Ground Fault Neutralizer for Wildfire Mitigation in California

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SUMMARY

As recent fire seasons have demonstrated in the western USA, climate-driven wildfire risks are increasing annually, and focused and sustained mitigation efforts are needed to reduce the threat and impact of wildfires. The U.S. Forest Service estimates that 147 million trees died in California from drought and invasive beetles from 2010-2018, which is just one of the factors that has contributed to the growing wildfire risk [1]. New technologies are being evaluated to reduce the risk of ignition from electric facilities operating in high fire risk areas. One approach is to compensate electric distribution networks with a Ground Fault Neutralizer instead of solidly grounding the neutral to limit the fault current below the ignition threshold.

Many types of distribution faults and equipment failures have the potential to cause outages and even ignite wildfires. Ground faults such as transformer failure, insulator failure, vegetation and animal contact, and downed power lines make up over 65% of the faults on electric distribution in high fire threat districts (HFTD). With the power system neutral solidly grounded, the prevalent practice in the USA, the ground fault current may range from a few hundreds to thousands of Amps, well above the ignition threshold in many cases with dry fuels present. In other parts of the world, resonant grounding is used to limit the fault current, primarily to limit damage to equipment, especially for large underground networks.

One technology which is an extension of resonant grounding is known as a Ground Fault Neutralizer (GFN). The modern GFN uses power electronics to limit the fault current to a much greater extent than conventional resonant grounding to levels below the fire ignition threshold in most instances. Through California's Electric Program Investment Charge (EPIC), Pacific Gas & Electric Co. is demonstrating the GFN to protect two distribution circuits in Napa Valley, California. The GFN is also referred to as a Rapid Earth Fault Current Limiter (REFCL) in other parts of the world.

The GFN technology was performance tested at the demonstration site and successfully limited ground fault current below 0.5 Amps, but integration challenges have shown it is not plug and play technology. Equipment failures in the substation and on the distribution circuits have been obstacles to the successful operationalization of the technology, and PG&E is performing final testing of the GFN to put it into day to day operation.

KEYWORDS

power system faults, REFCL, GFN, wildfire mitigation, resonant grounding, compensated networks

When a ground fault occurs, such as a powerline breaking and hitting the ground, it can create an arc, potentially starting a fire. A common practice in the USA is to solidly ground the neutral of the connected distribution circuits. While this has a reliability benefit, the fault duty is typically in the hundreds or thousands of amps, potentially resulting in a fire ignition in high fire risk areas.

The Ground Fault Neutralizer (GFN) is an extension of resonant grounding and installed in the distribution substation to protect the connected distribution networks. The GFN rapidly limits the fault current for single line to ground faults to less than 1 Amp, reducing the likelihood of fire ignition by 90% [2]. A GFN is only applicable for uni-grounded (3-wire) circuits with a single neutral point in the substation. Converting Multi-grounded (4-wire) circuits to uni-ground to support a GFN installation is very expensive and difficult. Multi-grounded electric distribution is very widely applied in the USA, but in Central and Northern California within PG&E's service territory, over 80% of the distribution circuits in high fire risk areas are uni-grounded 3-wire.

The GFN consists of an arc suppression coil (ASC), residual current compensator (RCC), and controllers (Figure 1) [3]. To package the GFN components more easily in a standard shipping container, a grounding transformer is connected to the substation 12 kV bus, creating an easily accessible neutral point for the ASC. The GFN detects a ground fault by measuring the zero sequence voltage, and once it exceeds a threshold, the RCC is activated to further increase the neutral voltage and reduce the faulted phase voltage, thus limiting the fault current to less than 1 Amp.

Figure 1 From left to right : ASC, RCC, Control Cabinet (Swedish Neutral AB)

Through California's Electric Program Investment Charge (EPIC), Pacific Gas & Electric Co. is demonstrating the GFN to protect two 12 kV distribution circuits in Napa Valley, California.

Changing how the neutral is grounded is a fundamental change, and the distribution substation design must be reviewed and modified to accommodate the GFN installation. The GFN adds a layer of more sensitive ground fault protection with the standard protective devices. When a ground fault occurs with the GFN in service, the line to ground voltage of the faulted phase collapses while the two healthy phase voltages increase by 1.7 times. This means that standard substation connections for equipment and their ratings need to be thoroughly reviewed and equipment may need to be changed.

For PG&E's demonstration GFN project, the following equipment had to be changed in the substation:

1. Existing voltage regulators connected Yg replaced with closed delta regulators and multi-phase controller for lock step operation of all 3 units like LTC operation
2. Existing station service transformer connected Yg replaced with line-line rated transformer
3. Bus potential transformers (PT)s rated 7,200V Yg replaced with 12,000V Yg
4. Bank secondary ground bus converted to 12 kV insulated neutral bus with a single pole line recloser acting as a switch to remotely change between solid grounding and resonant grounding
5. New three-phase line recloser with riser for 12 kV underground connections to GFN
6. New balanced current transformers (CTs) for the feeder breakers, including a 50:5 core balance CT for zero sequence current measurement
7. Station battery backup upgrade for supporting the additional controllers and communication equipment
8. Grounding study and ground grid improvements based on results of the study
9. Replacement of feeder breaker relays to current standards

Figure 2 GFN pilot substation in Napa Valley California

The substation bank is changed from solid grounding to resonant grounding based on the position of the Neutral Grounding Recloser, which operates as a switch. With the GFN in-service, it protects 100% of the primary distribution networks connected to the substation transformer bank secondary.

