Application of Standard Three Phase Power Transformer Protection Relays to Special Railway Transformers

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I INTRODUCTION

It is possible to protect special types of railway transformers in 50Hz or 60Hz railway supply systems using standard three-phase transformer protection relays. As these protection relays are designed for the protection of three-phase transformers, the analog quantities are treated in a three-phase manner. When using standard three-phase transformer protection relays for special railway transformer applications, the analog quantities will be treated in the same three-phase manner. This paper describes how standard three-phase transformer protection relays can be applied to different types of railway transformers on 50Hz or 60Hz railway supply systems. Railway supply systems at 50Hz or 60Hz are found in many countries around the world, including the US.

II OVERVIEW OF TRANSFORMER DIFFERENTIAL PROTECTION (87T)

Differential protection is based on summing the currents from all sides of the protected object. The primary currents are fed to the relays via CTs, and it is these CTs that form the zone boundaries of the differential protection zone. For no internal fault, the sum of the currents is zero, i.e. the currents entering and leaving the zone of protection are equal, whereas for an internal fault, the sum is non-zero, i.e. the currents entering and leaving are no longer equal. This non-zero sum represents the zone differential current.

When a transformer is the protected object, it is true to say that the differential measurement principle is based on the sum of power from all sides being zero, as the sum of currents will only be zero after all compensations have been performed. Differential protection of transformers therefore presents additional challenges, including:

- mismatch in magnitude between currents due to the voltage transformation across the windings
- phase angle shift between currents due to the different types of winding connections
- zero-sequence currents that cannot be transformed across the transformer, and so only flow on one side.

Due to the current magnitude mismatch, the primary currents entering and leaving the transformer are not equal, even under normal balanced load conditions.

Modern microprocessor-based relays perform all required compensations mathematically within the 87T function. The mathematical compensations take care of the magnitude mismatch, the phase angle shift, and the subtraction of zero-sequence currents as required.

III THREE-PHASE Dd0 POWER TRANSFORMER

The 87T differential protection function as applied to a standard Dd0 three-phase transformer will be described first. This will serve as a reference to facilitate a better understanding of the necessary adaptations needed to accomplish the 87T differential protection for the different types of railway transformer applications. Note that a three-phase Dd transformer is used as the reference as Dd vector groups are used for the railway transformer 87T differential protections.

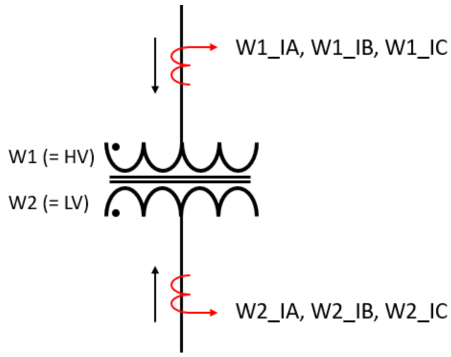


Figure 1: Three-phase, two-winding transformer (Dd0)

Current flow is in the positive direction "towards" the protected transformer.

For winding 1 (W1) current flow "towards' the three-phase transformer, phase angles of 0°, -120° and 120° can be assigned to, respectively, the currents in phases A, B and C.

For balanced through-load, the winding 2 (W2) current flow will be "away from" the transformer. With the W1-side current phase angles as shown above, for the three-phase Dd0 transformer, phase angles of 180°, 60° and -60° must be assigned to, respectively, the W2-side currents in phases A, B and C.

For the 87T differential protection it is necessary to set the rated data of the transformer. These settings include the rated current and the rated voltage for each winding of the three-phase transformer.

For a three-phase, two-winding transformer, the rated values for winding 1 (W1) and winding 2 (W2) are:

W1	$S_{R1} = S$	$V_{R1} = V_{HV}$	$I_{R1} = \frac{S}{\sqrt{3} * V_{HV}}$
W2	$S_{R2} = S$	$V_{R2} = V_{LV}$	$I_{R2} = \frac{S}{\sqrt{3} * V_{LV}}$

For balanced through-load:

$$|I_{HV}| = \left[\frac{V_{LV}}{V_{HV}}\right] * |I_{LV}|$$

For a conventional three-phase transformer with a Dd0 vector group, the equation for the calculation of the differential currents can be written as:

$$\overrightarrow{IDIFF} = \overrightarrow{I_{HV}} + \left[\frac{V_{LV}}{V_{HV}}\right] * \overrightarrow{I_{LV}}$$

Based on the above, the required matrix equation for the calculation of the per phase differential currents can be written as:

$$\begin{bmatrix} \overrightarrow{ID\_A} \\ \overrightarrow{ID\_B} \\ \overrightarrow{ID\_C} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} \overrightarrow{IA_{HV}} \\ \overrightarrow{IB_{HV}} \\ \overrightarrow{IC_{HV}} \end{bmatrix} + \frac{V_{LV}}{V_{HV}} * \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} \overrightarrow{IA_{LV}} \\ \overrightarrow{IB_{LV}} \\ \overrightarrow{IC_{LV}} \end{bmatrix}$$

from which:

$\overrightarrow{ID\_A} = \overrightarrow{IA_{HV}} + \frac{V_{LV}}{V_{HV}} * \overrightarrow{IA_{LV}}$
$\overrightarrow{ID\_B} = \overrightarrow{IB_{HV}} + \frac{V_{LV}}{V_{HV}} * \overrightarrow{IB_{LV}}$
$\overrightarrow{ID\_C} = \overrightarrow{IC_{HV}} + \frac{V_{LV}}{V_{HV}} * \overrightarrow{IC_{LV}}$

Note that the magnitude of the differential currents is referenced to the W1-side (HV-side).

The connection of the currents to the 87T function will be as follows:

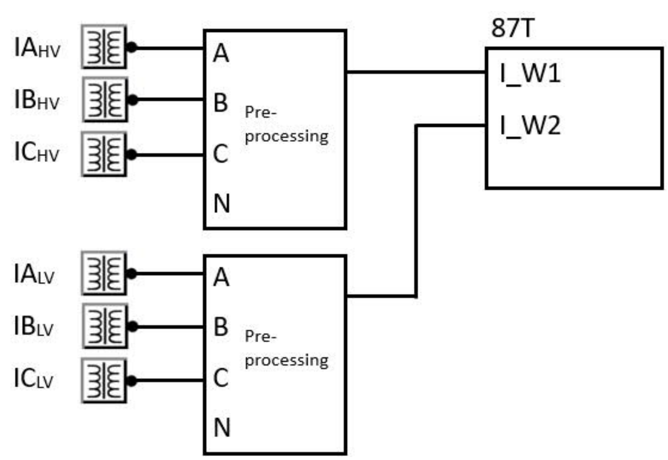


Figure 2: Connection of currents to the 87T function for a three-phase, two-winding transformer

Typical settings to accomplish the required differential measurement are:

Rated Voltage W1	V_{R1}
Rated Voltage W2	V_{R2}
Rated Current W1	I_{R1}
Rated Current W2	I_{R2}
Connect Type W1	Delta (D)
Connect Type W2	Delta (D)
Clock Number W2	0 (0 deg)
ZS Current Subtraction W1	Off
ZS Current Subtraction W2	Off

For W1 connection type = Delta, and W1 zero-sequence current subtraction = Off, the selected matrix for compensation of the W1 currents in the matrix equation for calculation of the differential currents will be the unit matrix which, as shown above, is the matrix that is required to correctly calculate the differential currents.

For W2 connection type = Delta, W2 zero-sequence current subtraction = Off, and the W2 clock number = 0 (0 deg) (the W2-side currents require no phase angle rotation to align with the W1-side currents), the selected matrix for compensation of the W2 currents in the matrix equation for calculation of the differential currents will also be the unit matrix which, as shown above, is the matrix that is required to correctly calculate the differential currents.

<u>Example 1</u>

Dd0 transformer; 120MVA

$V_{R1} = 230kV = V_{W1} = V_{HV}$

$V_{R2} = 66kV = V_{W2} = V_{LV}$

$I_{R1} = 301.2A$

$I_{R2} = 1{,}049.7A$

Say now that the actual LV-side currents are = 524.9A (= 50% of I_{R2}).

For balanced through-load, the HV-side currents would be = 150.6A.

IA_{HV}, IB_{HV} and IC_{HV} flow “towards” the transformer, and so can be assigned phase angles of, respectively, 0°, -120° and 120°.

$IA_{HV} = 150.6\angle 0°$

$IB_{HV} = 150.6\angle -120°$

$IC_{HV} = 150.6\angle 120°$

IA_{LV}, IB_{LV} and IC_{LV} flow “away from” the transformer, and so can be assigned phase angles of, respectively, 180°, 60° and -60°.

