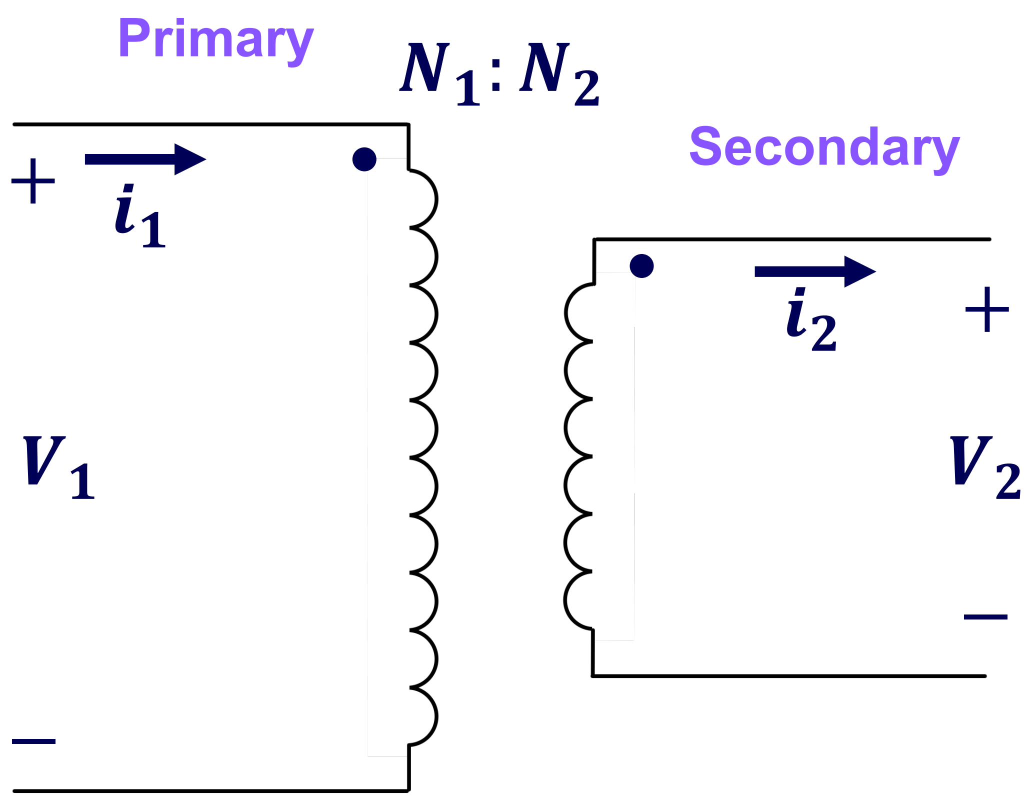
Regulator Theory

Regulator Theory

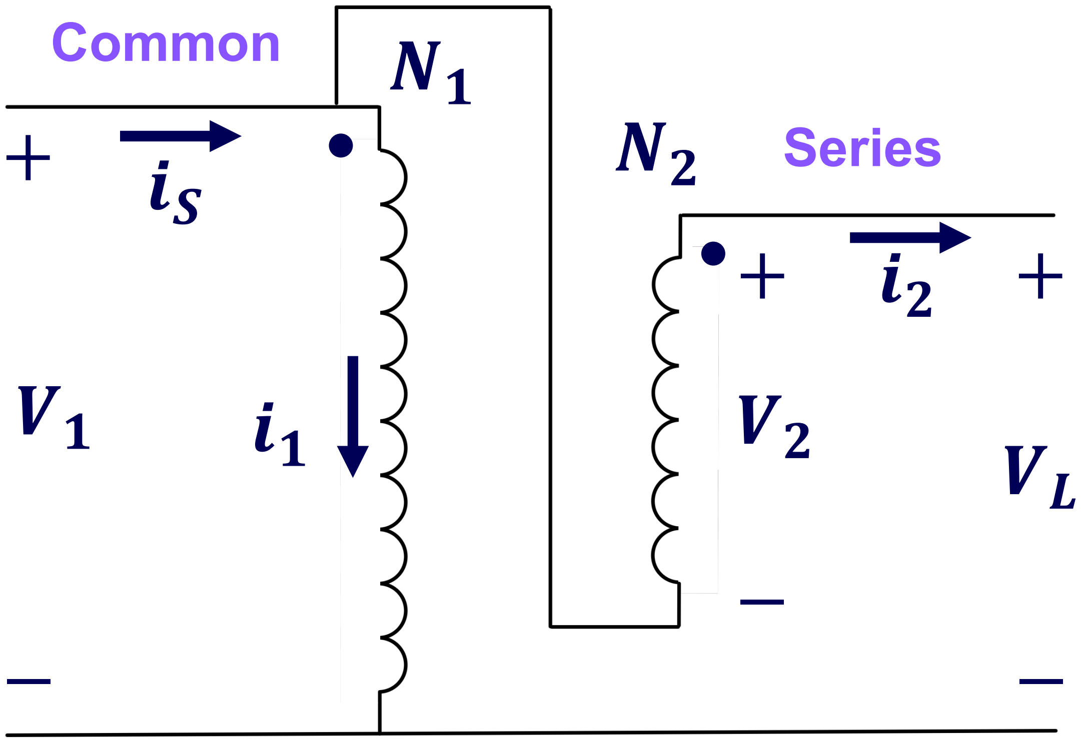


Transformation ratio: $a = \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$

Volts per turn conservation: $\frac{V_1}{N_1} = \frac{V_2}{N_2}$

Power: $kVA_{xfrm} = V_1 \cdot i_1 = V_2 \cdot i_2$

Step-up Connection



Voltage:

$$V_L = V_1 + V_2$$

$$V_2 = \frac{V_1}{N_1} \cdot N_2$$

$$V_L = V_1 + \frac{V_1}{N_1} \cdot N_2$$

$$\boldsymbol{V_L = V_1 \cdot \left(1 + \frac{N_2}{N_1}\right)}$$

Current:

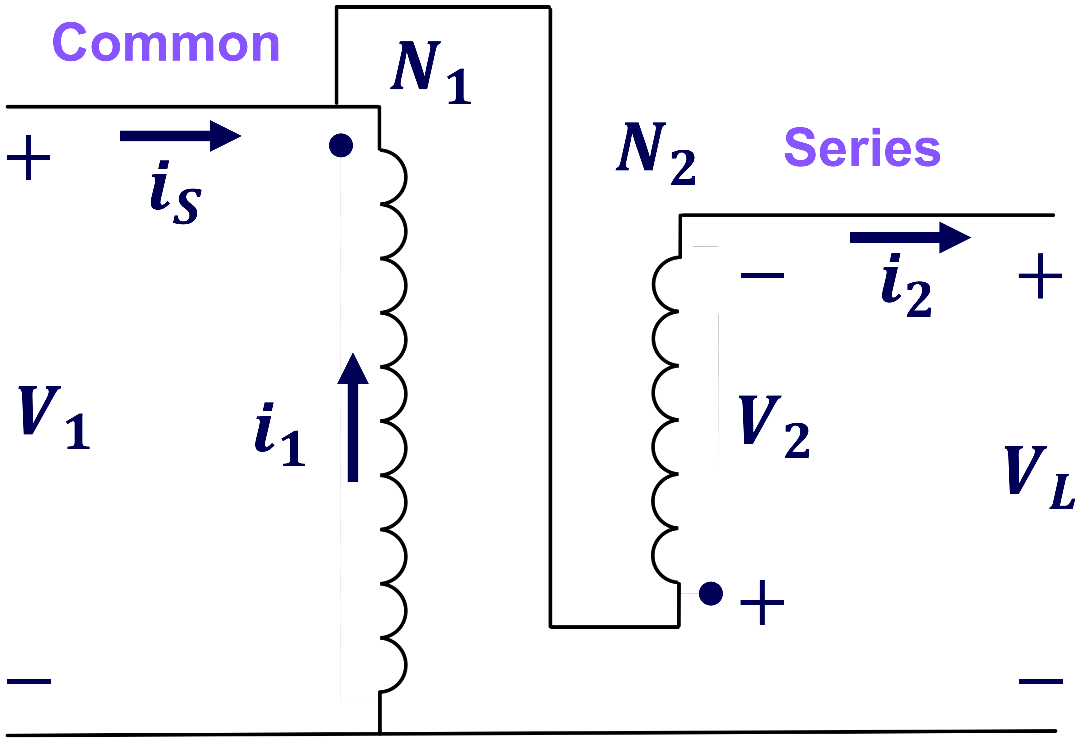
$$i_S = i_1 + i_2$$

$$\boldsymbol{i_1 = \frac{N_2}{N_1} \cdot i_2}$$

$$i_S = \frac{N_2}{N_1} \cdot i_2 + i_2$$

$$\boldsymbol{i_S = i_2 \cdot \left(1 + \frac{N_2}{N_1}\right)}$$

Step-down Connection



Voltage:

$$V_L = V_1 - V_2$$

$$V_2 = \frac{V_1}{N_1} \cdot N_2$$

$$V_L = V_1 - \frac{V_1}{N_1} \cdot N_2$$

$$\boldsymbol{V_L = V_1 \cdot \left(1 - \frac{N_2}{N_1}\right)}$$

Current:

$$i_S = i_2 - i_1$$

$$\boldsymbol{i_1 = \frac{N_2}{N_1} \cdot i_2}$$

$$i_S = i_2 - \frac{N_2}{N_1} \cdot i_2$$

$$\boldsymbol{i_S = i_2 \cdot \left(1 - \frac{N_2}{N_1}\right)}$$

kVA

Ratio: $$a_{auto} = 1 \pm \frac{N_2}{N_1}$$

Voltage: $$V_{auto} = V_L = V_1 \cdot \left(1 \pm \frac{N_2}{N_1}\right)$$

Let's develop the kVA

$$kVA_{auto} = V_{auto} \cdot i_2$$

$$kVA_{auto} = V_1 \cdot \left(1 \pm \frac{N_2}{N_1}\right) \cdot i_2$$

$$i_2 = \frac{N_1}{N_2} \cdot i_1 \qquad n_t = \frac{N_2}{N_1}$$

$$kVA_{auto} = \frac{(1 \pm n_t)}{n_t} \cdot V_1 \cdot i_1$$

kVA: $$kVA_{auto} = \frac{(1 \pm n_t)}{n_t} \cdot kVA_{xfrm}$$

+ sign, for additive polarity

- sign, for subtractive polarity

Example

Data:

$$N_1 = 1000\ turns$$

$$N_2 = 100\ turns$$

$$V_1 = 2400\ V$$

$$kVA_{xfrm} = 75\ kVA$$

$$2\ winding\ transformer$$
$$in\ step - up\ connection$$

Results:

$$V_{auto} = V_1 \cdot \left(1 + \frac{N_2}{N_1}\right) = 2400 \cdot \left(1 + \frac{100}{1000}\right)$$

