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Fault Current Distribution Across Special Transformers

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Summary

It is well known fact that for standard power transformer with vector group Yd (i.e. star-delta connection) the phase to ground fault on the HV side (i.e. star side) is manifested as phase-to-phase fault on the transformer LV side (i.e. delta side).

Question can be raised how different type of faults will be seen across the power transformer with variable phase angle shift? For example if a phase shifting transformer with rating 600MVA, 400kV, ±40° and with 64 tap positions is installed in the network how the fault current distribution will be across it when the phase angle shift is for example +17° or -17° ?

The knowledge of the fault current distribution is most important for transformer and system backup protection such as distance protection, over-current protection and earth-fault protection. Will these protections be affected by the fault current distribution when the phase angle shift across the transformer is varying?

This paper will give theoretical background and provide diagrams which will show fault current distribution for various phase angle shifts across the special power transformer.

Keywords

Variable Phase Angle Shift, Fault current distribution

1. Introduction

It has been shown in references [1,2] that the differential currents for the arbitrary three-phase power transformer with n-windings can be calculated by using the following phasor based equation:

$$\begin{bmatrix} Id\_L1(pu) \\ Id\_L2(pu) \\ Id\_L3(pu) \end{bmatrix} = \sum_{i=1}^{n} \frac{1}{Ib\_Wi} \times MX(\theta_{Wi}) \times \begin{bmatrix} IL1\_Wi(A) \\ IL2\_Wi(A) \\ IL3\_Wi(A) \end{bmatrix} \qquad (1)$$

where:

- Ib_Wi is base current for respective winding
- MX(Ɵwi) is a three-by-three matrix providing phase angle compensation and optional zero-sequence current reduction for respective winding
- Id_Lx & ILx_Wi are current phasors

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If one now consider only the case of two-winding transformer with arbitrary phase angle shift Ɵ, as shown in Figure 1 with additional assumption that during through-faults (i.e. external faults) all three differential currents will be zero in all phases, then the following equation can be derived to calculate the S-side individual phase currents I_S1, I_S2 & I_S3 from the L-side phase currents I_L1, I_L2 & I_L3 in primary amperes:

$$\begin{bmatrix} I\_S1(A) \\ I\_S2(A) \\ I\_S3(A) \end{bmatrix} = \frac{U_{Lr}}{U_{Sr}} \times MX(\theta) \times \begin{bmatrix} I\_L1(A) \\ I\_L2(A) \\ I\_L3(A) \end{bmatrix} \qquad (2)$$

where:

- U_{Lr} is the L-side rated ph-to-ph, no-load voltage (as stated on the rating plate)
- U_{Sr} is the S-side rated ph-to-ph, no-load voltage (as stated on the rating plate)
- MX(Ɵ) is a three-by-three matrix which has one of the following two forms as described below.

For power transformers which pass-through the zero sequence currents the following equation shall be used for MX matrix:

$$MX(\theta) = M(\theta) = \frac{1}{3}\begin{vmatrix} 1+2\cos(\theta) & 1+2\cos(\theta+120°) & 1+2\cos(\theta-120°) \\ 1+2\cos(\theta-120°) & 1+2\cos(\theta) & 1+2\cos(\theta+120°) \\ 1+2\cos(\theta+120°) & 1+2\cos(\theta-120°) & 1+2\cos(\theta) \end{vmatrix} \qquad (3)$$

For power transformers which stop the through-flow of the zero sequence currents the following equation shall be used for MX matrix:

$$MX(\theta) = M0(\theta) = \frac{2}{3}\begin{vmatrix} \cos(\theta) & \cos(\theta+120°) & \cos(\theta-120°) \\ \cos(\theta-120°) & \cos(\theta) & \cos(\theta+120°) \\ \cos(\theta+120°) & \cos(\theta-120°) & \cos(\theta) \end{vmatrix} \qquad (4)$$

Typical connection diagram for a special power transformer is shown in Figure 1. Note that two transformer sides (or windings) are called S (i.e. Source) and L (i.e. Load) as often used for special power transformer applications.

