Digital Energy
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GE Multilin technical note

Phase differential protection applications for autotransformers

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The UR-series T35 and T60 Transformer Protection Systems can be used for primary and backup protection of any type of autotransformer, including:

- Autotransformers with or without a delta tertiary winding.
- Autotransformers with or without three-phase CTs placed on the grounded neutral.
- Autotransformers with CTs inside or outside delta tertiary.
- Autotransformers with windings associated with more than one breaker.

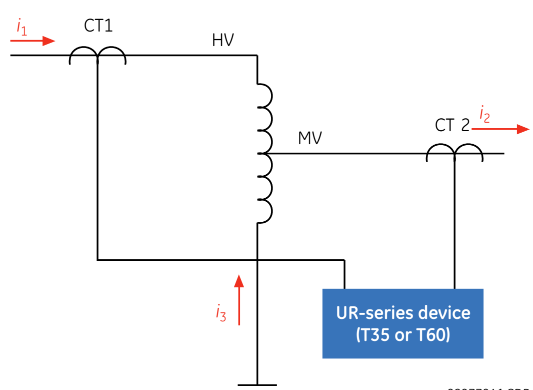
Depending on the availability of CTs and their locations, the autotransformer settings under the general transformer and winding settings menus can be changed. The two examples below describe how to program the transformer settings for two common autotransformer CT arrangements.

Standard configuration

Autotransformer with three-phase CTs installed on the HV and LV sides only.

The settings for the transformer windings follow the traditional approach of setting up protection of conventional type transformers, such as grounded wye/grounded wye two-winding transformers. In this case, the settings for each winding comply as follows.

Figure 1: Standard autotransformer configuration example



Consider a transformer with the following specifications:

- 672 MVA autotransformer.
- Ratio is 500 kV / 230 kV.
- CT ratios of CT1 = 1000:5 and CT2 = 2000:5.

The general transformer and winding settings are shown below.

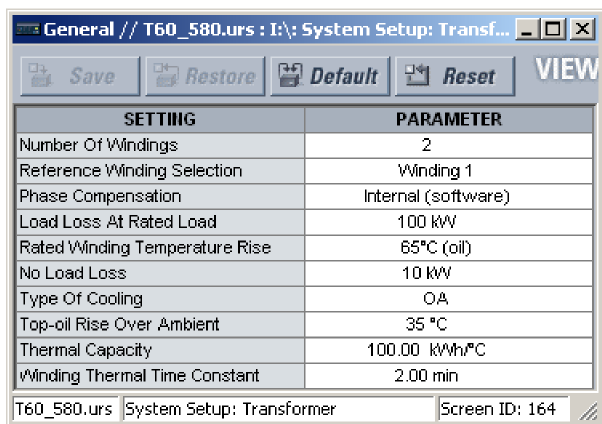
Transformer general settings

Make the following changes to the transformer general settings in the **System Setup > Transformer > General** menu.

1. Select the **Number of Windings** setting to "2" to indicate the number of windings with a three-phase CT available for differential protection.
2. Set the **Reference Winding Selection** setting for magnitude compensation.

   The relay uses the entered phase-to-phase voltage of the selected reference winding and the entered CT primary setting from the assigned source for that winding to compute the magnitude compensation factors (scaling factors) for the currents from all other non-reference windings. If "Winding1" is selected, the relay will take the 500 kV phase-to-phase voltage setting and the 1000 A CT primary setting as reference quantities, where 1000 A becomes the unit for magnitude compensation and per-unit calculation of the per phase differential and restraint currents.
3. The remaining general transformer settings should be set only if the T60 transformer thermal elements are used.

Figure 2: General settings window for standard autotransformer application



SETTING	PARAMETER
Number Of Windings	2
Reference Winding Selection	Winding 1
Phase Compensation	Internal (software)
Load Loss At Rated Load	100 kW
Rated Winding Temperature Rise	65°C (oil)
No Load Loss	10 kW
Type Of Cooling	OA
Top-oil Rise Over Ambient	35 °C
Thermal Capacity	100.00 kWh/°C
Winding Thermal Time Constant	2.00 min

