When Is Compensation A Bad Thing?

Problems In Applying Wye Connected Transformers With Delta Tertiary Windings On Distribution Feeders

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What are we talking about?

A delta connected winding on an auto transformer or a wye-wye transformer. Referred variously as compensating, stabilizing, or tertiary winding.

Why Do We Use Compensating Windings?

The IEEE/ANSI C57.12.80 definition of stabilizing winding is “a delta connected auxiliary winding used particularly in Y-connected transformers for such purposes as the following”:

1. Stabilize The Neutral Point Of The Fundamental Frequency Voltages
2. Minimize Third-harmonic Voltage And The Resultant Effects On The System
3. Mitigate Telephone Influence Due To Third-harmonic Currents And Voltages
4. Minimize The Residual Direct-current Magnetomotive Force On The Core
5. Decrease The Zero-sequence Impedance Of Transformers With Y-connected Windings

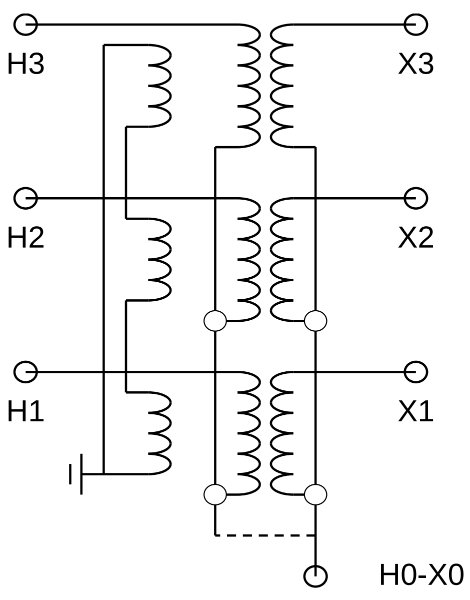


Figure 1 - Wye-Wye-Delta Transformer

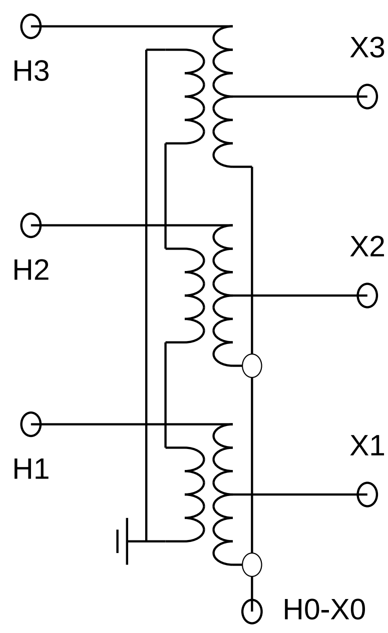


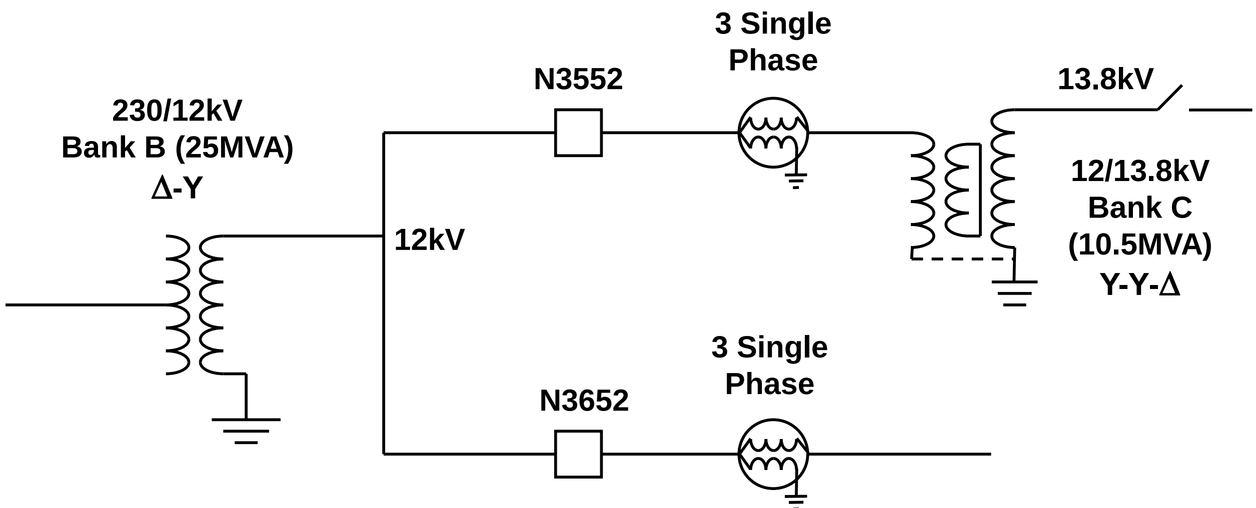
Figure 3 - Auto-Delta Transformer

Background

On Georgia Power Company's distribution wye-wye-delta and auto-delta transformers are frequently used on distribution feeders as step-up or step-down voltage converters when a particular distribution line requires a voltage different than the other lines in the station. These transformers are three phase and range in size from 5MVA to 20MVA. Most of them are located on the distribution line just inside the line disconnect switch. They are usually protected only by the overcurrent relays in the feeder breaker. There is not a differential relay or additional overcurrent relays connected to the step-up / step-down transformer.

Additionally, most distribution feeders operating at 12kV or 13.8kV have single phase voltage regulators installed between the distribution feeder breaker and the step-up / step-down transformer.

