Step Voltage Regulators

Don Wareham – Field Application Engineer
Today’s Agenda

- Introduction
- Voltage Regulator theory
- Voltage Regulator application considerations
- Installation and proper bypassing
- Wrap-up/questions
VLD = Voltage drop due to line losses
Regulator Theory – Purpose

• Why is voltage regulation needed?
  • Power quality criteria requires a constant voltage despite variations in load current
  • Load current variations are due to:
    • New loads
    • Load profiles – Daily and Seasonal
Why is Voltage Regulation Needed?

The inability to supply proper voltage effects the following:

<table>
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<th>Heating Element</th>
<th>Lighting</th>
<th>Motors</th>
<th>Electronics</th>
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</thead>
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<td><img src="image1" alt="Heating Element" /></td>
<td><img src="image2" alt="Lighting" /></td>
<td><img src="image3" alt="Motors" /></td>
<td><img src="image4" alt="Electronics" /></td>
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</table>

- A 10% voltage reduction reduces heat output by 9.75%
- Overvoltage may cause burnouts.

- A 10% voltage reduction reduces light output by 30%
- A 10% overvoltage reduces lamp life 70%.
- Incandescent light bulbs wear out much faster at higher voltages

- Low voltage causes overheating, reduced starting and running torques and overload capacity
- Operating at 90% nominal, the full load current is 10 to 50% higher; temperature rises by 10 to 15%
- At a reduced voltage, the motor has reduced starting torque

- Low voltage on computers and televisions can cause them to become inoperative

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Regulator Theory – Purpose

Voltage Regulators: Solve voltage drop problem

OLTC

L₁ L₄ L₂ L₅ L₃ L₆ L₇

+5%
Nominal Voltage
--5%

Applied at Substation and midpoint of Feeder.
Theory and Application

Methods of Regulation

(A) Regulation with OLTC Transformers

(B) Bus Regulation

(C) Feeder Regulation

Medium Voltage Substations

SVR = Step-Voltage Regulator

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Why Voltage Regulators vs. LTC?

- Regulate individual phases
- Separate regulation from voltage transformation
- Fast change out
- Maintenance will not disrupt service
- Standardized product
- Readily Available vs sub transformer LTs
Why LTC vs. Voltage Regulators?

- LTC ratings go beyond VR ratings
- Some prefer 3Ph Ganged Operation for dedicated 3Ph Loads
- Footprint
What is a Voltage Regulator?

- Voltage Regulator - A device which will provide a constant voltage output under varying input voltages and load currents.
- By standards, regulates +10% voltage and –10% voltage.
- Total of 33 steps; = 5/8% voltage per tap.
- 16 steps in the Raise direction, 16 steps in the Lower direction, and one Neutral position.
Three Basic Parts of a Voltage Regulator

• Autotransformer - A transformer in which part of one winding is common to both the primary and secondary windings
• Load Tap Changer - A switch designed to work under load to change the configuration of a transformer coil
• Voltage Regulator Control - A control which senses the system and automatically commands the tap changer.
TYPE A REGULATOR

SHUNT WINDING

SERIES WINDING

1.25%

REVERSING SWITCH

CURRENT X-FORMER

POTENTIAL TRANSFORMER

CONTROL

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Type A Design – “Straight”
TYPE B REGULATOR

REVERSING SWITCH

1.25% SERIES WINDING

CURRENT X-FORMER

SHUNT WINDING

CONTROL WINDING

CONTROL

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Type B Design – “Inverted”
Type A verses Type B Differences

Differences from Customer’s Point of View

1. No difference in external connections or operation

2. Type B Regulation Range is +10% and -8.3%. Type A Regulation Range is +10% and -10%

3. It is okay to 3 phase bank a mix of Type A & Type B units

4. If paralleling, place the affected units in the Neutral position during the switching operation. Having them on the same step other than Neutral can generate circulating current between the banks due to voltage differences caused by differences in regulation between a Type A and Type B.
Pressure Relief Device Rating and Location Defined
- Venting pressure = 34.5 kPa (5 psig) and flow of 50 Standard Cubic Feet per Minute SCFM
- Located on the tank above the 110 °C top fluid level, as determined by the manufacturer's calculation. It shall not be located in the quadrant of the tank that contains the control device.

Short Circuit Requirement Revised
- First Cycle Asymmetrical Peak increased to 2.60 from 2.26 for ratings greater than 165 kVA.
- Maximum short circuit current changed from 20,000 amps to 16,000 amps. Design must meet 25 times the rating or 16,000 maximum, whichever is less.

Nameplate Info Additions
- Symmetrical short circuit withstand ampere rating with time duration
- Tap changer model
- Ratio of load current to switched current (if series transformer is present)

Support Lugs (Hanger Bracket) Requirements
- Support lugs for pole mounting shall be provided for ratings 288 kVA and less, with rated line current of 328 amps or less.
- Substation voltage regulators shall be arranged for rolling in two directions: parallel to and right angles to one side of the voltage regulator. Bases for substation mounting shall be provided for 165 kVA and higher.

