PITFALLS OF FUSING POWER TRANSFORMERS

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Abstract

Fusing of power transformers is commonly used as an economical and convenient means of providing transformer protection. At Pacific Gas and Electric (PG&E), transformer fusing is used on transformers that are rated 12.5 MVA and below at 60/70kV and 16MVA and below at 115kV. Fusing a transformer provides the following advantages; a fault interrupting device is not required thereby, simplifying the DC system and station controls, simplification of outdoor construction, providing for an economical and quick installation. However as with everything in life it comes at a price and the disadvantages may not be as obvious as first thought. In addition to slower clearing times and the one time operation of the fuse resulting in increased customer outage minutes, there are other less obvious issues related to winding configuration and grounding that can have significant impact on the ability of fuses to detect and clear the fault, leading to catastrophic failure. This paper will cover the advantages, disadvantages, and less obvious winding configurations that should be avoided to allow fuses to properly protect the transformer, and examples of how the various winding configurations affect the ability of fuses to clear a transformer fault. Various forms of auxiliary protection will be included to help protect the load and transformer if fusing is utilized, such as negative sequence relays, tertiary fuse and tertiary overcorrect protection.

Background

PG&E is one of the largest combination electric and gas utilities in the United States. It serves about 15 million customers in the northern and central California. Approximately 20,000 employees serve its 70,000 square mile territory. It is a vertically integrated utility with Generation, Transmission and Distribution assets. Its transmission system is made up of approximately 18,610 miles of 500, 230, 115, 70 and 60kV lines.

Introduction

Power transformers are one of the most expensive and difficult to replace components in a power system. Transformers can be protected by various methods, using circuit breakers, circuit switchers, Transruptors and fuses. However, there are instances where the infrastructure for providing full transformer protection cannot be used. The use of circuit breakers requires the installation of protective relays, a DC system, battery and charger and other associated equipment such as a control building and, additionally, there may not be room for the installation. In these cases fuses may be the protection of choice.

Transformer Fusing Considerations

Before the choice can be made several factors should be taken into account as noted below:

- Fault interrupting capability – For voltages 60kV and above the typical maximum fault interrupting capability of fuses is 10kA.
- Coordination with upstream and downstream protective devices. Many times the fuse may not adequately coordinate with upstream ground overcurrent devices.
- Ability to adequately protect the transformer – Is there enough fault duty to adequately operate the fuse for the worst-case low voltage fault.
- Transformer inrush considerations. Typical fuse size of 1.5 to 2 times rated OA rating will address the inrush concerns.
- Cold load pick-up.

Fault clearing considerations

All though a fuse can be sized to properly protect the transformer for most faults, there are certain winding configurations that can continue to feed a fault after the faulted phase fuse operates. Several winding configurations are listed below with the currents before and after the fuse operates. The values of current for the two winding transformers are based on a rating of 13MVA, 70/12.47kV, Z = 11% and were obtained using the Aspen Oneliner fault simulation program. The three winding transformer values were based on a rating of 10MVA 70/7.2/12.47kV Z = 8%.

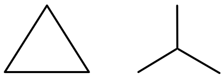
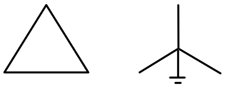
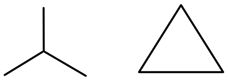
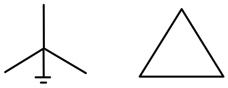
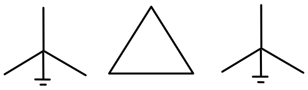
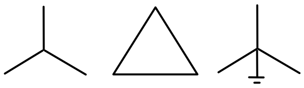
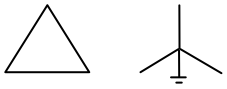
HV LV	HV Before Fuse Operates	HV After First Fuse Operates	LV After Fuse Operates
	DLG AB flt IA = 877 @-84 IB = 439@96 IC = 439 @96	DLG AB flt IA = 0 IB = 0 IC = 0	DLG AB flt Ia = 0 Ib = 0 Ic = 0
	DLG AB flt IA = 877 @-84 IB = 528@131 IC = 519 @62	DLG AB flt IA = 0@128 IB = 286 @6 IC = 286 @-52	DLG AB flt Ia = 2780 @ 6 Ib = 2780 @ 6 Ic = 0 3Io = 5561 @ 6
	DLG AB flt IA = 439 @-23 IB = 877 @ 157 IC = 439 @ -23	DLG AB flt IA = 0 IB = 0 IC = 0	Ia = 0 Ib = 0 Ic = 0
	DLG AB flt IA = 439 @-23 IB = 877 @ 157 IC = 439 @ -23	DLG AB flt IA = 386 @157 IB = 0 IC = 386 @157	DLG AB flt Ia = 1251 @157 Ib = 1251 @ -23 Ic = 0
	SLG A phase IA = 800 @ -86 IB = 300 @ 94 IC = 300 @ 94	SLG A phase IA = 0 IB = 233 @ -86 IC = 233 @ -86	SLG A phase Ia = 1350 @94 Ib = 0 Ic = 0
	IA = 465 @ -86 IB = 233 @ 94 IC = 233 @ 94	IA = 0 IB = 0 IC = 0	Ia = 0 Ib = 0 Ic = 0

Table 1
Fault Currents for Different Winding Configurations

As shown in Table 1 for Double Line to Ground (DLG) faults, the two winding configurations have current in the intact phases after the first fuse operates, however there is enough fault current to allow the remaining fuses to operate thereby clearing the fault. The same cannot be said for the three winding transformers for a sustained SLG fault.

Delta Wye Grounded.



