SA2008-000519

Differential Protection Schemes for Auto-Transformers

Application Example

1 Introduction

This document describes application of RET 670 for auto-transformers. The application of the differential protection to auto-transformers is somewhat special because such scheme can be arranged in a number of different ways. Most commonly used schemes are described in this document. One auto-transformer will be used for all differential scheme examples presented in the document. This autotransformer has the following rated quantities: 400/400/130MVA; 400/231/10.5kV; 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.
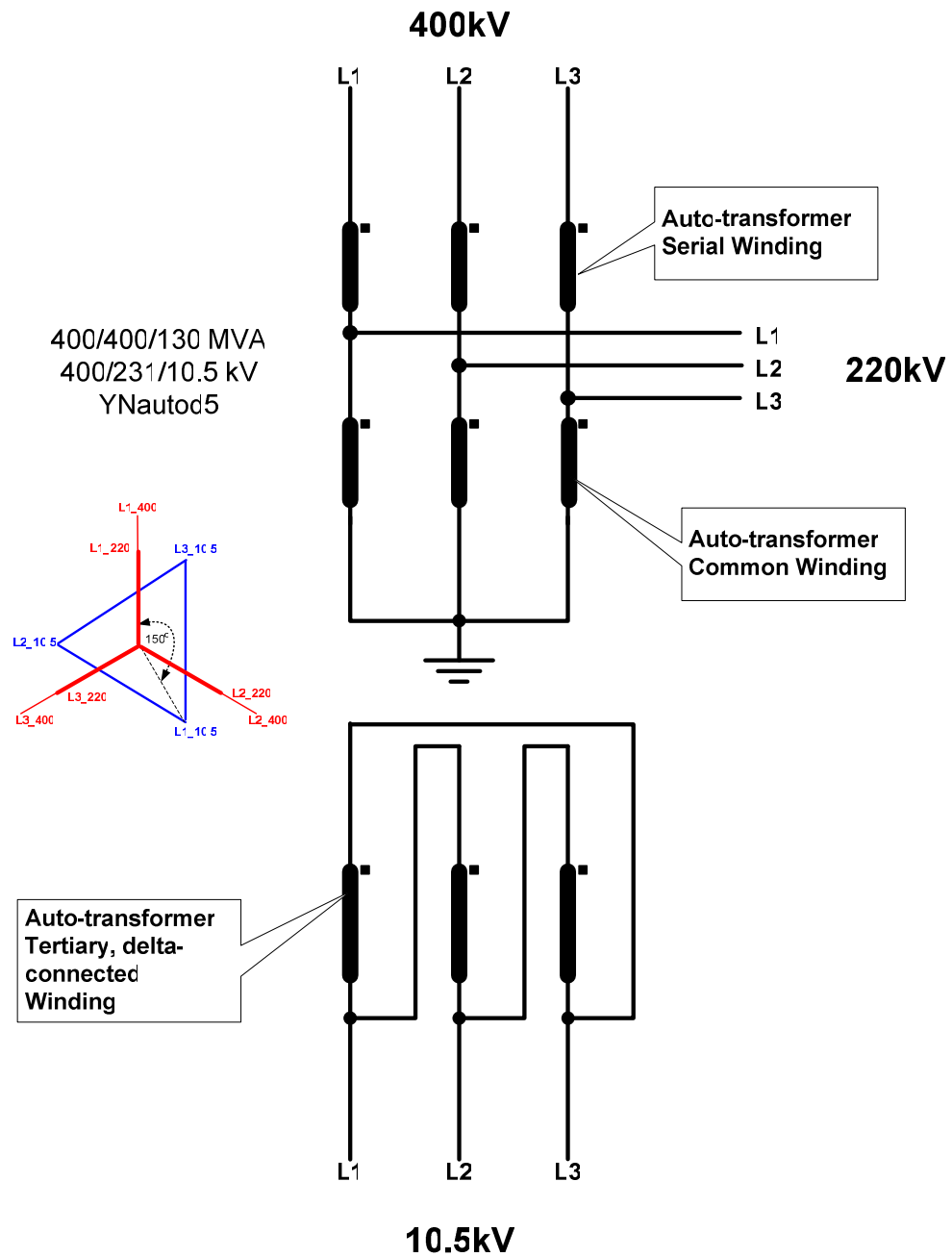
Figure 1: Rating data for Auto-transformer used as example in this document

Individual winding rated currents for this auto-transformer are calculated as shown in Table 1. Note that these rated currents are calculated for individual winding MVA rating.

Table 1: Calculation of winding rated currents for example auto-transformer

Winding/Side	Rated Current [Primary Amperes]
400kV Side	$I_{r\_400} = \dfrac{400MVA}{\sqrt{3} \cdot 400kV} = 577.4A$

220kV Side	$I_{r\_220} = \dfrac{400MVA}{\sqrt{3} \cdot 231kV} = 999.7A$
Common Winding	$I_{r\_CW} = I_{r\_220} - I_{r\_400} = 999.7 - 577.4 = 422.3A$
10.5kV Winding; outside delta winding	$I_{r\_10.5\_out\_\Delta} = \dfrac{130MVA}{\sqrt{3} \cdot 10.5kV} = 7148A$
10.5kV Winding; inside delta winding	$I_{r\_10.5\_in\_\Delta} = \dfrac{130MVA}{3 \cdot 10.5kV} = 4127A$

Please note the following:

1. All CT connections shown in this document correspond with setting "ToObject" in RET 670; thus it is assumed that for all shown applications all CT inputs in RET 670 should have such setting value. If in your application some of the main CTs are stared in opposite way, just simply change value of this parameter to "FromObject" for such inputs, in order to ensure proper balancing of the auto-transformer differential protection.

2. Exact main CT ratios are not shown in this document. It is assumed that actual ratios of the main CTs are properly set within RET 670. These settings are entered under General Settings/Analog modules in PCM 600 tool.

3. It is assumed that the differential protection function in RET 670 is properly configured. That means that input CT currents are connected to the function in proper order. Necessary CT connections will be shown for every differential scheme application. More info about transformer differential function in RET 670 can be found in [6].

1.1 Some basic facts about auto-transformers

An auto-transformer is a transformer in which at least two windings have a common part [1]. For standard auto-transformer design [1] & [2] this common part is the common winding shown in Figure 1. Typically auto-transformers are used to interconnect two electrical networks with similar voltage levels (e.g. system intertie transformer).

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). This can be represented for the example auto-transformer by the following equation:

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

where:

> S is auto-transformer total through power

> U_{220} is voltage on the 220kV side

> I_{220} is current on the 220kV side

> I_{400} is current on the 400kV side

> I_{CW} is current in the common winding

> S_G is part of power transferred by galvanic connection

> S_T is a part of power transferred by magnetic circuit (transformer effect)

Obviously only one part of the auto-transformer through power is transferred by magnetic circuit (transformer effect). Thus, the whole auto-transformer construction 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 same rated voltages and rated through power. It can be shown that this reduction factor can be calculated for the example auto-transformer by using the following equation:

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

Thus, example auto-transformer has rated through power of 400MVA, but its active part is designed for 169MVA only. 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 [5]. The drawbacks are galvanic connection of the two power systems, which makes any overvoltage easily transferable from one to the other system; need to ground the common winding neutral point; the short-circuit duty of auto-transformer is more severe as compared with that of an equivalent power transformer with two separate windings and the fact that due to "smaller magnetic size" auto-transformers typically have lower short circuit impedances compared with that of an equivalent power transformer with two separate windings [5]. This last point affects the magnitude of the short-circuit currents for through faults.

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 zero

sequence impedance for five-limb core construction. 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.

1.2 Base currents and no-load voltages for example auto-transformer

In order to properly balance numerical transformer differential protection proper base quantities shall be used [3] and [6]. The following two tables summarize base quantities for the example auto-transformer.

Table 2: Differential protection base quantities for total rating of 400MVA

Winding/Side	Base ph-ph no load voltage	Base current
400kV side	$400kV$	$\dfrac{400MVA}{\sqrt{3}\cdot 400kV}=577A$
220kV side	$231kV$	$\dfrac{400MVA}{\sqrt{3}\cdot 231kV}=1000A$
Delta side (outside triangle)	$10.5kV$	$\dfrac{400MVA}{\sqrt{3}\cdot 10.5kV}=21994A$
Delta side (inside triangle)	$\sqrt{3}\cdot 10.5=18.2kV$	$\dfrac{400MVA}{\sqrt{3}\cdot 18.2kV}=12689A$

Table 3: Differential protection base quantities for the rating of the active part (i.e. 169MVA)

Winding/Side	Base ph-ph no load voltage	Base current
Serial winding	$400-231=169kV$	$\dfrac{169MVA}{\sqrt{3}\cdot 169kV}=577A$
Common winding	$231kV$	$\dfrac{169MVA}{\sqrt{3}\cdot 231kV}=422A*$
Delta winding (inside triangle)	$\sqrt{3}\cdot 10.5=18.2kV$	$\dfrac{169MVA}{\sqrt{3}\cdot 18.2kV}=5361A$

* Note that exactly this amount of current will also flow through common winding when auto-transformer is fully loaded with 400MVA (i.e. $1000-577\approx 422$).

For every auto-transformer differential protection scheme correct selection of the base quantities is crucial. Correct selection of base quantities for different auto-transformer differential protection scheme will be presented in this document.

2 Differential Protection Schemes 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:

$$N_1 \cdot I_1 + N_2 \cdot I_2 = 0 \quad or \quad I_1 + \frac{N_2}{N_1} \cdot I_2$$

Where:

> ➢ N_1 is number of turns in the first winding

> ➢ I_1 is current in the first winding

> ➢ N_2 is number of turns in the second winding

> ➢ I_2 is current in the second winding

Note that power transformer magnetizing currents are neglected in this equation. In the power system typically three phase power transformers are used, thus such equation shall be written for every magnetic core limb (i.e. every phase). Typically matrix equations are used for three-phase power transformers [3] and [6].

Additionally the following properties can affect the differential protection for three-phase power transformers:

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 1A or 5A 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 my 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 for measured current magnitude difference on different sides of the protected transformer;

> ➢ transformer phase angle shift compensation; and

> ➢ 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 [3] and [6].

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 (e.g. false) differential current seen by differential relay. Traditionally the differential schemes were only balanced for the mid-tap position. Differential protection in RET 670 can on-line compensate for up to two on-load tap-changers.

2.1 Auto-transformer with not Loaded Tertiary Delta Winding

Quite often the auto-transformer tertiary winding is not loaded and it is used as a delta-connected equalizer winding, as defined in [1]. Typical CT locations for the differential protection of such auto-transformer are shown in Figure 3. In this scenario the auto-transformer is protected as a two-winding power transformer.

The vector group of the protected auto-transformer is YNautod5, thus the 220kV positive sequence, no-load voltage component is in phase with 400kV positive sequence, no-load voltage component. Therefore, for such differential protection scheme the transformer vector group shall be set as Yy0. 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. The relevant parameter settings for 2-winding differential protection in RET 670 shall be entered as shown in Figure 2. These values are calculated in Table 2.