When a ground fault occurs with the GFN in-service, the neutral voltage passively increases and the GFN detects the fault once the voltage rises above the threshold setting. Within about 50 ms, the RCC activates to further increase the neutral voltage, which brings the faulted phase voltage typically below 250V primary. A side effect of this neutral shift is that the line to ground voltage of the two healthy phases increases to line-to-line magnitude as shown in Figure 3. The fault current follows Ohm's Law and is rapidly reduced as the faulted phase to ground voltage drops, limiting the current below 1 Amp. Note that the phase-to-phase voltage is maintained, customer's service voltages remain the same as the service transformers are all connected Phase to Phase.

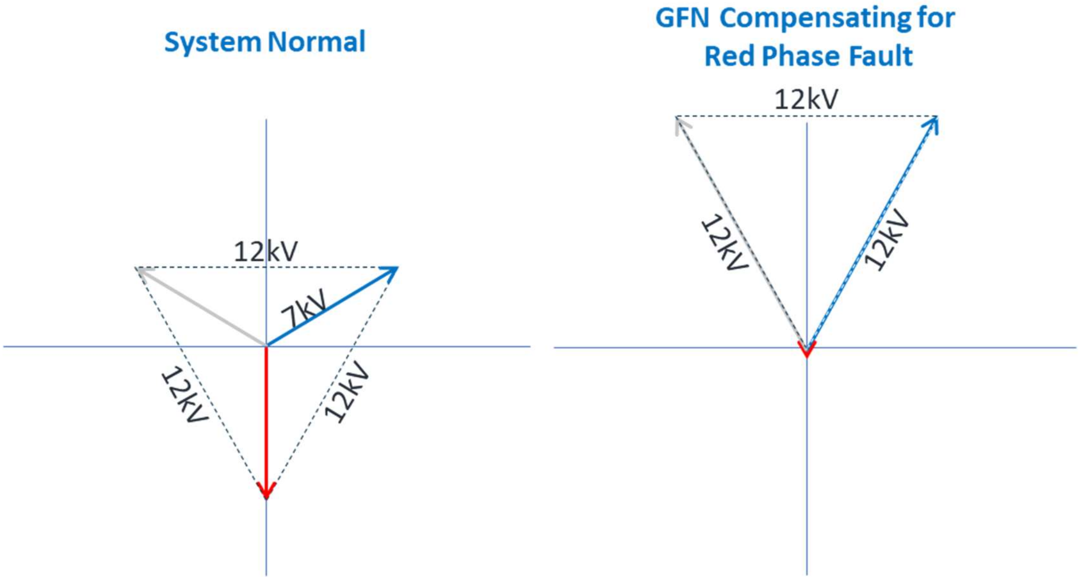

Figure 3 The GFN shifts the neutral, reducing the line to ground voltage of the faulted phase

While the GFN is compensating for the fault and the fault current is so low, a time delay of four seconds elapses before fault confirmation is performed to identify the faulted circuit. The GFN does this by making small adjustments to the neutral voltage phasor via angle or magnitude and measuring the change (delta) in zero sequence admittance for each circuit. The circuit with the largest change (delta) in admittance is identified as the faulted circuit. The faulted circuit breaker is then opened to isolate the fault. If the fault is momentary and vanishes before fault confirmation completes, the system rides through with no service interruption. For a sustained fault, the substation circuit breaker for the fault identified circuit is tripped to isolate the fault.

For PG&E’s demonstration GFN project, the following equipment had to be changed for the distribution circuits:

Insulation review of all primary connected equipment to withstand 1.73 times nominal line to ground voltage for 10 minutes. Underground cable and surge arrestors will fail if not properly rated.

Closed delta voltage regulation (replace open delta banks)

Group tapping of all three phases of voltage regulators banks

Balanced line capacitance charging currents to minimize the standing neutral voltage on the bank [4]. The zero sequence charging currents are the result of the unbalanced line to ground capacitances (Figure 4).

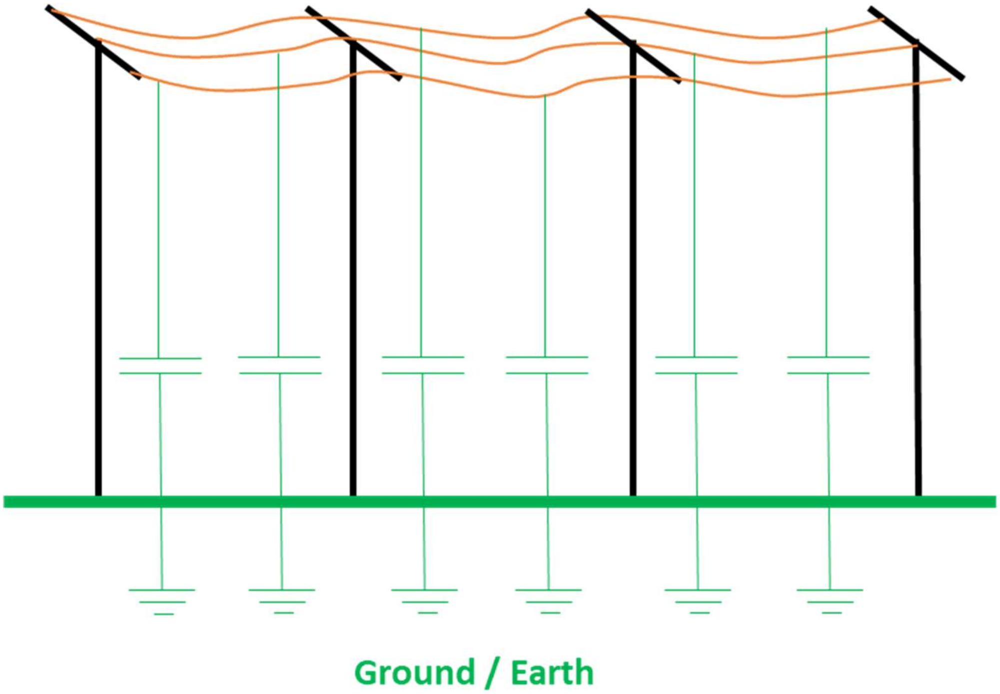

Figure 4 Line to ground capacitance of the lines results in zero sequence charging currents