$$V_{auto} = \mathbf{2,640\ V}$$

$$kVA_{auto} = \frac{(1 + n_t)}{n_t} \cdot kVA_{xfrm}$$

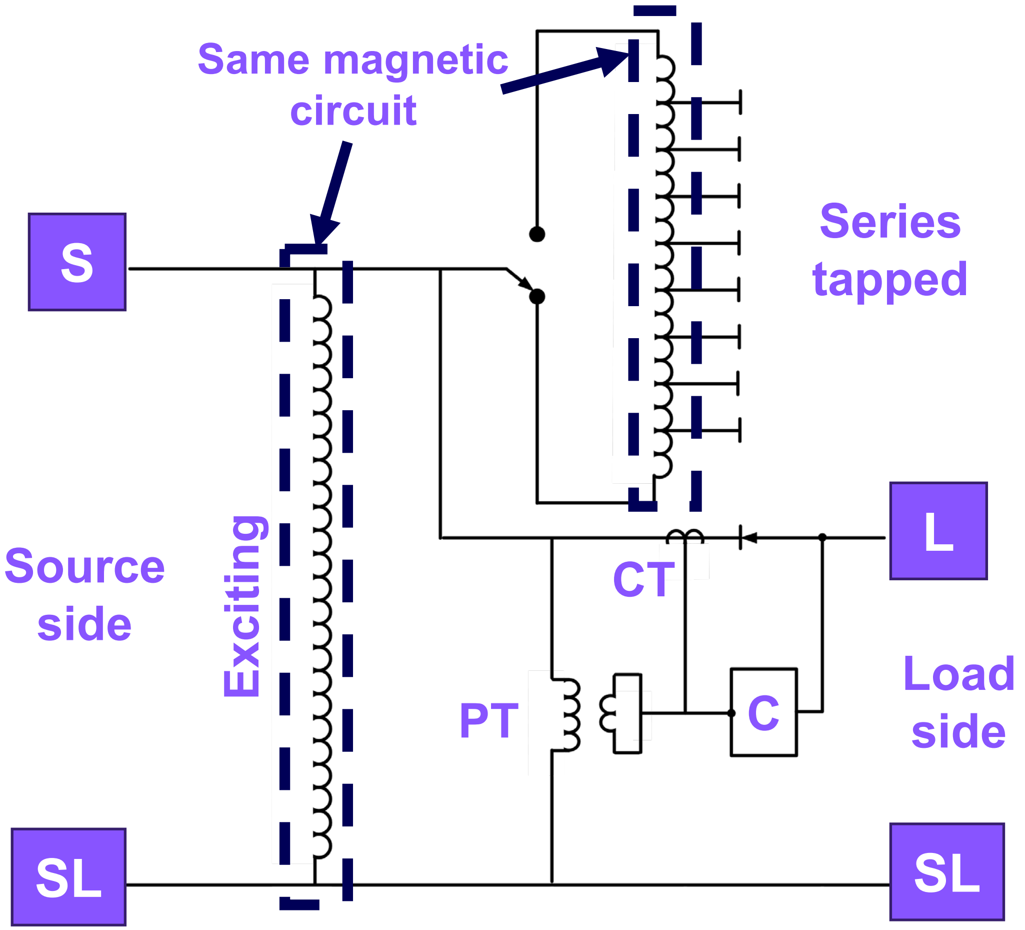
$$kVA_{auto} = \frac{(1 + 0.1)}{0.1} \cdot 75 = \mathbf{825\ kVA}$$

$$\boldsymbol{Autotransformer\ would\ be\ rated\ as}$$

$$\mathbf{825\ kVA, 2400 - 2640\ V}$$

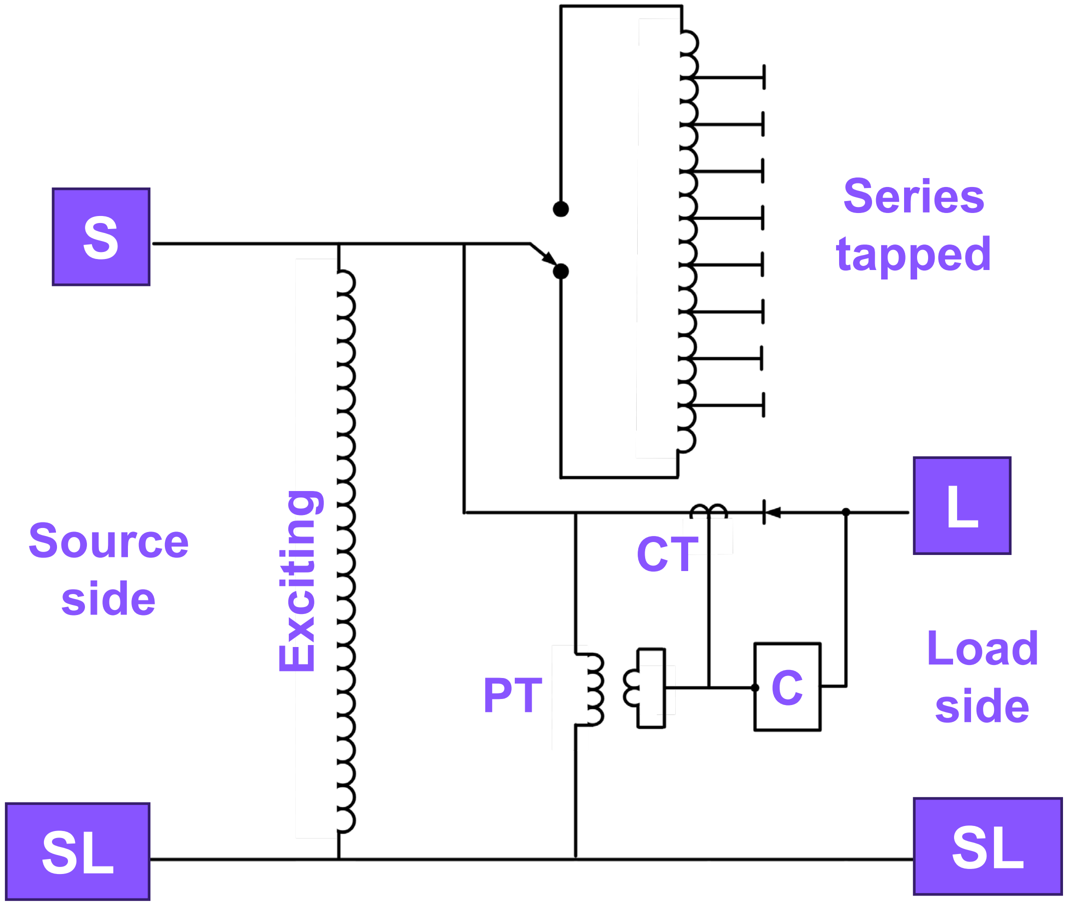
Regulator Theory

3. Voltage regulator (VR)



- **Exciting winding:** connected in parallel to the distribution line. This winding generates the excitation in the magnetic circuit.
- **Series winding:** divided in taps and connected in series with the distribution line. This winding will allow the VR to raise or lower the voltage and will carry the line current.
- **On load tap changer (OLTC):** device for selection of tap connections from the series winding, suitable for operation while the VR is energized or on load.
- **Reverse switch:** allows to connect the series winding in either additive or subtractive polarity. This element is part of the mechanism of the OLTC.
- **PT & CT:** instruments transformers to provide data to the controller.
- **Controller (C):** electronic device that performs control on the OLTC and other important routines.

3. Voltage regulator (VR)

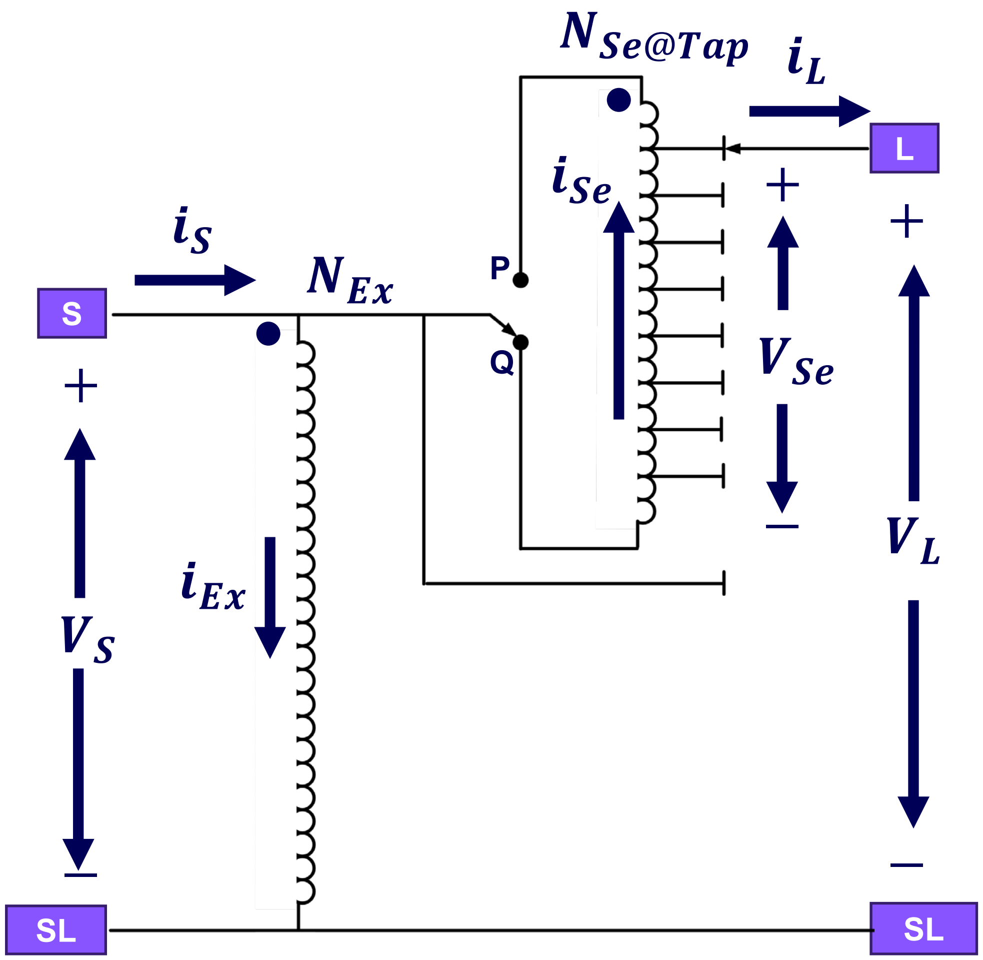


Per **IEEE Std C57.15 sec 6.2.2**, the rating of a VR shall be expressed in the following terms:

- **Kilovoltampere (kVA)**
- **Number of phases**
- **Frequency**
- **Voltage**
- **Current**
- **Voltage range in percent (Raise and Lower)**

VR shall be approximately compensated for their internal regulation to provide the specified voltage range at rating in kVA with an 80% lagging power factor load.