$IA_{LV} = 524.9\angle 180°$

$IB_{LV} = 524.9\angle 60°$

$IC_{LV} = 524.9\angle -60°$

$$\begin{bmatrix} \overrightarrow{ID\_A} \\ \overrightarrow{ID\_B} \\ \overrightarrow{ID\_C} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 150.6\angle 0° \\ 150.6\angle -120° \\ 150.6\angle 120° \end{bmatrix} + \frac{66}{230} * \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 524.9\angle 180° \\ 524.9\angle 60° \\ 524.9\angle -60° \end{bmatrix}$$

$$= \begin{bmatrix} 150.6\angle 0° \\ 150.6\angle -120° \\ 150.6\angle 120° \end{bmatrix} + \begin{bmatrix} 150.6\angle 180° \\ 150.6\angle 60° \\ 150.6\angle -60° \end{bmatrix}$$

$$= \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

The complete protection scheme for a three-phase, two-winding transformer application would typically comprise the following:

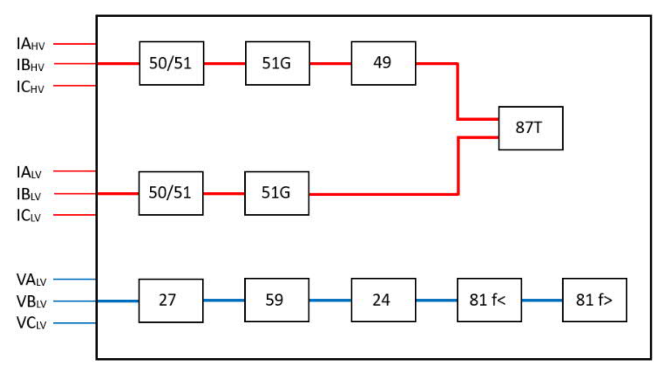


Figure 3: Typical protection scheme for a three-phase, two-winding transformer application

For a three-phase, three-winding transformer it’s just a case of adding the third winding to the measurement and calculation.

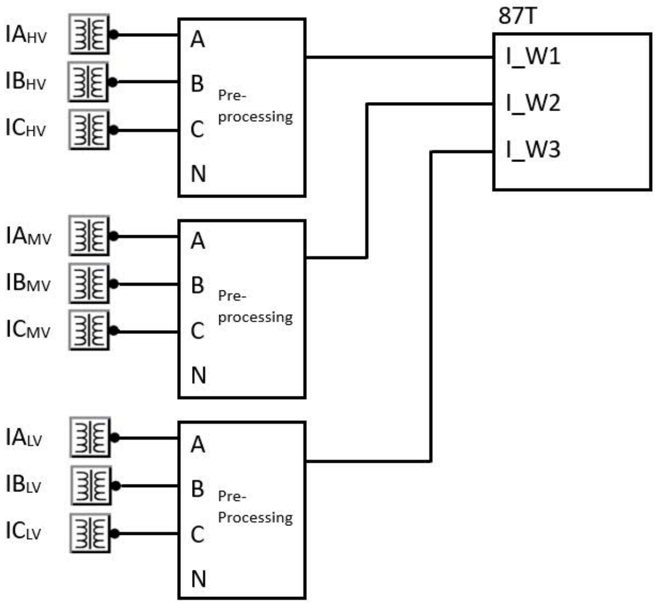


Figure 4: Connection of currents to the 87T function for a three-phase, three-winding transformer

For a three-phase, three-winding transformer, the rated values for winding 1 (W1), winding 2 (W2) and winding 3 (W3) are:

W1	$S_{R1} = S_{HV}$	$V_{R1} = V_{HV}$	$I_{R1} = \frac{S_{HV}}{\sqrt{3}*V_{HV}}$
W2	$S_{R2} = S_{MV}$	$V_{R2} = V_{MV}$	$I_{R2} = \frac{S_{MV}}{\sqrt{3}*V_{MV}}$
W3	$S_{R3} = S_{LV}$	$V_{R3} = V_{LV}$	$I_{R3} = \frac{S_{LV}}{\sqrt{3}*V_{LV}}$

For a three-phase, three-winding Dd0d0 transformer, the matrix equation for the calculation of the per phase differential currents can be written as:

$$\begin{bmatrix} \overrightarrow{ID\_A} \\ \overrightarrow{ID\_B} \\ \overrightarrow{ID\_C} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} \overrightarrow{IA_{HV}} \\ \overrightarrow{IB_{HV}} \\ \overrightarrow{IC_{HV}} \end{bmatrix} + \frac{V_{MV}}{V_{HV}} * \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} \overrightarrow{IA_{MV}} \\ \overrightarrow{IB_{MV}} \\ \overrightarrow{IC_{MV}} \end{bmatrix}$$

$$+ \frac{V_{LV}}{V_{HV}} * \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} \overrightarrow{IA_{LV}} \\ \overrightarrow{IB_{LV}} \\ \overrightarrow{IC_{LV}} \end{bmatrix}$$

from which:

$$\overrightarrow{ID\_A} = \overrightarrow{IA_{HV}} + \frac{V_{MV}}{V_{HV}} * \overrightarrow{IA_{MV}} + \frac{V_{LV}}{V_{HV}} * \overrightarrow{IA_{LV}}$$

$$\overrightarrow{ID\_B} = \overrightarrow{IB_{HV}} + \frac{V_{MV}}{V_{HV}} * \overrightarrow{IB_{MV}} + \frac{V_{LV}}{V_{HV}} * \overrightarrow{IB_{LV}}$$

$$\overrightarrow{ID\_C} = \overrightarrow{IC_{HV}} + \frac{V_{MV}}{V_{HV}} * \overrightarrow{IC_{MV}} + \frac{V_{LV}}{V_{HV}} * \overrightarrow{IC_{LV}}$$

Typical settings to accomplish the required differential measurement are:

Rated Voltage W1	V_{R1}
Rated Voltage W2	V_{R2}
Rated Voltage W3	V_{R3}
Rated Current W1	I_{R1}
Rated Current W2	I_{R2}
Rated Current W3	I_{R3}
Connect Type W1	Delta (D)
Connect Type W2	Delta (D)
Connect Type W3	Delta (D)
Clock Number W2	0 (0 deg)
Clock Number W3	0 (0 deg)
ZS Current Subtraction W1	Off
ZS Current Subtraction W2	Off
ZS Current Subtraction W3	Off

The above settings will select the unit matrix, as is required, for the compensation of the W1-, W2- and W3-side currents in the matrix equation for calculation of the differential currents.

IV SINGLE-PHASE RAILWAY TRANSFORMER

This type of transformer is commonly used in older types of railway installations.

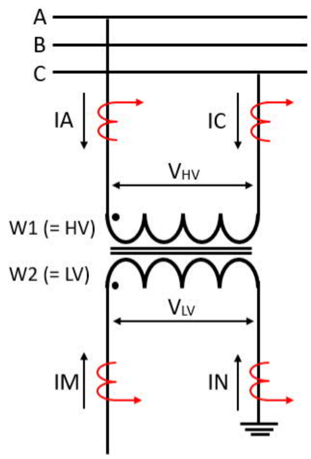


Figure 5: Single-phase railway transformer

As for three-phase transformers, it is necessary to set the rated data of the single-phase railway transformer. These settings include the rated current and the rated voltage for each winding of the single-phase railway transformer.

Note that for all railway transformer applications, these parameters need to be set in a 'special way', since the railway transformers are not of a three-phase design.

For single-phase railway transformers the rated values for W1 and W2 are:

W1	$S_{R1} = S$	$V_{R1} = V_{HV}$	$I_{R1} = \frac{S}{V_{HV}}$
W2	$S_{R2} = S$	$V_{R2} = V_{LV}$	$I_{R2} = \frac{S}{V_{LV}}$

For balanced through-load:

$$|IA| = \left[\frac{V_{LV}}{V_{HV}}\right] * |IM|$$

$$|IC| = \left[\frac{V_{LV}}{V_{HV}}\right] * |IN|$$

The equations for the calculation of the differential currents can therefore be written as:

$$\overrightarrow{IDIFFA} = \overrightarrow{IA} + \left[\frac{V_{LV}}{V_{HV}}\right] * \overrightarrow{IM}$$

$$\overrightarrow{IDIFFC} = \overrightarrow{IC} + \left[\frac{V_{LV}}{V_{HV}}\right] * \overrightarrow{IN}$$

From the above equations for the differential currents it can be readily seen that the matrices required in the matrix equation to calculate the differential currents are the unit matrix, i.e. the same matrices as used in the matrix equation for three-phase transformers with a Dd0 (or Dd0d0) vector group. Therefore, the required matrix equation for the calculation of the differential currents for single-phase railway transformers can be written as:

$$\begin{bmatrix} \overrightarrow{ID\_A} \\ \overrightarrow{ID\_B} \\ \overrightarrow{ID\_C} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} \overrightarrow{IA} \\ 0 \\ \overrightarrow{IC} \end{bmatrix} + \frac{V_{LV}}{V_{HV}} * \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} \overrightarrow{IM} \\ 0 \\ \overrightarrow{IN} \end{bmatrix}$$

from which:

$\overrightarrow{ID\_A} = \overrightarrow{IA} + \frac{V_{LV}}{V_{HV}} * \overrightarrow{IM}$
$\overrightarrow{ID\_B} = 0$
$\overrightarrow{ID\_C} = \overrightarrow{IC} + \frac{V_{LV}}{V_{HV}} * \overrightarrow{IN}$

The connection of the currents to the 87T function will be as follows:

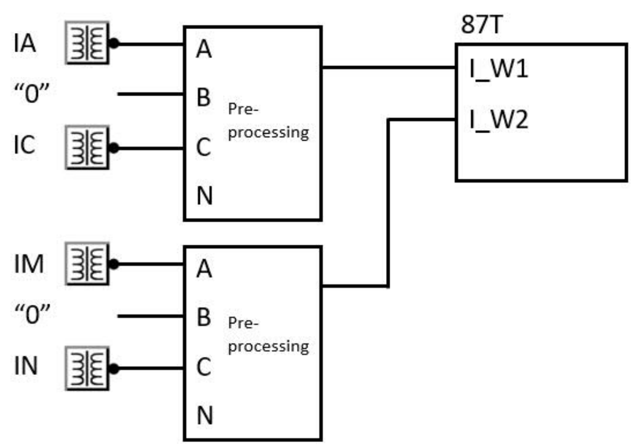
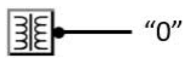


Figure 6: Connection of currents to the 87T function for a single-phase railway transformer

Standard three-phase transformer protection relays treat the analog quantities in a three-phase manner. Because of this, for the differential protection of single-phase railway transformers, it is necessary to use a current signal with a value of zero to build a three-phase application from a two-phase system.

This zero-current signal is obtained from a relay current input that is not connected to anything, i.e. it is intentionally left unwired.



The above illustrates a relay current input to which no physical current has been connected (wired). The same unconnected current input can be used for all the transformer windings where a zero-current value is required.

The analog pre-processing functions “see” that all three phases of current are connected to relay current inputs, and so treat these three current inputs in a three-phase manner. Therefore, the standard three-phase transformer protection relay operates as designed in a three-phase manner. To accomplish the differential measurement for single-phase railway transformers, the one phase current (in this example phase B) is “seen” to be there, but will always just have a zero value.

Typical settings to accomplish the required differential measurement are:

Rated Voltage W1	V_{R1}
Rated Voltage W2	V_{R2}
Rated Current W1	I_{R1}
Rated Current W2	I_{R2}
Connect Type W1	Delta (D)
Connect Type W2	Delta (D)
Clock Number W2	0 (0 deg)
ZS Current Subtraction W1	Off
ZS Current Subtraction W2	Off

The above settings will select the unit matrix, as is required, for the compensation of the W1- and W2-side currents in the matrix equation for calculation of the differential currents.

<u>Example 2</u>

Single-phase railway transformer; 30MVA

V_{R1} = 115kV = V_{W1} = V_{HV}

V_{R2} = 27.5kV = V_{W2} = V_{LV}

I_{R1} = 260.9A

I_{R2} = 1,090.9A

Say now that the actual LV-side currents are = 545.5A (=50% of I_{R2}).

For balanced through-load, the HV-side currents would be = 130.4A.

IA flows “towards” the transformer, and so can be assigned a phase angle of 0°. IC flows “away from” the transformer, and so can be assigned a phase angle of 180°.

IA = 130.4∠0°, and

IC = 130.4∠180°

IM flows “away from” the transformer, and so can be assigned a phase angle of 180°. IN flows “towards” the transformer, and so can be assigned a phase angle of 0°.

IM = 545.5∠180°, and

IN = 545.5∠0°

$$\begin{bmatrix} \overrightarrow{ID\_A} \\ \overrightarrow{ID\_B} \\ \overrightarrow{ID\_C} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 130.4\angle 0^\circ \\ 0.0 \\ 130.4\angle 180^\circ \end{bmatrix} + \frac{27.5}{115} * \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 545.5\angle 180^\circ \\ 0.0 \\ 545.5\angle 0^\circ \end{bmatrix}$$

$$= \begin{bmatrix} 130.4\angle 0^\circ \\ 0.0 \\ 130.4\angle 180^\circ \end{bmatrix} + \begin{bmatrix} 130.4\angle 180^\circ \\ 0.0 \\ 130.4\angle 0^\circ \end{bmatrix}$$

$$= \begin{bmatrix} 0.0 \\ 0.0 \\ 0.0 \end{bmatrix}$$

The complete protection scheme for a single-phase railway transformer application would typically comprise the following:

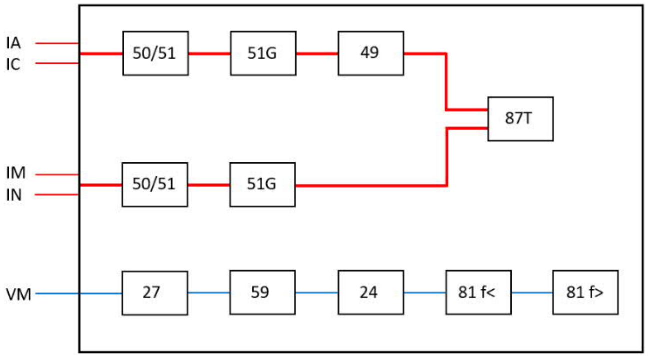


Figure 7: Typical protection scheme for a single-phase railway transformer application

The connection of the HV- and LV-side currents to the current-measuring protection functions will be as follows:

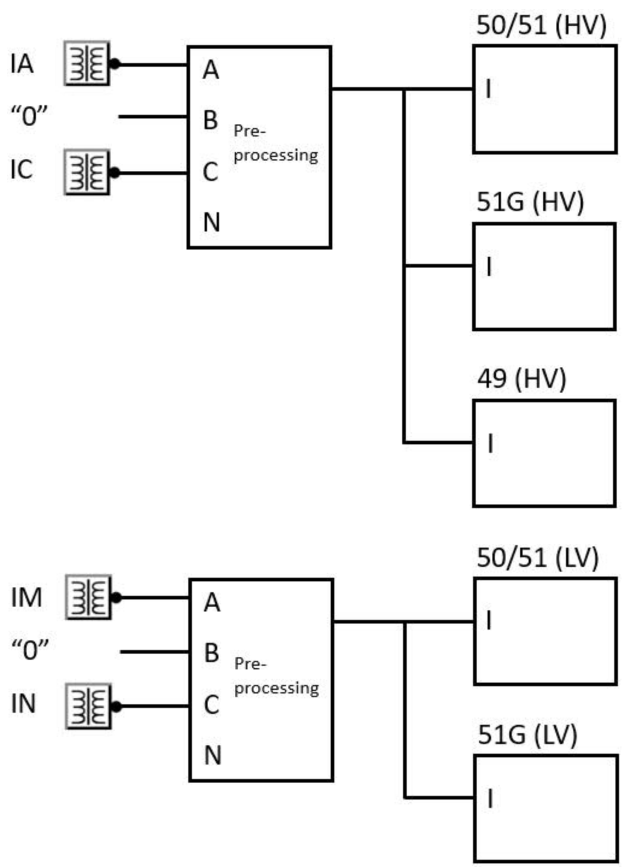


Figure 8: Connection of currents to the current-measuring protection functions for a single-phase railway transformer

V SPLIT SINGLE-PHASE RAILWAY TRANSFORMER

This type of transformer is commonly used in newer types of railway installations.

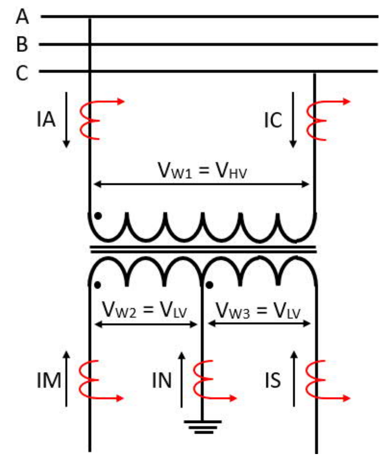


Figure 9: Split single-phase railway transformer

For split single-phase railway transformers the rated values for W2, W3 and W3 are:

W1	$S_{R1} = S$	$V_{R1} = V_{HV}$	$I_{R1} = \frac{S}{V_{HV}}$
W2	$S_{R2} = \frac{S}{2}$	$V_{R2} = V_{LV}$	$I_{R2} = \frac{S}{2*V_{LV}}$
W3	$S_{R3} = \frac{S}{2}$	$V_{R3} = V_{LV}$	$I_{R3} = \frac{S}{2*V_{LV}}$

For balanced through-load, a typical load profile would be as follows:

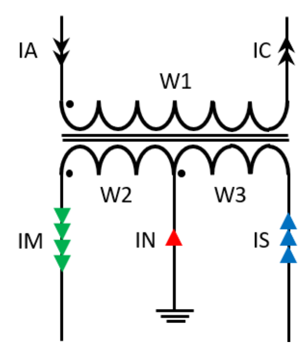


Figure 10: Typical load profile for a split single-phase railway transformer

For balanced through-load:

$$|IA| = \left[\frac{V_{LV}}{V_{HV}}\right] * |IM| + \left[\frac{V_{LV}}{V_{HV}}\right] * |IS|$$

$$|IC| = \left[\frac{V_{LV}}{V_{HV}}\right] * |IS| + \left[\frac{V_{LV}}{V_{HV}}\right] * |IM|$$

IA flows “towards” the transformer. IM flows “away from” the transformer whilst IS flows “towards” the transformer. As IM and IS flow in “opposite” directions (direction required is “away from” the transformer to achieve the through-load balance with IA flow “towards” the transformer), the angle of IS needs to be rotated by 180° to balance the current measurement and correctly calculate the differential current. The equation for the calculation of the differential current can therefore be written as:

$$\overrightarrow{IDIFFA} = \overrightarrow{IA} + \left[\frac{V_{LV}}{V_{HV}}\right] * \overrightarrow{IM} + \left[\frac{V_{LV}}{V_{HV}}\right] * (-\overrightarrow{IS})$$

IC flows “away from” the transformer. IS flows “towards” the transformer whilst IM flows “away from” the transformer. As IS and IM flow in “opposite” directions (direction required is “towards” the transformer to achieve the through-load balance with IC flow “away from” the transformer), the angle of IM needs to be rotated by 180° to balance the current measurement and correctly calculate the differential current. The equation for the calculation of the differential current can therefore be written as:

$$\overrightarrow{IDIFFC} = \overrightarrow{IC} + \left[\frac{V_{LV}}{V_{HV}}\right] * \overrightarrow{IS} + \left[\frac{V_{LV}}{V_{HV}}\right] * (-\overrightarrow{IM})$$

From the above equations for the differential currents it can be seen that:

- the unit matrix is required where no 180° rotation of the currents is required, and
- the matrix with diagonal elements -1 and all other elements 0 is required where the 180° rotation of the currents is required.

Therefore, the required matrix equation for the calculation of the differential currents for split single-phase railway transformers can be written as:

$$\begin{bmatrix}\overrightarrow{ID\_A}\\ \overrightarrow{ID\_B}\\ \overrightarrow{ID\_C}\end{bmatrix} = \begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix} * \begin{bmatrix}\overrightarrow{IA}\\ 0\\ \overrightarrow{IC}\end{bmatrix} + \frac{V_{LV}}{V_{HV}} * \begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix} * \begin{bmatrix}\overrightarrow{IM}\\ 0\\ \overrightarrow{IS}\end{bmatrix}$$

$$+ \frac{V_{LV}}{V_{HV}} * \begin{bmatrix}-1 & 0 & 0\\ 0 & -1 & 0\\ 0 & 0 & -1\end{bmatrix} * \begin{bmatrix}\overrightarrow{IS}\\ 0\\ \overrightarrow{IM}\end{bmatrix}$$

from which:

$\overrightarrow{ID\_A} = \overrightarrow{IA} + \frac{V_{LV}}{V_{HV}} * \overrightarrow{IM} + \frac{V_{LV}}{V_{HV}} * (-\overrightarrow{IS})$
$\overrightarrow{ID\_B} = 0$
$\overrightarrow{ID\_C} = \overrightarrow{IC} + \frac{V_{LV}}{V_{HV}} * \overrightarrow{IS} + \frac{V_{LV}}{V_{HV}} * (-\overrightarrow{IM})$

The connection of the currents to the 87T function will be as follows:

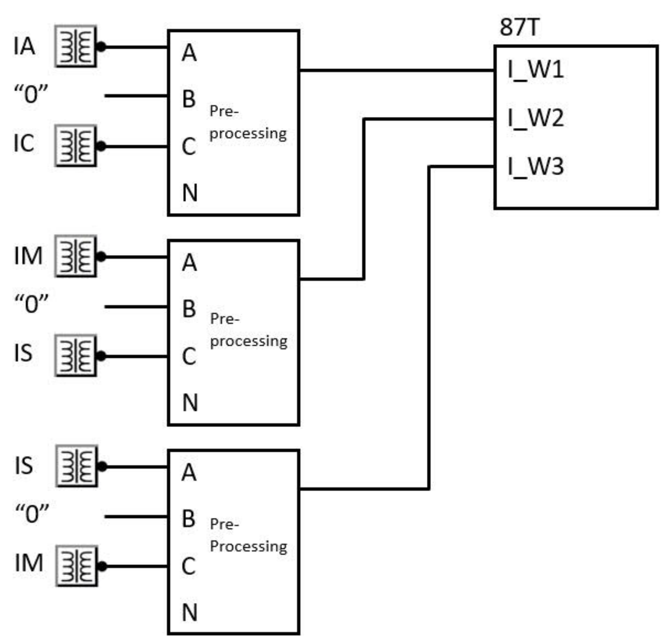


Figure 11: Connection of currents to the 87T function for a split single-phase railway transformer

As for the single-phase railway transformer, for the split single-phase railway transformer 87T measurement it is again necessary to use a current input with a zero value to build a three-phase application.

Typical settings to accomplish the required differential measurement are:

Rated Voltage W1	V_{R1}
Rated Voltage W2	V_{R2}
Rated Voltage W3	V_{R3}
Rated Current W1	I_{R1}
Rated Current W2	I_{R2}
Rated Current W3	I_{R3}
Connect Type W1	Delta (D)
Connect Type W2	Delta (D)
Connect Type W3	Delta (D)
Clock Number W2	0 (0 deg)
Clock Number W3	6 (180 deg)
ZS Current Subtraction W1	Off
ZS Current Subtraction W2	Off
ZS Current Subtraction W3	Off

For W1 and W2 connection type = Delta and zero-sequence current subtraction = Off, the selected matrix for compensation of the W1 and W2 currents in the matrix equation for calculation of the differential currents will be the unit matrix which, as shown above, is the matrix that is required to correctly calculate the differential currents.

For W3 connection type = Delta, W3 zero-sequence current subtraction = Off, and the W3 clock number = 6 (180 deg) (the W3-side currents require a 180° phase angle rotation to align with the W2-side currents), the selected matrix for compensation of the W3 currents in the matrix equation for calculation of the differential currents will be the matrix with -1 for the diagonal elements and 0 for all other elements which, as shown above, is the matrix that is required to correctly calculate the differential currents.

<u>Example 3</u>
Split single-phase railway transformer
60MVA (W1), 30MVA (W2), 30MVA (W3)
V_{R1} = 115kV = V_{W1} = V_{HV}
V_{R2} = 27.5kV = V_{W2} = V_{LV}
V_{R3} = 27.5kV = V_{W3} = V_{LV}

I_{R1} = 521.7A
I_{R2} = 1,090.9A
I_{R3} = 1,090.9A

Say now that the actual IM current is = 545.5A (= 50% of I_{R2}), and that IN is = ⅓*IS so that IN is = 136.4A, and IS is = 409.1A (i.e. IS = ¾*IM).

For balanced through-load, the HV-side currents would be = 228.3A.

IA flows “towards” the transformer, and so can be assigned a phase angle of 0°. IC flows “away from” the transformer, and so can be assigned a phase angle of 180°.
IA = 228.3∠0°, and
IC = 228.3∠180°

IM flows “away from” the transformer, and so can be assigned a phase angle of 180°. IS flows “towards” the transformer, and so can be assigned a phase angle of 0°.
IM = 545.5∠180°, and
IS = 409.1∠0°

$$\begin{bmatrix}\overrightarrow{ID\_A}\\ \overrightarrow{ID\_B}\\ \overrightarrow{ID\_C}\end{bmatrix} = \begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix} * \begin{bmatrix}228.3\angle 0°\\0.0\\228.3\angle 180°\end{bmatrix} + \frac{27.5}{115} * \begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix} * \begin{bmatrix}545.5\angle 180°\\0.0\\409.1\angle 0°\end{bmatrix}$$
$$+ \frac{27.5}{115} * \begin{bmatrix}-1&0&0\\0&-1&0\\0&0&-1\end{bmatrix} * \begin{bmatrix}409.1\angle 0°\\0.0\\545.5\angle 180°\end{bmatrix}$$
$$= \begin{bmatrix}228.3\angle 0°\\0.0\\228.3\angle 180°\end{bmatrix} + \begin{bmatrix}130.4\angle 180°\\0.0\\97.8\angle 0°\end{bmatrix} + \begin{bmatrix}97.8\angle 180°\\0.0\\130.4\angle 0°\end{bmatrix}$$
$$= \begin{bmatrix}0.0\\0.0\\0.0\end{bmatrix}$$

For increased internal fault sensitivity, low impedance restricted earthfault protection (87N) can be applied to the LV-windings.