Balancing the charging currents to minimize the standing neutral voltage and maintain it is not a trivial task. In the USA, single phase – 2 wire laterals are commonly used on distribution circuits, especially on rural circuits where there are minimal 3 phase loads. To address long single phase laterals, phasing reconnection changes are performed for coarse balancing and a new type of equipment called a Capacitive Balancing Unit (CBU) is installed at major protection zones on the circuits to remotely inject ground current from each phase in 0.03 Amp increments, up to 0.5A maximum per phase (Figure 5). Single phase transformers or 5-limb three-phase transformers are to be used for the CBU so that the excitation of each phase is nearly identical [4]. To maintain balance, some single phase fuse locations need to be replaced with three-phase ganged protection to prevent false operation of the GFN in case of line-line faults [4].

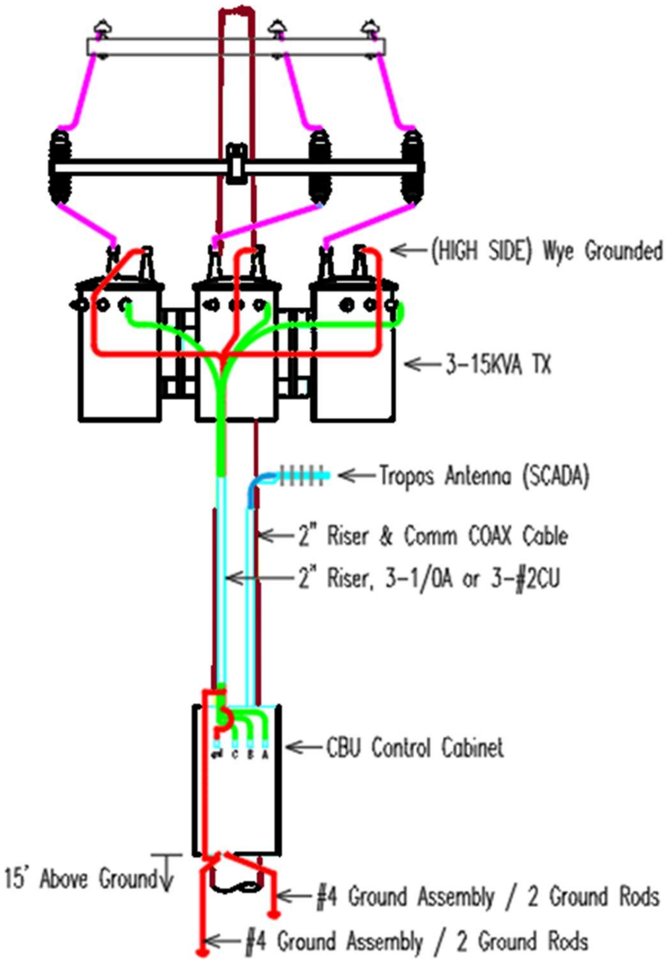

Figure 5 Capacitive Balancing Unit

The GFN is field tested with primary faults to verify performance. The Powerline Bushfire Safety Program in Victoria, Australia developed a performance benchmark based on ignition testing [2][4]:. Details of the benchmark are as follows.

1. For a high-impedance fault:

a. GFN must detect the fault within 1.5 seconds of its occurrence

b. Within two seconds of fault occurrence, GFN must limit the voltage on the faulted conductor to less than 250 volts except during diagnostic tests

c. During diagnostic tests to confirm if the fault is sustained or not or to identify which powerline it is on, the GFN must:

i. Limit the fault current to less than 0.5 amps

ii. Limit the I^2t to less than 0.1 A^2s

2. For a low impedance fault:

a. Within 85 milliseconds of fault occurrence the GFN must limit the voltage on the faulted conductor to less than 1,900 volts

b. Within 500ms of fault occurrence the GFN must further limit the voltage on the faulted conductor to less than 750 volts

c. Within two seconds of fault occurrence the GFN must further limit the voltage on the faulted conductor to less than 250 volts except during diagnostic tests.

The definitions of high-impedance fault and low-impedance fault should be:

High impedance fault: a resistance from any high voltage powerline conductor to earth of value equal in ohms to twice the nominal phase-to-earth voltage in volts (13,800 Ohms in a 12kV network); and

Low impedance fault: a resistance from any high voltage powerline conductor to earth of value equal in ohms to the nominal phase-to-earth voltage in volts divided by 31.75 (200 Ohms in a 12kV network).

PG&E performed commissioning and testing of the GFN to determine the performance targets using a spreadsheet which considers the neutral damping of the power system. The resonant point was 76 Amps with damping of 3%. The target for 0.5 Amp performance was a fault impedance of 11k-ohm.

A specialty trailer with high voltage resistor bank was procured (Figure 6). This allowed for selecting different fault resistance to perform staged fault testing on the distribution primary to verify GFN performance and finalize settings of the controller.

Figure 6 Test trailer with high voltage resistor bank up to 25,400 ohms

PG&E's first staged fault test on the distribution circuit was at 3200 ohms (Figure 7). The current was limited to less than 0.5 Amps and the fault confirmation correctly identified the faulted circuit. The fault confirmation steps occurred after 4 seconds.

