Calculation of tie-in resistors

Product information

This product information describes how suitable tie-in resistors shall be calculated. Calculations shall be performed on all transformers with plus/minus or coarse/fine regulation.

Background

During the change-over selector operation when the regulating winding is galvanically disconnected from the main winding the contacts of the change-over selector can be exposed to high capacitively divided voltage. A breaking sequence can generate an audible sound from the tap changer due to generation and extinction of an electric spark between the change-over selector contacts. If the voltage is high, gas generation and noise will be unacceptably high and if very high, there will be a risk for regulating winding short-circuit.

In order to limit the transient voltage between the change-over selector contacts, a suitable tie-in resistor is connected between the middle of the regulating winding and the end of the main or coarse winding. The resistance value is chosen so the recovery voltage is limited to a permitted value. Allowed values are stated in the technical guides for each tap-changer and below:

<table>
<thead>
<tr>
<th>Type</th>
<th>Max recovery voltage $U_R$</th>
<th>Max capacitive current $I_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>UBB</td>
<td>25 kV</td>
<td>100 mA</td>
</tr>
<tr>
<td>VUBB</td>
<td>40 kV</td>
<td>250 mA</td>
</tr>
<tr>
<td>UZ</td>
<td>40 kV</td>
<td>200 mA</td>
</tr>
<tr>
<td>Tap selector III</td>
<td>35 kV</td>
<td>300 mA</td>
</tr>
<tr>
<td>Tap selector C</td>
<td>35 kV</td>
<td>200 mA</td>
</tr>
<tr>
<td>Tap selector F</td>
<td>50 kV, 20 kV</td>
<td>300 mA, 500 mA</td>
</tr>
<tr>
<td>Tap selector IV (UCC)</td>
<td>35 kV</td>
<td>300 mA</td>
</tr>
</tbody>
</table>
Preparation before calculation
Following needs to be known before performing the calculation. This is for the most common configurations. For specific needs, please do not hesitate to contact ABB Components.
- Capacitances from the regulating winding to the surrounding. If windings are placed axially the capacitances between them shall also be given. Include capacitance to leads that can influence the calculations.
- Layout, connection and the voltages of the windings. (Observe that the recovery voltage for a delta connected is reduced if the regulating winding is placed in the middle of a delta). Clearly indicate if the figures given are phase or system voltage.

Basic winding configuration
The configuration consists of:
- Inner winding (V1) or core limb
- Regulating winding (RW), plus/minus or fine tapping winding
- Outer winding (V3) or tank

General winding arrangement:

![General winding arrangement diagram]

The windings are located concentrically on the limb.

Note:
- \( C_1 \) = Capacitance to the nearest inner winding or to the core limb (for inner regulating winding).
- \( C_2 \) = Capacitance to the nearest outer winding or to the tank wall (for outer regulating winding).
- \( V_1 \) = Potential to which the geometrical middle point of the nearest inner winding is raised in service or zero for the core limb.
- \( V_3 \) = Potential to which the geometrical middle point of the nearest outer winding is raised in service or zero for the tank wall.
**Definitions used during the calculations**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>U1</td>
<td>Voltage specified in the order data sheet as the high voltage (HV).</td>
</tr>
<tr>
<td>U2</td>
<td>Voltage specified in the order data sheet as the low voltage (LV).</td>
</tr>
<tr>
<td>r.r</td>
<td>Regulating winding (fine winding) voltage in percent of main winding.</td>
</tr>
<tr>
<td>r.s</td>
<td>Step in percent, part of the regulating range.</td>
</tr>
<tr>
<td>( V_{x1} )</td>
<td>Mean capacitive voltage potential along regulating winding when change-over switch is temporarily in open position, without tie-in resistor.</td>
</tr>
<tr>
<td>( V_{x2} )</td>
<td>Mean capacitive voltage potential along regulating winding when change-over switch is temporarily in open position, with tie-in resistor.</td>
</tr>
<tr>
<td>( V_s )</td>
<td>Potential on that contact of the change-over selector which is galvanically connected to the main winding or to the coarse regulating winding.</td>
</tr>
<tr>
<td>( U_c )</td>
<td>Potential over the coarse winding.</td>
</tr>
<tr>
<td>( U_R )</td>
<td>Highest recovery voltage across the change-over selector contacts.</td>
</tr>
<tr>
<td>( U_{RW} )</td>
<td>Service voltage across the fine regulating winding.</td>
</tr>
<tr>
<td>( U_{phase} )</td>
<td>Phase voltage is the voltage over the main winding. When the transformer is star connected the phase voltage is calculated according to the formula below, where you take the system voltage and divided it with ( \sqrt{3} ).</td>
</tr>
<tr>
<td>( U_c )</td>
<td>Rated step voltage is the voltage over each step in the regulating winding. The step voltage is calculated by taking the phase voltage times the step (%).</td>
</tr>
<tr>
<td>( P_{tr} )</td>
<td>Short time losses appear in a tie-in resistor during the breaking sequence when it carries capacitive current.</td>
</tr>
<tr>
<td>( P_c )</td>
<td>Continuous losses in the tie-in resistor when the switch is closed.</td>
</tr>
<tr>
<td>( P_{cz} )</td>
<td>Value of the losses when the fine winding is connected and the coarse winding is disconnected.</td>
</tr>
<tr>
<td>( P_{cm} )</td>
<td>Value of the losses when the fine winding is connected and the coarse winding is connected.</td>
</tr>
<tr>
<td>N</td>
<td>Number of loops.</td>
</tr>
<tr>
<td>R</td>
<td>Resistance value for the tie-in resistor.</td>
</tr>
<tr>
<td>Is</td>
<td>Capacitive breaking current flowing through change-over selector from the main winding towards the regulating winding.</td>
</tr>
<tr>
<td>G</td>
<td>Conductance of the tie-in resistor.</td>
</tr>
<tr>
<td>Y1</td>
<td>( j \omega C_1 )</td>
</tr>
<tr>
<td>Y2</td>
<td>( j \omega C_2 )</td>
</tr>
<tr>
<td>Vr</td>
<td>Voltage at the midpoint of the regulating winding when the switch is closed.</td>
</tr>
</tbody>
</table>

