MVA METHOD FOR 3-WINDING TRANSFORMER

By: Ver Pangonilo, PEE RPEQ
Date: 20 April 2011

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I. Introduction

Modeling a 3-winding transformer is different from an ordinary 2-winding transformer. There are several possibilities of modeling a 3-winding transformer but only two options will be presented here.

Case 1 Equivalent (Three Bus Equivalent). The 3-winding transformer is split into two transformers. This is a simplistic method of representing this type of transformer. It does not consider the impedance of the primary winding.

Case 2 Equivalent (Four Bus Equivalent). The 3-winding transformer is split into three transformers. This is a more accurate representation of a 3-winding transformer. The upper transformer is actually considered to have 1:1 ratio.

These equivalent representations of a 3-winding transformer prove that its use is more economical than using multiple units of transformers notwithstanding the additional protection, additional structures and the wider real estate required if multiple units will be installed.

In some applications, the tertiary winding is a vital part of the 3-winding transformer. This is when both the primary and secondary windings are wye connected; the tertiary winding is connected delta to trap the zero sequence current during an earth fault.

The 3-winding transformer equivalents are shown below.

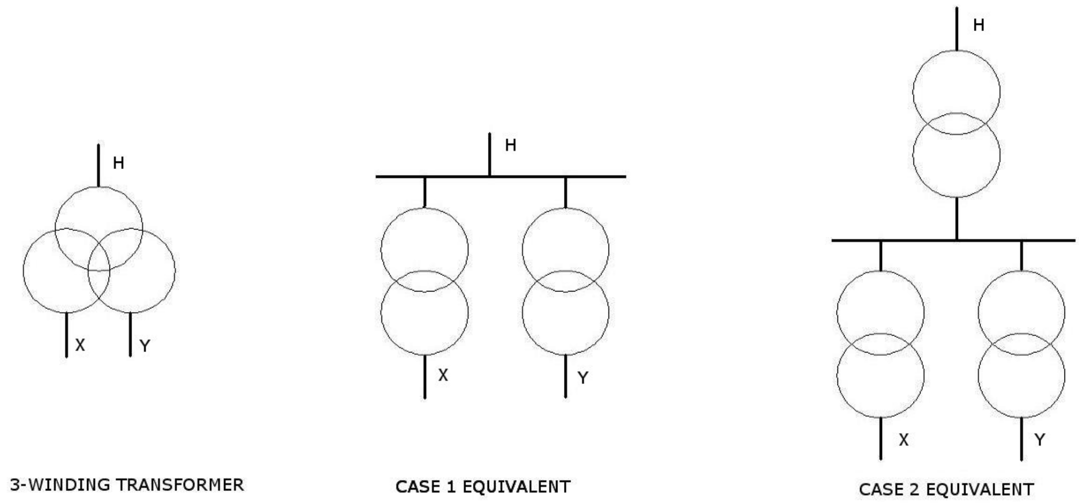

Figure 1 3-Winding Transformer and Equivalents

Terminal Designations:

IEEE	IEC	Description*
P (H)	A	High Voltage – Primary
S (X)	B	Medium Voltage – Secondary
T (Y)	C	Low Voltage – Tertiary

** Typical description may vary depending on application.*

We shall be using IEEE designations in this tutorial.

II. Leakage Impedance

The primary and secondary windings of a two-winding transformer have equal KVA ratings. For a 3-winding transformer, the windings may have different KVA ratings.

The impedances of each winding of a 3-winding transformer may be specified as a percent or in per-unit based on the rating of its own winding, or could be referred to a common base.

The impedances are usually measured by the standard short-circuit tests and represented as follows:

- Z_{PS} — leakage impedance measured in primary with secondary short circuited and tertiary open
- Z_{PT} — leakage impedance measured in primary with tertiary short circuited and secondary open
- Z_{ST} — leakage impedance measured in the secondary with tertiary short circuited and primary open

Since these impedances are referred to the primary, individual impedances of the windings can be calculated as follows:

$$\mathbf{Z_P = \tfrac{1}{2} (Z_{PS} + Z_{PT} - Z_{ST})} \qquad (1)$$

$$\mathbf{Z_S = \tfrac{1}{2} (Z_{ST} + Z_{PS} - Z_{PT})} \qquad (2)$$

$$\mathbf{Z_T = \tfrac{1}{2} (Z_{PT} + Z_{ST} - Z_{PS})} \qquad (3)$$

where:
Z_P = primary winding impedance
Z_S = secondary winding impedance
Z_T = tertiary winding impedance

The leakage impedances of the 3-winding transformer can also be calculated as follows:

$$\mathbf{Z_{PS} = Z_P + Z_S} \qquad (4)$$

$$\mathbf{Z_{PT} = Z_P + Z_T} \qquad (5)$$

$$\mathbf{Z_{ST} = Z_S + Z_T} \qquad (6)$$

Important: In equations (1) to (6), the formulae are vector addition.

