Application of Unit Protection Schemes for Auto-Transformers

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1. INTRODUCTION

The application of the unit protection schemes for auto-transformers is somewhat special because such scheme can be arranged in a number of different ways. An auto-transformer is a power transformer in which at least two windings have a common part [1]. For standard auto-transformer design this common part is the common winding. Typically auto-transformers are used to interconnect two electrical networks with similar voltage levels (e.g. system intertie transformer). In practice auto-transformer tertiary delta winding is normally included. It serves to limit generation of third harmonic voltages caused by magnetizing currents and to lower the zero sequence impedance for five-limb core constructions or for auto-transformers built from three single phase units. Standard practice is to size the tertiary delta winding for at least one third of the rated total through power of the auto-transformer. This is done in order to achieve adequate short-circuit withstand strength of the delta winding during earth fault in the HV systems.

Unit protection schemes for auto-transformers can be arranged in a number of ways:

- Based on autotransformer ampere-turn balance
- Based on the first Kirchhoff's law between galvanically interconnected parts
- Based on zero-sequence currents (restricted earth-fault protection)
- Dedicated unit protection schemes for only tertiary delta winding.

Most commonly used auto-transformer unit protection schemes will be described in this document and advantages and disadvantages of the schemes will be discussed.

One auto-transformer will be used as an example for all presented differential protection schemes in this document. This auto-transformer has the following rating: 400/400/130 MVA; 400/231/10.5 kV; YNautod5 in accordance with [1]. The phase angle displacement between the tertiary delta winding and the other two windings is 150°, as shown in Figure 1.

It can be shown that power is transferred in two different ways through an auto-transformer. One part of the power is transferred by galvanic connection and the other part is transferred via magnetic circuit (i.e. transformer action) [1], [4]. This can be represented for the example auto-transformer by the following equation:

$$S = \sqrt{3} \times U_{220} \times I_{220} = \sqrt{3} \times U_{220} \times (I_{400} + I_{CW}) = \sqrt{3} \times U_{220} \times I_{400} + \sqrt{3} \times U_{220} \times I_{CW} = S_G + S_T,$$

where: S is the auto-transformer total throughput power; U_{220} is the voltage on the 220 kV side; I_{220} is the current on the 220 kV side; I_{400} is the current on the 400 kV side; I_{CW} is the current in the common winding; S_G is one part of the total throughput power transferred by galvanic connection; S_T is the second part of total throughput power transferred by magnetic circuit (transformer effect).

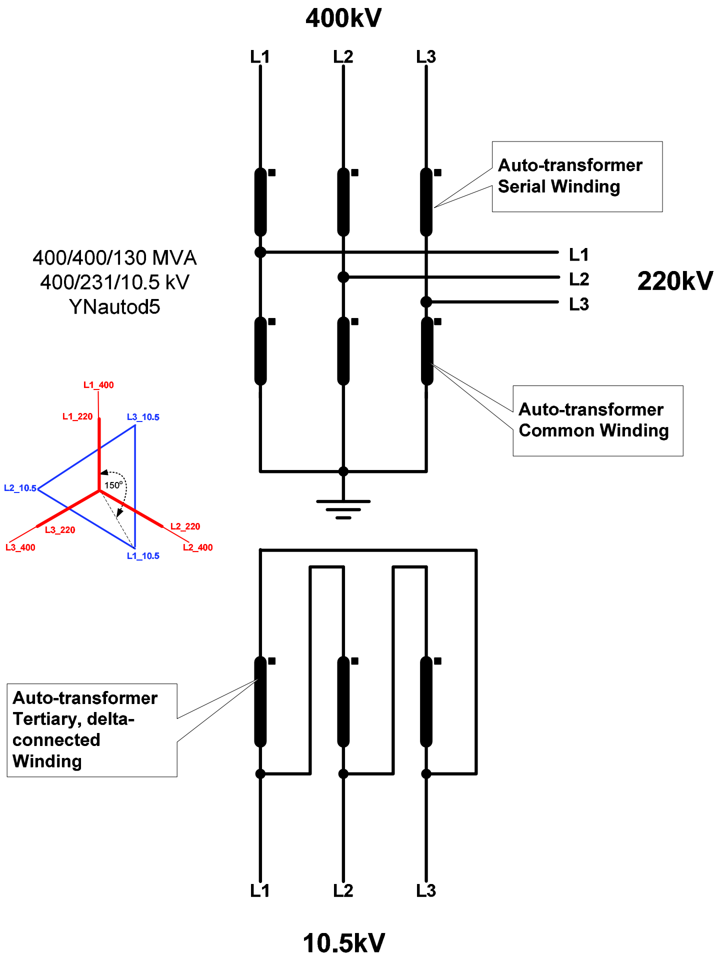


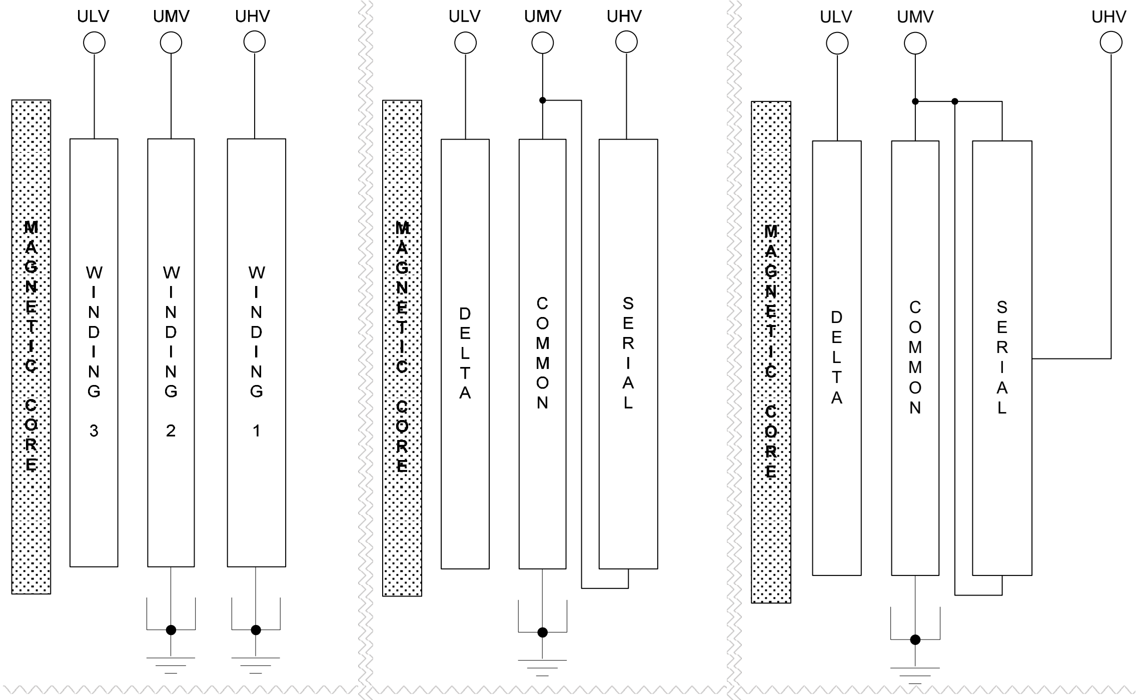
Fig. 1: Rating data for Auto-transformer used as an example transformer throughout this document

Obviously only one part of the auto-transformer total throughput power (i.e. S_T) is transferred by magnetic circuit (transformer effect). Thus, the whole auto-transformer active part can be sized accordingly. Consequently auto-transformer can be design with less active material (i.e. copper and steel) in comparison with a standard two-winding power transformer design for the same rated voltages and rated throughput power. It can be shown that this rated power of the auto-transformer active part can be calculated for the example auto-transformer by using the following equation:

$$S_{rT} = \frac{I_{r\_220} - I_{r\_400}}{I_{r\_220}} \times S_r = \frac{U_{r\_400} - U_{r\_220}}{U_{r\_400}} \times S_r = \frac{400 - 231}{400} \times 400 = 169\ MVA$$

Thus, example auto-transformer has rated throughput power of 400 MVA, but its active part is designed for 169 MVA only. Therefore, the advantages of auto-transformers compared with equivalent two-winding transformers of the same voltage ratio and through power consist basically in their smaller size, lower losses, greater efficiency, easier transportation and lower cost [4].

