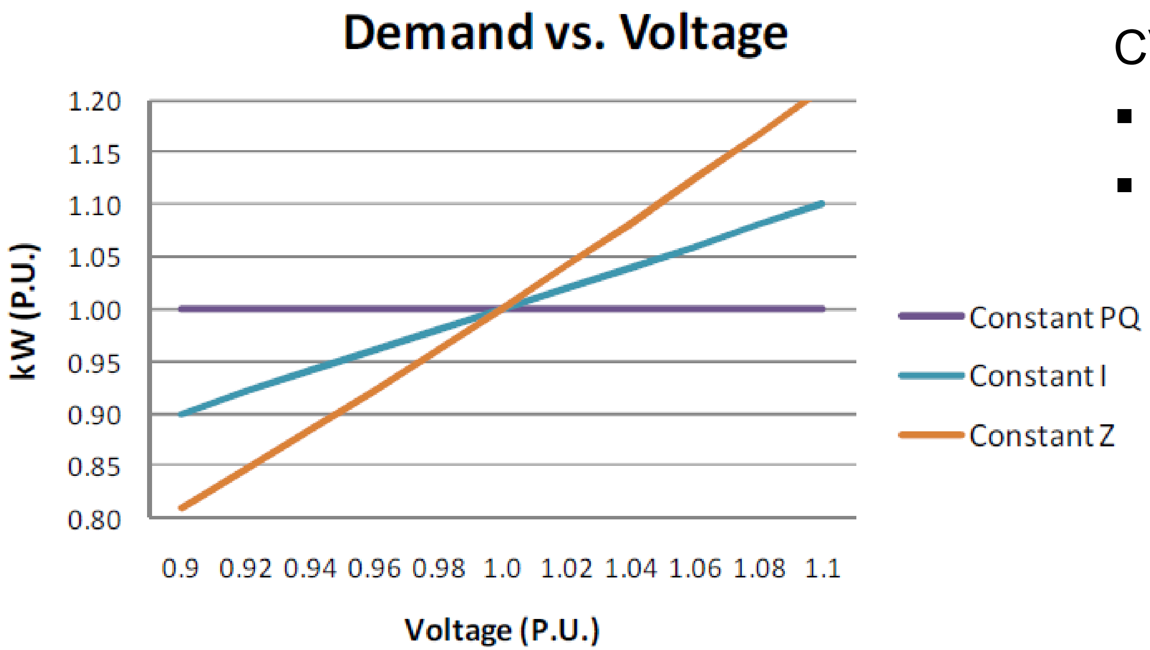
Load Models and CVR Factor



$CVR_f = \Delta P / \Delta V$

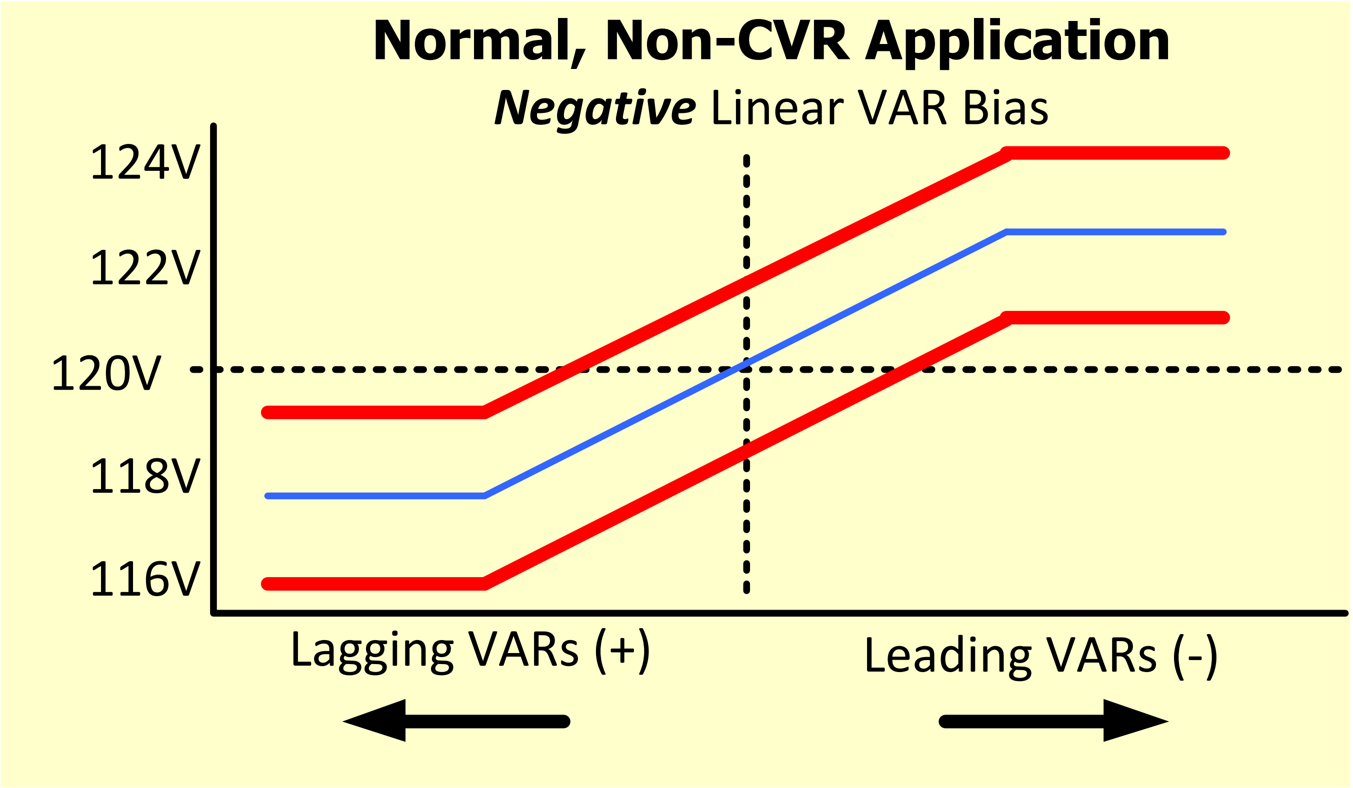
- 0.5 is typical
- Greater than 1 is really good

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

Evaluating Conservation Voltage Reduction with WindMil® - Milsoft

Negative VAR-Bias

- Called "negative" as lagging VAR causes voltage band to be lowered
- Designed to maintain unity pf and coax proper voltage asset, OLTC or reactive asset, to act depending on the cause of the voltage change
  - ✓ Voltage change from real power change, use OLTC asset
  - ✓ Voltage change by reactive power change, use VAR asset



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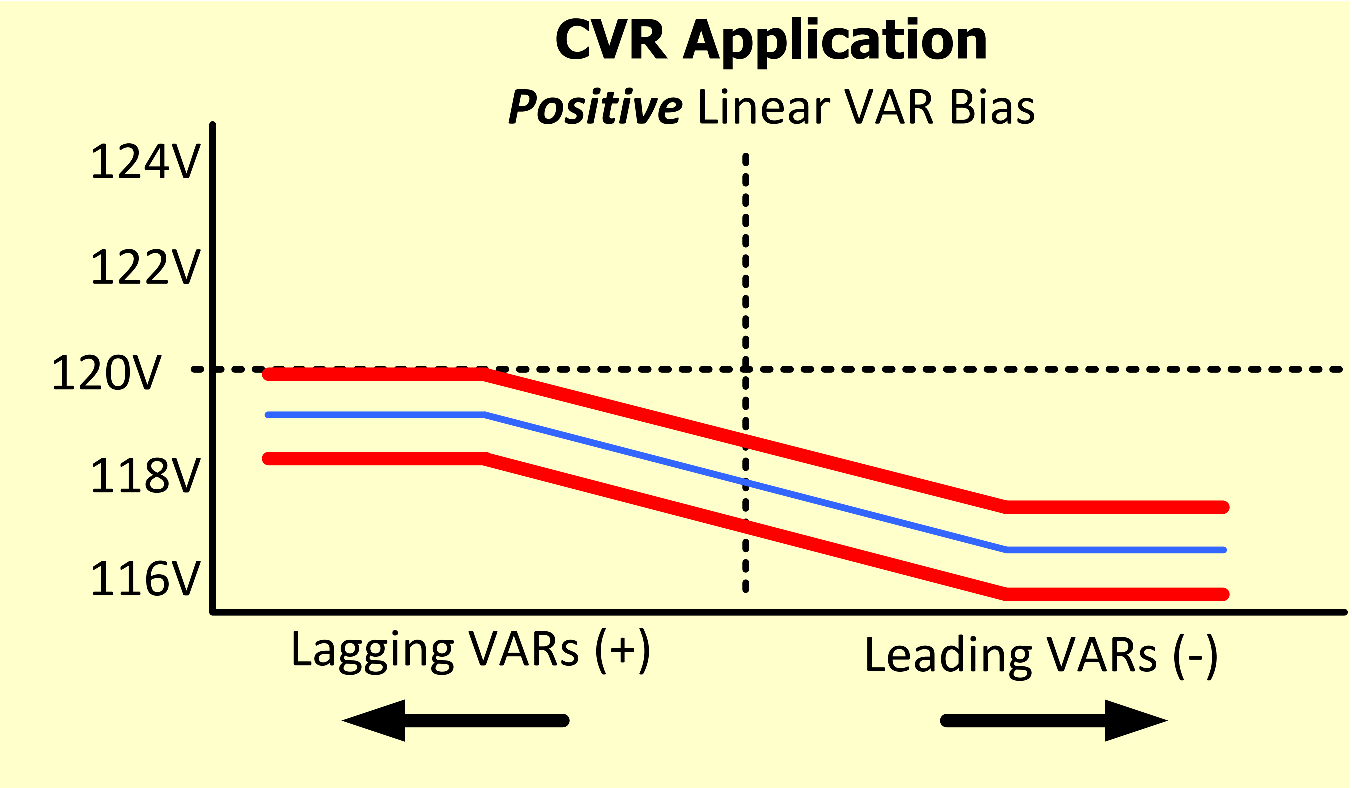
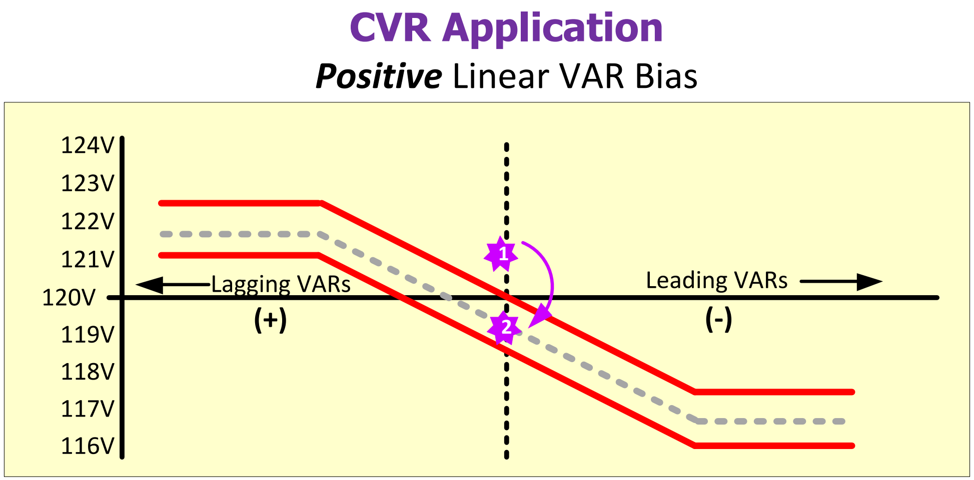
Positive VAR-Bias

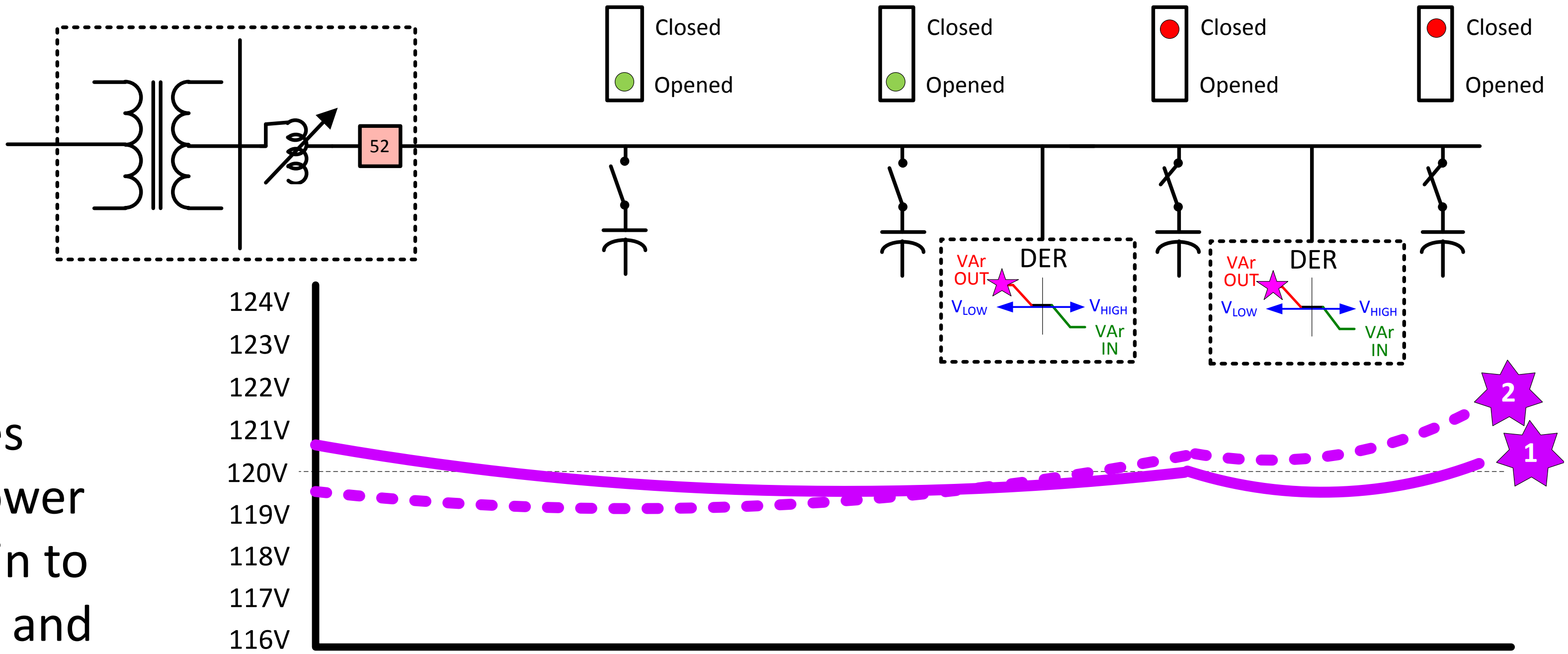
- Called "positive" as leading VAR causes voltage band to be lowered
- Designed to cause leading pf and raise voltage at end of the feeder
  - ✓ Allows head of feeder to lower voltage near ANSI C84.1 low limits
  - ✓ Fosters greater power reduction during CVR operation



CVR Operation: Positive VAR-Bias



CVR OPERATION

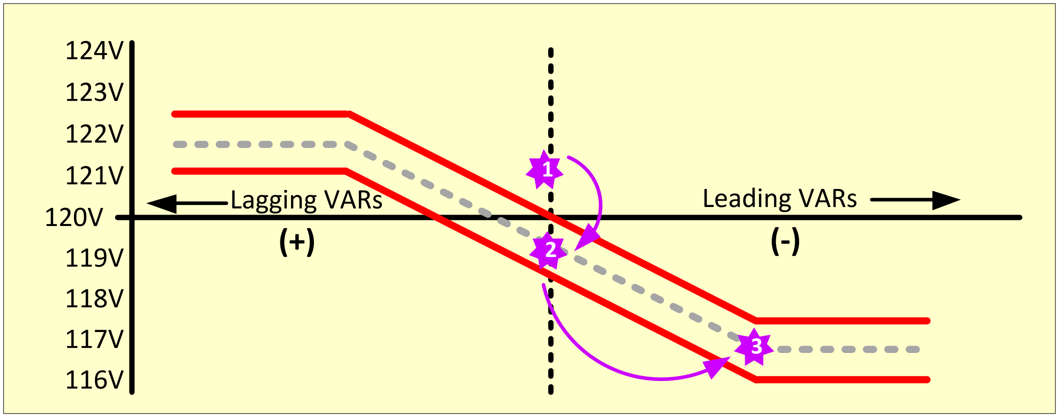


- REG forces voltage lower
- CAPs begin to switch on and DER outputs VAr

CVR Operation: Positive VAR-Bias

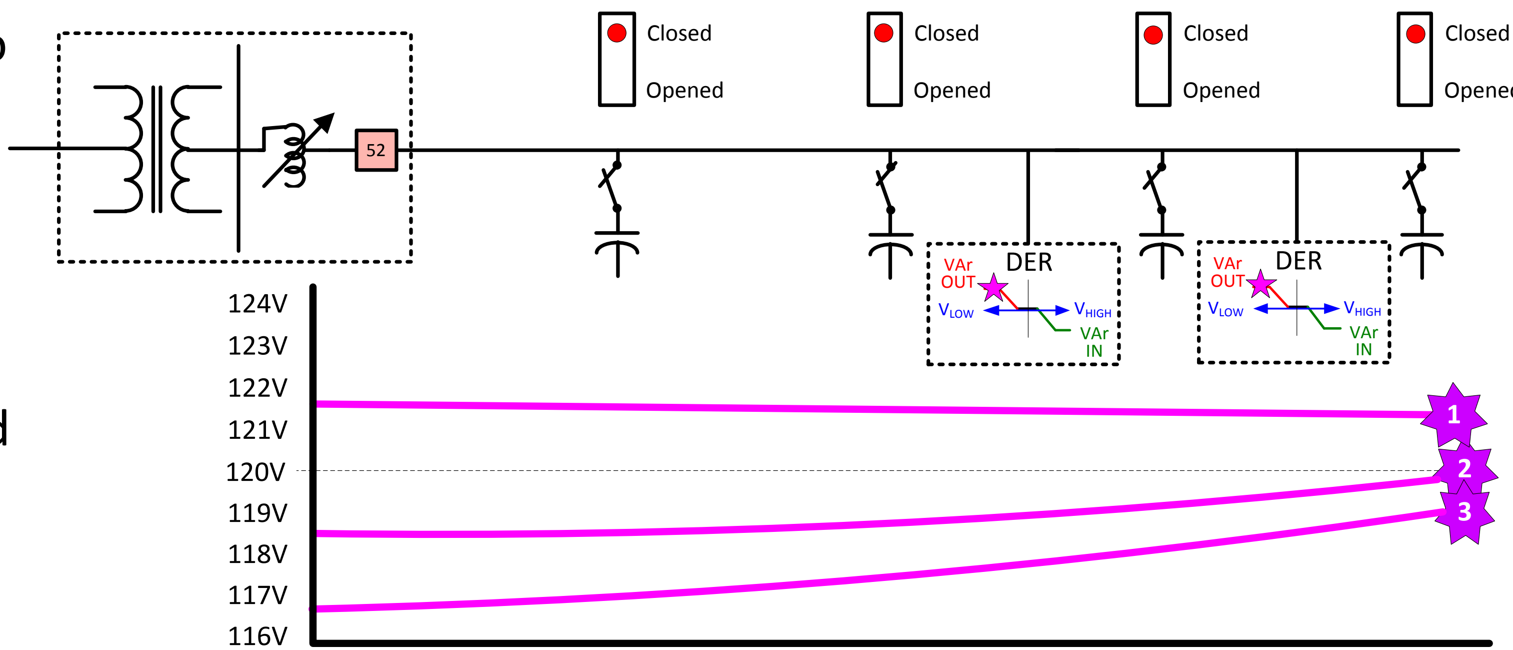
CVR Application

Positive Linear VAR Bias

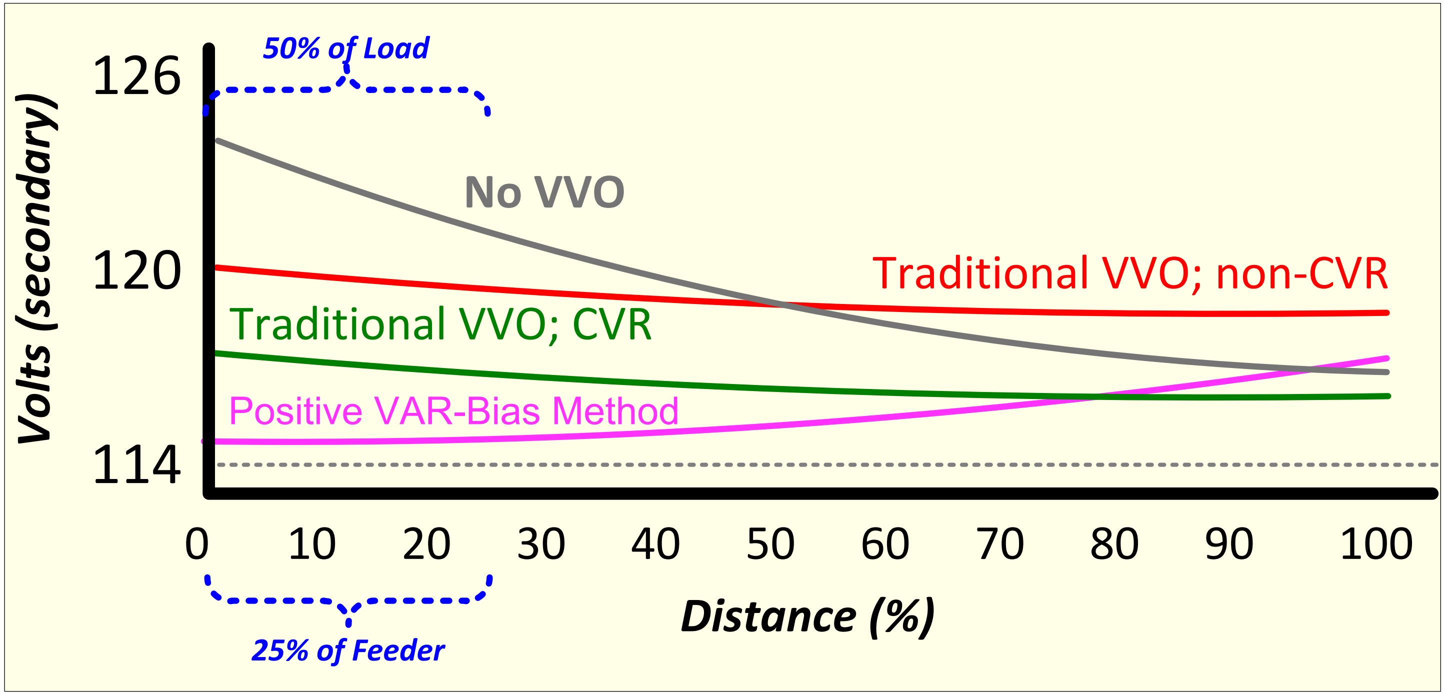


CVR OPERATION

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



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)