III. Impedance Transformation

If the KVA or MVA ratings of a 3-winding transformer is designated as follows:

KVA_A = primary winding KVA rating
KVA_B = secondary winding KVA rating
KVA_C = tertiary winding KVA rating

the impedances referred to the primary can be calculated below:

$$Z'_S = Z_S \, (KVA_S / KVA_P) = Z_S \, (MVA_S / MVA_P) \quad (7)$$

$$Z'_T = Z_T \, (KVA_T / KVA_P) = Z_T \, (MVA_T / MVA_P) \quad (8)$$

where:
Z'_S = secondary winding impedance rating referred to the primary
Z'_T = tertiary winding impedance rating referred to the primary

IV. Fault Calculation

From the previous section, we have presented the equivalents representation and impedances of a 3-winding transformer. We should now be ready to deal with the main purpose of this tutorial, to be able to perform MVA method of short circuit calculation for a 3-winding transformer.

To illustrate, let us provide an example:

Utility:

$MVA_U = 600$ MVA $\quad$ $KV_U = 132$ KV

3-Winding Transformer:

$MVA_A = 150$ MVA $\quad$ $KV_A = 132$ KV

$MVA_B = 100$ MVA $\quad$ $KV_B = 66$ KV

$MVA_C = 50$ MVA $\quad$ $KV_C = 22$ KV

$Z_{PS} = 17\%$ $\quad$ $X/R_{PS} = 5$

$Z_{PT} = 16\%$ $\quad$ $X/R_{PT} = 5$

$Z_{CA} = 15\%$ $\quad$ $X/R_{ST} = 3.5$

Please note that the leakage impedances are calculated on the transformer MVA rating. In this case, it is 150 MVA.

Using equations (4) to (6), the individual impedances can be calculated:

$Z_A = 9\%$ @ 150 MVA_{BASE}

$Z_B = 8\%$ @ 150 MVA_{BASE}

$Z_C = 7\%$ @ 150 MVA_{BASE}

To calculate the impedances based on the winding actual rating, we need to use equations (7) & (8):

$Z'_B = Z_B\ (MVA_B / MVA_A)$

$Z'_B = 8\%\ (100 / 150)$

$Z'_B = 5.33\%$ @ 100 MVA

$Z'_C = Z_C\ (MVA_C / MVA_A)$

$Z'_C = 7\%\ (50 / 150)$

$Z'_C = 2.33\%$ @ 50 MVA

In practical situations, the impedances based on the winding ratings are not calculated.

In order for us to have a comparison of the two equivalent representations of 3-winding transformers, let us solve the fault MVAs and currents on both cases.

Case 1 : Three Bus Equivalent

As the impedances are given in individual values, to enable us to solve for Case 1, we need to know the leakage impedances of the transformer which we could solve using (4), (5) and (6).

$Z_{PS} = Z_A + Z_B$

$Z_{PS} = 9\% + 8\%$

$Z_{PS} = 17\%$

$Z_{PT} = Z_A + Z_C$

$Z_{PT} = 9\% + 7\%$

$Z_{PT} = 16\%$

$Z_{ST} = Z_B+Z_C$

$Z_{ST} = 8\% + 7\%$

Z_{ST} = 15%

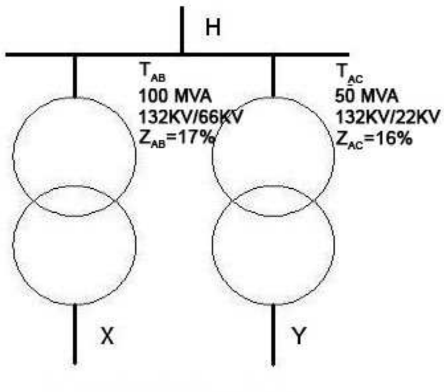

Figure 2 Three Bus Equivalent

From Figure 2, the MVAs of each equivalent transformer can be calculated below.

Primary - Secondary:

$MVA_{PS\text{-}SC}$ = 150 / 17%

$MVA_{PS\text{-}SC}$ = 882 MVA

Primary - Tertiary:

$MVA_{PT\text{-}SC}$ = 150 / 16%

$MVA_{PT\text{-}SC}$ = 937.5 MVA

If we add the utility fault level

Primary - Secondary:

$MVA_{PS+U} = (MVA_U \times MVA_{PS\text{-}SC})/(MVA_U + MVA_{PS\text{-}SC})$

$MVA_{PS+U} = (600 \times 882)/(600 + 882)$

MVA_{PS+U} = 357 MVA

I_{PS} = (357 MVA) / ($\sqrt{3}$ x 66 KV)

I_{PS} = 3.12 kA

Primary - Tertiary:

$MVA_{PT+U} = (MVA_U \times MVA_{PT\text{-}SC})/(MVA_U + MVA_{PT\text{-}SC})$

$MVA_{PT+U} = (600 \times 937.5)/(600 + 937.5)$

MVA_{PT+U} = 365.8 MVA

I_{PT} = (365.8 MVA) / ($\sqrt{3}$ x 22 KV)

I_{PT} = 9.6 kA

Case 2 : Four Bus Equivalent

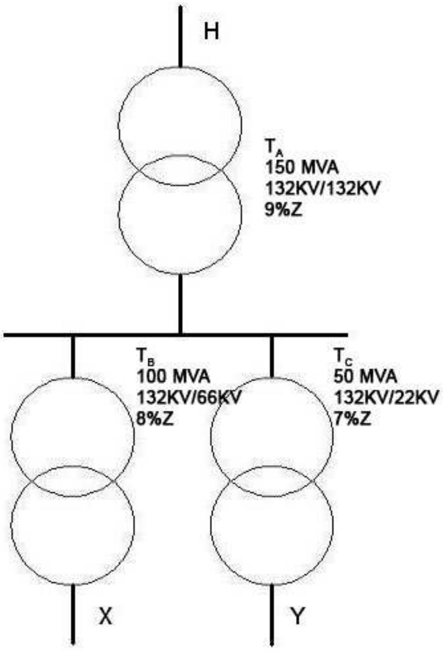

Figure 3 Four Bus Equivalent

Let us now calculate the MVA equivalents of the different windings.

Primary:

$\mathbf{MVA_{P\text{-}SC} = 150 / 9\%}$

$\mathbf{MVA_{P\text{-}SC} = 1667\ MVA}$

Secondary:

$\mathbf{MVA_{S\text{-}SC} = 150 / 8\% = 100 / 5.33\%}$

$\mathbf{MVA_{S\text{-}SC} = 1875\ MVA}$

Tertiary:

$\mathbf{MVA_{T\text{-}SC} = 150 / 7\% = 50 / 2.33\%}$

$\mathbf{MVA_{T\text{-}SC} = 2143\ MVA}$

From above individual winding fault MVAs, we can calculate the primary-secondary and primary-tertiary faults MVAs including the utility fault level.

Primary - Secondary:

$MVA_{PS+U} = 1/(1/MVA_U + 1/MVA_{P\text{-}SC} + 1/MVA_{S\text{-}SC})$

$MVA_{PS+U} = 1/(1/600 + 1/1667 + 1/1875)$

$MVA_{PS+U} = 357\ MVA$

$I_{PS} = (357\ MVA) / (\sqrt{3} \times 66\ KV)$

$I_{PS} = 3.12\ kA$

Primary - Tertiary:

$MVA_{PT+U} = 1/(1/MVA_U + 1/MVA_{P\text{-}SC} + 1/MVA_{T\text{-}SC})$

$MVA_{PT+U} = 1/(1/600 + 1/1667 + 1/2143)$

$MVA_{PT+U} = 365.9\ MVA$

$I_{PT} = (365.9\ MVA) / (\sqrt{3} \times 22\ KV)$

$I_{PT} = 9.6\ kA$

IV. ETAP Calculation

To confirm the results of the MVA method for 3-winding transformer, I modeled the transformer into ETAP which provided the following results:

Fault @ 66KV Bus:

Three-Phase Fault Currents: (Prefault Voltage = 100 % of the Bus Nominal Voltages)

Bus Information		Device Information		Interrupting Duty				Device Capability			
ID	kV	ID	Type	Symm. kA rms	X/R Ratio	M.F.	Adj Sym. kA rms	kV	Test PF	Rated Int.	Adjusted Int.
Bus2	66.00			3.130	8.1						

Fault @ 22KV Bus:

Three-Phase Fault Currents: (Prefault Voltage = 100 % of the Bus Nominal Voltages)

Bus Information		Device Information		Interrupting Duty				Device Capability			
ID	kV	ID	Type	Symm. kA rms	X/R Ratio	M.F.	Adj Sym. kA rms	kV	Test PF	Rated Int.	Adjusted Int.
Bus3	22.00			9.619	8.3						

V. Summary

Analyzing the table below, we can conclude that regardless of the method on how to model a 3-winding transformer, the result will be the same. Moreover, MVA method of fault calculation is comparable to software modeling like ETAP.

	Secondary Fault @ 66KV	Tertiary Fault @ 22KV
Three Bus Equivalent	3.12 kA	9.6 kA
Four Bus Equivalent	3.12 kA	9.6 kA
ETAP Modeling	3.13 kA	9.6 kA

V. References

1. IEC 60909-0 Short-circuit currents in three-phase a.c. systems Part 0: Calculation of currents
2. IEEE Std 399 IEEE Recommended Practice for Power System Analysis