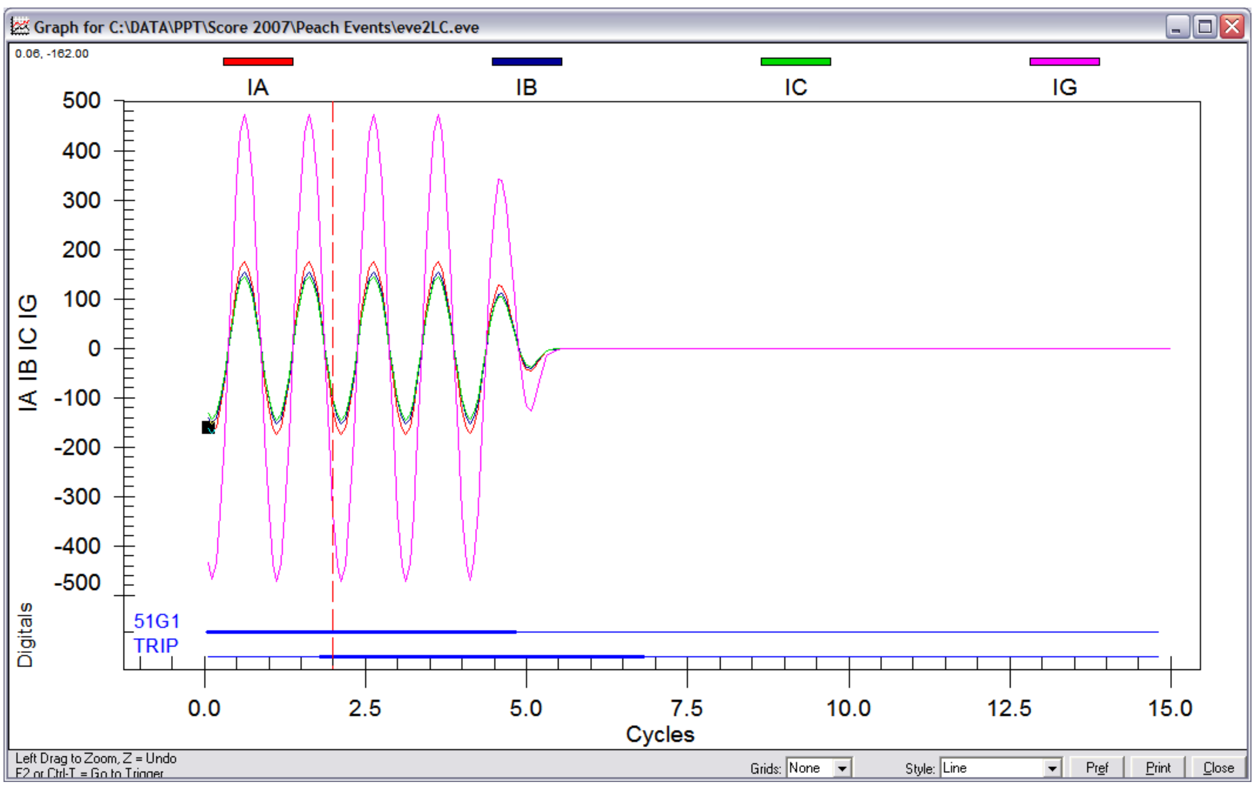
Case #1 – Peach Orchard



Peach Orchard Station Bank B Arrangement

Peach Orchard - Initial Problem

- 13.8kV Feeder N3552 locked out from a ground trip.
- The line side disconnect was opened, N3552 was closed and immediately tripped again.
- The regulators and 12/13.8kV transformer were tested and no problems were found.
- Several of these trips occurred and it was found that they all coincided with a regulator “running away”.

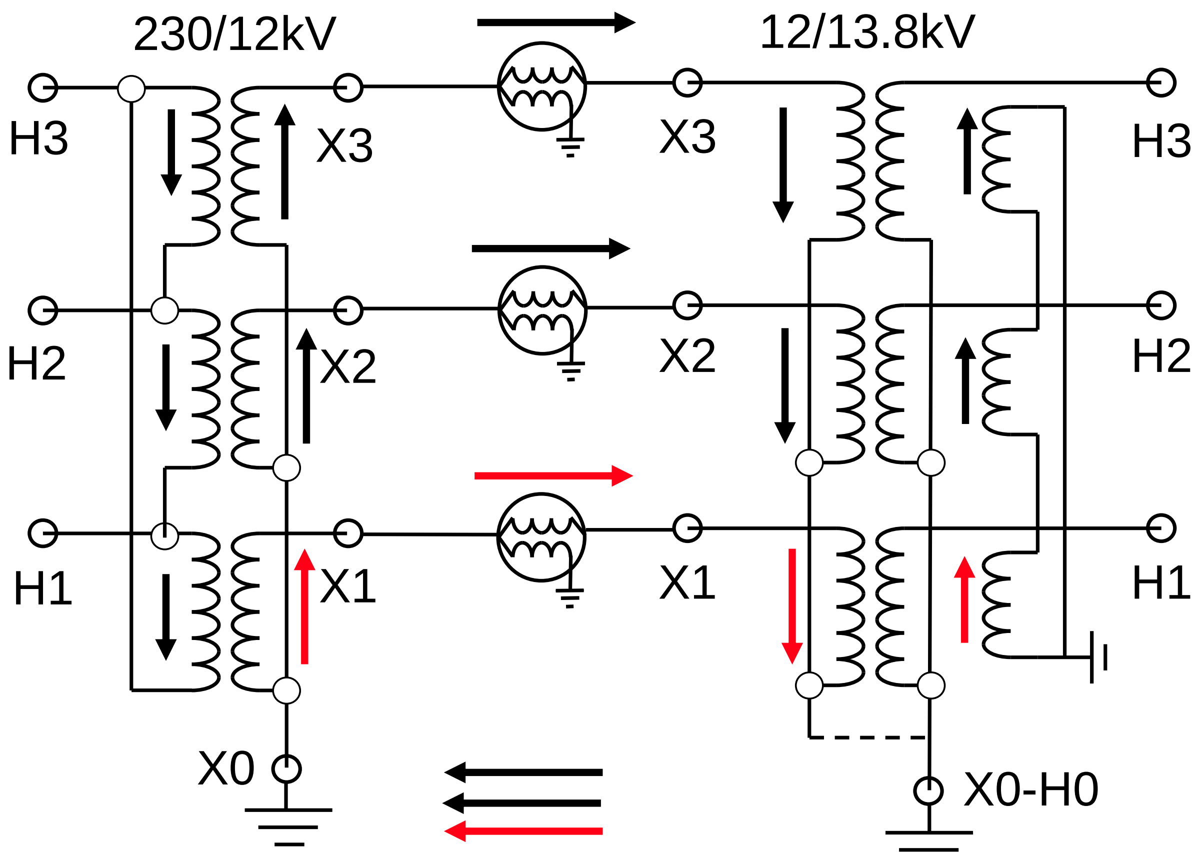


Peach Orchard - Feeder Relay Event Report

As can be seen in the event file, the phase A, B, & C currents are of equal magnitude and phase angle – a classic $3I_0$ display. The residual current is the sum of the three phases and exceeded the pickup of the residual ground time overcurrent element in the relay causing the relay to trip the breaker.