The equation for the calculation of the zero-sequence differential current can be written as:

$$\overrightarrow{ID\_0} = \overrightarrow{IN} + \overrightarrow{3I0}$$
$$= \overrightarrow{IN} + (\overrightarrow{IM} + 0 + \overrightarrow{IS})$$

As the standard three-phase transformer protection relays treat the analog quantities in a three-phase manner, to calculate 3I0 the analog pre-processing function must “see” that all three phases of current are connected to physical current inputs. Therefore it is again necessary to use a current input with a zero value to build a three-phase application. The phase B current input is “seen” to be there by the analog pre-processing function, but will always have a zero value – the relay current input connected to the phase B input of the pre-processing function is not connected to anything, i.e. is intentionally left unwired.

The connection of the currents to the 87N function will be as follows:

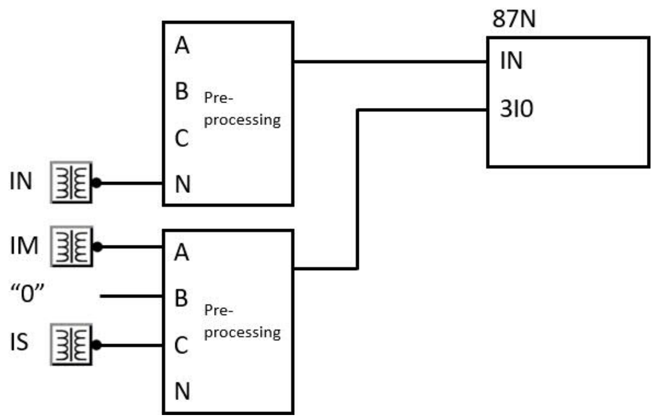


Figure 12: Connection of currents to the 87N function for a split single-phase railway transformer

The complete protection scheme for a split single-phase railway transformer application would typically comprise the following:

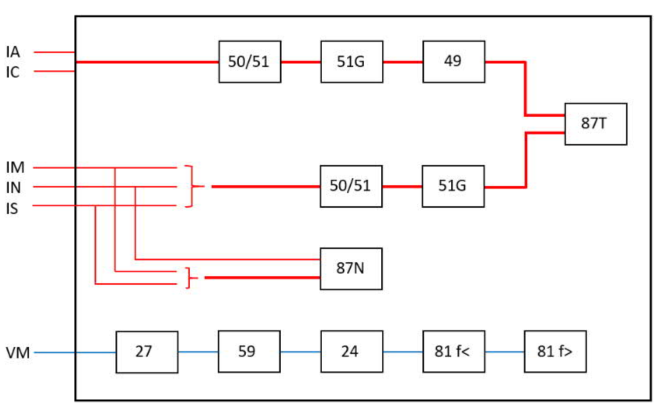


Figure 13: Typical protection scheme for a split single-phase railway transformer application

The connection of the HV- and LV-side currents to the current-measuring protection functions will be as follows:

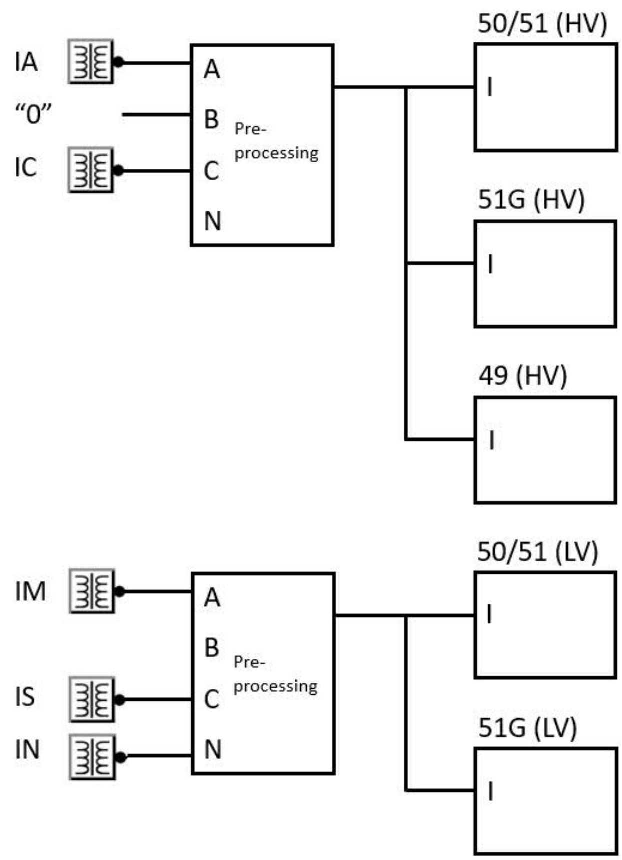


Figure 14: Connection of currents to the current-measuring protection functions for a split single-phase railway transformer

VI RAILWAY AUTOTRANSFORMER

Single-phase railway autotransformers are always used together with split single-phase transformers on railway supply systems.

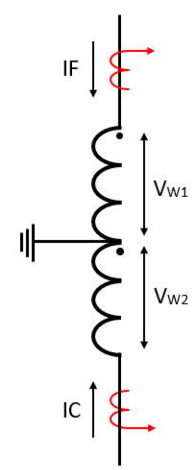


Figure 15: Single-phase railway autotransformer

For single-phase railway autotransformers the rated values for W1 and W2 are:

W1	$S_{R1} = S$	$V_{R1} = V_{HV}$ (= V_{LV})	$I_{R1} = \frac{S}{V_{HV}}$
W2	$S_{R2} = S$	$V_{R2} = V_{LV}$ (= V_{HV})	$I_{R2} = \frac{S}{V_{LV}}$

A typical load profile for the single-phase autotransformer would be as follows:

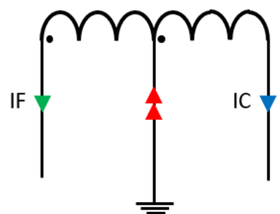


Figure 16: Typical load profile for a single-phase railway autotransformer

For balanced load:

$$|IF| = \left[\frac{V_{LV}}{V_{HV}}\right] * |IC|$$

where:

$$\left[\frac{V_{LV}}{V_{HV}}\right] = 1$$

IF flows “away from” the transformer. IC also flows “away from” the transformer. Therefore, to balance the current measurement and correctly calculate the differential current, the angle of IC needs to be rotated by 180°. The equation for the calculation of the differential current can therefore be written as:

$$\overrightarrow{IDIFF} = \overrightarrow{IF} + \left[\frac{V_{LV}}{V_{HV}}\right] * (-\overrightarrow{IC})$$
$$= \overrightarrow{IF} + (-\overrightarrow{IC})$$

From the above equation for the differential current it can be seen that:

- the unit matrix is required where no 180° rotation of the IF current is required, and
- the matrix with diagonal elements -1 and all other elements 0 is required where the 180° rotation of the IC current is required.

Therefore, the required matrix equation for the calculation of the differential current for single-phase railway autotransformers can be written as:

$$\begin{bmatrix} \overrightarrow{ID\_A} \\ \overrightarrow{ID\_B} \\ \overrightarrow{ID\_C} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 0 \\ 0 \\ \overrightarrow{IF} \end{bmatrix} + \frac{V_{LV}}{V_{HV}} * \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} * \begin{bmatrix} 0 \\ 0 \\ \overrightarrow{IC} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} 0 \\ 0 \\ \overrightarrow{IF} \end{bmatrix} + \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} * \begin{bmatrix} 0 \\ 0 \\ \overrightarrow{IC} \end{bmatrix}$$

from which:

$\overrightarrow{ID\_A} = 0$
$\overrightarrow{ID\_B} = 0$
$\overrightarrow{ID\_C} = \overrightarrow{IF} + \frac{V_{LV}}{V_{HV}} * (-\overrightarrow{IC}) = \overrightarrow{IF} + (-\overrightarrow{IC})$

The connection of the currents to the 87T function will be as follows:

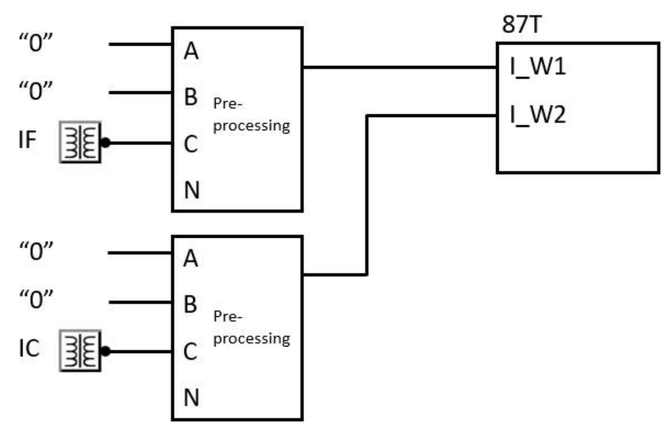


Figure 17: Connection of currents to the 87T function for a single-phase railway autotransformer

As for the previously described railway transformer types, for the single-phase railway autotransformer 87T measurement it is again necessary to use a current input with a zero value to build a three-phase application, but this time connected to two phases for each winding (in this example phases A and B).