**Star connected winding layout:**

U_{phase} = \frac{U_{system}}{\sqrt{3}}

**Delta connected winding layout:**

U_{system} = U_{phase}

**Schedule over the plus/minus regulation:**

**Schedule over the coarse/fine regulation:**
**Capacitance formula**

The capacitances $C_1$ and $C_2$ can be calculated according to the following formula:

$$C_1 = \frac{\varepsilon_{eq} \varepsilon_0 \cdot WH \cdot \pi \cdot (D_1 + D_2)}{2 \cdot T_{12}}$$

$$C_2 = \frac{\varepsilon_{eq} \varepsilon_0 \cdot WH \cdot \pi \cdot (D_2 + D_3)}{2 \cdot T_{23}}$$

Where:

- WH = Winding height
- $D_1$ = Mean diameter of the inner winding (1) or limb diameter
- $D_2$ = Mean diameter of the regulating winding
- $D_3$ = Mean diameter of the outer winding (3) or distance to the tank wall
- $T_{12}$ = Duct between inner (1) and the regulating winding or distance from the core to the regulating winding
- $T_{23}$ = Duct between the regulating and outer winding (3) or distance from the regulating winding to the tank
- $\varepsilon_{eq}$ = Equivalent relative permeability of the duct insulation. For normal transformer isolation the $\varepsilon_{eq}$ value is approximately 2.7. If a more solid isolation than normal is used, the $\varepsilon_{eq}$ value should be adjusted accordingly.
- $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m

**Recovery voltage**

The recovery voltage is the temporary power frequency voltage that occurs between the moving and the fixed contact during change-over selector operation after extinction of the electric arc when the moving contact is temporarily in the intermediate open position. The recovery voltage ($U_R$) is shown in kV.

$$D_1 = 2a + (b - a)$$

$$D_2 = 2c + (d - c)$$

$$D_3 = 2 \cdot (d + e)$$

$$T_{12} = c - b$$

$$T_{23} = e$$
Calculations for two windings transformers (not auto-transformers)

General
Remember that if the transformer is Δ-Y (delta – star) connected, the phase angles will be different if you compare to a Y-Y connected transformer and you need to use the complex method but the same formulas can be used. If the transformer is delta connected remove √3 from all following formulas except formulas marked with number one (1).

For plus/minus regulation (kV)
\[ V_{x1} = \frac{V1 \cdot C1 + V3 \cdot C2}{(C1 + C2)} \]

The potential (Vs) at the change-over selector are decided by following formulas.
At the line end: \[ \frac{U_{\text{system}}}{\sqrt{3}} \]
Neutral end: Vs = 0 kV
In the middle of the winding: \[ \frac{U_{\text{system}}}{2 \cdot \sqrt{3}} \]

The service voltage across the regulating winding:
\[ U_{\text{RW}} = \frac{U_{\text{system}} \cdot r \cdot r}{\sqrt{3}} \]

Recovery voltages:
\[ U_{R+} = V_S + U_C - V_{x1} - \frac{U_{\text{RW}}}{2} \]
\[ U_{R-} = V_S - V_{x1} - \frac{U_{\text{RW}}}{2} \]

Where \( U_C \) is the voltage over the coarse winding.