Peach Orchard – Reason for Misoperation

The 12/13.8kV transformer had a delta tertiary that caused the transformer to supply zero sequence current back into the 12kV bus. In this case the “runaway” regulator was driving the zero sequence current as shown in the following diagram:



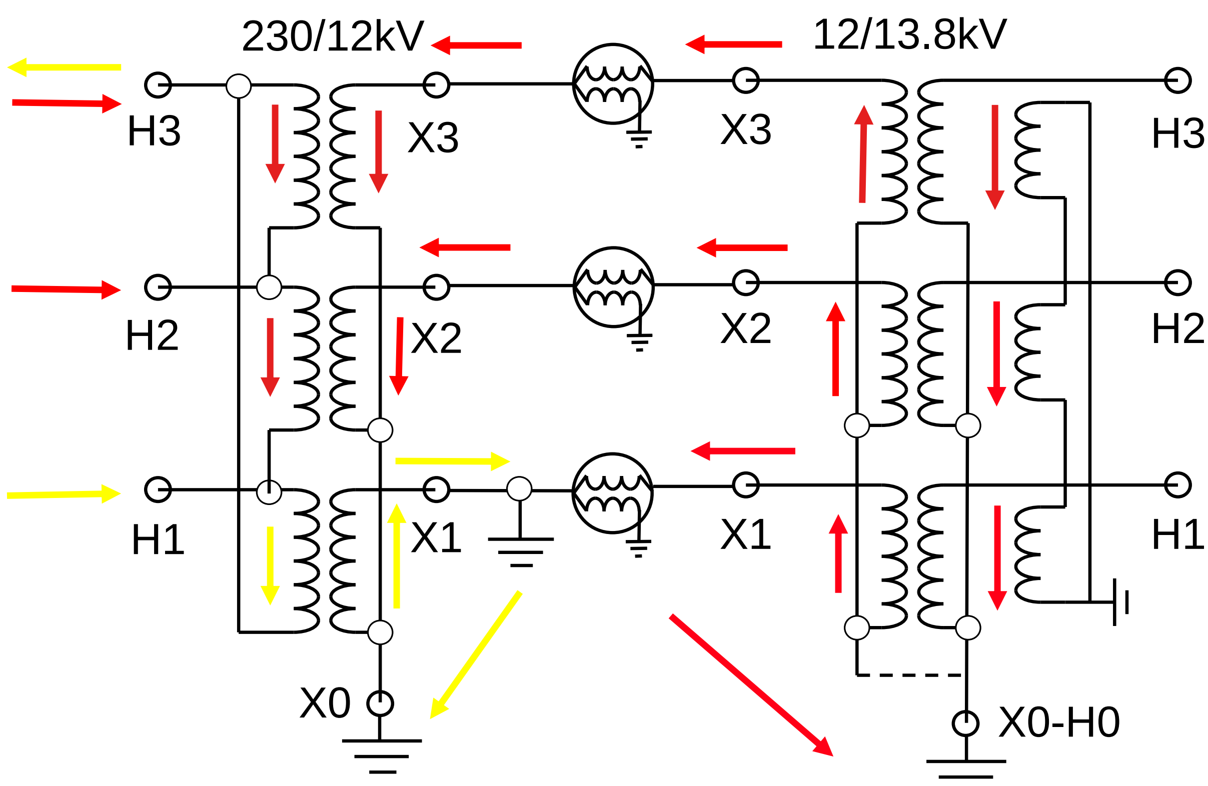
In the above diagram, the red vectors indicate the current flow generated when the voltage regulator attempts to raise the voltage on one phase. The delta winding attempts to re-balance the unequal phase voltages. Current is forced into the 12/13.8kV transformer and circulates in the delta winding which then draws current from the other two phases in the station main transformer.

Peach Orchard – Operational Problems

- A ground fault on the 12kV feeder will be fed by the 12/13.8kV transformer as well as the main 230/12kV bank. If the ground relay setting on the 13.8kV feeder is faster than the 12kV feeder the 13.8kV feeder could trip and possibly lock out for a fault on the 12kV feeder.

- This additional zero-sequence source will also desensitize the ground relay on the feeder breaker protecting the line and transformer for faults on the 13.8kV side of the transformer

- The backup ground relay on the main transformer neutral will be desensitized for faults on either feeder since the 12/13.8kV transformer will be supplying zero-sequence current to ground faults on either feeder.



This diagram illustrates how a fault on between the main transformer in the step-up transformer will be fed from both. The feeder breaker is omitted from this drawing for clarity, it would be located between the 230/12kV transformer and the voltage regulators.

