Measurement of zero sequence impedance for three-winding transformers

Using actual measurements from a reputable transformer manufacturer, Er. Lee Wai Meng explains the required connection scheme and associated calculations.

A three-winding transformer has the following specifications:

- Primary winding of 300 MVA, 230 kV, star connected with the neutral accessible, and connected to the local grid.
- Secondary winding of 300 MVA, 132 kV, star connected with the neutral accessible, and connected to the load of the consumer.
- Tertiary winding of 90 MVA, 15.75 kV, delta connected, and not connected to any load. The sole purpose of the tertiary winding is to allow the flow of zero sequence current during fault conditions.

Model for zero sequence

A three-winding transformer has zero sequence impedance for the primary, secondary, and tertiary windings.

- X_{OP} = zero sequence impedance of the primary winding
- X_{OS} = zero sequence impedance of the secondary winding
- X_{OT} = zero sequence impedance of the tertiary winding

The equivalent circuit for the zero sequence impedance is illustrated in Figure 1. It is important to recognise that point K in Figure 1 is a fictitious point and does not represent the neutral point of the transformer. The connection of the zero sequence impedance to the system is determined by imaginary switch A_P, A_S, A_T, B_P, B_S, and B_T. Switch A_P, A_S, or A_T will be closed if the winding is star connected and with the neutral connected to ground. Switch A_P, A_S, or A_T will be opened if the winding is star connected and with the neutral not connected to ground. Switch B_P, B_S, or B_T will be closed only if the winding is delta connected.

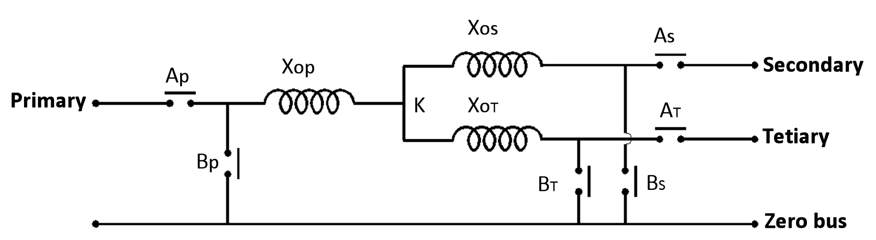

Figure 1 - Zero sequence impedance

Configuration of Windings	Status of Switch	
	A_P, A_S, or A_T	B_P, B_S, or B_T
1) Delta	Open	Closed
2) Star with neutral connected to ground	Closed	Open
3) Star with neutral NOT connected to ground	Open	Open

With the combinations of the switches in various open and closed states, the values of X_{OP}, X_{OS} and X_{OT} can be calculated from measurements of injected voltage and induced current at the primary, secondary and tertiary terminals of the transformers.

Connection scheme

In order to solve for the three unknowns (X_{OP}, X_{OS} and X_{OT}), at least three equations or three measurements are needed. Figures 2A to 5A show the connection schemes. Figures 2B to 5B show the zero sequence impedance diagram for the connection schemes in Figures 2A to 5A.

The test source can be connected either at the primary or secondary windings. The test source is a single phase AC source, and there is no need for a three phase AC source for the measurement of the zero sequence impedance. The measurement of the positive sequence impedance will however require a three phase AC source.

Connection Scheme	Zero Sequence Impedance
Figure 2A	$X_{OP} + X_{OT}$
Figure 3A	$X_{OP} + \dfrac{X_{OS} X_{OT}}{X_{OS} + X_{OT}}$
Figure 4A	$X_{OS} + X_{OT}$
Figure 5A	$X_{OS} + \dfrac{X_{OT} X_{OP}}{X_{OT} + X_{OP}}$

