Testing CT in Delta Winding – A Case Study

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Abstract

Measuring the ratio of a current transformer (CT) mounted in a transformer delta winding can often be confusing if the electrical principals are not understood. This can be the case especially if there is wiring error leading to incorrect identification of the CT being tested.

This paper discusses the principles around performing a ratio measurement of CT's mounted in delta winding. A case study is also presented to explain the test results due to incorrect CT wiring.

Keywords: Current Transformer, Delta Winding, Turns-Ratio.

CT's in Delta Winding

Tertiary Delta Windings are commonly found in transformers with Wye-Wye Primary-Secondary Windings to provide stability when the loading is unsymmetrical and also to provide an auxiliary source in different voltage level (Figure 1). CT's mounted in the tertiary winding can be used as a source for zero sequence polarizing current for directional overcurrent protection, or for overcurrent protection if the tertiary winding is loaded.

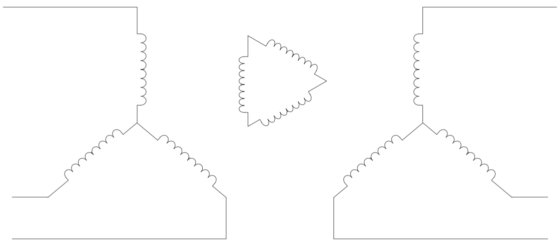


Fig. 1 Wye-Wye-Delta Transformer

Ratio Measurement for Bushing CT

When measuring ratio of CT's mounted at the bushing of the transformer winding terminals, the voltage injection method is normally used instead of the current injection method due to the impedance of the transformer winding. For this method, a test voltage (V_s) is applied to the secondary of the CT and a voltage measurement (V_m) is taken at the bushing terminals of the transformer windings (Figure 2).

The ratio is then calculated using the formula:

$$\text{CT Ratio} = V_m/V_s$$

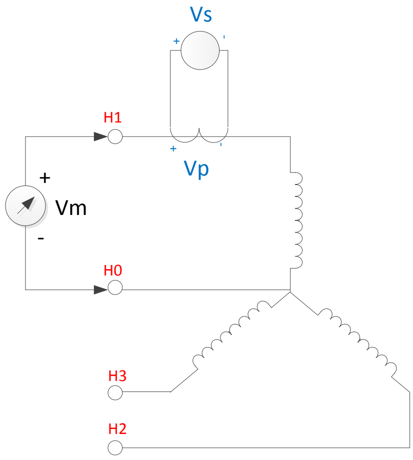


Fig. 2 Ratio Measurement with Voltage Method

Vm is used for the ratio calculation since the true primary ratio voltage (V_p) is not accessible. However, since the impedance of the measurement input is much higher than the impedance of the transformer winding, V_m is effectively equal to V_p.

Ratio Measurement in Delta Winding

When measuring the ratio of the CT for the delta winding, consideration must be given to whether the CT is inside the delta or outside the delta.

<u>CT Outside the Delta Winding</u>

For CT's which are mounted outside the delta winding, no compensation factor to the ratio is required (Figure 3). This is due to the fact that impedance of the voltage measurement input is much higher than the impedance of the transformer winding.

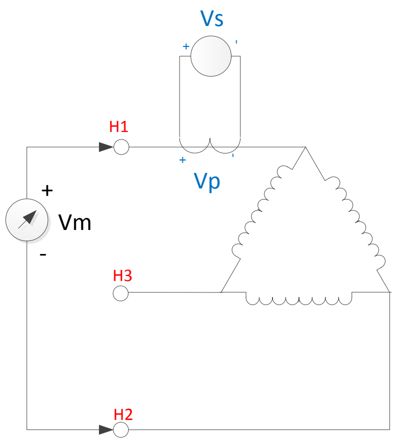


Fig. 3 Ratio Measurement with CT Outside the Delta Winding

CT Inside the Delta Winding

For CT's which are mounted inside the delta winding, a compensation factor needs to be applied (Figure 4). Depending on where the primary voltage measurement is made, and also whether the opposite winding is shorted or not, this compensation could be different.