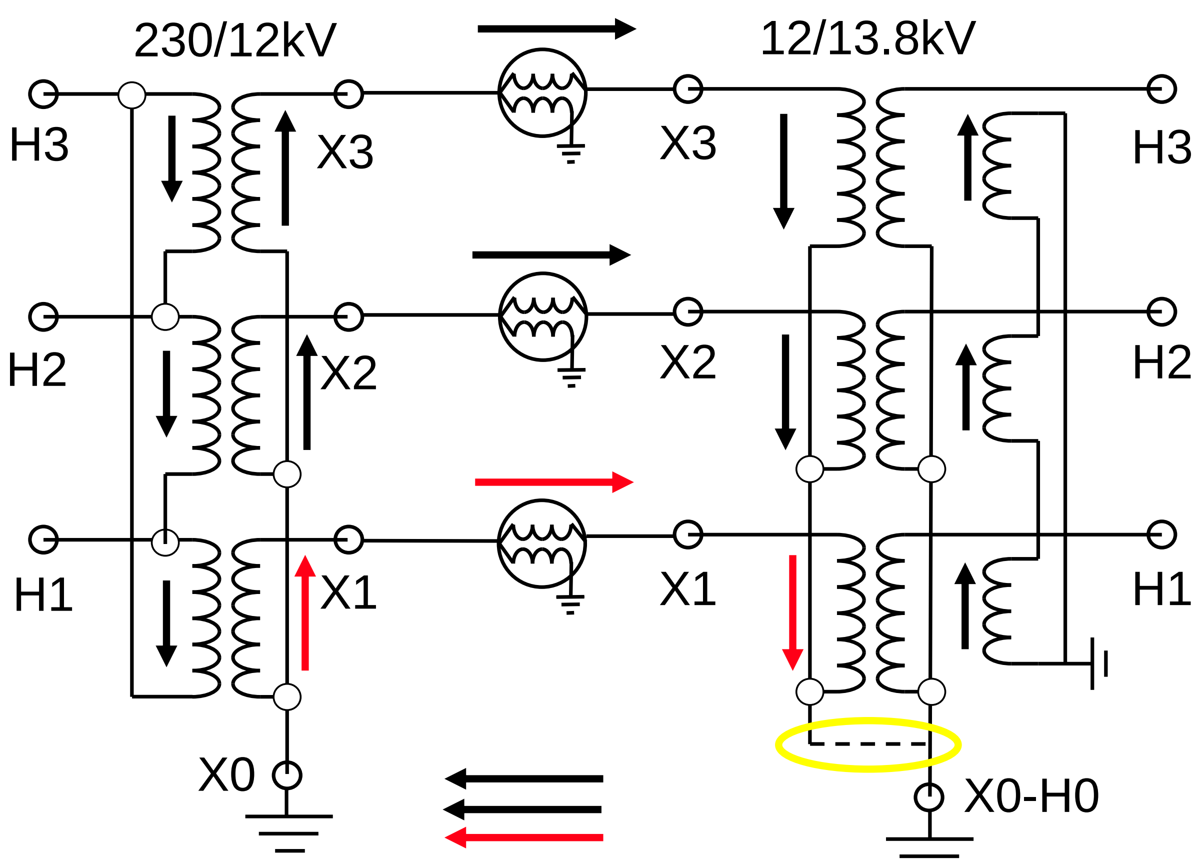
Peach Orchard - Solutions Explored

1. Unground X0 bushing to isolate the 12kV side of the transformer from the 12kV bus zero sequence network.

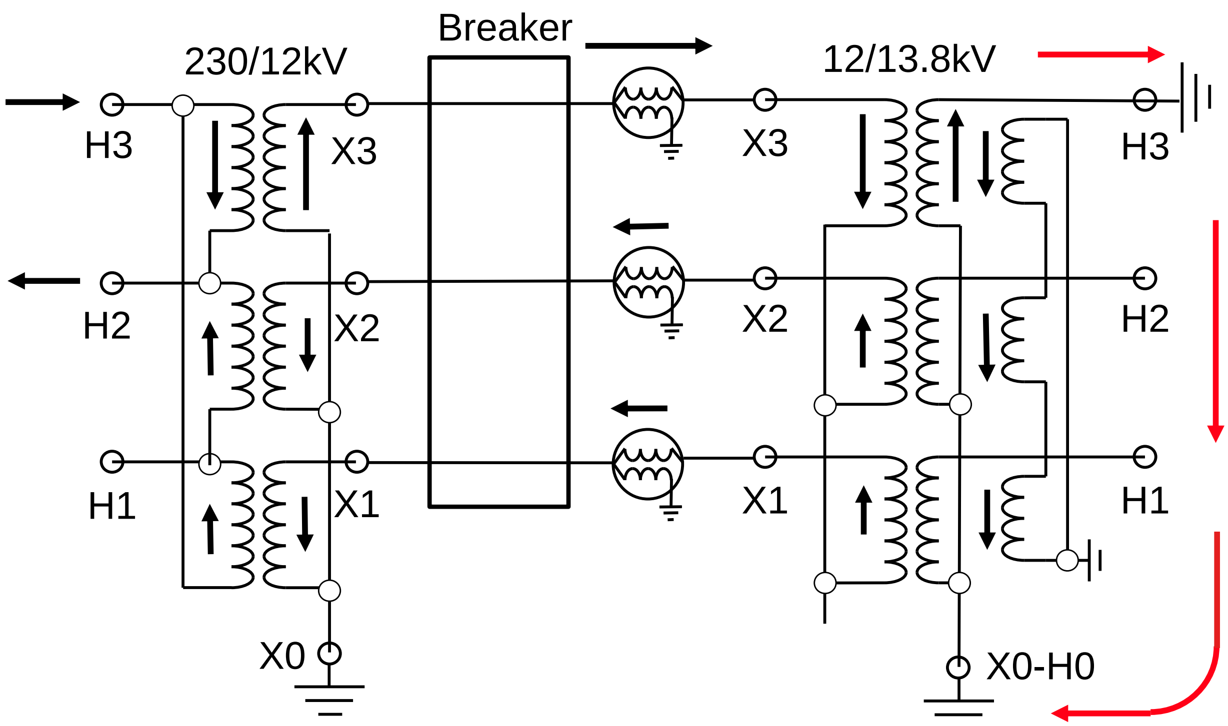
2. Break the delta tertiary so that the transformer is no longer a source of zero sequence current.

Peach Orchard - Solution #1 Investigation

The manufacturer of the transformer was asked if there is an objection to lifting the secondary Y Ground (bushing X0).



Since the X0, X1, X2, and X3 bushings are on the source side (towards the 12kV bus) this would eliminate the transformer being a source of zero sequence current back into the 12kV bus. However, this would also require bringing in a separate ground current from the 13.8kV side of the transformer to the breaker relay. In the diagram below, the current flowing into the fault from H3 of the 12/13.8kV transformer causes current to flow in the 12/13.8kV transformer delta winding. This circulating current is in turn reflected back into all three phases on the 12kV side. The current seen at X1 & X2 is ½ the X3 current and opposite in phase angle. Because the vector sum of the currents seen in the breaker for an external ground is zero, the residual ground relay in the breaker will not operate for a ground fault on the 13.8kV feeder.



The manufacturer’s response to removing the ground connection to X0::

I understand that "lifting" means opening/disconnecting the ground connection of the neutral. This will cause the neutral to "shift" if the three line currents are not balanced perfectly. We are not trained to provide expert opinions on "systems" issues like this one, and often do not have information necessary to perform the analysis. However, as long as the maximum transient over-voltages that can appear at the neutral point is below the 110 kV BIL level, transformer is designed to withstand it. “The worst case condition would be a single line to ground fault near the transformer. At this condition, even if the line to line voltages are well balanced, line to ground voltages can vary significantly, depending on the amount of imbalance between lines.

Customer needs to verify that this will not cause problems with protective relaying and any line to ground connected load. I highly recommend that this question be best answered by the GPC Systems engineer with proper training and information.”