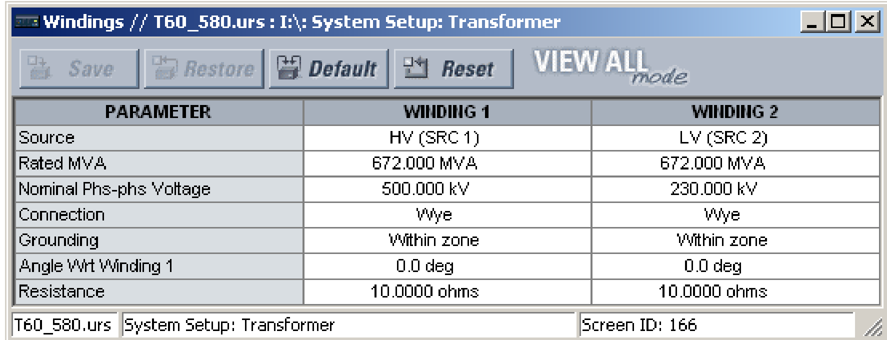
Winding settings

Make the following changes to the transformer general settings in the **System Setup > Transformer > Windings** menu.

1. Enter the **Rated MVA** setting for each winding to the autotransformer MVA rating specified by the autotransformer nameplate.
2. Enter the **Nominal Phs-Phs Voltage** setting for each winding to the phase-to-phase voltage specified by the autotransformer nameplate.
3. Enter the **Connection** type as "Wye" for both windings.
4. Enter the **Grounding** setting as "Within zone" for both windings.

   This setting is applicable to the removal of zero-sequence currents from the measured winding phase currents for each winding. This is important during external ground faults.
5. Enter the **Angle WRT Winding 1** setting as "0°" (WRT = With Respect To) for both windings.

Figure 3: Winding settings window for standard autotransformer application



PARAMETER	WINDING 1	WINDING 2
Source	HV (SRC 1)	LV (SRC 2)
Rated MVA	672.000 MVA	672.000 MVA
Nominal Phs-phs Voltage	500.000 kV	230.000 kV
Connection	Wye	Wye
Grounding	Within zone	Within zone
Angle Wrt Winding 1	0.0 deg	0.0 deg
Resistance	10.0000 ohms	10.0000 ohms

Example

Recall the transformer with the following specifications:

- 672 MVA autotransformer.
- Ratio is 500 kV / 230 kV.
- CT ratios of CT1 = 1000:5 and CT2 = 2000:5.

During normal loading conditions the autotransformer primary currents sum to zero:

$$i_1 + i_2 + i_3 = 0 \qquad \textbf{(Eq 1)}$$

However, since the current i_3 is not available, the relay takes the entered transformer data and performs the magnitude and phase compensations using the measured winding currents from both windings. The magnitude compensation factor for the winding 1 currents is automatically calculated as follows.

$$M(W_1) = \frac{500\ \text{kV} \times 1000}{500\ \text{kV} \times 1000} = 1 \qquad \textbf{(Eq 2)}$$

Likewise, the magnitude compensation factor for winding 2 currents is automatically calculated as follows.

$$M(W_2) = \frac{230\ \text{kV} \times 2000}{500\ \text{kV} \times 1000} = 0.92 \qquad \textbf{(Eq 3)}$$

When the rules mentioned above are followed, the T35/T60 scales the measured secondary currents internally, thus resulting in zero differential current under normal conditions. Therefore, the per-unit differential and restraint currents on the relay will be as follows.

$$\begin{aligned} I_d &= \overrightarrow{i_{1(sec)}}(\text{pu}) + \overrightarrow{i_{2(sec)}}(\text{pu}) = 0 \\ I_r &= \max(\text{abs}(\overrightarrow{i_{1(sec)}}(\text{pu}), \overrightarrow{i_{2(sec)}}(\text{pu}))) \end{aligned} \qquad \textbf{(Eq 4)}$$

For 100% loading, the per-unit winding currents, as well as the per-unit differential and restraint currents calculated by the relay are shown below. The winding 1 nominal primary current is calculated as follows.

$$I(W_{1(\text{nom})}) = \frac{672\ \text{MVA}}{500\ \text{kV} \times \sqrt{3}} = 776\ \text{A} \qquad \textbf{(Eq 5)}$$

The winding 1 per-unit current is calculated as follows.

$$I(W_{1(\text{pu})}) = \frac{776\ \text{A}}{1000\ \text{A}} \times 1 = 0.776\ \text{pu} \qquad \textbf{(Eq 6)}$$

The winding 2 nominal primary current is calculated as follows.

$$I(W_{2(\text{nom})}) = \frac{672\ \text{MVA}}{230\ \text{kV} \times \sqrt{3}} = 1687\ \text{A} \qquad \textbf{(Eq 7)}$$

The winding 2 per-unit current is calculated as follows.

$$I(W_{2(pu)}) = \frac{1687\ \text{A}}{2000\ \text{A}} \times 0.92 = 0.776\ \text{pu} \quad \textbf{(Eq 8)}$$

The differential and restraint currents are calculated as follows.

