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Tutorial Videos

3 Winding Transformers

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Introduction

At the beginning of a project engineers have many options to choose from when developing the design for the electrical distribution system. For instance consider the case of a new power plant consisting of 2 generators. Three transformation approaches are typically considered to interconnect the generators to the power system. The simplest approach is to serve both generators from a single 2-winding transformer, fig. 1a. This design is typically characterized with the lowest transformation cost but highest available fault duties on the generator bus. The second approach is to supply a single transformer for each generator, fig.1b. This design solves the fault current problem however the transformation costs increase dramatically. Many times to balance cost and fault current issues, engineers select 3-winding transformers, fig. 1c.

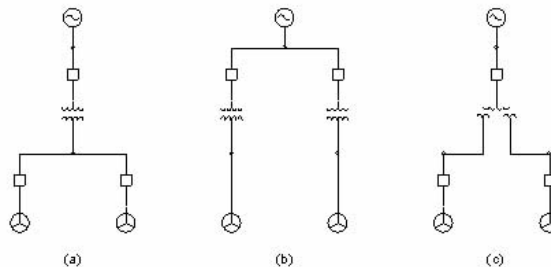


Fig. 1 Power system design options

The term 3-winding transformer can be misleading since a 3-winding transformer may have three or more windings internal to the tank of the transformer. Actually the term 3-winding means a transformer with 3 sets of bushings labeled H for the primary, X for the secondary, and Y for the tertiary, see fig. 2.

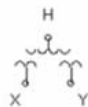


Fig. 2 Standard terminal markings

Impedances are then specified from the H-X, H-Y and X-Y terminals in percent on a chosen winding (typically the X winding) kVA base. The design engineer is responsible for determining the impedances required for the application. The ANSI impedance tolerance for 3-winding transformers is $\pm 10\%$, not $\pm 7\frac{1}{2}\%$, for 2-winding transformers.

Transformer Winding Configurations

Several winding configurations are used in the industry, each with inherent impedance characteristics that engineers must be aware of. The Loosely-Coupled Stacked Secondary (LCSS) design is shown in fig. 3. Notice with this design there are actually four windings around the core. Physically, the H winding is split in two to match the height of the X and Y windings. Electrically, the H1 and H2 windings are configured in parallel inside the tank. This design approach is taken to balance the fields in the H windings when the secondary fields are unbalanced due to an imbalance in load or a fault condition. This design is intended to serve load equally and continuously through the secondary windings. It is not a good design selection if the secondary windings will serve an unbalanced load for an extended period of time, e.g., one secondary breaker open.

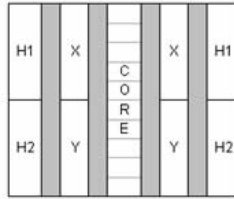


Fig. 3 Loosely-coupled stacked secondary

In this case, with equal capacities on both the X and Y windings and impedances expressed on the same base, the following relationships hold.

$$Z_{H-X} = Z_{H-Y} = K \pm 10\% \tag{1}$$

$$Z_{X-Y} = \sim 2 K \pm 10\% \tag{2}$$

Another winding configuration is the Tightly-Coupled Stacked Secondary (TCSS) design, see fig. 4. In this case the secondary and tertiary windings are alternately wound around the core. The H-X and H-Y impedances are as previously defined. The X-Y impedance has the following relationship.

$$Z_{X-Y} = \sim 0.1 K \pm 10\% \tag{3}$$

This is not a good design selection in applications where high secondary and tertiary winding fault currents are a concern. This design is more commonly used in traction power and rectifier applications.

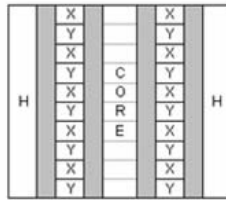


Fig. 4 Tightly-coupled stacked secondary

A third option is the Low-High-Low (LHL) Design shown in fig. 5. Again the H-X and H-Y impedances are as previously defined. The impedance range available from the X-Y windings would be slightly larger than the LCSS design.

$$\sim 2 K < Z_{X-Y} < \sim 2.5 K \text{ with a tolerance of } \pm 10\% \tag{4}$$

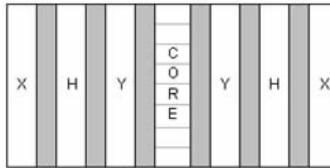


Fig. 5 Low-high-low

Example 1

Consider a new 480V distribution system that includes 3000kVA of motor load and 600kVA of miscellaneous non-motor load. Assume all motors have an X_d'' of 0.15 Ω p.u. The utility service is rated 13.8kV with a short circuit capacity of 600MVA. Investigate the following design configurations.