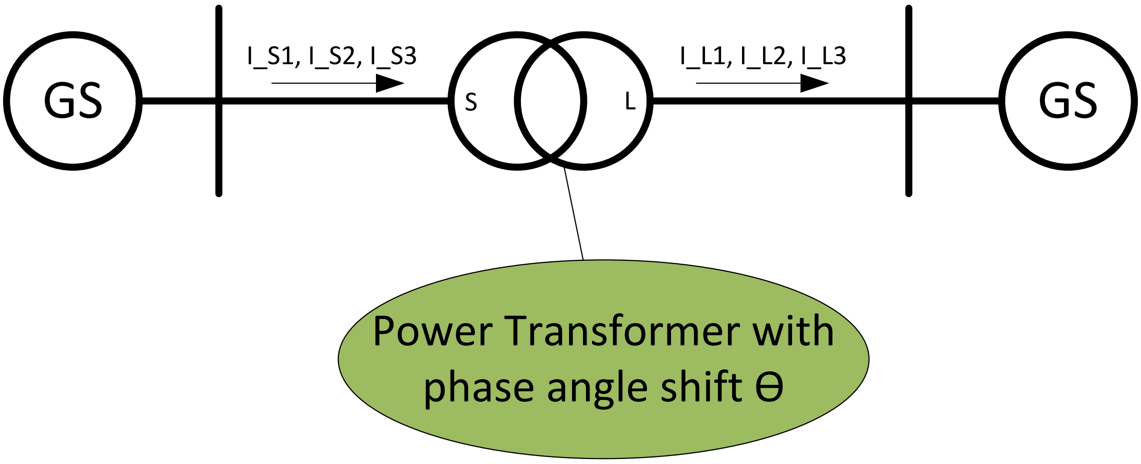


Figure 1: Typical connection diagram for a special transformer (e.g. phase shifting transformer)

Note that angle Θ is positive when L-side positive sequence quantities lag the S-side positive sequence quantities for angle Θ. This is typical nomenclature used on rating plates for standard and special power transformers. For example, for the standard Yd5 power transformer Θ=+150°. Note also that this approach is exactly opposite to “anti-clock-wise” angle definition commonly used in power system engineering.

In this paper current magnitude diagrams will be only provided for -60° < Θ < 60° which is the most commonly used range for the phase shift angle of special power transformers in practical installations. At the same time current magnitude will be given in per-unit (or percent) system. By doing so the diagrams are applicable to all transformers irrespective of the voltage levels on the two sides.

2. Ideal Single-Phase-to-Ground Fault (L1-Gnd) on L-side

All calculations will be done in per-unit (or percent) system. Thus the current in faulty phase will have the magnitude 100. The used L side currents for this calculation have the following phasor values: I_L1=100 @0°; I_L2=0; I_L3=0.

2.1 Special transformer which pass-through the zero sequence current

Example of such transformer is symmetrical single-core or symmetrical double-core phase shifting transformers. For such applications M matrix (see equation 3) must be used on L-side. Therefore the corresponding magnitudes of the fault currents on the S-side are shown in Figure 2.

