Implementing Volt/VAR Optimization with DER Penetration

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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.”
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 = $\frac{\Delta P}{\Delta V}$ (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 1\textsuperscript{st} 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
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 (?)
• 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
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

25% of Feeder Length

50% of Feeder Load

126
120
114

Volts (secondary)

Voltage Profile

1 2 3 4 5 6 7 8

Loads only No VVO

25% of Feeder Length
Capacitors decrease losses proving flatter voltage profile
Capacitors decrease losses proving flatter voltage profile
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 1\textsuperscript{st} house protection!!!
Line Drop Compensation Principle

Without LDC

- Voltage
- Distance
- Load Center
- Regulated Bus
- Fixed
- Peak Loading
- Light Loading
Line Drop Compensation Principle

With LDC

- Peak Loading
- Light Loading

Voltage

Distance

Regulated Bus

Load Center

Fixed
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:
- 120V
- 118V
- 115V

With LDC at full Load and unity power factor (X=5):
- 125V
- 123V
- 120V
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

Volts (Secondary)

<table>
<thead>
<tr>
<th>Capacitor Bank State</th>
<th>ON</th>
<th>OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>114</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>126</td>
<td></td>
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</tr>
</tbody>
</table>

Deadband
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

Inverter (Var)

Injection/Capacitive

Absorption/Inductive

Reference

Deadband

Volts (Secondary)

114 120 126
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
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.

![Graph showing Normal, Non-CVR Application with Negative Linear VAR Bias. The graph illustrates the voltage levels for Lagging VARs (+) and Leading VARs (-).]
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

**Normal, Non-CVR Application**

**Negative Linear VAR Bias**

- Lagging VARs (+)
  - 120V
  - 118V
  - 116V
- Leading VARs (-)
  - 122V
  - 124V
  - 126V
VAR-Bias: Near or at Unity PF

Normal, Non-CVR Application

\[ \text{Negative Linear VAR Bias} \]

- \(124V\)
- \(122V\)
- \(120V\)
- \(118V\)
- \(116V\)

Lagging VARs (⁺)  Leading VARs (⁻)

OLTC Tap Down
OLTC Tap Up
VAR-Bias:
Bandcenter Decreases with Lagging VAR

Normal, Non-CVR Application

Negative Linear VAR Bias

As voltage falls:
- CAPs switch ON
- DER exports VAr
- Voltage rises from increase in VAr

Lagging VARs (+)
Leading VARs (-)
VAR-Bias:

Bandcenter Increases with Leading VAR

Normal, Non-CVR Application

Negative Linear VAR Bias

As voltage rises:
- CAPs switch OFF
- DER absorbs VAr
- Voltage lowers from decrease in VAr

NO Tap Command

Leading VARs (-)

124V
122V
120V
118V
116V

Lagging VARs (+)
Normal Operation:
Negative VAR-Bias

- Voltage near center of band
- Near unity power factor
Normal Operation: Negative VAR-Bias

Normal, Non-CVR Application

*Negative* Linear VAR Bias

- 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

- 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

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

NORMAL OPERATION (non-CVR)
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

- CAPS and DER furthest away from source have shorter time delay than upline similar devices.
- This example 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.

![Diagram of voltage settings and timings with labels and timing values: 3V 80 sec., 70 sec., 75 sec., 60 sec., 3V 95 sec., 45 sec., 50 sec., 30 sec., 52, VLOW, VHIGH, VAr OUT, VAr IN, REG, DER, CAP.]
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
  - $V = I \times R$ 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)
  ▪ 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

<table>
<thead>
<tr>
<th>Constant Power (PQ or kVA)</th>
<th>Constant Impedance (Z)</th>
<th>Constant Current (I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motors (at rated load)</td>
<td>Incandescent/Dimmable LED Lighting</td>
<td>Welding Units</td>
</tr>
<tr>
<td>Power Supplies</td>
<td>Resistive (Strip) Water Heaters</td>
<td>Electroplating</td>
</tr>
<tr>
<td>Fluorescent/LED Lighting</td>
<td>Electric Stoves</td>
<td></td>
</tr>
<tr>
<td>Washing Machines</td>
<td>Clothes Dryers</td>
<td></td>
</tr>
</tbody>
</table>

\[ CVR_f = \frac{\Delta P}{\Delta V} \]

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

Evaluating Conservation Voltage Reduction with WindMil® - Milsoft
Load Models and CVR Factor

\[ CVR_f = \frac{\Delta P}{\Delta V} \]
- 0.5 is typical
- Greater than 1 is really good

Constant Power (PQ or kVA)
- Motors (at rated load)
- Power Supplies
- Fluorescent/LED Lighting
- Washing Machines

Constant Impedance (Z)
- Incandescent/Dimmable LED Lighting
- Resistive (Strip) Water Heaters
- Electric Stoves
- Clothes Dryers

Constant Current (I)
- Welding Units
- Electroplating

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

In normal, non-CVR application, the linear VAR bias is negative.