Type A (Source Excited)



Voltage at the load (reverse switch at Q):

$$V_L = V_S + V_{Se}$$

$$V_{Se} = \frac{N_{Se@Tap}}{N_{Ex}} \cdot V_S$$

$$V_L = V_S + \frac{N_{Se@Tap}}{N_{Ex}} \cdot V_S$$

$$V_L = V_S \cdot \left(1 + \frac{N_{Se@Tap}}{N_{Ex}}\right)$$

$$V_L = V_S \cdot \left(\frac{N_{Ex} + N_{Se@Tap}}{N_{Ex}}\right)$$

Voltage at the load (reverse switch at P):

$$V_L = V_S - V_{Se}$$

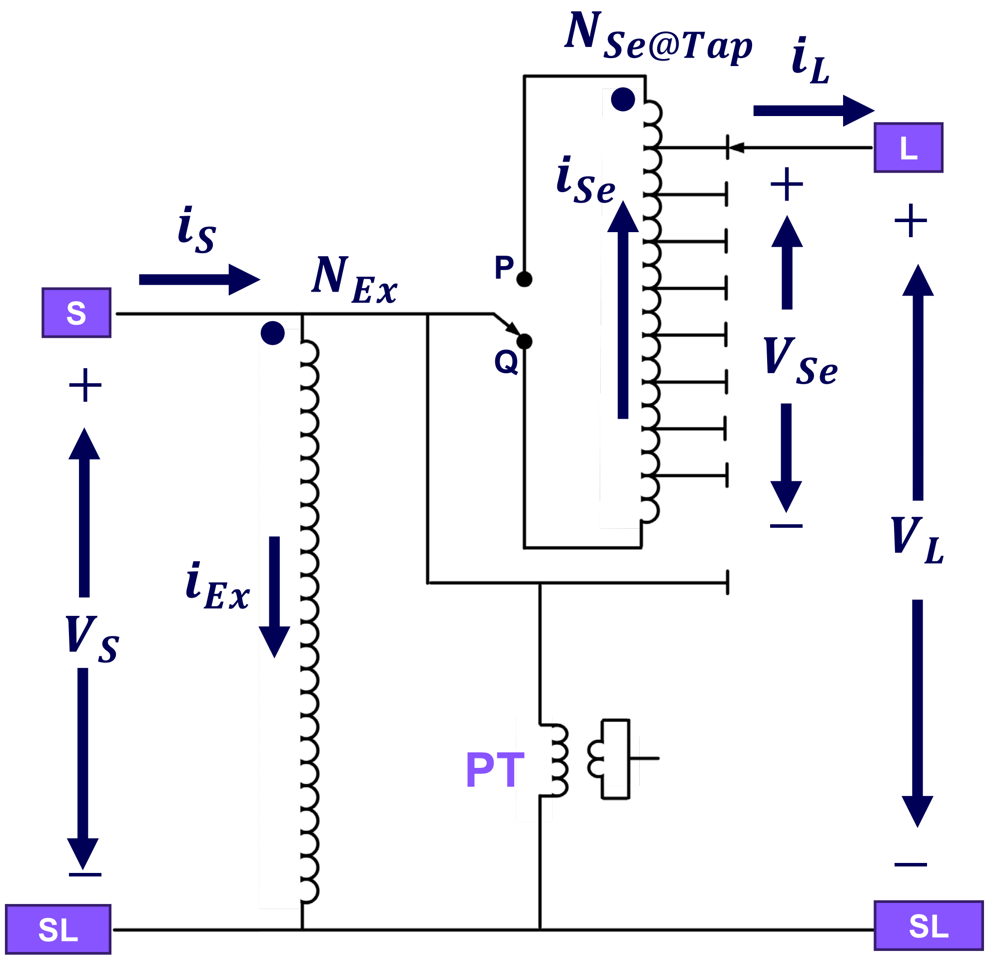
$$V_{Se} = \frac{N_{Se@Tap}}{N_{Ex}} \cdot V_S$$

$$V_L = V_S - \frac{N_{Se@Tap}}{N_{Ex}} \cdot V_S$$

$$V_L = V_S \cdot \left(1 - \frac{N_{Se@Tap}}{N_{Ex}}\right)$$

$$V_L = V_S \cdot \left(\frac{N_{Ex} - N_{Se@Tap}}{N_{Ex}}\right)$$

Type A Equations



Transformation ratio: $a_{VRA} = \dfrac{N_{Ex} \pm N_{Se@Tap}}{N_{Ex}}$

Voltage at load: $V_L = V_S \cdot \left(\dfrac{N_{Ex} \pm N_{Se@Tap}}{N_{Ex}}\right)$

+ sign, to rise the voltage (reverse switch at Q).

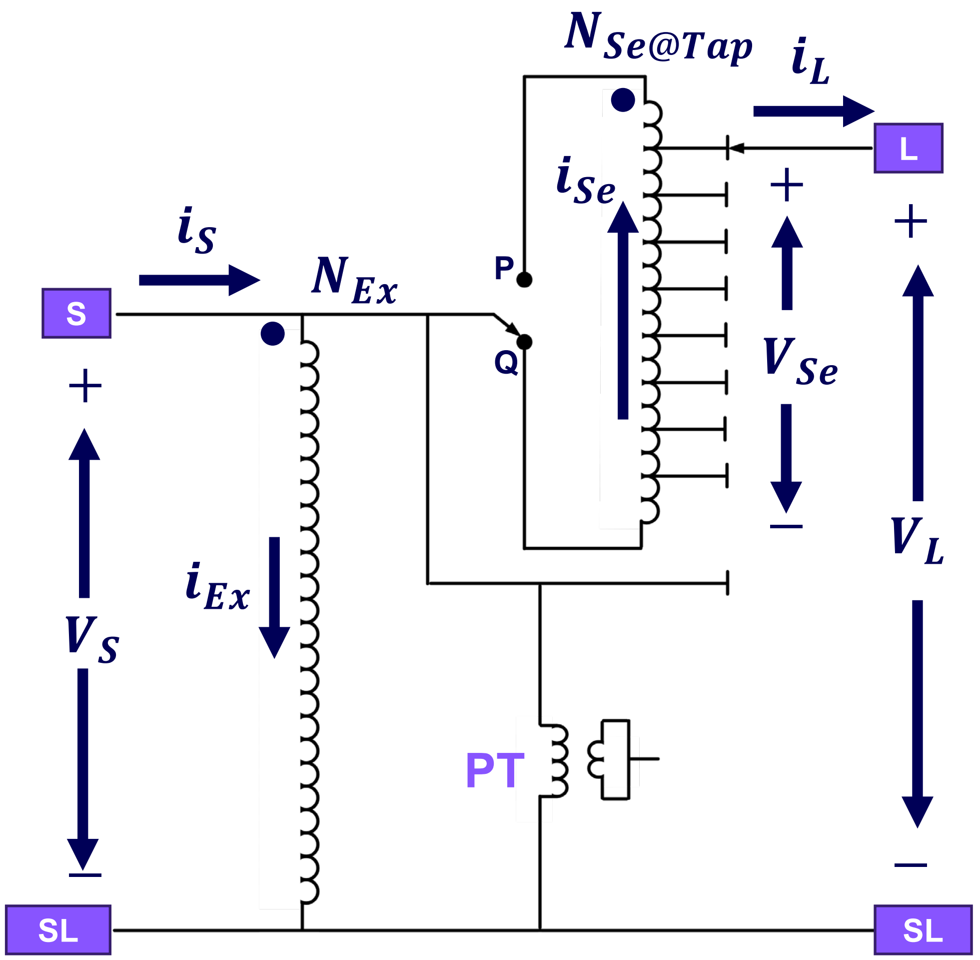
- sign, to lower the voltage (reverse switch at P).

Exciting winding is connected at the unregulated circuit voltage V_S.

Core excitation varies with the source voltage.

Separate voltage transformer (PT) assists in providing the regulated voltage supply to the control.

Type A Equations



Currents (reverse switch at Q):

$$i_S = i_{Ex} + i_L \qquad i_{Se} = i_L$$

$$\boldsymbol{i_{Ex} = \frac{N_{Se@Tap}}{N_{Ex}} \cdot i_L}$$

$$i_S = \frac{N_{Se@Tap}}{N_{Ex}} \cdot i_L + i_L$$

$$i_S = i_L \cdot \left(1 + \frac{N_{Se@Tap}}{N_{Ex}}\right)$$

$$\boldsymbol{i_S = i_L \cdot \left(\frac{N_{Ex} + N_{Se}}{N_{Ex}}\right)}$$

Currents (reverse switch at P):

$$i_S = i_L - i_{Ex} \qquad i_{Se} = i_L$$

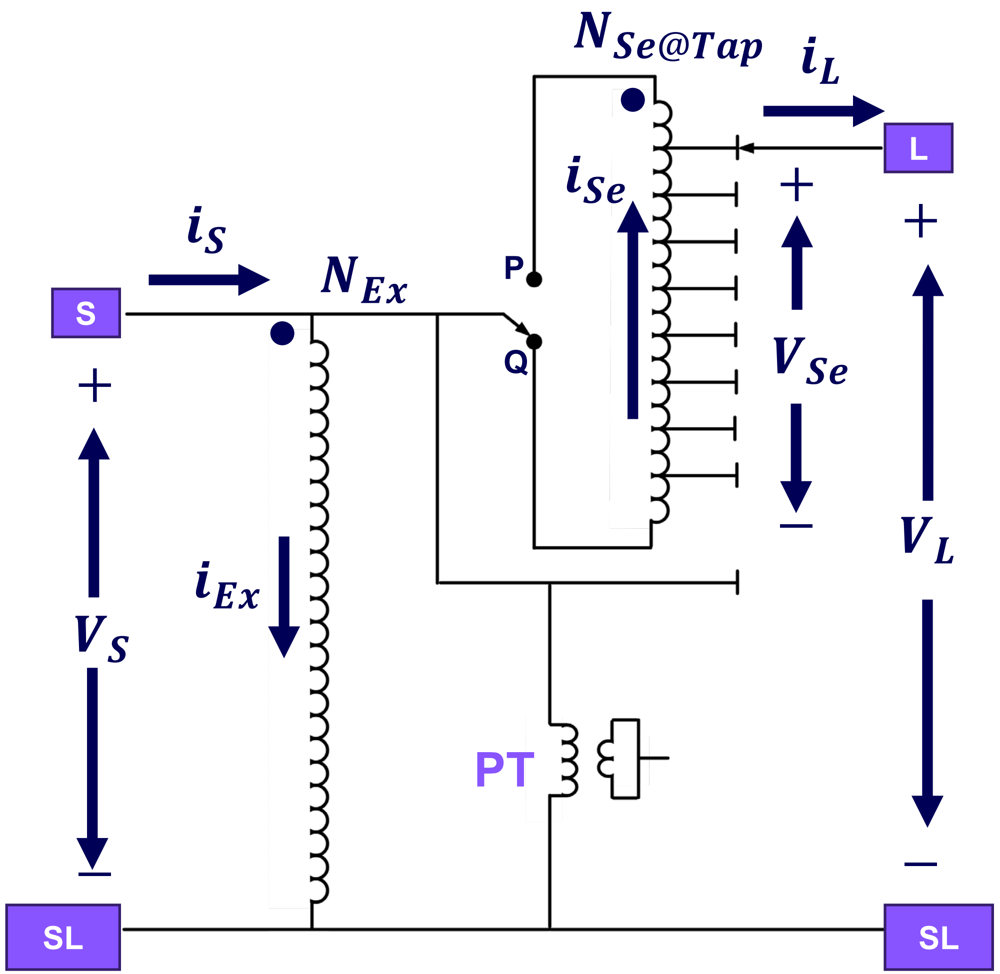
$$\boldsymbol{i_{Ex} = \frac{N_{Se@Tap}}{N_{Ex}} \cdot i_L}$$

$$i_S = i_L - \frac{N_{Se@Tap}}{N_{Ex}} \cdot i_L$$

$$i_S = i_L \cdot \left(1 - \frac{N_{Se@Tap}}{N_{Ex}}\right)$$

$$\boldsymbol{i_S = i_L \cdot \left(\frac{N_{Ex} - N_{Se}}{N_{Ex}}\right)}$$

Type A Equations



kVA:

The required rating of a VR is based upon the kVA transformed and not the rating of the line.