The sequence network for a DLG fault for this winding configuration is illustrated below:

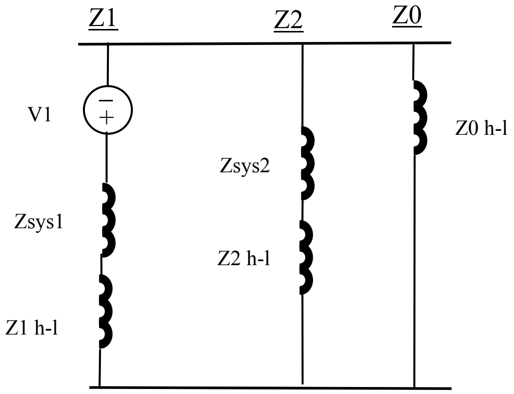


Figure 1
Delta Wye DLG fault

Shown below is an AB phase DLG fault simulation with the resulting fault current distribution before and after the fuse operates.

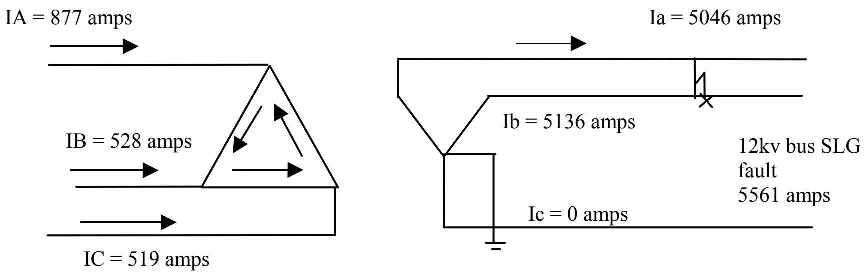


Figure 2
70/12.47kV XFMR Grounded HV Wye w/ 125E Fuse
DLG fault before fuse operates

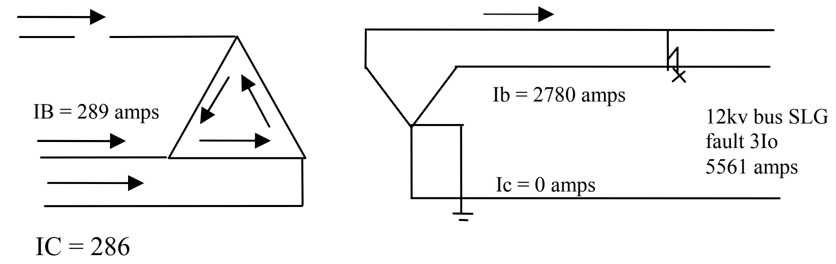
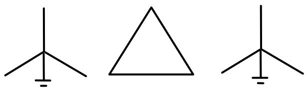


Figure 3
70/12.47kV XFMR Grounded HV Wye w/ 125E Fuse
DLG fault after fuse operates

As can be seen in Figures 2 and 3, for the Delta – Wye gnd connection for an A-B phase DLG fault causes one of the 70kV phase fuses to operate after which the current in remaining two phases increases, causing those fuses to operate. The fuse should be sized adequately to operate for the resulting fault currents.

Wye Grounded Delta Wye Grounded.



This is one of the most common transformer winding configurations on the PG&E system. The three winding configurations with the delta tertiary are the configurations in which fault clearing after the faulted phase fuse operates can be a potential problem. This issue is identified in the following sections.

A phase SLG Fault

The sequence network for this winding configuration during an A phase SLG fault is illustrated in Figure 4 below:

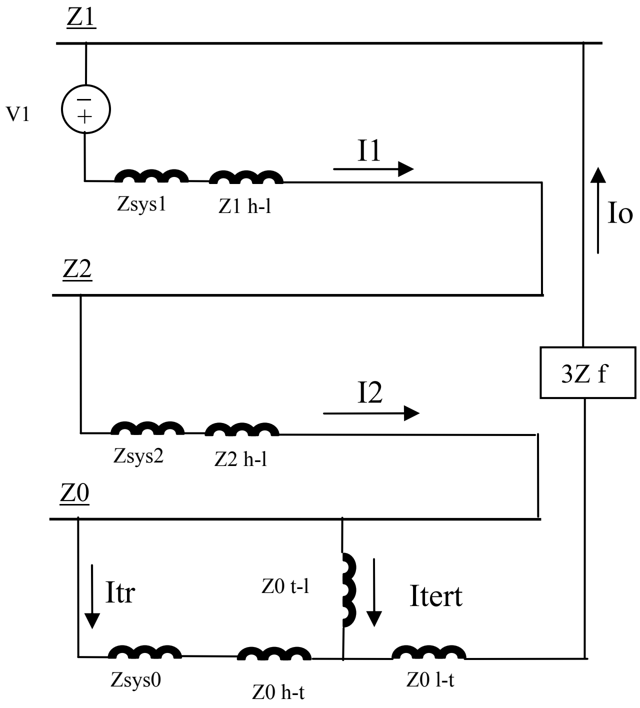


Figure 4
A phase SLG Fault

After the faulted phase fuse operates, the delta tertiary will continue to feed the fault, and the resulting High Voltage (HV) fault current is not high enough to operate the fuses in the two remaining phases. The resulting tertiary current can be over five times the rated current resulting in eventual failure of the transformer if no further mitigating actions are taken The sequence network model with load impedance neglected, and the solution with matrix equations are shown below as well. Current values are shown below for a typical fused transformer 10 MVA. The current values were derived using the Aspen Oneliner Simultaneous faults feature.