Typical settings to accomplish the required differential measurement are:

Rated Voltage W1	V_{R1}
Rated Voltage W2	V_{R2}
Rated Current W1	I_{R1}
Rated Current W2	I_{R2}
Connect Type W1	Delta (D)
Connect Type W2	Delta (D)
Clock Number W2	6 (180 deg)
ZS Current Subtraction W1	Off
ZS Current Subtraction W2	Off

For W1 connection type = Delta, and W1 zero-sequence current subtraction = Off, the selected matrix for compensation of the W1 currents in the matrix equation for calculation of the differential currents will be the unit matrix which, as shown above, is the matrix that is required to correctly calculate the differential currents.

For W2 connection type = Delta, W2 zero-sequence current subtraction = Off, and the W2 clock number = 6 (180 deg) (the W2-side IC current requires a 180° phase angle rotation to align with the W1-side IF current), the selected matrix for compensation of the W2 currents in the matrix equation for calculation of the differential currents will be the matrix with -1 for the diagonal elements and 0 for all other elements which, as shown above, is the matrix that is required to correctly calculate the differential currents.

<u>Example 4</u>

Single-phase railway autotransformer; 5MVA

V_{R1} = 27.5kV = V_{W1} = V_{HV} (= V_{LV})

V_{R2} = 27.5kV = V_{W2} = V_{LV} (= V_{HV})

I_{R1} = 181.8A

I_{R2} = 181.8A

Say now that the actual W2-side IC current is = 136.4A.

IC flows “away from” the transformer, and so can be assigned a phase angle of 180°.

IC = 136.4∠180°

For the typical load profile (see Figure 16), the W1-side IF current would also be = 136.4A.

IF also flows “away from” the transformer, and so can be assigned a phase angle of 180°.

IF = 136.4∠180°.

$$\begin{bmatrix}\overrightarrow{ID\_A}\\ \overrightarrow{ID\_B}\\ \overrightarrow{ID\_C}\end{bmatrix} = \begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix} * \begin{bmatrix}0.0\\0.0\\136.4\angle 180^\circ\end{bmatrix} + \frac{27.5}{27.5} * \begin{bmatrix}-1&0&0\\0&-1&0\\0&0&-1\end{bmatrix} * \begin{bmatrix}0.0\\0.0\\136.4\angle 180^\circ\end{bmatrix}$$

$$= \begin{bmatrix}0.0\\0.0\\136.4\angle 180^\circ\end{bmatrix} + \begin{bmatrix}0.0\\0.0\\136.4\angle 0^\circ\end{bmatrix}$$

$$= \begin{bmatrix}0.0\\0.0\\0.0\end{bmatrix}$$

The complete protection scheme for a single-phase railway autotransformer application would typically comprise the following:

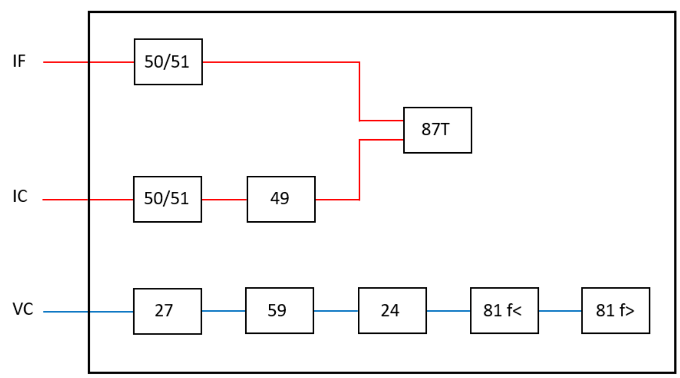


Figure 18: Typical protection scheme for a single-phase railway autotransformer application

The connection of the IF and IC currents to the current-measuring protection functions will be as follows:

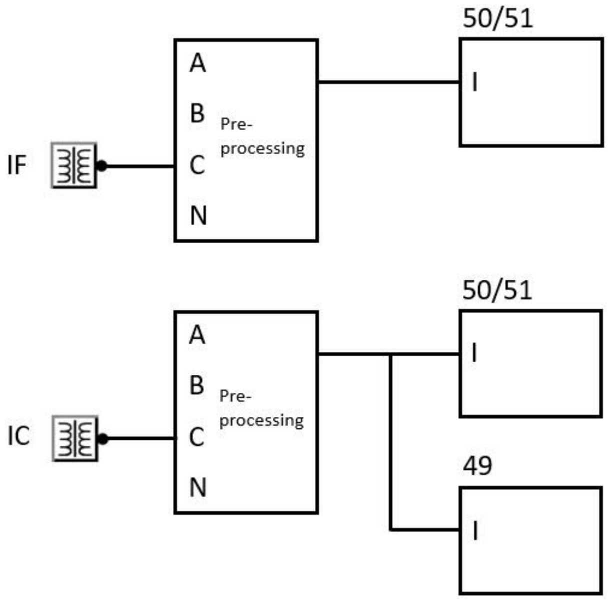


Figure 19: Connection of currents to the current-measuring protection functions for a single-phase railway autotransformer

One autotransformer is often shared between two railway track sections. In such cases, the single line diagram showing the application would be as follows:

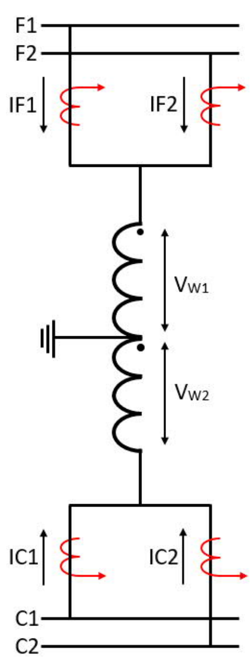


Figure 20: Single-phase railway autotransformer that is shared between two railway track sections

The required matrix equation for the calculation of the differential current for single-phase railway autotransformers sharing two railway track sections can be written as:

$$\begin{bmatrix}\overrightarrow{ID\_A}\\ \overrightarrow{ID\_B}\\ \overrightarrow{ID\_C}\end{bmatrix} = \begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix} * \begin{bmatrix}0\\0\\ \overrightarrow{IF1}\end{bmatrix} + \begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix} * \begin{bmatrix}0\\0\\ \overrightarrow{IF2}\end{bmatrix}$$

$$+ \frac{V_{LV}}{V_{HV}} * \begin{bmatrix}-1&0&0\\0&-1&0\\0&0&-1\end{bmatrix} * \begin{bmatrix}0\\0\\ \overrightarrow{IC1}\end{bmatrix} + \frac{V_{LV}}{V_{HV}} * \begin{bmatrix}-1&0&0\\0&-1&0\\0&0&-1\end{bmatrix} * \begin{bmatrix}0\\0\\ \overrightarrow{IC2}\end{bmatrix}$$

from which:

$\overrightarrow{ID\_A} = 0$
$\overrightarrow{ID\_B} = 0$
$\overrightarrow{ID\_C} = \overrightarrow{IF1} + \overrightarrow{IF2} + \frac{V_{LV}}{V_{HV}} * (-\overrightarrow{IC1}) + \frac{V_{LV}}{V_{HV}} * (-\overrightarrow{IC2}) = \overrightarrow{IF1} + \overrightarrow{IF2} + (-\overrightarrow{IC1} + -\overrightarrow{IC2})$

The connection of the currents to the 87T function will be as follows:

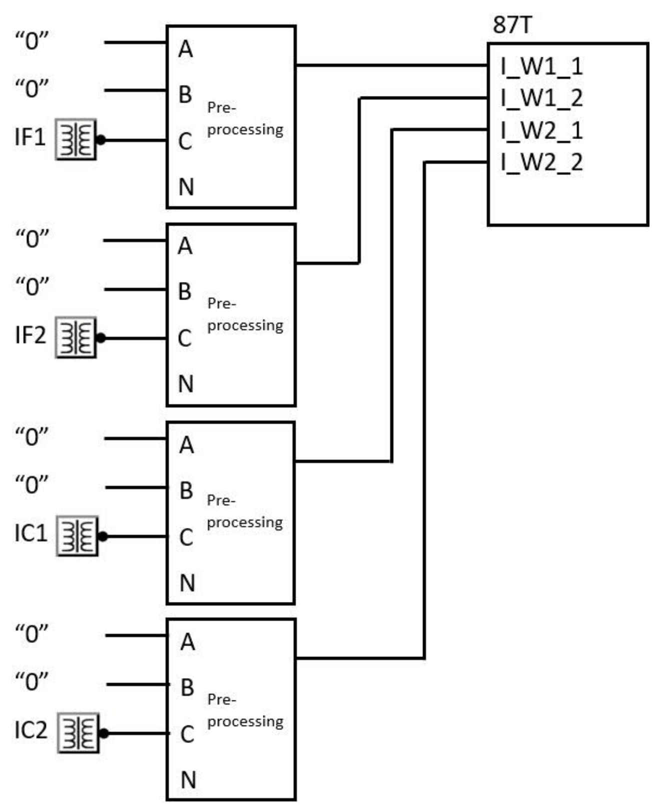


Figure 21: Connection of currents to the 87T function for a single-phase railway autotransformer sharing two railway track sections