- Single 2-winding transformer
- Two 2-winding transformers
- 3-winding transformer utilizing a LCSS design
- 3-winding transformer utilizing a TCSS design
- 3-winding transformer utilizing a LHL design

In this application a total transformer winding capacity of 4000kVA is appropriate. Based on a primary voltage rating of 13.8kV and a standard BIL of 110kV, a typical impedance of 6% is assumed for the application. Table 1 summarizes the transformer ratings selected for each configuration.

Table 1 Transformer ratings

Case	Configuration	Unit	Windings	kVA	%Z	X/R
1	Single 2-Winding Transformer	1	H-X	4000	6.0	10.0
2	Two 2-Winding Transformers	1	H-X	2000	6.0	10.0
		2	H-X	2000	6.0	10.0
3	3-Winding Transformer LCSS	1	H-X	2000	6.0	10.0
			H-Y	2000	6.0	10.0
			X-Y	2000	12.0	10.0
4	3-Winding Transformer TCSS	1	H-X	2000	6.0	10.0
			H-Y	2000	6.0	10.0
			X-Y	2000	0.6	10.0
5	3-Winding Transformer LHL	1	H-X	2000	6.0	10.0
			H-Y	2000	6.0	10.0
			X-Y	2000	15.0	10.0

The results are summarized in Table 2. The initial rationale for considering a 3-winding transformer is confirmed. The single 2-transformer case has the highest fault duties with the lowest transformation cost. The two 2-winding transformer case has the highest transformation cost. A single 3-winding transformer balances both fault current and cost concerns. However, to maintain low fault duties, transformers of the LCSS or LHL design should be utilized.

Table 2 Short circuit study results

Case	Configuration	Unit	Location	Voltage	SC kA	X/R
1	Single 2-Winding Transformer	1	Secondary	480	96.1	9.8
2	Two 2-Winding Transformers	1	Secondary	480	50.0	9.9
		2	Secondary	480	50.0	9.9
3	3-Winding Transformer LCSS	1	Secondary	480	50.0	9.9
			Tertiary	480	50.0	9.9
4	3-Winding Transformer TCSS	1	Secondary	480	60.5	9.9
			Tertiary	480	60.5	9.9
5	3-Winding Transformer LHL	1	Secondary	480	50.3	9.9
			Tertiary	480	50.3	9.9

The results do indicate a peculiar behavior with respect to 3-winding transformers. Note the difference between cases 3 and 5. The secondary-to-tertiary impedance goes up from 12% in case 3 to 15% in case 5, yet the fault duties track opposite. To understand these results a closer inspection of the circuit model is necessary. The 3-winding transformer circuit model consists of 3 impedances connected in star, see fig. 6. Equations 8, 9 and 10 are necessary to convert Z H-X, Z H-Y and Z X-Y impedances to their Z H, Z X and Z Y equivalents.

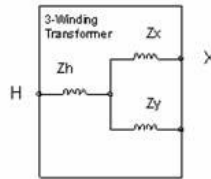


Fig. 6 Circuit model

$$Z_{H-X} = Z_H + Z_X \tag{5}$$

$$Z_{H-Y} = Z_H + Z_Y \tag{6}$$

$$Z_{X-Y} = Z_X + Z_Y \tag{7}$$

$$Z_H = ((Z_{H-X} + Z_{H-Y}) - Z_{X-Y}) / 2 \tag{8}$$

$$Z_X = Z_{H-X} - Z_H \tag{9}$$

$$Z_Y = Z_{H-Y} - Z_H \tag{10}$$

The equivalent circuit shown in fig. 6 accurately represents the transformer from a leakage impedance, mutual effects between windings, and load loss standpoint [1]. Exciting currents and no load losses are ignored. Also, please note it is not uncommon for one of the impedances to be negative or zero!

Example 2

Calculate the winding impedances for Cases 3 and 5 listed in Table 1, and then illustrate the calculation of the available fault current on the tertiary bus, see fig. 7. To simplify the calculations assume all reactance.

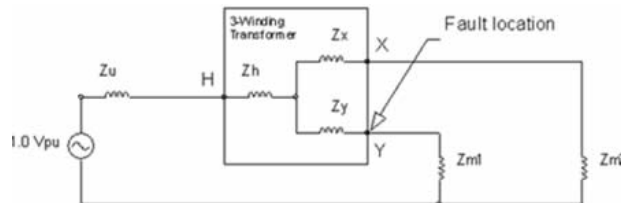


Fig. 7 Fault impedance circuit model

Solution

First, convert system impedances to a 2MVA, 480V base.

$$Z_u = 2MVA / 600MVA = 0.003 \Omega \text{ p.u.}$$

$$Z_{m1} = Z_{m2} = 0.15 (2MVA / 1.5MVA) = 0.200 \Omega \text{ p.u.}$$

Calculate the Thévenin equivalent fault impedance at the tertiary winding using (11).