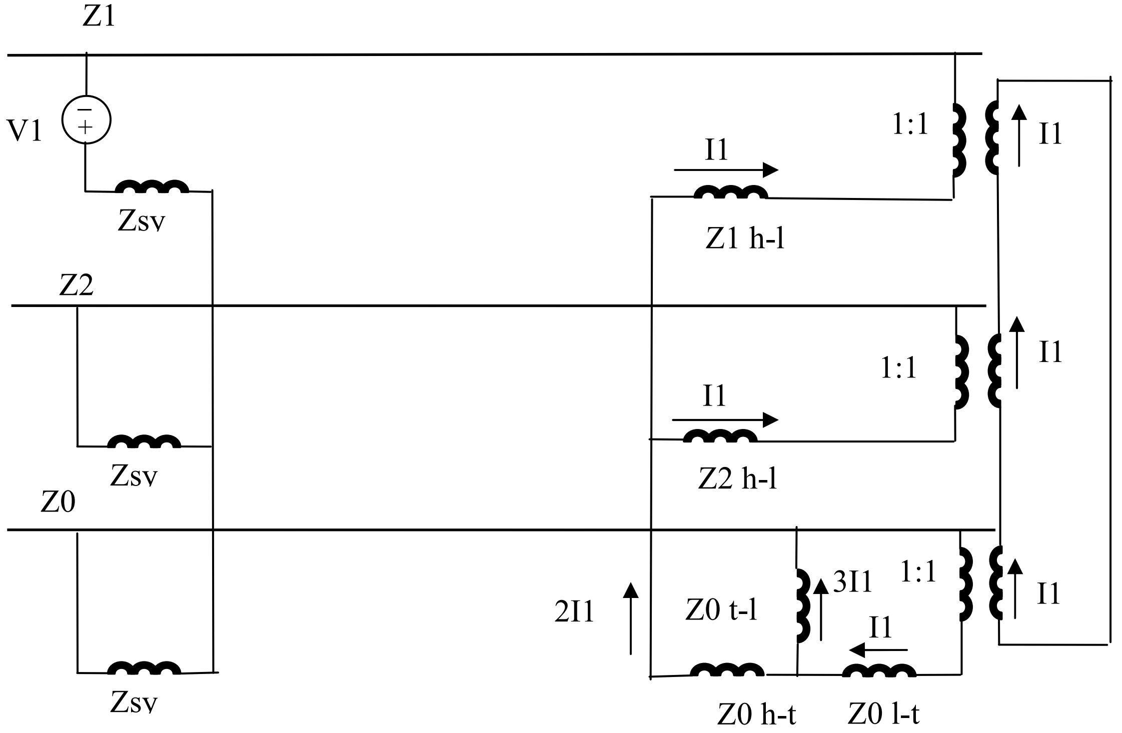


Figure 5

Sequence network for open HV A phase fuse and sustained LV SLG fault

Figure 6 shows a simplification of the above network where the system impedance has been removed and only reactance is shown:

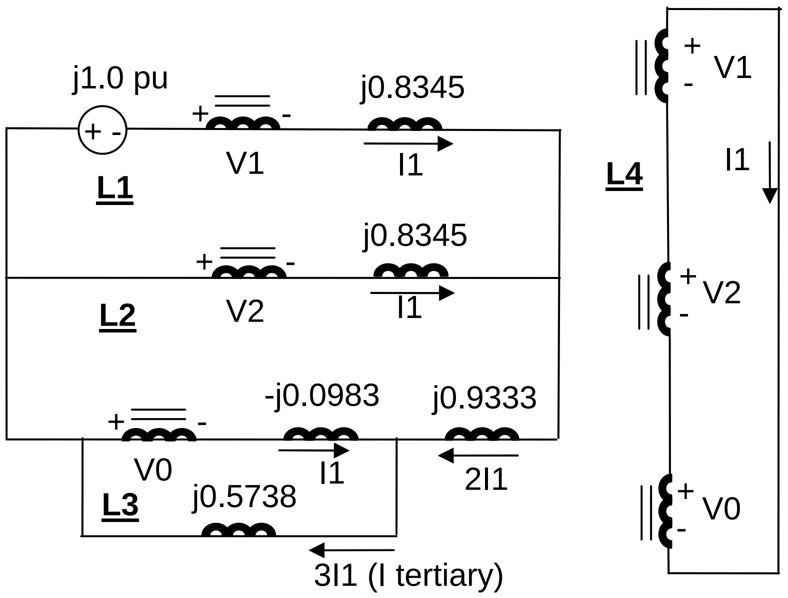


Figure 6
Simplified sequence network

From the above network the following equations are derived:

L1
$1.0 = -V1 + j0.8345 - j0.8345 + V2$

L2
$0 = -V2 + j0.8345 * I1 + (j0.9333)(2I1) - (-j.0983)I1 + V0$
$0 = -V2 + j2.79 * I1 + V0$

L3
$0 = -V0 + (-j0.0983)I1 + (j0.5738)(3I1)$
$0 = -V0 + j1.62 * (2I1)$

L4
$0 = V1 + V2 + V0$

Solving the above equations for v1,v2, v0, and I1 on a per unit basis

$$\begin{pmatrix} v1 \\ v2 \\ v0 \\ I1 \end{pmatrix} := \begin{pmatrix} -1 & 1 & 0 & 0 \\ 0 & -1 & 1 & 2.79 \\ 0 & 0 & -1 & 1.62 \\ 1 & 1 & 1 & 0 \end{pmatrix}^{-1} \cdot \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

The resulting per unit values are shown below

$$\begin{pmatrix} v1 \\ v2 \\ v0 \\ I1 \end{pmatrix} = \begin{pmatrix} -0.578 \\ 0.422 \\ 0.155 \\ 0.096 \end{pmatrix}$$

Per Unit Current Value

$I1 = 0.096$ amps pu

Convert to phase current values

$$\begin{pmatrix} IA \\ IB \\ IC \end{pmatrix} := \begin{pmatrix} 1 & 1 & 1 \\ 1 & a2 & a \\ 1 & a & a2 \end{pmatrix} \cdot \begin{pmatrix} I1 \\ I1 \\ -2I1 \end{pmatrix}$$

