On-site Low Voltage Determination of Zero Sequence Impedances for Station Auxiliary Transformers

A research collaboration between

TVA & UTC

Background

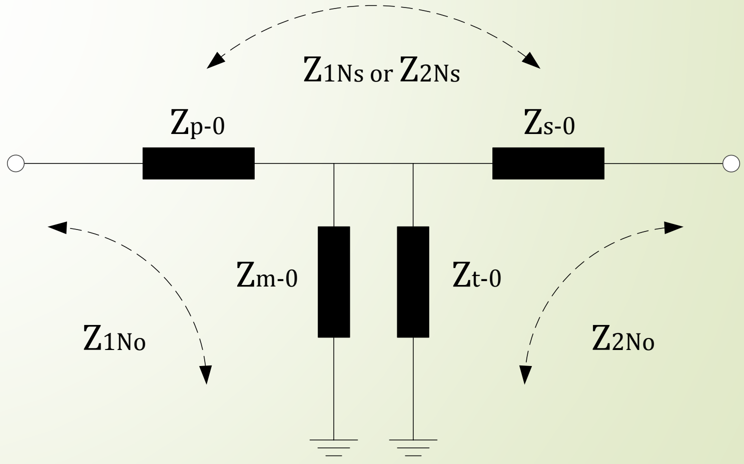
Motivation for this research was the incident of January 30, 2012 at Byron Station NPP which involved an open-phase condition on the primary of two SATs.

- This research describes a new method for finding the zero sequence parameters for typical SATs.
- The method cuts the costs of prevailing methods, particularly for on-site measurements.
- Initial simulations were promising. Method was then validated using actual measurements.

Background - 2

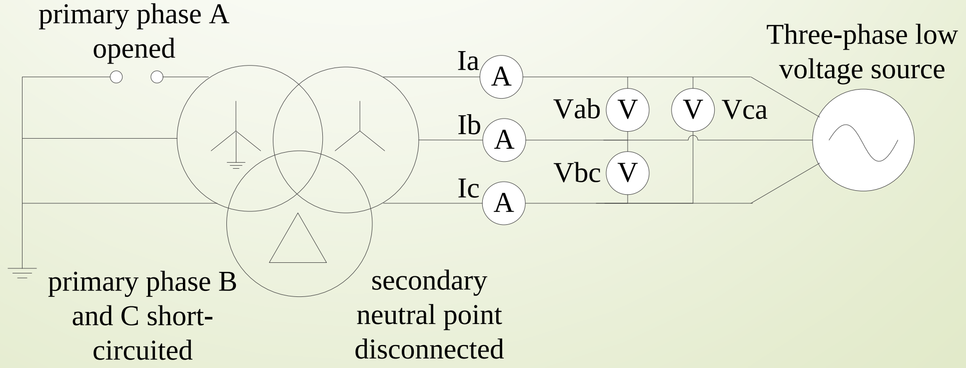
In the standard IEEE/ANSI method, at least one measurement must be carried out from the high voltage side. This measurement is shown in figure as Z1No

- The usual setting for this test would be a high voltage laboratory, where suitable test voltages are available.



Background - 3

- Onsite measurements however would require renting high voltage mobile laboratories at a high cost.
- Our method eliminates the high voltage test, and replaces it with the low voltage test shown below.
- Only a low voltage (230 – 400 V) three phase supply is required.