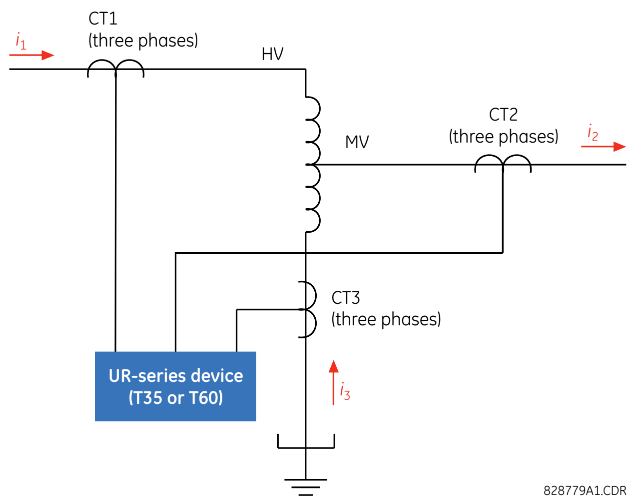
$$\begin{aligned} I_d &= \overrightarrow{i_{1(sec)}}(\text{pu}) + \overrightarrow{i_{2(sec)}}(\text{pu}) = 0.776\ \text{pu} + (-0.776\ \text{pu}) = 0 \\ I_r &= \max(\text{abs}(\overrightarrow{i_{1(sec)}}(\text{pu}), \overrightarrow{i_{2(sec)}}(\text{pu}))) = \max(|0.776\ \text{pu}|, |0.776\ \text{pu}|) = 0.776\ \text{pu} \end{aligned} \quad \textbf{(Eq 9)}$$

Alternate configuration

Autotransformer with three-phase CTs on the grounded neutral side.

An alternate configuration can be used for the example below, since the autotransformer high, low, and neutral sides are electrically connected and their currents are available on the relay.

Figure 4: Alternate autotransformer configuration example



This approach requires a CT in each phase of the neutral. This is commonly the case where the autotransformer bank is made up of three separate single-phase transformers. This alternative approach creates a differential zone across the high-side winding, the low-side winding, and the neutral connection. These currents should always sum to zero unless there is an internal fault. In this differential protection application, the zone of protection is similar to the phase-segregated bus zone protected by a differential protection scheme.

The voltage of each winding is programmed to be the same in the relay. This allows the magnitude compensation to be dependent only on the mismatch of the autotransformer CTs. In such cases, the second harmonic restraint may not be used, as the currents from the electrically connected autotransformer sides measured by the relay sum to zero during energization.

The T35/T60 setup for this alternate configuration is described below.

Transformer general settings

Make the following changes to the transformer general settings in the **System Setup > Transformer > General** menu.

1. Select the **Number of Windings** setting to “3” to indicate the number of windings with a three-phase CT available for differential protection.
2. Set the **Reference Winding Selection** setting for magnitude compensation.

The relay uses the entered phase-to-phase voltage of the selected reference winding and the entered CT primary setting from the assigned source for that winding to compute the magnitude compensation factors (scaling factors) for the currents from all other non-reference windings. If “Winding1” is selected, the relay will take the 500 kV phase-to-phase voltage setting and the 1000 A CT primary setting as reference quantities, where 1000 A becomes the unit for magnitude compensation and per-unit calculation of the per phase differential and restraint currents.

3. The remainder of the general transformer settings should be set only if the T60 transformer thermal elements are used.

Figure 5: General settings window

General // T60_580.urs : I:\: System Setup: Transf...

Save | Restore | Default | Reset | VIEW

SETTING	PARAMETER
Number Of Windings	3
Reference Winding Selection	Winding 1
Phase Compensation	Internal (software)
Load Loss At Rated Load	100 kW
Rated Winding Temperature Rise	65°C (oil)
No Load Loss	10 kW
Type Of Cooling	OA
Top-oil Rise Over Ambient	35 °C
Thermal Capacity	100.00 kWh/°C
Winding Thermal Time Constant	2.00 min

T60_580.urs | System Setup: Transformer | Screen ID: 164

Winding settings

Make the following changes to the transformer general settings in the **System Setup > Transformer > Windings** menu.

1. Program the **Rated MVA** setting for all three windings to the autotransformer MVA rating as per the autotransformer nameplate.
2. Enter the **Nominal Phs-Phs Voltage** setting for all three windings to the same phase-to-phase voltage (kV).
3. Set the **Connection** type to “Wye” for all three windings.
4. Enter “Within zone” for the **Grounding** setting for all three windings.