Per **IEEE Std C57.15**, this will be 10% of the line rating since rated current flows through the series winding, which represents the ±10% voltage change. Thus:

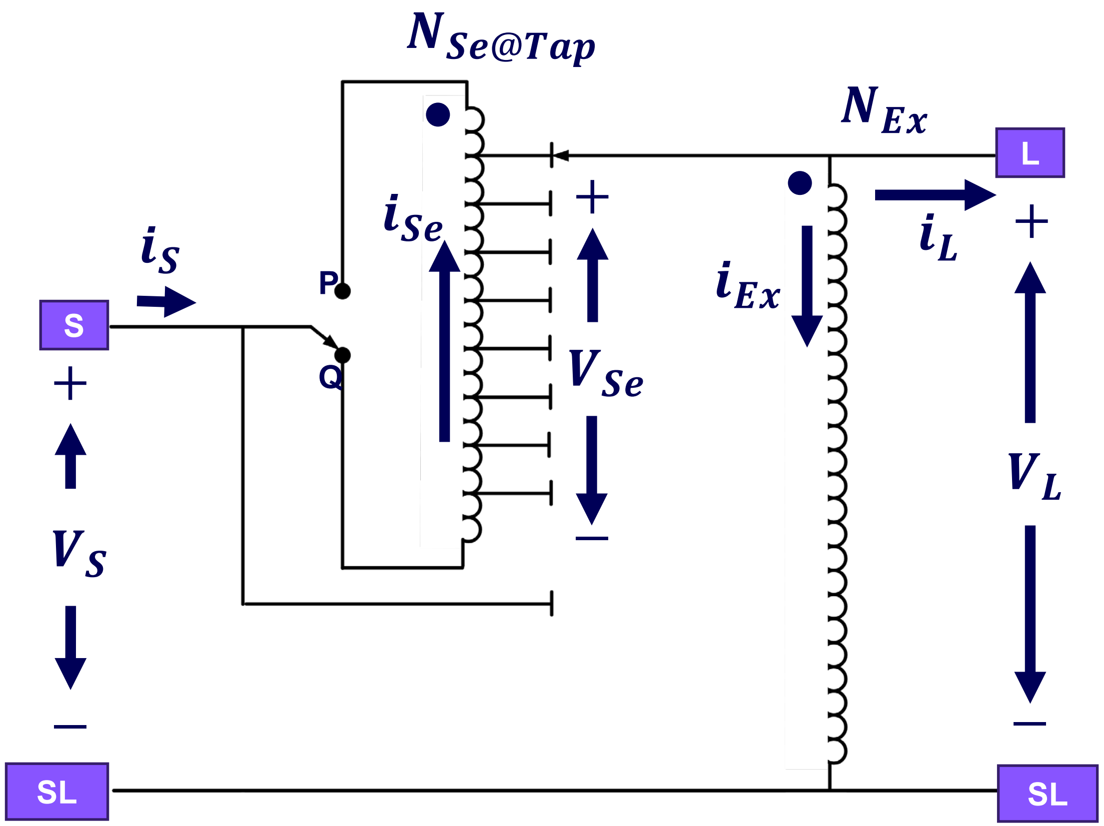
$$kVA_{VR} = \%Reg \cdot V_{Rated} \cdot i_L$$

$\%Reg$, 10% per standard.

V_{Rated}, rated voltage.

i_L, rated current circulating in the distribution line.

Type B (Load Excited)



Voltage at the load (reverse switch at Q):

$$V_S = V_L - V_{Se}$$

$$V_{Se} = \frac{N_{Se@Tap}}{N_{Ex}} \cdot V_L$$

$$V_S = V_L - \frac{N_{Se@Tap}}{N_{Ex}} \cdot V_L$$

$$V_S = V_L \cdot \left(1 - \frac{N_{Se@Tap}}{N_{Ex}}\right)$$

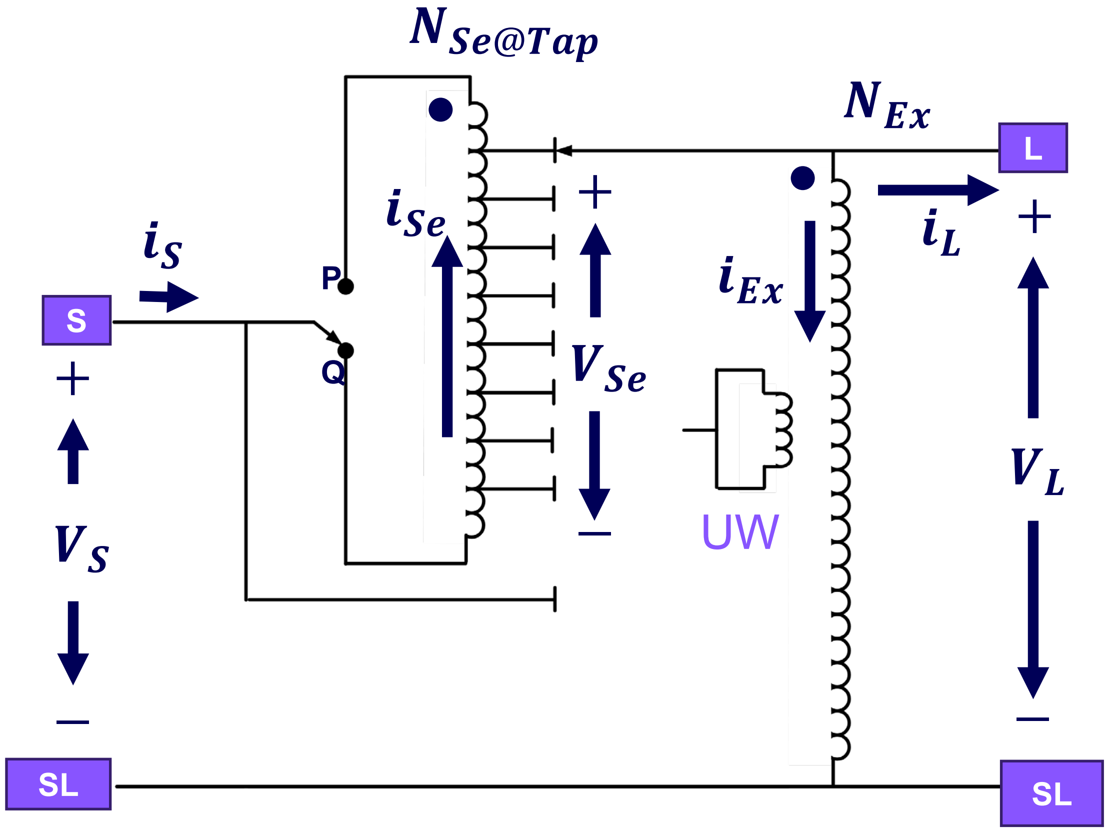
$$V_S = V_L \cdot \left(\frac{N_{Ex} - N_{Se@Tap}}{N_{Ex}}\right)$$

$$V_L = V_S \cdot \left(\frac{N_{Ex}}{N_{Ex} - N_{Se@Tap}}\right)$$

Voltage at the load (reverse switch at P):

$$V_L = V_S \cdot \left(\frac{N_{Ex}}{N_{Ex} + N_{Se@Tap}}\right)$$

Type B



Transformation ratio: $a_{VRB} = \frac{N_{Ex}}{N_{Ex} \mp N_{Se@Tap}}$

Voltage at load: $V_L = V_S \cdot \left(\frac{N_{Ex} \mp N_{Se@Tap}}{N_{Ex}} \right)$

- sign, to rise the voltage (reverse switch at Q).

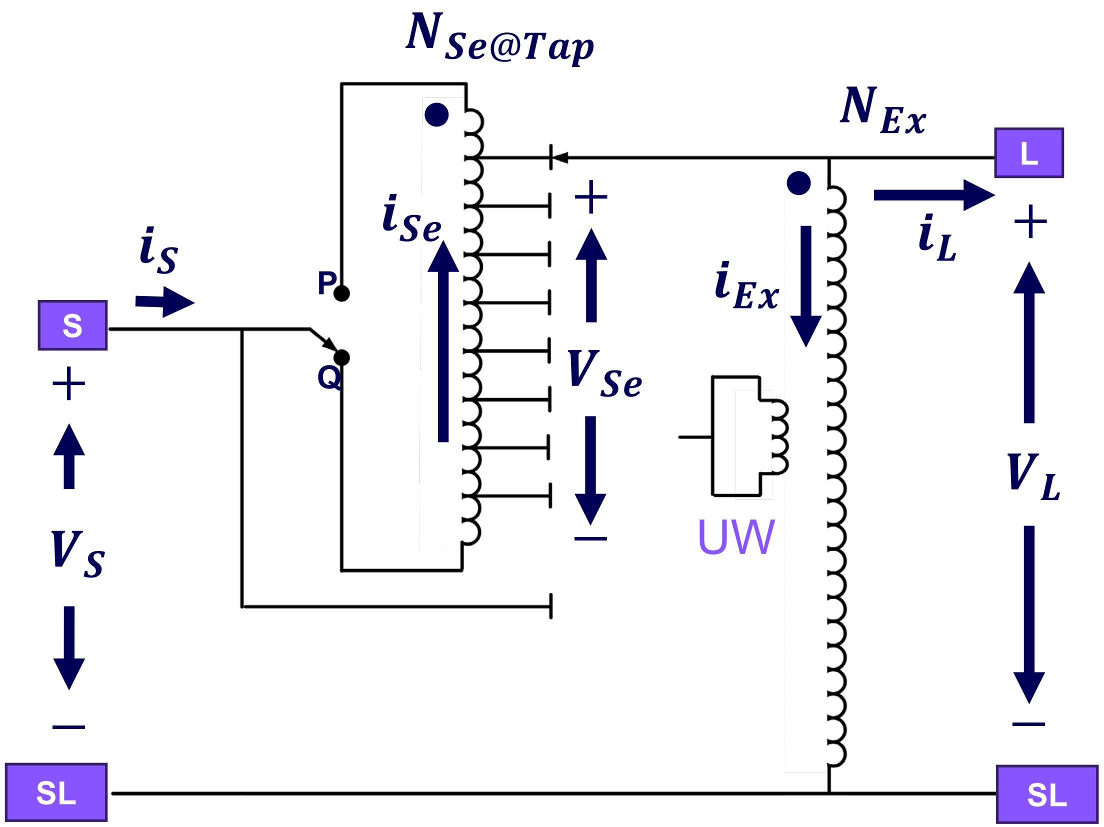
+ sign, to lower the voltage (reverse switch at P).