Group / Parameter Name	IED Value	PC Value	Unit	Min	Max
T2D1					
RatedVoltageW1		400,00	kV	0,05	2000,00
RatedVoltageW2		231,00	kV	0,05	2000,00
RatedCurrentW1		577	A	1	99999
RatedCurrentW2		1000	A	1	99999
ConnectTypeW1		WYE (Y)			
ConnectTypeW2		WYE (Y)			
ClockNumberW2		0 [0 deg]			
ZSCurrSubtrW1		On			
ZSCurrSubtrW2		On			
TconfigForW1		No			
TconfigForW2		No			
LocationOLTC1		Not Used			

Figure 2: Relevant "General Settings" under differential protection (e.g. T2D1) for this application

Make sure that currents are connected to the RET 670 differential function as follows:

> ➤ 400kV currents to I3PW1CT1 input

> ➤ 220kV currents to I3PW2CT1 input

With such settings and configuration RET 670 will calculate the differential currents (in primary amperes related to 400kV side) in accordance with the following matrix equation:

$$
\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_400} \\ I_{L2\_400} \\ I_{L3\_400} \end{bmatrix} + \frac{231kV}{400kV} \cdot \frac{1}{3} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_220} \\ I_{L2\_220} \\ I_{L3\_220} \end{bmatrix}
$$

Advantages of this solution:

> ➤ No CT required on the tertiary delta side of the protected auto-transformer

Disadvantages of this solution:

> ➤ Reduced sensitivity due to mandatory zero sequence current reduction

> ➤ Possible lower sensitivity for faults in the tertiary delta winding due to auto-transformer impedance between windings

> ➤ Low sensitivity for the earth faults located close to the star point of the auto-transformer common winding
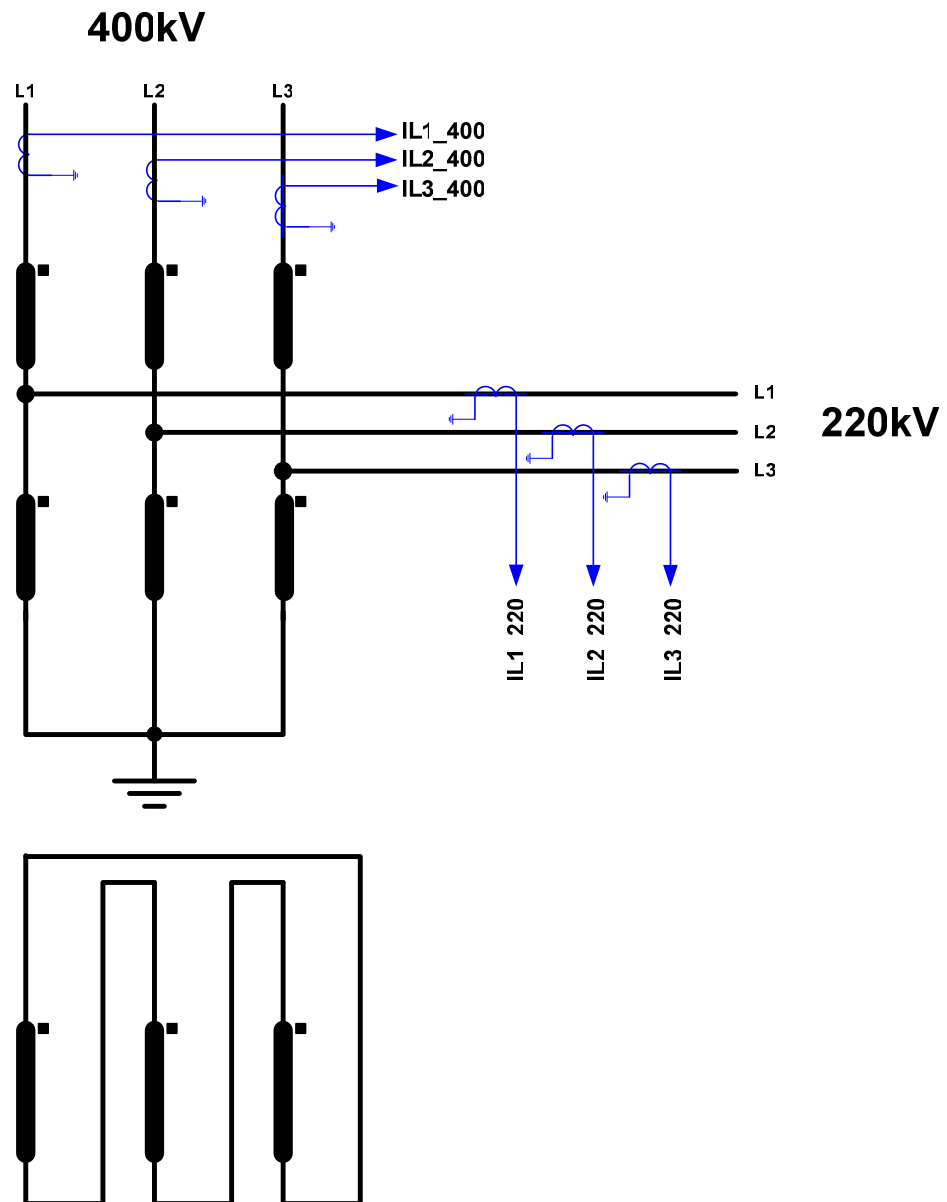
400kV

Figure 3: Differential protection scheme for auto-transformer with not loaded tertiary delta winding

2.2 Auto-transformer with not Loaded Tertiary Delta Winding but with at least one CT available inside the tertiary delta winding

Sometimes two bushings are available on the tertiary delta side as shown in Figure 4. This is done in order to close the tertiary delta winding outside of the tank. Such arrangement gives opportunity to measure the current inside delta winding. Because this delta winding is not loaded only zero-sequence current can circulate through it. Thus, this single CT located inside the tertiary delta winding can be used as a current input to all three phases of the differential protection from the tertiary delta winding side. This is possible because all three tertiary windings are connected in series and consequently all three individual phase currents inside the delta winding are exactly the same. Of course pre-request is that this tertiary delta winding is not loaded. Note that it is quite easy to connect one measured current from inside of the delta winding as "three phase" current input into the differential protection in RET 670 by using Signal Matrix Tool in the PCM 600. For this scheme three-winding differential protection in RET 670 shall be used, as shown in Figure 4.

The actual vector group of the protected auto-transformer is YNautod5. However, current is measured inside of the delta winding for the differential protection and the transformer vector group shall be set as Yy0y0 and tertiary delta winding rating data shall be set as shown in the last row of Table 2.

Because the current inside the delta winding is connected to the differential protection, the zero sequence current shall not be eliminated from any side. The relevant parameter settings for 3-winding differential protection in RET 670 shall be entered as shown in Figure 5. Additionally please make sure that currents are connected to the RET 670 differential function as follows:

> ➢ 400kV currents to I3PW1CT1 input

> ➢ 220kV currents to I3PW2CT1 input

> ➢ 10.5kV currents to I3PW3CT1 input

With such settings and configuration RET 670 will calculate the differential currents (in primary amperes related to 400kV side) in accordance with the following matrix equation:

$$
\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_400} \\ I_{L2\_400} \\ I_{L3\_400} \end{bmatrix} + \frac{231kV}{400kV} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_220} \\ I_{L2\_220} \\ I_{L3\_220} \end{bmatrix} + \frac{18.2kV}{400kV} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_10.5} \\ I_{L2\_10.5} \\ I_{L3\_10.5} \end{bmatrix}
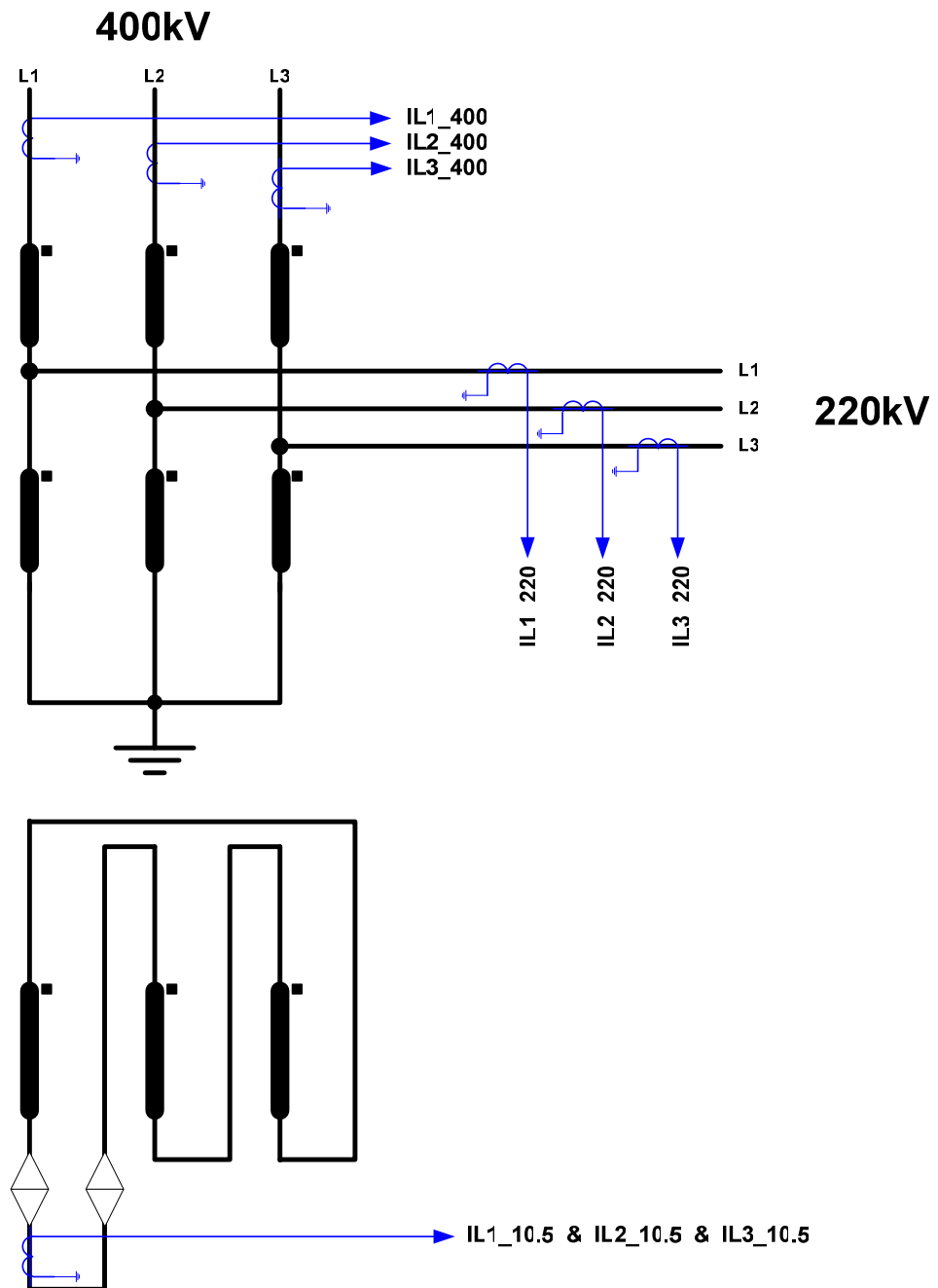$$

400kV

220kV

IL1_400
IL2_400
IL3_400

IL1 220   IL2 220   IL3 220

IL1_10.5 & IL2_10.5 & IL3_10.5

Figure 4: Differential protection scheme for auto-transformer with a CT available within not loaded tertiary delta winding

Group / Parameter Name	IED Value	PC Value	Unit	Min	Max
T3D1					
RatedVoltageW1		400,00	kV	0,05	2000,00
RatedVoltageW2		231,00	kV	0,05	2000,00
RatedVoltageW3		18,20	kV	0,05	2000,00
RatedCurrentW1		577	A	1	99999
RatedCurrentW2		1000	A	1	99999
RatedCurrentW3		12689	A	1	99999
ConnectTypeW1		WYE (Y)			
ConnectTypeW2		WYE (Y)			
ConnectTypeW3		WYE (Y)			
ClockNumberW2		0 [0 deg]			
ClockNumberW3		0 [0 deg]			
ZSCurrSubtrW1		Off			
ZSCurrSubtrW2		Off			
ZSCurrSubtrW3		Off			
TconfigForW1		No			
TconfigForW2		No			
TconfigForW3		No			
LocationOLTC1		Not Used			
LocationOLTC2		Not Used			

Figure 5: Relevant "General Settings" under differential protection (e.g. T3D1) for this application

Advantages of this solution:

➢ Increased sensitivity because zero sequence current reduction is not required

➢ Somewhat increased sensitivity for the earth faults located close to the star point of the auto-transformer common winding, since the current is measured inside of the tertiary delta winding

➢ Clear indication of a faulty phase because differential current strictly correspond to windings located on the same magnetic limb (i.e. all three matrixes are unit matrixes in previous equation)

Disadvantages of this solution:

➢ Necessity for a CT inside tertiary delta winding

➢ Some practical difficulties to check proper polarity/staring of the CT located within tertiary delta winding for such application

2.3 Auto-transformer with Loaded Tertiary Delta Winding

Sometimes the auto-transformer tertiary delta winding is loaded. The connected equipment/object varies 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 be used to supply station auxiliary services and/or local communities in substation surroundings. Finally, sometimes generators are connected to the tertiary winding and then auto-transformer is used as a step-up transformer. Typical CT locations for differential protection in such application are shown in Figure 6.