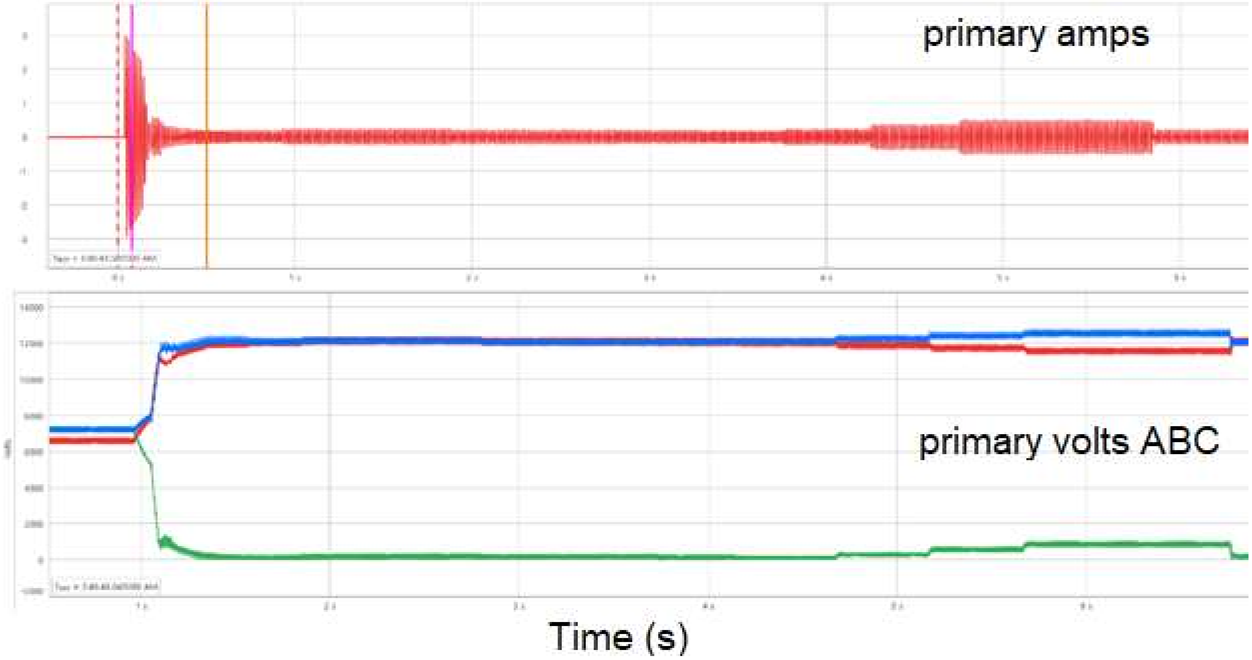

Figure 7 3200 Ohm fault current (top) and bus voltages (bottom)

The GFN successfully detected and limited the fault current for a 14,400 ohm fault. This fault is representative of a high impedance wire down or tree contact. Measurements at the fault site are shown in Figure 8. This fault location was far from the substation, so it took time for the neutral voltage to rise above the detection threshold when the GFN RCC started to drive the voltage down (orange cursor). The initial fault current was less than 0.5 Amps, and the GFN RCC reduced the faulted phase voltage to limit the current at the fault site to less than 0.025 Amps primary (magenta cursor). The GFN performed its soft fault confirmation after five seconds to identify the faulted feeder (not shown).

Low impedance faults were tested using a fault resistance of 200 ohms (Figure 9). The current initially reached the total charging current for the circuit, which was 34 Amps primary. Within 30 ms, the GFN RCC was active and driving the voltage down on the faulted phase, ultimately limiting the fault current to approximately 1 Amp primary. The GFN performed its soft fault confirmation after four seconds to identify the faulted feeder (not shown). In operation, this would result in tripping the faulted feeder within about ten seconds to isolate the fault. Different settings groups can be used to remove the time delay and trip the faulted circuit breaker as soon as fault confirmation is completed, one to two seconds after fault inception. The faster trip settings would be used during red flag warning conditions.