Exciting winding is connected at the regulated circuit voltage V_L.

Core excitation is essentially continuous.

A utility winding (UW) in the main coil is used instead of a separate voltage transformer providing the regulated voltage supply to the control.

Type B



Currents (reverse switch at Q):

$i_L = i_S - i_{Ex} \qquad i_{Se} = i_S$

$$i_{Ex} = \frac{N_{Se@Tap}}{N_{Ex}} \cdot i_{Se}$$

$$i_L = i_{Se} - \frac{N_{Se@Tap}}{N_{Ex}} \cdot i_{Se}$$

$$i_L = i_{Se} \cdot \left(1 - \frac{N_{Se@Tap}}{N_{Ex}}\right)$$

$$i_L = i_{Se} \cdot \left(\frac{N_{Ex} - N_{Se}}{N_{Ex}}\right)$$

$$i_{Se} = i_L \cdot \left(\frac{N_{Ex}}{N_{Ex} - N_{Se}}\right)$$

Currents (reverse switch at P):

$$i_{Se} = i_L \cdot \left(\frac{N_{Ex}}{N_{Ex} + N_{Se}}\right)$$

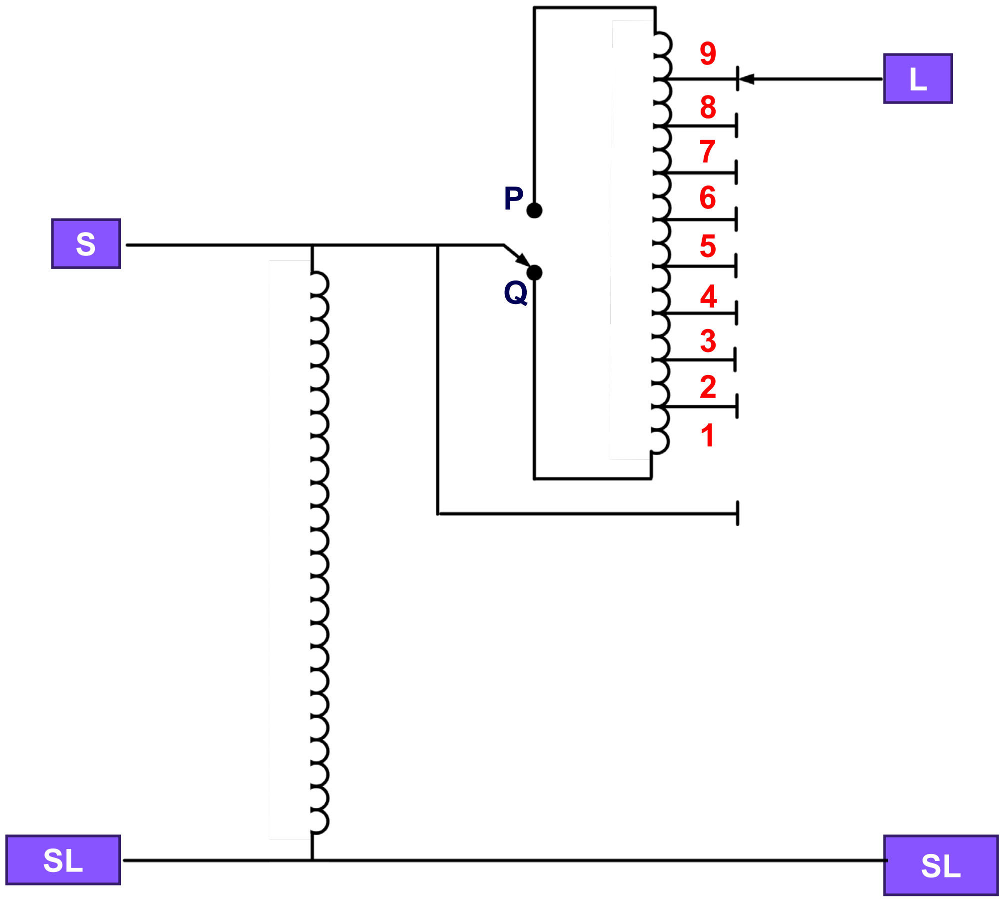
Type A & B Ratio Comparison

	Type A		Type B
Rise	$a_{VRA} = \frac{1000 + 100}{1000} = \mathbf{1.10}$	$N_{Ex} = 1000\ turns$ $N_{Se} = 100\ turns$	$a_{VRB} = \frac{1000}{1000 - 100} = \mathbf{1.111}$
Lower	$a_{VRA} = \frac{1000 - 100}{1000} = \mathbf{0.90}$		$a_{VRB} = \frac{1000}{1000 + 100} = \mathbf{0.909}$

Per **IEEE Std C57.15 sec 6.4**, minimum range of regulation in the raise direction shall be 10%.

	Type A	Type B
Rise		$a_{VRB} = \frac{1000}{1000 - x} = \mathbf{1.10}$ $\quad x = 90.90 \approx 91\ turns$
Lower		$a_{VRB} = \frac{1000}{1000 + 91} = \mathbf{0.9165}$

Taps Requirements



Per **IEEE Std C57.15 sec 6.4**, it is required to have:

- **16 taps above, 16 taps below.**
- **Minimum range of regulation in the raise direction shall be 10%.**
- Thus, each tap shall be:

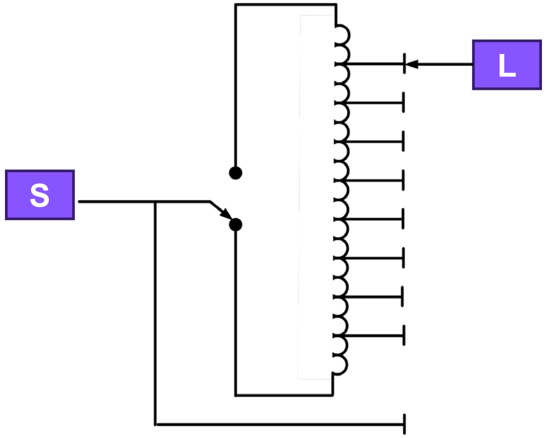
$$\%\boldsymbol{Tap} = \frac{\mathbf{10\%}}{\mathbf{16}} = \frac{\mathbf{5}}{\mathbf{8}}\%$$

The individual taps are commonly not identical when combined to achieve the maximum range of regulation.

The series winding is designed with 9 sections, but only 8 can be engaged in each direction, thus:

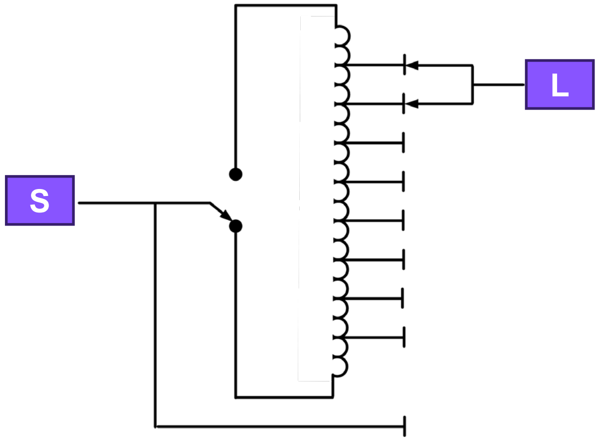
$$\%\boldsymbol{Ser_{Sec}} = \frac{\mathbf{10\%}}{\mathbf{8}} = \mathbf{1.25\%}$$

Non-bridging vs Bridging Positions



Non-bridging positions are easy to get:

- They are located at the **even** taps like 0 (neutral), 2, 4, 6, … , 16.
- To generate these taps would be only require a single moving contact at the OLTC.



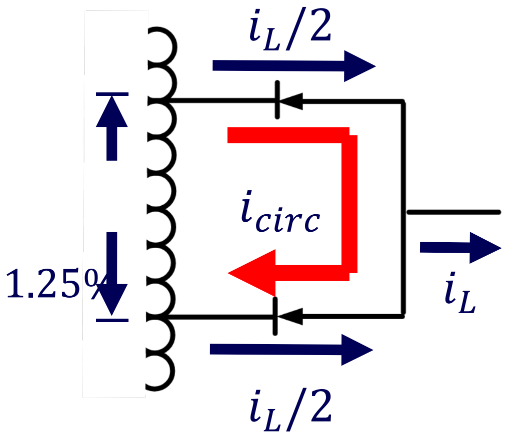
Bridging positions are more complicated:

- They are located at the **odd** taps like 1, 3, 5, 7, … , 15.
- To generate these taps would be require to have two moving contacts.
- Each moving contact will be at a different tap (adjacent to each other).
- Being moving contacts at different taps causes the voltage change to be half the 1.25%.

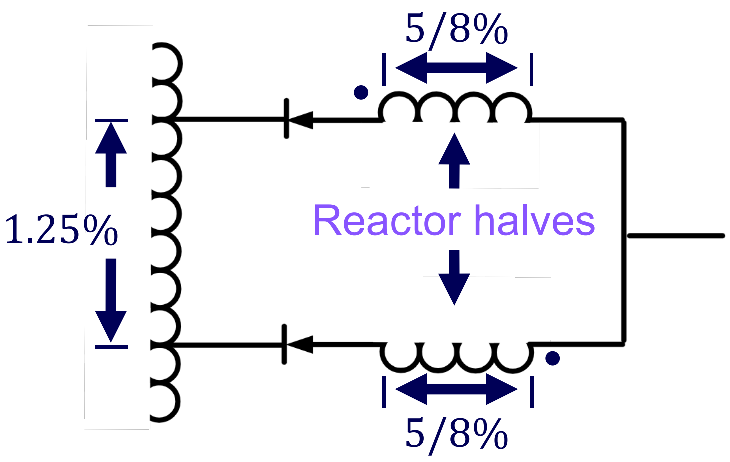
Non-bridging vs Bridging

- Unfortunately, connecting adjacent taps will cause a **circulating current** since they are at different voltage
- A **reactor** is incorporate to limit the circulating current by generating a reactive impedance in the circuit
- At **odd positions**, the reactor is energized with 1.25% of the line voltage
- At **even positions**, the reactor is not being energized.