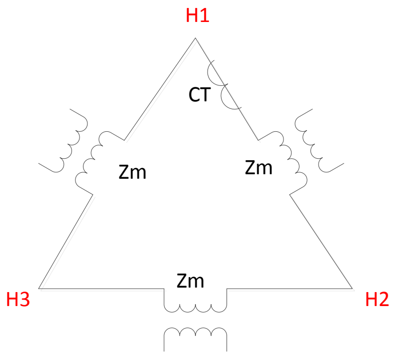


Fig. 4 CT Inside the Delta Winding

Ratio Measurement with Delta Compensation

According to the CT Analyzer reference manual, when the primary measurement is taken from the same leg as where the CT is located, then a compensation factor of 2/3 needs to be applied (Figure 5). This means the measured voltage (V_m) no longer equal to V_p as in the cases where the CT is outside the delta winding, but $V_m = 2/3 * V_p$.

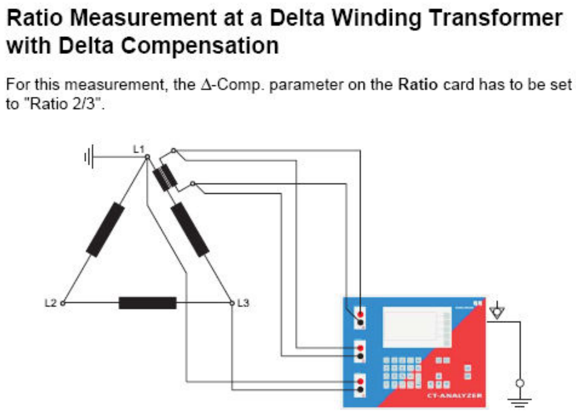


Fig. 5 Ratio Measurement with Delta Compensation

When the primary measurement is taken from the adjacent leg of where the CT is located (i.e. L1-L2 in Figure 5), then the compensation factor is 1/3. This means $V_m = 1/3 * V_p$.

Ratio Measurement without Delta Compensation

When the primary measurement is taken from the same leg as where the CT is located, and the opposite winding of that leg is short circuited, then a compensation factor of one (no compensation) is applied (Figure 6).

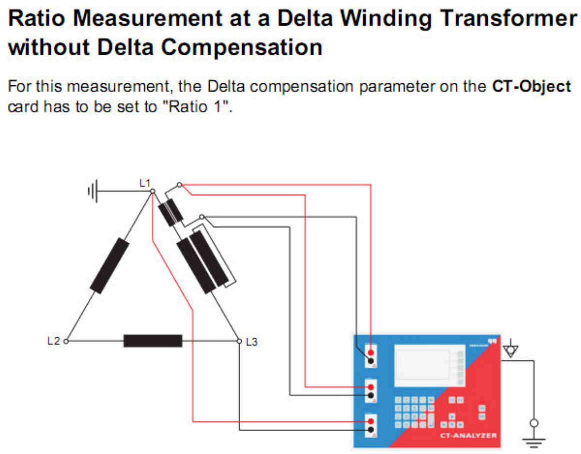
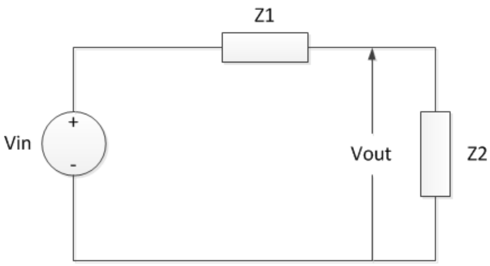


Fig. 6 Ratio Measurement Without Delta Compensation

The following section will explain the electrical principles behind the applications of these various delta compensations.