It is also interesting to notice the difference in physical winding arrangements between equivalent three-winding power transformers with vector group Yyd, shown in Figure 2a, and auto-transformers with tertiary delta winding shown in Figure 2b and Figure 2c.



a) 3-winding transformer b) Auto-transformer c) Auto-transformer

Fig. 2: Typical physical winding arrangements for core type, power transformers

Another special thing for auto-transformers is the possible CT locations. In Figure 3 the possible CT locations are shown. Note that in this document it is assumed that for every differential protection scheme all used CTs are star (i.e. wye) connected and have their star point towards the protected zone. Such practices follows the well established principles used by many relay manufactures which are based on traditional practice used with older types of differential relays [7] and [8].

For auto-transformer applications, such practice will actually cause that for different differential protection schemes CTs installed at the same place need to be star differently. For actual examples see CT5 and CT6 installed at the auto-transformer star point or CT8 and CT9 installed inside the tertiary delta winding, as shown in Figure 3. Note that in further text it is clearly shown which of these CTs need to be used for which type of the auto-transformer differential protection scheme.

2. DIFFERENTIAL PROTECTION BASED ON AMPERE-TURN BALANCE

Low impedance, biased, differential protection for power transformers has been used for decades. It is based on ampere-turn-balance of all windings mounted on the same magnetic core limb. Well-known ampere-turn balanced equation for a two-winding, single phase transformer can be written in the following way:

$$N_1 \times I_1 + N_2 \times I_2 = 0 \ \ or \ \ I_1 + \frac{N_2}{N_1} \times I_2 = 0,$$

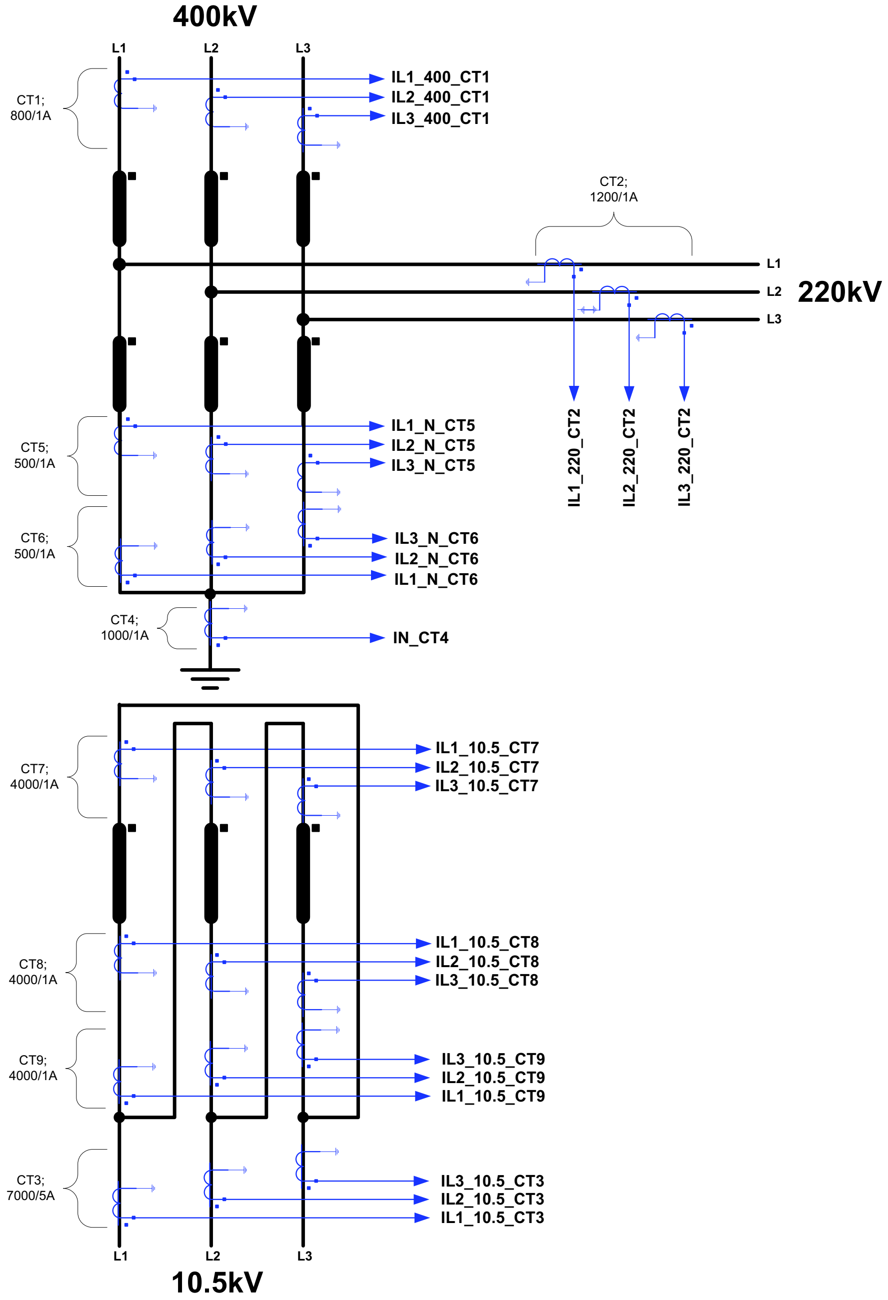


Fig. 3: Possible CT location for example Auto-transformer

Where: N_1 is the number of turns in the first winding; I_1 is the current in the first winding; N_2 is the number of turns in the second winding; I_2 is the current in the second winding.

Note that power transformer magnetizing currents are neglected in this equation. For a particular power transformer the following properties affect this kind of differential protection:

1. Exact number of turns in every winding is not known. Instead the rated no-load voltages of each winding are used because they are directly proportional to the number of turns. These voltages are readily available on power transformer rating plate.

2. Current transformers are used to step down the primary current to the standard 1 A or 5 A secondary level for the differential protection. Thus if the main CT ratios are not matched on all sides the secondary current magnitudes can be different on different sides of the power transformer.

3. Different connections of the three-phase windings (e.g. star, delta or zig-zag) introduce a possible phase angle shift between two power transformer sides.

4. Zero sequence currents may follow through star or zig-zag connected windings, but such currents are trapped by delta connected windings making current unbalance on the two power transformer sides.

Consequently, in order to correctly apply transformer differential protection for the three-phase power transformers the following compensations shall be provided:

- current magnitude compensation of the secondary CT current
- transformer phase angle shift compensation
- zero sequence current compensation (i.e. zero sequence current elimination).