$a2 := -.5 - .866i$ $\arg(a2) = -120.001$ deg

$a := -.5 + .866i$ $\arg(a) = 120.001$ deg

$$\begin{pmatrix} IA \\ IB \\ IC \end{pmatrix} = \begin{pmatrix} 0 \\ 0.144 - 0.249i \\ 0.144 + 0.249i \end{pmatrix}$$

Per Unit HV Current @ 100MVA, 70kV

$$\frac{100000000}{1.73 \cdot 70000} = 825.764$$

HV phase currents

$|IB| \cdot 825 = 237$ amps

$|IC| \cdot 825 = 237$ amps

Per Unit Tertiary Current @ 100MVA, 7.2kV

$$ITERTpu := \frac{10000000(}{1.73 \cdot 7200}$$

$ITERTpu = 8028$ amps

Resulting tertiary fault current:

$ITERT := ITERTpu \cdot 3 \cdot I1$

$$\frac{ITERT}{1.73} = 1334 \text{ amps}$$

$$Itertrated := \frac{2940000}{1.73 \cdot 7200} \qquad Itertrated = 236 \text{ amps}$$

Fault current percentage over rated

$$\frac{ITERT}{1.73 \cdot Itertrated} = 565\%$$

Figures 7 and 8 below show the resulting fault currents before and after the fuse operates.

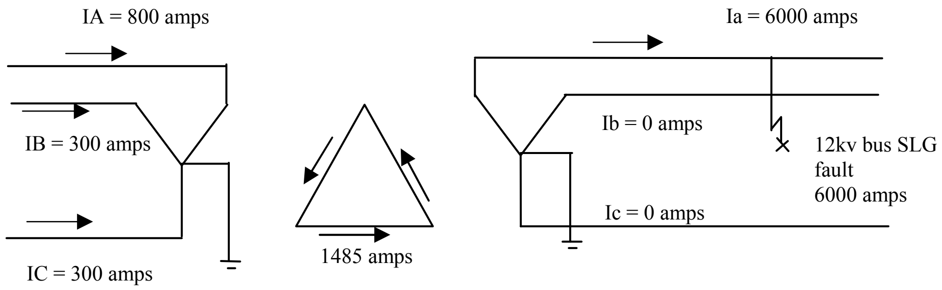


Figure 7
70/7.2/12.47kV XFMR Grounded HV Wye w/ 125E Fuse
SLG fault before fuse operates

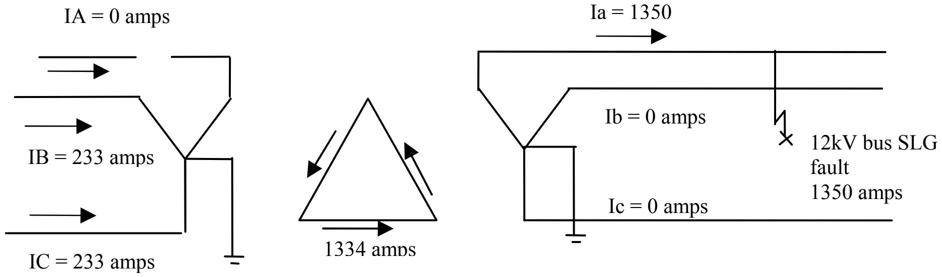


Figure 8
70/7.2/12.47kV XFMR Grounded HV Wye w/ 125E Fuse
SLG fault after fuse operates

Transmission Line Open Phase with SLG Fault

Another potential problem with this winding configuration is for an open phase on the HV side of the transformer with a sustained SLG fault, such a parted conductor where one side stays suspended on the tower and the other side falls to the ground creating a SLG fault, refer to Figure-9 below.