Voltage Divider Principle

The voltage divider principle states that for an electrical circuit with two impedances (Z1, Z2), the voltage at the point between Z1 and Z2 is as follows:



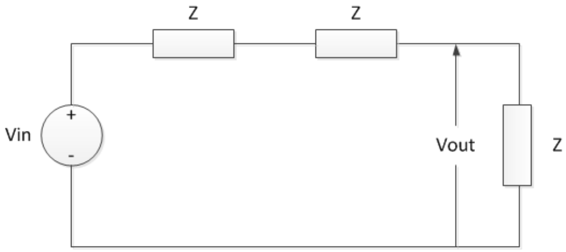
$$Vout = \frac{Z2}{(Z1+Z2)} \times Vin$$

If Z1 = Z2, then

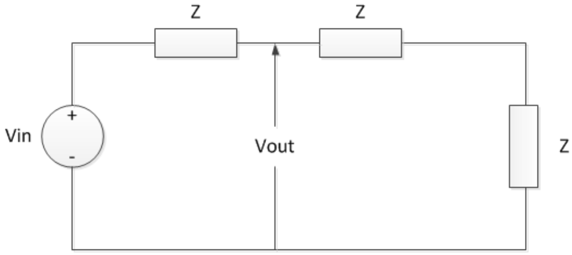
$$Vout = \frac{1}{2} \times Vin$$

Voltage Divider with Three Impedances

For an electrical with three equal impedances, the voltages between the impedances are given as follows:



$$Vout = \frac{Z}{3Z} \times Vin = \frac{1}{3} \times Vin$$



$$Vout = \frac{2Z}{3Z} \times Vin = \frac{2}{3} \times Vin$$

Ratio Measurement

When the voltage divider principle is applied to the ratio measurement, the delta compensation factors can be explained.

Case #1 – 2/3 Compensation

In this case, the primary measurement V_m is in the same leg as the CT. The equivalent voltage divider circuit for this case is as follows:

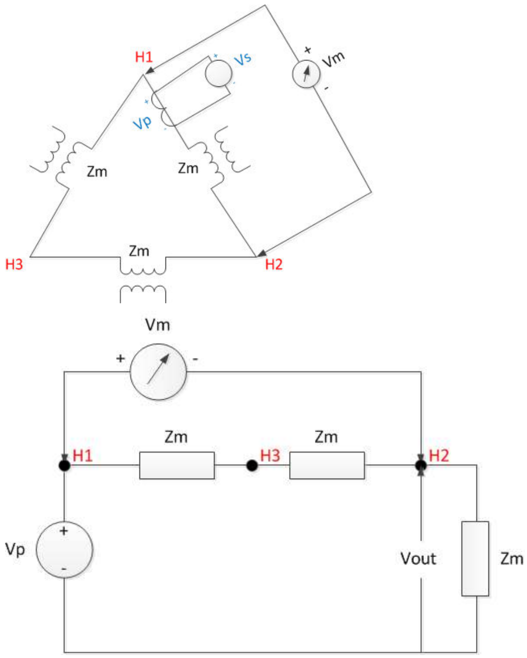


Fig. 7 Case #1 – 2/3 Compensation

The resulting formula for V_m is:

$$Vm = Vp - Vout$$

$$Vout = \frac{1}{3} \times Vp$$

Therefore,

$$Vm = Vp - \frac{1}{3} \times Vp = \frac{2}{3} \times Vp$$

Delta Compensation Factor = 2/3

Case #2 – 1/3 Compensation

In this case, the primary measurement V_m is in the adjacent leg of where the CT is located. The equivalent voltage divider circuit for this case is as follows:

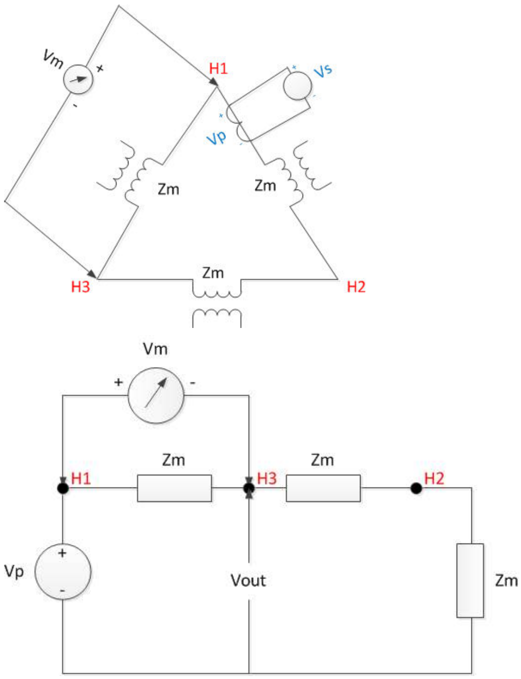


Fig. 8 Case #2 – 1/3 Compensation

The resulting formula for V_m is:

$$Vm = Vp - Vout$$

$$Vout = \frac{2}{3} \times Vp$$

Therefore,

$$Vm = Vp - \frac{2}{3} \times Vp = \frac{1}{3} \times Vp$$

Delta Compensation Factor = 1/3

Case #3 – No Compensation

In this case, the primary measurement V_m is in the same leg as the CT. However, the opposite winding of the same leg is short circuited.

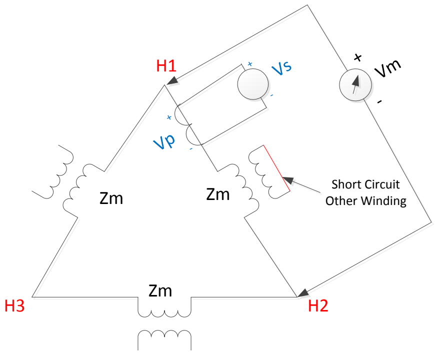


Fig. 9 Case #3 – No Compensation

In order to understand why no compensation is needed for this case, one must first look at a simple equivalent circuit of the transformer (Figure 10).

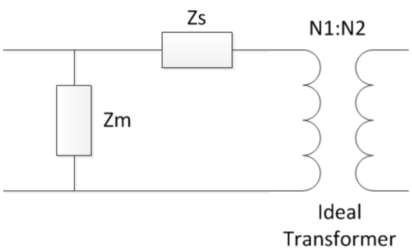
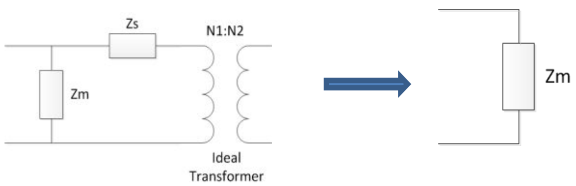


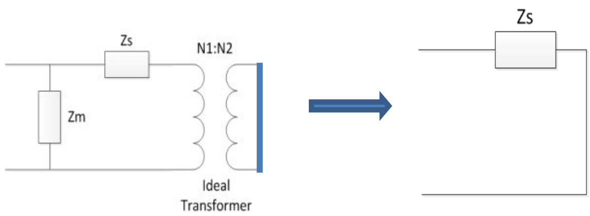
Fig. 10 Transformer Equivalent Circuit

The magnetizing impedance (Z_m) is much greater than the short-circuit impedance (Z_s).

Under open circuit conditions, the equivalent circuit becomes mainly Z_m:



Under short-circuit conditions, the equivalent circuit becomes mainly Z_s:



Therefore, in Case #3 where the opposite winding is short-circuited, the impedance of the winding where the CT is located effectively becomes equal to Z_s. The equivalent circuit then becomes as follows:

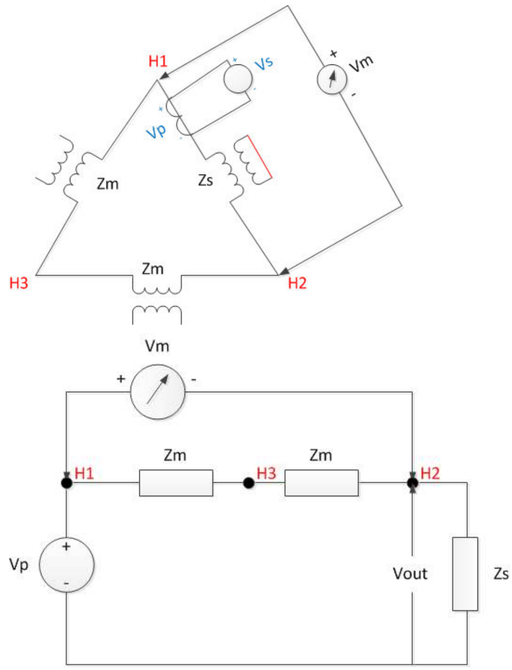


Fig. 11 Case #3 – No Compensation

The resulting formula for V_m is:

$$Vm = Vp - Vout$$

$$Vout = \frac{Zm}{2Zm + Zs} \times Vp$$

But,

$Zm >> Zs$, therefore $Vout \approx 0$

Therefore,

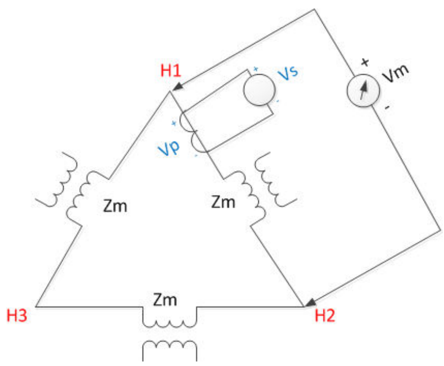
$$Vm = Vp - 0 = 1 \times Vp$$

Delta Compensation Factor = 1 (no compensation)

Summary

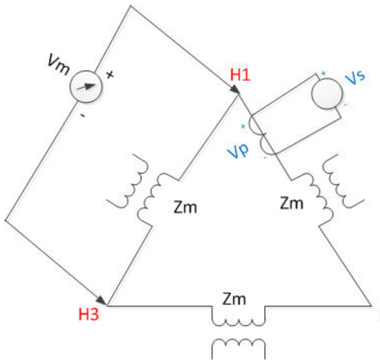
The following is a summary of the three cases:

<u>Case #1:</u>



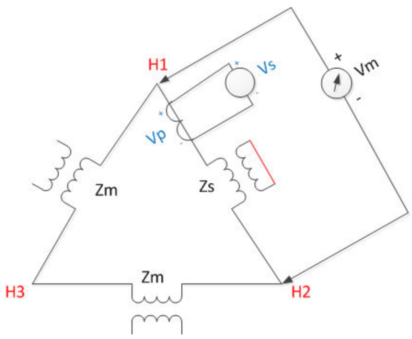
Delta Compensation Factor = 2/3

Case #2:



Delta Compensation Factor = 1/3

Case #3:



Delta Compensation Factor = 1

Case Study

The following is a case study of a test performed at a utility in Colorado, USA. The voltage divider principle is used to explain the behavior of some quite unexpected test results.

The CT's under test were located inside a delta tertiary winding of a 230/115/13.8kV Wye-Wye-Delta transformer.

