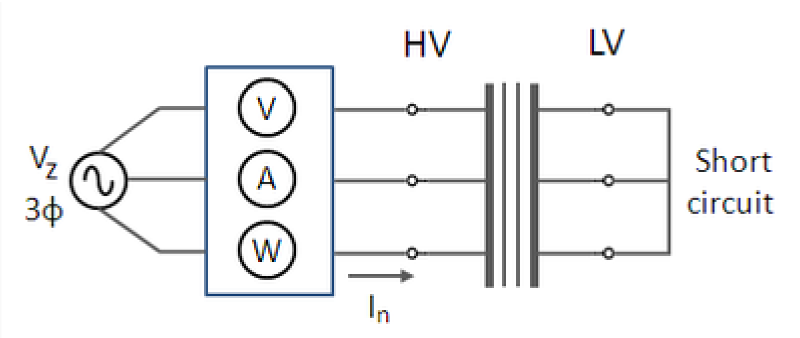
Transformer Impedance

Positive Sequence Impedance

The transformer positive sequence impedance is also called the short circuit impedance (because it is measured from a short circuit test) or the impedance voltage (because a voltage is measured from the short circuit test - more details below).

Two Winding Transformer

Impedance Measurement



Positive sequence impedance test circuit for three-phase 2-winding transformer

The positive sequence impedance is measured from a standard short circuit test (see figure right). In this test, one set of windings is shorted (typically the LV windings) and a three-phase voltage source is applied to the other set of windings. The voltage is steadily increased until the rated phase current is measured.

The voltage at this point is called the impedance voltage. When the impedance voltage is expressed as a per-unit value (on the transformer rated line-to-line voltage), the impedance voltage is equivalent to the per-unit impedance, i.e.

$$\frac{V_z}{V_n} = \frac{I_n}{I_n}\frac{Z_1}{Z_b} = Z_{1,pu}$$

where V_z is the measured impedance voltage (V)

V_n is the rated transformer line-to-line voltage / base voltage (V)

I_n is the rated transformer current (A)

Z_1 is the positive sequence impedance (Ω)

Z_b is the transformer base impedance (Ω)

$Z_{1,pu}$ is the positive sequence impedance (pu)

The impedance voltage is also often expressed as a percentage (Z%).

Copper Losses

Full load copper (or iron) losses are measured in the same test as the impedance voltage by taking the power reading (from the wattmeter in the test circuit). The copper losses represent the I^2R losses from the full load current in the phase windings, as well as stray losses due to induced eddy currents from leakage fluxes in the windings, core clamps, tank and other magnetic pathways.

Calculation of R_1 and X_1

The resistive and reactive components of the positive sequence transformer impedance can be estimated from the two short circuit test measurements - 1) impedance voltage, and 2) full load copper losses. The expressions below calculate the resistance and reactance in per-unit quanitities.

$$R_{1,pu} = \frac{P_c}{1000S_n}$$

$$X_{1,pu} = \sqrt{Z_{1,pu}^2 - R_{1,pu}^2}$$

Where $R_{1,pu}$ is the positive sequence resistance (pu)

$X_{1,pu}$ is the positive sequence reactance (pu)

$Z_{1,pu}$ is the positive sequence impedance (pu)

P_c are the full load copper losses (W)

S_n is the transformer rated power (kVA)

Application in Transformer Models

The positive sequence impedance measured and calculated above is most often applied in the standard positive sequencetwo-winding transformer model as representing the transformer leakage impedance. This representation assumes that the parallel magnetising and core loss branch in the T-circuit is a negligible part of the measured positive sequence impedance (note that the magnetising reactance and core losses are estimated separately in no-load (open circuit) tests).

You will notice that the standard positive sequence transformer model has leakage impedances on both the primary and secondar sides of the transformer. However in our measurements, we only calculate a single impedance. It is common practice to distribute the impedance across both sides (for example, 50%-50% if no other information is available).