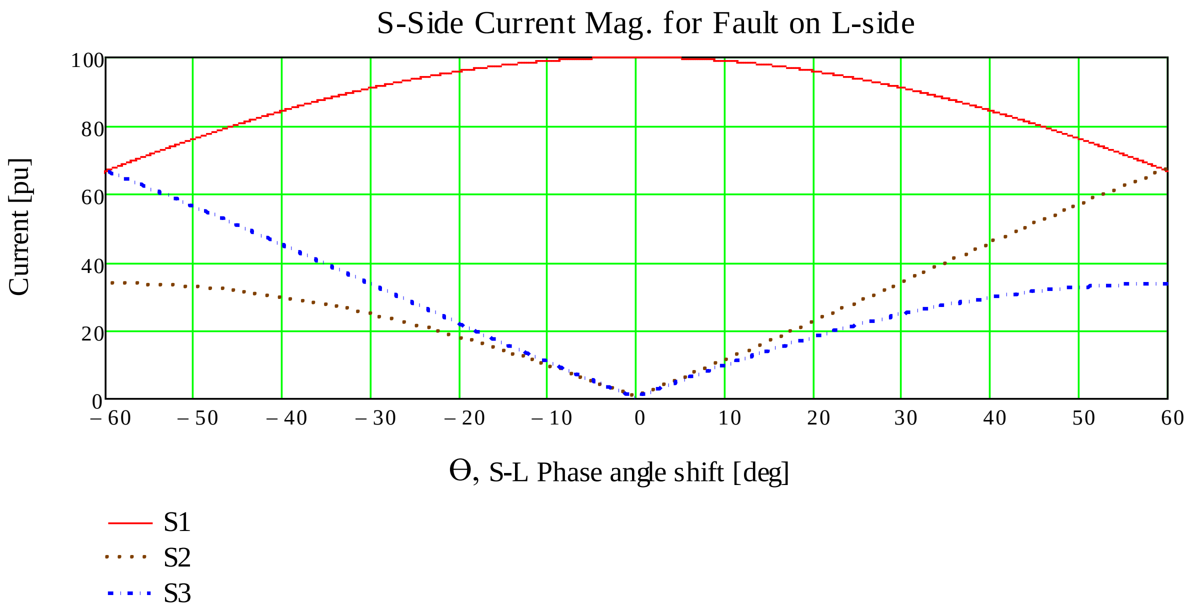


Figure 2: S-side current magnitudes for -60° < Θ < 60°

2.2 Special transformer which stops the zero sequence current flow

Example of such transformer is industrial converter transformer with extended delta – wye configuration. For such applications M0 matrix (see equation 4) which removes the zero-sequence current must be used on L-side. Therefore the corresponding magnitudes of the fault currents on the S-side are shown in Figure 3. Note that this figure can be used even for standard Dy connected power transformers (e.g. ϴ=30° for Dy1 and ϴ=-30° for Dy11).

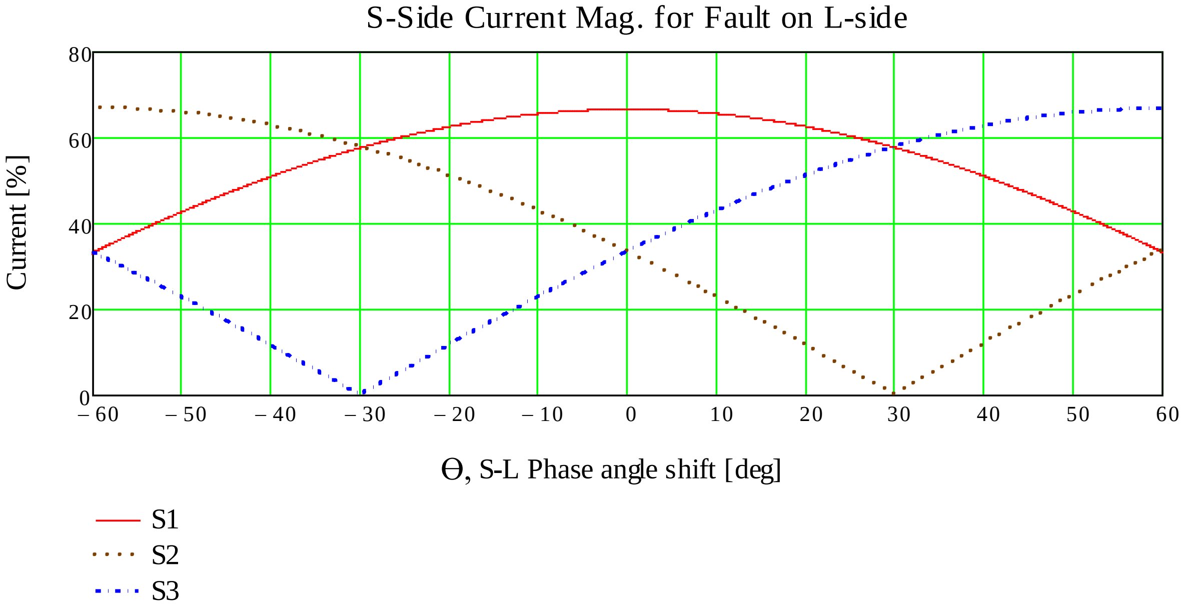


Figure 3: S-side current magnitudes for -60° < ϴ < 60°

3. Ideal Phase-to-Phase Fault (L2-L3) on L-side

All calculations will be done in per-unit (or percent) system. Thus the current in faulty phases will have the magnitude 100. The used L side currents for this calculation have the following phasor values: I_L1=0; I_L2=100 @0°; I_L3=100 @180°.