The complete protection scheme for a single-phase railway autotransformer application sharing two railway track sections would typically comprise the following:

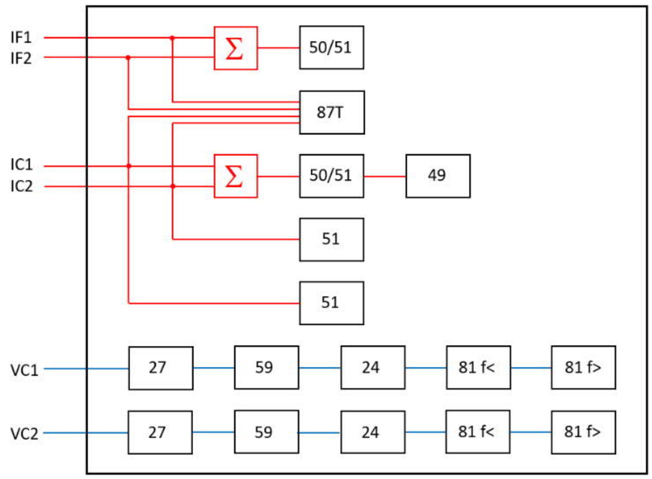


Figure 22: Typical protection scheme for a single-phase railway autotransformer application sharing two railway track sections

The connection of the currents to the current-measuring protection functions will be as follows:

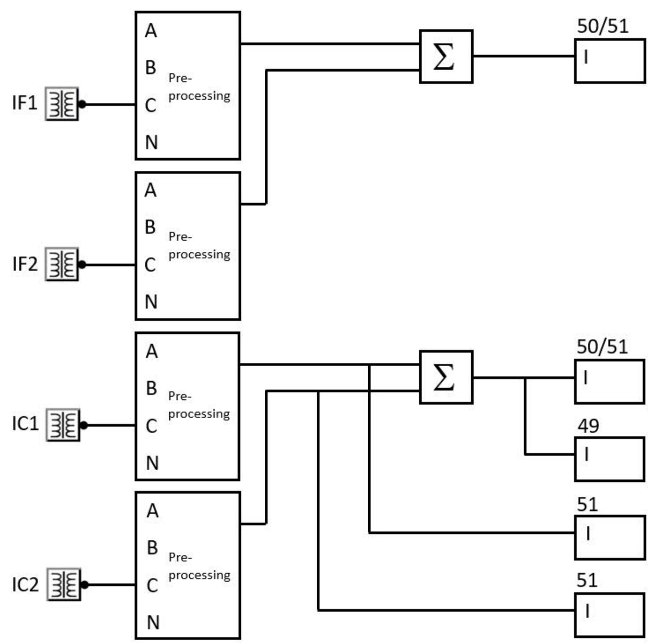


Figure 23: Connection of currents to the current-measuring protection functions for a single-phase railway autotransformer sharing two railway track sections

VII SCOTT TRANSFORMER

Its main feature is the ability to transfer a three-phase power supply system to a two-phase railway supply system.

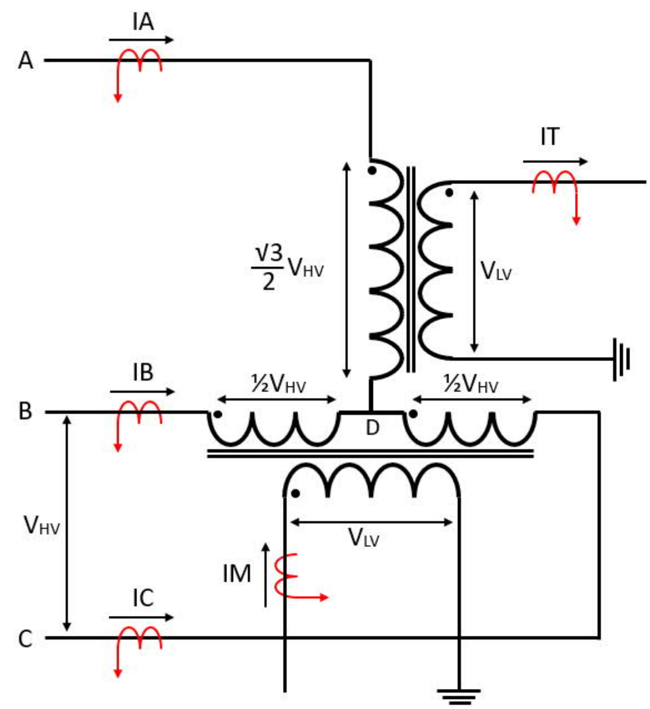
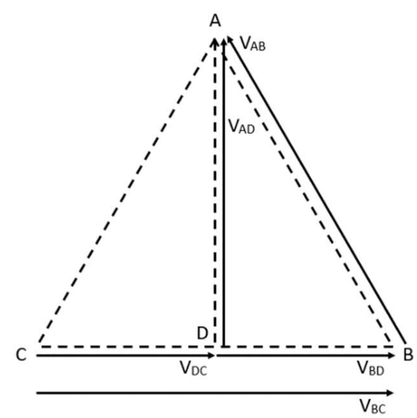


Figure 24: Scott transformer



$|V_{BC}| = |V_{AB}| = |V_{CA}| = |V_{HV}|$

$|V_{BD}| = |V_{DC}| = \frac{1}{2}|V_{BC}| = \frac{1}{2}|V_{HV}|$

$\overrightarrow{V_{BC}} = \overrightarrow{V_{DC}} + \overrightarrow{V_{BD}}$

$\overrightarrow{V_{DC}}$ and $\overrightarrow{V_{BD}}$ are in phase with $\overrightarrow{V_{BC}}$

$\overrightarrow{V_{AB}} = \overrightarrow{V_{DB}} + \overrightarrow{V_{AD}} = -\overrightarrow{V_{BD}} + \overrightarrow{V_{AD}}$

$\overrightarrow{V_{AD}} = \overrightarrow{V_{BD}} + \overrightarrow{V_{AB}}$

$= \frac{1}{2}|V_{HV}| + (-\frac{1}{2}|V_{HV}| + j\frac{\sqrt{3}}{2}|V_{HV}|)$

$= j\frac{\sqrt{3}}{2}|V_{HV}|$

$\overrightarrow{V_{AD}}$ leads $\overrightarrow{V_{BD}}$ and $\overrightarrow{V_{DC}}$ by 90°

For balanced load:

$$|IM| = \left[\frac{\tfrac{1}{2}V_{HV}}{V_{LV}}\right] * |IB - IC|$$

$$|IT| = \left[\frac{\frac{\sqrt{3}}{2}V_{HV}}{V_{LV}}\right] * |IA|$$

The equations for the calculation of the differential currents can therefore be written as:

$$\overrightarrow{IDIFFM} = \overrightarrow{IM} + \left[\frac{\tfrac{1}{2}V_{HV}}{V_{LV}}\right] * (\overrightarrow{IB} - \overrightarrow{IC})$$

$$\overrightarrow{IDIFFT} = \overrightarrow{IT} + \left[\frac{\frac{\sqrt{3}}{2}V_{HV}}{V_{LV}}\right] * \overrightarrow{IA}$$

IM and IT are assigned as W1-side currents, IA as W2-side current, and IB – IC as W3-side current. With this being so, and from the above equations, the required matrix equation for the calculation of the differential currents for Scott railway transformers can be written as:

$$\begin{bmatrix}\overrightarrow{ID\_A}\\ \overrightarrow{ID\_B}\\ \overrightarrow{ID\_C}\end{bmatrix} = \begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix} * \begin{bmatrix}\overrightarrow{IT}\\ 0\\ \overrightarrow{IM}\end{bmatrix} + \frac{\frac{\sqrt{3}}{2}V_{HV}}{V_{LV}} * \begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix} * \begin{bmatrix}\overrightarrow{IA}\\ 0\\ 0\end{bmatrix}$$

$$+ \frac{\tfrac{1}{2}V_{HV}}{V_{LV}} * \begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix} * \begin{bmatrix}0\\ 0\\ \overrightarrow{IB}\text{-}\overrightarrow{IC}\end{bmatrix}$$

from which:

$\overrightarrow{ID\_A} = \overrightarrow{IT} + \left[\frac{\frac{\sqrt{3}}{2}V_{HV}}{V_{LV}}\right] * \overrightarrow{IA}$
$\overrightarrow{ID\_B} = 0$
$\overrightarrow{ID\_C} = \overrightarrow{IM} + \left[\frac{\tfrac{1}{2}V_{HV}}{V_{LV}}\right] * (\overrightarrow{IB} - \overrightarrow{IC})$

Note that the magnitude of the differential currents is referenced to the LV-sides.