With modern numerical transformer differential relays all above compensations are provided in the relay software. Typically matrix equations are used to present calculations performed by numerical differential relays [2], [3] and [5].

Additional application difficulties arise from the fact that power transformer ampere-turn based differential schemes are affected by tapping of on-load tap-changer. The reason is that such tapping will change number of turns within one winding and will cause unbalance and false differential current will be seen by the differential relay. Traditionally the differential schemes were only balanced for the mid-tap position. Some modern differential protection relays [5] can read actual tap-changer position and on-line compensate for the position of up to two OLTCs.

2.1. Base values for transformer differential protection

The only common electrical quantity for power transformer windings is electrical power which flows through them. Therefore for the transformer differential protection the maximum apparent power among all power transformer windings is typically selected as the base quantity [8]. That was the reason why interposing CTs for the solid-state relays were as well calculated using this maximum power as a base [7]. Note that the maximum value among all windings, as stated on the protected power transformer rating plate, is typically selected. This can be simply written as following equation:

$$S_{Base} = S_{Max}\,[MVA].$$

When the base power is known the base primary current on each power transformer side can be calculated by using the following equation:

$$I_{BasePri\_Wi}[A] = \frac{1000 \times S_{Base}[MVA]}{\sqrt{3} \times U_{r\_Wi}[kV]},$$

where: $I_{BasePri\_Wi}$ is the winding base current in primary amperes in A; S_{Base} is the defined base apparent power for this application in MVA; U_{r_Wi} is the winding rated phase-to-phase, no-load voltage in kV. It is proportional to the number of turns in the winding. The value for each transformer winding is typically stated on the power transformer rating plate.

For a star connected main CT the corresponding base current value on the CT secondary side is easily obtained by using the following equation:

$$I_{BaseSec\_Wi\_CT=Y} = \frac{I_{BasePri\_Wi}}{CTR_{Wi}},$$

where: $I_{BaseSec\_Wi\_CT=Y}$ is the winding base current in secondary amperes for a wye connected main CT; $I_{BasePri\_Wi}$ is the defined winding base current in primary amperes; CTR_{Wi} is the actual CT ratio used on that power transformer side.

As explained previously auto-transformer actually has two ratings. One total throughput power (i.e. 400 MVA for the example auto-transformer) and the other for its active part (i.e. 169MVA for the example auto-transformer). The following two tables summarize possible base quantities for the example auto-transformer.

Winding/Side	Base ph-ph no load voltage	Base current in primary Amperes
400 kV side	400 kV	$\frac{400\ \text{MVA}}{\sqrt{3}\times 400\ \text{kV}} = 577\ \text{A}$
220 kV side	231 kV	$\frac{400\ \text{MVA}}{\sqrt{3}\times 231\ \text{kV}} = 1000\ \text{A}$
Delta side (outside delta)	10.5 kV	$\frac{400\ \text{MVA}}{\sqrt{3}\times 10{,}5\ \text{kV}} = 21\,994\ \text{A}$
Delta side (inside delta)	$\sqrt{3}\times 10{,}5 = 18{,}187$ kV	$\frac{400\ \text{MVA}}{\sqrt{3}\times 18{,}187\ \text{kV}} = 12\,698\ \text{A}$

Table 1: Base quantities for total rating of 400 MVA

Winding/Side	Base ph-ph no load voltage	Base current in primary Amperes
Serial winding	$400 - 231 = 169$ kV	$\frac{169\ \text{MVA}}{\sqrt{3}\times 169\ \text{kV}} = 577\ \text{A}^*$
Common winding	231 kV	$\frac{169\ \text{MVA}}{\sqrt{3}\times 231\ \text{kV}} = 422\ \text{A}^*$
Delta winding (inside delta)	$\sqrt{3}\times 10{,}5 = 18{,}187$ kV	$\frac{169\ \text{MVA}}{\sqrt{3}\times 18{,}187\ \text{kV}} = 5365\ \text{A}$

* Note that exactly this amount of current will also flow through the serial and the common winding when the auto-transformer is loaded with rated 400 MVA

Table 2: Base quantities for the rating of the active part (i.e. 169 MVA)

Obviously, for every auto-transformer differential protection application, correct selection of the base power is crucial. Additionally, based on the location of the CTs on the tertiary side, it is also necessary to correctly select rated no-load voltage and vector group for every winding. Correct selection of base power, no-load voltage and vector group for different auto-transformer differential protection scheme will be presented in this document.

3. AUTO-TRANSFORMER DIFFERENTIAL PROTECTION SCHEMES APPLIED AS FOR AN EQUIVALENT STANDARD POWER TRANSFORMER

3.1. Auto-transformer with not Loaded Tertiary Delta Winding

Quite often the auto-transformer tertiary winding is not loaded and it is used only as a delta-connected equalizer winding, as defined in [1]. Such auto-transformer can actually be protected as an equivalent two-winding Yy0(d) power transformer [1]. For such application differential relay with two restraint inputs is required.

The relevant application data to set up such differential protection for the example auto-transformer are given in Table 3. The zero sequence current must be eliminated from the two sides because the zero sequence current can circulate inside tertiary delta winding, but its magnitude is not available to the differential protection.

Winding	**W1**	**W2**
Base Power [MVA]	400	400
Ph-Ph, No-Load Voltage [kV]	400	231
Base Primary Current [A]	577	1000
Vector Group	Y	y0
Zero Sequence Current Elimination	Yes (Mandatory)	Yes (Mandatory)
Connected to CT (See Figure 3)	CT1	CT2
Base current on CT secondary side [A]	0.721	0.833

Table 3: Differential protection using CT1 and CT2

For such protection scheme the differential currents in per-unit can be calculated in accordance with the following matrix equation:

$$\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \frac{1}{0.721} \cdot \frac{1}{3} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_400\_CT1} \\ I_{L2\_400\_CT1} \\ I_{L3\_400\_CT1} \end{bmatrix} + \frac{1}{0.833} \cdot \frac{1}{3} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_220\_CT2} \\ I_{L2\_220\_CT2} \\ I_{L3\_220\_CT2} \end{bmatrix} \quad (1)$$

Advantages of this solution:

- No CTs required on the tertiary delta side of the protected auto-transformer

Disadvantages of this solution:

- Reduced protection sensitivity for turn to turn and internal ground faults due to mandatory zero sequence current reduction
- Low sensitivity for internal earth faults located close to the star point of the auto-transformer common winding
- Possible lower sensitivity for faults in the tertiary delta winding due to auto-transformer impedance between windings

3.2. Auto-transformer with Loaded Tertiary Delta Winding

Sometimes the auto-transformer tertiary delta winding is loaded. Connected equipment/objects to the tertiary delta winding vary quite a lot across the world. In some countries it is common to connect either shunt reactors or shunt capacitors to the tertiary delta winding in order to provide reactive power support to the rest of the power system. In some other countries tertiary winding can be used to supply station auxiliary services and/or local communities in the substation surroundings. Finally, generators can be connected to the tertiary winding and then the auto-transformer is used as a step-up transformer. For such differential protection application the auto-transformer is protected as an equivalent three-winding power transformer with vector group Yyd [1]. Thus the differential relay with three restraint inputs is required. The zero sequence current must be eliminated from the two high-voltage sides because the zero sequence current can circulate inside the tertiary delta winding, but its magnitude is not available to the differential protection. The relevant application data to setup such differential protection for the example auto-transformer are given in Table 4.