3.1 Special transformer which pass-through the zero sequence current

Example of such transformer is symmetrical single-core or double-core phase shifting transformers. For such applications M matrix (see equation 3) must be used on L-side. Corresponding magnitudes of the fault currents on the S-side are shown in Figure 4.

3.2 Special transformer which stops the zero sequence current flow

Example of such transformer is industrial converter transformer with extended delta – wye configuration. For such applications M0 matrix (see equation 4) which removes the zero-sequence current must be used on L-side. Therefore the corresponding magnitudes of the fault currents on the S-side are shown in Figure 5. Note that this figure can be used even for standard Dy connected power transformers (e.g. ϴ=30° for Dy1 and ϴ=-30° for Dy11).

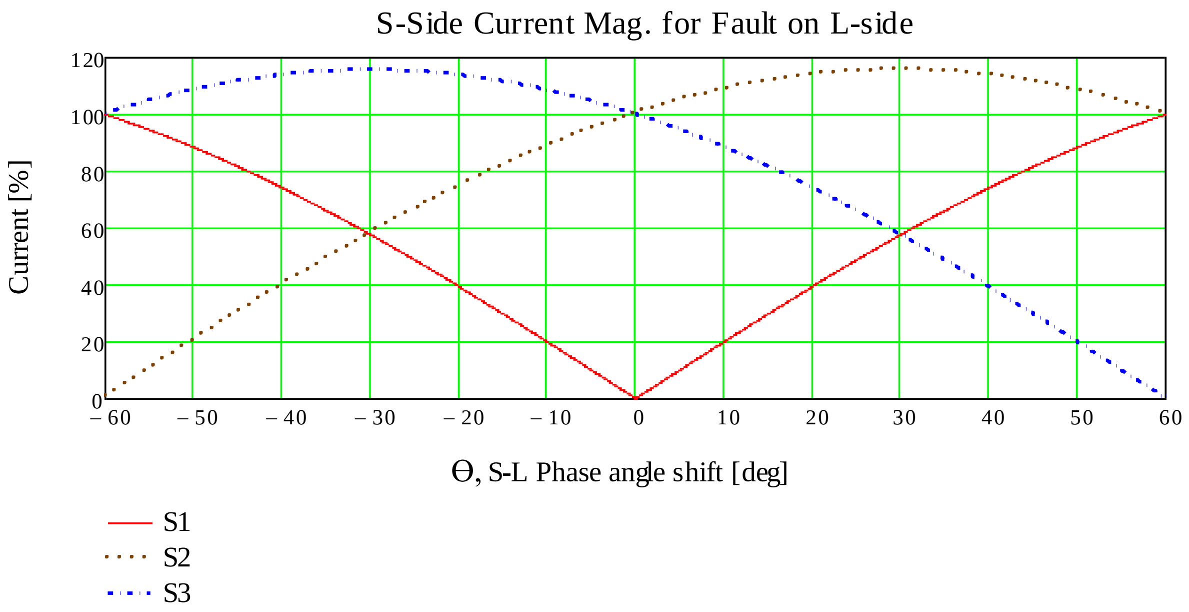


Figure 4: S-side current magnitudes for -60° < Θ < 60°

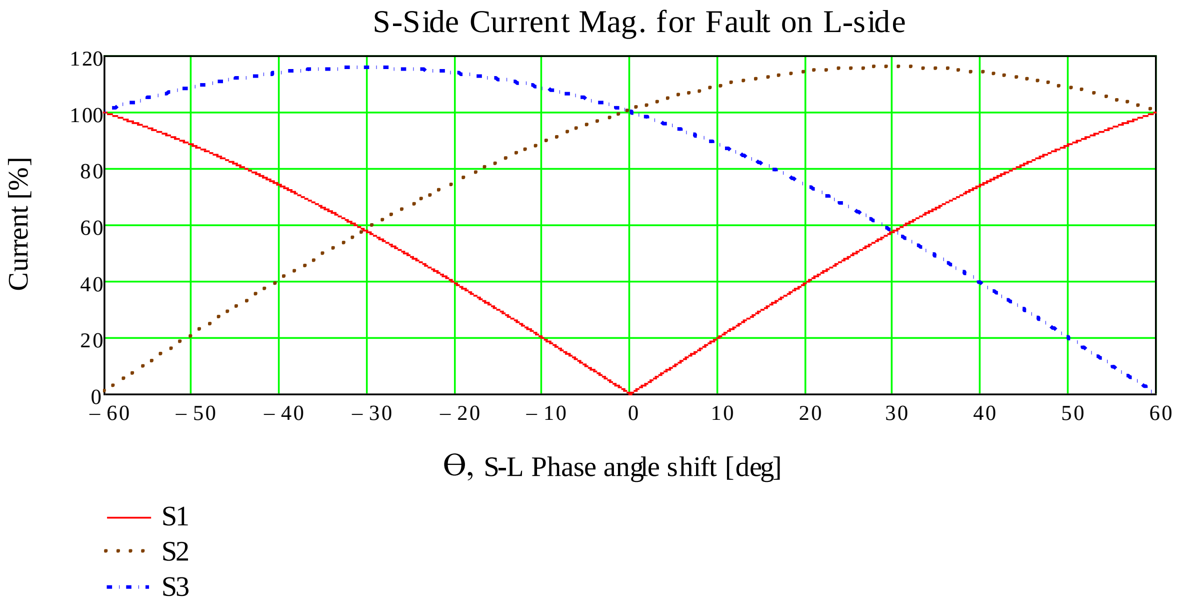


Figure 5: S-side current magnitudes for -60° < Θ < 60°

Note that the above two figures are practically the same. The reason is that for ph-to-ph faults the zero sequence currents are equal to zero (i.e. non-existent).

4. Ideal Phase-to-Phase-to-Ground Fault (L2-L3-Gnd) on L-side

All calculations will be done in per-unit (or percent) system. Thus the current in faulty phases will have the magnitude 100. The used L side currents for this calculation have the following phasor values: I_L1=0; I_L2=100 @230°; I_L3=100 @130°. Note that during real ph-ph-gnd fault, the phase angle between currents in the two faulty phases is typically smaller than 120°. In the paper this angle was selected to be 100°.

4.1 Special transformer which pass-through the zero sequence current

Example of such transformer is symmetrical single-core or double-core phase shifting transformers. For such applications M matrix (see equation 3) must be used on L-side. Therefore the corresponding magnitudes of the fault currents on the S-side are shown in Figure 6.