Bushing Terminals Requirements Added
- 4-hole spade terminals to be provided on current ratings above 668 amps
Regulator Sizing

Given:  10 MVA, 3φ transformer, 13.2 kV system voltage, grounded wye

Find:  The proper regulator rating to use……

• Watch the units!  10 MVA = 10,000 KVA
• For the regulator current rating:

\[
\text{Line current} = \frac{\text{Transformer size}}{\sqrt[3]{\text{VL-L}} \times 3} = \frac{10,000 \text{kVA}}{13.2 \text{kV} \times 1.732} = 438 \text{ A}
\]

• For Regulator kVA Rating:

\[
\text{kVA rating} = V_{L-G} \times I \times \% \text{ Regulation} = 7.62 \text{kV} \times 438 \times 0.10 = 333 \text{ kVA}
\]

• Choose standard rating from tables
<table>
<thead>
<tr>
<th>Rated Volts</th>
<th>Rated kVA</th>
<th>Regulation Range</th>
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<td></td>
<td>±10%</td>
<td>±7 1/2%</td>
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<td>±8 3/4%</td>
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**Table 3. ADD-AMP Capabilities of 60 Hz Ratings**

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<th>Rated Volts</th>
<th>Rated kVA</th>
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Single Phase Voltage Regulators

- Self contained
- +/- 10% regulation in 32- 5/8% steps
- 55/65 °C average winding rise (12% more capacity)
- 25 to 2000 kVA (pad 875 A)
- 2400 V to 34500 V (60-200 BIL)
- Mineral oil or FR3
- Fan cooling option (33% more capacity)
- Substation, pole and pad mounted designs
Padmount Voltage Regulator
Basic Control Settings Function Codes

- FC 1 - Set Voltage
- FC 2 - Bandwidth
- FC 3 - Time Delay
- FC 4 – LDC Resistance
- FC 5 – LDC Reactance
- FC 39 - Source Side Calculation
  - FC 140 Regulator Type
- FC 41 - Regulation Configuration
- FC 42 - Control Operating Mode
- FC 43 - Systems Voltage (Nominal)
- FC 44 - PT Ratio
- FC 45 - CT Ratio
- FC 49 - Tap Changer Type

- FC 50 - Clock
  - FC 143 - Time Format
  - FC 142 - Date Format
- FC 56 - Reverse Sensing Mode
- FC 69 - Auto Blocking Status
- FC 70 - Voltage Reduction
- FC 80 - Voltage Limiter Mode
Set Voltage

- The voltage level (on 120V base) to which the control will regulate
- Settable for both forward & reverse power flow
Bandwidth

• The *total* voltage range around the set voltage which the control will consider acceptable

• Acceptable voltage range defined as:
  \[ \text{Range} = \text{SV} \pm \frac{1}{2} \text{BW} \]
Time Delay

• The number of seconds the control waits, from the start of an out-of-band condition, before initiating a tap change
Given: TD = 30
Cascading Regulators

Rule 1: Each succeeding regulator in series down line from the source requires a longer time delay

Rule 2: The minimum time delay from one regulator to the next in cascade is 15 seconds
Voltage Profile
Without LDC

Maximum voltage
Min. load
Minimum voltage
Max. load

VOLTAGE

128
124
120
116
112

FEEDER DISTANCE
Line Drop Compensation

- Control compensates for line losses – load, resistance and impedance are considered.
- Dialing in line drop compensation moves the set voltage point from the load bushing to the ‘Load Center’. $V_R > 0$, and $V_X > 0$. 

![Line Drop Compensation Diagram](image-url)
Regulator - Capacitor Comparison

![Graph showing the comparison between voltage and feeder distance with R and C labels.](image-url)
Coordination w/Capacitors

- Any capacitor on the source side of a regulator does not affect regulator settings, as current through the line drop compensator is proportional to load current.
- Any capacitor at the load center of a regulator (or beyond) does not affect regulator settings as current through the line drop compensator is proportional to load current.
Coordination w/Capacitors

• A regulator with capacitors located between the regulator and the load center must have its set voltage adjusted to compensate for additional voltage drop due to capacitor current flowing back to the source
• Only applies if LDC setting are used
Reverse Sensing Mode

- Reverse Sensing Mode defines power flow condition settings
- Reverse Sensing Mode Options
  - Locked Forward (default setting)
  - Locked Reverse
  - Reverse Idle
  - Bi-directional
  - Neutral Idle
  - Co-generation
  - React Bi-directional
When DG generates power that does not meet the load demand, DG will offset current through the VR and may cause VR to tap down, considering this situation as light loading.