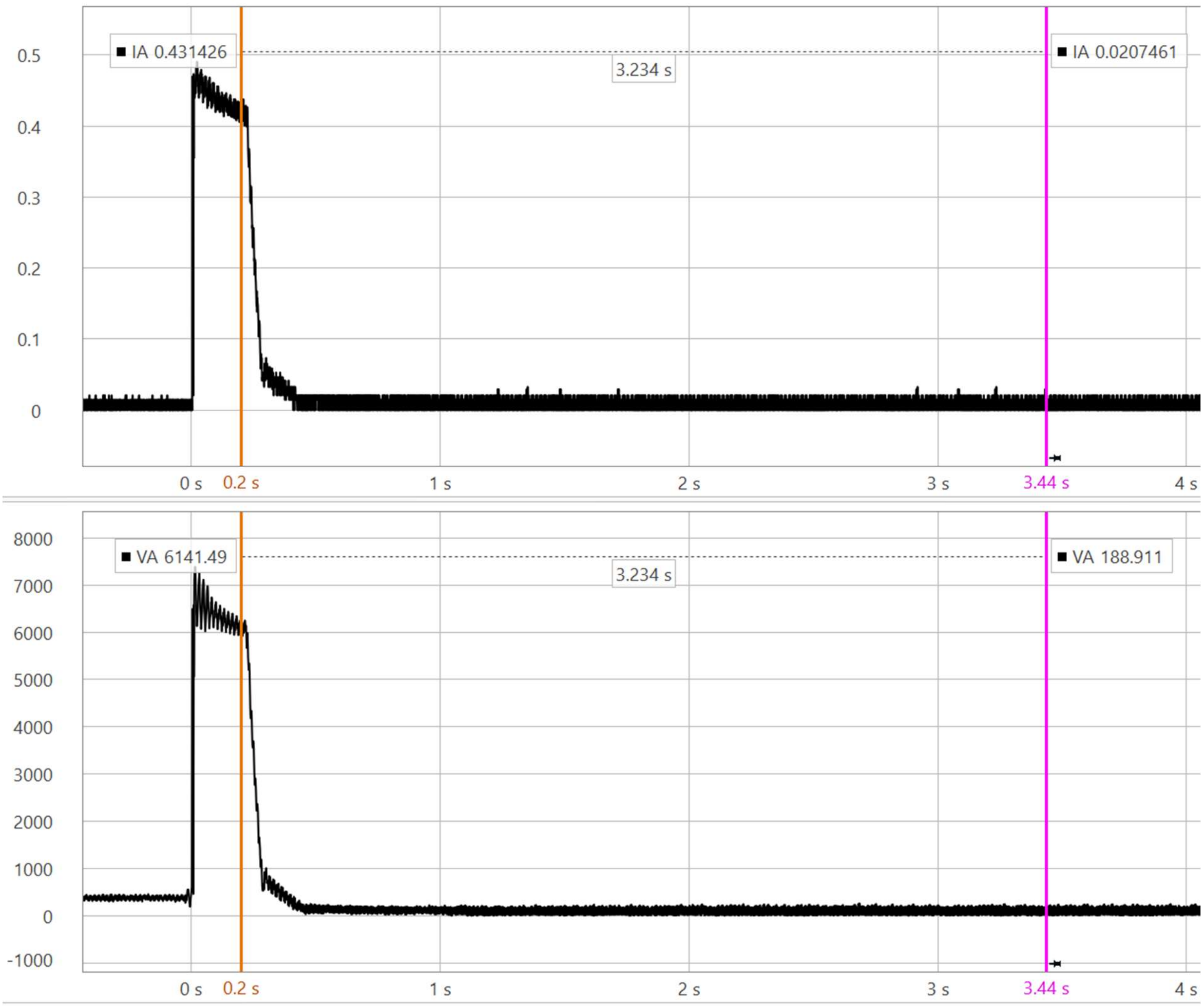

Figure 8 Measurements at fault site for 14,400 ohm fault with GFN operating

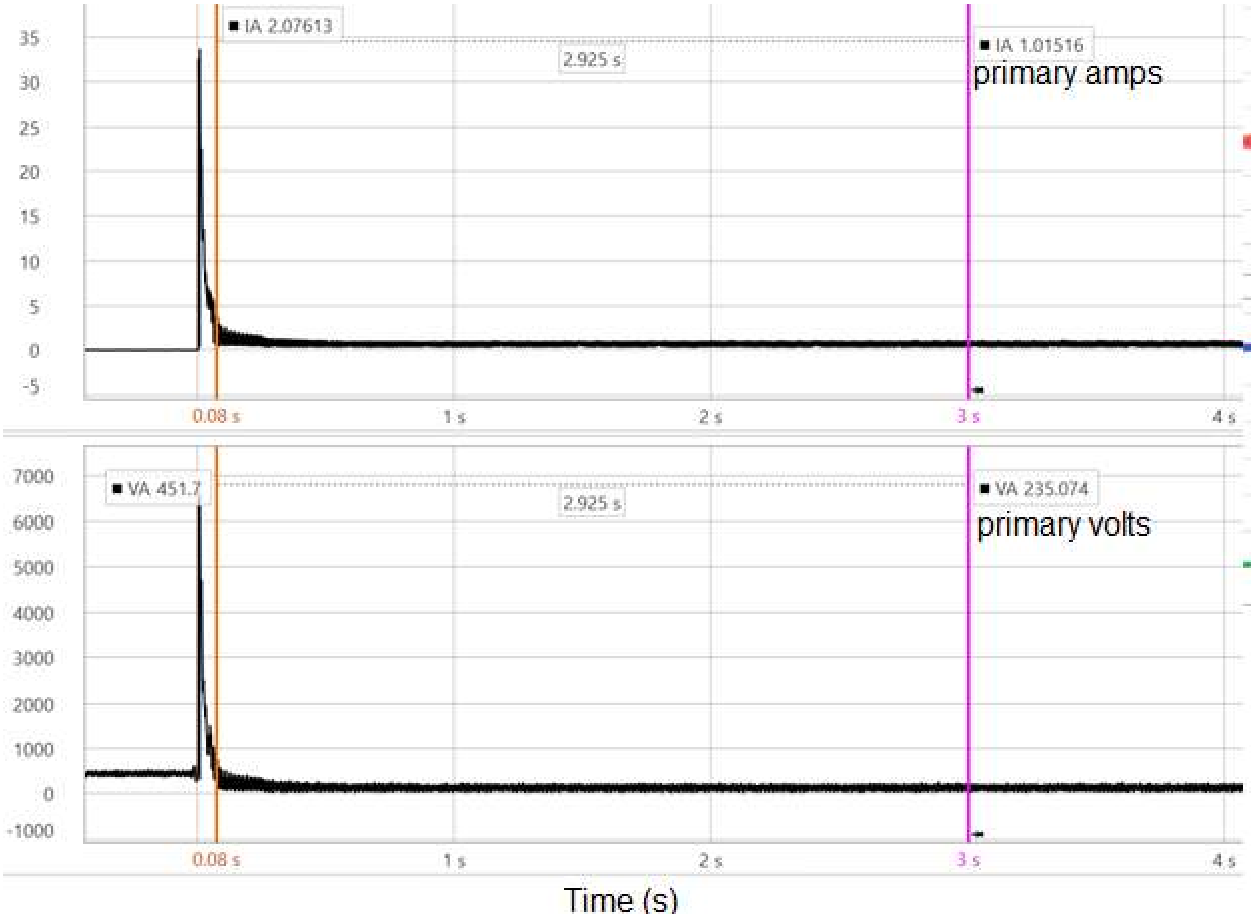

Figure 9 Measurements at fault site for 200 ohm fault with GFN operating

The GFN performance for low impedance faults could be further improved with harmonic compensation. For this test, the harmonics were analyzed (Figure 10). The THD was over 80%, with the 3rd (55%), 5th (59%), and 7th (26%) harmonics dominating. This is likely due to the core in the arc suppression coil. The GFN settings allow for specifying static values, compensating each of these harmonics once the neutral voltage exceeds a threshold. These values should be measured at a staged fault location very close to the substation to determine the compensation limits.