VAR-Bias

Take Away

- The cost is ADVVOCs, which you need anyway

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

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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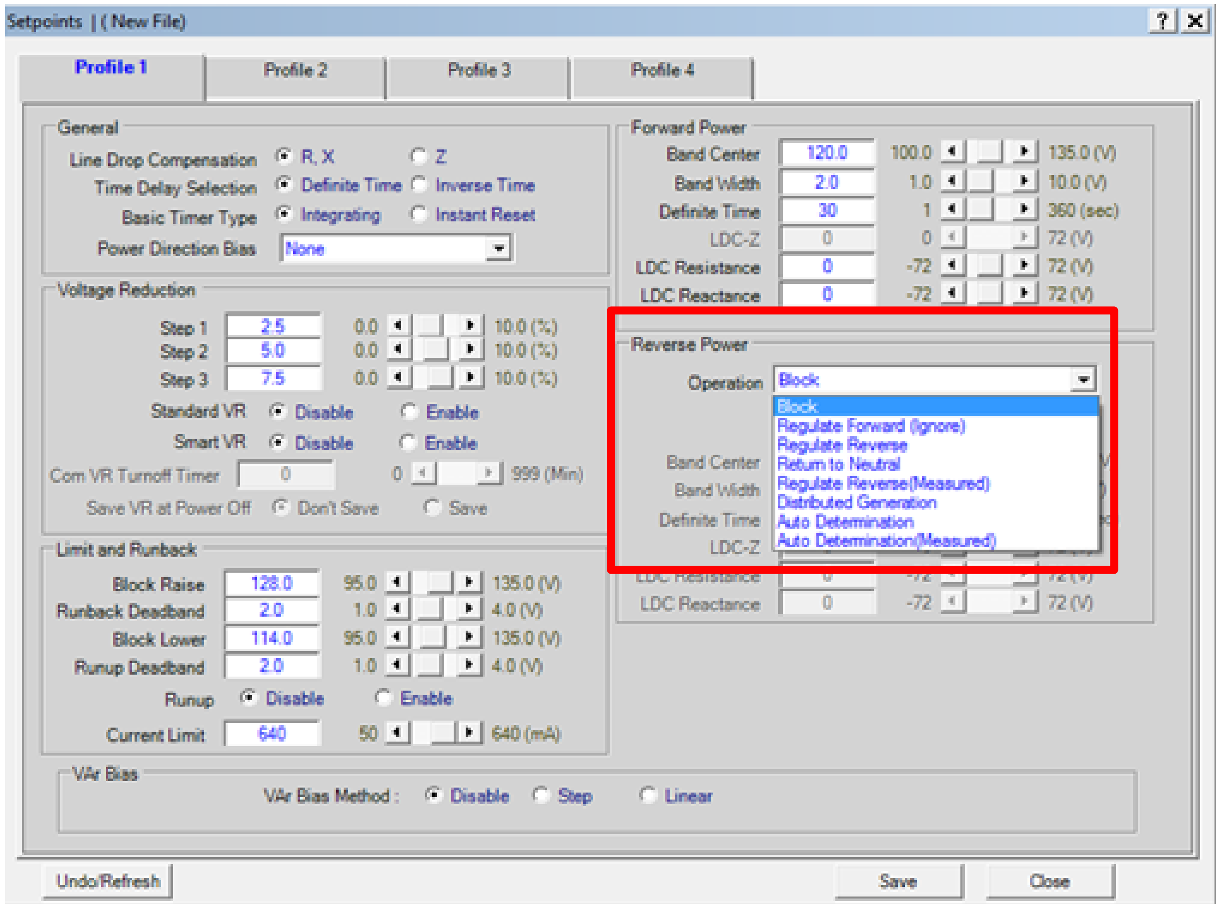
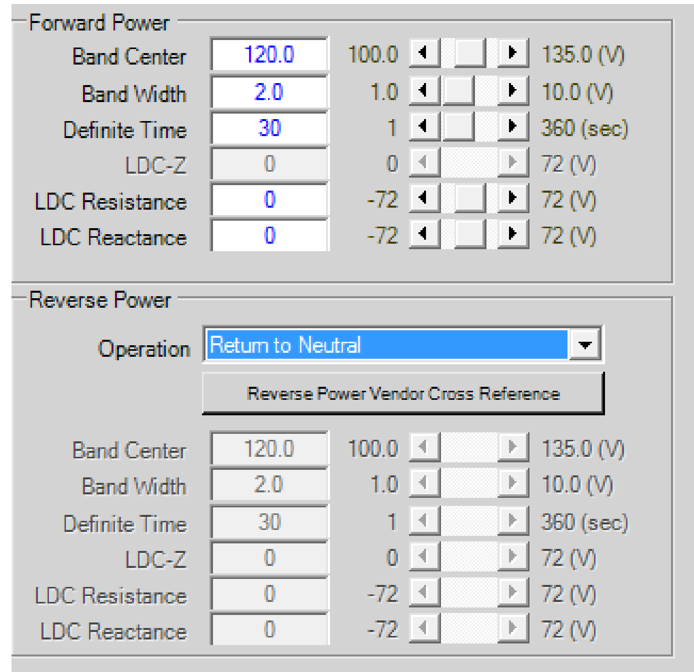
REGC/LTCC: Reverse Power Method Discussion



RPF Selection

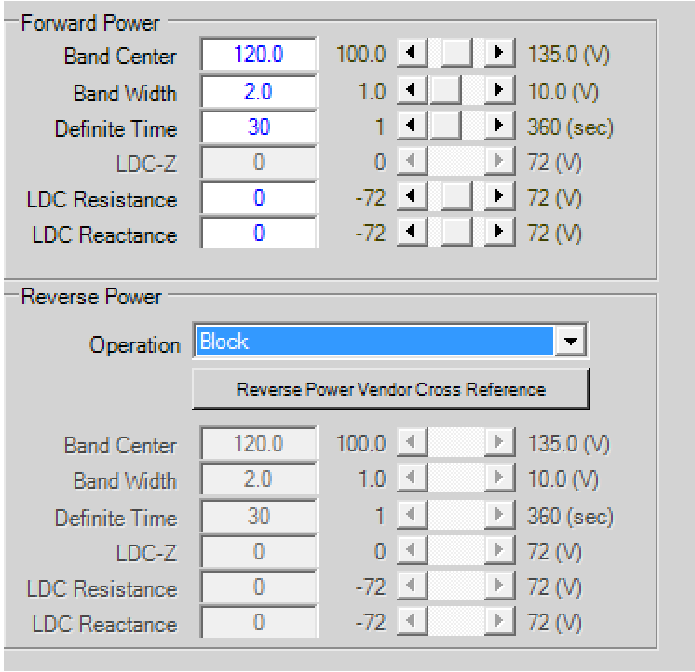
Return to Neutral

- **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



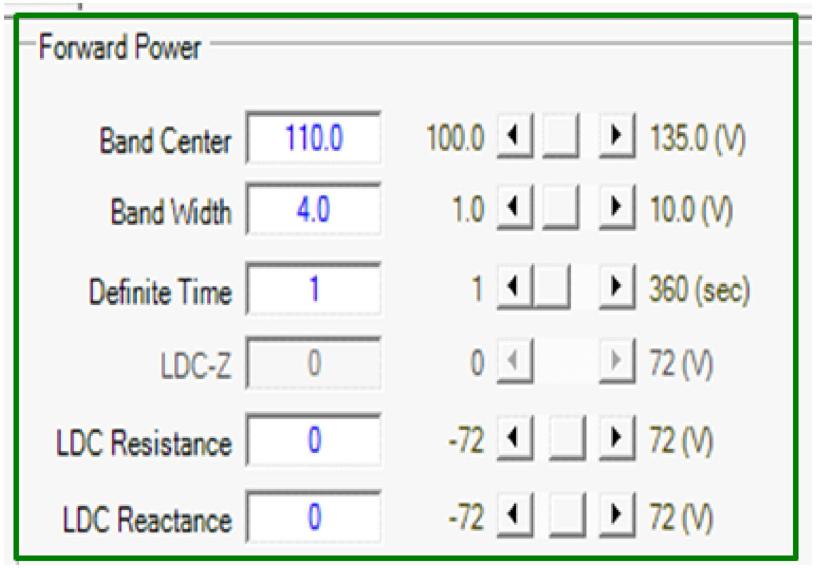
Block

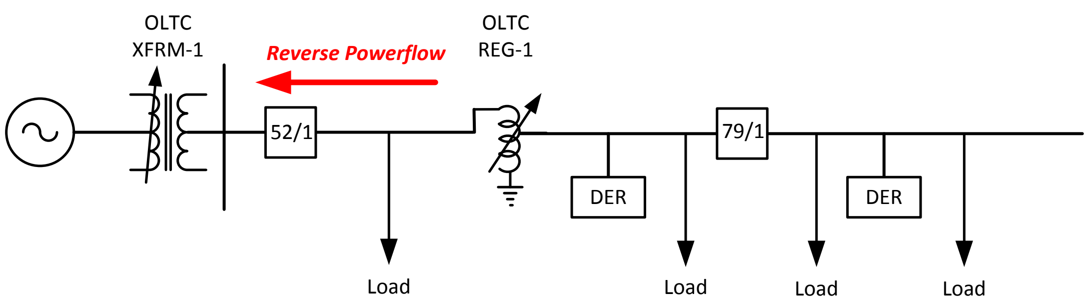
- **Block** – inhibits automatic operation, leaving regulator on present tap
  - Use where source of RPF is not expected to change voltage on RPF side of REG
  - Also a “feel safe” strategy when one cannot distinguish the source strength of the RFP
    - Is it DER, and possible weak?
    - Is it DA,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



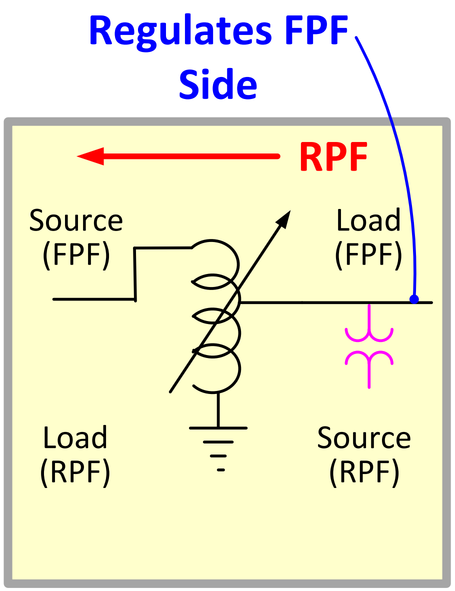
Ignore: Regulate Forward

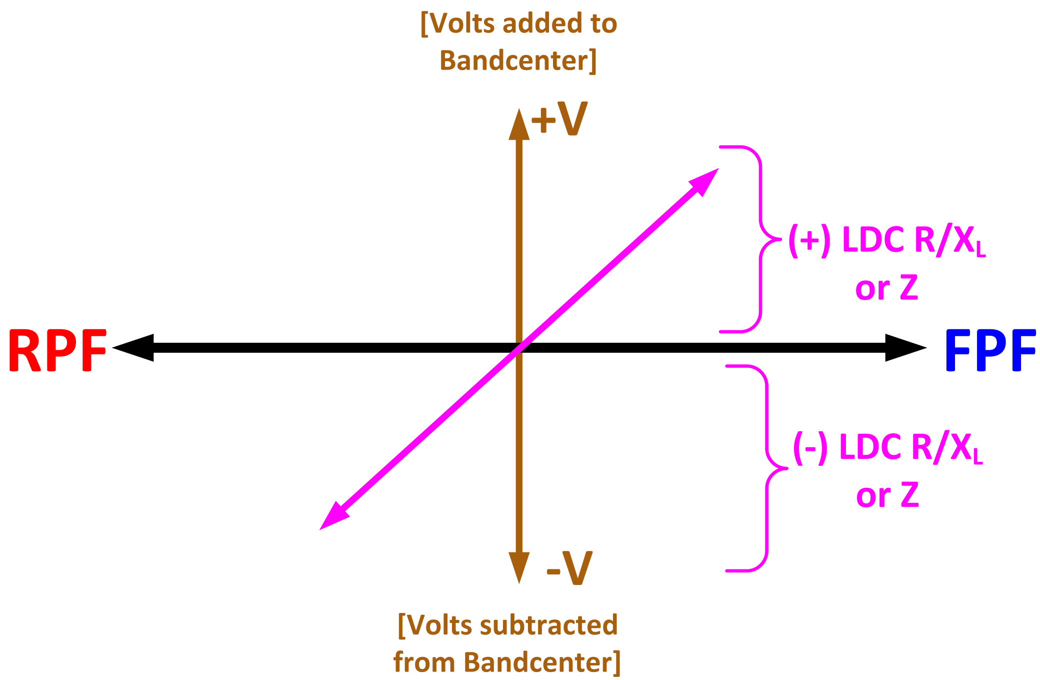
- **Regulate Forward (Ignore)** – continues control action as though forward power flow continued to exist.
  - Uses same settings with normal forward power flow
  - May use with small amounts of RPF, or when you need to drive down voltage due to DER causing a voltage rise
  - With strong reverse power flows, LDC will drive voltage down





Ignore: Regulate Forward with RFP





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

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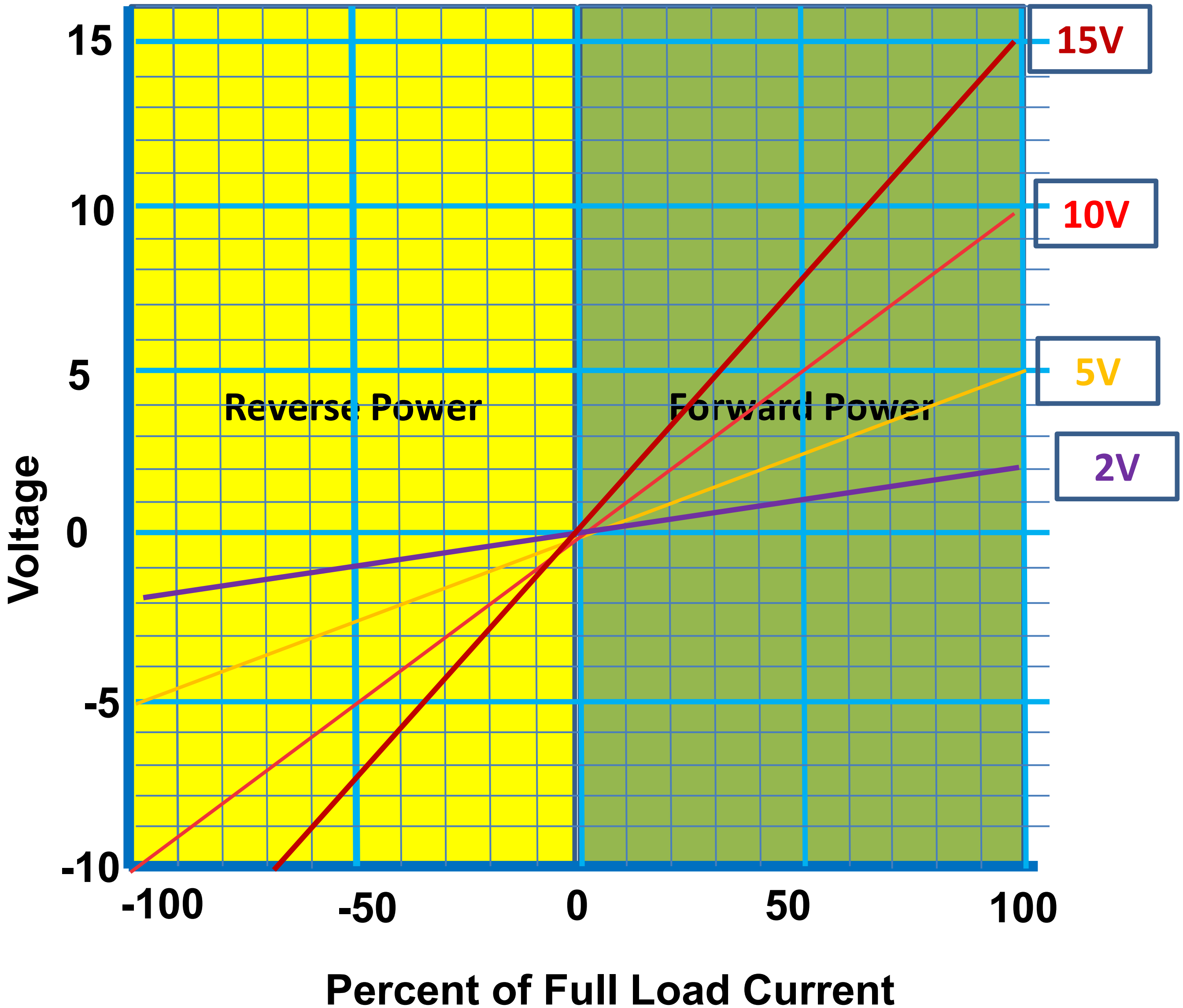
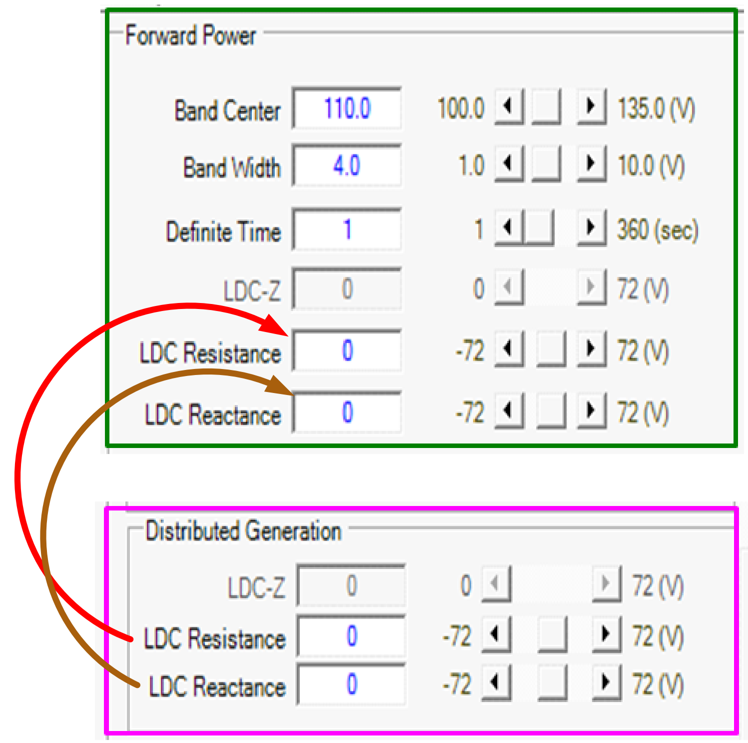
Regulate Forward and LDC