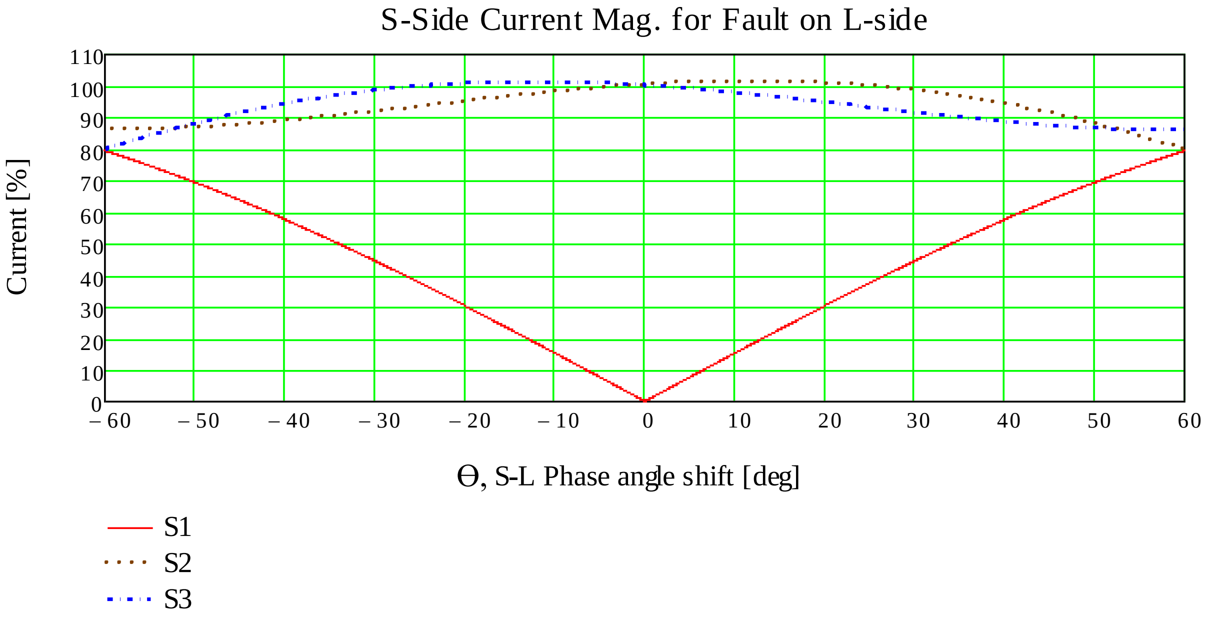


Figure 6: S-side current magnitudes for -60° < Θ < 60°

4.2 Special transformer which stops the zero sequence current flow

Example of such transformer is industrial converter transformer with extended delta – wye configuration. For such applications M0 matrix (see equation 4) which removes the zero-sequence current must be used on L-side. Therefore the corresponding magnitudes of the fault currents on the S-side are shown in Figure 7. Note that this figure can be used even for standard Dy connected power transformers (e.g. Θ=30° for Dy1 and Θ=-30° for Dy11).

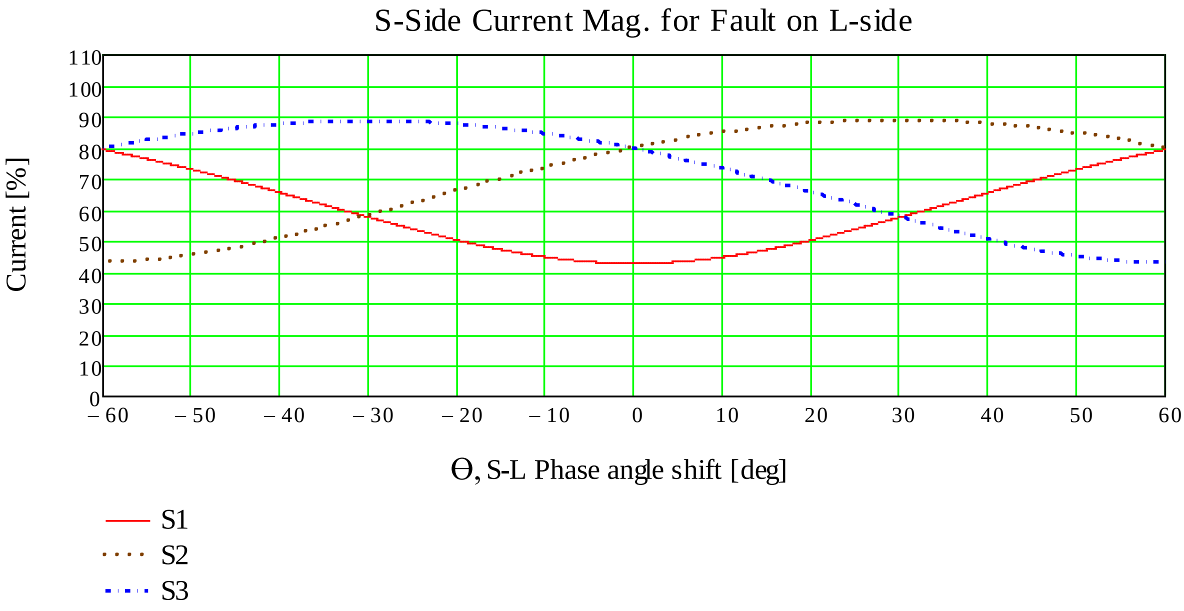


Figure 7: S-side current magnitudes for -60° < ϴ < 60°

5. Other types of faults and through-load conditions

The three phase fault will not be discussed here. The reason is that current on the two sides will be exactly the same (i.e. 100%) irrespective of the phase angle shift across the power transformer. The reason for that is existence of only positive sequence current components during a three-phase fault. For more information see references [1,2].