For such differential protection application the transformer vector group for the differential protection shall be set as Yy0d5. The zero sequence current must be eliminated from two high-voltage sides because the zero sequence current can circulate inside tertiary delta winding, but its magnitude is not available to the differential protection.

The relevant settings for 3-winding differential protection in RET 670 shall be set as shown in Figure 7. Additionally please make sure that currents are connected to the RET 670 differential function as follows:

> ➢ 400kV currents to I3PW1CT1 input

> ➢ 220kV currents to I3PW2CT1 input

> ➢ 10.5kV currents to I3PW3CT1 input

With such settings and configuration RET 670 will calculate the differential currents (in primary amperes related to 400kV side) in accordance with the following matrix equation:

$$
\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_400} \\ I_{L2\_400} \\ I_{L3\_400} \end{bmatrix} + \frac{231kV}{400kV} \cdot \frac{1}{3} \cdot \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_220} \\ I_{L2\_220} \\ I_{L3\_220} \end{bmatrix} + \frac{10.5kV}{400kV} \cdot \frac{1}{\sqrt{3}} \cdot \begin{bmatrix} -1 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_10.5} \\ I_{L2\_10.5} \\ I_{L3\_10.5} \end{bmatrix}
$$

Advantages of this solution:

> ➢ Most commonly used solution because all needed CTs are readily available

Disadvantages of this solution:

> ➢ Reduced sensitivity due to mandatory zero sequence current reduction

> ➢ Low sensitivity for the earth faults located close to the star point of the auto-transformer common winding
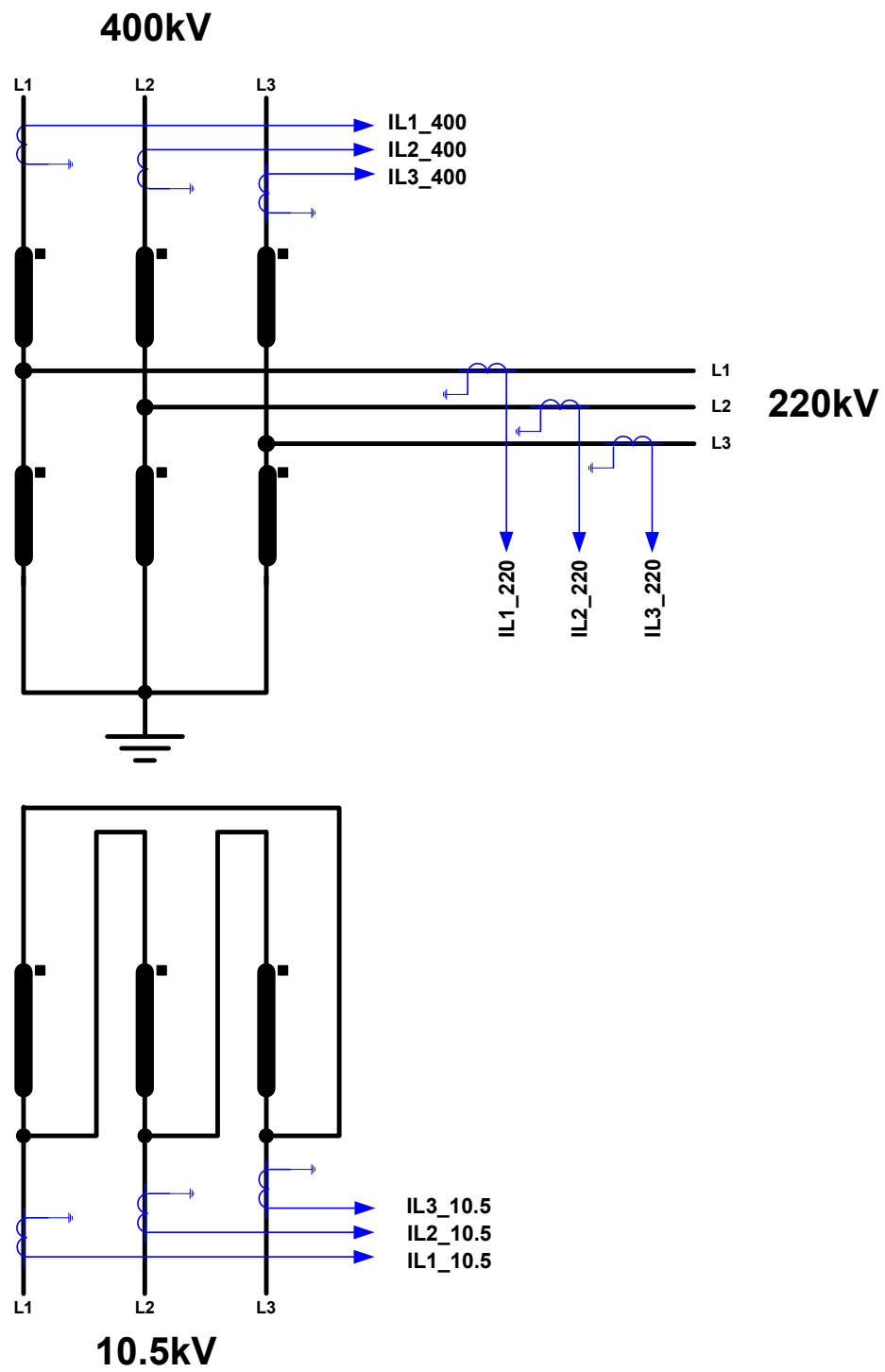
400kV

Figure 6: Differential protection scheme for auto-transformer with loaded tertiary delta winding

Group / Parameter Name	IED Value	PC Value	Unit	Min	Max
T3D1					
RatedVoltageW1		400,00	kV	0,05	2000,00
RatedVoltageW2		231,00	kV	0,05	2000,00
RatedVoltageW3		10,50	kV	0,05	2000,00
RatedCurrentW1		577	A	1	99999
RatedCurrentW2		1000	A	1	99999
RatedCurrentW3		21994	A	1	99999
ConnectTypeW1		WYE (Y)			
ConnectTypeW2		WYE (Y)			
ConnectTypeW3		Delta (D)			
ClockNumberW2		0 [0 deg]			
ClockNumberW3		5 [150 deg lag]			
ZSCurrSubtrW1		On			
ZSCurrSubtrW2		On			
ZSCurrSubtrW3		Off			
TconfigForW1		No			
TconfigForW2		No			
TconfigForW3		No			
LocationOLTC1		Not Used			
LocationOLTC2		Not Used			

Figure 7: Relevant "General Settings" under differential protection (e.g. T3D1) for this application

2.4 Auto-transformer built from three single phase units

Sometimes, due to easier transportation and possibility to have fourth spare transformer or even sometimes for historical reasons, the auto-transformer is built from three single-phase transformer units. In such application differential protection scheme as already shown in Figure 6 can be applied. However, very often for such auto-transformer design bushing CTs are available. This enables to arrange two dissimilar differential protection schemes as shown in Figure 8 and Figure 9 respectively.

From the differential relay point of view, the differential protection scheme shown in Figure 8 is almost identical with scheme presented in Figure 4. The only difference is that all three individual currents within tertiary delta winding are available to the relay. Consequently the tertiary delta winding can be loaded with such arrangement. Used equation and advantages of such differential scheme are already given in Section 2.2.

Scheme shown in Figure 9 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.

The actual vector group of the protected auto-transformer is YNautod5. However, current is measured inside of the delta winding and also in series with the common autotransformer winding. Consequently the transformer vector group shall be set as

Yy0y0 for such application. Additionally the power transformer base data shall be set in a special way as shown Figure 10. Note that rated currents and rated no-load voltages shall be entered using only magnetic through power of the protected auto-transformer as a base, see Table 3 for more information.

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 parameter settings for 3-winding differential protection in RET 670 shall be entered as shown in Figure 10. Additionally please make sure that currents are connected to the RET 670 differential function as follows:

> ➤ 400kV currents to I3PW1CT1 input

> ➤ Currents from common winding star point to I3PW2CT1 input

> ➤ 10.5kV currents to I3PW3CT1 input

With such settings and configuration RET 670 will calculate the differential currents (in primary amperes related to 400kV side) in accordance with the following matrix equation:

$$
\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_400} \\ I_{L2\_400} \\ I_{L3\_400} \end{bmatrix} + \frac{231kV}{169kV} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_N} \\ I_{L2\_N} \\ I_{L3\_N} \end{bmatrix} + \frac{18.2kV}{169kV} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_10.5} \\ I_{L2\_10.5} \\ I_{L3\_10.5} \end{bmatrix}
$$

Advantages of this solution:

> ➤ Increased sensitivity because 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

> ➤ Clear indication of the faulty phase because differential current strictly correspond to windings located on the same magnetic limb (i.e. all three matrixes are unit matrixes in above equation)

> ➤ Increased sensitivity for faults inside tertiary delta winding.