Winding	W1	W2	W3
Base Power [MVA]	400	400	400
Ph-Ph, No-Load Voltage [kV]	400	231	10.5
Base Primary Current [A]	577	1000	21994
Vector Group	Y	y0	d5
Zero Sequence Current Elimination	Yes (Mandatory)	Yes (Mandatory)	No / (Yes)
Connected to CT (See Figure 3)	CT1	CT2	CT3
Base current on CT secondary side [A]	0.721	0.833	15.71

Table 4: Differential protection using CT1, CT2 and CT3

For such protection scheme the differential currents in per-unit can be calculated in accordance with the following matrix equation:

$$\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \frac{1}{0.721}\cdot\frac{1}{3}\cdot\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\cdot\begin{bmatrix} I_{L1\_400\_CT1} \\ I_{L2\_400\_CT1} \\ I_{L3\_400\_CT1} \end{bmatrix} + \frac{1}{0.833}\cdot\frac{1}{3}\cdot\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\cdot\begin{bmatrix} I_{L1\_220\_CT2} \\ I_{L2\_220\_CT2} \\ I_{L3\_220\_CT2} \end{bmatrix} + \frac{1}{15.71}\cdot\frac{1}{\sqrt{3}}\cdot\begin{bmatrix} -1 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix}\cdot\begin{bmatrix} I_{L1\_10.5\_CT3} \\ I_{L2\_10.5\_CT3} \\ I_{L3\_10.5\_CT3} \end{bmatrix} \quad (2)$$

Advantages of this solution:

- Most commonly used solution because all needed CTs are readily available in the standard substation switchgear arrangements.

Disadvantages of this solution:

- Reduced protection sensitivity for turn to turn and internal ground faults due to mandatory zero sequence current reduction
- Low sensitivity for internal earth faults located close to the star point of the auto-transformer common winding.

4. AUTO-TRANSFORMER BUILT FROM THREE SINGLE PHASE UNITS WHEN ONLY ONE CT SET IS USED INSIDE THE TERTIARY DELTA WINDING

Sometimes, due to easier transportation and possibility to have a fourth spare transformer or even sometimes for historical reasons, the auto-transformer is built from three single-phase transformer units. In such application the already shown differential protection schemes can also be applied. However, very often for such single phase auto-transformer design bushing CTs in the common winding star point and inside the tertiary delta winding are available and can be used for the differential protection.

4.1. Scheme 1 based on the auto-transformer total throughput power

This differential protection scheme shown is similar with the scheme presented in Table 4. The only difference is that all three individual currents within the tertiary delta winding are available to the relay. Note that the tertiary delta winding can be loaded with such arrangement. The relevant application data to set up such differential protection for the example auto-transformer are given in Table 5.

Winding	W1	W2	W3
Base Power [MVA]	400	400	400
Ph-Ph, No-Load Voltage [kV]	400	231	√3 × 10,5 = 18,187 kV*
Base Primary Current [A]	577	1000	12698
Vector Group	Y	y0	y0*
Zero Sequence Current Elimination	No / (Yes)	No / (Yes)	No / (Yes)
Connected to CT (See Figure 3)	CT1	CT2	CT7
Base current on CT secondary side [A]	0.721	0.833	3.175

* Influenced by CT location within tertiary delta winding

Table 5: Differential protection using CT1, CT2 and CT7

For such protection scheme the differential currents in per-unit can be calculated in accordance with the following matrix equation:

$$\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \frac{1}{0.721} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_400\_CT1} \\ I_{L2\_400\_CT1} \\ I_{L3\_400\_CT1} \end{bmatrix} + \frac{1}{0.833} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_220\_CT2} \\ I_{L2\_220\_CT2} \\ I_{L3\_220\_CT2} \end{bmatrix} + \frac{1}{3.175} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_10.5\_CT7} \\ I_{L2\_10.5\_CT7} \\ I_{L3\_10.5\_CT7} \end{bmatrix} \quad (3)$$

Advantages of this solution:

- Increased sensitivity for turn to turn and internal ground faults because the zero sequence current reduction is not required
- Somewhat increased sensitivity for internal earth faults located close to the star point of the auto-transformer common winding
- Clear indication of the faulty phase because the differential current strictly correspond to windings located on the same magnetic limb (i.e. all three matrixes are unit matrixes in the above equation)
- Increased sensitivity for internal faults located inside tertiary delta winding.

Disadvantages of this solution:

- Necessity for a CT inside the tertiary delta winding.

4.2. Scheme 2 based on the rating of the auto-transformer active part

This scheme is quite different from previously presented differential protection schemes. From the CT location point of view such application is most similar to the standard power transformer differential protection, because the currents are measured inside each individual winding present in the auto-transformer (see Figure 2).

Currents are directly measured in all windings which are located around one magnetic core limb. Consequently the zero sequence current shall not be eliminated from any side. The relevant application data to set up such differential protection for the example auto-transformer are given in Table 6.

Winding	W1	W2	W3
Base Power [MVA]	169	169	169
Ph-Ph, No-Load Voltage [kV]	169	231	√3 × 10,5 = 18,187 kV*
Base Primary Current [A]	577	422	5365

Winding	W1	W2	W3
Vector Group	Y	y0	y0*
Zero Sequence Current Elimination	No / (Yes)	No / (Yes)	No / (Yes)
Connected to CT (See Figure 3)	CT1	CT5	CT7
Base current on CT secondary side [A]	0.721	0.844	1.341

* Influenced by CT location within the tertiary delta winding

Table 6: Differential protection using CT1, CT5 and CT7

For such protection scheme the differential currents in per-unit can be calculated in accordance with the following matrix equation:

$$\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \frac{1}{0.721} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_400\_CT1} \\ I_{L2\_400\_CT1} \\ I_{L3\_400\_CT1} \end{bmatrix} + \frac{1}{0.844} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_N\_CT5} \\ I_{L2\_N\_CT5} \\ I_{L3\_N\_CT5} \end{bmatrix} + \frac{1}{1.341} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_10.5\_CT7} \\ I_{L2\_10.5\_CT7} \\ I_{L3\_10.5\_CT7} \end{bmatrix} \quad (4)$$

Advantages of this solution:

- Increased sensitivity because the zero sequence current reduction is not required
- Increased sensitivity for earth faults located close to the star point of the auto-transformer common winding since the current is measured exactly there
- Clear indication of the faulty phase because the differential current strictly correspond to the windings located on the same magnetic limb (i.e. all three matrixes are unit matrixes in above equation)
- Increased sensitivity for faults inside the tertiary delta winding.

Disadvantages of this solution:

- Low sensitivity for internal winding faults located close to the 220 kV side connection point
- All faults on the 220 kV conductor are seen as external faults (e.g. such differential scheme will not operate for faults in the 220 kV side bushing).

5. AUTO-TRANSFORMER BUILT FROM THREE SINGLE PHASE UNITS WHEN TWO CT SETS ARE USED INSIDE THE DELTA WINDING (ONE ON EACH SIDE)

When an auto-transformer is made from three single-phase units the CTs on both sides of the tertiary delta winding are often available. Thus, it is possible to connect two CT sets from inside of the delta winding to the differential protection scheme. This will increase the sensitivity for internal faults within the tertiary delta winding [2].

5.1. Scheme 1 based on the auto-transformer total throughput power

This scheme is very similar to the scheme given in Table 5. The only difference is that two CT inputs are available from the tertiary delta winding. Thus the differential relay with four restraint inputs is required. The relevant application data to set up such differential protection for the example auto-transformer are given in Table 7.