It follows from the above that the required rated values to be set for a Scott transformer for W1, W2 and W3 are:

W1	$S_{R1} = \frac{S}{2}$	$V_{R1} = V_{LV}$	$I_{R1} = \frac{S}{2V_{LV}}$
W2	$S_{R2} = \frac{S}{2}$	$V_{R2} = \frac{\sqrt{3}}{2} V_{HV}$	$I_{R2} = \frac{S}{\sqrt{3}V_{HV}}$
W3	$S_{R2} = \frac{S}{2}$	$V_{R2} = \tfrac{1}{2}V_{HV}$	$I_{R3} = \frac{S}{V_{HV}}$

The connection of the currents to the 87T function will be as follows:

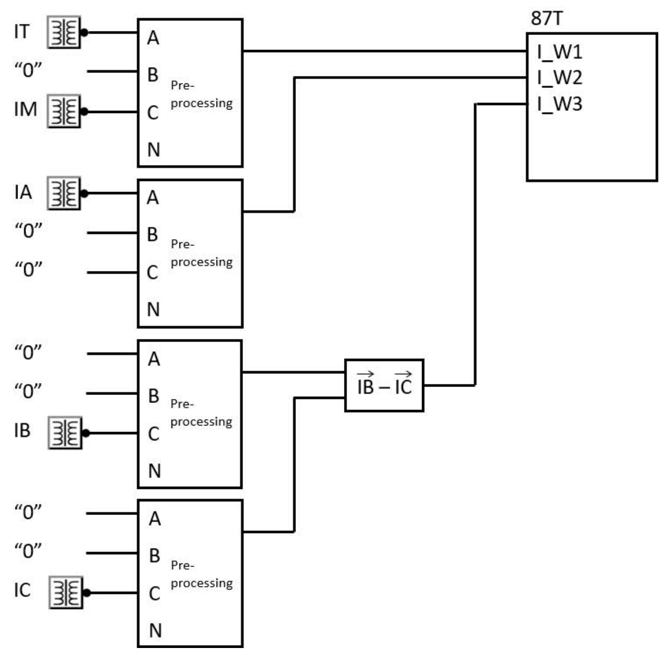


Figure 25: Connection of currents to the 87T function for a Scott transformer

As for the previously described railway transformer types, for the Scott transformer 87T measurement it is again necessary to use a current input with a zero value to build a three-phase application.

Typical settings to accomplish the required differential measurement are shown below:

Rated Voltage W1	V_{R1}
Rated Voltage W2	V_{R2}
Rated Voltage W3	V_{R3}
Rated Current W1	I_{R1}
Rated Current W2	I_{R2}
Rated Current W3	I_{R3}
Connect Type W1	Delta (D)
Connect Type W2	Delta (D)
Connect Type W3	Delta (D)
Clock Number W2	0 (0 deg)
Clock Number W3	0 (0 deg)
ZS Current Subtraction W1	Off
ZS Current Subtraction W2	Off
ZS Current Subtraction W3	Off

The above settings will select the unit matrix, as is required, for the compensation of the W1-, W2- and W3-side currents in the matrix equation for calculation of the differential currents.

<u>Example 5</u>
Scott transformer
S = 90MVA
V_{LV} = 55kV
V_{HV} = 154kV
V_{R1} = 55kV = V_{LV}
V_{R2} = 133.4kV = $(\sqrt{3}/2)*V_{HV}$
V_{R3} = 77kV = $½*V_{HV}$
I_{R1} = 818.2A
I_{R2} = 337.4A.
I_{R3} = 584.4A

Say now that the actual IM and IT currents are = 409.1A (= 50% of I_{R1}).

For balanced load, the values for the IA, IB and IC currents would be = 168.7A.

IT leads IM by 90° (this example takes IM and IT to be in quadrature, but the angle between IM and IT depends on the power factor of both loads).

IM flows “away from” the transformer, and so can be assigned a phase angle of 180°.
IM = $409.1\angle 180^\circ$

IT flows “away from” the transformer, and so can be assigned a phase angle of -90°.
IT = $409.1\angle -90^\circ$

The IA, IB and IC currents are therefore as follows:

IA = $168.7\angle 90^\circ$
IB = $168.7\angle -30^\circ$
IC = $168.7\angle -150^\circ$
IB-IC = $292.2\angle 0^\circ$

$$\begin{bmatrix}\overrightarrow{ID\_A}\\ \overrightarrow{ID\_B}\\ \overrightarrow{ID\_C}\end{bmatrix} = \begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix} * \begin{bmatrix}409.1\angle -90^\circ\\0.0\\409.1\angle 180^\circ\end{bmatrix} + \frac{133.4}{55} * \begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix} * \begin{bmatrix}168.7\angle 90^\circ\\0.0\\0.0\end{bmatrix} + \frac{77}{55} * \begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix} * \begin{bmatrix}0.0\\0.0\\292.0\angle 0^\circ\end{bmatrix}$$

$$= \begin{bmatrix}409.1\angle -90^\circ\\0.0\\409.1\angle 180^\circ\end{bmatrix} + \begin{bmatrix}409.1\angle 90^\circ\\0.0\\0.0\end{bmatrix} + \begin{bmatrix}0.0\\0.0\\409.1\angle 0^\circ\end{bmatrix}$$

$$= \begin{bmatrix}0.0\\0.0\\0.0\end{bmatrix}$$

The complete protection scheme for a Scott transformer application would typically comprise the following:

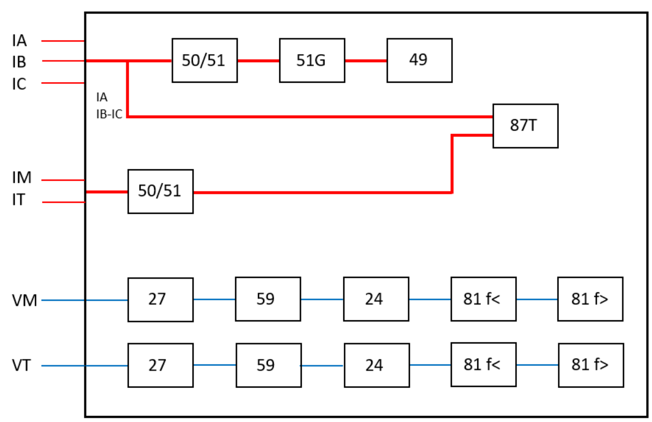


Figure 26: Typical protection scheme for a Scott transformer application

The connection of the currents to the current-measuring protection functions will be as follows:

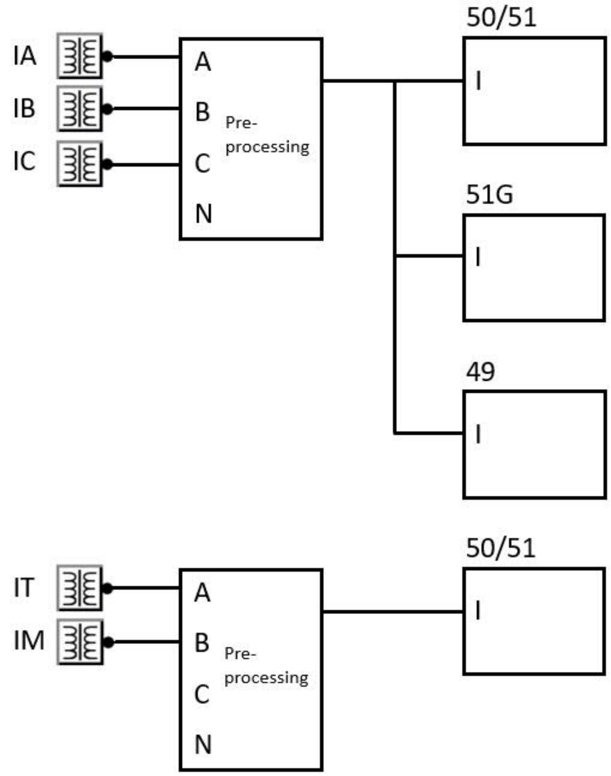


Figure 27: Connection of currents to the current-measuring protection functions for Scott transformer

VIII CONCLUSION

The protection of the most common types of railway transformers in 50Hz or 60Hz railway supply systems using standard three-phase transformer protection relays was presented. It was shown that although the standard protection relays are designed for the protection of three-phase transformers, with the analog quantities inside treated in a three-phase manner, these standard relays can be successfully applied to different types of railway transformers on 50Hz or 60Hz railway supply systems.

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