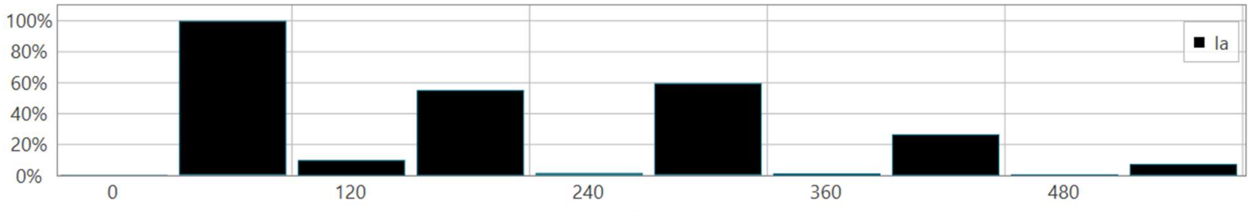

Figure 10 Harmonics for 200 ohm fault

The GFN technology was “not plug and play,” and some integration challenges were encountered.

The substation went through some design iterations due to encountering unexpected ferro-resonance, which led to high voltages and damage to equipment. A circuit capable of ferro-resonance consists of a series capacitance with a saturable inductance, shown in Figure 11 [6].

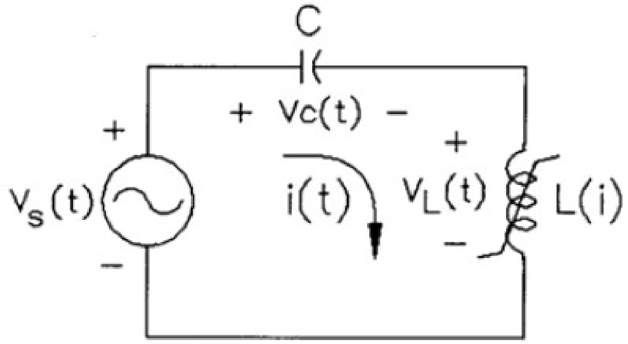

Figure 11 A nonlinear L-C circuit capable of ferro-resonance [6]

Ferro-resonance of Voltage Regulators in substation

The standard design for distribution substations with single phase transformer bank is for Wye-grounded single phase voltage regulators. Due to the increased line to ground voltages during GFN operation, the voltage regulators in the substation had to be swapped out and connected Delta. The station service transformer was also swapped to be connected line-line instead of line-ground. To support construction efforts, a temporary station service transformer was installed and connected to the main panel.

At the time of initial energization and testing of the new voltage regulators, the new service transformer has no load on it. The standard practice during the test program is to check voltage at the secondaries of the bus potential transformers (PT) before closing the test switches one by one so that the relays see the voltage. When the first PT test switch was closed, the breaker for the test source to the new regulators tripped and the Phase A regulator pressure relief opened momentarily. Testing was stopped and the regulator was removed for inspection. Upon inspection, the internal potential transformer (PT) within the regulator was destroyed. It was determined that the secondary single phase switching on the bus PT changed the ferro-resonance operating point, causing over two times nominal voltage and saturation of the regulator internal PT, leading to its destruction. The regulator PT was designed for 1.2 pu voltage.

The equivalent circuit for the substation voltage regulators is shown in Figure 12. The three phases are red, white, and blue to show the line-to-line connection of the regulators in closed delta. The unloaded service transformer is a capacitance in series with the Phase A voltage regulator internal potential transformer. After determining ferro-resonance had occurred, corrective actions were taken to eliminate reoccurrence:

1. Relocation of station service transformer to source side of voltage regulators and removal of temporary service transformer to ensure load on the permanent station service transformer.

2. Replacement of voltage regulators with Type "B" regulators which use a tap on the main core and coil and not an internal PT. If an internal PT rated for 2.0 pu voltage was available, a Type "A" regulator would have been selected
3. Modification to test program to check voltages at the open bus PT secondaries and then isolate the test source, close all three PT secondaries, and close in the test source

After taking these actions, the voltage regulators operated with the GFN without issue.