Winding	W1	W2	W3	W3
Base Power [MVA]	400	400	400	400
Ph-Ph, No-Load Voltage [kV]	400	231	$\sqrt{3}\,\frac{10{,}5}{2} = 9{,}093$ kV*	$\sqrt{3}\,\frac{10{,}5}{2} = 9{,}093$ kV*
Base Primary Current [A]	577	1000	25396	25396
Vector Group	Y	y0	y0	y0
Zero Sequence Current Elimination	No / (Yes)	No / (Yes)	No / (Yes)	No / (Yes)
Connected to CT (See Figure 3)	CT1	CT2	CT7	CT8
Base current on CT secondary side [A]	0.721	0.833	6.349	6.349

* Influenced by existence of two CTs located within the tertiary delta winding

Table 7: Differential protection using CT1, CT2, CT7 and CT8

For such protection scheme the differential currents in per-unit can be calculated in accordance with the following matrix equation:

$$\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \frac{1}{0.721}\cdot\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\cdot\begin{bmatrix} I_{L1\_400\_CT1} \\ I_{L2\_400\_CT1} \\ I_{L3\_400\_CT1} \end{bmatrix} + \frac{1}{0.833}\cdot\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\cdot\begin{bmatrix} I_{L1\_220\_CT2} \\ I_{L2\_220\_CT2} \\ I_{L3\_220\_CT2} \end{bmatrix} + \frac{1}{6.349}\cdot\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}\cdot\begin{bmatrix} I_{L1\_10.5\_CT7} + I_{L1\_10.5\_CT8} \\ I_{L2\_10.5\_CT7} + I_{L2\_10.5\_CT8} \\ I_{L3\_10.5\_CT7} + I_{L3\_10.5\_CT8} \end{bmatrix} \quad (5)$$

Advantages of this solution:

- Increased sensitivity because the zero sequence current reduction is not required
- Increased sensitivity for faults inside the tertiary delta winding
- Clear indication of the faulty phase because the differential current strictly correspond to windings located on the same magnetic limb (i.e. all three matrixes are unit matrixes in the above equation)

Disadvantages of this solution:

- Necessity for two CT sets inside the tertiary delta winding

5.2. Scheme 2 based on the rating of the auto-transformer active part

This scheme is very similar to the scheme given in Table 6. The only difference is that two CT inputs are available from the tertiary delta winding. Thus the differential relay with four restraint inputs is required. The relevant application data to set up such differential protection for the example auto-transformer are given in Table 8.

Winding	W1	W2	W3	W3
Base Power [MVA]	169	169	169	169
Ph-Ph, No-Load Voltage [kV]	400	231	$\sqrt{3}\,\frac{10{,}5}{2} = 9{,}093$ kV*	$\sqrt{3}\,\frac{10{,}5}{2} = 9{,}093$ kV*
Base Primary Current [A]	577	422	10730	10730
Vector Group	Y	y0	y0	y0
Zero Sequence Current Elimination	No / (Yes)	No / (Yes)	No / (Yes)	No / (Yes)
Connected to CT (See Figure 3)	CT1	CT5	CT7	CT8
Base current on CT secondary side [A]	0.721	0.844	2.683	2.683

* Influenced by existence of two CTs located within tertiary delta winding

Table 8: Differential protection using CT1, CT5, CT7 and CT8

For such protection scheme the differential currents in per-unit can be calculated in accordance with the following matrix equation:

$$\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \frac{1}{0.721} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_400\_CT1} \\ I_{L2\_400\_CT1} \\ I_{L3\_400\_CT1} \end{bmatrix} + \frac{1}{0.844} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_N\_CT5} \\ I_{L2\_N\_CT5} \\ I_{L3\_N\_CT5} \end{bmatrix} + \frac{1}{2.683} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_10.5\_CT7} + I_{L1\_10.5\_CT8} \\ I_{L2\_10.5\_CT7} + I_{L2\_10.5\_CT8} \\ I_{L3\_10.5\_CT7} + I_{L3\_10.5\_CT8} \end{bmatrix} \quad (6)$$

Advantages of this solution:

- Increased sensitivity because the zero sequence current reduction is not required
- Increased sensitivity for the earth faults located close to the star point of the auto-transformer common winding since the current is measured exactly there
- Increased sensitivity for faults inside the tertiary delta winding
- Clear indication of the faulty phase because the differential current strictly correspond to windings located on the same magnetic limb (i.e. all three matrixes are unit matrixes in the above equation).

Disadvantages of this solution:

- Low sensitivity for internal winding faults located close to the 220 kV side connection point
- All faults on the 220 kV conductor are seen as external fault (e.g. such differential scheme will not operate for faults in the 220 kV side bushing).

Note that the rated no-load voltage of the tertiary delta winding was intentional reduced by one half in order to compensate for "double current measurement" within the delta winding for the two differential protection schemes presented in this section.

6. DIFFERENTIAL PROTECTION BASED ON THE FIRST KIRCHHOFF'S LAW

Due to a galvanic connection between the serial and the common winding (see Figure 1) it is possible to arrange a bus-like differential protection for auto-transformers. This differential protection is based on the First Kirchhoff's Law which says that the sum of all currents flowing into one common node shall be zero. Such protection arrangement can be achieved by using either low or high impedance differential protection [6].

6.1. Low-impedance, phase segregated bus-like differential protection for auto-transformers

Note that for such scheme the rated current for 220 kV side (i.e. the biggest of the three measured currents) is typically selected as the base current. Zero sequence current reduction is not at all required for such scheme. The relevant application data to set up such low-impedance differential protection for the example auto-transformer are given in Table 9.

Winding	W1	W2	W3
Base Power [MVA]	400	400	400
Ph-Ph, No-Load Voltage [kV]	231	231	231
Base Primary Current [A]	1000	1000	1000
Vector Group	Y	y0	y0
Zero Sequence Current Elimination	No	No	No
Connected to CT (See Figure 3)	CT1	CT2	CT6
Base current on CT secondary side [A]	1.25	0.833	2.00

Table 9: Differential protection using CT1, CT2 and CT6

For such protection scheme the differential currents in per-unit can be calculated in accordance with the following matrix equation:

$$\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \frac{1}{1.25} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_400\_CT1} \\ I_{L2\_400\_CT1} \\ I_{L3\_400\_CT1} \end{bmatrix} + \frac{1}{0.833} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_220\_CT2} \\ I_{L2\_220\_CT2} \\ I_{L3\_220\_CT2} \end{bmatrix} + \frac{1}{2.0} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_N\_CT6} \\ I_{L2\_N\_CT6} \\ I_{L3\_N\_CT6} \end{bmatrix} \qquad (7)$$

Advantages of such phase segregated, low or high impedance, bus-like differential protection scheme:

- Protects common and serial winding against internal short circuits and earth faults
- Increased sensitivity for faults located close to the star point of the auto-transformer common winding since currents are measured exactly there
- Not affected by auto-transformer inrush currents
- Clear indication of the faulty phase because the differential current strictly corresponds to windings located on the same magnetic core limb.

Disadvantages of this bus-like phase segregated differential protection scheme:

- The tertiary delta winding is not protected at all with such scheme (i.e. this scheme protects only the serial and the common windings)
- It will not detect any turn to turn fault inside the serial and the common windings
- Phase segregated CTs are required in the common winding star point
- Dedicated CT cores with equal ratios and magnetizing characteristics shall be used when a high impedance differential relay is used.