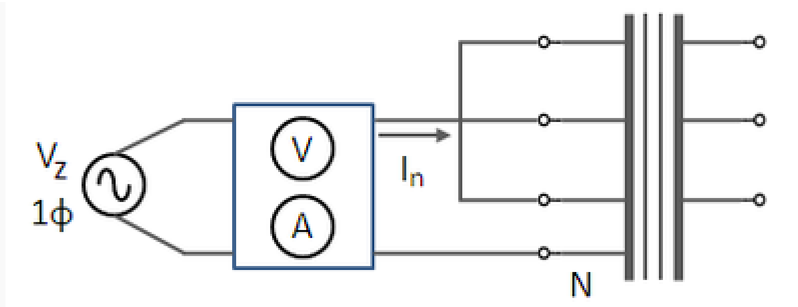
Winding Connections

It is worth noting that the transformer impedance voltage (expressed in percent or per-unit) is independent of the winding connection. This is because each winding is tested separately and normally quoted as a per-unit (or percent) impedance voltage based on the transformer's rated line-to-line voltage (see IEEE Std C57.12.90). If the winding connections are changed, then the line-to-line voltage would also have to change. But since it is a per-unit (or percent) value, the impedance voltage would remain the same.

Zero Sequence Impedance

Two Winding Transformer

Impedance Measurement



Zero sequence impedance test circuit for three-phase 2-winding transformer (with accessible neutral)

In the zero sequence test, a single-phase voltage source is applied between the three phase terminals (connected together) and an externally available neutral terminal (see the test circuit in the figure right). Like in the positive sequence test, the voltage is steadily increased until the rated current is measured.

$$\frac{V_z}{V_n} = \frac{1}{3}\frac{I_n}{I_n}\frac{Z_0}{Z_b} = \frac{1}{3}Z_{0,pu}$$

where V_z is the measured zero sequence impedance voltage (V)

V_n is the rated transformer line-to-line voltage / base voltage (V)

I_n is the rated transformer current (A)

Z_0 is the zero sequence impedance (Ω)

Z_b is the transformer base impedance (Ω)

$Z_{0,pu}$ is the zero sequence impedance (pu)

Note that the measured impedance voltage is actually equivalent to a third of Z_0. This is because the three phase windings are connected together and the current flowing through each individual winding is a third of the measured rated current.

Tleis [2] also suggests that for earthed star-star (YNyn) transformers with a three-limbed core construction, zero sequence flux can circulate around a path through the core, tank, insulating oil and air. Therefore this magnetic path acts like a "virtual" delta winding, and the zero sequence impedance can be lower than the standard measured value. Tleis suggests treating these transformers like three-winding transformers and performing at least three test measurements.

Calculation of R_0 and X_0

Occasionally the zero sequence copper losses ($P_{c,0}$) are also measured as part of the zero sequence test. When this is the case, calculations similar to that of the positive sequence impedance can be applied:

$$R_{0,pu} = \frac{P_{c,0}}{1000 S_n}$$

$$X_{0,pu} = \sqrt{Z_{0,pu}^2 - R_{0,pu}^2}$$

Where $R_{0,pu}$ is the zero sequence resistance (pu)

$X_{0,pu}$ is the zero sequence reactance (pu)

$Z_{0,pu}$ is the zero sequence impedance (pu)

$P_{c,0}$ are the zero sequence copper losses (W)

S_n is the transformer rated power (kVA)

However, when the zero sequence copper losses are not known, it is common to use the same X/R ratio as in the positive sequence, i.e.

$$R_{0,pu} = \frac{Z_{0,pu}}{\sqrt{1 + \left(\frac{X_1}{R_1}\right)^2}}$$

$$X_{0,pu} = \left(\frac{X_1}{R_1}\right) R_{0,pu}$$

Where $\frac{X_1}{R_1}$ is the positive sequence X/R ratio

References

[1] IEEE Std C57.12.90, "IEEE Standard Test Code for Liquid-Immersed Distribution, Power and Regulating Transformers", 2010

[2] Tleis, N., "Power Systems Modelling and Fault Analysis - Theory and Practice", Newnes, 2008

Source:

http://www.openelectrical.org/wiki/index.php?title=Transformer_Impedance