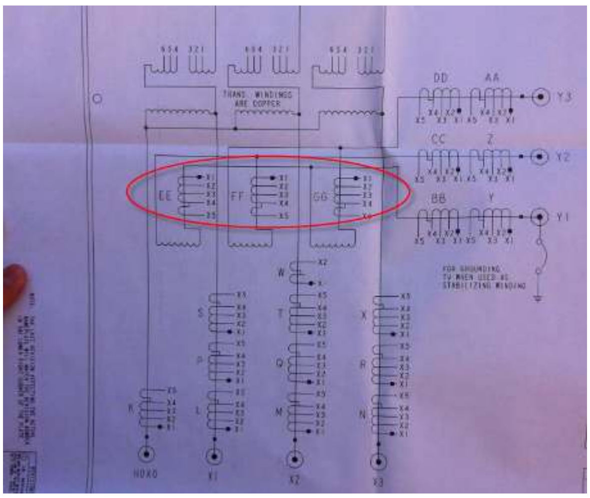
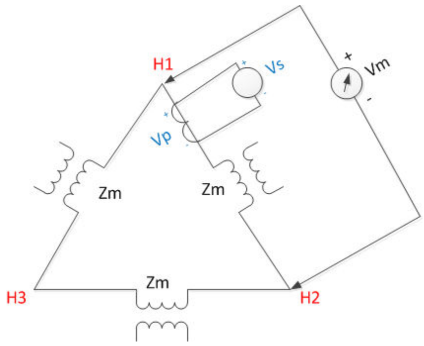


Fig. 12 CTs Under Test

The three cases using different delta compensations were tested and the resutls are as follows.

Case #1 – 2/3 Compensation

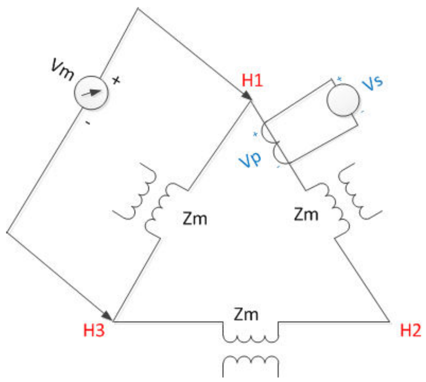


In this case, the expected compensation factor is 2/3, however the following results were observed:

- Nameplate Ratio: 1200:5A (Ratio = 240)
- Test Result: 3600:5A (Ratio = 720)
- Apply the Factor of 2/3: Ratio = 720 x 2/3 = 480
- But when we apply the Factor 1/3: Ratio = 720 x 1/3 = 240

A delta compensation factor of 1/3 instead of 2/3 was required to obtain the correct CT ratio.

Case #2 – 1/3 Compensation

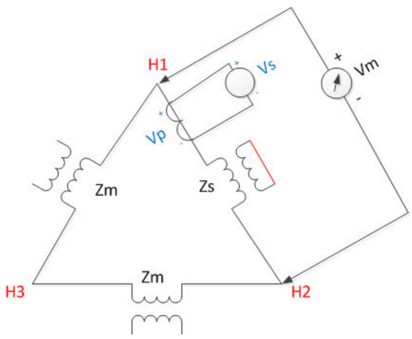


In this case, the expected compensation factor is 1/3, however the following results were observed:

- Nameplate Ratio: 1200:5A (Ratio = 240)
- Test Result: 3600:5A (Ratio = 720)
- Apply the Factor of 1/3: Ratio = 720 x 1/3 = 240
- But the Polarity was inversed

The delta compensation was as expected, but the polarity of the CT was inversed.

Case #3 – No Compensation



In this case, the expected compensation factor is 1 (no compensation), however the following results were observed:

- Nameplate Ratio: 1200:5A (Ratio = 240)
- Test Result: 50,000:5A
- Check Ratio with QuickTest: V_m = near 0V (noise)

The test result gave the most puzzling observation. With V_m equal to zero,

CT Ratio = V_s / V_m = Infinite Ratio

This is confirmed by the CT Analyzer's ratio of 50,000:5A which is the highest the test set can measure.

Fig. 13 Testing at a Utility in Colorado, USA

Case Study – Explained

After some investigation, it was found that the CT wiring was not according to the wiring diagram. In fact, the CT under test was in a different leg of the delta winding.