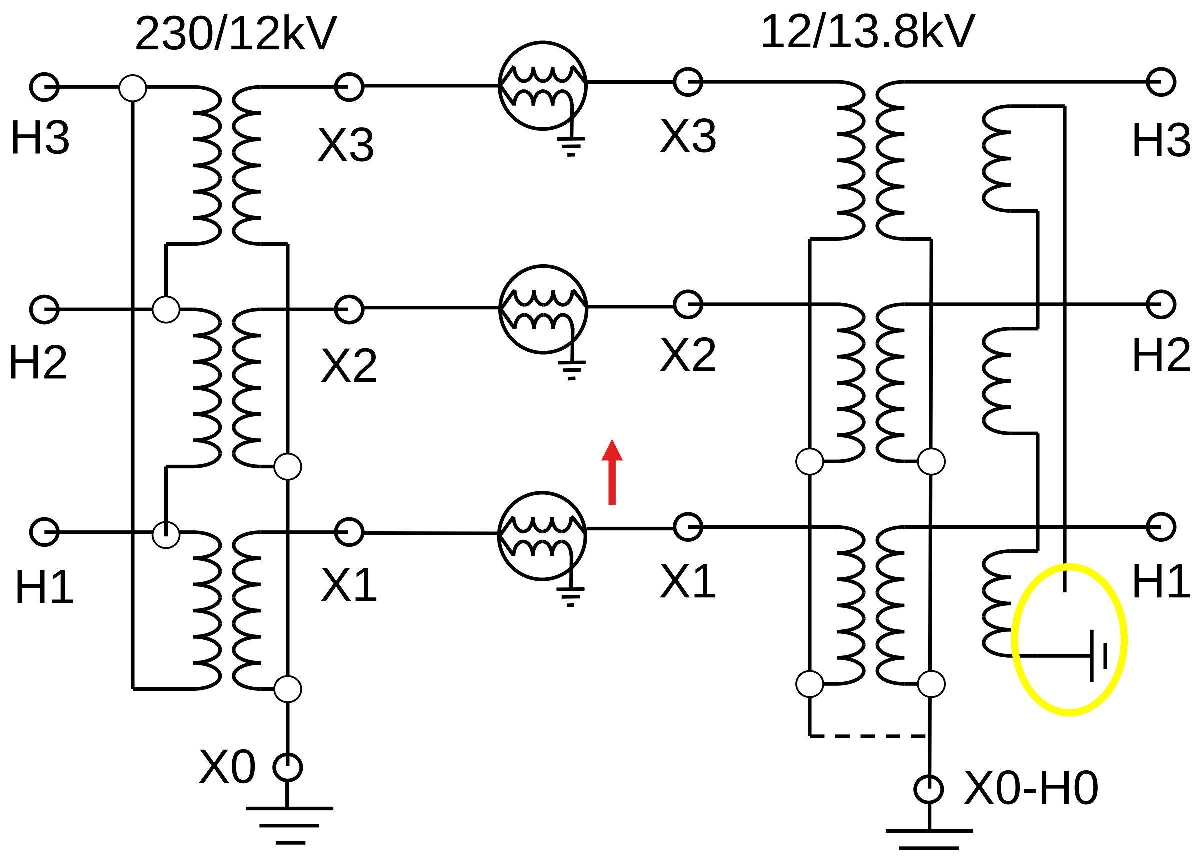
Peach Orchard - Solution #2 Investigation

The manufacturer of the transformer was asked if there is an objection to “breaking” the delta tertiary.

Their response was:

Without an intact delta tertiary, the transformer would no longer be a source of zero sequence current. The zero sequence current seen on the 12kV side of the transformer would be in direct proportion to the zero sequence current on the 13.8kV side. There would be no need to change the relay connections in the 12kV source side breaker.

Solution #2 - Break tertiary delta connection

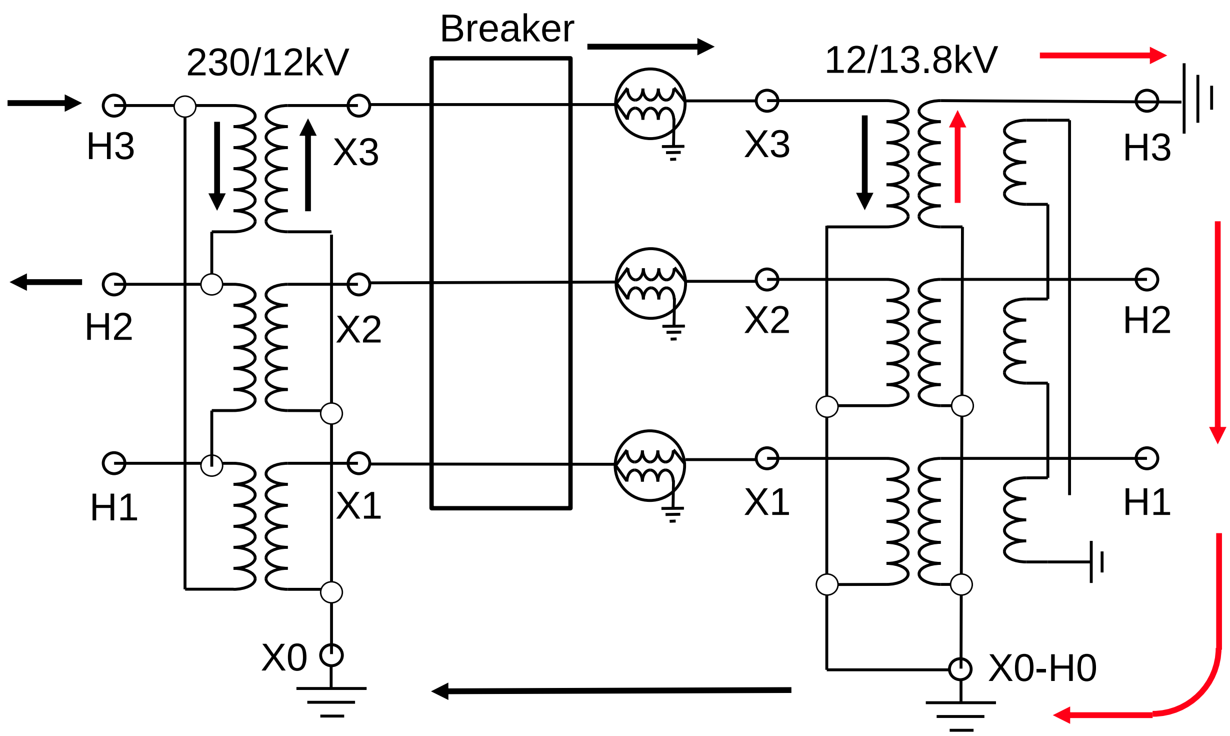


The manufacturer's response:

This will increase the zero-sequence impedance somewhat, but this transformer is a 3-phase, 3-legged design, which means that the magnetic circuit (core) is "OPEN" for any zero phase flux. For this reason, it is unlikely that eliminating delta-connected tertiary will cause any problem. For any other core design, such as shell form, 4 or 5 legged, or bank of single phase units, it is most likely required to have a delta connected tertiary as a "stabilizing" winding.