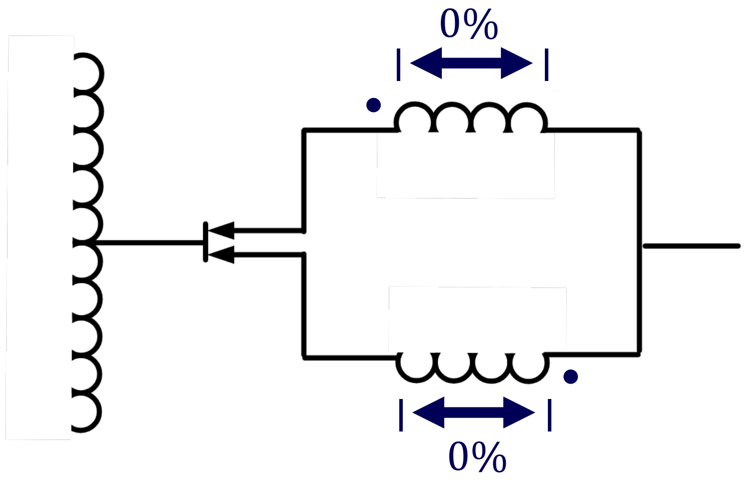
Circulating current



Odd positions



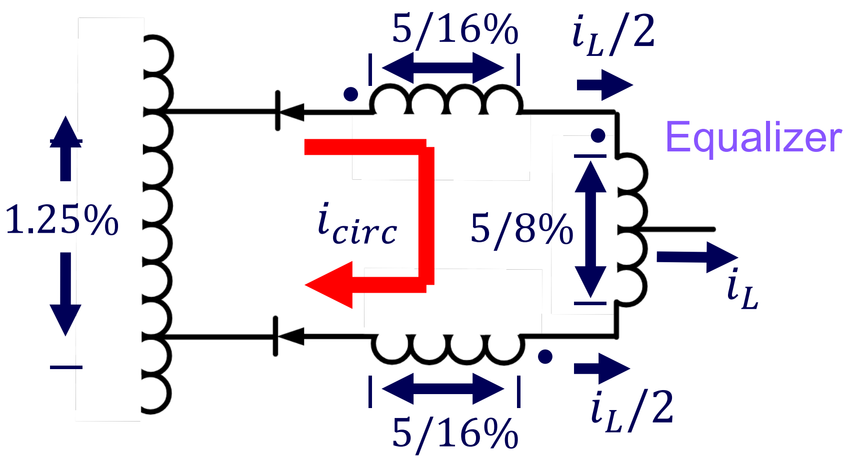
Even positions



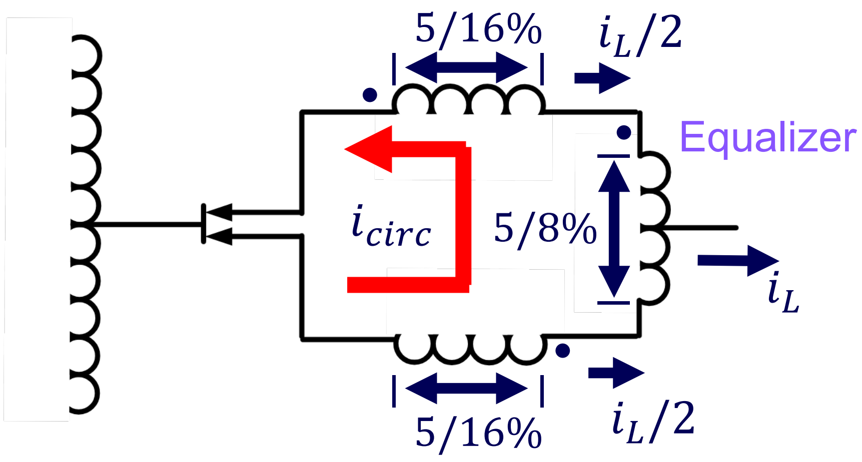
Non-bridging vs Bridging

- To improve OLTC contact life an **equalizer winding** is incorporated into the reactor circuit.
- The equalizer is a 5/8% winding on the **same magnetic** circuit **as** the **exciting** and **series winding**.
- Thus, the reactor is energized at 5/8% of the line voltage on both even and odd positions.
- With this, the interrupted voltage and the interrupted kVA have been halved, reducing the tap changer interruption duty.

Odd positions



Even positions

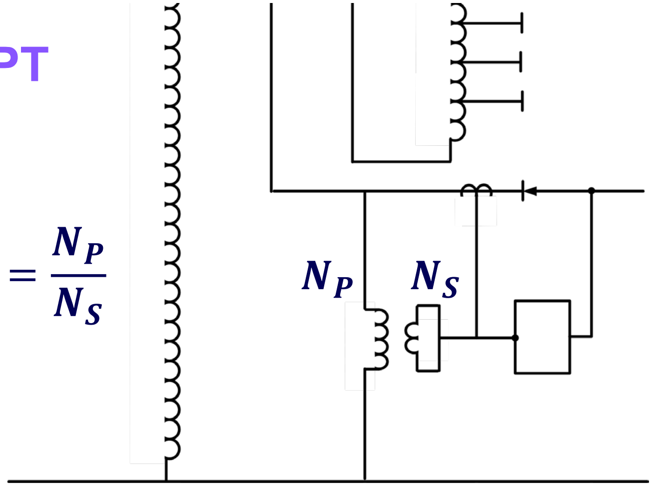


Voltage Supply Ratio for Control

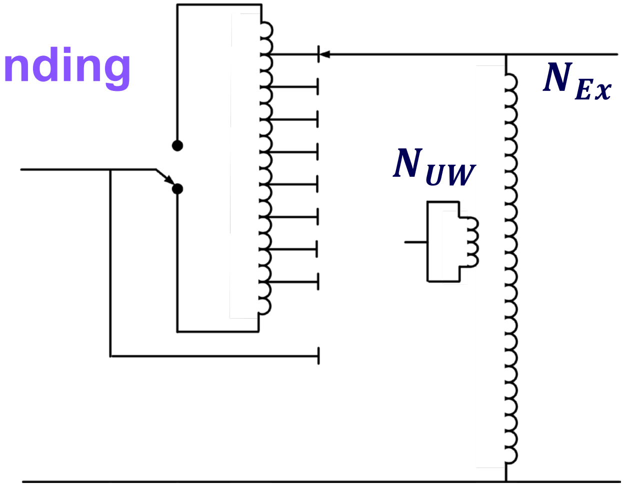
- Per **IEEE Std C57.15 sec 6.5**, an ancillary transformer may be furnished within the control to modify the ratio
- Most of the supply ratios provide a 120 V value on the secondary of the ancillary transformer
- As mentioned before, the ancillary transformer can be a
  - PT (external to the main coil), mostly used in type A designs.
  - Utility winding (inside the main coil), mostly used in type B designs.
  - A combination of both (in a series connection), used in both type A and B designs.

PT

$$a_{PT} = \frac{N_P}{N_S}$$



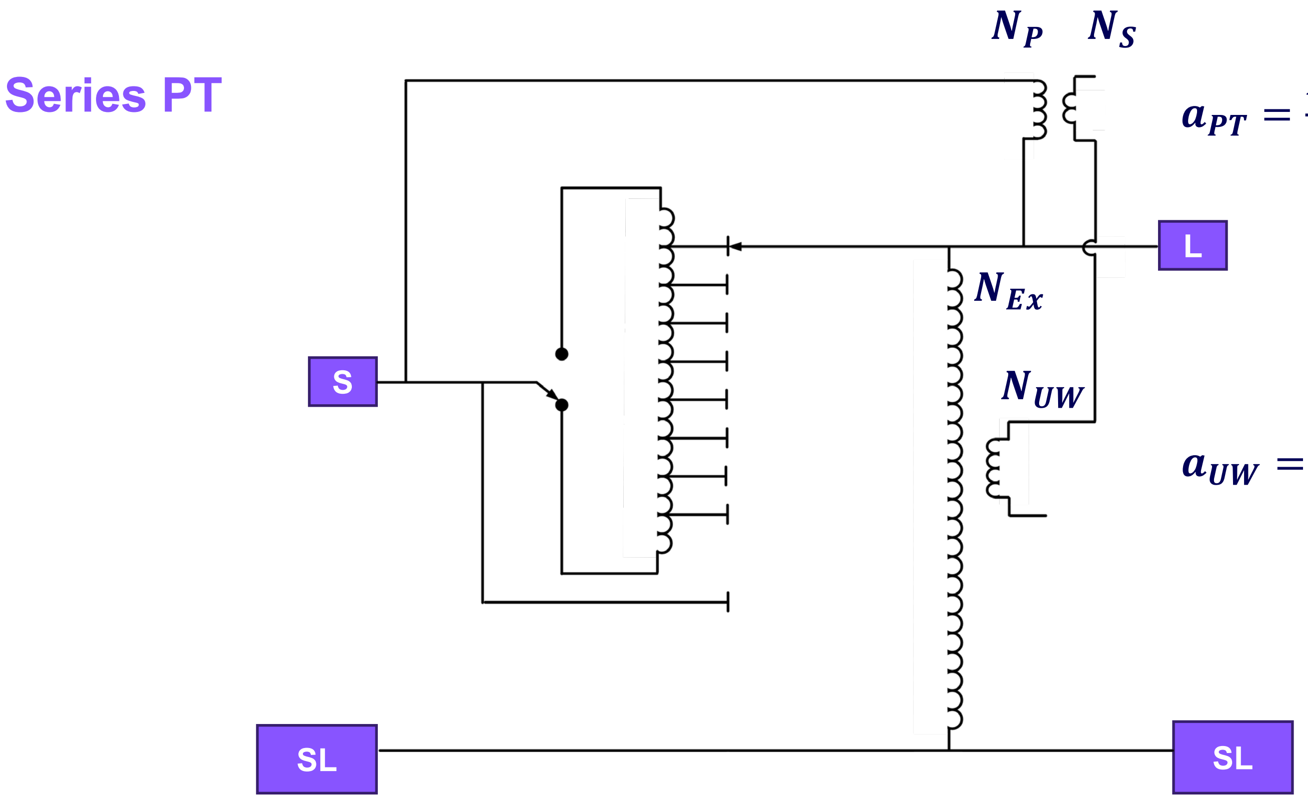
Utility winding



$$a_{UW} = \frac{N_{Ex}}{N_{UW}}$$

Voltage Supply Ratio for Control

A combination of both PT and UW (in a series connection), used in both type A and B designs.