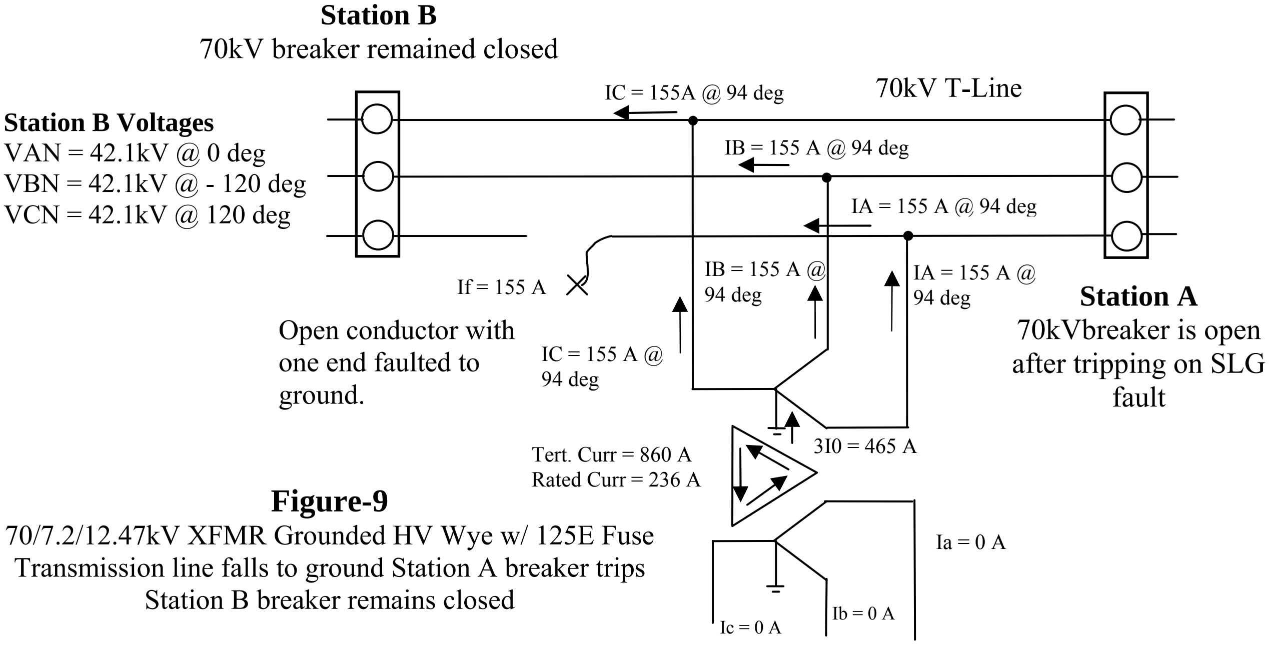


Figure-9
70/7.2/12.47kV XFMR Grounded HV Wye w/ 125E Fuse
Transmission line falls to ground Station A breaker trips
Station B breaker remains closed

The example in Figure -9 is the same transformer as used in Figure -7 and 8, tapped on a 70kV transmission line. The current values were obtained using the Aspen Oneliner "Simultaneous Fault" feature. As can be seen in Figure-9 the resulting SLG fault trips the 70kV circuit breaker at Station A, since the conductor on the other side of the opened phase is still suspended on the tower the relays on the Station B side of the line do not detect the fault. The fault continues to be back fed from the HV ground and tertiary winding of the transformer. The resulting fault current is not high enough to operate the transformer fuses, but the resulting tertiary current can be many times the rated value resulting in eventual transformer failure. The mitigation features listed below can be used to prevent this type of failure.

Mitigation Methods:
The following methods can be used to mitigate this protection deficiency.

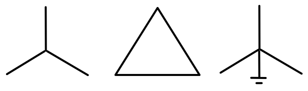
- **Unground the HV winding** – this will remove the zero sequence path from the HV winding thereby removing the fault.
    - If this method is used ensure the HV winding, H0 bushing, and lightning arrestors are rated for L-L voltage (For transformers 69KV and above graded insulation toward the neutral, therefore this is not an option).
- **Trip station HV circuit breaker** (if available).
    - A tertiary relay can be installed to trip the station breakers (this may not be an option if the bank was fused in the first place).
- **Fuse the tertiary winding** – This will also open the zero sequence path thereby removing the fault after the faulted phase fuse operates.
    - Ensure the fuse coordinates with transmission and distribution ground relays. Due to the size of the fuse and the magnitude of the resulting tertiary fault current there may be a problem coordinating with downstream and up stream ground protective devices. Subsequent operation of this fuse may not be detected resulting in an open tertiary winding resulting in power quality problems, notably triple harmonic distortion on the loads served by this transformer.

- **Open the tertiary winding.**
    - Discuss with the transformer manufacturer whether the transformer can be operated with the tertiary winding open.
    - Since this winding is used to suppress third harmonic currents from the transmission system operation of this winding open should be discussed with the distribution engineer to determine if there have been power quality issues or complaints related to electrical noise on the feeders served by this transformer.

- **Transformer's with a virtual tertiary winding configuration where the tertiary is not accessible**. For transformers with a virtual tertiary opening the tertiary winding is not an option. The following alternatives are available:
    - Do not fuse the bank, install circuit interrupting device.
    - Install CT and relay on HV neutral and trip station HV breakers, if available or trip LV feeder breakers.

It should be noted with the tertiary winding open either intentionally or when the tertiary fuse operates the tertiary winding will no longer feed the fault, however load will continue to be supplied from the remaining two phases resulting in single phasing the load.

Wye Ungrounded Delta Wye Grounded.



The “Wye Ungrounded Delta Wye grounded” configuration is another one of the more common configurations on the PG&E system. Operating with the HV winding ungrounded is limited to 70kV and below, where the HV winding and Ho bushing is fully insulated for the Line–Line voltage. At 70kV and above windings generally cannot operate with the neutral lifted since the windings consist of graded insulation, where the H0 portion of the winding is rated at 12kV.

For a single line to ground fault on this type of winding configuration when the fuse operates the lifted HV ground opens the zero sequence path thereby extinguishing the fault. It should be noted the loads supplied by this transformer will be single phased. The sequence network for this winding configuration for an A phase SLG fault is shown in Figure 10.