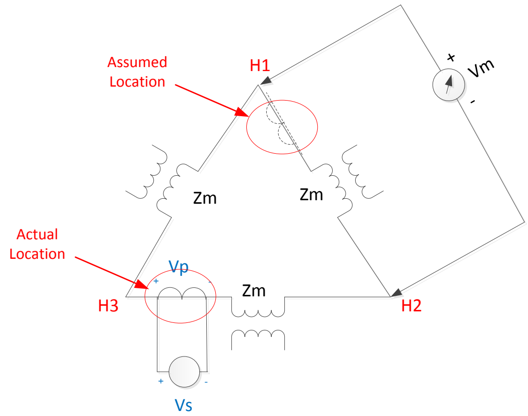
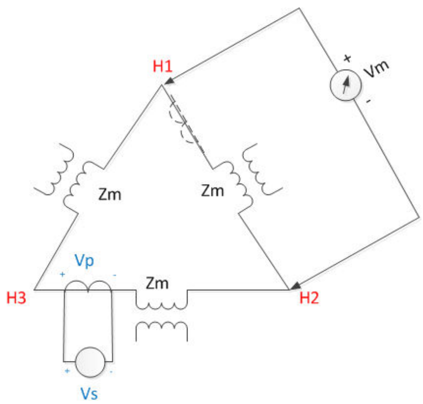


Fig. 14 Incorrect CT Location

With this in mind, the following explanations were given for the three cases:

Case #1 - Explained

In this case, the CT is located in the adjacent leg of the delta winding as the voltage measurement Vm.



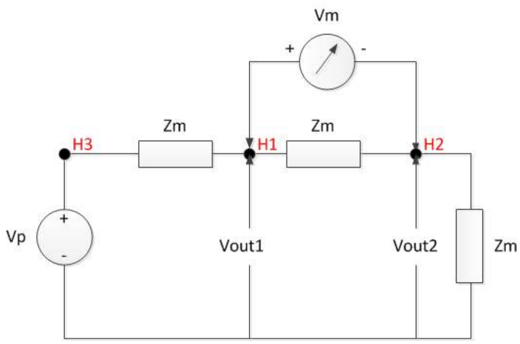


Fig. 15 Case #1 Actual Equivalent Circuit

The resulting formula for V_m is:

$$Vm = Vout1 - Vout2$$

$$Vout1 = \frac{2}{3} \times Vp$$

$$Vout2 = \frac{1}{3} \times Vp$$

Therefore,

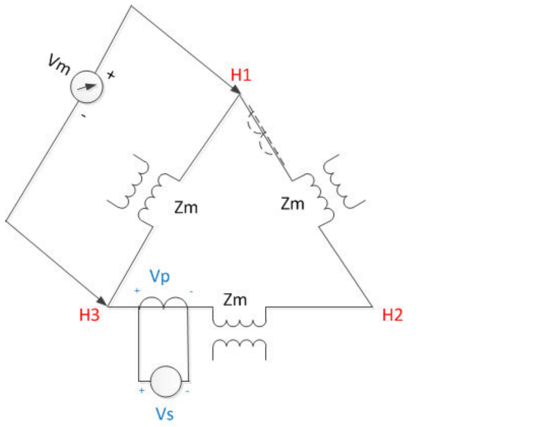
$$Vm = \frac{2}{3} \times Vp - \frac{1}{3} \times Vp = \frac{1}{3} \times Vp$$

The correct delta compensation factor in this case is 1/3. This coincides with the observed test result for Case #1:

- Nameplate Ratio: 1200:5A (Ratio = 240)
- Test Result: 3600:5A (Ratio = 720)
- Apply the Factor of 1/3: Ratio = 720 x 1/3 = 240

Case #2 – Explained

In this case, the CT is located in the other adjacent leg of the delta winding as the voltage measurement Vm.