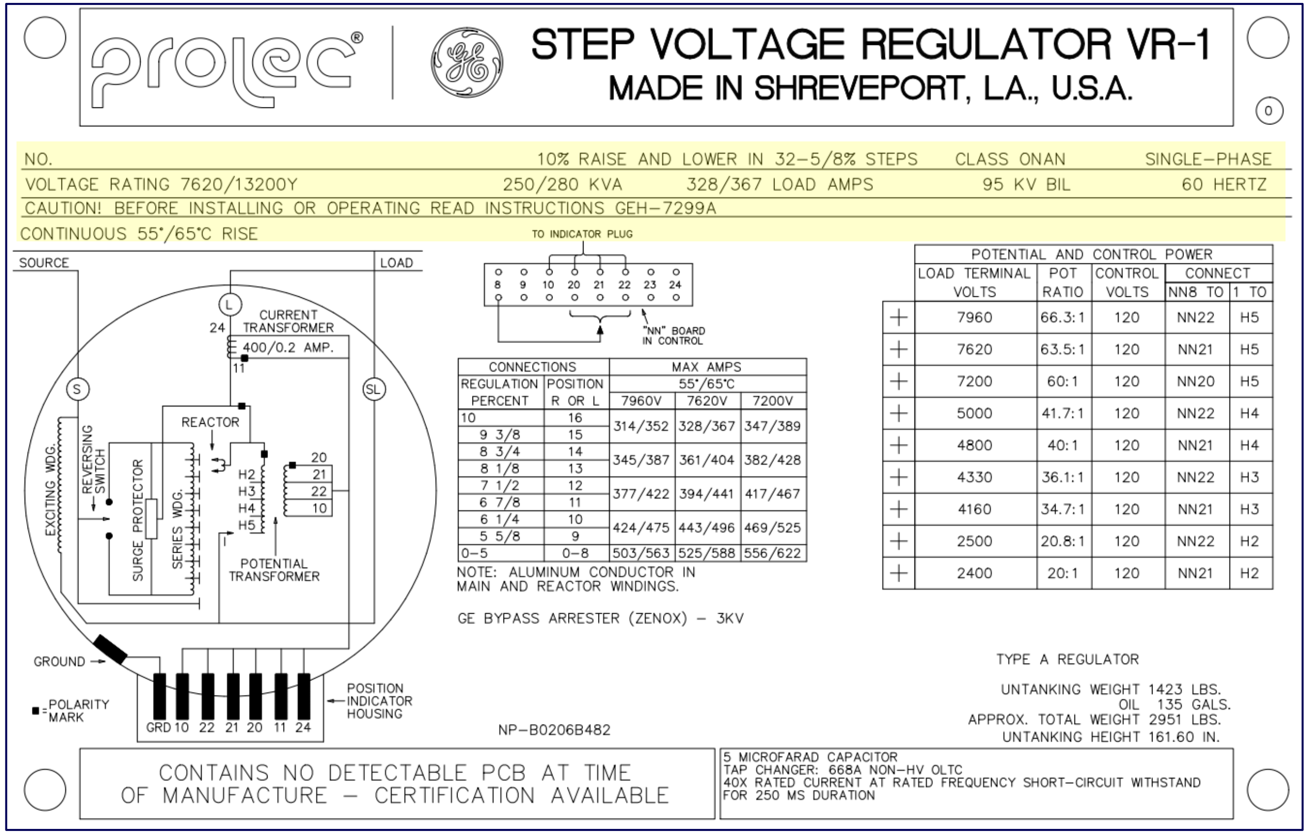


$$a_{PT} = \frac{N_P}{N_S}$$

$$a_{PT} = a_{UW}$$

$$a_{UW} = \frac{N_{Ex}}{N_{UW}}$$

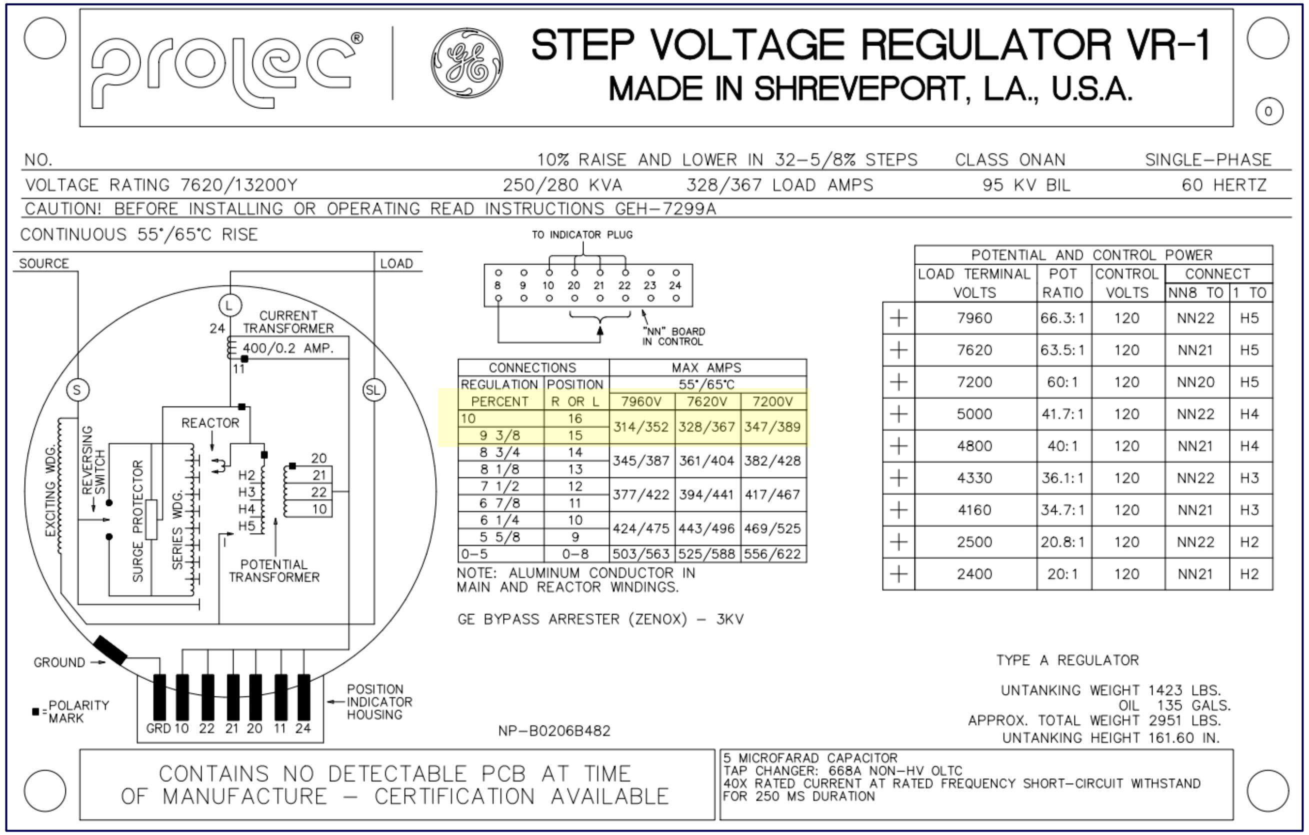
Nameplate Ratings



Ratings:

- Cooling class
- Number of phases
- Rated kVA
- Rated current
- Rated voltage
- Rated range of regulation
- Rated frequency
- Impulse level, full wave in kV
- Average winding rise in degrees Celsius

Nameplate & Supplementary Ratings

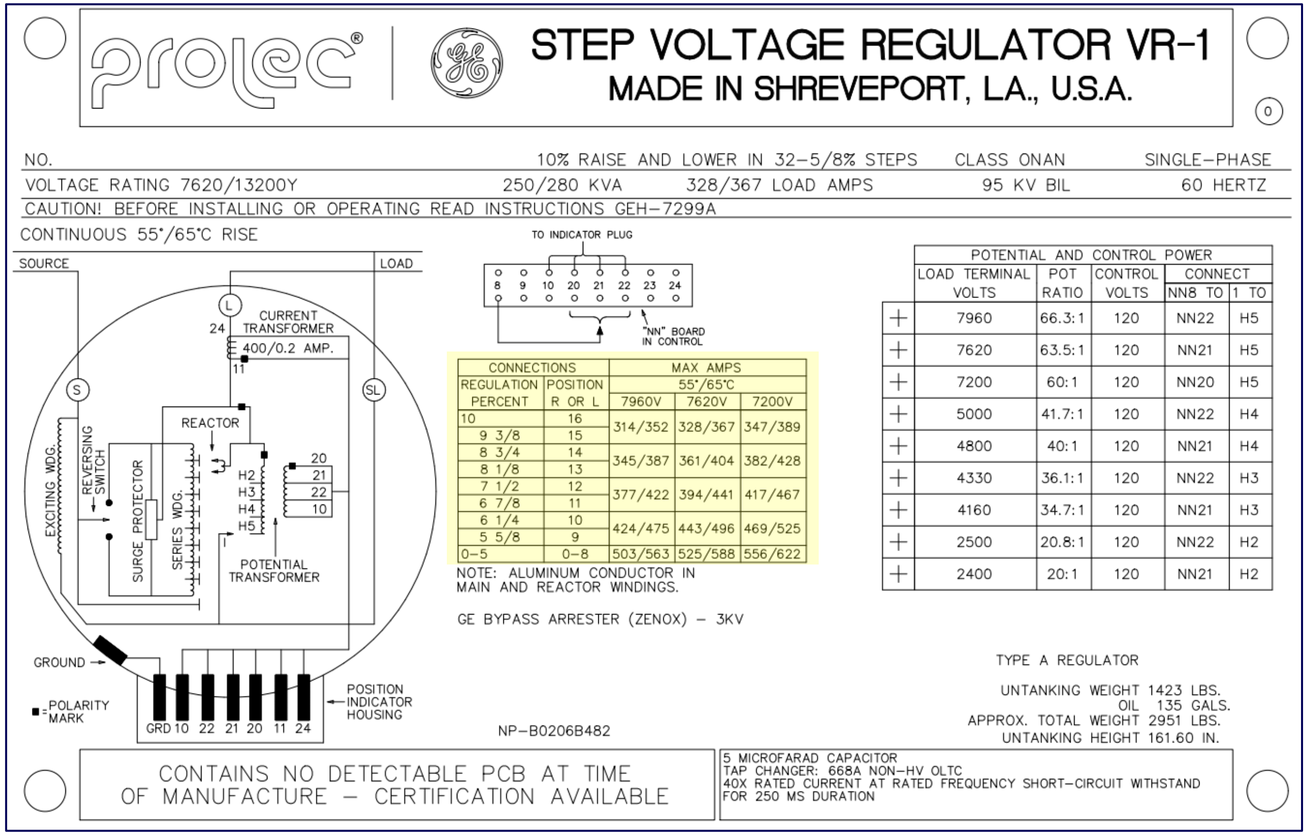


Supplementary voltage ratings:

Per **IEEE Std C57.15 sec 6.2.4.1**, in addition to the rated voltage, voltage regulators shall deliver rated line amperes without exceeding the temperature rise limits 55°C or 65°C (specified in the nameplate).