### Normal, Non-CVR Application

**Negative** Linear VAR Bias

- 124V
- 122V
- 120V
- 118V
- 116V

**Lagging VARs (+)**

**Leading VARs (-)**
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 Application Diagram](image-url)
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

- 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

<table>
<thead>
<tr>
<th>Beckwith Reverse Power Mode</th>
<th>Cooper/Siemens Reverse Power Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block</td>
<td>Locked Forward Mode</td>
</tr>
<tr>
<td>Regulate Forward (Ignore) *</td>
<td>Reverse Idle Mode</td>
</tr>
<tr>
<td>Regulate Reverse</td>
<td>Bi-Directional Mode</td>
</tr>
<tr>
<td>Return to Neutral *</td>
<td>Neutral Idle Mode</td>
</tr>
<tr>
<td>Regulate in Reverse (Measured) *</td>
<td>Bi-Directional Mode</td>
</tr>
<tr>
<td>Distributed Generation</td>
<td>Cogeneration Mode</td>
</tr>
<tr>
<td>Auto Determination</td>
<td>None</td>
</tr>
</tbody>
</table>

*Low Current block feature must also be enabled to be equivalent to this Cooper Reverse Power Mode.*
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
Regulating **forward**, +LDC *raises* bandcenter as **FPF** becomes larger

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

**DG Mode**
Regulate Forward
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), \textit{forward regulation} should be employed
  - With \textit{reconfig} (strong source switches), \textit{reverse regulation} should be employed

\textbf{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?
Volt/VAR Control Considerations from DA

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

Reverse Powerflow with DER

Forward Powerflow without DER
No RPF Source: Open Loop

Forward Powerflow without Reconfig

Forward Powerflow without Reconfig

Forward Powerflow without Reconfig

Forward Powerflow without Reconfig

OLTC XFRM-1

Load

OLTC REG-1

Load

OLTC REG-2

Load

OLTC REG-3

Load

OLTC REG-4

Load
Strong FPF Source: Reconfig
Strong RPF Source: Reconfig
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
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
Simulation of LTC Transformer/Regulator with Two sources: Simplified Model

\[ VT_1 = 100\% - X_1 \cdot \left( \frac{\Delta V}{X_1 + X_T + X_2} \right) \]  \hspace{1cm} (1)

\[ VT_2 = 100\% + X_2 \cdot \left( \frac{\Delta V}{X_1 + X_T + X_2} \right) \]  \hspace{1cm} (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)
## Simulation Results

<table>
<thead>
<tr>
<th>Case #</th>
<th>DPI₁</th>
<th>DPI₂</th>
<th>Reactive Current (Iₓ) Through the transformer</th>
<th>VT₁</th>
<th>VT₂</th>
<th>ΔV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2%</td>
<td>∞</td>
<td>0</td>
<td>100%</td>
<td>100.625%</td>
<td>.625</td>
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<tr>
<td>2</td>
<td>∞</td>
<td>2%</td>
<td>0</td>
<td>99.375%</td>
<td>100%</td>
<td>.625</td>
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<tr>
<td>3</td>
<td>2%</td>
<td>20%</td>
<td>1.953 %</td>
<td>99.96%</td>
<td>100.4%</td>
<td>.04</td>
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<td>20%</td>
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<tr>
<td>5</td>
<td>2%</td>
<td>2%</td>
<td>7.14 %</td>
<td>99.85%</td>
<td>100.14%</td>
<td>.29</td>
</tr>
</tbody>
</table>

1 & 2: System reconfiguration; one source, radial
3 & 4: DER (weak) vs. System (strong)
5: Two weak sources
Autodetermination of Source Strength with RPF

- When RPF is detected, operation is set initially to “DG Mode”
- $\Delta V$ is measured for two tap operations:
  $$\Delta V = V_{MBT} - V_{MAT}$$
  where $V_{MBT} = \text{measured load side voltage just before a tap change}$
  $V_{MAT} = \text{measured load side voltage one second after the tap change}$

- If the measured $\Delta V$ 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 $\Delta V$ is $\leq 0.31V$ (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

User Manually Designates Source Strength

"DG Mode"

"Regulate Reverse"
Reverse Power Source Strength Determination: Autodetermination

Reverse Power Flow Detected

Autodetermination
Dynamiclly Designates Source Strength

Weak

“DG Mode”

Strong

“Regulate Reverse”
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)

**Forward Power**

**Reverse Power**

**Distributed Generation**
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

Bandwidth (2 VAC)

119 VAC

120 VAC

121 VAC

< Time Delay

Time Delay

> Time Delay

Lower tap Command
In this diagram, the inverse curve OLTC time characteristic is plotted, relating the time delay (as a percentage of the inverse time delay setting) to the voltage deviation in multiples of $\Delta V$. The equation $\Delta V = BW/2$ is indicated on the graph.
Inverse TD Example

Example
Bandcenter = 120 V
Bandwidth = 2 V
Inverse Time Delay = 120 V
Sensed Voltage = 123 V
Time Delay Factor = \((V_{\text{sense}} - V_{\text{bandcenter}})/(BW/2)\)
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.
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**
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
Directionalization **toward DER** helps prevent sympathy trips from out-of-section faults

- Directional phase and ground overcurrent elements
- Use voltage polarization
Directionalization **toward Substation** provides remote breaker failure protection

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

Per IEEE 1547

- Reconnect / Reenergize Timer
- DER Long Clearing Timer

Reconnect Permissive
Reenergize Permissive

Timer
PU
DO

Delay on
Pick Up

ALL Phases
< 5% Nominal

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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.
New York Field Tests - 1989
Field Test Circuit (NYSEG)

Ferroresonance: Test Circuit Setup

Schematic of Test Circuit.
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)
ANY QUESTIONS?
Recommended Reading


• IEEE 1547-2017 (Draft 6.7)


• Application of Automated Controls for Voltage and Reactive Power Management – Initial Results, US DOE, 12/2012

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.


Recommended Reading

- Evaluating Conservation Voltage Reduction with WindMil, Milsoft, G. Shirek, 2011
- 1547a and Rule 21, Smart Inverter Workshop, June 21, 2013, SCE
Recommended Reading

• Implementing VVO with DER Penetration, IEEE Innovative Smart Grid Technology (ISGT) Conference, Washington DC, 2017


• On-Site Power Generation, by EGSA, ISBN# 0-9625949-4-6