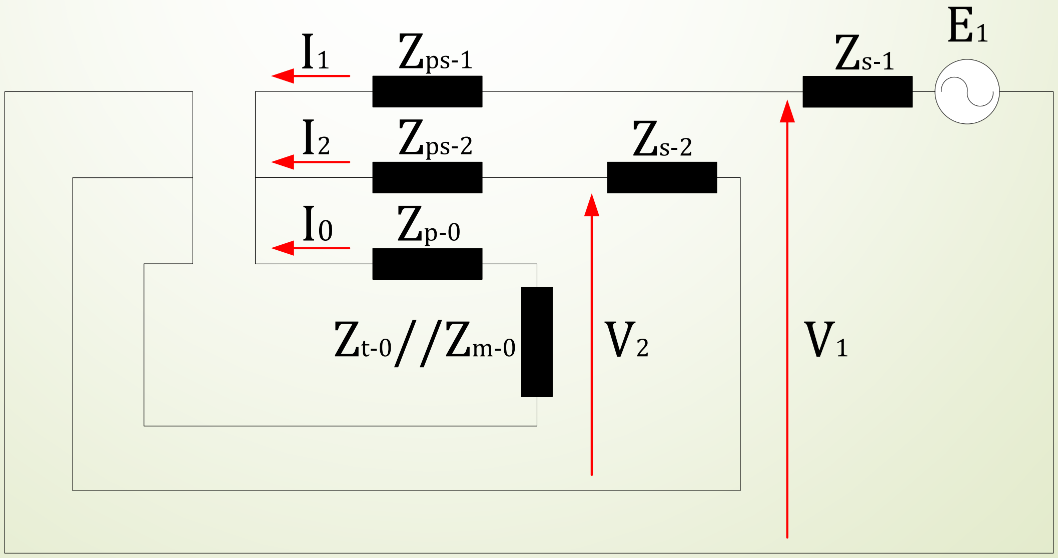


Background - 4

- Our test configuration requires application of a three phase voltage to the secondary under the following conditions:
  1. Secondary neutral is disconnected.
  2. Two primary (high voltage) terminals are shorted to the neutral, with the remaining terminal left open.
- This connection creates conditions involving all three sequence component voltages and currents.

Methods

- The method exploits the primary open phase sequence model.
- Two methods were proposed. A simplified “approximate “ method and an iterative based “exact” method.



Approximate Method

- The parameter that we seek to estimate is $\boldsymbol{Z_{pt-0}} = \left(\boldsymbol{Z_{p-0}} + \boldsymbol{Z_{t-0}}//\boldsymbol{Z_{m-0}}\right)$

- Since secondary neutral is open, the zero sequence current on the secondary side is non-existent, and the following applies for the secondary currents:

$$\bar{I}_a + \bar{I}_b + \bar{I}_c = 0$$

$$\bar{I}_a = \bar{I}_1 + \bar{I}_2$$

Approximate Method

- Phase A on the primary side is also open, thus (for the primary):

$$\bar{I}_0 + \bar{I}_1 + \bar{I}_2 = 0$$

- We can thus conclude that (compare with previous slide)

$$\bar{I}_0 = -\bar{I}_a$$

- Or

$$I_0 = |\bar{I}_a|$$

Approximate Method

- Additionally, with the sequence network assumed purely reactive, all currents are in phase, and the following non-vector relation applies:

$$I_1 = I_0 + I_2$$

- Since I_1 and I_2 are geometrically opposite, then (assuming angle of I_1= 0°)

$$\bar{I}_b = a^2 I_1 + a I_2 \angle 180° \longrightarrow \bar{I}_b = a^2 I_1 - a I_2$$
$$\bar{I}_c = a I_1 + a^2 I_2 \angle 180° \longrightarrow \bar{I}_c = a I_1 - a^2 I_2$$

Approximate Method

- Or

$$\bar{I}_b = -\frac{1}{2}(I_1 - I_2) - j\frac{\sqrt{3}}{2}(I_1 + I_2) = I\angle - \theta$$

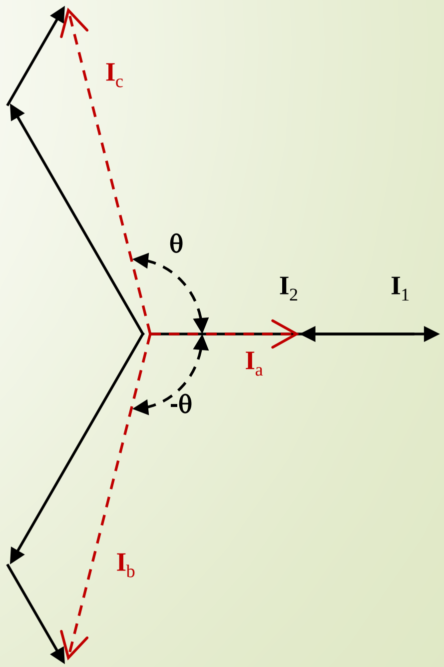
$$\bar{I}_c = -\frac{1}{2}(I_1 - I_2) + j\frac{\sqrt{3}}{2}(I_1 + I_2) = I\angle\theta$$