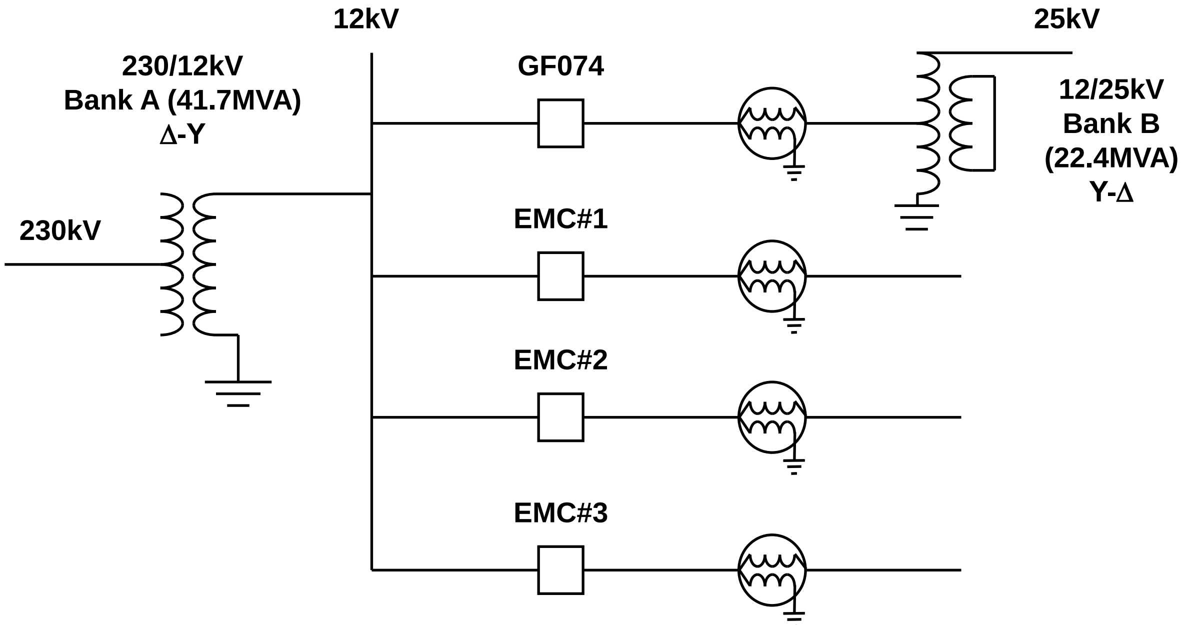
Solution #2 was chosen for Peach Orchard. The tertiary winding was opened. The leads from one corner of the tertiary were connected to a grounding lug near an access cover on top of the transformer. One lead was removed and smoothed off to prevent corona, insulated, and tied clear of any other leads or windings.

With the delta tertiary winding broken, the currents on the 12kV side of the 12/13.8kV transformer are now directly proportional to the current on the 13.8kV side. This makes it simple to set the breaker relay to protect for faults out on the 13.8kV line.



Line to Ground fault on feeder with delta winding broken

Case #2 – Busbee Parkway



Busbee Parkway is a station owned by one of our ITS partners. There are three feeders supplying EMC load at 12kV and a fourth feeder supplying Georgia Power load through a 12/25kV autotransformer with a delta tertiary. As was the case at the Peach Orchard station, all the voltage regulators are single phase.

The following problems were seen on the Georgia Power feeder at Busbee Parkway:

- A major customer on the feeder GF074 reported extreme variations in voltage, from 100V to 140V secondary. Most of the load was switched to other sources. A visit to the substation showed the regulator taps varied from -12 to +8.

- The 25kV feeder current was checked with a clamp-on ammeter and 18 amps was found in 2 phases, no current in the third phase.

- Reading current in the breaker relay showed 52 amps in each of 2 phases, 76 amps in the third phase, and 170 amps of residual current.

- One of the regulators was found to be locked out for reverse power.

- The investigation was hampered by the fact that it in this substation, the differential currents on the main transformer and the autobank were wired in delta making it harder to compare currents between CT circuits.

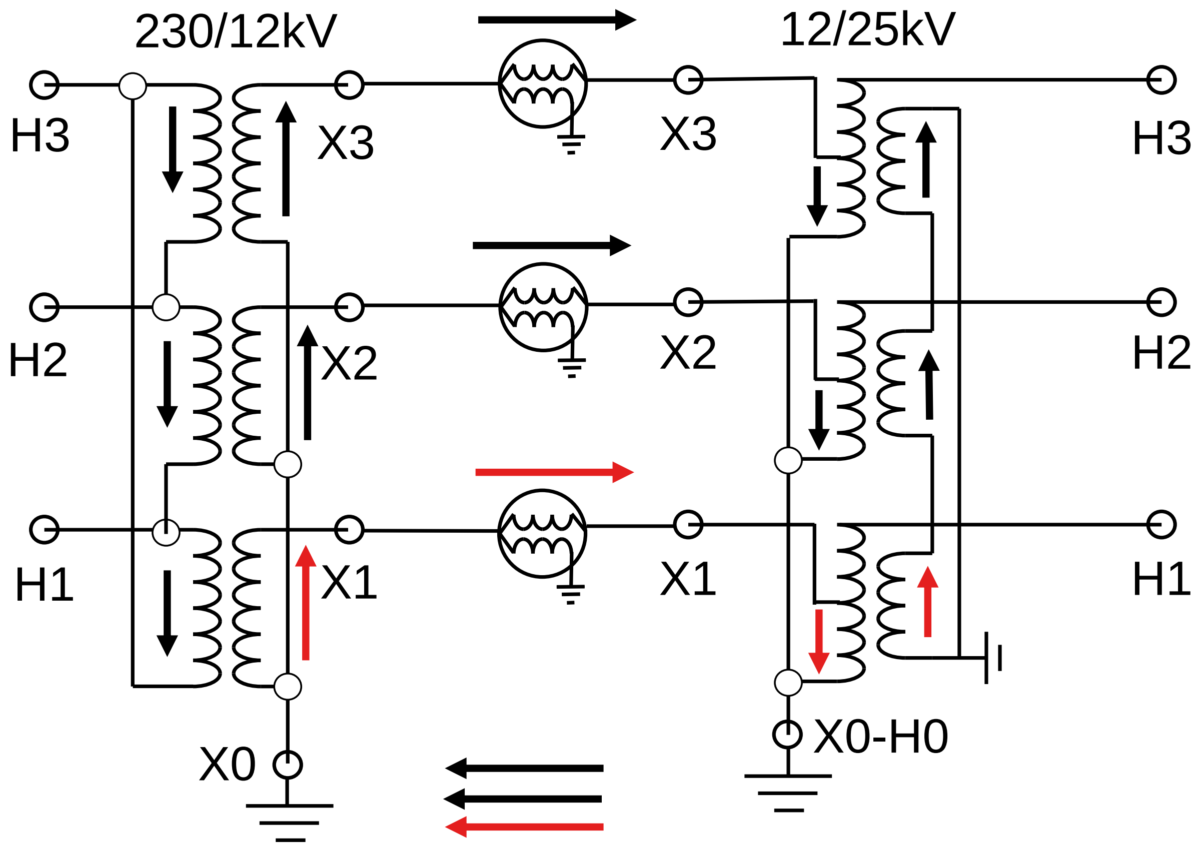
- The breaker ground relay cut-out switch was opened because of the fear that the breaker would trip erroneously on ground current.

Looking at the 12/25kV transformer nameplate it was noted that just like Peach Orchard, this transformer had a delta tertiary winding. This transformer is an autotransformer where Peach Orchard was wye-wye but the problem is exactly the same. When a single phase voltage regulator tries to change the voltage the delta tertiary tries to rebalance the voltage causing current to circulate in the tertiary and this circulating current is then reflected back into the source side of the transformer.