Note that equation (2) can be used to calculate S-side individual phase currents even during balanced and unbalanced through-load conditions or even during real faults in the network. In the latter case the pre-fault load current component will be actually superimposed onto the fault current component. Thus, the only pre-request to use this equation is that individual current phasors from the L-side are known for the actual operating condition of the special transformer.

6. How to use information from this paper

Two examples will be given here which will represent the use of the Figures given in this paper.

6.1 Single-phase to ground fault currents for Double Core, Symmetrical PST

Question: What will be the individual phase current magnitudes of the S-side in case of a 20kA single phase to ground fault on the L-side of 600MVA, 400kV, ±40º PST for the phase angle shift of ϴ=+40º (i.e. L-side no-load voltage lags the S-side no-load voltage for 40 degrees).

Answer: From Figure 2 for ϴ=+40º one can estimate that S-side currents will be: I_S1=85%, I_S2=45% & I_S3=30%. Therefore in primary amperes current will have the following values:

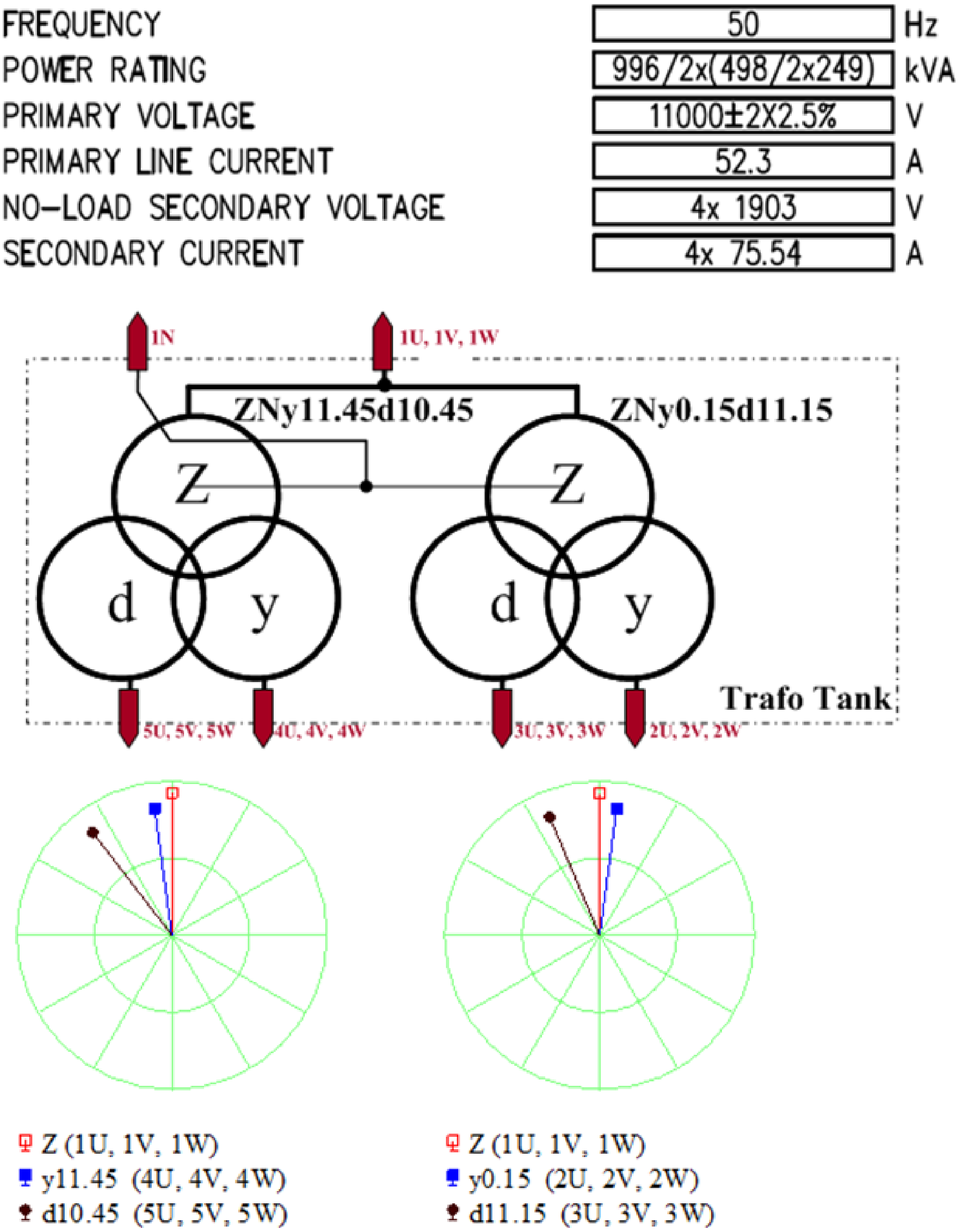
$$I_{S1} = \frac{85}{100} \times \frac{400}{400} \times 20 = 17\text{kA}$$