- We then clearly have condition of symmetry involving all currents $\bar{I}_a, \bar{I}_b$ and $\bar{I}_c$

Approximate Method

- This assumed symmetry allows to calculate positive and negative sequence currents from line currents Ia, Ib and Ic .

$$\bar{I}_b + \bar{I}_c = -(I_1 - I_2) = -I_0 = 2I\cos\theta$$
$$\bar{I}_c - \bar{I}_b = j\sqrt{3}(I_1 + I_2) = j2I\sin\theta$$



- From which

$$\theta = \cos^{-1}\left(-\frac{|\bar{I}_a|}{2I}\right)$$
$$I_1 = \frac{-2}{\sqrt{3}} I\cos(\theta + 30°)$$
$$I_2 = \frac{2}{\sqrt{3}} I\cos(\theta - 30°)$$

Approximate Method

- Similar calculation can be carried out for the voltages. It can easily be shown that the voltages V_1 and V_2 would be in-phase, which would then allow us to write V_{ab} and V_{ca} as

$$\bar{V}_{ab} = V_1(1 - a^2) + V_2(1 - a)$$

$$\bar{V}_{ca} = V_1(a - 1) + V_2(a^2 - 1)$$

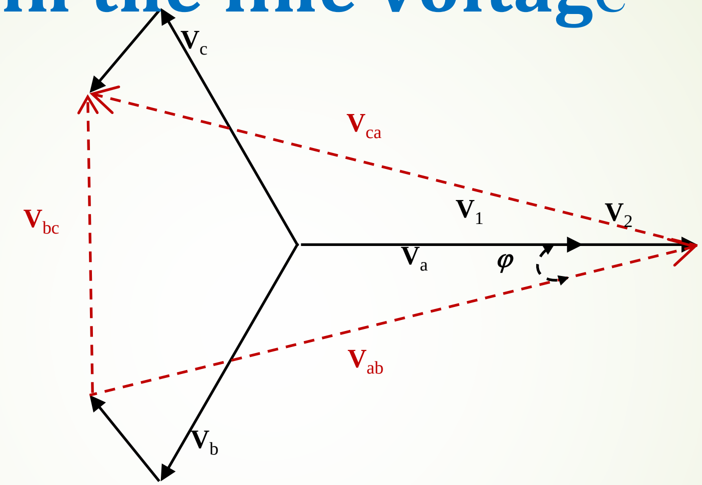
Or, in terms of real and imaginary components

$$\bar{V}_{ab} = \frac{3}{2}(V_1 + V_2) + j\frac{\sqrt{3}}{2}(V_1 - V_2) = V\angle\varphi$$

$$\bar{V}_{ca} = -\frac{3}{2}(V_1 + V_2) + j\frac{\sqrt{3}}{2}(V_1 - V_2) = V\angle(180 - \varphi)$$

Approximate Method

- Again we observe a pattern of sym metry in the line voltage



- From which

$$\bar{V}_{ab} + \bar{V}_{ca} = j\sqrt{3}(V_1 - V_2) = j2V\sin\emptyset$$

$$\bar{V}_{ab} - \bar{V}_{ca} = 3(V_1 + V_2) = 2V\cos\emptyset$$

Approximate Method

- Therefore

$$\emptyset = \sin^{-1}\frac{|\bar{V}_{bc}|}{2V}$$

$$V_1 = \frac{2}{3}V\sin(\emptyset + 30°)$$

$$V_2 = \frac{-2}{3}V\sin(\emptyset - 30°)$$

Approximate Method

- Having now obtained I_1 and I_0 from the current measurements, and V_1 from the voltage measurements, we can simply find the required zero sequence impedance as:

$$Z_{pt-0} = \frac{\left(V_1 - I_1 Z_{ps-1}\right)}{I_0}$$

Exact Method

- For the exact method, we assume all the sequence currents and sequence voltages are phasors with unknown angles and magnitudes.
- We will need to find four phasors I_1 , I_2 , V_1 and V_2 . Since all quantities are complex, we need eight equations to determine real and imaginary parts of each.