   Since the currents are measured each side from all three electrically connected legs that belong to the same phase, the protection becomes phase segregated, and zero-sequence removal is not required.
5. Enter the **Angle WRT Winding 1** setting as “0°” (WRT = With Respect To) for all three windings.

Figure 6: Winding settings window

Windings // T60_580.urs : I:\: System Setup: Transformer

Save | Restore | Default | Reset | VIEW ALL mode

PARAMETER	WINDING 1	WINDING 2	WINDING 3
Source	HV (SRC 1)	LV (SRC 2)	NTRL (SRC 3)
Rated MVA	672.000 MVA	672.000 MVA	672.000 MVA
Nominal Phs-phs Voltage	500.000 kV	500.000 kV	500.000 kV
Connection	Wye	Wye	Wye
Grounding	Within zone	Within zone	Within zone
Angle Wrt Winding 1	0.0 deg	0.0 deg	0.0 deg
Resistance	10.0000 ohms	10.0000 ohms	10.0000 ohms

T60_580.urs | System Setup: Transformer | Screen ID: 166

Example

Again, consider a transformer with the following specifications:

- 672 MVA autotransformer.
- Ratio is 500 kV / 230 kV.
- CT ratios of CT1 = 1000:5 and CT2 = 2000:5.

The T35/T60 performs CT mismatch correction to accommodate the differences between the CT ratios from the autotransformer terminals. Exact replicas of the autotransformer primary currents are presented to the relay.

For 100% loading, the per-unit winding currents, as well as the per-unit differential and restraint currents calculated by the relay are shown below. For winding 1 currents (with winding 1 as reference), the winding 1 primary nominal current passing through CT1 primary side is shown below.

$$I(W_{1(\text{nom})}) = \frac{672\text{ MVA}}{500\text{ kV} \times \sqrt{3}} = 776\text{ A} \qquad \textbf{(Eq 10)}$$

The winding 1 per-unit current is calculated as follows.

$$I(W_{1(\text{pu})}) = \frac{776\text{ A}}{1000\text{ A}} \times 1 = 0.776\text{ pu} \qquad \textbf{(Eq 11)}$$

The winding 2 nominal primary current passing through the CT2 primary side is calculated as follows.

$$I(W_{2(\text{nom})}) = \frac{672\text{ MVA}}{230\text{ kV} \times \sqrt{3}} = 1687\text{ A} \qquad \textbf{(Eq 12)}$$

The magnitude compensation for the winding 2 current is calculated as follows.

$$M(W_2) = \frac{500 \times 2000}{500 \times 1000} = 2 \qquad \textbf{(Eq 13)}$$

The winding 2 per-unit current is calculated as follows.

$$I(W_{2(\text{pu})}) = \frac{1687\text{ A}}{2000\text{ A}} \times 2 = 1.687\text{ pu} \qquad \textbf{(Eq 14)}$$

Since the currents from all three legs on per-phase basis sum to zero, the current from the neutral side for winding 3 is calculated as shown below. The winding 3 primary current passing through the CT3 primary side is calculated as follows.

$$1687\text{ A} - 776\text{ A} = 911\text{ A} \qquad \textbf{(Eq 15)}$$

The magnitude compensation for the winding 3 current is calculated as follows.

$$M(W_3) = \frac{500 \times 2500}{500 \times 1000} = 2.5 \qquad \textbf{(Eq 16)}$$

The winding 3 per-unit current is calculated as follows.

$$I(W_{3(\text{pu})}) = \frac{911\text{ A}}{2500\text{ A}} \times 2.5 = 0.911\text{ pu} \qquad \textbf{(Eq 17)}$$

The differential and restraint currents are calculated as follows.

$$\begin{aligned} I_d &= \overrightarrow{i_{1(sec)}}(\text{pu}) + \overrightarrow{i_{2(sec)}}(\text{pu}) + \overrightarrow{i_{3(sec)}}(\text{pu}) \\ &= (1.687\text{ pu} + (-0.776\text{ pu}) + (-0.911\text{ pu})) = 0 \\ I_r &= \max(\text{abs}(\overrightarrow{i_{1(sec)}}(\text{pu}), \overrightarrow{i_{2(sec)}}(\text{pu}), \overrightarrow{i_{3(sec)}}(\text{pu}))) \\ &= \max(|0.776\text{ pu}|, |1.687\text{ pu}|, |0.911\text{ pu}|) = 1.687\text{ pu} \end{aligned} \qquad \textbf{(Eq 18)}$$