6.2. Restricted earth fault protection for auto-transformers

Restricted earth fault (REF) is a zero-sequence current based differential scheme. It is also based on the First Kirchhoff's Law which is as well valid for zero-sequence currents. It will detect all earth faults within the common and serial winding of the protected auto-transformer.

The relevant application data to set up such REF differential protection for the example auto-transformer are given in Table 10.

Winding	W1	W2	Neutral Point
Base Primary Current [A]	1000	1000	1000
Connected to CT (See Figure 3)	CT1	CT2	CT4
Base current on CT secondary side [A]	1.25	0.833	1.00

Table 10: Low impedance REF protection using CT1, CT2 and CT4

For such low-impedance REF protection scheme the differential current in per-unit can be calculated in accordance with the following matrix equation:

$$Id\_REF = \frac{1}{1.25} \cdot \begin{bmatrix} 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_400\_CT1} \\ I_{L2\_400\_CT1} \\ I_{L3\_400\_CT1} \end{bmatrix} + \frac{1}{1.25} \cdot \begin{bmatrix} 1 & 1 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_220\_CT2} \\ I_{L2\_220\_CT2} \\ I_{L3\_220\_CT2} \end{bmatrix} + \frac{1}{1.0} \cdot I_{N\_CT4} \qquad (8)$$

The REF protection for an auto-transformer can also be arranged as a high impedance scheme [6].

Advantages of the auto-transformer REF protection schemes:

- Protects the common and the serial winding against internal earth faults
- Increased sensitivity for earth faults located close to the star point of the auto-transformer common winding since current is measured exactly there
- Not affected by auto-transformer inrush currents
- The protection scheme requires just one single CT in the common auto-transformer star point.

Disadvantages of the auto-transformer REF protection schemes:

- The tertiary delta winding is not protected at all with such scheme (i.e. this schemes protects only the serial and the common windings against earth faults)
- It will not detect any turn to turn or short-circuit faults within the serial and the common windings
- Dedicated CT cores with equal ratios and magnetizing characteristic shall be used for high impedance REF schemes.

7. UNIT PROTECTION SCHEMES FOR THE TERTIARY DELTA WINDING

As mentioned before, standard auto-transformer differential protection schemes might have limited sensitivity for short-circuits in the tertiary delta winding. The main reasons are the auto-transformer self impedance and reduced rating of the tertiary delta winding. In order to improve the sensitivity for tertiary winding faults dedicated differential schemes are sometimes used.

7.1. Dedicated differential protection scheme for the tertiary delta winding

When an auto-transformer is consisting of three single-phase units then CTs on both sides of the tertiary delta winding are often available. In such installations it is possible to arrange dedicated, bus-like differential protection scheme for every phase of the delta winding.

As this is a scheme based on the First Kirchhoff's Law, it is not necessary to deduct the zero sequence current on any side. Note that the rated current of the tertiary delta winding shall be used as the base current because this differential scheme is a dedicated protection for that winding only. The relevant application data to set up such differential protection for the example auto-transformer are given in Table 11.

Winding	**W3**	**W3**
Base Power [MVA]	130	130
Ph-Ph, No-Load Voltage [kV]	√3 × 10,5 = 18,187 kV*	√3 × 10,5 = 18,187 kV*
Base Primary Current [A]	4127	4127
Vector Group	Y	y0
Zero Sequence Current Elimination	No	No
Connected to CT (See Figure 3)	CT7	CT9
Base current on CT secondary side [A]	1.032	1.032

Table 11: Differential protection using CT7 and CT9

For such protection scheme the differential currents in per-unit can be calculated in accordance with the following matrix equation:

$$\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \frac{1}{1.032} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_10.5\_CT7} \\ I_{L2\_10.5\_CT7} \\ I_{L3\_10.5\_CT7} \end{bmatrix} + \frac{1}{1.032} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_10.5\_CT9} \\ I_{L2\_10.5\_CT9} \\ I_{L3\_10.5\_CT9} \end{bmatrix} \tag{9}$$

Advantages of this solution:

- Increased sensitivity for faults in the tertiary delta winding because the differential scheme can be sized in accordance with the rating of the tertiary delta winding and not on the rating of the whole auto-transformer
- Clear indication of the faulty phase within the delta winding.

Disadvantages of this solution:

- Two set of CTs are required within the tertiary delta winding
- Such scheme will not detect internal earth faults if the tertiary delta winding or connected power system is not grounded
- This scheme will not detect any turn to turn faults inside the delta winding.

It is also possible to arrange such differential protection as a high impedance scheme.

7.2. Dedicated earth fault protection scheme for a not-loaded tertiary delta winding

When a tertiary delta winding is not loaded it is possible to solidly ground one corner of the delta winding as shown in Figure 4. If a CT is positioned in this grounding connection a simple overcurrent relay can be used to protect the tertiary delta winding against any earth fault. Typical pickup value for such overcurrent relay is around 150A primary.

Advantages of this solution:

- Increased sensitivity for earth faults in the tertiary delta winding.

Disadvantages of this solution:

- Not clear indication of the faulty phase inside the delta winding
- Requirement to have access to one of the corners of the delta winding
- This scheme will not detect any short-circuits or turn to turn faults inside the delta winding.

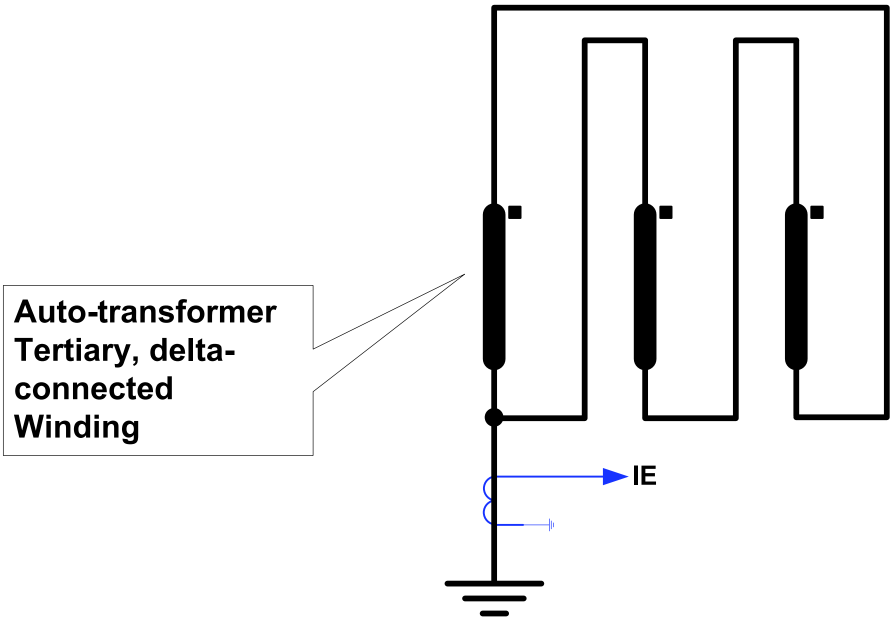


Figure 4: Dedicated earth-fault protection scheme for a not-loaded tertiary delta winding

8. FIELD RECORDINGS

The example transformer is an actual auto-transformer where the tertiary delta winding is not loaded. In the existing installation the following CTs are available: CT1, CT2, CT4 and CT7 in accordance with designations shown in Figure 3. By using the first Kirchhoff's law it is also possible to calculate the common winding currents (i.e. CT5) for any external fault from captured recordings. Due to space limitation only one captured recording will be presented here. This is an external L2-Gnd fault which before clearing evolved into a L2-L3-Gnd fault. In Figure 5 the following traces, either captured or calculated, are shown for this external fault:

a) 400kV side current waveforms (i.e. CT1) in primary amperes (recorded)

b) 220kV side current waveforms (i.e. CT2) in primary amperes (recorded)

c) Common winding side current waveforms (i.e. CT5) in primary amperes (calculated)