Disadvantages of this solution:

> ➤ Low sensitivity for the internal winding faults located close to the 220kV side connection point

> ➤ All faults on 220kV conductor are seen as external fault (e.g. such differential scheme will not operate for fault in 220kV side bushing)
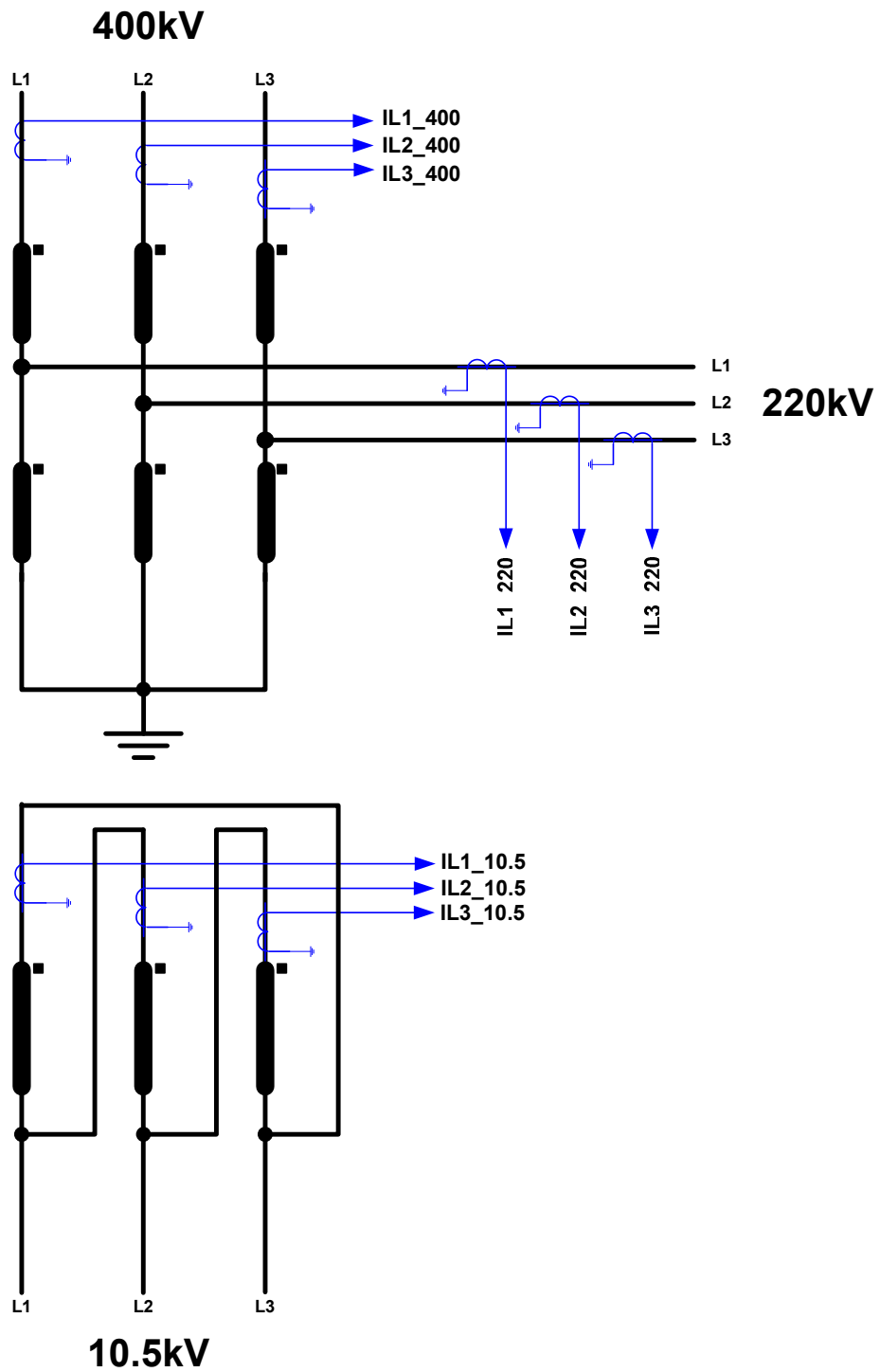
400kV

Figure 8: Differential protection scheme for auto-transformer with three CTs available within tertiary delta winding
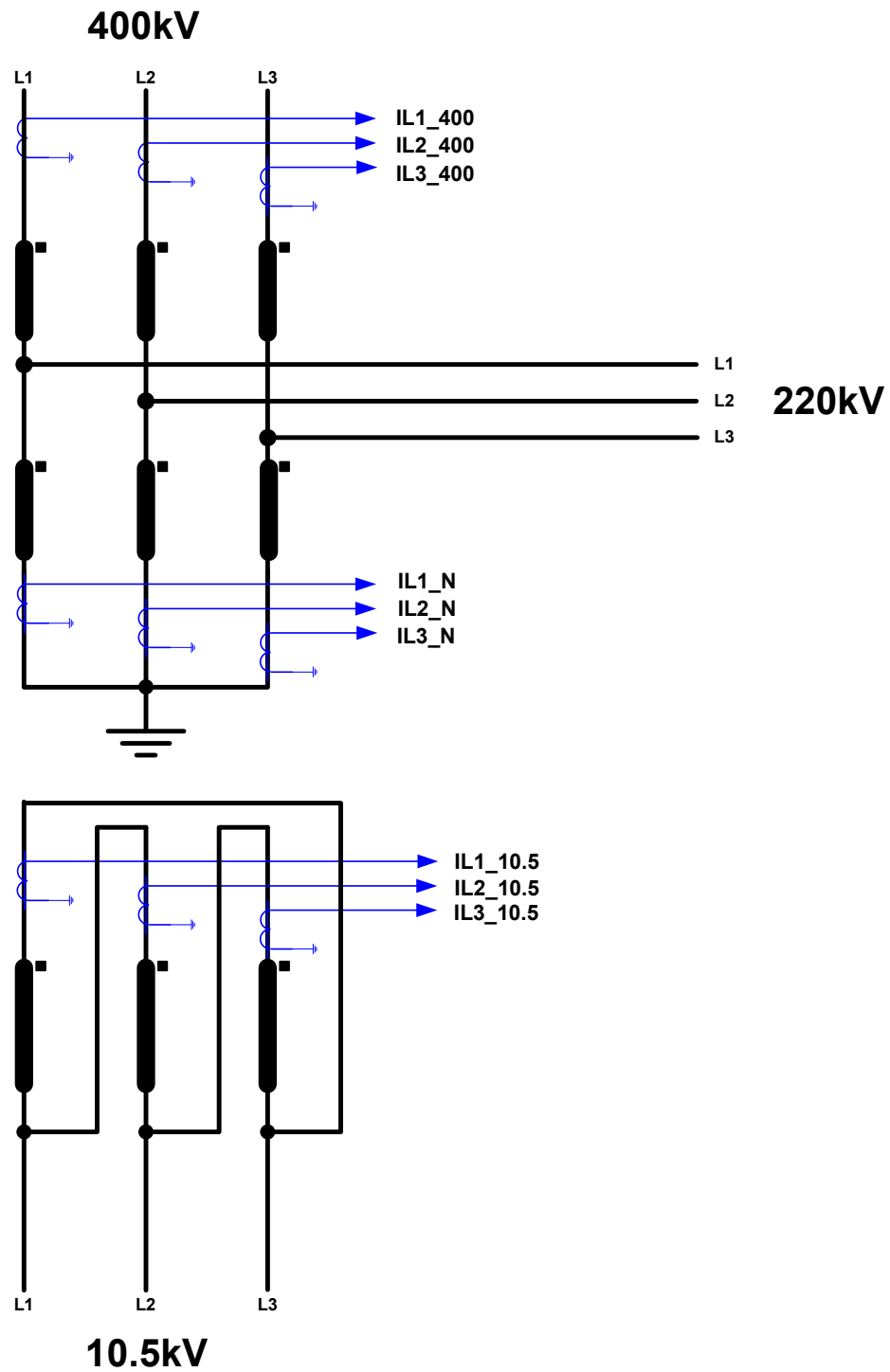
400kV

Figure 9: Differential protection scheme for auto-transformer with three individual CTs available in the star point of the common winding

Group / Parameter Name	IED Value	PC Value	Unit	Min	Max
T3D1 👁					
RatedVoltageW1		169,00	kV	0,05	2000,00
RatedVoltageW2		231,00	kV	0,05	2000,00
RatedVoltageW3		18,20	kV	0,05	2000,00
RatedCurrentW1		577	A	1	99999
RatedCurrentW2		422	A	1	99999
▶ RatedCurrentW3		5361	A	1	99999
ConnectTypeW1		WYE (Y)			
ConnectTypeW2		WYE (Y)			
ConnectTypeW3		WYE (Y)			
ClockNumberW2		0 [0 deg]			
ClockNumberW3		0 [0 deg]			
ZSCurrSubtrW1		Off			
ZSCurrSubtrW2		Off			
ZSCurrSubtrW3		Off			
TconfigForW1		No			
TconfigForW2		No			
TconfigForW3		No			
LocationOLTC1		Not Used			
LocationOLTC2		Not Used			

Figure 10: Relevant "General Settings" under differential protection (e.g. T3D1)
for application shown in Figure 9

2.5 Two CT inputs from one side of the auto-transformer

Depending on the primary station layout (e.g. one-and-a-half breaker arrangement) it is possible to have two CT inputs from one auto-transformer side. Note that differential function in RET 670 is fully capable to accept two main CT inputs from any auto-transformer side. Thus, in such applications both CT secondary circuits shall be connected to RET 670. Care shall be taken that they are connected to appropriate current inputs (i.e. 1A or 5A). Then in the configuration these two currents shall be connected to the two CT inputs for that side, which are available into the differential function. Additionally, corresponding settings shall be entered under differential protection function settings, as shown in Figure 11. This figure shows situation where two main CTs with ratio 1200/1 and 1500/5 are connected from the first auto-transformer side (i.e. from the 400kV winding in the example application) to the differential relay.

TconfigForW1		Yes			
CT1RatingW1		1200	A	1	99999
CT2RatingW1		1500	A	1	99999

Figure 11: Setup when two main CTs (1200/1 and 1500/5) are connected from winding 1 side

2.6 Auto-transformer with two CTs per phase inside tertiary delta winding

When auto-transformer is made from three single-phase units then CTs on both sides of tertiary delta winding are often available. Thus, it is then possible to connect two CT sets from the delta winding to the differential protection scheme as shown in Figure 12 and Figure 13. This will increase sensitivity for internal faults within the tertiary delta winding.

From the differential relay point of view, the differential protection scheme shown in Figure 12 is almost identical with scheme presented in Figure 8. The only difference is that two CT sets are connected from the tertiary delta winding to the relay. Consequently the tertiary delta winding can be loaded with such arrangement.

Because the current inside the delta winding is connected to the differential protection, the zero sequence current shall not be eliminated from any side. The relevant parameter settings for 3-winding differential protection in RET 670 shall be entered as shown in Figure 14. Additionally please make sure that currents are connected to the RET 670 differential function as follows:

> ➢ 400kV currents to I3PW1CT1 input
>
> ➢ 220kV currents to I3PW2CT1 input
>
> ➢ 10.5kV_#1 currents to I3PW3CT1 input
>
> ➢ 10.5kV_#2 currents to I3PW3CT2 input

With such settings and configuration RET 670 will calculate the differential currents (in primary amperes related to 400kV side) in accordance with the following matrix equation:

$$
\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_400} \\ I_{L2\_400} \\ I_{L3\_400} \end{bmatrix} + \frac{231kV}{400kV} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_220} \\ I_{L2\_220} \\ I_{L3\_220} \end{bmatrix} + \frac{9.1kV}{400kV} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_10.5\_\#1} + I_{L1\_10.5\_\#2} \\ I_{L2\_10.5\_\#1} + I_{L2\_10.5\_\#2} \\ I_{L3\_10.5\_\#1} + I_{L3\_10.5\_\#2} \end{bmatrix}
$$

Advantages of this solution:

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

Disadvantages of this solution:

> ➢ Necessity for two CT sets inside tertiary delta winding

Scheme shown in Figure 13 is quite similar to the scheme presented in Figure 9. The only difference is that current within delta winding is measured twice. Because the current inside the delta winding is connected to the differential protection, the zero sequence current shall not be eliminated from any side. The relevant parameter settings for 3-winding differential protection in RET 670 shall be entered as shown in Figure 15. Additionally please make sure that currents are connected to the RET 670 differential function as follows:

> 400kV currents to I3PW1CT1 input

> Neutral Point currents to I3PW2CT1 input

> 10.5kV_#1 currents to I3PW3CT1 input

> 10.5kV_#2 currents to I3PW3CT2 input

With such settings and configuration RET 670 will calculate the differential currents (in primary amperes related to 400kV side) in accordance with the following matrix equation:

$$
\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_400} \\ I_{L2\_400} \\ I_{L3\_400} \end{bmatrix} + \frac{231kV}{169kV} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_N} \\ I_{L2\_N} \\ I_{L3\_N} \end{bmatrix} + \frac{9.1kV}{169kV} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_10.5\_\#1} + I_{L1\_10.5\_\#2} \\ I_{L2\_10.5\_\#1} + I_{L2\_10.5\_\#2} \\ I_{L3\_10.5\_\#1} + I_{L3\_10.5\_\#2} \end{bmatrix}
$$

Advantages of this solution:

> Increased sensitivity because 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 tertiary delta winding

> Clear indication of the faulty phase because differential current strictly correspond to windings located on the same magnetic limb (i.e. all three matrixes are unit matrixes in above equation)

Disadvantages of this solution:

> Low sensitivity for the internal winding faults located close to the 220kV side connection point

> All faults on 220kV conductor are seen as external fault (e.g. such differential scheme will not operate for fault in 220kV side bushing)

Thus, it is important to notice that intentional reduction of parameter "RatedVoltageW3" value by one half actually directly compensate for "double current measurement" within the delta winding for the two differential protection schemes presented in this section.
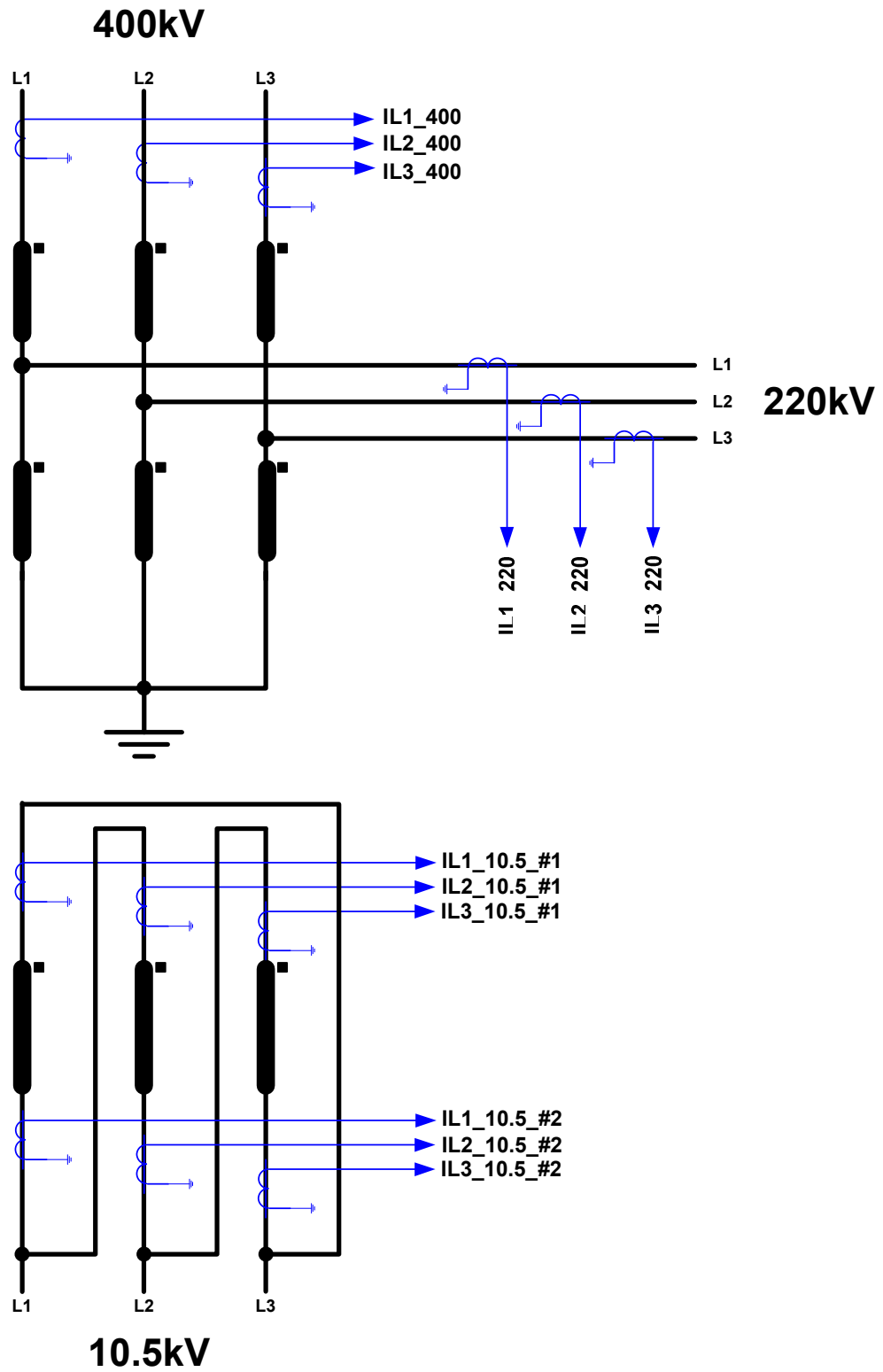
400kV

220kV

10.5kV

Figure 12: First differential protection scheme for auto-transformer with two CT sets available within tertiary delta winding

400kV

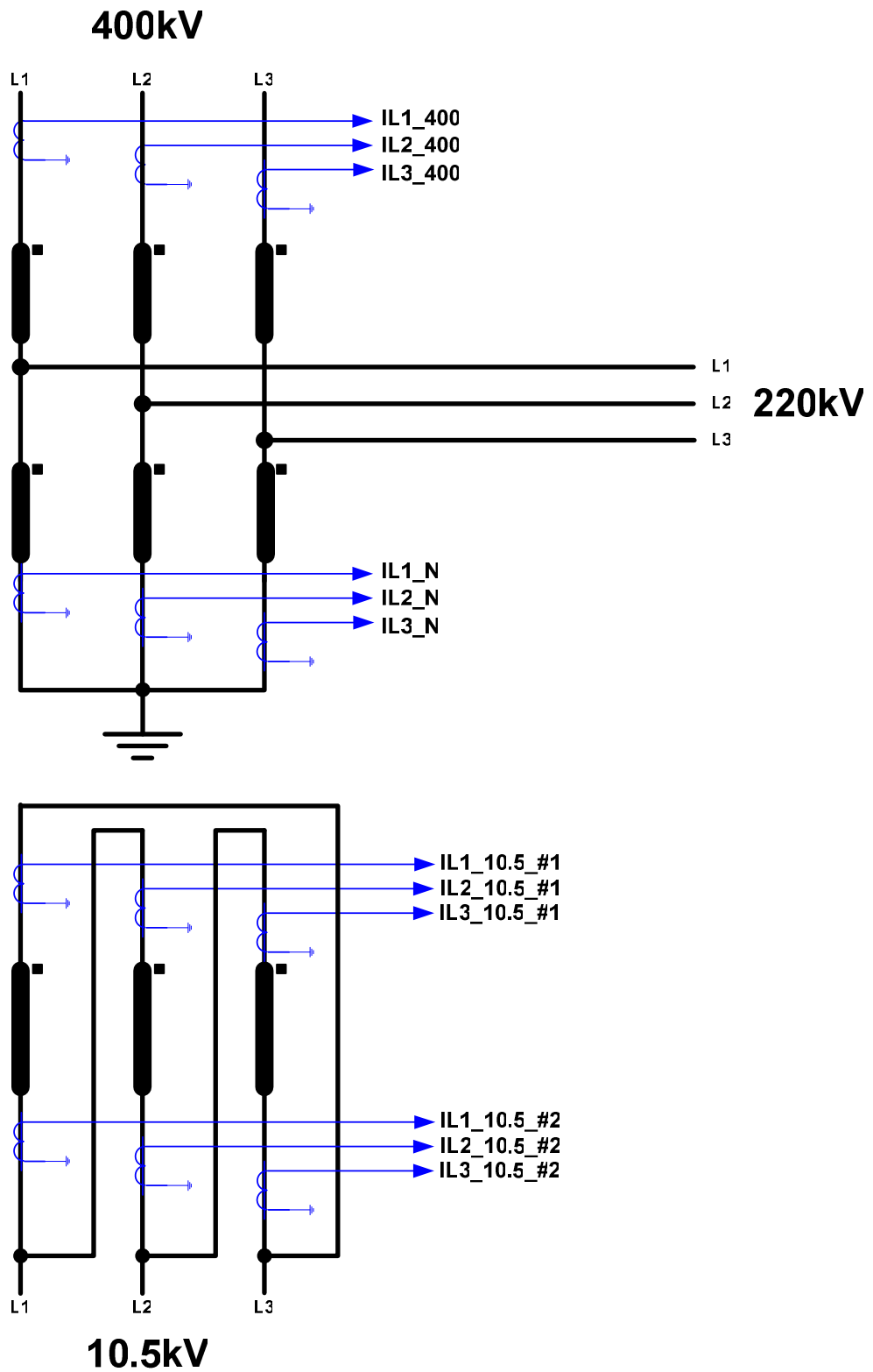
Figure 13: Second differential protection scheme for auto-transformer with two CT sets available within tertiary delta winding

T3D1 👁					
RatedVoltageW1		400,00	kV	0,05	2000,00
RatedVoltageW2		231,00	kV	0,05	2000,00
RatedVoltageW3		9,10	kV	0,05	2000,00
RatedCurrentW1		577	A	1	99999
RatedCurrentW2		1000	A	1	99999
RatedCurrentW3		25378	A	1	99999
ConnectTypeW1		WYE (Y)			
ConnectTypeW2		WYE (Y)			
ConnectTypeW3		WYE (Y)			
ClockNumberW2		0 [0 deg]			
ClockNumberW3		0 [0 deg]			
ZSCurrSubtrW1		Off			
ZSCurrSubtrW2		Off			
ZSCurrSubtrW3		Off			
TconfigForW1		No			
TconfigForW2		No			
TconfigForW3		Yes			
LocationOLTC1		Not Used			
LocationOLTC2		Not Used			

Figure 14: Relevant "General Settings" under differential protection (e.g. T3D1) for application shown in Figure 12

T3D1 👁					
RatedVoltageW1		169,00	kV	0,05	2000,00
RatedVoltageW2		231,00	kV	0,05	2000,00
RatedVoltageW3		9,10	kV	0,05	2000,00
RatedCurrentW1		577	A	1	99999
RatedCurrentW2		422	A	1	99999
RatedCurrentW3		10716	A	1	99999
ConnectTypeW1		WYE (Y)			
ConnectTypeW2		WYE (Y)			
ConnectTypeW3		WYE (Y)			
ClockNumberW2		0 [0 deg]			
ClockNumberW3		0 [0 deg]			
ZSCurrSubtrW1		Off			
ZSCurrSubtrW2		Off			
ZSCurrSubtrW3		Off			
TconfigForW1		No			
TconfigForW2		No			
TconfigForW3		Yes			
LocationOLTC1		Not Used			
LocationOLTC2		Not Used			

Figure 15: Relevant "General Settings" under differential protection (e.g. T3D1) for application shown in Figure 13

2.7 Settings for Differential Function Characteristic

Typical settings for RET 670 differential protection characteristic for auto-transformer applications are shown in Figure 16. Note that for these settings the following assumptions are made:

➢ No OLTC is installed in auto-transformer (i.e. fixed turns ratio)

➢ Only one CT input is connected from every auto-transformer side

When OLTC is installed inside auto-transformer and its position is available to the differential function settings can remain as shown in Figure 16. However if OLTC position is not available, set value for parameter "IdMin" (i.e. function minimum pickup) shall be increased to approximately two times the OLTC tapping range. Typical setting values for parameter "IdMin" under such circumstances are within range from 0,25 to 0,4 pu.