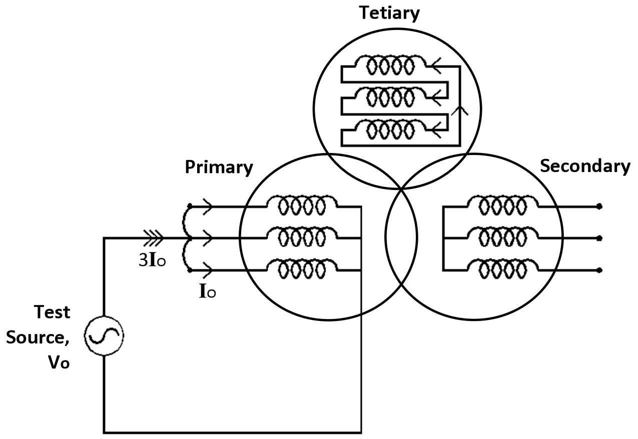

Figure 2A - Test source at Primary, $X_{OP} + X_{OT}$

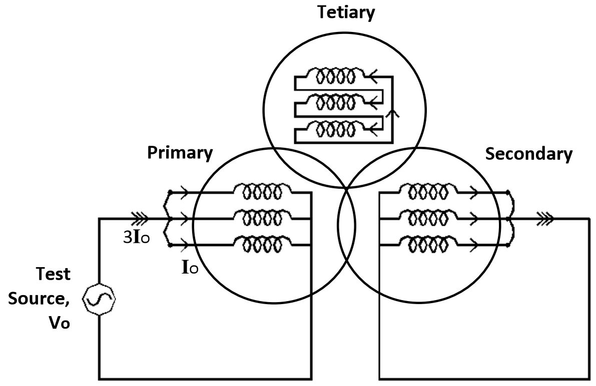

Figure 3A - Test source at Primary, $X_{OP} + \frac{X_{OS}\ X_{OT}}{X_{OS} + X_{OT}}$

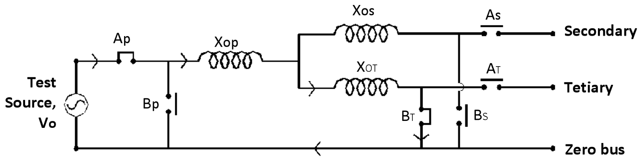

Figure 2B - Zero sequence impedance, $X_{OP} + X_{OT}$

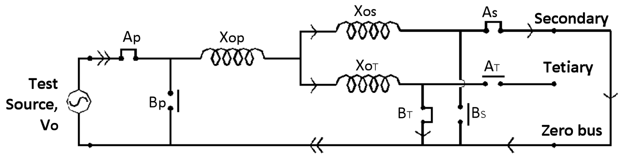

Figure 3B - Zero sequence impedance, $X_{OP} + \frac{X_{OS}\ X_{OT}}{X_{OS} + X_{OT}}$

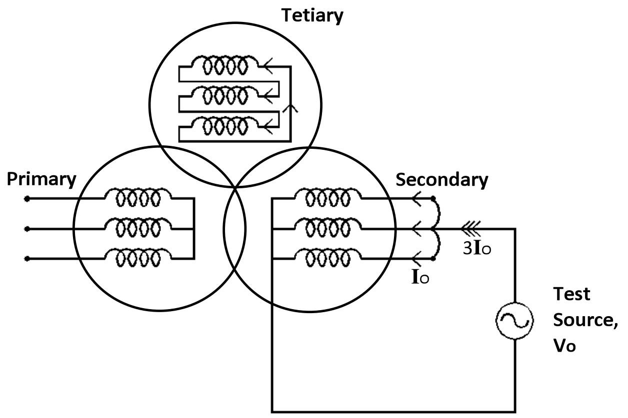

Figure 4A - Test source at Secondary, $X_{OS} + X_{OT}$

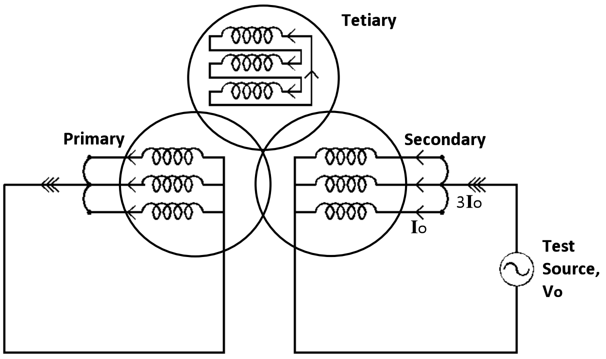

Figure 5A - Test source at Secondary, $X_{OS} + \frac{X_{OT}\,X_{OP}}{X_{OT} + X_{OP}}$

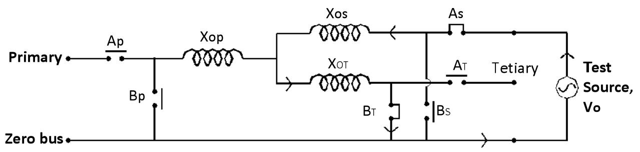

Figure 4B - Zero sequence impedance, $X_{os} + X_{OT}$

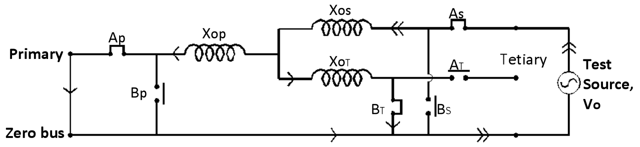

Figure 5B - Zero sequence impedance, $X_{os} + \frac{X_{OT}\,X_{OP}}{X_{OT} + X_{OP}}$

Measurement results

The measurement results in the table on the right have been obtained from a reputable transformer vendor for an installation at a customer's facility in Jurong Island.