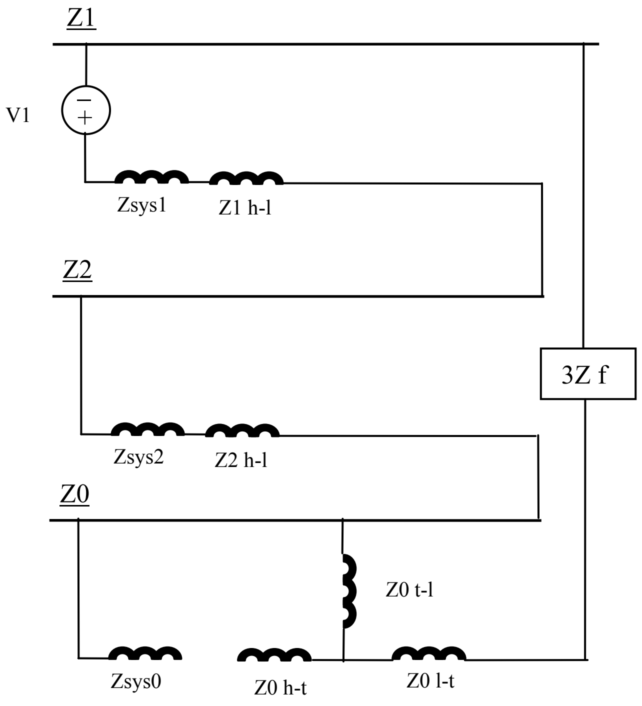


Figure 10
A phase SLG with HV winding H0 lifted, before the fuse operates

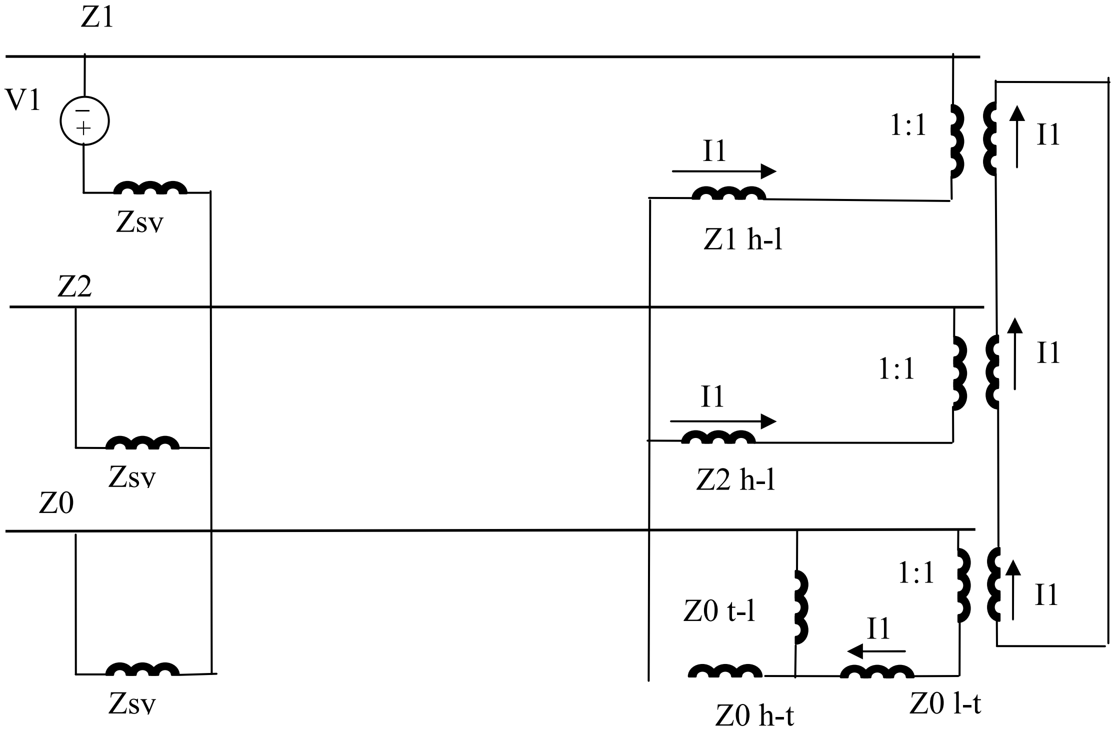


Figure 11
SLG after A phase HV fuse Operates

Figure 11 shows the sequence network after the fuse operates, in which I1 will go to zero. Figures 12 and 13 show the fault current simulation associated with the fault for an A phase single line to ground fault, before and after the fuse operates.

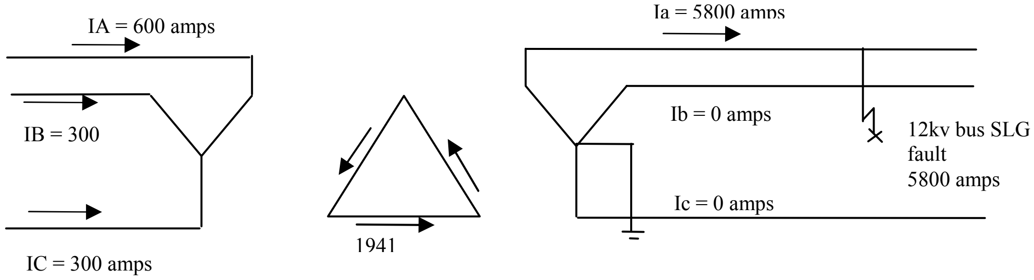


Figure 12
70/7.2/12.47kV XFMR Ungrounded HV Wye w/ 125E Fuse
SLG fault before fuse blows

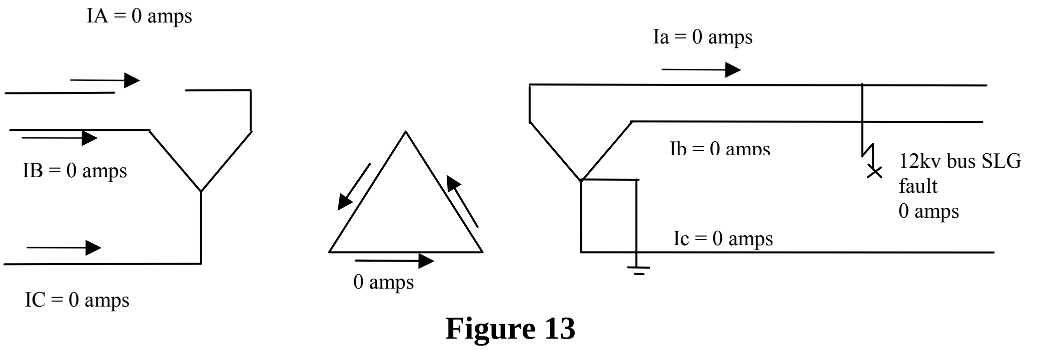


Figure 13
70/7.2/12.47kV XFMR Ungrounded HV Wye
SLG fault after fuse blows, fault is cleared.