- Putting all the regulators on the same tap reduced the current in the breaker to around 40 to 45 amps in each phase and around 90 amps residual current.

- Even though the current was reduced in the 12kV breaker, the load seen by the relay did not correctly represent what was on the 25kV feeder.

Current flow in wye-delta auto when a regulator pushes circulating current through the 2 wye-delta connections.



Busbee Parkway – Issues

- The autotransformer will supply ground current to faults on the 25kV GPC feeder greatly reducing the sensitivity of the ground relay located in breaker GF074.
- Any zero-sequence (ground) currents on the 25kV feeder will be converted to phase current on the 12kV side making it impossible to judge the true feeder loading and unbalance.
- The autotransformer will also be a source of ground fault current on the 12kV side. The impact of this will be that the ground element in GPC breaker GF074 relay will see faults that occur on the EMC feeders. If the EMC feeders ground setting is slower than the GPC feeder ground setting, the GPC breaker could trip and/or lockout for a fault on an EMC feeder.

- This ground fault current contribution also makes the 230/12kV transformer ground relay less sensitive to ground faults if a breaker were to fail to trip.

- With single-phase regulators, any voltage imbalance not correctly compensated for by the regulators will create circulating current between the main station transformer, regulators, and auto transformer. This not only further obscures the true loading on the feeder, the circulating current can drive the regulator into reverse power shutting down the regulator control. Because of the circulating current, the regulators will not be unable to properly regulate the voltage on this feeder.

Busbee Parkway – Possible Solutions

1. Remove the removable tertiary link in the auto-transformer. The nameplate has the following statement: “The delta connected tertiary winding is provided for third harmonic currents and stabilization of the neutral. Do not change this connection.” The "benefits" touted in the warning are exactly what is wrong with having the tertiary in this application. We absolutely do not want stabilization of the neutral in this situation. The question asked of the manufacturer is: Will this transformer be harmed if the removable link is removed? Most of the step up/step down transformers on the system are wye-wye with no tertiary and they handle unbalanced load with no problems.

2. Change the transformer to an auto or wye-wye that has no tertiary or stabilizing winding.

3. Move the regulators and the feeder protection relay current connections to the 25kV side of the auto transformer. This would fix the concerns with reading the correct currents on the relay, would prevent the feeder for operating for faults on Cobb EMC feeders, and would allow the regulators to function correctly. However, it does not change the fact that the auto will still be contributing ground fault current to the Cobb EMC feeders. This solution also prevents the feeder relay from being backup protection for the auto if the auto were to fail and the differential did not operate. The auto still desensitizes the main transformer backup ground protection

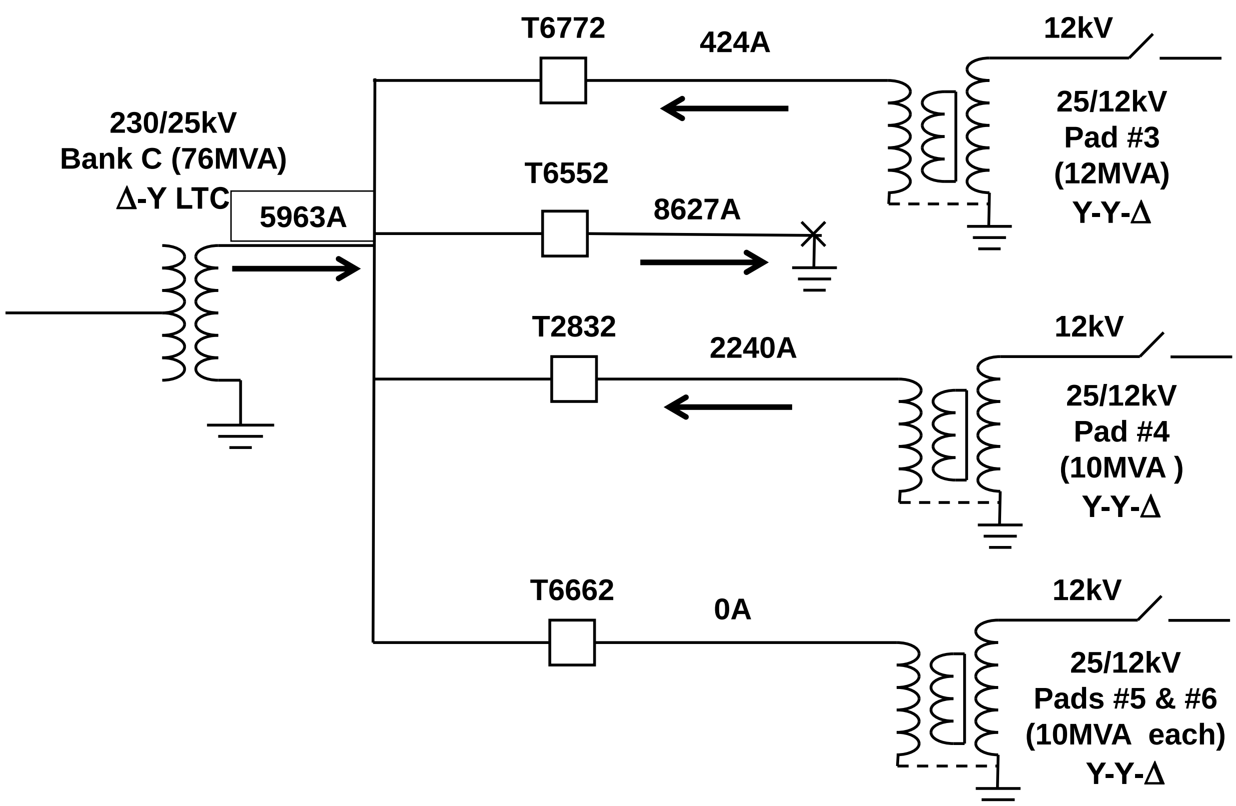
Busbee Parkway – Solution

The owner of the substation decided to break the tertiary winding as we did at Peach Orchard. This was done and the problem was solved.

QTS Event

A Georgia Power customer, QTS is fed by 6 padmount transformers connected through switchgear with multiple throw-over schemes between 4 feeders. Overcurrent protection is also provided on the 25kV side of the padmounts. A fault occurred on overhead feeder T6552 which caused the switchgear on padmount #4 connected to feeder T2832 to trip on overcurrent.

Initially it was assumed that the trip was caused by sympathetic inrush, but an examination of the event records showed that current flowed from the padmount into the distribution bus.



QTS – Solution

Same as Peach Orchard and Busbee Parkway, the decision was made break the tertiary winding.