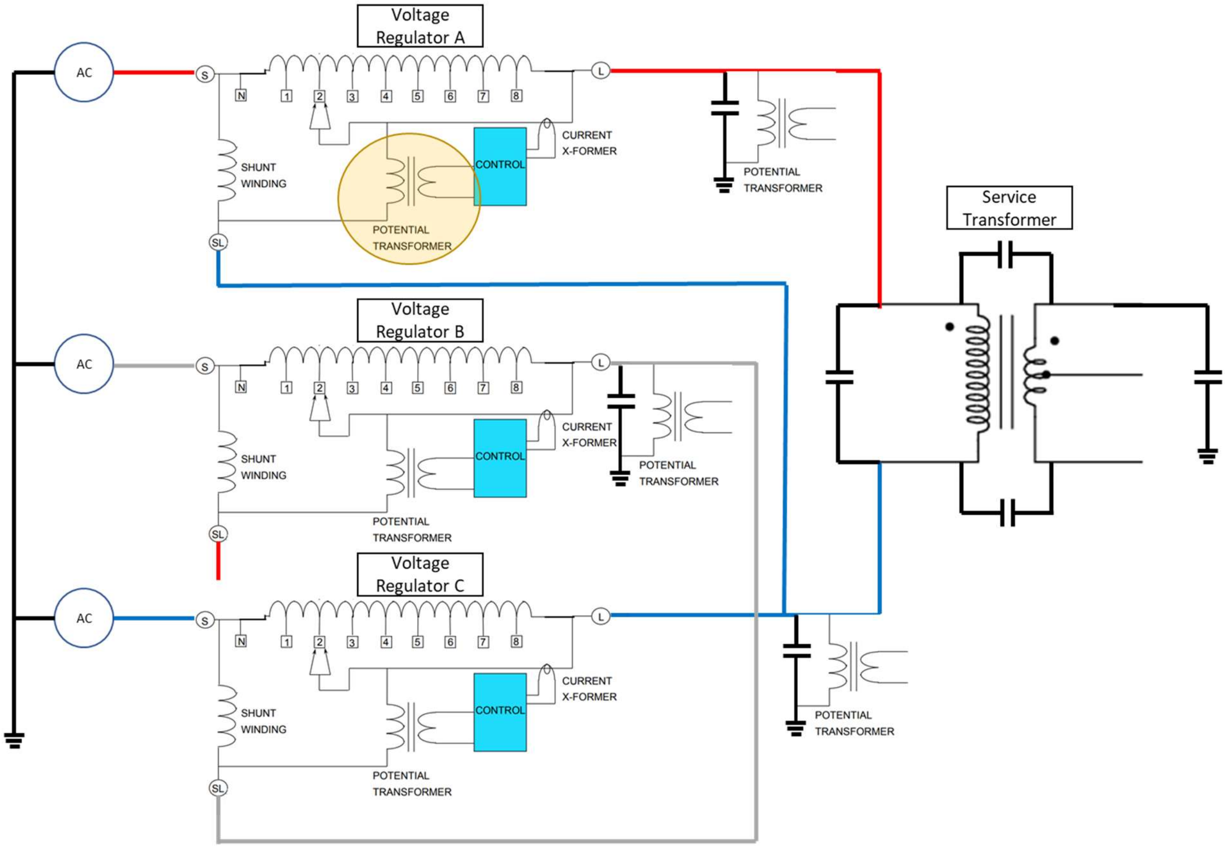

Figure 12 Substation voltage regulators equivalent circuit capable of ferro-resonance

Ferro-resonance of Grounding Transformer in substation

The supplier installed the GFN equipment in a standard seavan shipping container for international shipment. The service voltage of the GFN equipment was 400Y/230V, which is an uncommon voltage in North America. To simplify connections and service power, a zig zag grounding transformer was supplied to accept 3-phase 12 kV and create a neutral point and step down to the 400Y/230V service. The arc suppression coil was connected to this neutral point. The bank secondary neutral was kept separate and solidly grounded while the GFN was not in service (Figure 13).

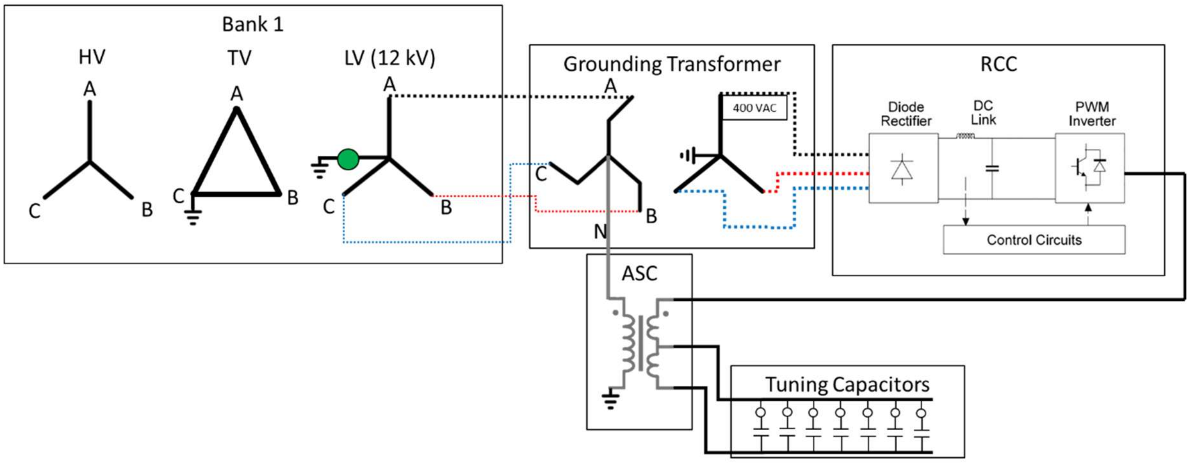

Figure 13 GFN and Bank connections with Grounding Transformer

The connections with the grounding transformer and the bank neutral resulted in an equivalent circuit capable of ferro-resonance (Figure 14). The ASC was tuned to the previously determined resonant point of 76A to match the zero sequence capacitance of the distribution lines. The ASC was left at this position while the substation bank secondary neutral was solidly grounded. At some point while in this configuration, a single line to ground (SLG) fault on Phase A occurred. This caused the ferro-resonance operating point to change, and the grounding transformer saw high voltage on the other two phases. No load was on the grounding transformer when this occurred, so the peak voltage reached levels great enough to flash over between de-energized tap changer (DETC) leads on the grounding transformer high voltage side windings. No other primary equipment was damaged.