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

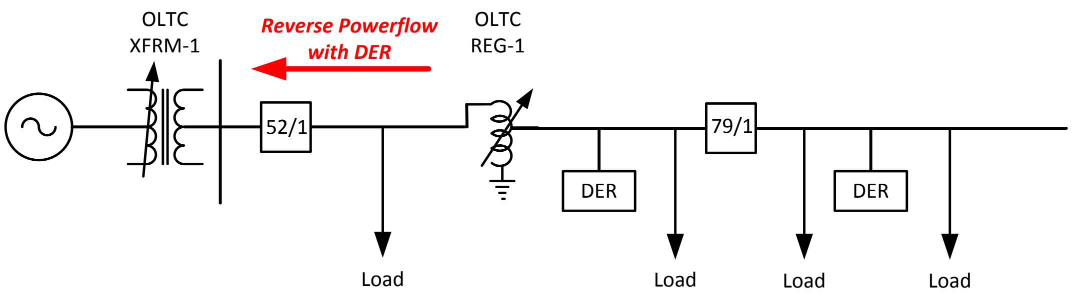
DG Mode: Regulate Forward with New LDC Settings

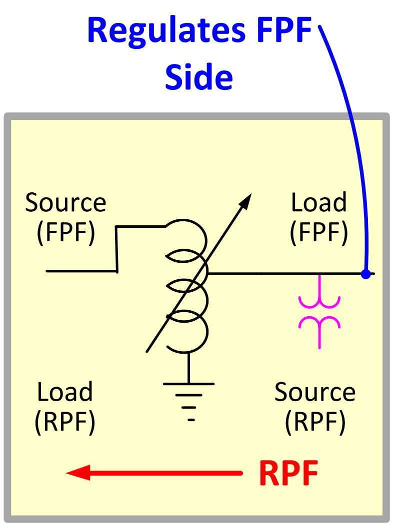
- **Regulate Forward (DG Mode)**
  - This mode of operation is the same as the Ignore mode, plus provides ability to change line drop compensation (LDC)
  - Use where DER power output is large enough to warrant new LDC settings

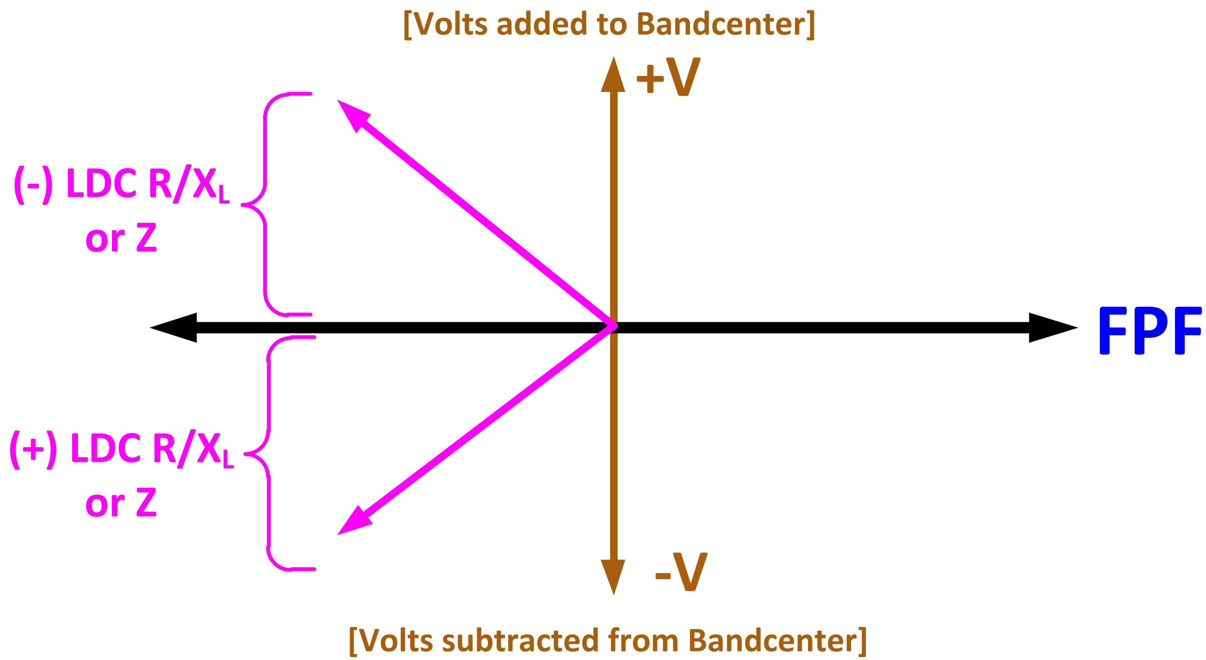


- A separate set of LDC settings can be specified which will be applied during reverse power
  - This can include LDC factor magnitudes, signs and the use of R and X_L , or Z
  - VAR-Bias may also be selected

"DG Mode"
Regulate Forward



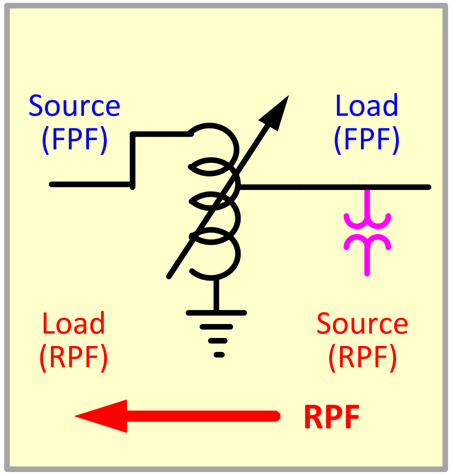




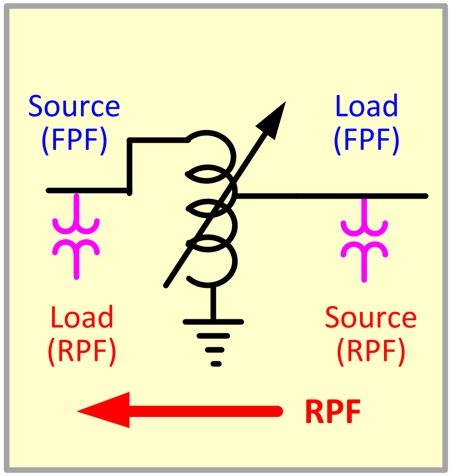
- Regulating **forward**, -LDC *raises* bandcenter as **RPF** becomes larger
- Regulating **forward**, +LCD *lowers* bandcenter as **RPF** becomes larger

REGC/LTCC: Reverse Power, "Regulate Reverse"

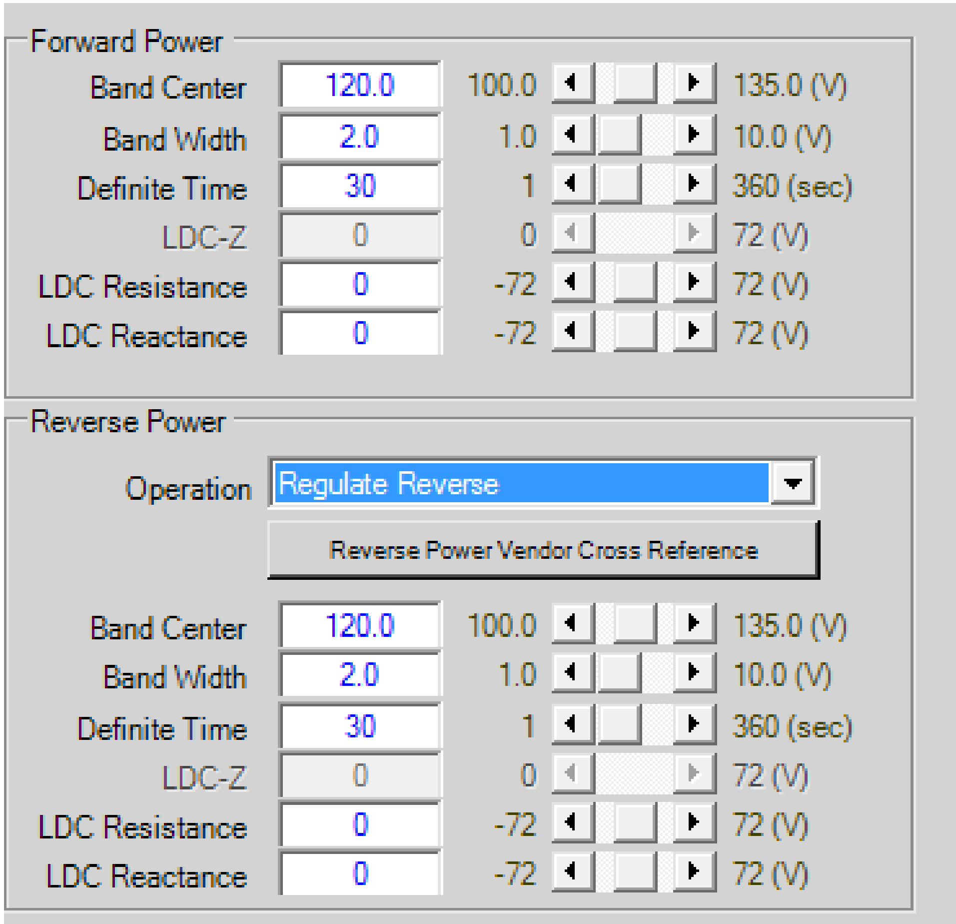
- **Regulate Reverse (Calculated):**
  - Voltage Sensing: With RPF, control uses tap position knowledge and FPF side voltage
  - Regulates according to reverse power settings
    - Use where RPF source to OLTC is a stronger source
    - Regulate voltage on the RPF side of the OLTC
      - Typically used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

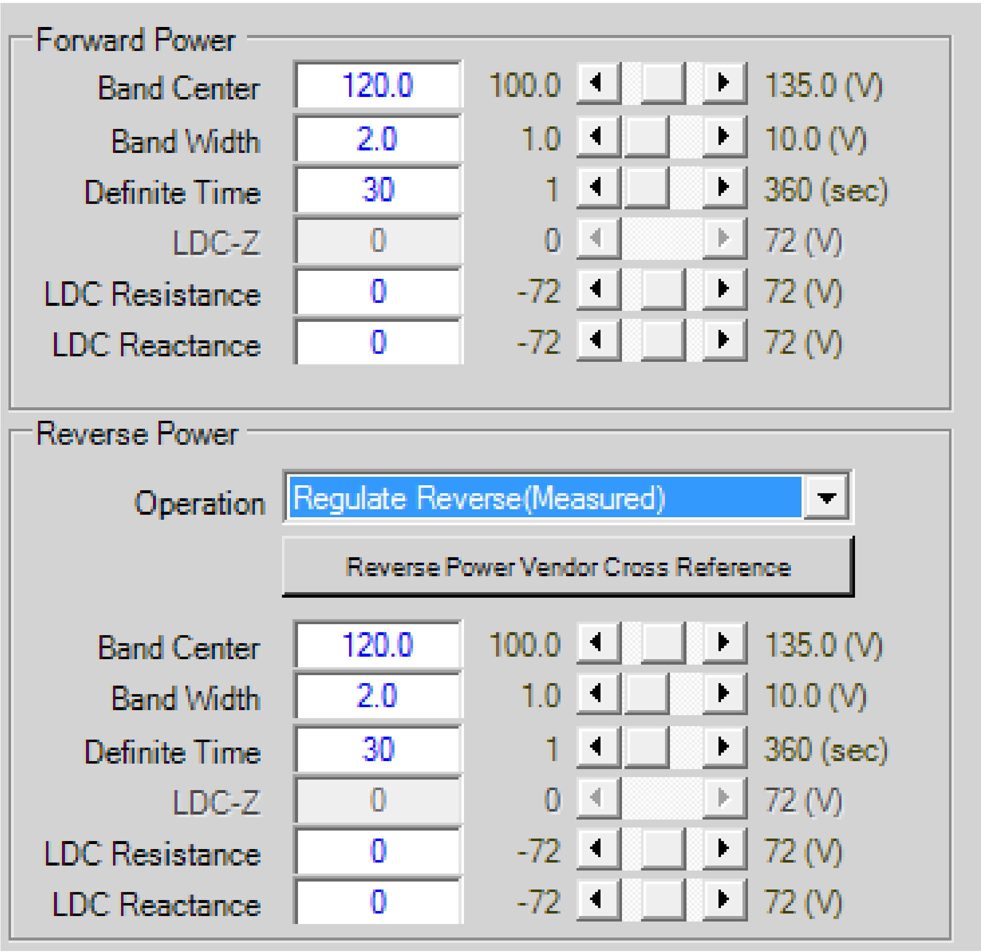


REGC/LTCC: Reverse Power, “Regulate Reverse”



- “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
- Additional VT not needed

REGC/LTCC: Reverse Power, “Regulate Reverse”



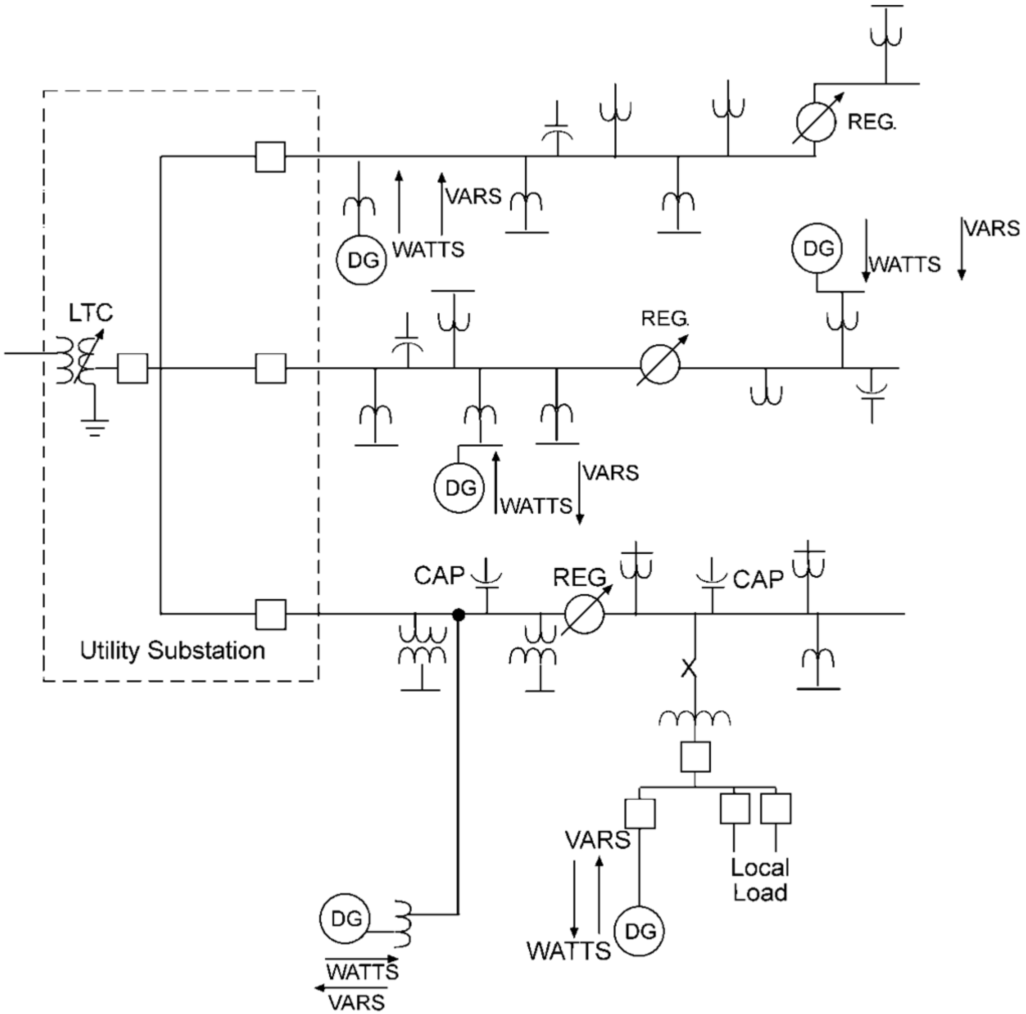
- “Regulate Reverse”
  - Measured
- Regulates reverse with new voltage setpoints and LDC values
- Use with strong RPF source (reconfig)
- Uses additional VT on previous supply side of regulator

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?

High Penetration of DER and/or DA on Distribution Systems Requires Smart Technology to obtain VVO/CVR



- How do you know after a reconfiguration which side of a regulator has the string source?
- How do you control caps relocated due to reconfiguration
- Normal power from Utility to load
  - Utility strong source
- DER may backfeed
  - Typically a weaker source
- What to do with power reversal from sectionalizing?
- What to do with power reversal from DER?
- What to do about LDC with DER influencing?

Sample DA Scenarios

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

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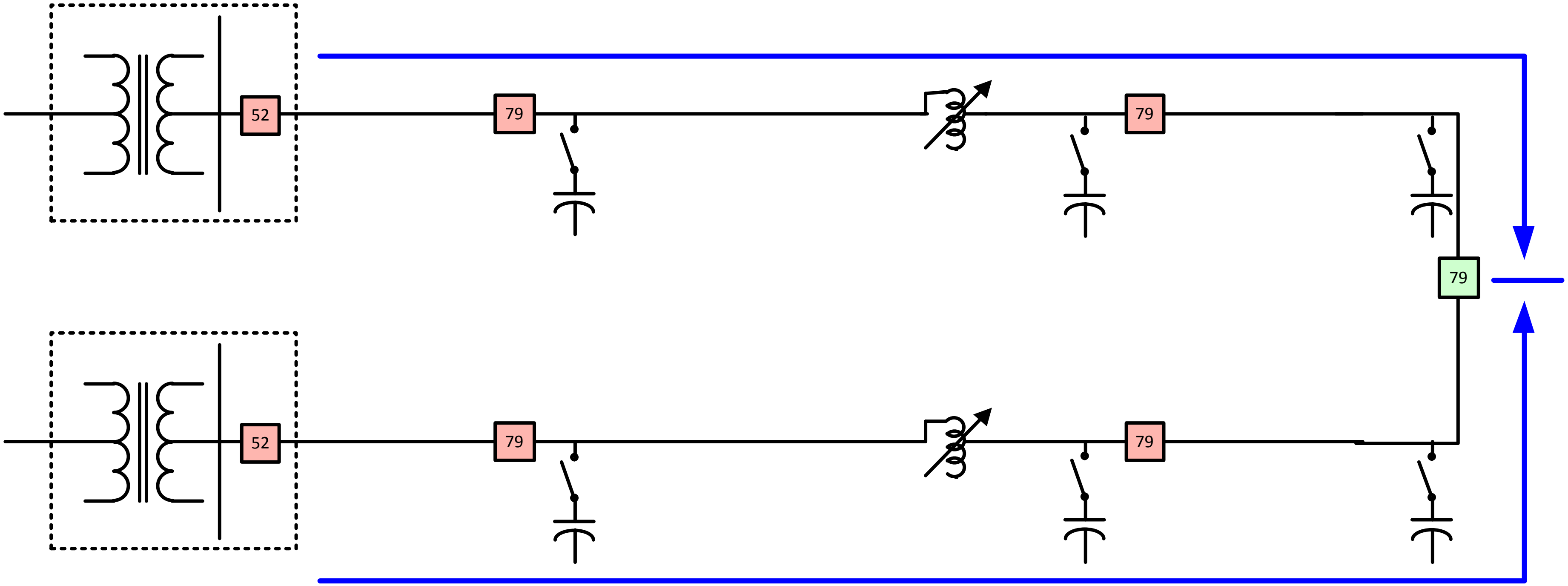
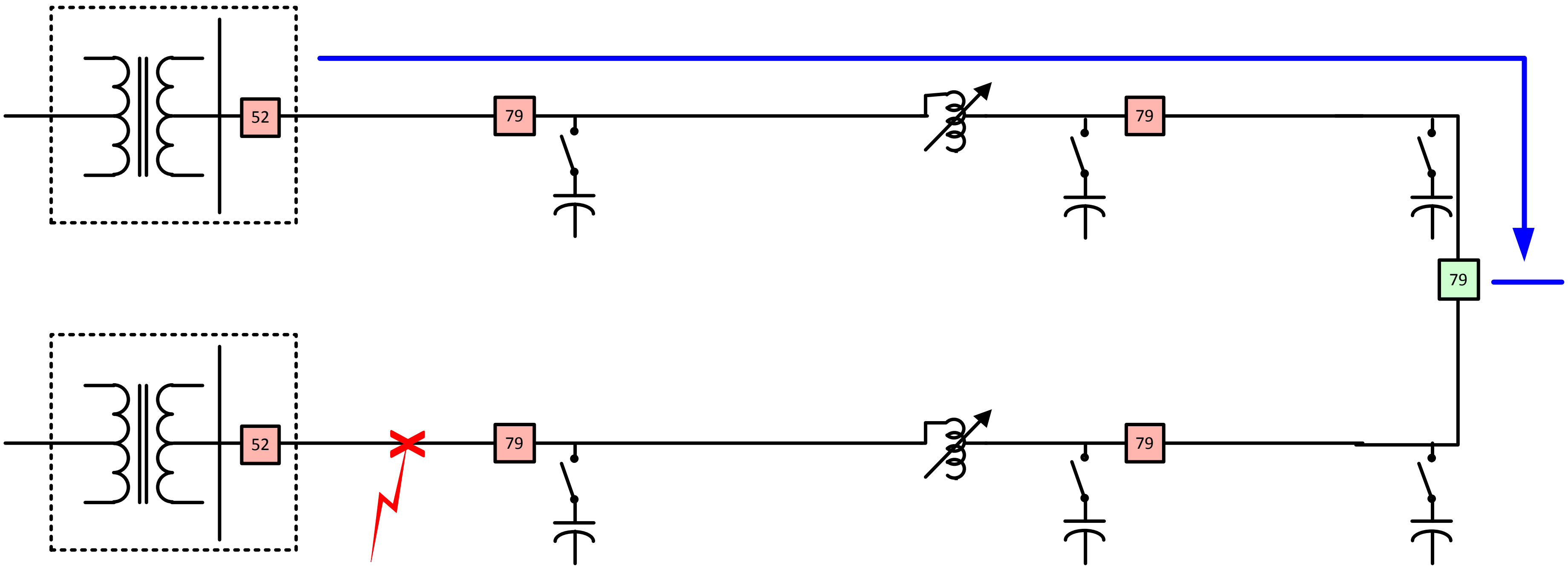
Volt/VAR Control Considerations from DA