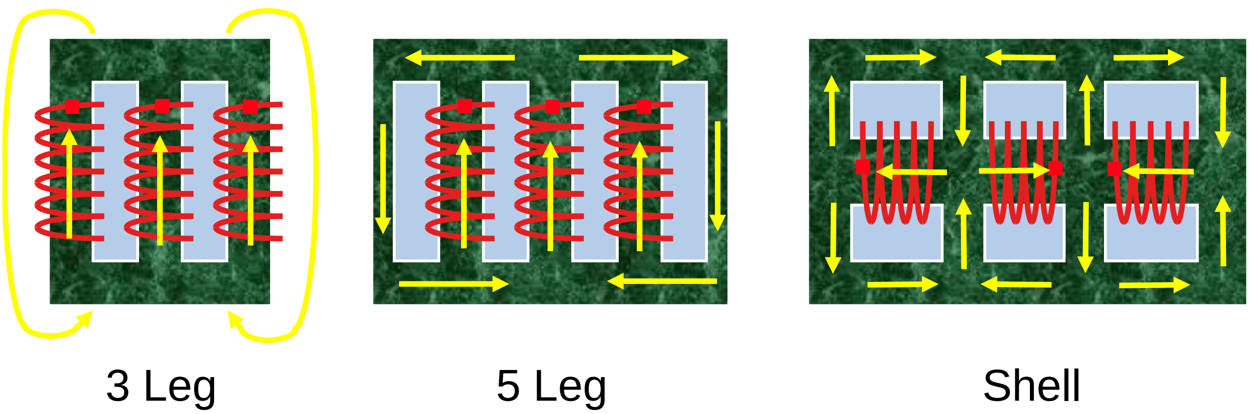
In this case removing the the ground connection on the 25kV side would also have solved the problem, however breaking the tertiary was chosen to be consistent with other distribution padmounts not containing delta tertiary windings.

Initial Conclusion

Solving the problem with the wye connected transformers containing delta stabilizing windings is easy – simply break the tertiary connection and everything is fine!

However, we soon learned: Any subject you don't fully understand is simple.

It turns out that breaking the delta tertiary winding does not necessary eliminate the ability of the transformer to supply zero sequence current. In the three legged core design the magnetic circuit is open to all zero sequence current flows. This has the effect of reducing the zero sequence shunt impedance, commonly known as the "phantom tertiary" effect. In other words, even with the tertiary opened up or not even installed on a three legged core transformer, the transformer is still able to supply some zero-sequence current to a fault or unbalanced load.



Common Transformer Core Designs

Positive, Negative, & Zero Sequence Magnetic Circuits
For Various Transformer Core Configurations

Core Type	Types Of Magnetic Circuits		
	Positive Sequence Flux	Zero Sequence Flux	Third Harmonic Flux
Single Phase	Closed	Closed	Closed
3 Legged Three Phase	Closed	Open	Open
Shell Form	Closed	Closed *	Closed
5 Legged Three Phase	Closed	Closed *	Closed

* Saturates and becomes open magnetic circuit before 100% zero sequence excitation is reached.

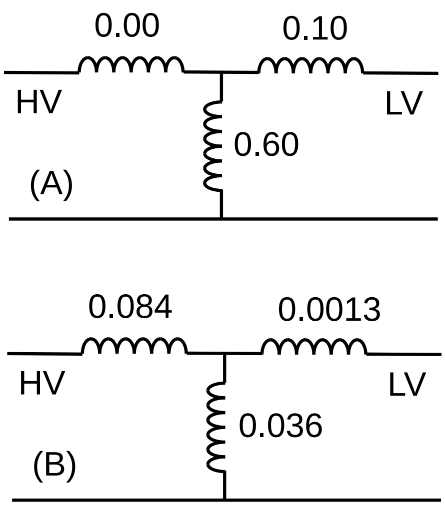
For three legged cores the zero sequence flux path is always open reducing the zero-sequence shunt impedance for any current level, however as fault current increases, more magnetic flux is coupled into other parts the transformer such as the oil, tank, radiators, pad, ground field, etc. changing the impedance.

For 4 or 5 legged and shell type cores the point where the core starts to saturate is typically 35% to 50% of the bank three phase rating, and the magnetic circuit will be open at 100% of the three phase rating for zero sequence current flow. Thus the impedance in the short circuit model may not represent the actual impedance during a high level fault. Once the core starts to saturate, the magnetic flux leaves the core and is coupled into other components just like a three legged core

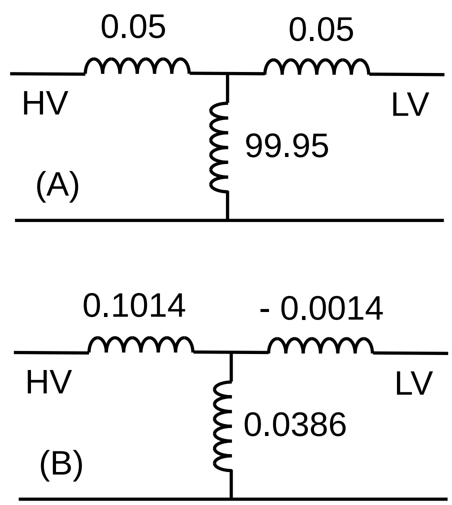
The variation in impedance with fault level could have implications for the transmission system short circuit model as well. Most large auto transformer test reports check zero sequence impedance at a fraction of the transformer rating, frequently around 20%. Some would like to see zero sequence impedance tests at 100% of the transformer rating, however the manufacturers are resisting because of the difficulty in producing the test current and fears of damage to the transformer being tested.

Zero Sequence Networks

Without Stabilizing Winding (A), With Stabilizing Winding (B)



Wye Connected 3 Legged Core



Wye Connected Shell Form Core

In looking at the above impedances measured by B. A. Cogbill, the zero sequence branch for core 3 legged core form transformers without a delta tertiary appears to be much lower than a shell form transformer without a delta tertiary. However, under heavy fault conditions the zero sequence branch impedance may drop. Whether this is a problem most likely will depend on application.

More study is needed to better understand the impact of impedance change with fault current on the transmission and distribution network.

Follow-up Issues

A survey of all the transformers with similar size and voltage ratings reveals that we have 31 wye connected banks with stabilizing windings, and another 17 for which we have no nameplate data. These applications will all need to be reviewed to see if the same problems seen at Peach Orchard and Busbee Parkway exist in these other installations as well.

It would make good sense to install monitoring equipment on both sides of the Peach Orchard transformer to see how great an effect this phantom tertiary has on fault currents and zero-sequence unbalance

References

B. A. Cogbill, Are Stabilizing Windings Necessary in All Y-Connected Transformers?, AIEE October 1959

R. C. Dugan & A. W. Bartek, Autotransformer Application with and without Tertiary Windings, Missouri Valley Electric Association Conference, April 1977.

ANSI C57.12. 80