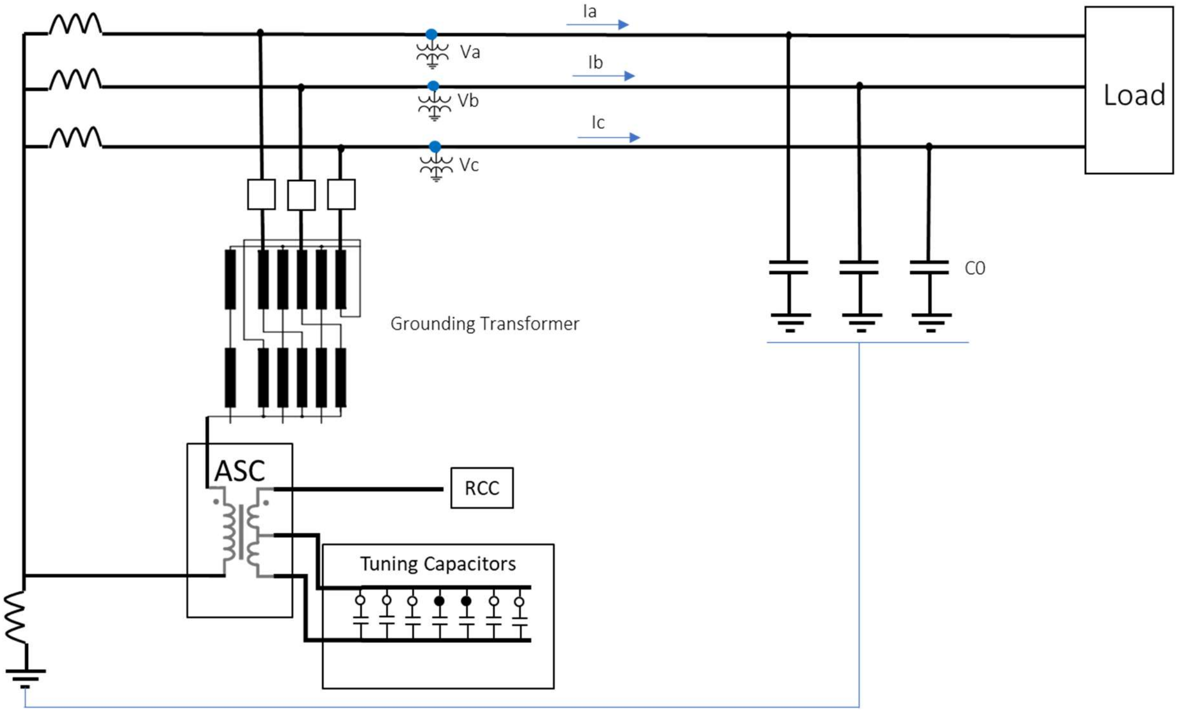

Figure 14 Equivalent circuit with grounding transformer capable of ferro-resonance

After determining ferro-resonance had occurred, corrective actions were taken to eliminate reoccurrence (Figure 15):

1. Eliminate grounding transformer from the design and install delta-wye 12 kV station service with 480:400Y V step down transformer
2. Install new neutral cable and disconnect switch between ASC and bank secondary neutral

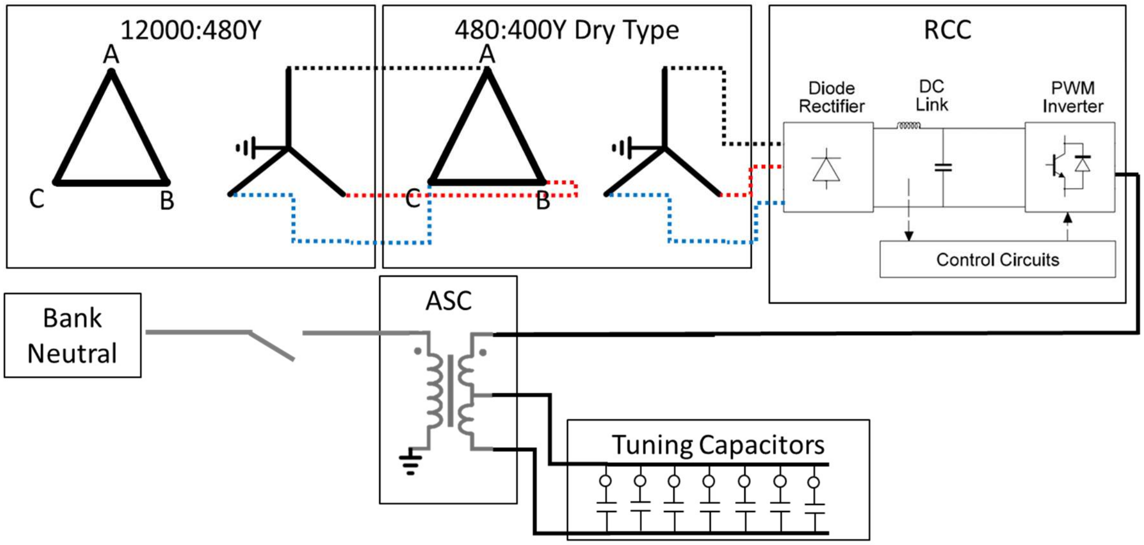

Figure 15 Updated substation configuration with no grounding transformer

After taking these actions, no further ferro-resonance issues were observed.

During GFN commissioning and staged fault testing, some equipment on the distribution circuits failed. These included a 10 KVA service transformer, underground cable connector, and underground cable splice (Figure 16). Due to the increased voltages during commissioning and testing, these failures were not unexpected, but they did cause delays in operationalizing the GFN.

Figure 16 Cable splice which failed during staged fault testing

PG&E is still testing and evaluating the GFN technology in the field demonstration to gain more operational experience with the GFN as of Summer 2022.

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