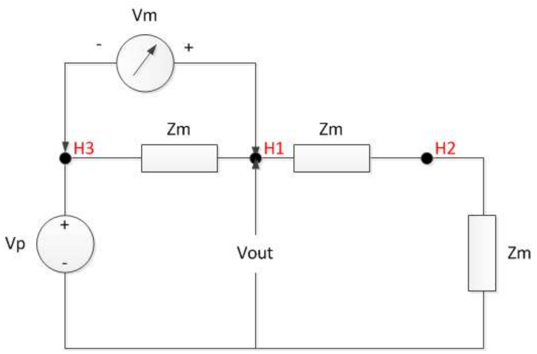


Fig. 16 Case #2 Actual Equivalent Circuit

The resulting formula for V_m is:

$$Vm = Vout - Vp$$

$$Vout = \frac{2}{3} \times Vp$$

Therefore,

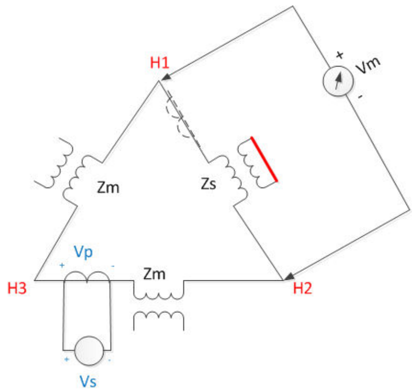
$$Vm = \frac{2}{3} \times Vp - Vp = -\frac{1}{3} \times Vp$$

The correct delta compensation factor in this case is 1/3, but with the polarity inversed. This coincides with the observed test result for Case #2:

- Nameplate Ratio: 1200:5A (Ratio = 240)
- Test Result: 3600:5A (Ratio = 720)
- Apply the Factor of 1/3: Ratio = 720 x 1/3 = 240
- Polarity Reversed

Case #3 – Explained

In this case, the CT is located in the adjacent leg of the delta winding as the voltage measurement V^m, but the opposite winding of the adjacent leg is short-circuited.



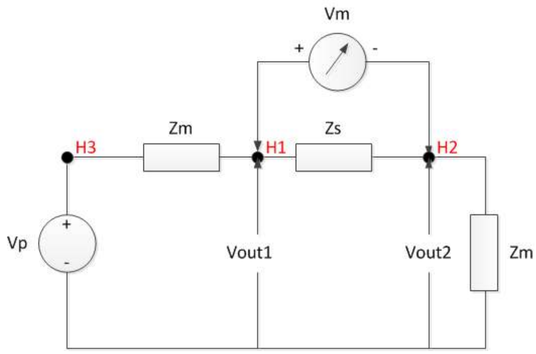


Fig. 17 Case #3 Actual Equivalent Circuit

The resulting formula for V_m is:

$$Vm = Vout1 - Vout2$$

$$Vout1 = \frac{Zs + Zm}{Zs + 2Zm} \times Vp$$

But,

$$Zm >> Zs$$

Therefore,

$$Vout1 = \frac{Zm}{2Zm} \times Vp = \frac{1}{2} \times Vp$$

Also,

$$Vout2 = \frac{Zm}{Zs + 2Zm} \times Vp$$

But,

$$Zm >> Zs$$

Therefore,

$$Vout2 = \frac{Zm}{2Zm} \times Vp = \frac{1}{2} \times Vp$$

And therefore,

$$Vm = Vout1 - Vout2$$

$$Vm = \left(\frac{1}{2} \times Vp \right) - \left(\frac{1}{2} \times Vp \right) = 0$$

This coincides with the observed test result for Case #3 with $V_m = 0$ and infinite ratio.

Conclusion

Ratio Measurement for CT's located inside the delta winding requires a compensation factor to correct for the voltage divider effect of the transformer windings. Proper understanding of the equivalent circuit using the voltage divider principle can help to understand how these compensation factors are derived and can also help in cases of unexpected results.

References

[1] OMICRON electronics GmbH: CT Analyzer Reference Manual

About the Author

Peter Fong is a Professional Engineer registered in the province of British Columbia. Peter was previously an Application Engineer with OMICRON electronics Corp. USA and has vast experience with relay and substation testing equipment. Peter is a member of IEEE and has given papers in various technical conferences. He is currently the General Manager of Sequence Instruments Inc. in Vancouver, Canada.

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