When DG generates power that exceeds the load demand, some power is exported back to the power system. In this case, DG may increase current through the VR and cause VR to tap up, considering this situation as heavy loading. This may occur when the VR source voltage is near ANSI upper limit. As a result, voltage at the load may be excessive.
Co-Generation Mode

- When DG generates real power that does not meet the local load demand, some real power is provided by the power system. The VR will regulate voltage at the DG location in Forward Mode.
- When DG generates real power that exceeds the load demand, some real power is exported back to the power system. However, the VR will not reverse direction and will continue to regulate voltage on the DG side.

Regulated voltage during forward or reverse power flow
Co-Generation Mode

Why Co-Generation Mode may not be suitable for Loop Scheme applications?

When one source is lost, power flow will change and some VRs should change direction of the voltage regulation.
Reactive Bi-Directional Mode

- DG operates with constant power factor mode, consuming some reactive power from the system. The VR controls voltage on its load side (DG side).
- The VR controls voltage on its load side irrespective of the real power flow that can be in both directions depending on the DG operation.

Direction of voltage regulation during normal operation (Tie Recloser Open)

Source 1
- CB1 Closed

Source 2
- CB2 Closed

Tie Recloser Open
Reactive Bi-Directional Mode

- When the Tie Recloser is closed and CB1 open, the reactive power through the VR will change. When the VR detects the reactive power change, it will change the direction of the voltage regulation and will regulate voltage on the CB1 side.

Direction of voltage regulation during Loss of Source 1 (CB1 Open) (Tie Recloser Closed)
Solar Field Application

- Application: Need to be able to react to a 12-20% drop in utility voltage and correct it to 12% in less than 5 seconds.
- Solution: Utilize voltage limiting threshold to establish limits to initiate quick response to bring voltage back within threshold with minimal time delay

![Response to Undervoltage](image)
Voltage Limiting

• Places a high and/or low limit on the output at the load bushing
• Highest priority of all operating functions
• Options
  • Off
  • High limit only; then requires High Limit Value
  • High & Low limits; then requires High and Low Limits Values.
• Default value = Off
Voltage Limiter Response

- High Limit + 3 volts
- High Limit
- High Bandwidth Edge
- Set Voltage
- Low Bandwidth Edge
- Low Limit
- Low Limit + 3 volts

- **c=0**
  - C is adjustable on CL-7

- **c=10 (CL-6)**
  - Response delay between tap changes adjustable on CL-7

- **c=30**
  - 2s delay between tap changes

**Time Delay counter (C) activated**

**Time Delay = 30 Seconds**
Regulator Installation

- Ground the regulator tank AND the control cabinet.
Connections

4 Wire grounded wye:
• 3 regulators required
• ± 10% regulation

3 Wire open delta:
• 2 regulators required
• ± 10% regulation

3 Wire closed delta:
• 3 regulators required
• ± 15% regulation
Paralleling Regulators

2 situations to consider:

- Continuous Parallel operation (in substation)
- Tying Feeders through N.O. point (or with Bus Tie switch)
Paralleling Regulators

Simplified Diagram – 2 Voltage sources, 2 Impedances

Must have:
- Same %Z
- Same turns ratio

Regulators must use a “Leader-Follower” control setup
Paralleling Regulators

Tying Feeders through a N.O. switching operation

How do you set the Regulators?
Block Regulators (at least one)
- Match Tap position? What tap?
- Match Voltage? Where?
- Impedance is your friend
Bypassing a Regulator

Definition: Bypassing means installing a regulator or removing a regulator from service.

⚠️ Warning!

Installing or removing the regulator with the tap changer off neutral will short circuit part of the series winding! Before bypassing, the regulator must be in neutral.
Bypassing a Regulator
Prior to Bypassing

- Place the regulator in neutral position
- A minimum of four indications are recommended for neutral determination.
  - Neutral lamp is “on” continuously
  - Verify the tap position of the control indicates Neutral
  - Position indicator is in neutral position
  - Verify that there is no voltage difference between the S and L bushings
Theory and Application
BYPASSING

1 step = 5/8% = .00625

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Bypassing a Regulator
Prior to Bypassing

- Take action to prevent the tap changer motor operation

- Power switch is OFF
- ‘Auto/Off/Manual’ switch is OFF
- Remove motor fuse
- V1 & V6 knife switches are OPEN
Bypassing
Regulator Connected Line-to-Ground (GY)

Source

Phase A

Disconnect

Bypass

Disconnect

SL

S

L

Load

Neutral
Bypassing - Remove Procedure
Regulator Connected Line-to-Ground (GY)

Step 1 is Critical Operation.
Bypassing
Regulator Connected Line-to-Line (Delta)
Bypassing - Remove Procedure
Regulator Connected Line-to-Line (Delta)

Step 1 is Critical Operation.
Regulators

• Questions??