When two CT inputs from Hv or MV auto-transformer side are connected to RET 670, see Section 2.5, special care must be taken to avoid unwanted operation of the unrestraint level for external busbar faults on that side. Typical setting values for parameter "IdUnre" (i.e. unrestraint level pickup) under such circumstances are within range from 15 to 30 pu.

Group / Parameter Name	IED Value	PC Value	Unit	Min	Max
T2D1					
Operation		On			
SOTFMode		On			
IDiffAlarm		0,05	%IB	0,05	1,00
tAlarmDelay		10,000	s	0,000	60,000
IdMin		0,20	IB	0,10	0,60
EndSection1		1,25	IB	0,20	1,50
EndSection2		3,00	IB	1,00	10,00
SlopeSection2		40,0	%	10,0	50,0
SlopeSection3		80,0	%	30,0	100,0
IdUnre		8,00	IB	1,00	50,00
I2/I1Ratio		15,0	%	5,0	100,0
I5/I1Ratio		25,0	%	5,0	100,0
CrossBlockEn		On			
NegSeqDiffEn		On			
IMinNegSeq		0,04	IB	0,02	0,20
NegSeqROA		60,0	Deg	30,0	120,0
OpenCTEnable		Off			
tOCTAlarmDelay		3,000	s	0,100	10,000
tOCTResetDelay		0,250	s	0,100	10,000
tOCTUnrstDelay		10,00	s	0,10	6000,00

Figure 16: Typical settings for differential function characteristic

3 Differential Protection Schemes Based on First Kirchhoff Low

Due to a galvanic connection between serial and 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 Low which says that 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 function in RET 670.

3.1 Phase segregated bus-like differential protection for auto-transformers

It is possible to arrange such low impedance scheme as shown in Figure 18. In order to achieve such scheme the relevant parameter settings for 3-winding differential protection in RET 670 shall be entered as shown in Figure 17. Note that the rated current for 220kV side is selected as base current because this is the biggest rated current of all sides connected to such differential scheme.

Group / Parameter Name	IED Value	PC Value	Unit	Min	Max
T3D1					
RatedVoltageW1		231,00	kV	0,05	2000,00
RatedVoltageW2		231,00	kV	0,05	2000,00
RatedVoltageW3		231,00	kV	0,05	2000,00
RatedCurrentW1		1000	A	1	99999
RatedCurrentW2		1000	A	1	99999
RatedCurrentW3		1000	A	1	99999
ConnectTypeW1		WYE (Y)			
ConnectTypeW2		WYE (Y)			
ConnectTypeW3		WYE (Y)			
ClockNumberW2		0 [0 deg]			
ClockNumberW3		0 [0 deg]			
ZSCurrSubtrW1		Off			
ZSCurrSubtrW2		Off			
ZSCurrSubtrW3		Off			
TconfigForW1		No			
TconfigForW2		No			
TconfigForW3		No			
LocationOLTC1		Not Used			
LocationOLTC2		Not Used			

Figure 17: Required settings for low impedance phase segregated scheme
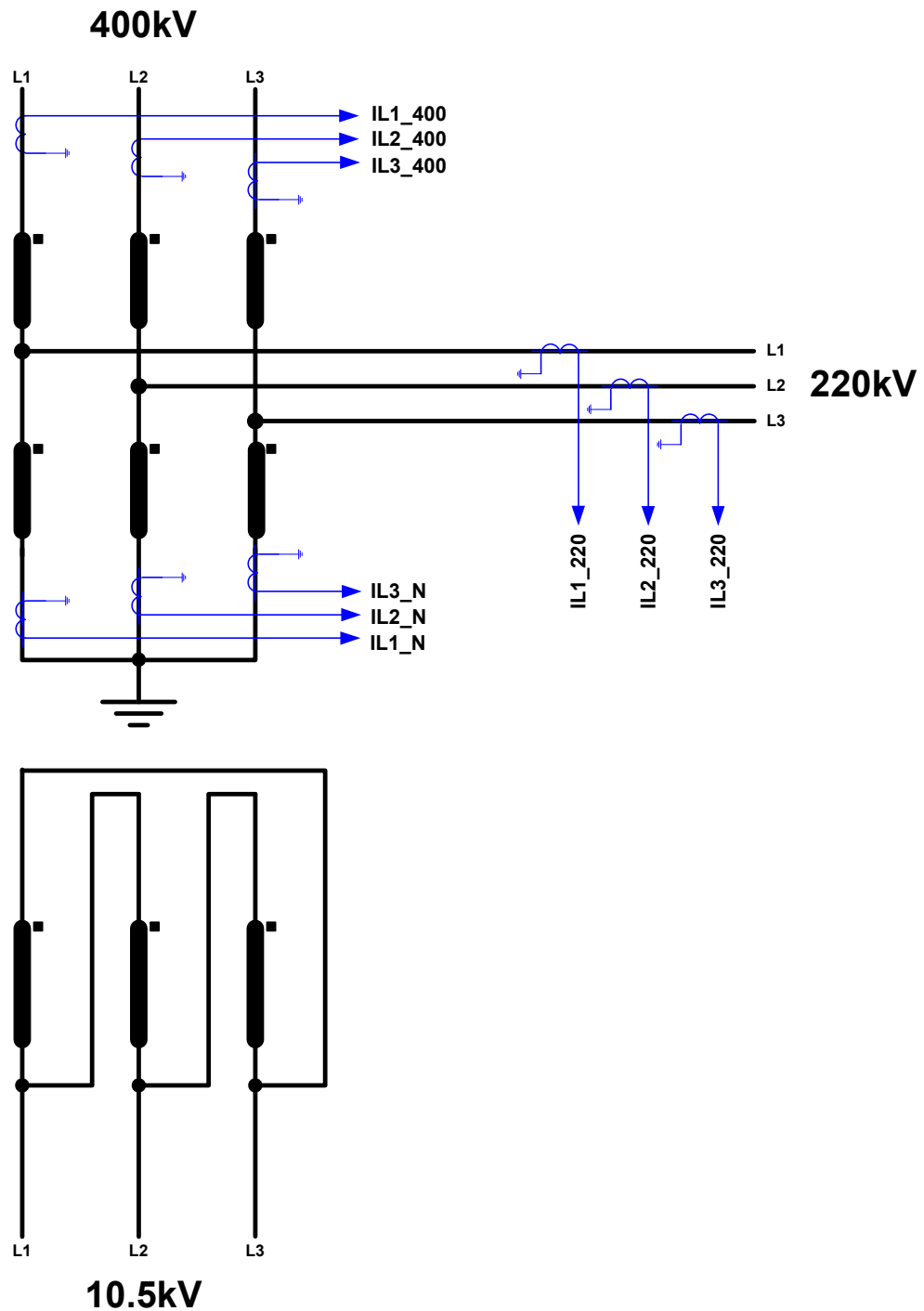
400kV

Figure 18: Low Impedance phase segregated bus-like differential protection scheme

Make sure that currents are connected to the RET 670 differential function as follows:

- ➢ 400kV currents to I3PW1CT1 input
- ➢ 220kV currents to I3PW2CT1 input
- ➢ Currents from common winding star point to I3PW3CT1 input

With such settings and configuration RET 670 will calculate the differential currents (in primary amperes) in accordance with the following matrix equation:

$$
\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_400} \\ I_{L2\_400} \\ I_{L3\_400} \end{bmatrix} + \frac{231kV}{231kV} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_220} \\ I_{L2\_220} \\ I_{L3\_220} \end{bmatrix} + \frac{231kV}{231kV} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_N} \\ I_{L2\_N} \\ I_{L3\_N} \end{bmatrix}
$$

High impedance, phase segregated, bus-like differential protection scheme can be arranged as shown in Figure 19. More detailed information about high impedance differential protection with IED 670 can be found in reference [4].

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 the 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 differential current strictly correspond to windings located on the same magnetic core limb.

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

- ➢ Tertiary delta winding is not protected at all with such scheme (i.e. this scheme protects only serial and common windings)

- ➢ It will not detect any turn to turn fault inside serial and common windings

- ➢ Phase segregated CTs are required in the common winding star point

- ➢ Dedicated CT cores with equal ratio and magnetizing characteristic shall be used for such high impedance scheme

Note that RET 670 is fully capable to accept two CT inputs (i.e. one-and-a-half breaker arrangement) from both sides of the auto-transformer for either low or high impedance, phase segregated, bus-like differential scheme.
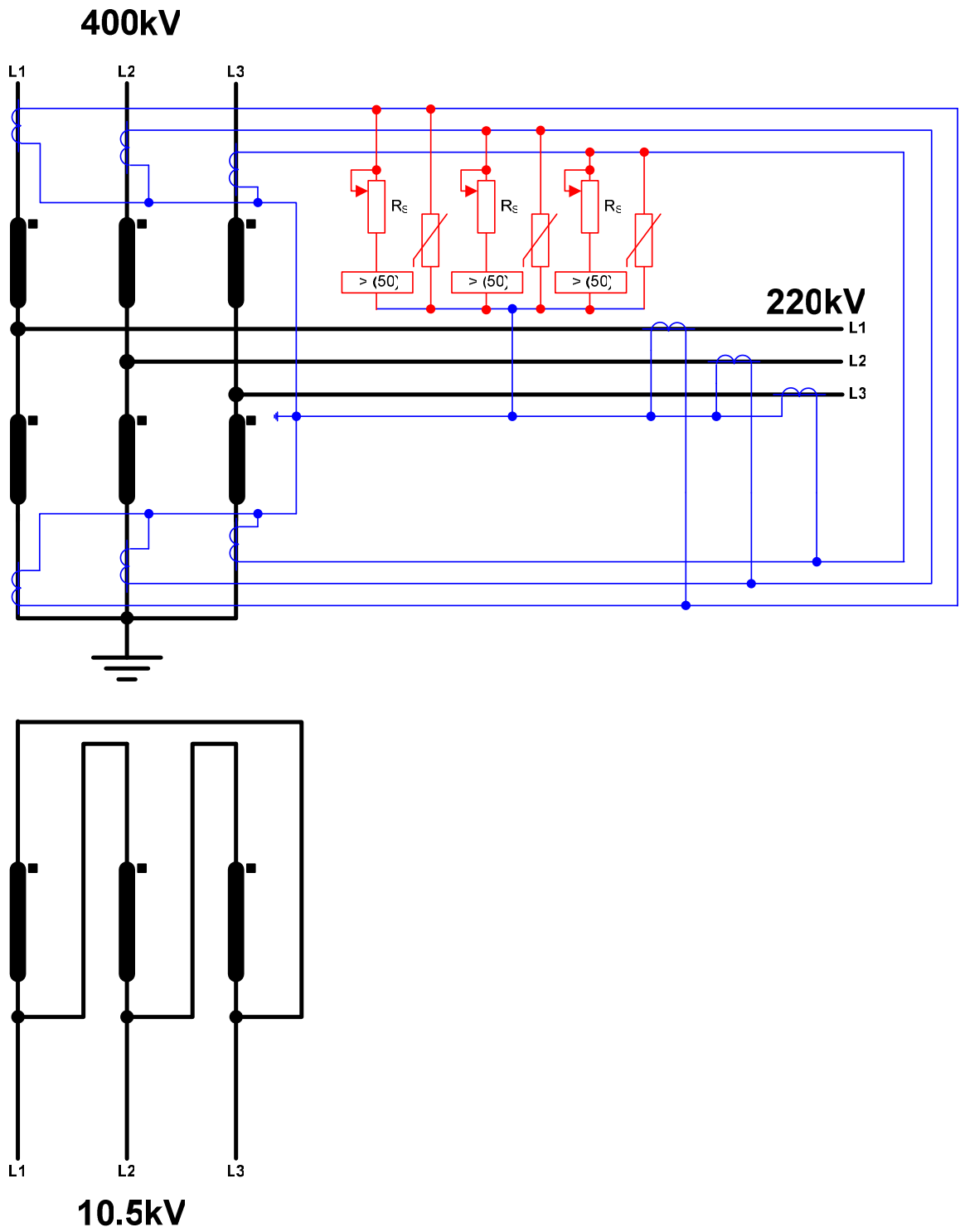
Figure 19: High Impedance phase segregated bus-like differential protection scheme