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

Volt/VAR Control Considerations from DA



- Fault occurs on feeder

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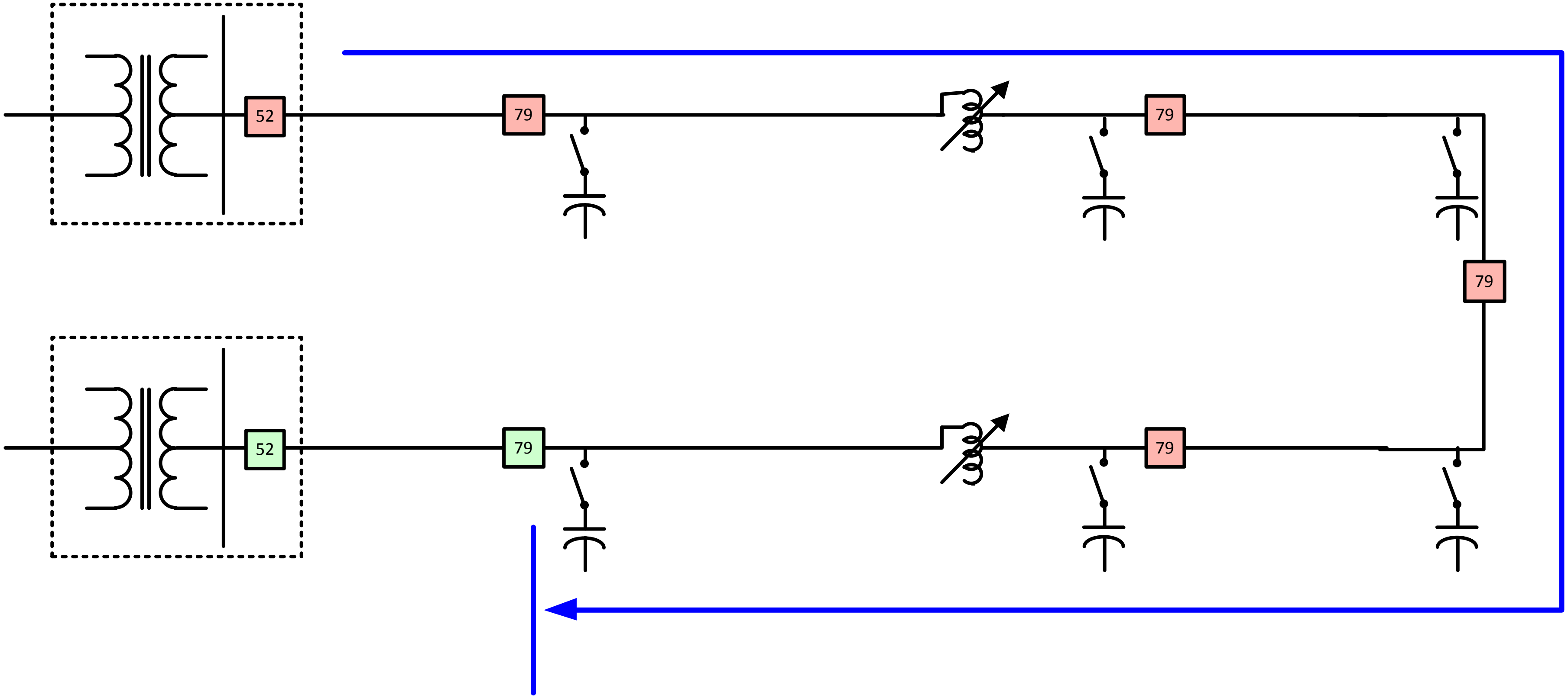
Volt/VAR Control Considerations from DA



- 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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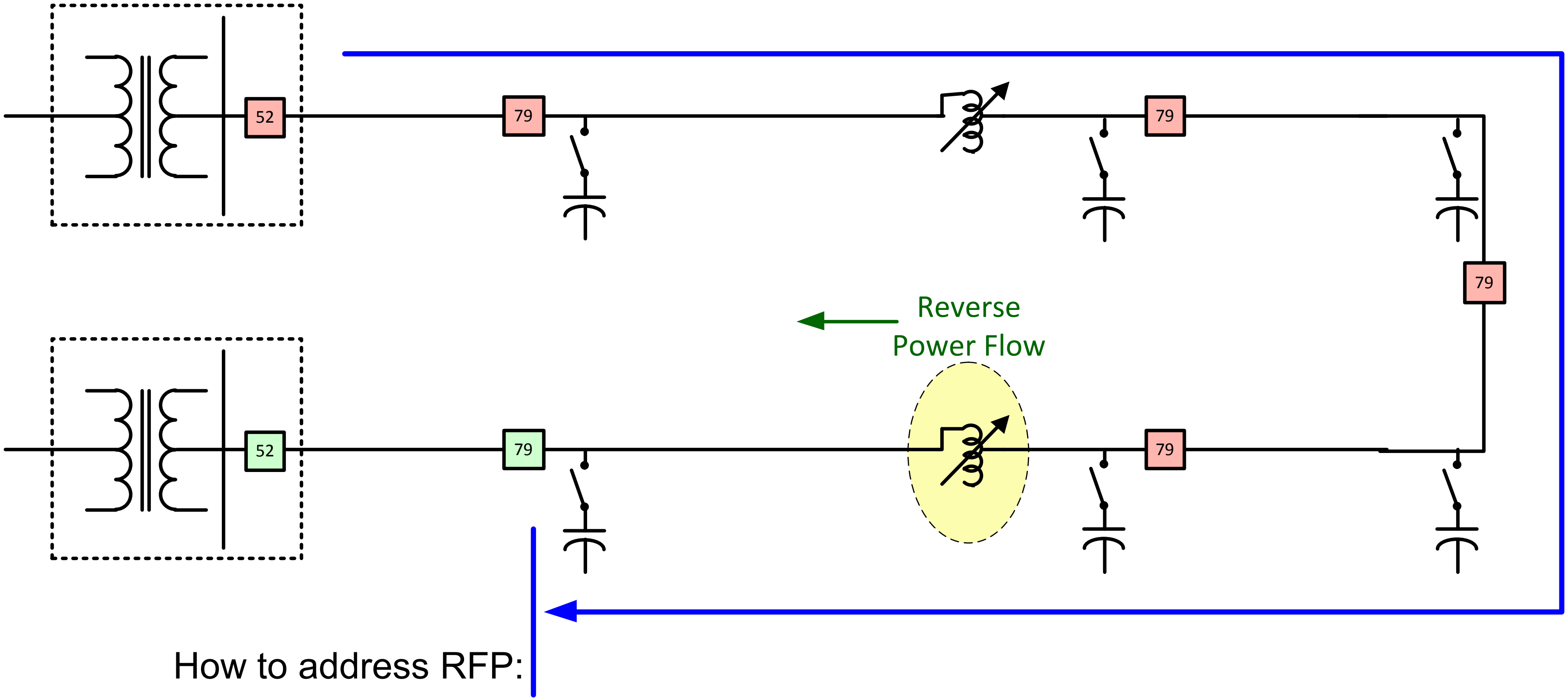
Voltage Control Considerations from DA: REGC



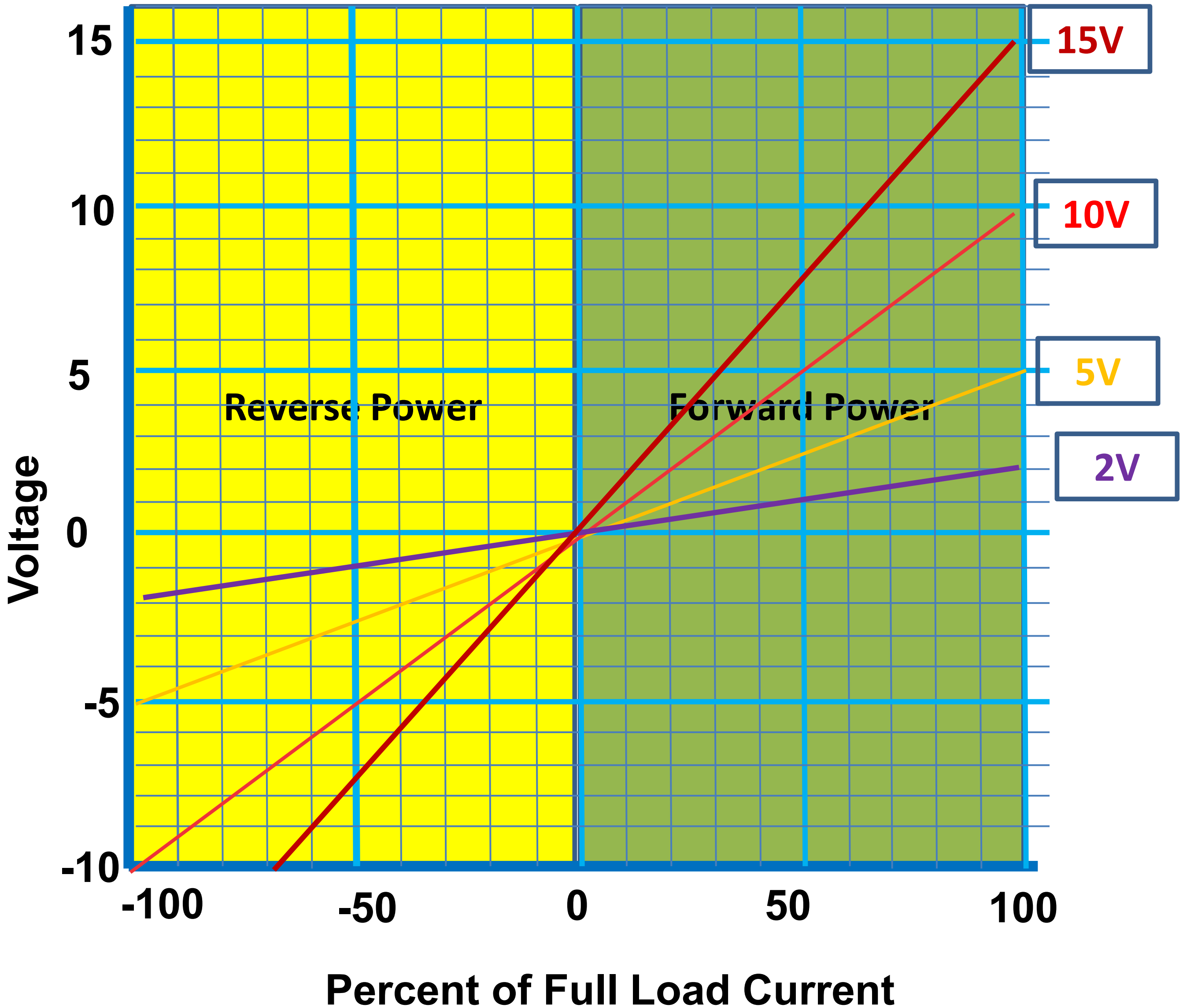
How to address RFP:

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

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

Forward Power and LDC



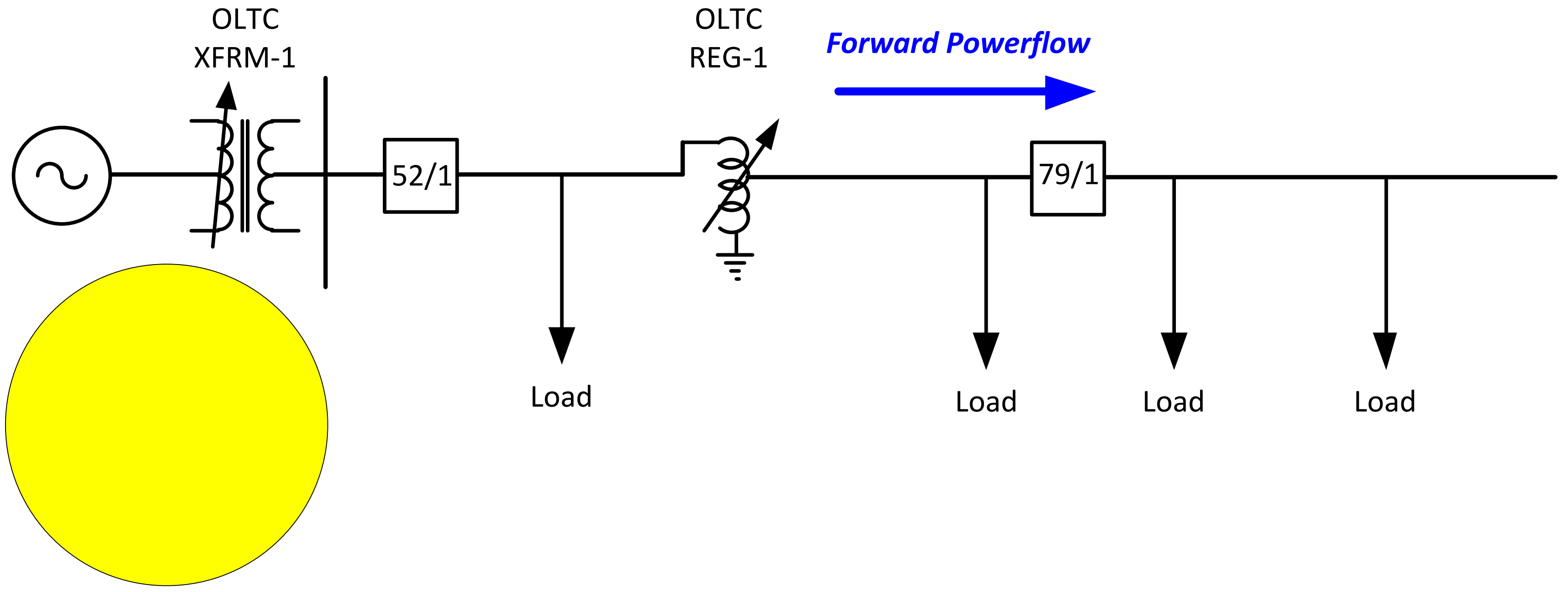
Notice that if the current is reverse, LDC drops the voltage instead of raising it

The Reverse Power Flow (RPF) Problem

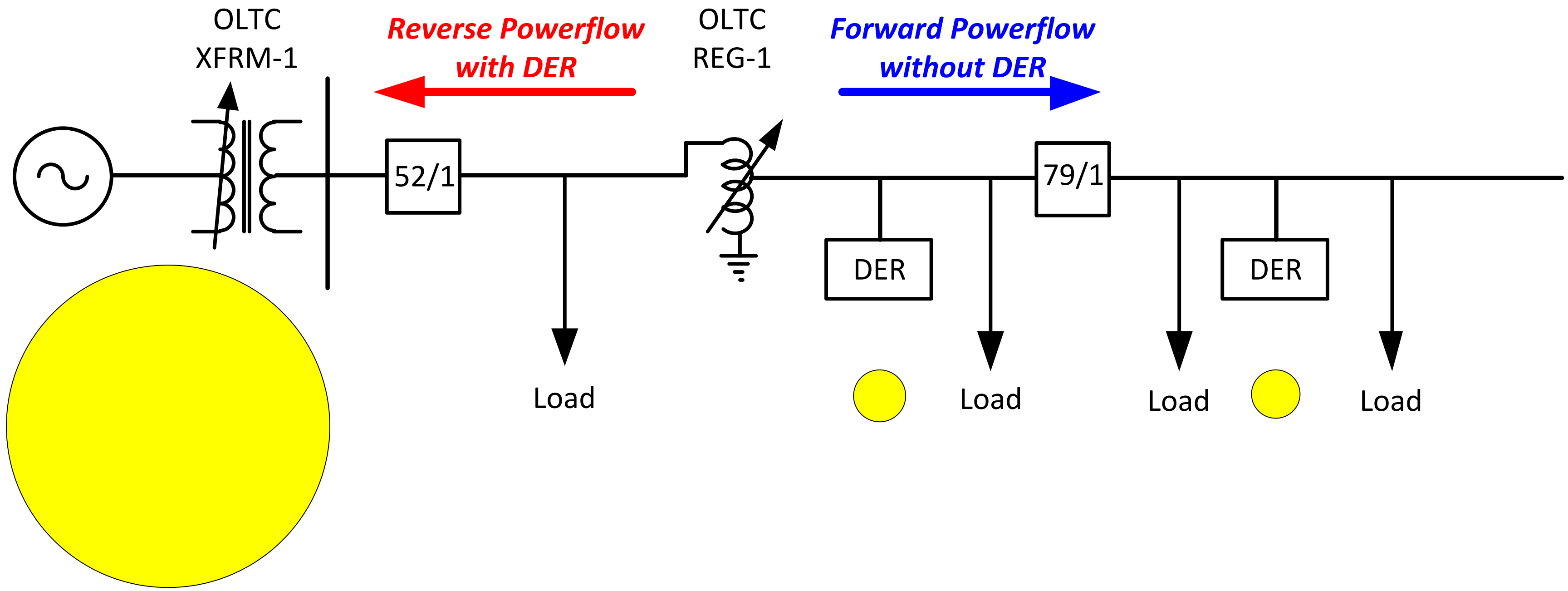
- It's all about **source strength**
  - If the source is weak, small impact (most DER)
  - If the source is strong, big impact (reconfiguration)

- Impacts of **strong source** RPF: 
  - Drives LDC the wrong way
  - Regulation should be in the now reverse direction
    - The tail *cannot* wag the dog