Connection Scheme	Measured Voltage in kV	Measured Current in Ampere	Calculated Impedance in ohm per phase	Calculated Impedance in %
Figure 2A	10.95	424	77.5	44
Figure 3A	10.19	676	45.2	26
Figure 4A	2.61	1034	7.5	13
Figure 5A	1.52	1027	4.4	7
The base values are 300 MVA, 230 kV or 300 MVA, 132 kV				

For the connection scheme in Figure 2A, the impedance recorded by the test source will be (10950 / 424) or 25.8 ohm. The equivalent zero sequence impedance will be (3 x 25.8) or 77.5 ohm per phase or $X_{OP} + X_{OT} = 77.5$ ohm per phase. To convert the ohm per phase to the equivalent % value, the base impedance at the primary winding must be calculated, and this is equal to (230 x 230) / 300 or 176 ohm. The % impedance value will be (77.5 / 176) or 44%. The calculations for Figure 3A are similar to that for Figure 2A because the test source is connected at the primary winding.

For the connection scheme in Figure 4A, the impedance recorded by the test source will be (2610 / 1034) or 2.5 ohm. The equivalent zero sequence impedance will be 3 x 2.5 or 7.5 ohm per phase or $X_{OS} + X_{OT} = 7.5$ ohm per phase. To convert the ohm per phase to the equivalent % value, the base impedance at the secondary winding must be calculated, and this is equal to (132 x 132) / 300 or 58 ohm. The % impedance value will be (7.5 / 58) or 13%. The calculations for Figure 5A are similar to that for Figure 4A because the test source is connected at the secondary winding.

Calculation results

From the measurement results, we have the following:

$$X_{OP} + X_{OT} = 44\%$$

$$X_{OP} + \frac{X_{OS}\,X_{OT}}{X_{OS} + X_{OT}} = 26\%$$

$$X_{OS} + X_{OT} = 13\%$$

$$X_{OS} + \frac{X_{OT}\,X_{OP}}{X_{OT} + X_{OP}} = 7\%$$

Solving the equations, we will have

$X_{OP} = 29\%$
$X_{OS} = -2\%$
$X_{OT} = 15\%$

X_{OP}, X_{OS} and X_{OT}, are fictitious zero sequence impedances and hence may have negative values. The physical values of zero sequence impedance are across the physical terminals of the primary, secondary, and tertiary windings. These physical values of zero sequence impedance are

$X_{O\_PS} = X_{OP} + X_{OS} = 27\%$
$X_{O\_PT} = X_{OP} + X_{OT} = 44\%$
$X_{O\_ST} = X_{OS} + X_{OT} = 13\%$

Zero sequence impedance

The measurement of the zero sequence impedance for transformers is seldom done for small transformers, and is done only for large transformers. It is common to assume that the zero sequence impedance of the transformer is equal to the positive sequence impedance which is the transformer leakage impedance. The exceptions to this are the three phase transformers with three limbs for the core. This type of construction does not provide the return path for the zero sequence flux through the core of the three limbs. The return path for the zero sequence flux is through the metal body of the transformer tank. Therefore the zero sequence impedance will not be equal to the positive sequence impedance, and typical values are 85% to 90% of the positive sequence impedance.

Single phase to ground fault

The single phase to ground fault will depend on the positive, negative, and zero sequence impedance.

Single Phase to Ground Phase =

$$\frac{3V_o}{X_1 + X_2 + X_o} = \frac{3\,I_F}{1 + \frac{X_2}{X_1} + \frac{X_o}{X_1}}$$

where
V_o is the pre-fault phase to neutral voltage
X_1 is the positive sequence impedance
X_2 is the negative sequence impedance
X_0 is the zero sequence impedance
I_F is the three phase fault current

In most applications, $X_1 = X_2$ and hence the single phase to ground fault current will be $\left(\frac{3}{2 + K}\right)$ of the three phase fault current, where

$$K = \frac{X_o}{X_1}$$

- When $X_O = X_1$, the single phase to ground fault current equals the three phase fault current.
- When X_O is less than X_1, the single phase to ground fault current is more than the three phase fault current.
- When X_O is greater than X_1, the single phase to ground fault current is less than the three phase fault current.

Therefore measurement of the zero sequence impedance of a transformer is important when the transformer is of large MVA size because of the possibility that the single phase to ground fault current is greater than the three phase fault current.

[Er. Lee Wai Meng is Principal Consultant/Director of J.M. Pang & Seah (Pte) Ltd, an electrical and mechanical consultancy. A Singapore-registered professional engineer, he has a 230 kV switching licence from Energy Market Authority (EMA)].