The highest recovery voltage is shown:
\[ U_R = \text{max}(|U_{R+}|, |U_{R-}|) \]

For coarse/fine regulation (kV)
\[ V_{x1} = \frac{V1 \cdot C1 + V3 \cdot C2}{(C1 + C2)} \]

The potential (Vs) at the change-over selector are decided by following formulas.
At the line end: \[ \frac{U_{\text{system}}}{\sqrt{3}} \]
Neutral end: Vs = 0 kV
In the middle of the winding: \[ \frac{U_{\text{system}}}{2 \cdot \sqrt{3}} \]

The service voltage across the regulating winding:
\[ U_{\text{RW}} = \frac{U_{\text{system}} \cdot r \cdot r}{\sqrt{3}} \]

Recovery voltages:
\[ U_{R+} = V_S + U_C - V_{x1} - \frac{U_{\text{RW}}}{2} \]
\[ U_{R-} = V_S - V_{x1} - \frac{U_{\text{RW}}}{2} \]

Where \( U_C \) is the voltage over the coarse winding.

The highest recovery voltage is shown:
\[ U_R = \text{max}(|U_{R+}|, |U_{R-}|) \]

Calculation of capacitive breaking current
The capacitive breaking current is defined as being the current through the closed change-over selector switch before opening.
\[ I_S = U_S \cdot j\omega (C1 + C2) \quad [A] \]
Where \( \omega = 2\pi \cdot f \)
\( f \) = rated frequency in Hz.

Note:
Derivation of the formula in the end of the instruction, see page 11.
Regulating transformers

Theoretical models of regulating transformers: The layouts of the transformers winding has several designs and below the most used are shown (plus/minus shown).

HV regulated

a) Tap-changer is placed in the neutral end
b) Tap-changer is placed in the middle of the HV winding
c) Tap-changer is placed in the line end

LV regulated

a) Tap-changer is placed in the neutral end
b) Tap-changer is placed in the middle of the HV winding
c) Tap-changer is placed in the line end
Transient voltage across the contacts of the change-over selector after the connection of the tie-in resistor

The transient voltage can be calculated by following formulas:

**For plus/minus regulation (kV)**

\[ U_{R+} = V_s \left( \frac{V_1 Y_1 + V_3 Y_2 + V_4 G}{Y_1 + Y_2 + G} \right) + \frac{U_{sw}}{2} \]

\[ U_{R-} = V_s \left( \frac{V_1 Y_1 + V_3 Y_2 + V_4 G}{Y_1 + Y_2 + G} \right) - \frac{U_{sw}}{2} \]

The highest recovery voltage is shown:

\[ U_R = \text{Max} \{ |U_{R+}|, |U_{R-}| \} \]

**For coarse/fine regulation (kV)**

\[ U_{R+} = V_s \left( U_C + \frac{V_1 Y_1 + V_3 Y_2 + V_4 G}{Y_1 + Y_2 + G} \right) - \frac{U_{sw}}{2} \]

\[ U_{R-} = V_s \left( \frac{V_1 Y_1 + V_3 Y_2 + V_4 G}{Y_1 + Y_2 + G} \right) - \frac{U_{sw}}{2} \]

The highest recovery voltage is shown:

\[ U_R = \text{Max} \{ |U_{R+}|, |U_{R-}| \} \]

Where the capacitive breaking current \( I_s \) may be calculated by following formula.

\[ |I_s| = U_{Rmax} \cdot \left( \frac{1}{R} + j \omega (C_1 + C_2) \right) \]

Derivation of \( I_s \) can be found in the end of the instruction.
Regulating auto-transformers

Common information
The auto-transformer has the following standard regulating arrangements.

An auto-transformer has two windings and they are the high voltage (HV) - and the low voltage (LV) - winding. In some instructions and manuals the HV winding is called series winding and the LV winding is called common winding.

This instruction will not show how to calculate on the coarse/fine regulation because it is very rare and the delta connected HV winding is not used.

In some cases the auto-transformer has a tertiary winding that is delta connected. The tertiary winding is often located between the high voltage winding and the regulating winding, why this winding must be used calculating the recovery voltage. In those cases the winding layout will be different and the phase angles must be enclosed in the calculation.