Rated Voltage (V RMS)	Operating Voltage (V RMS)
7,620 / 13,200 Y	7,200 / 12,470 Y
15,000	14,400

Supplementary Continuous - Current Ratings



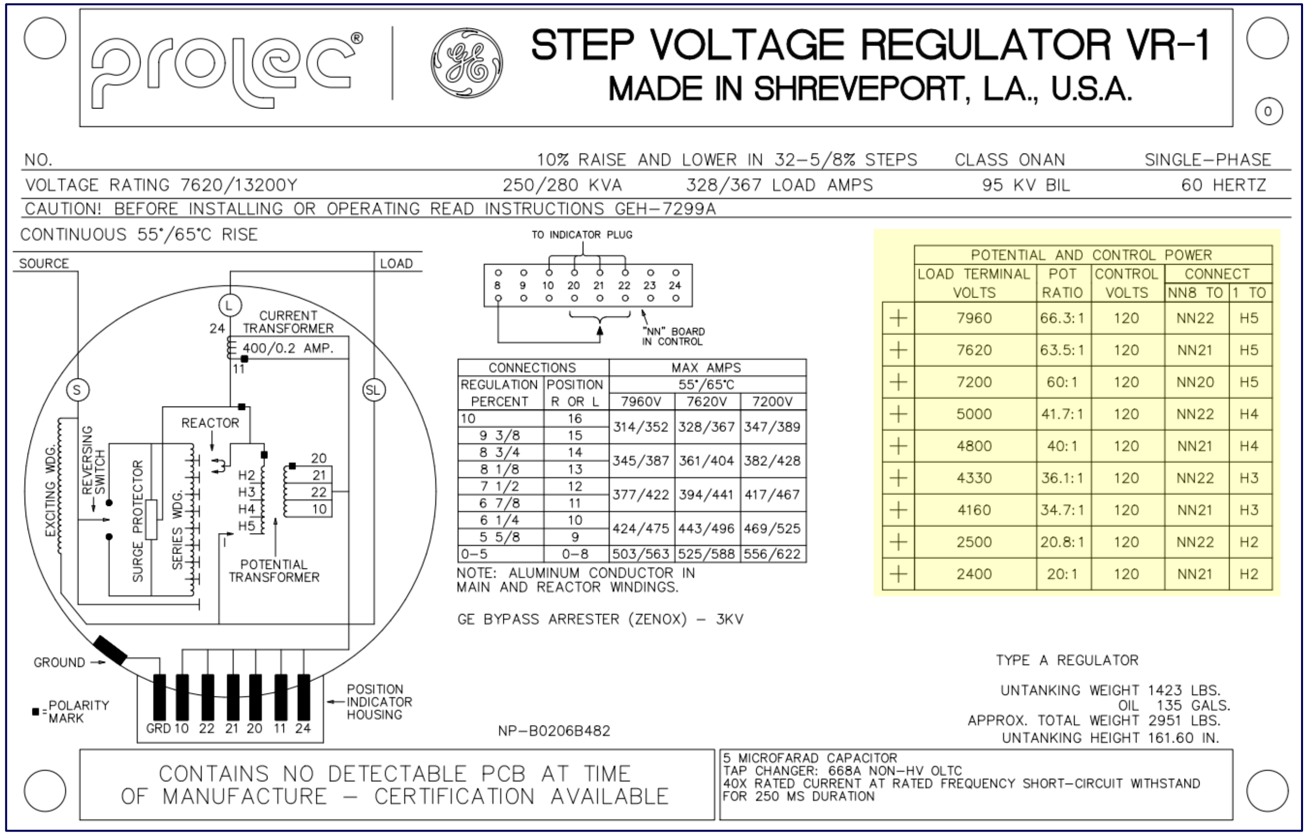
Supplementary continuous-current ratings:

- Per **IEEE Std C57.15 sec 6.3.1**, shall have supplementary continuous-current ratings on intermediate ranges of steps.

Range of voltage regulation (%)	Position R or L	Continuos-current rating (%)
10.00	16 & 15	100
8.75	14 & 13	110
7.50	12 & 11	120
6.25	10 & 9	130
5.00	0 to 8	160

- Maximum continuous-current shall be 668 A.

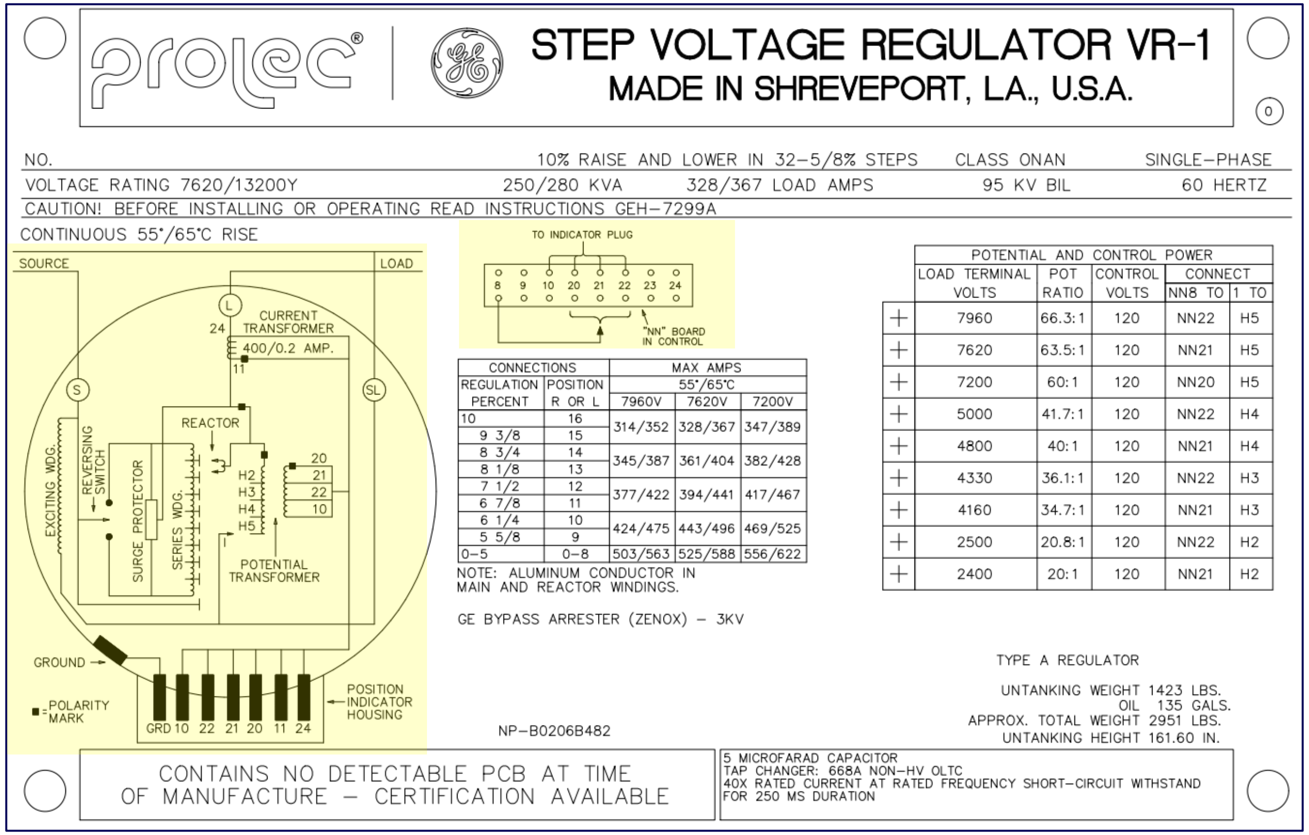
Voltage Regulator Ratios



- Per **IEEE Std C57.15 sec 6.5**, values of voltage supply ratios are:

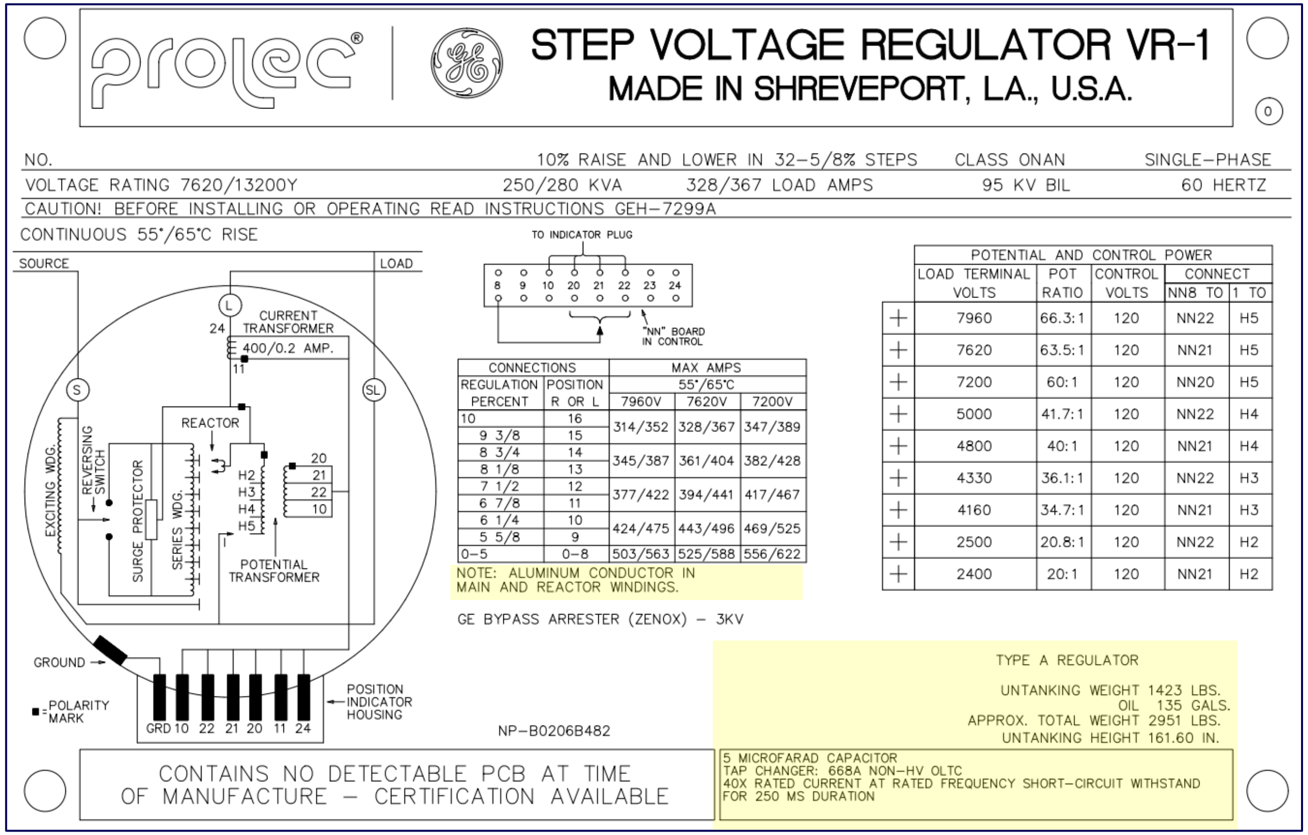
Voltage regulator rating (V RMS)	Values of voltage supply ratios
2,500	20, 20.8
5,000	40, 41.7
6,350	52.9
6,600	55
7,620	60, 63.5
7,970	66.4
11,000	91.7
13,800	115, 110
14,400	120
15,000	125, 127
19,920	166

Diagrams



- Terminals (S, L and SL)
- Exciting and series winding connections
- Instrument transformers (PT and/or UW and CT)
- OLTC (moving contacts and reverse switch)
- Zenox by-pass arrester
- Position indicator terminals
- PT/UW winding taps
- Terminal block inside control cabinet

Nameplate



- Regulator type
- Weights
- Insulating liquid type
- Conductor material
- Symmetrical SC withstand
- Asymmetrical SC withstand
- OLTC model number and max through-current rating
- Tap-changer motor capacitor rating