3.2 Restricted earth fault protection for auto-transformers

Restricted earth fault (REF) is a zero-sequence current based differential scheme. It is based on the First Kirchhoff Law which is as well valid for zero-sequence currents. It will detect all earth faults within the protected zone. Low impedance REF scheme in RET 670 shall be arranged as shown in Figure 21. Note that low impedance REF function in RET 670 is specially design for auto-transformer applications. That is the reason way currents from the two auto-transformer sides shall be correctly connected to this function. In order to achieve such scheme the relevant parameter settings for low impedance REF protection function in RET 670 shall be entered as shown in Figure 20. Note that the rated current for 220kV side is selected as base current because this is the biggest rated current of all sides connected to the REF scheme.

Group / Parameter Name	IED Value	PC Value	Unit	Min	Max
REF1					
Operation		On			
IBase		1000	A	1	99999
IdMin		30,0	%IB	4,0	100,0
ROA		60	Deg	60	90
CTFactorPri1		1,0		1,0	10,0
CTFactorPri2		1,0		1,0	10,0
CTFactorSec1		1,0		1,0	10,0
CTFactorSec2		1,0		1,0	10,0

Figure 20: Settings for low impedance REF function

Make sure that currents are connected to the RET 670 REF function as follows:

> ➢ 400kV currents to I3PW1CT1 input
>
> ➢ 220kV currents to I3PW2CT1 input
>
> ➢ Current from common neutral point to I3P input

With such settings and configuration REF function in RET 670 will calculate the differential current (in primary amperes) in accordance with the following equation:

$$Id\_REF = (IL1\_400 + IL2\_400 + IL3\_400) + (IL1\_220 + IL2\_220 + IL3\_220) + IN$$

A high impedance REF scheme for auto-transformer can be arranged as shown in Figure 22. More detailed information about high impedance differential protection with IED 670 can be found in reference [4].

Advantages of auto-transformer REF protection schemes:

➢ Protects common and serial winding against internal earth faults

➢ Increased sensitivity for the 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

➢ Single CT in the common auto-transformer star point is only required

Disadvantages of auto-transformer REF protection schemes:

➢ Tertiary delta winding is not protected at all with such scheme (i.e. this schemes protects only serial and common windings against earth faults)

➢ It will not detect any turn to turn or short-circuit faults within serial and common windings

➢ Dedicated CT cores with equal ratio and magnetizing characteristic shall be used for high impedance REF scheme

Note that RET 670 is fully capable to accept two CT inputs (i.e. one-and-a-half breaker arrangement) from both sides of the auto-transformer for either low or high impedance REF scheme.
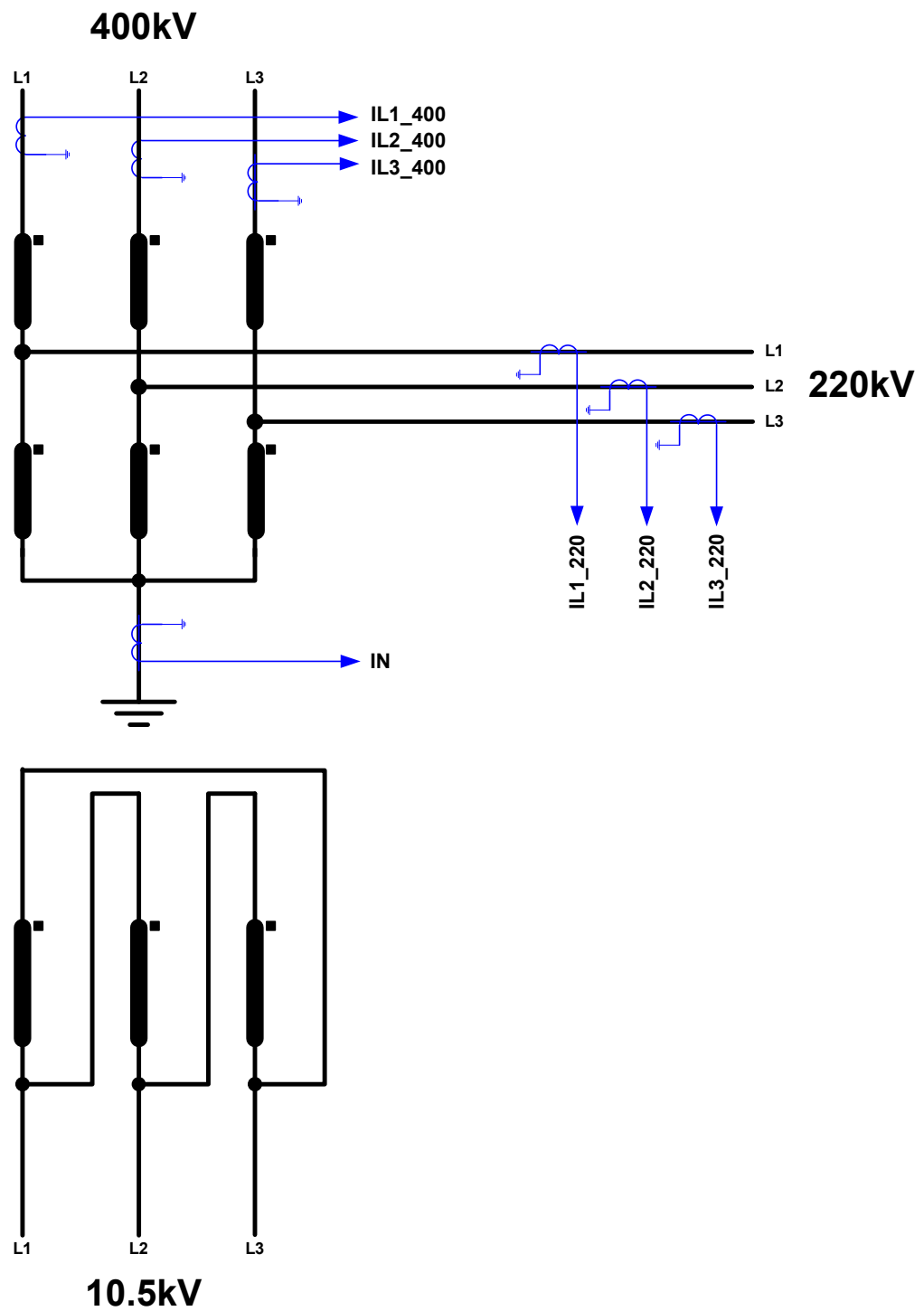
400kV

220kV

10.5kV

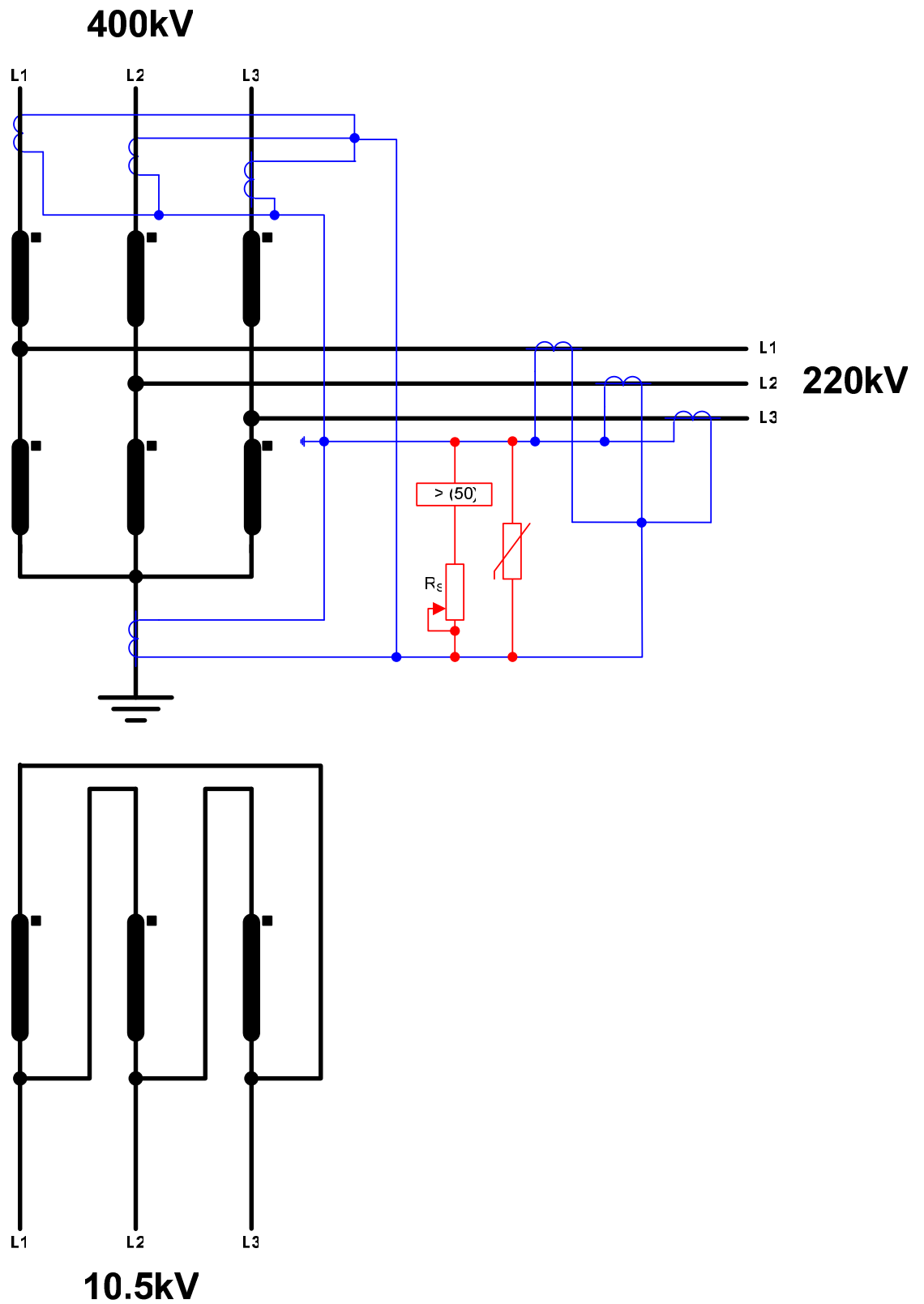*Figure 21: Low Impedance REF scheme for auto-transformer*

Figure 22: High Impedance REF scheme for auto-transformer

4 Unit Protection Schemes for Tertiary Delta Winding

As mentioned before, standard auto-transformer differential protection schemes might have limited sensitivity for short-circuits in the tertiary delta winding. If tertiary side is not grounded, earth faults within delta winding will not be detected at all. In order to improve sensitivity for tertiary winding faults dedicated differential schemes are sometimes used.