No RPF Source



Weak RPF Source



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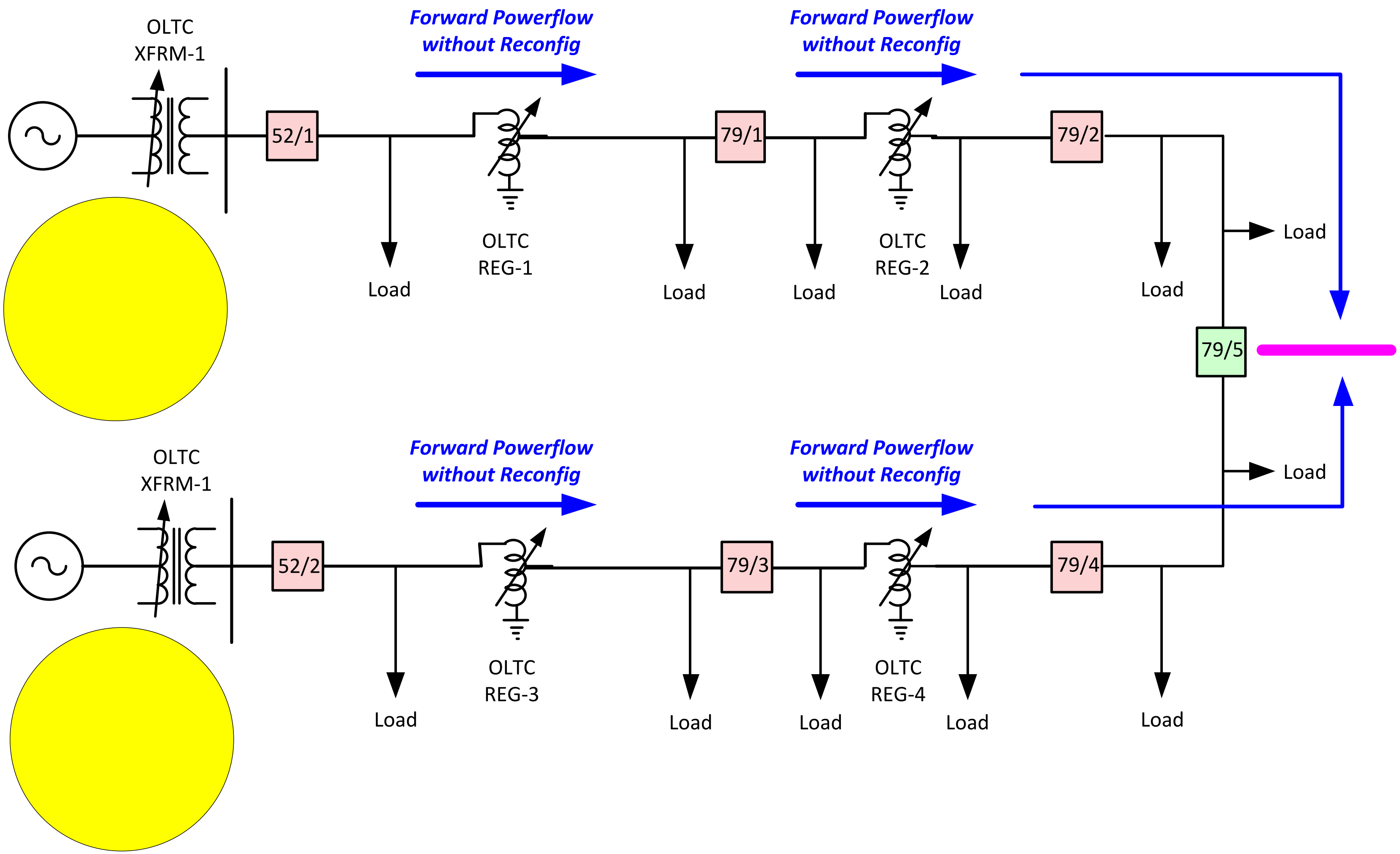
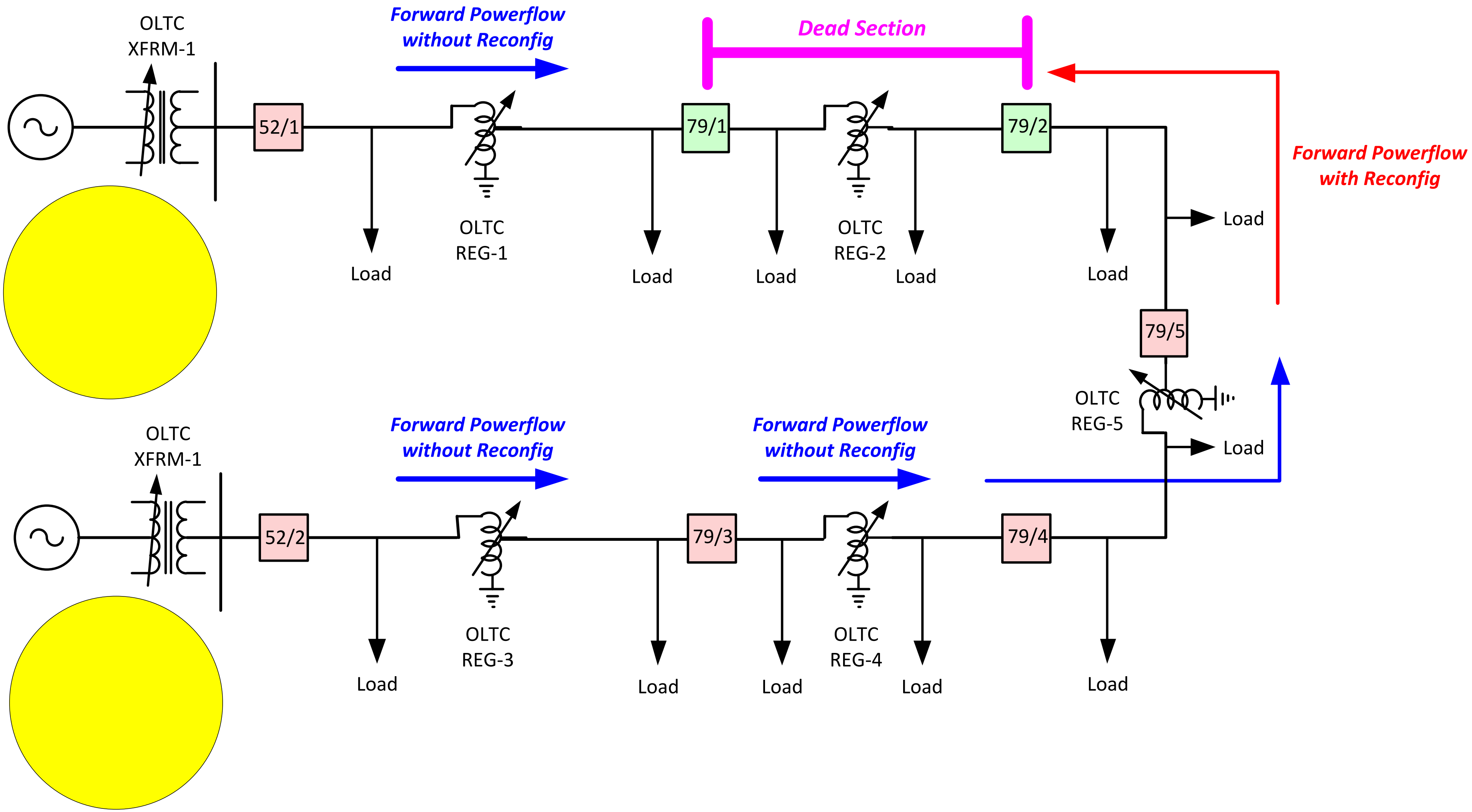
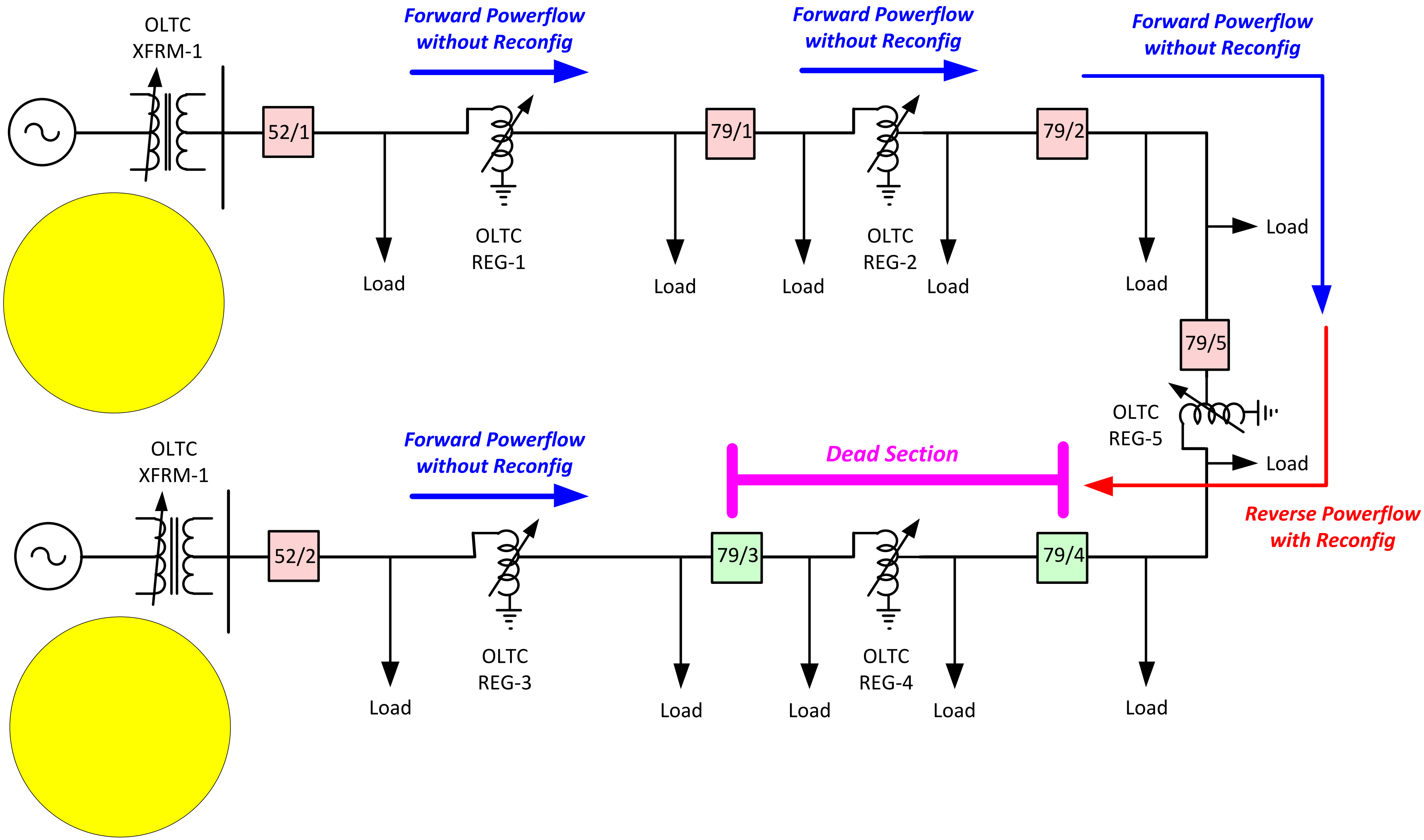
No RPF Source: Open Loop



Strong FPF Source: Reconfig



Strong RPF Source: Reconfig



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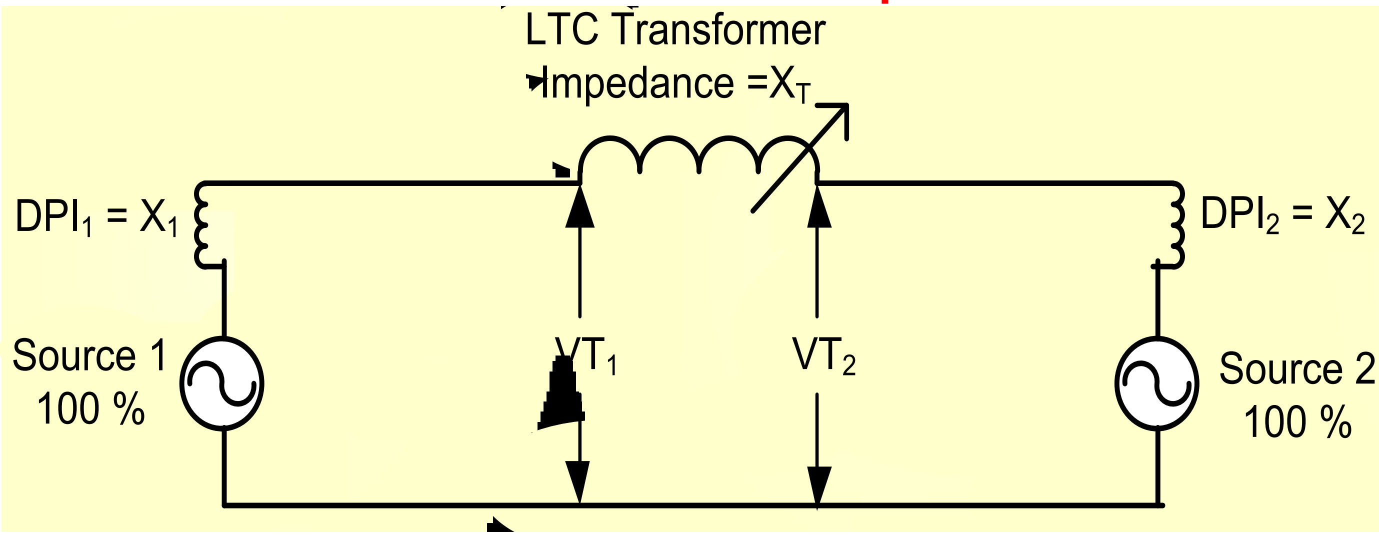
How Can One Know About Source Strength

- **Guess it, assume it**
- Cheap and easy if one can make assumptions or guess
- LTC or REG makes RPF determination and goes into <u>*predetermined*</u> 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

Knowing Relative Source Strength is KEY

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

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



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

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

$\Delta V = 0.625\%$ 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:

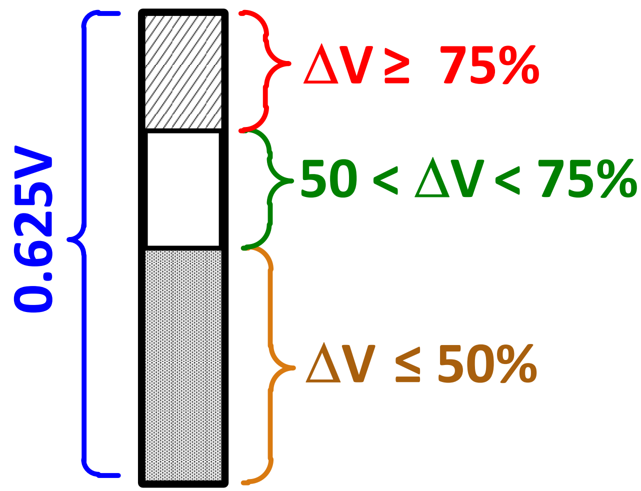
$$\Delta V = V_{MBT} - V_{MAT}$$

where V_{MBT} = **measured** load side voltage **just before a tap change**

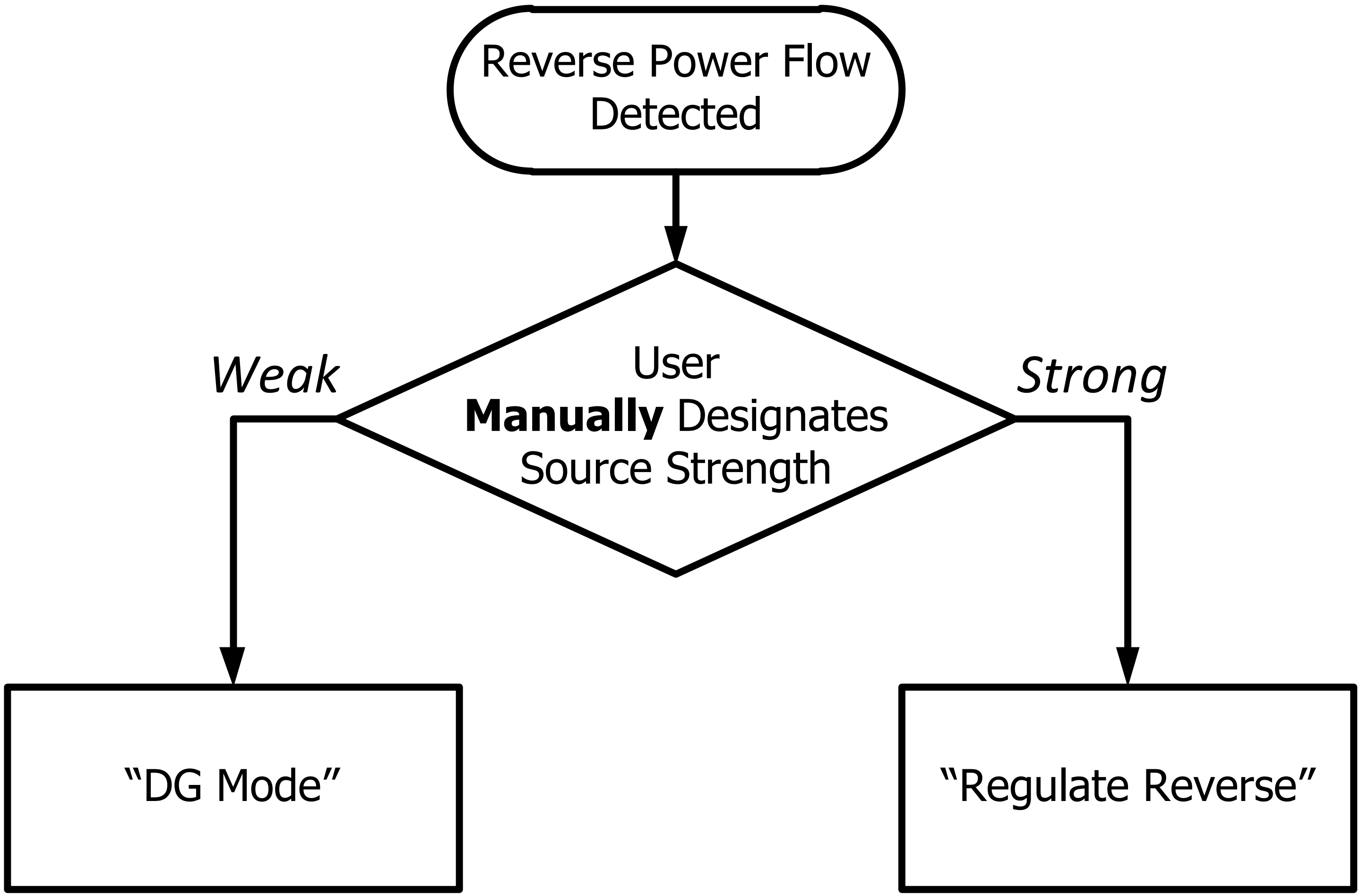
V_{MAT} = **measured** load side voltage one second **after the tap change**

Normally expect 0.625V per tap

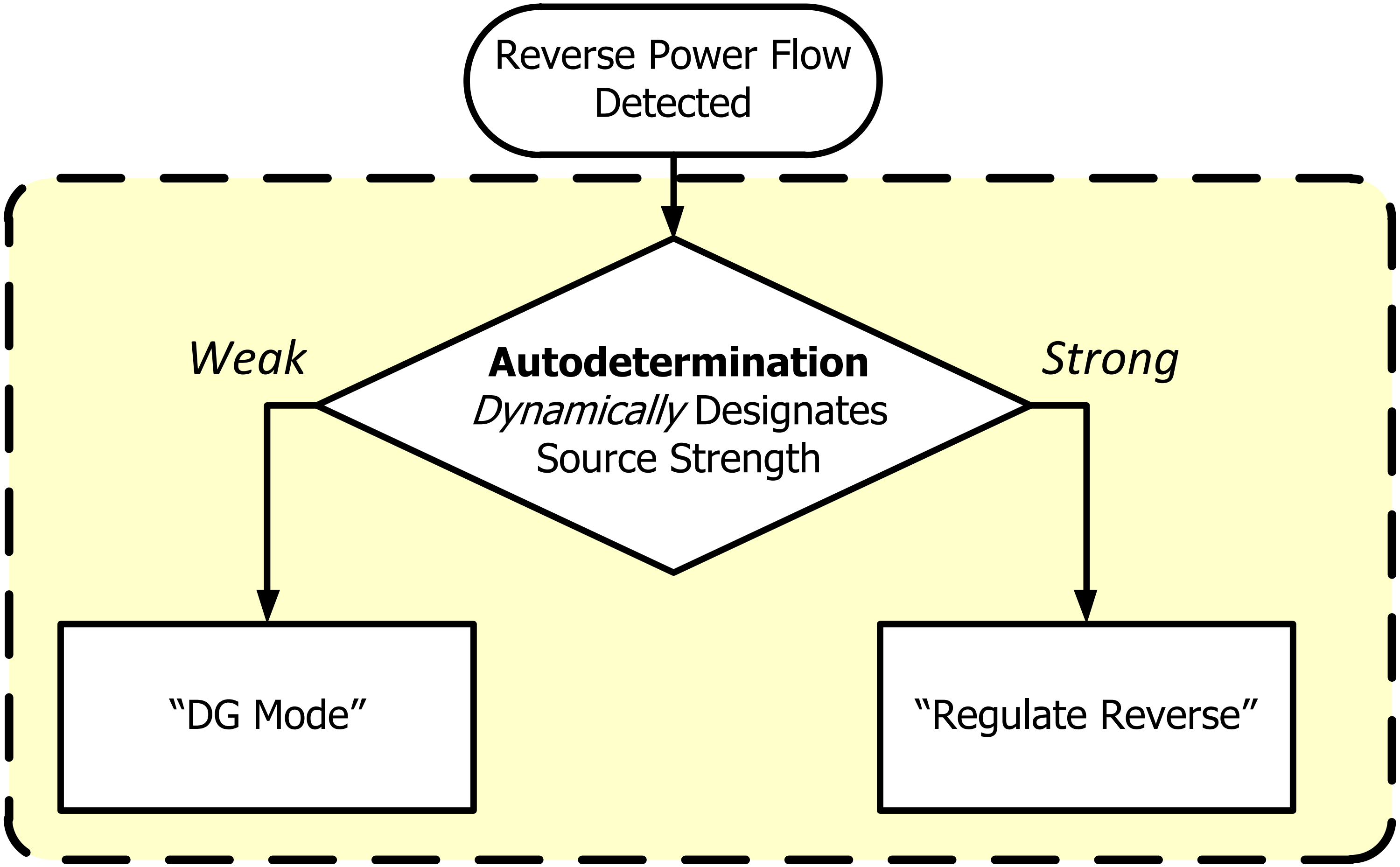
- If the measured ΔV is > 0.47 (75%) of the normal expected value (0.625V) for two consecutive tap changes, Autodetermination will maintain “DG Mode” operation
- If the measured ΔV is <= 0.31V (50%) of the normal expected value (0.625V) for two consecutive tap changes, Autodetermination changes to “Regulate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