Single Phase Mitigation Methods

Voltage Unbalance Scheme

Single phasing the LV distribution circuits can result in damage to three phase loads, before operating personnel can take corrective actions, therefore a method of mitigating the single phase condition is to install a negative sequence voltage relay. This relay will detect the negative sequence voltage due to the open fuse trip and lockout the affected feeders. The resulting voltage vectors for the open fuse are shown below in Figure 14.

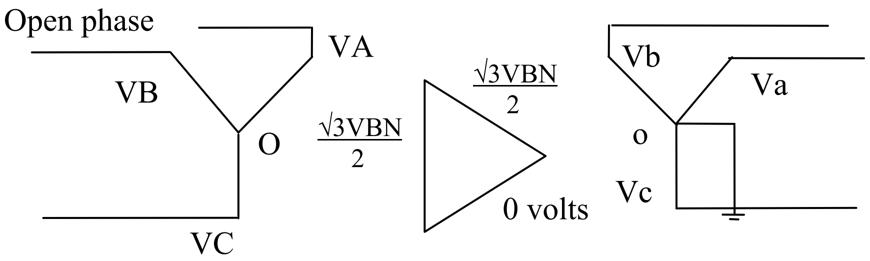


Figure 14

Effects of open phase on LV winding voltage

Primary Winding voltages	Secondary Winding voltages
$VBC = \sqrt{3}VBN$	$Vbc = \sqrt{3}VBN$
$VBN = \frac{\sqrt{3}VBN}{2}$	$VbN = \frac{\sqrt{3}VBN}{2}$
$VCN = \frac{\sqrt{3}VBN}{2}$	$VcN = \frac{\sqrt{3}VBN}{2}$
VAO = 0 volts	Vao = 0 volts

Resulting Secondary Per Unit voltages for open A phase

$$VC := \left(\frac{\sqrt{3}}{2} + 0i\right)$$

$$a := -.5 + .866 \qquad \arg(a) = 120.001\mathrm{deg}$$

$$a2 := -.5 - .866 \qquad \arg(a2) = -120.001\mathrm{deg}$$

$$VB := \frac{-\sqrt{3}}{2} - (0)\cdot i$$

$$|VB| = 0.866$$

$$\arg(VB) = 180\mathrm{deg}$$

$$VA := 0$$

$$\arg(VC) = 0\mathrm{deg}$$

Per Unit Value for Sequence Components

$$\begin{pmatrix} va0 \\ va1 \\ va2 \end{pmatrix} := \frac{1}{3}\cdot\begin{pmatrix} 1 & 1 & 1 \\ 1 & a2 & a \\ 1 & a & a2 \end{pmatrix}\cdot\begin{pmatrix} VA \\ VB \\ VC \end{pmatrix}$$

$$\begin{pmatrix} va0 \\ va1 \\ va2 \end{pmatrix} = \begin{pmatrix} 0 \\ 0.5i \\ -0.5i \end{pmatrix}$$

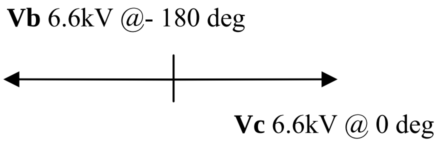
Resulting Positive and Negative Sequence Voltages

$|va2| = 0.5$ $\quad$ $\arg(va2) = -90\,deg$

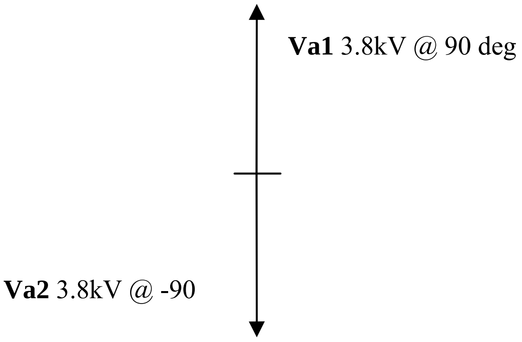
$|va1| = 0.5$ $\quad$ $\arg(va1) = 90\,deg$

Resulting phase and sequence vectors for an open HV winding A phase fuse.

12kV Phase Voltages for an A phase SLG Fault



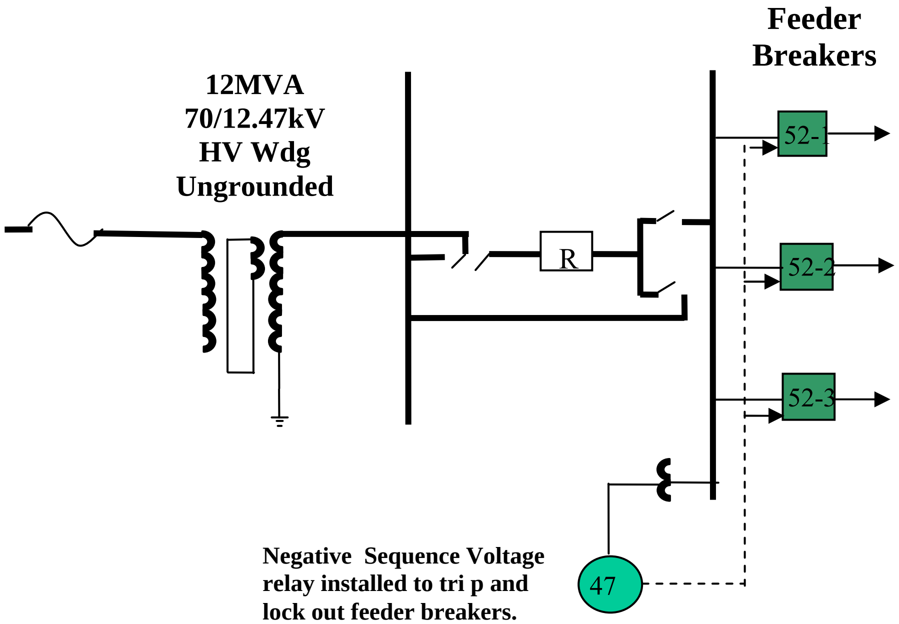
Resulting Sequence Voltages



Negative phase Sequence Overvoltage Scheme

The above negative sequence voltage can be detected by the installation of a negative sequence relay on the Low Voltage (LV) bus The negative sequence relay will pick-up once the HV winding fuse operates tripping the feeder breakers connected to the LV bus. This element can be time delayed on the order of seconds thereby protecting the single phase loads and allowing coordination with transmission and distribution protective devices.