Exact Method

$$V_{1-re} - V_{2-re} = R_1(I_{1-re} - I_{2-re}) - X_1(I_{1-im} - I_{2-im}) \quad \text{.....(1)}$$

$$V_{1-im} - V_{2-im} = R_1(I_{1-im} - I_{2-im}) + X_1(I_{1-re} - I_{2-re}) \quad \text{.....(2)}$$

$$|\bar{I}_a|^2 = (I_{1-re} + I_{2-re})^2 + (I_{1-im} + I_{2-im})^2 \quad \text{.....(3)}$$

$$|\bar{I}_b|^2 = \left[-\frac{1}{2}(I_{1-re} + I_{2-re}) + \frac{\sqrt{3}}{2}(I_{1-im} - I_{2-im})\right]^2 + \left[-\frac{1}{2}(I_{1-im} + I_{2-im}) - \frac{\sqrt{3}}{2}(I_{1-re} - I_{2-re})\right]^2 \quad \text{.....(4)}$$

$$|\bar{I}_c|^2 = \left[-\frac{1}{2}(I_{1-re} + I_{2-re}) - \frac{\sqrt{3}}{2}(I_{1-im} - I_{2-im})\right]^2 + \left[-\frac{1}{2}(I_{1-im} + I_{2-im}) + \frac{\sqrt{3}}{2}(I_{1-re} - I_{2-re})\right]^2 \quad \text{.....(5)}$$

Exact Method

$$|\bar{V}_{ab}|^2 = \left[\frac{3}{2}(V_{1-re} + V_{2-re}) - \frac{\sqrt{3}}{2}(V_{1-im} - V_{2-im})\right]^2 +$$

$$\left[\frac{3}{2}(V_{1-im} + V_{2-im}) + \frac{\sqrt{3}}{2}(V_{1-re} - V_{2-re})\right]^2 \quad .....(6)$$

$$|\bar{V}_{bc}|^2 = \left[\sqrt{3}(V_{1-re} - V_{2-re})\right]^2 + \left[\sqrt{3}(V_{1-im} - V_{2-im})\right]^2 \quad .....(7)$$

$$|\bar{V}_{ca}|^2 = \left[\frac{-3}{2}(V_{1-re} + V_{2-re}) - \frac{\sqrt{3}}{2}(V_{1-im} - V_{2-im})\right]^2 +$$

$$+\left[\frac{-3}{2}(V_{1-im} + V_{2-im}) + \frac{\sqrt{3}}{2}(V_{1-re} - V_{2-re})\right]^2 \quad .....(8)$$

Exact Method

- Taking $\bar{V}_1$ as a reference vector (setting V_{1-im} equal to zero) results in having 8 nonlinear equations in 7 variables.
- The equations are non-linear and further overdetermined by one. Thus, a non-linear least square estimation method, for example the Newton-Gauss method is used for a solution.

Results

- Summary of results for a test carried out on a TVA 18 MVA SAT at a test site in Virginia.

TABLE 1
MEASURED VOLTAGES AND CURRENTS

Standard ANSI/IEEE Test (from 161 kV side)		
$V_0 = 1402.91$ V	$3I_0 = 28.17$ A	$P_0 = 3114.11$ W
Proposed Method Test (from 6.9 kV side)		
$V_{ab} = 359.21$ V	$V_{bc} = 329.63$ V	$V_{ca} = 365.29$ V
$I_a = 282.78$ A	$I_b = 775.71$ A	$I_c = 772.46$ A
$P = 14301$ W		

TABLE 2
CALCULATED IMPEDANCE (%)

	Standard ANSI/IEEE Test	Proposed Method			
		Approximate Model		Exact Model	
		Value	Error	Value	Error
Z_{pt-0}	10.37	10.54	1.68%	10.41	0.42%
R_0	0.82	0.78	4.9%	0.83	1.2%

Conclusions

- The test is expected to be valuable to those seeking to determine zero sequence parameters not available on many legacy SAT units with affordable costs.
- Method is extendable to transmission type transformers – authors are developing model.
- Field testing has confirmed the high accuracy offered by the method.