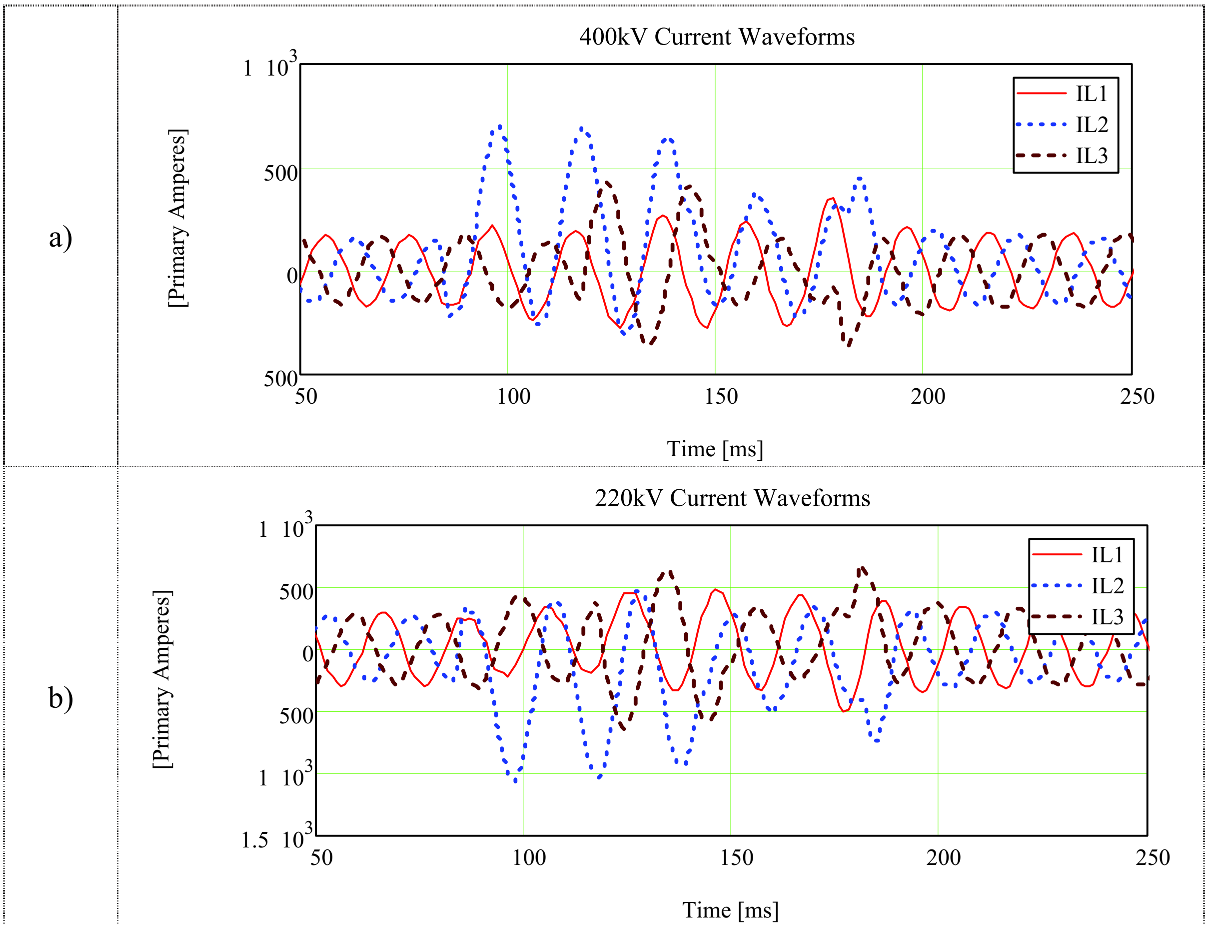
d) Waveforms for current inside the tertiary delta winding (i.e. CT7-note that just one phase is shown because the delta winding is not loaded) and the neutral point current (i.e. CT4) in primary amperes (both recorded)

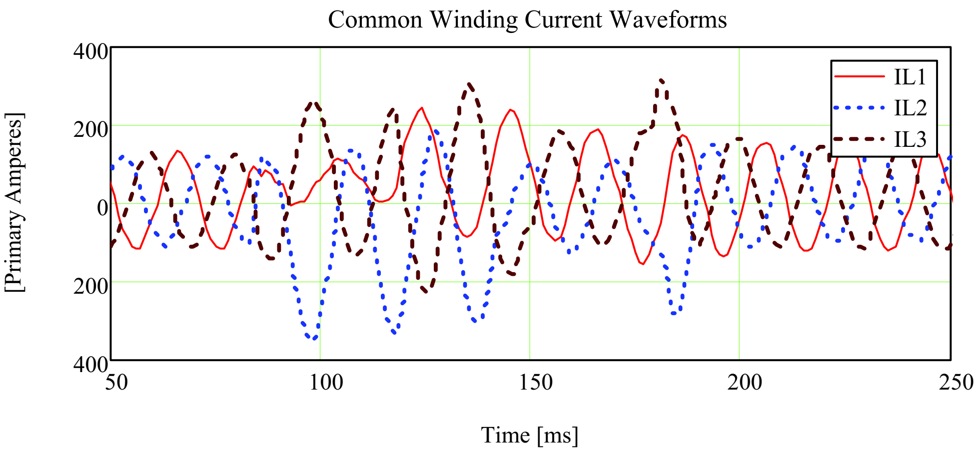
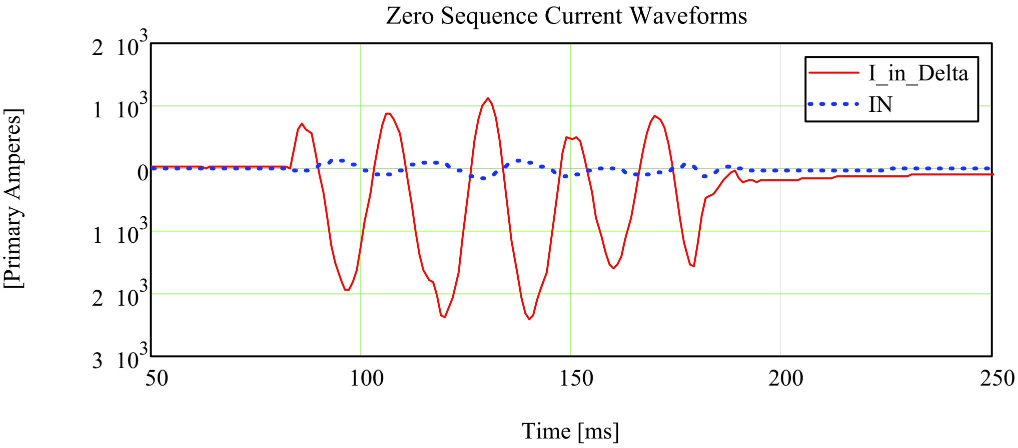
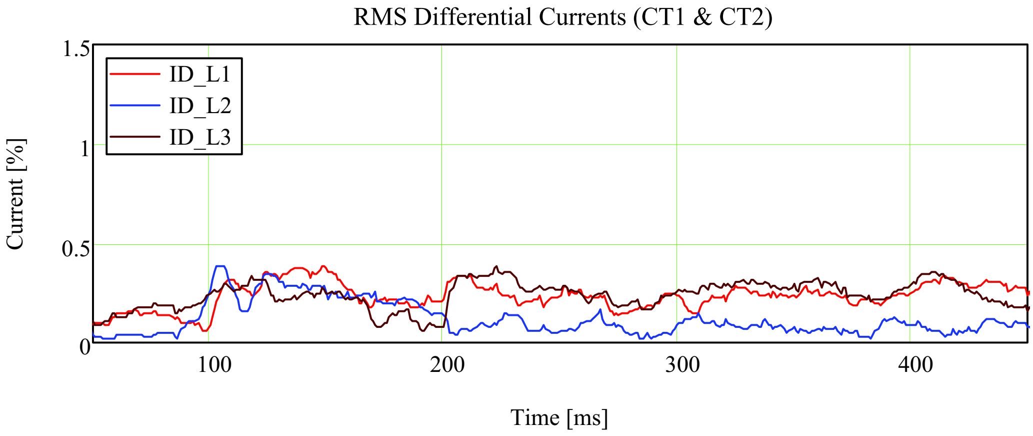
e) Calculated differential current RMS values in percent for the differential protection scheme in accordance with Table 3 and equation (1)