The use of the negative sequence relay can also be used on transformer configuration with the fused tertiary; once the HV winding fuse and tertiary fuse operates the negative phase voltage relay will also operate tripping the feeders prevent single phasing of the connected loads.



Negative Sequence Voltage relay installed to tri p and lock out feeder breakers.

Figure 15

Example of Phase Voltage Negative Sequence Tripping for fuse protected XFMR

Tertiary Overcurrent Scheme

Another alternative to the voltage unbalance relay is the installation of a tertiary overcurrent relay. In this scheme a CT and time overcurrent relay is placed in the tertiary delta to monitor tertiary current. See Figure 16. During an open phase or severe unbalance condition the tertiary winding will have circulating current. The overcurrent relay will be set at a percentage above the tertiary rating and trip the feeder breakers when the pick-up value is reached. Operation of this relay will protect the tertiary winding from overload due to an unbalanced or blown HV fuse condition. It should be noted that for a sustained SLG fault on the LV bus, tripping the feeder breakers will not protect the transformer.

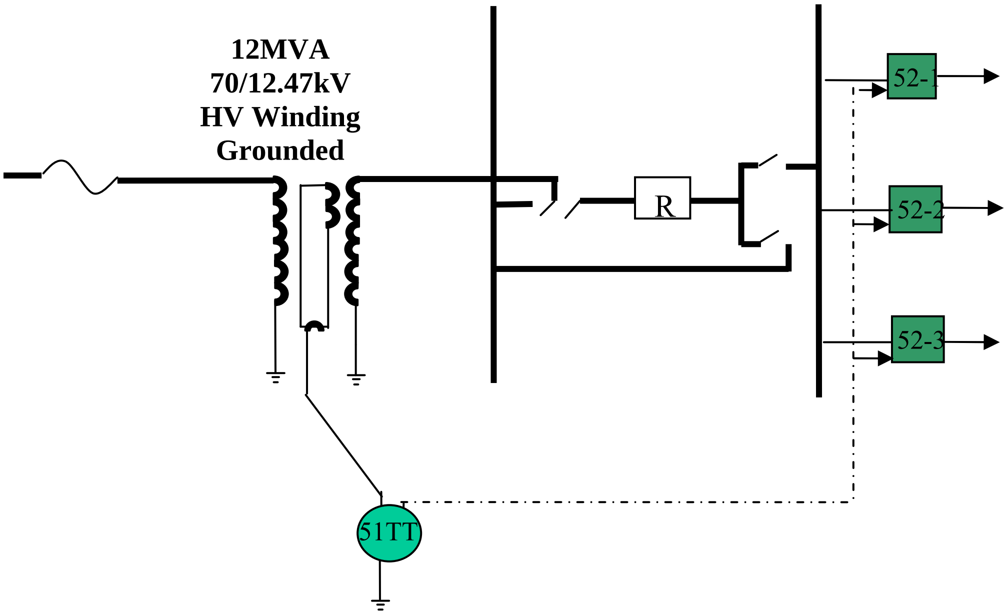


Figure 16
Tertiary over current relay installed to trip and lock out feeder breakers

HV Neutral Overcurrent relay

If the tertiary CT is not available or for a three phase transformer with a virtual tertiary a CT in the HV neutral can be installed and the same time overcurrent relay can be installed. The setting for the HV neutral relay should be based on the HV neutral current that flows when rated current flows in the tertiary. The bank OA rating can be used to determine the relay setting. If the tertiary rating is not listed on the nameplate, or if there is no tertiary winding, assume a capability of 20% of the main winding. The neutral overcurrent relay will only detect zero sequence current the resultant current will be 3Io. As with the tertiary overcurrent relay this relay trips the feeders protecting the tertiary from an overload due to a blown fuse, it will not protect the transformer from a sustained LV fault.

Summary

Fusing transformers is not as straight foreword as it seems, certain winding configurations can lead to sustained faults that cannot be cleared even after the faulted phase fuse operates. Care should be taken to ensure fault simulations take into account the unique winding configurations to ensure the transformer is fully protected with the designated fuses, both before and after the fuse operates. For those transformer configurations where fusing may not adequately clear a sustained fault there are mitigation measures that can be taken to eliminate the issue. If these methods cannot be applied fuses should not be used and a three phase interrupting device should be applied.

Author: Mike Jensen
Affiliation: Pacific Gas and Electric Company

References:

"Protective Relaying Principals and Applications" by J. Lewis Blackburn – 1st edition.

IEEE Std C37.91 2008 "IEEE Guide for Protecting Power Transformers"

Biography:

Mike Jensen is a Supervising Protection Engineer with Pacific Gas and Electric, with 17 years of transmission protection, substation design, nuclear power plant maintenance and design experience. Served 6 years in the U.S. Navy on board nuclear submarines. Received a BS in Electrical Engineering from California Polytechnic University, San Luis Obispo in 1992 and is a registered professional engineer in the state of California