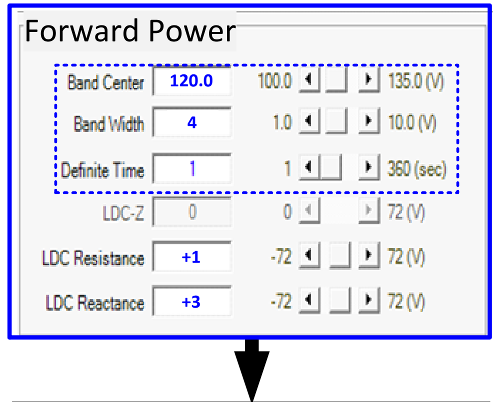
Reverse Power Source Strength Determination: *User Manually Designates*



Reverse Power Source Strength Determination: *Autodetermination*

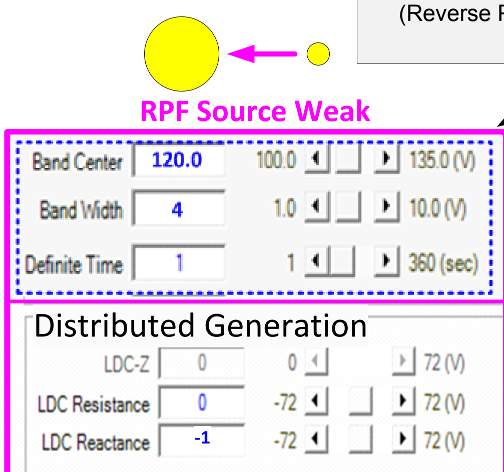


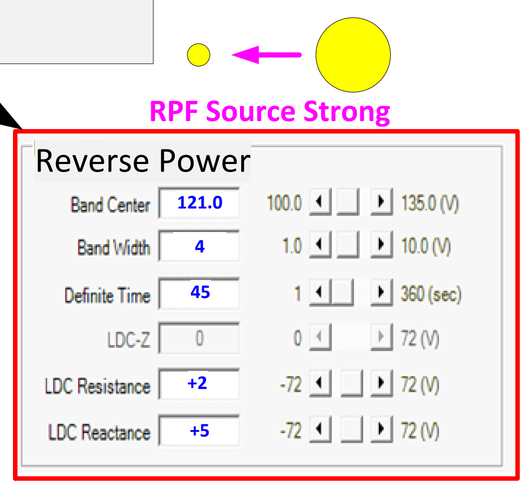
REGC/LTCC: Autodetermination of Operating Mode with Reverse Power



Autodetermination:
Senses Reverse Powerflow (RPF), then:

- If normal load side remains ***weak source***, switches to "**DG Mode**"
- If normal load side changes to ***strong source***, switches to "**Regulate Reverse**" (Reverse Power)

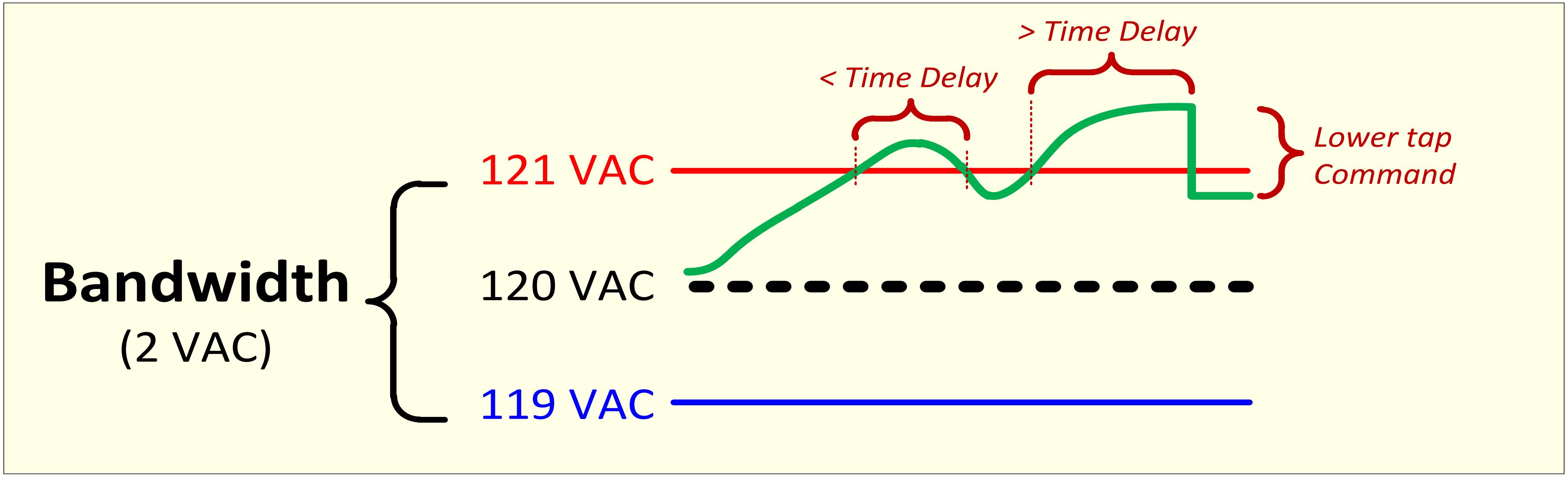




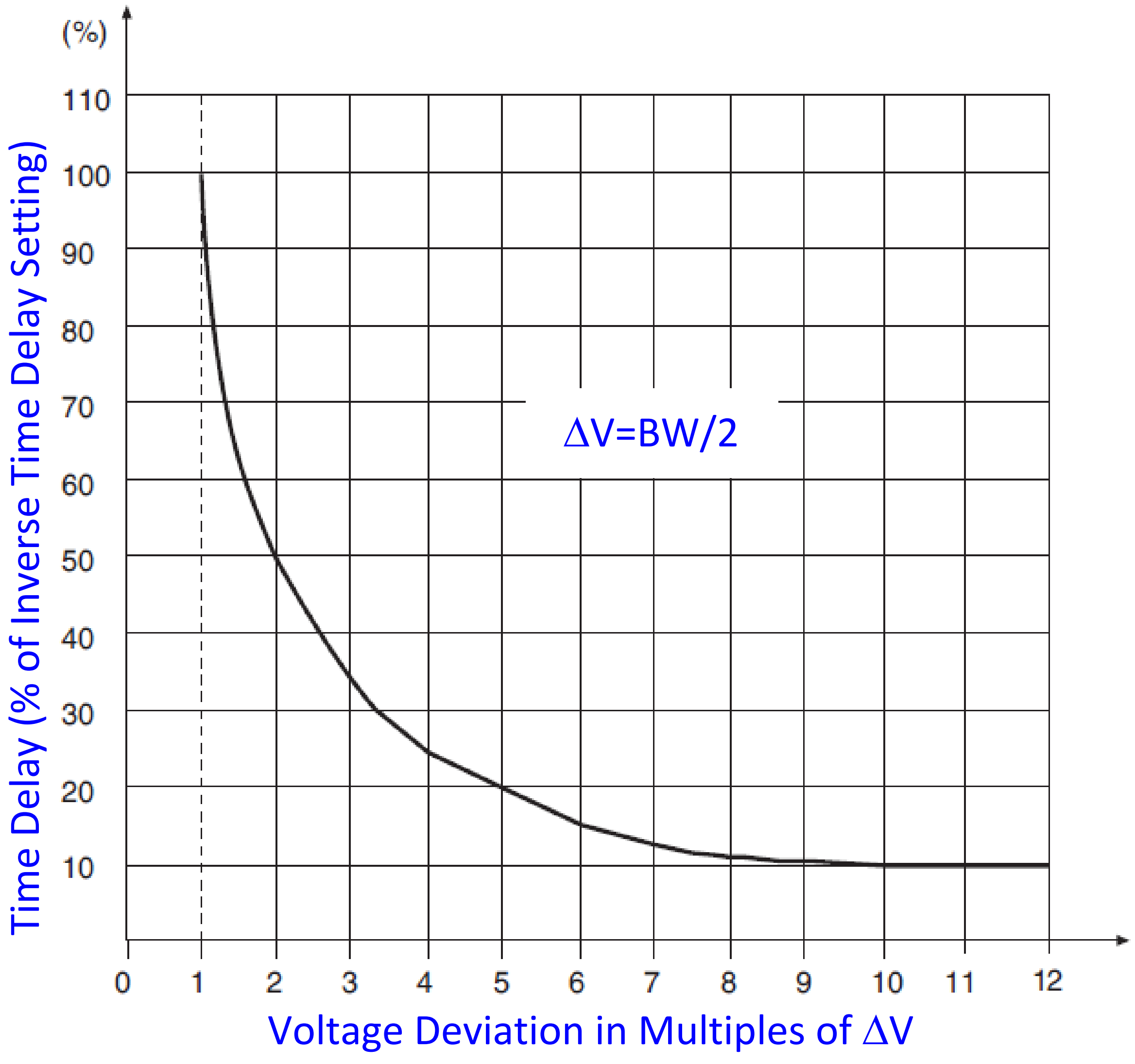
Handling DER rapid output change

- Irradiance and wind velocity can change very quickly
- Large rise or drop in power (W, VAR) can cause large voltage swings
- Normal fixed timing in OLTCs may not respond fast enough for good control
- Employ inverse response curve for time delay
  - Small changes yield longer time delays
  - Large changes yield shorter time delays

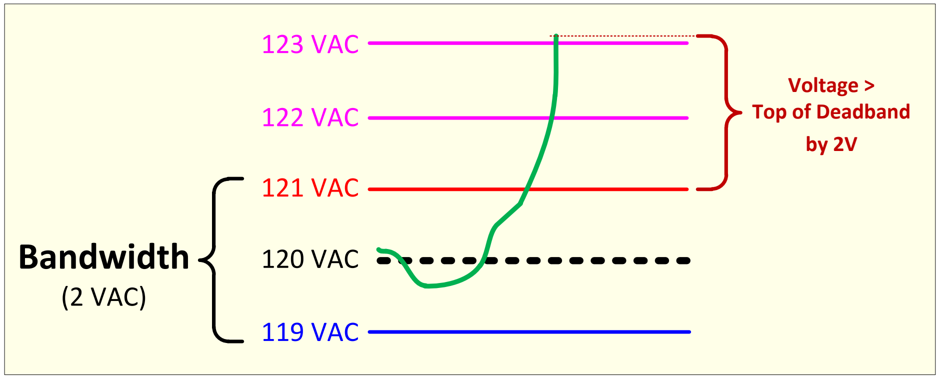
Definite Time OLTC Characteristic

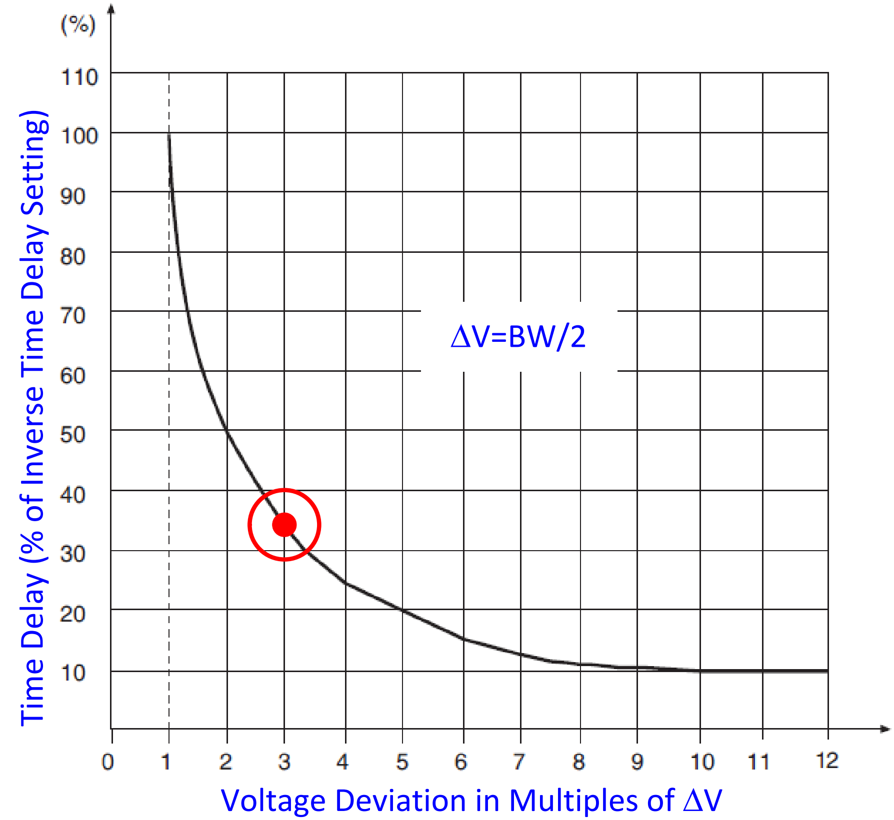


Inverse Curve OLTC Time Characteristic



Inverse TD Example





Example

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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Protection Concepts and DER Issues

- *Bidirectional Fault Current & Directionalization*
- *Reclosing treatment :*
  - *Increase of 1st Shot Time Delay*
  - *Adaptive protection with voltage control of reclosing*
- *Ferroresonance on islanded feeder s*
- *Ungrounded fault backfeed into transmission protection*

IEEE Distribution Practices Survey – 1/02

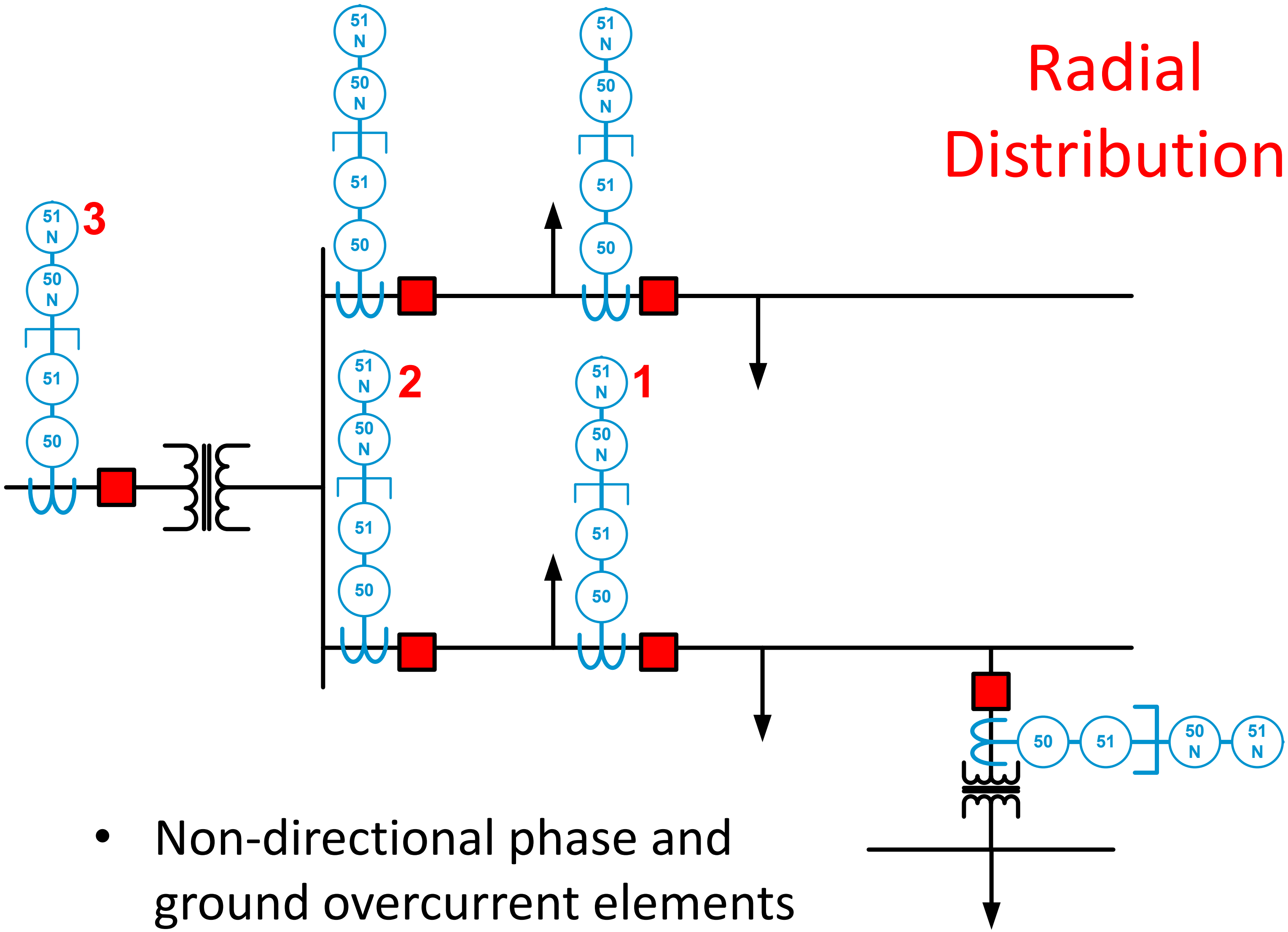
Impact on Utility Protection

- No effect – 22%
- Revised feeder coordination – 39%
- Added directional ground relays – 25%
- Added direction phase relays – 22%
- Added supervisory control - 22%
- Revised switching procedures – 19%

Bidirectional Fault Currents: Coordination

- Use directional elements in substation protection, mid-line reclosers and DER
  - Substation
    - Directionalize using 67 and 67N (instead of 50/51 and 50/51N)
    - Trip toward DER (downstream) to avoid sympathy trips for out-of-section faults
    - Trip toward Substation for remote breaker failure
  - Reclosers
    - Directionalize using 67 and 67N (instead of 50/51 and 50/51N)
    - Trip toward Substation for remote breaker failure
  - DER
    - Directionalize using 67 and 67N (instead of 50/51 and 50/51N)
    - Trip direction away from DER (upstream)