f) Calculated differential current RMS values in percent for the differential protection scheme in accordance with Table 5 and equation (3)

g) Calculated differential current RMS values in percent for the differential protection scheme in accordance with Table 6 and equation (4)

h) Calculated differential current RMS value in percent for the low-impedance REF protection scheme in accordance with Table 10 and equation (8)



c)	Common Winding Current Waveforms [Primary Amperes] 400 200 0 200 400 50 100 150 200 250 Time [ms] IL1 IL2 IL3
d)	Zero Sequence Current Waveforms [Primary Amperes] 2 10^3 1 10^3 0 1 10^3 2 10^3 3 10^3 50 100 150 200 250 Time [ms] I_in_Delta IN
e)	RMS Differential Currents (CT1 & CT2) Current [%] 1.5 1 0.5 0 100 200 300 400 Time [ms] ID_L1 ID_L2 ID_L3

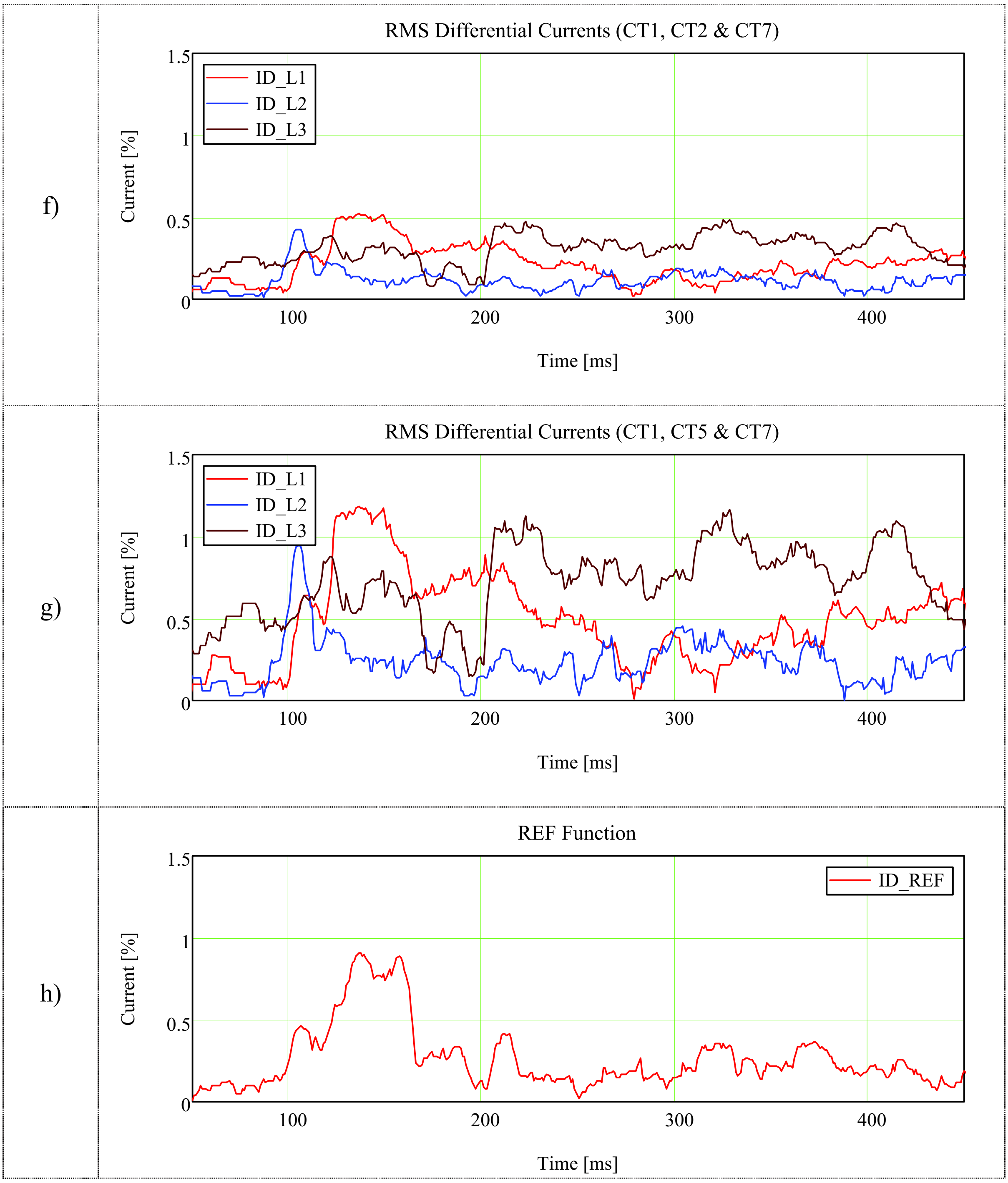


Fig. 5: Evaluation of captured disturbance file from the example auto-transformer installation

From Figure 5 it can be seen that for all presented differential protection schemes calculated differential current will be less than 1.5% during the entire external fault. Thus all presented schemes are correctly balanced and consequently correctly applied for the protection of the example auto-transformer.

9. CONCLUSION

Different types of auto-transformer differential protection schemes have been presented. Once more note that the following data are crucial for proper application of the selected differential protection scheme:

- Which base quantities (i.e. power, no load voltage and current) shall be used
- Which vector group shall be entered
- Whether or not zero sequence current elimination shall be enabled.

Once this important data is known instruction for the particular relay make shall be followed to derive relay-specific settings. Actual implementation for all of these differential protection schemes for a particular relay model can be found in reference [6].

Which particular scheme that will be used is mostly determined by availability of the main CTs in a specific installation and possibly previous experience of a particular utility. It is recommended that in addition to the standard differential protection scheme (e.g. as shown in Table 3 or Table 4) additional differential scheme is applied which is sensitive for faults close to the common winding star point (e.g. as for example shown in Table 6, Table 8 or Table 10). Other possible solution is to combine two differential schemes which have different properties (e.g. as for example two schemes shown in Table 5, Table 4 and Table 6). Due to size and importance of auto-transformers in modern power system (e.g. mostly used as system intertie transformers) full duplication of such protection scheme can also be justified.

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