4.1 Dedicated differential protection scheme for tertiary delta winding

When auto-transformer is consisting of three single-phase units then CTs on both sides of 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 shown in Figure 24.

Because this is the scheme based on the First Kirchhoff Law, it is not necessary to deduct zero sequence current on any side. The relevant parameter settings for 2-winding differential protection in RET 670 shall be entered as shown in Figure 23. Note that the rated current for delta winding, as calculated in Table 1, is selected as base current because this differential scheme is limited to this winding only.

Group / Parameter Name	IED Value	PC Value	Unit	Min	Max
T2D1					
RatedVoltageW1		10,50	kV	0,05	2000,00
RatedVoltageW2		10,50	kV	0,05	2000,00
RatedCurrentW1		4127	A	1	99999
RatedCurrentW2		4127	A	1	99999
ConnectTypeW1		WYE (Y)			
ConnectTypeW2		WYE (Y)			
ClockNumberW2		0 [0 deg]			
ZSCurrSubtrW1		Off			
ZSCurrSubtrW2		Off			
TconfigForW1		No			
TconfigForW2		No			
LocationOLTC1		Not Used			

Figure 23: Required settings for separate differential protection for tertiary delta winding

Make sure that currents are connected to the RET 670 differential function as follows:

> ➢ 10.5kV - #1 currents to I3PW1CT1 input

> ➢ 10.5kV - #2 currents to I3PW2CT1 input
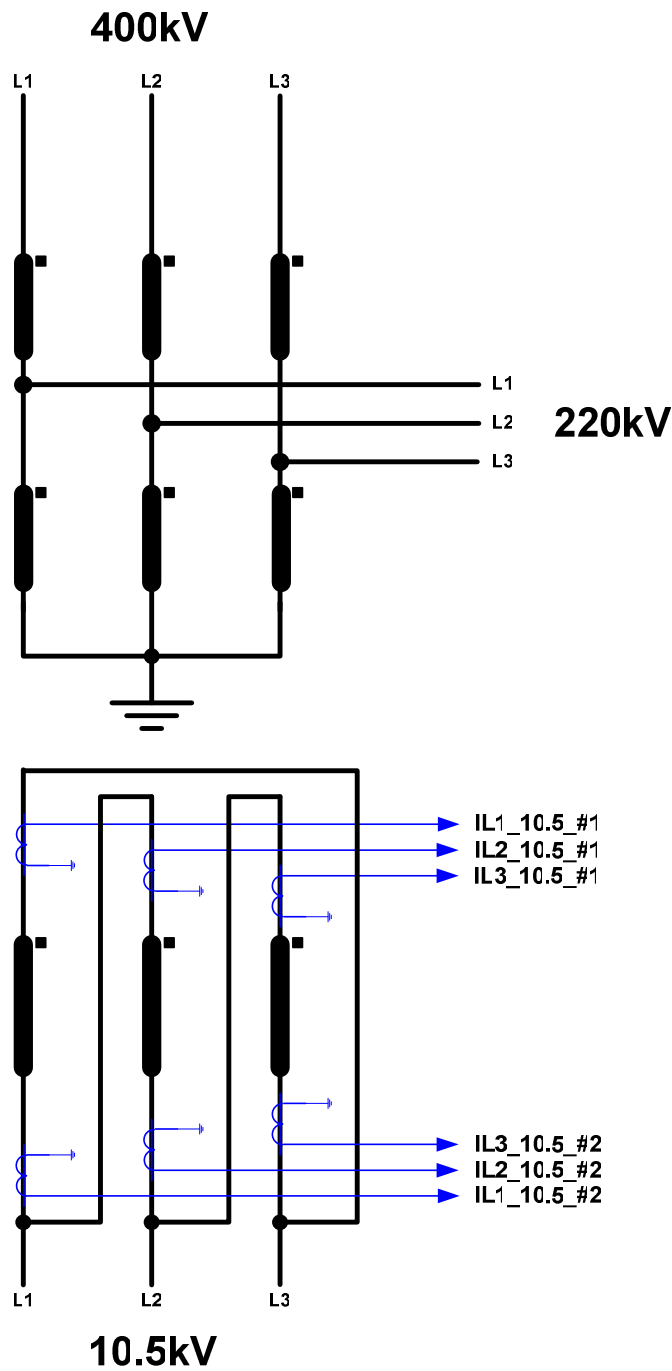
400kV

220kV

10.5kV

Figure 24: Delta winding differential scheme

With such settings and configuration RET 670 will calculate the differential currents (in primary amperes) in accordance with the following matrix equation:

$$
\begin{bmatrix} Id\_L1 \\ Id\_L2 \\ Id\_L3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_10.5\_\#1} \\ I_{L2\_10.5\_\#1} \\ I_{L3\_10.5\_\#1} \end{bmatrix} + \frac{10.5kV}{10.5kV} \cdot \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} I_{L1\_10.5\_\#2} \\ I_{L2\_10.5\_\#2} \\ I_{L3\_10.5\_\#2} \end{bmatrix}
$$

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 delta winding

Disadvantages of this solution:

> Two set of CTs required within 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 delta winding.

It is also possible to arrange such differential protection as high impedance scheme. For more information please refer to Section 3.1 and references [4] and [6].

4.2 Dedicated earth fault protection scheme for not-loaded tertiary delta winding

When tertiary delta winding is not loaded it is possible to solidly ground one corner of the delta winding as shown in Figure 25. If a CT is positioned in this grounding connection simple overcurrent relay can be used to protect the tertiary delta winding against any earth fault. Note that such scheme can be easily achieved in RET 670 by using one Earth Fault function or one Multi-Purpose function [6].

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 in the delta winding

> Requirement to have access to one of the corners of the delta winding

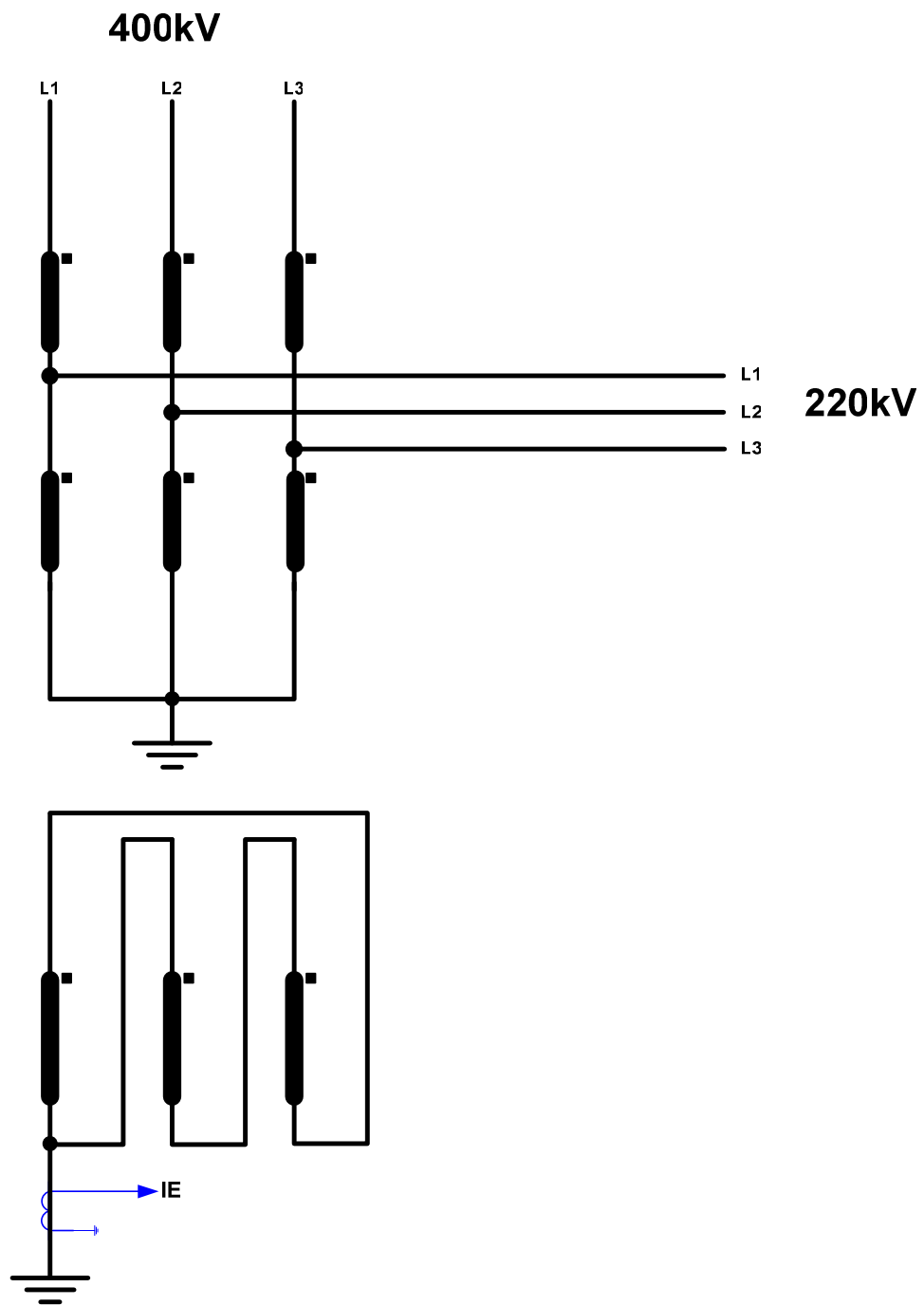> This scheme will not detect any short-circuits or turn to turn faults inside delta winding

400kV

Figure 25: Grounding of one corner of the tertiary delta winding via CT

5 Conclusion

Different types of auto-transformer differential protection scheme have been presented. Which scheme will be used is mostly determined by availability of the main CTs in a particular installation. It is recommended that in addition to the standard differential protection scheme (e.g. as shown in Figure 4 or Figure 6) additional differential scheme is applied which is sensitive for the faults close to the common winding star point (i.e. as shown in Figure 18 or Figure 20). Other possible solution is to combine two differential schemes which have different properties (e.g. as shown in Figure 6 and Figure 9).

Due to size and importance of auto-transformers in modern power system (e.g. mostly used as system intertie transformers) full duplication of the protection scheme is typically easily justified.

6 References

[1] Power transformers – Part 1: General, International Standard IEC 60076-1, Edition 2.1, 2000-04.

[2] Power transformers – Application guide, International Standard IEC 60076-8, First edition, 1997-10.

[3] Z. Gajić, "Differential Protection for Arbitrary Three-Phase Power Transformer", PhD Thesis, Lund University, Sweden, February 2008, ISBN: 978-91-88934-47-5; available at:

http://www.iea.lth.se/publications/pubphd.html

[4] ABB Application Note, "Differential Applying High Impedance Differential Protection with IED 670", Document ID: SA2007-000725; available at: http://www.abb.com/substationautomation.

[5] G. Bertagnolli, "Short-Circuit Duty of Power Transformers", Appendix 10, ABB Book, Legano – Italy, December 1996.

[6] ABB RET 670 Technical reference manual, Document ID: 1MRK 504 086-UEN