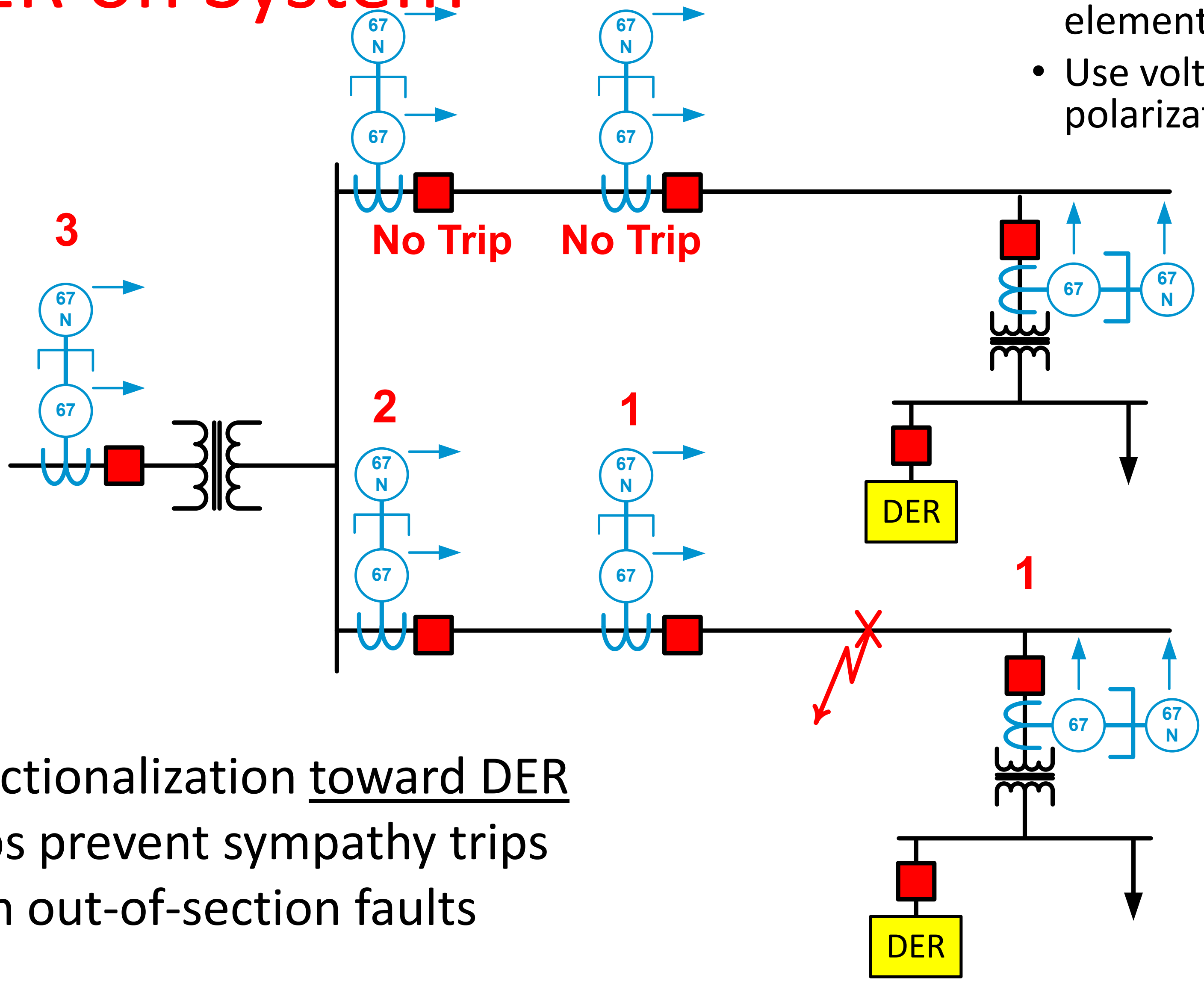
Radial Distribution



- Non-directional phase and ground overcurrent elements

DER on System

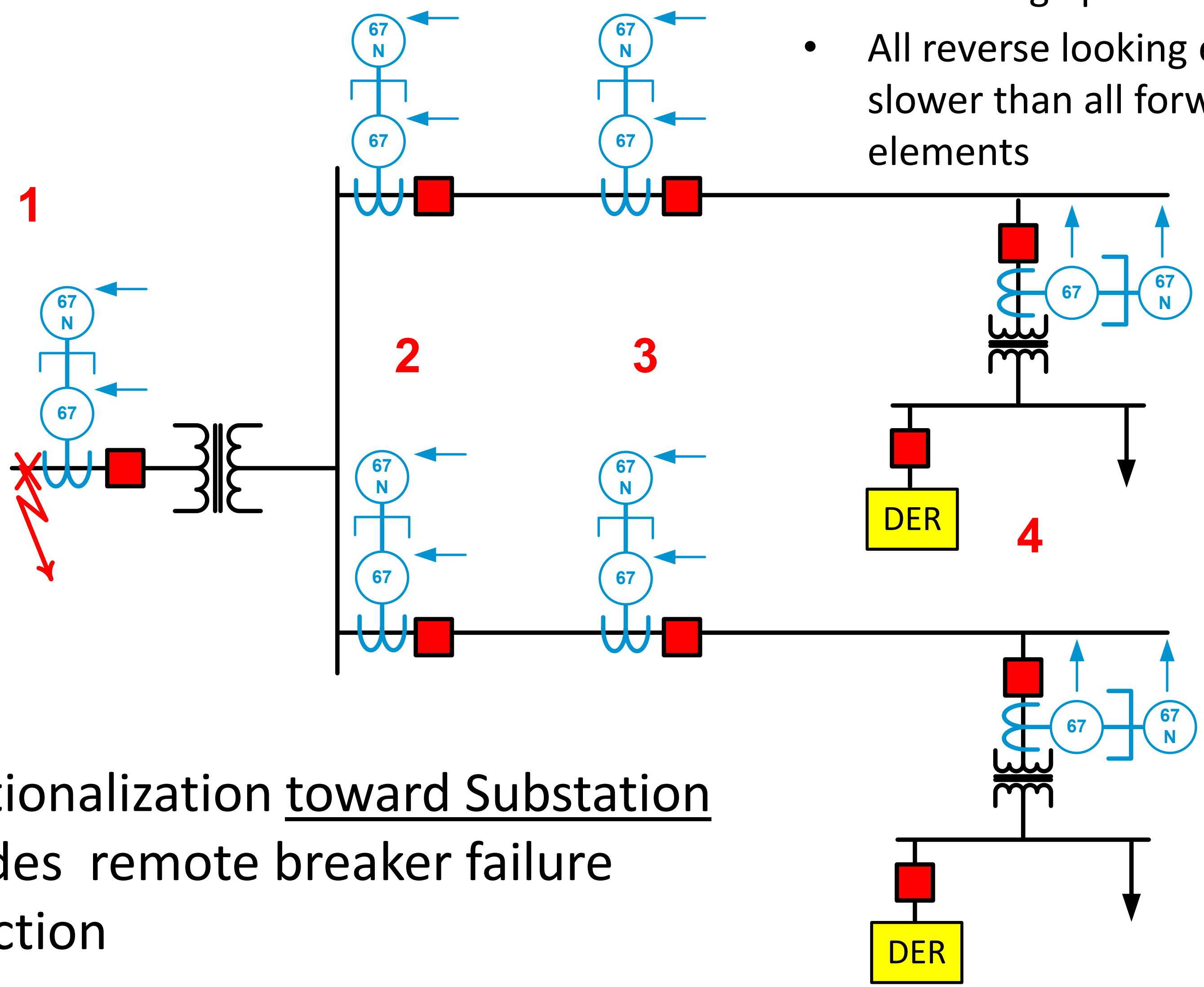
- Directional phase and ground overcurrent elements
- Use voltage polarization



Directionalization toward DER helps prevent sympathy trips from out-of-section faults

DER on System

- Directional phase and ground overcurrent elements
- Use voltage polarization
- All reverse looking elements trip slower than all forward looking elements



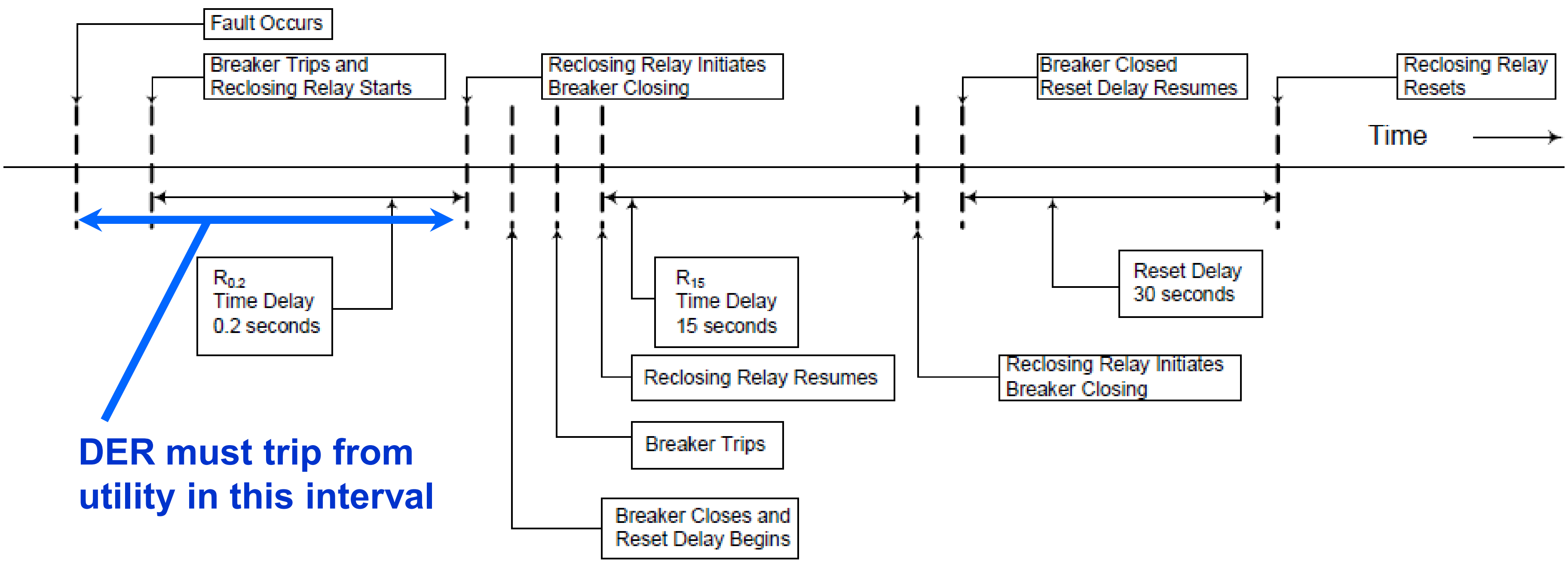
Directionalization toward Substation provides remote breaker failure protection

IEEE Distribution Practices Survey – 1/02

DER Impact on Utility Reclosing

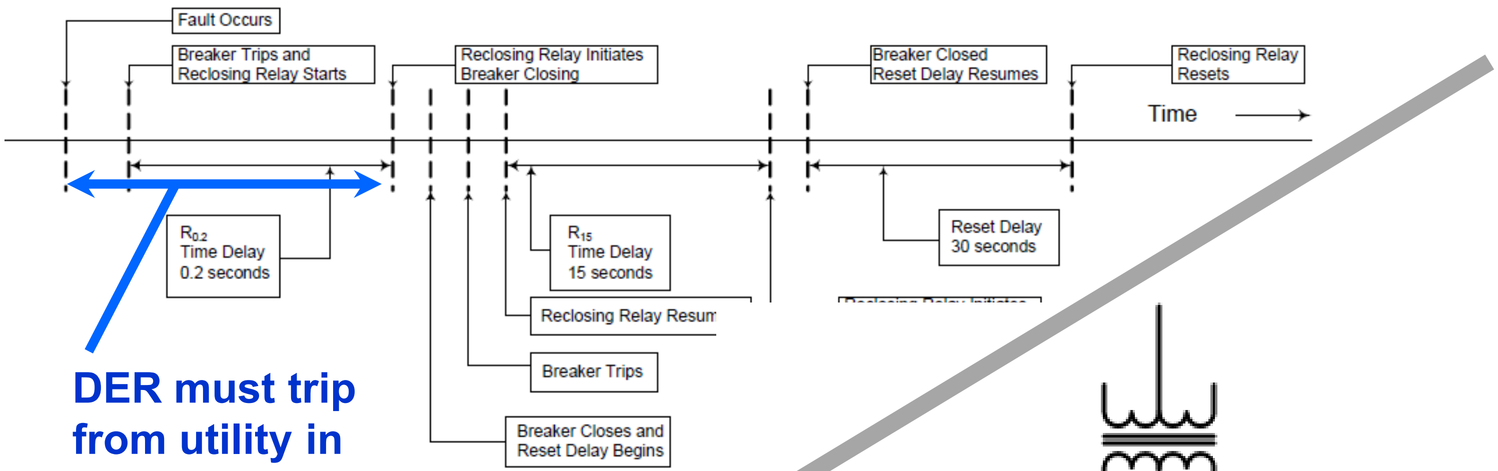
- Revise reclosing practices – 50%
- Added voltage relays to supervise reclosing – 36%
- Extend 1st shot reclose time – 26%
- Added transfer trip – 20%
- Eliminate reclosing – 14%
- Added sync check – 6%
- Reduce reclose attempts – 6%

Utility Reclosing Issues:
It is all about time……….

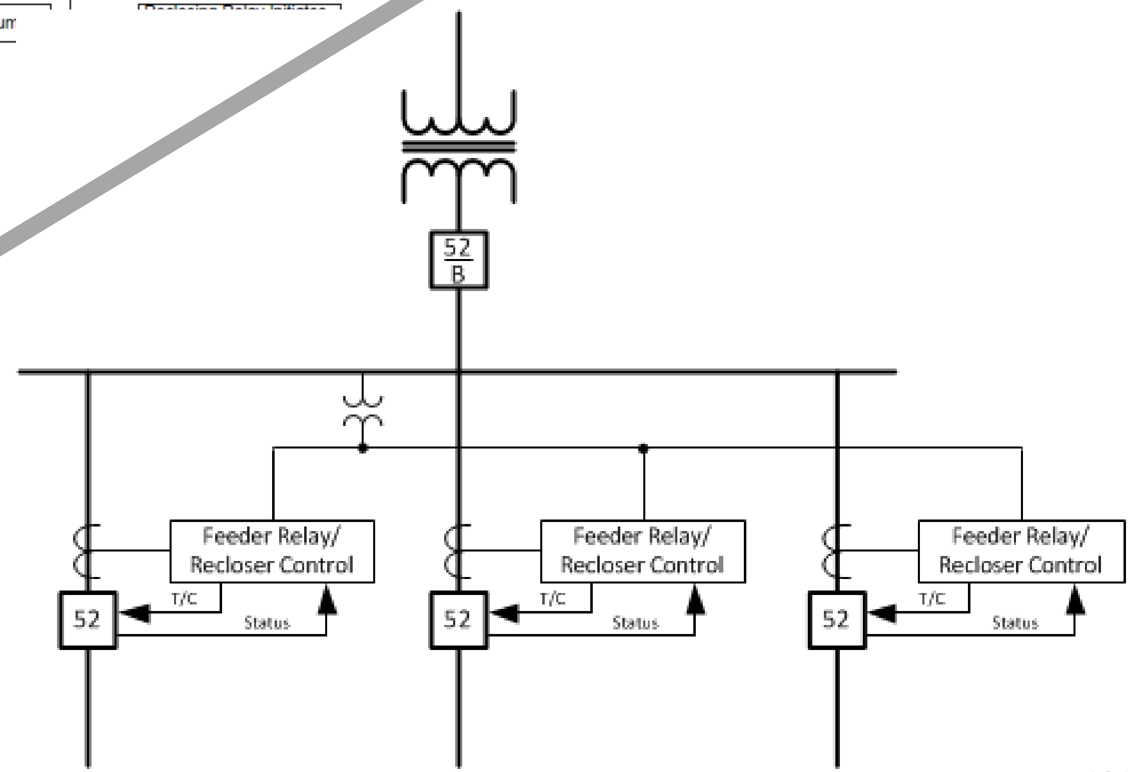


- If high-speed reclosing is employed, the DER interconnection protection must be faster!
- Clearing time includes protection operation and breaker opening

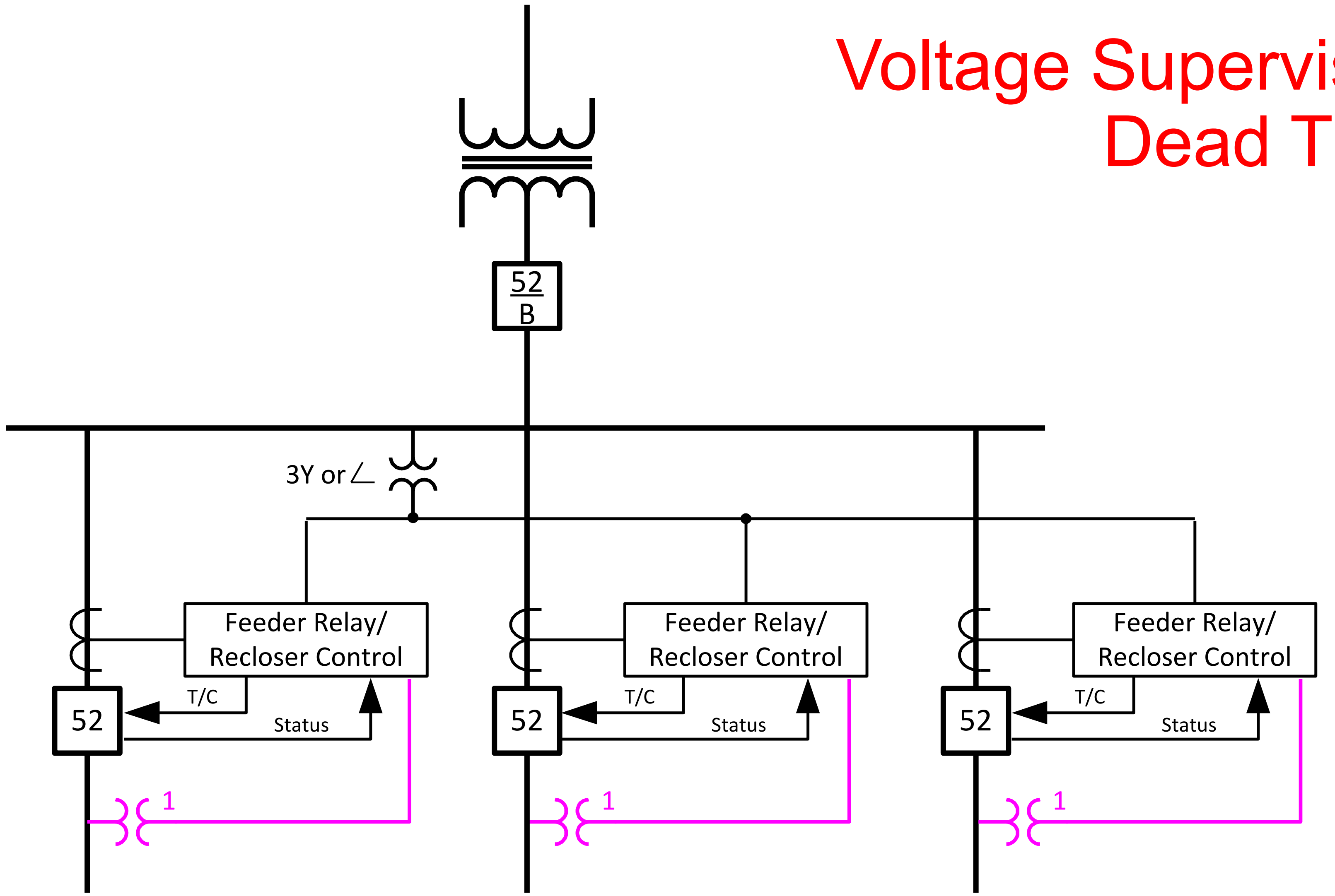
Utility Reclosing Issues:
It is all about time……….