$$I_{S2} = \frac{45}{100} \times \frac{400}{400} \times 20 = 9kA$$

$$I_{S3} = \frac{30}{100} \times \frac{400}{400} \times 20 = 6kA$$

6.2 Two-phase fault currents for Converter Transformer

Question: On assumption that the LV side fault currents will be only supplied from the HV side network, determine what will be the HV-side individual phase current magnitudes in case of 15kA, two-phase fault on the secondary side of the converter transformer which is shown in Figure 8.



FREQUENCY	50	Hz
POWER RATING	996/2x(498/2x249)	kVA
PRIMARY VOLTAGE	11000±2X2.5%	V
PRIMARY LINE CURRENT	52.3	A
NO-LOAD SECONDARY VOLTAGE	4x 1903	V
SECONDARY CURRENT	4x 75.54	A

Figure 8 : Converter transformer data and vector diagram

Answer: First of all angle ϴ shall be determined for every of the four LV windings. These ϴ values are easily determined from Figure 8 and Table 1 provides these values.

Table 1 : Value of angle ϴ for four LV windings

	Wndg 2 (2U, 2V, 2W)	Wndg 3 (3U, 3V, 3W)	Wndg 4 (4U, 4V, 4W)	Wndg 5 (5U, 5V, 5W)
ϴ	+7,5°	-22,5°	-7,5°	-37,5°

Based on these angle ϴ values, from Figure 5 the following percentage magnitude values for HV side individual phase currents (i.e. I_1U, I_1V, I_1W) can be determined, as shown in Table 2. Note that HV side individual phase current magnitudes will actually vary depending on which of the four LV windings the phase-to-phase fault will happen!

Table 2 : Value of angle ϴ for four LV windings

	Wndg 2 (2U, 2V, 2W)	Wndg 3 (3U, 3V, 3W)	Wndg 4 (4U, 4V, 4W)	Wndg 5 (5U, 5V, 5W)
I_1U	15%	44%	15%	70%
I_1V	107%	70%	92%	44%
I_1W	92%	115%	107%	115%

Now the HV side currents in primary amperes can be determined. Here the necessary calculation for phase-to-phase fault on winding 2 (i.e. phase 2V to phase 2W fault) will only be given (i.e. percentage values from Table 2/coulm 2 are used):

$$I_{1U} = \frac{15}{100} \times \frac{1903}{11000} \times 15 = 0{,}39kA$$

$$I_{1V} = \frac{107}{100} \times \frac{1903}{11000} \times 15 = 2{,}78kA$$

$$I_{1W} = \frac{92}{100} \times \frac{1903}{11000} \times 15 = 2{,}38kA$$

In the same way HV side fault currents in primary amperes can be determined for faults on any other LV winding for this converter transformer installation.

7. Conclusion

This document gives guidelines how to calculate the fault current distribution across the power transformer with arbitrary phase angle shift. It is interesting to notice that individual phase currents on the S-side can be even bigger (percentage vise) than the L-side currents for a ph-ph or ph-ph-gnd fault on the L-side. This may cause problem with backup protection coordination if not considered during calculation of the relay settings.

Bibliography

[1] Z. Gajić, “Differential protection methodology for arbitrary three-phase power transformers”, DPSP 2008 Conference, Glasgow-UK, (2008).

[2] Z. Gajić, “Use of Standard 87T Differential Protection for Special Three-Phase Power Transformers—Part I: Theory”, IEEE Transactions on Power Delivery, Volume 27, Issue 3 (2012).