$$Z_{\text{fault}} = [(Z_u + Z_H) \parallel (Z_X + Z_{m2}) + Z_Y] \parallel Z_{m1} \tag{11}$$

For Case 3

$$Z_H = ((Z_{H-X} + Z_{X-Y}) - Z_{X-Y}) / 2 = ((6.0 + 6.0) - 12.0) / 2 = 0.0\%$$

$$Z_X = Z_{H-X} - Z_H = 6.0 - 0.0 = 6.0\%$$

$$Z_Y = Z_{H-Y} - Z_H = 6.0 - 0.0 = 6.0\%$$

$$Z_{\text{Thévenin}} = [(0.003 + 0.000) \parallel (0.060 + 0.200) + 0.060] \parallel 0.200 = 0.0479 \Omega \text{ p.u.}$$

$$I_{3\text{-Phase}} = 2MVA / (\sqrt{3} \times 0.48kV \times 0.0479) = 50.2kA \text{ (~50.0kA of Table 2)}$$

For Case 5

$$Z_H = ((Z_{H-X} + Z_{H-Y}) - Z_{X-Y}) / 2 = ((6.0 + 6.0) - 15.0) / 2 = -1.5\%$$

$$Z_X = Z_{H-X} - Z_H = 6.0 - (-1.5) = 7.5\%$$

$$Z_Y = Z_{H-Y} - Z_H = 6.0 - (-1.5) = 7.5\%$$

$$Z_{\text{Thévenin}} = [(0.003 - 0.015) \parallel (0.075 + 0.200) + 0.075] \parallel 0.200 = 0.0476 \Omega \text{ p.u.}$$

$$I_{3\text{-Phase}} = 2MVA / (\sqrt{3} \times 0.48kV \times 0.0476) = 50.5kA \text{ (~50.3kA of Table 2)}$$

Z s-t IMPEDANCE LIMITS

The TCSS design establishes the lower limit for the secondary-tertiary winding impedance, while the LHL design establishes the upper limit. A theoretical upper limit can be calculated by assuming an infinite bus at the primary of the transformer while shorting the secondary and tertiary terminals (12).

$$Z_{\text{Thévenin}} = Z_H + Z_X \parallel Z_Y \tag{12}$$

Again this assumes equal capacities on both the X and Y windings with all impedances expressed on the same base. Impedance limits are summarized in Table 3. The results indicate a maximum upper limit for Z X-Y around 4 times Z H-X. At this point, the Thévenin impedance at the shorted secondary and tertiary terminals approaches zero.

Note when $Z_{X-Y} > 4 Z_{H-X}$, the result is an overall negative Thévenin impedance seen outside of the tank of the transformer. This is not possible.

Table 3 Practical impedance limits of Z_{X-Y} with Z_{H-X} = Z_{H-Y}
(All Impedances Expressed in multiples of Z_{H-X})

Z _{H-X}	Z _{H-Y}	Z _{X-Y}	Z _H	Z _X	Z _Y	Z _H + Z _X Z _Y
1.00	1.00	0.00	1.00	0.00	0.00	1.00
1.00	1.00	0.50	0.75	0.25	0.25	0.87
1.00	1.00	1.00	0.50	0.50	0.50	0.75
1.00	1.00	1.50	0.25	0.75	0.75	0.62
1.00	1.00	2.00	0.00	1.00	1.00	0.50
1.00	1.00	2.50	-0.25	1.25	1.25	0.37
1.00	1.00	3.00	-0.50	1.50	1.50	0.25
1.00	1.00	3.50	-0.75	1.75	1.75	0.12
1.00	1.00	4.00	-1.00	2.00	2.00	0.00
1.00	1.00	4.50	-1.25	2.25	2.25	-0.13
1.00	1.00	5.00	-1.50	2.50	2.50	-0.25

Example 3

Apply the results listed in this guide to the 3-winding transformer case of example 1, but in this case assume Z H-Y = Z H-X = 6.50% with equal capacities on both the X and Y windings.

- for Z_{X-Y} = 0.65% (TCSS) corresponds to a SC kA on the LV terminals of 57.5kA
- for Z_{X-Y} = 13.0% (LCSS) corresponds to a SC kA on the LV terminals of 47.0kA
- for Z_{X-Y} = 16.25% (LHL) corresponds to a SC kA on the LV terminals of 47.3kA
- for Z_{X-Y} = 26.0% corresponds to a SC kA on the LV terminals of 56.2k

These results illustrate that there is no practical advantage to increasing the secondary-to-tertiary impedance beyond ~2 times the primary-to-secondary impedance. Since higher impedances will only result in higher fault duties and losses.

References

- Electrical Transmission and Distribution Reference Book, ABB Power T&D Company, Raleigh, North Carolina, 1997.
- Harlow, J.H., Electric Power Transformer Engineering, CRC Press, New York, 2004.