DER must trip from utility in this interval

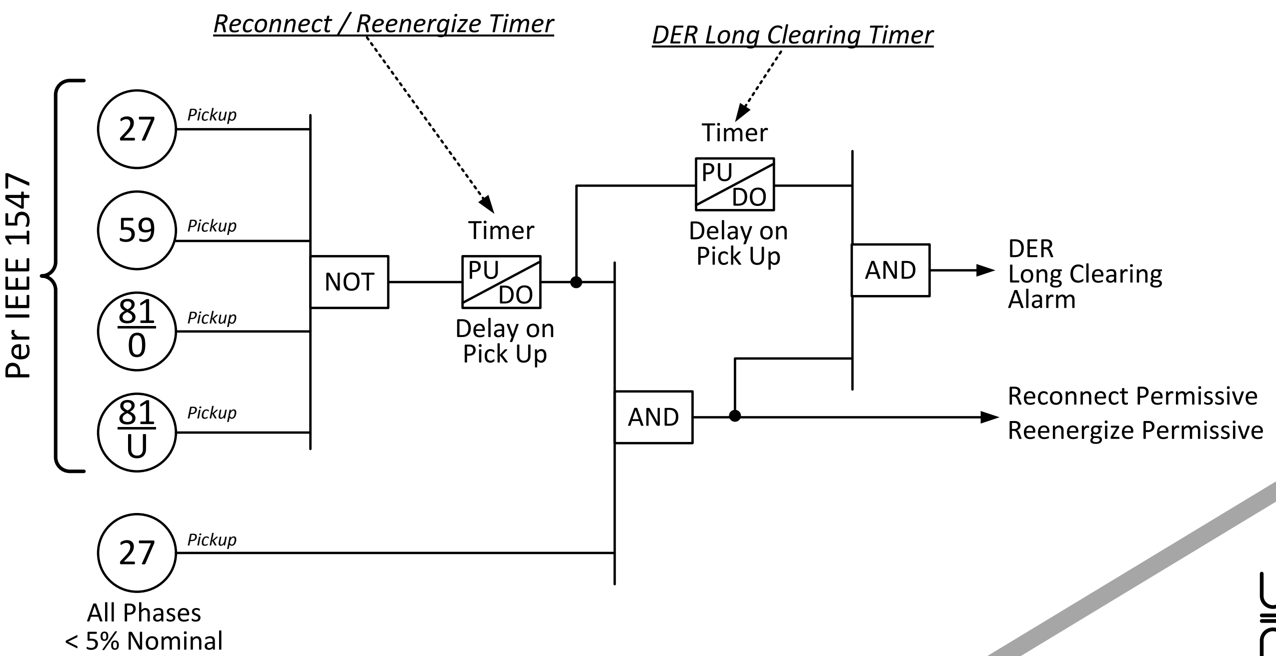


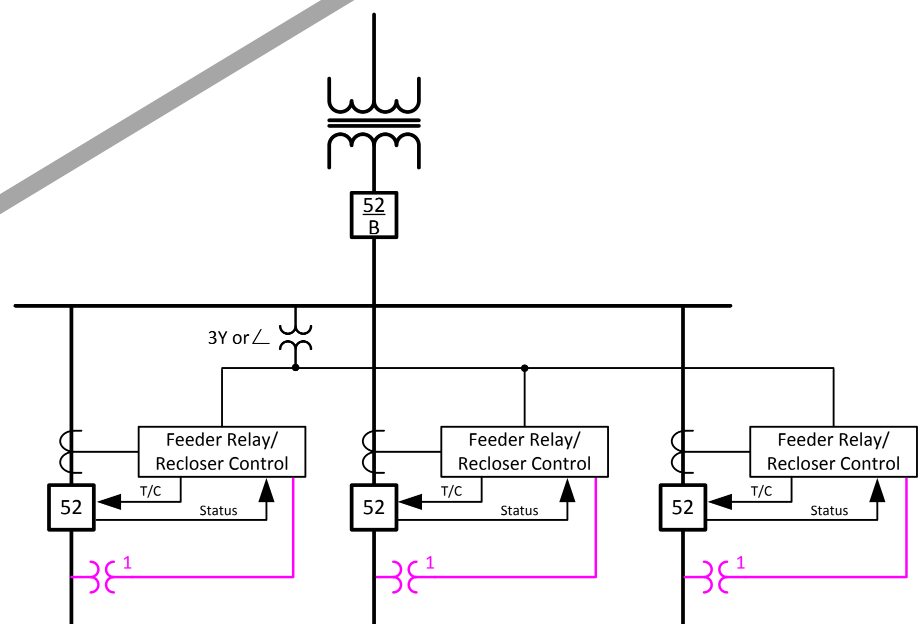
Voltage Supervised Dead Time



Use minimal dead time and voltage supervision for the reconnect t/reenergize permissive

Voltage Supervised Dead Time





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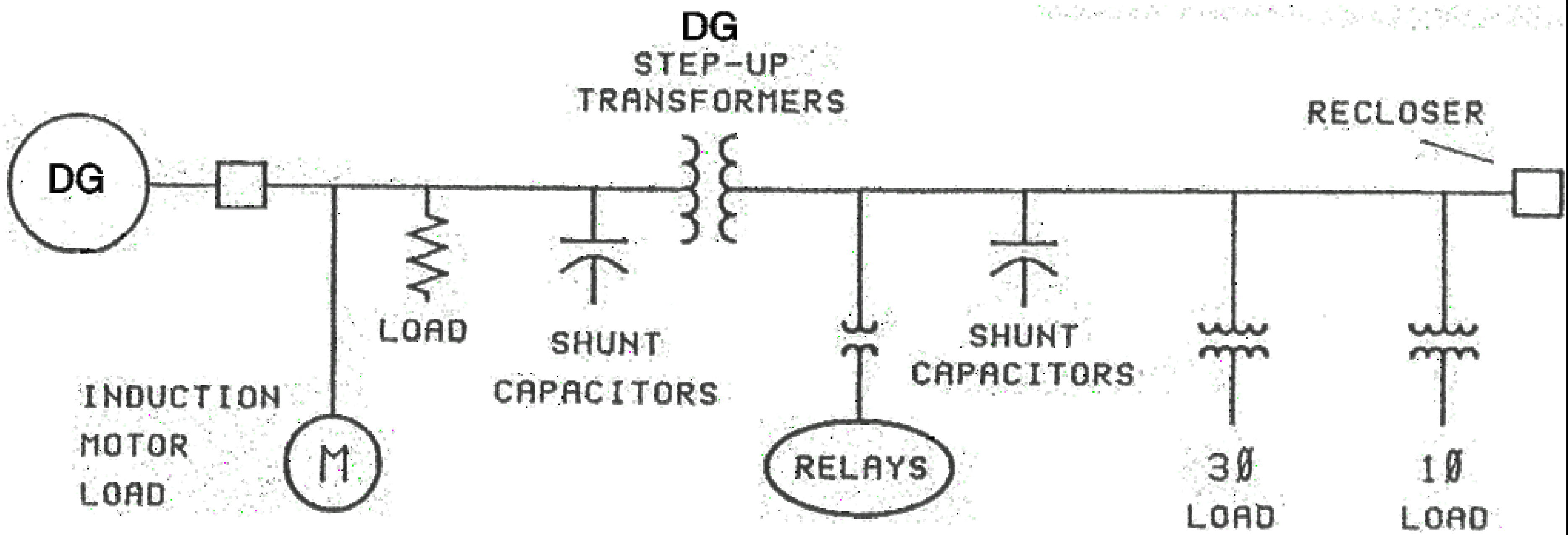
Ferroresonance

- Ferroresonance can take place between an induction generator and capacitors after utility disconnection from feeder
  - Ferroresonance can also occur from Synchronous Generators and Inverter-based DER!
- Generator is excited by capacitors if the reactive components of the generator (X_G) and aggregated capacitors (X_C) are close in value
- This interplay produces non-sinusoidal waveforms with high voltage peaks. This causes transformers to saturate, causing non-linearities that exacerbate the problem.

Ferroresonance: Test Circuit Setup

New York Field Tests- 1989

Field Test Circuit (NYSEG)



Schematic of Test Circuit.

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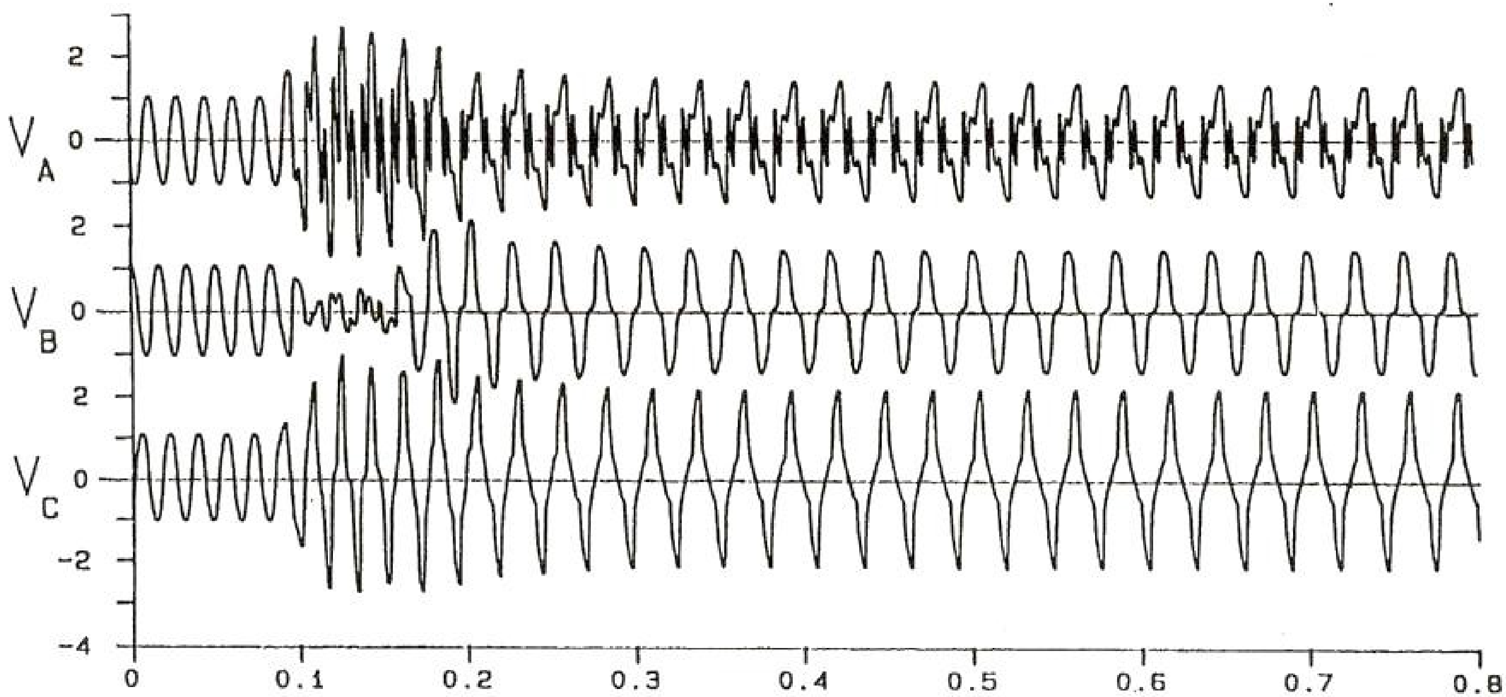
Ferroresonance: Observed Waveforms

New York Field Tests - 1989

Field Test Circuit (NYSEG)

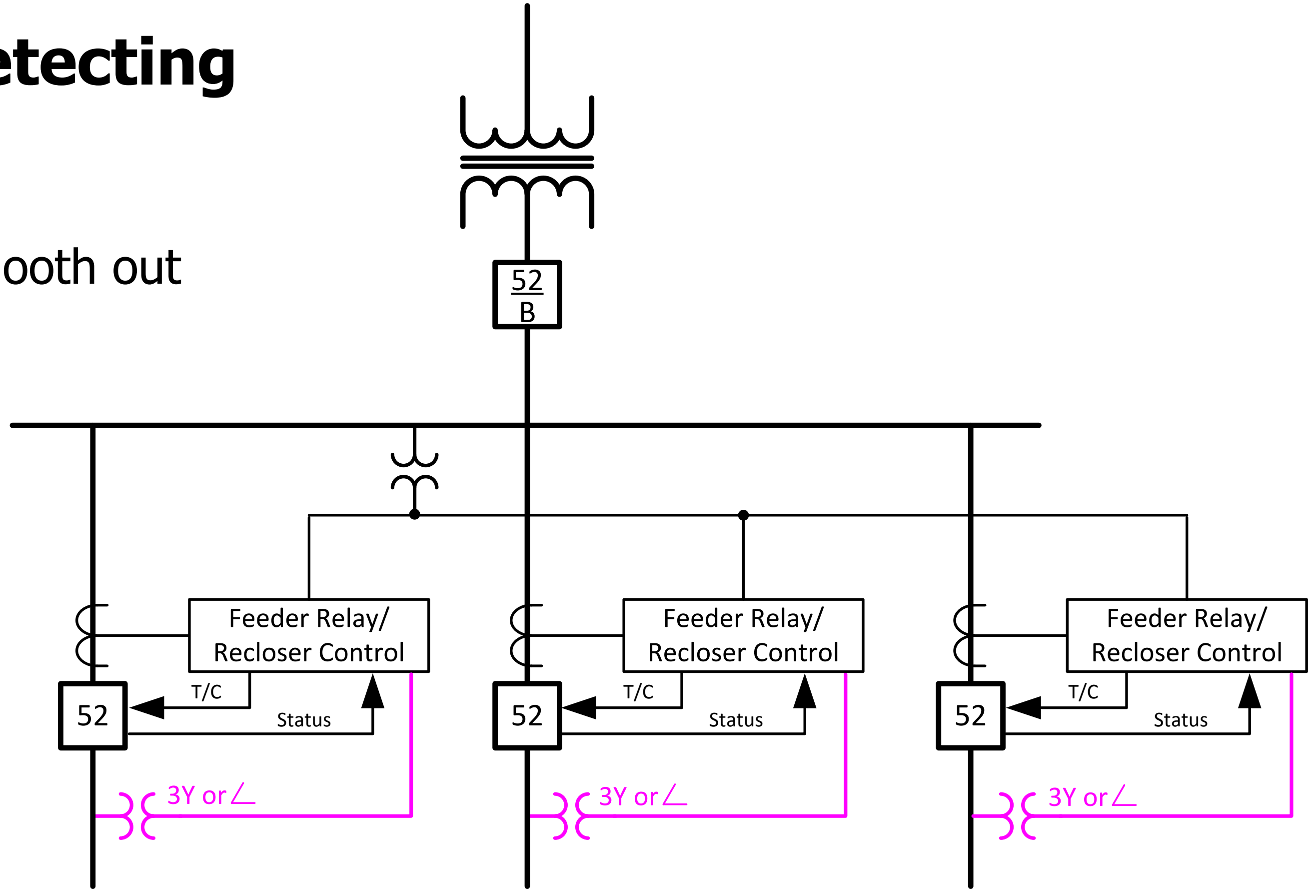


Conditions:

Wye-Wye Transformers, 100kVAr capacitance, 60kW generator, 12kW load

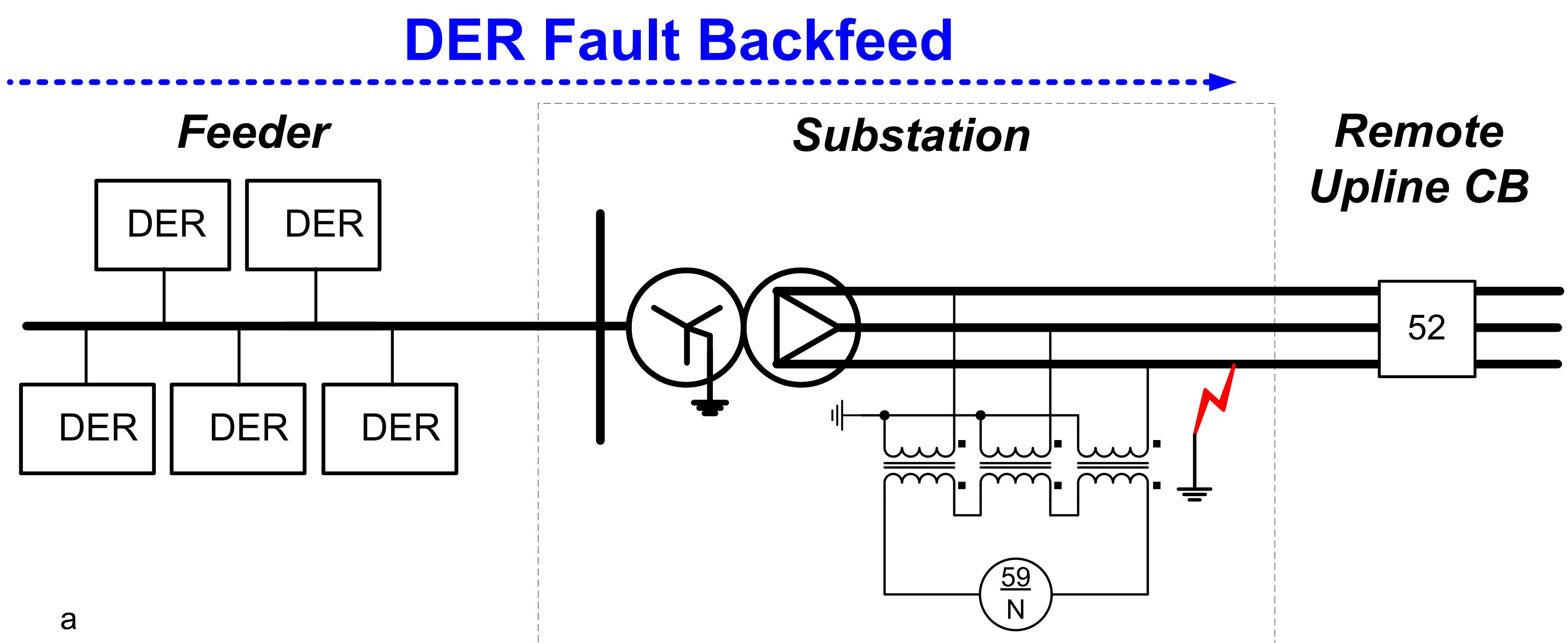
Ferroresonance

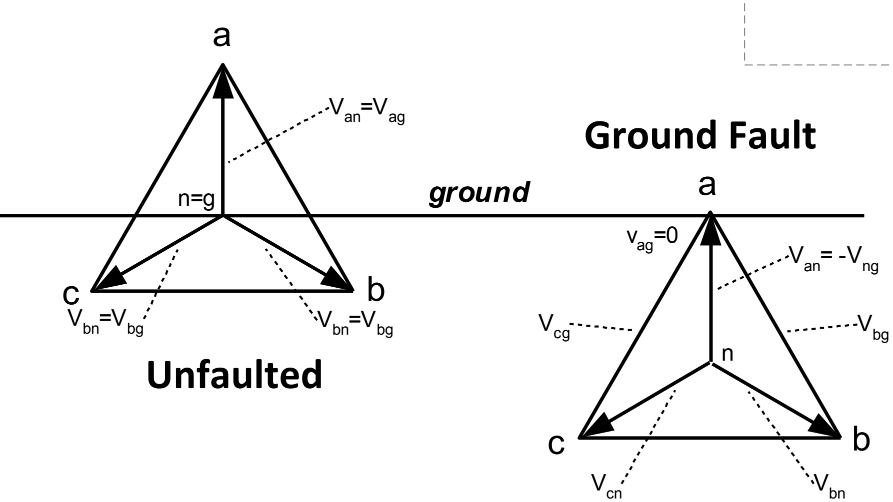
- Need a **peak detecting** relay element
  - "59I"
  - "RMSing" may smooth out high peaks



- May be applied at DER Interconnection (PoI)
- May be applied at feeder origin to detect ferroresonance after feeder is islanded (line side of CB)

Sensing Ungrounded System Ground Faults






ANY
QUESTIONS?

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Recommended Reading

- IEEE 1547 Series of Standards for Interconnecting Distributed Resources with Electric Power Systems, http://grouper.ieee.org/groups/scc21/
- IEEE 1547-2017 (Draft 6.7)
- IEEE 1547a, 2014, Standard for Interconnecting Distributed Resources with Electric Power Systems, Addendum 1.
- Application of Automated Controls for Voltage and Reactive Power Management – Initial Results, US DOE, 12/2012
- Beckwith Electric Company, M-2001D Loadtapchanger Control Instruction Book, Chapter 6, 2016.

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Recommended Reading

- "Smart Reverse Power Operating Mode for Distribution Voltage Regulators to Handle Distributed Generation along with Feeder Reconfiguration," Dr. Murty V.V.S. Yalla. Presented at the PacWorld Conference, 2015.
- R. Bravo B. Yinger, P. Arons, "Fault Induced Delayed Voltage Recovery (FIDVR) Indicators," IEEE T&D, 2014
- Distribution Line Protection Practices Industry Survey Results, Dec. 2002, IEEE PSRC Working Group Report
- D. James, J. Kueck, " Commercial Building Motor Protection Response Report," US DOE, Pacific Northwest National Laboratory, 2015

Recommended Reading

- Evaluating Conservation Voltage Reduction with WindMil, Milsoft, G. Shirek, 2011
- C37.230, IEEE Guide for Protective Relay Applications to Distribution Lines, IEEE Power System Relaying Committee, Second Edition, 2007
- 1547a and Rule 21, Smart Inverter Workshop, June 21, 2013, SCE
- Bob McFetridge, Barry Stephens, "Can a Grid Be Smart without Communications? A Look at IVVC Implementation: Georgia Power's Distribution Efficiency Program." Presented at the Clemson Power Systems Conference, 2013.

Recommended Reading

- Implementing VVO with DER Penetration, IEEE Innovative Smart Grid Technology (ISGT) Conference, Washington DC, 2017
- Chuck Whitaker, Jeff Newmiller, Michael Ropp, Benn Norris, "Renewable Systems Interconnection Study: Distributed Photovoltaic Systems Design and Technology Requirements," Sandia National Labs, Dec. 2012.
- Turan Gonen, *Electric Power Distribution Engineering,* 2008, pp. 398-404.
- On-Site Power Generation, by EGSA, ISBN# 0-9625949-4-6
- Effect of Distribution Automation on Protective Relaying, 2012, IEEE PSRC Working Group Report