A tertiary winding is used to improve the transformer behaviour with asymmetric deflection and to reduce harmonics made by non-linear magnetization curve were the third harmonic component (150 Hz) is dominant.
Calculations

**HV regulated**

![Diagram of HV, RW, LV connections]

**Note:**

HV/LV = U1/U2

**Step voltage is calculated by following formula:**

\[ U_{\text{step}} = \frac{U_1 \cdot r \cdot s}{\sqrt{3}} \]

**a) Plus/minus regulation (kV)**

The potential (V_s) at the change-over selector is:

\[ V_s = \frac{U_2}{\sqrt{3}} \]

The potential for each winding:

\[ V_1 = \frac{U_1 - U_2}{2 \cdot \sqrt{3}} + \frac{U_2}{\sqrt{3}} \]

\[ V_3 = \frac{U_2}{2 \cdot \sqrt{3}} \]

\[ V_x = (V_1 - V_3) \cdot \frac{C_1}{C_1 + C_2} + V_3 \]

**Recovery voltages:**

\[ U_{R+} = V_s - V_x + \frac{U_{\text{RW}}}{2} \]

\[ U_{R-} = V_s - V_x - \frac{U_{\text{RW}}}{2} \]

The highest recovery voltage is shown:

\[ U_R = \text{Max} \{ |U_{R+}|, |U_{R-}| \} \]
**LV regulated**

To calculate the LV’s regulated recovery voltage there is no difference in the calculation of the HV regulated auto-transformer, the same formulas are used. The only thing that is different is the part when the step voltage is calculated. Then you used the LV voltage (U2) instead of the HV voltage (U1).

\[
U_{\text{step}} = \frac{U_2 \cdot r \cdot s}{\sqrt{3}}
\]

**Taps and neutral end**

In most cases auto-transformer with taps at neutral end are regulated from the low voltage side because the regulating range (±5–±20 %) is larger than if it is regulated from the high voltage side (±5–±13 %).

When the auto-transformers have its tapings in the neutral end, in most cases the winding layout consists of a tertiary V1-regulating- and the common V3- winding.

**a) Plus/minus regulation unit: (kV)**

The potential (Vs) at the change-over selector is:

\[
V_s = 0
\]

The potential for each winding:

\[
V_3 = \frac{U_2}{2 \cdot \sqrt{3}} \quad V_1 = \frac{U_1 - U_2}{2 \cdot \sqrt{3}} + U_2 \quad \frac{U_2 \sqrt{3}}{\sqrt{3}}
\]

\[
V_{x1} = (V_1 - V_3) \cdot \frac{C_1}{C_1 + C_2} + V_3
\]

Recovery voltages

\[
U_{R+} = V_s - V_{x1} + \frac{U_{nw}}{2}
\]

\[
U_{R-} = V_s - V_{x1} - \frac{U_{nw}}{2}
\]

The highest recovery voltage is shown:

\[
U_R = \text{Max } (|U_{R+}|, |U_{R-}|)
\]

**Calculation of capacitive breaking current**

Capacitive breaking current (I_s) flowing through change-over selector from the main winding towards the regulating winding (see page 11).

\[
I_s = \frac{U_e \cdot j \omega (C_1 + C_2)}{2}
\]

Where \( \omega = 2\pi \cdot f \)

f = rated frequency in Hz.
Losses in tie-in resistor
It is important to find losses in the tie-in resistor, because the losses generate temperature rises that can damage the resistor, or cause gas generation in the oil. In the worst case losses can cause flashovers in the oil. The losses in a tie-in resistor may be divided into two types:

- Short time losses during change-over selector operation, $P_{tr}$
- Losses at continuous connection of a tie-in resistor, $P_{cr}$

Short time losses (kW/phase)
Short time losses appear in a tie-in resistor during the breaking sequence when it carries capacitive current and the losses appear when the switch is temporarily in open position.

$$P_{tr} = \frac{|V_s - V_x|^2}{R}$$

Continuous losses (kW/phase)
For coarse/fine regulation

$$P_{c1} = \frac{\left(\frac{U_{rw}}{2}\right)^2}{R} \quad P_{c2} = \frac{\left(\frac{U_c - U_{rw}}{2}\right)^2}{R}$$

$P_{cm} = \max(P_{c1}, P_{c2})$

For plus/minus regulation

$$P_c = \frac{\left(\frac{U_{rw}}{2}\right)^2}{R}$$

Continuous losses in a tie-in resistor are presented even at no-load and must be taken into consideration at calculation of no-load losses. If no acceptable value of the tie-in resistance with respect to these losses can be chosen, the on-load tap-changer with disconnector (so called tie-in resistor switch) should be ordered.

Derivations of current formula
The breaking current ($I_s$) is determined by the circuit below and from the nodal equation.

Derivations of current formula
The breaking current ($I_s$) is determined by the circuit below and from the nodal equation.

$$I_s = (V_r - V_1 Y_1 + (V_r - V_3 Y_2 + (V_r - V_s)G)$$

$$V_x = (V_1 Y_1 + V_3 Y_2 + V_s G)/(Y_1 + Y_2 + G)$$

Insert (2) in (1)

$$I_s = (V_r - V_x) (Y_1 + Y_2 + G)$$

Insert (3) in (4)

$$U_s = V_r - V_x$$

$$I_s = U_r \cdot j\omega(C_1 + C_2)$$
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