Ground Fault Protection and the Multi-wire Branch Circuit: A Troubled Marriage

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August, 2016
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Both ground fault protection and the multi-wire branch circuit (MWBC) are common topics. This article discusses their union: the use of a 2-pole[1] GFCI/GFPE breaker to provide protection to the two 120V legs (L1 and L2) of a 120V/240V, three wire (L1/L2/N), shared neutral circuit. You may be surprised, as I was, to find that the protection provided is attended with subtle, if not troublesome and problematic, differences from the protection provided by a single pole breaker on a 2-wire circuit (Hot/Neutral). The manifestation of these differences in a marine environment will be highlighted.

Several months ago I was thinking about the effects of marina basin background current (sometimes called foreign or stray current) on the measurement of AC leakage from boats as is commonly made by clamping the shore power cord with an ammeter. I concluded that the effect of background current depends on whether it originates from the same or opposite leg (L1/L2) of the distribution source as the current leaking from the boat circuit.

That led to the question of how faults/leaks[2] from different legs of a main or feeder panel would be seen by a 2-pole (L1/L2/N) ground fault protection breaker. I have so far been unable to locate a treatment of this subject. (Perhaps readers will be able to provide me with references.) So based on my own analysis, simulation, and testing as well as interaction with a few electrical professionals, I have reached preliminary conclusions. They are presented in this article with the expectation that they will elicit comment and critique.

The GFCI Current Transformer

Before considering the 2-pole ground fault protection breaker on a MWBC, let's look briefly the single-pole, 2-wire (H/N), GFCI/GFPE breaker. (See Figure 1.) Its heart is the residual current transformer (CT). The core of the transformer is typically a toroid - a doughnut shaped ring of magnetic material (the heavy black ring in Figure 1). Both the hot and neutral conductors are passed through the toroid making each of these conductors a single-turn primary winding of the CT.

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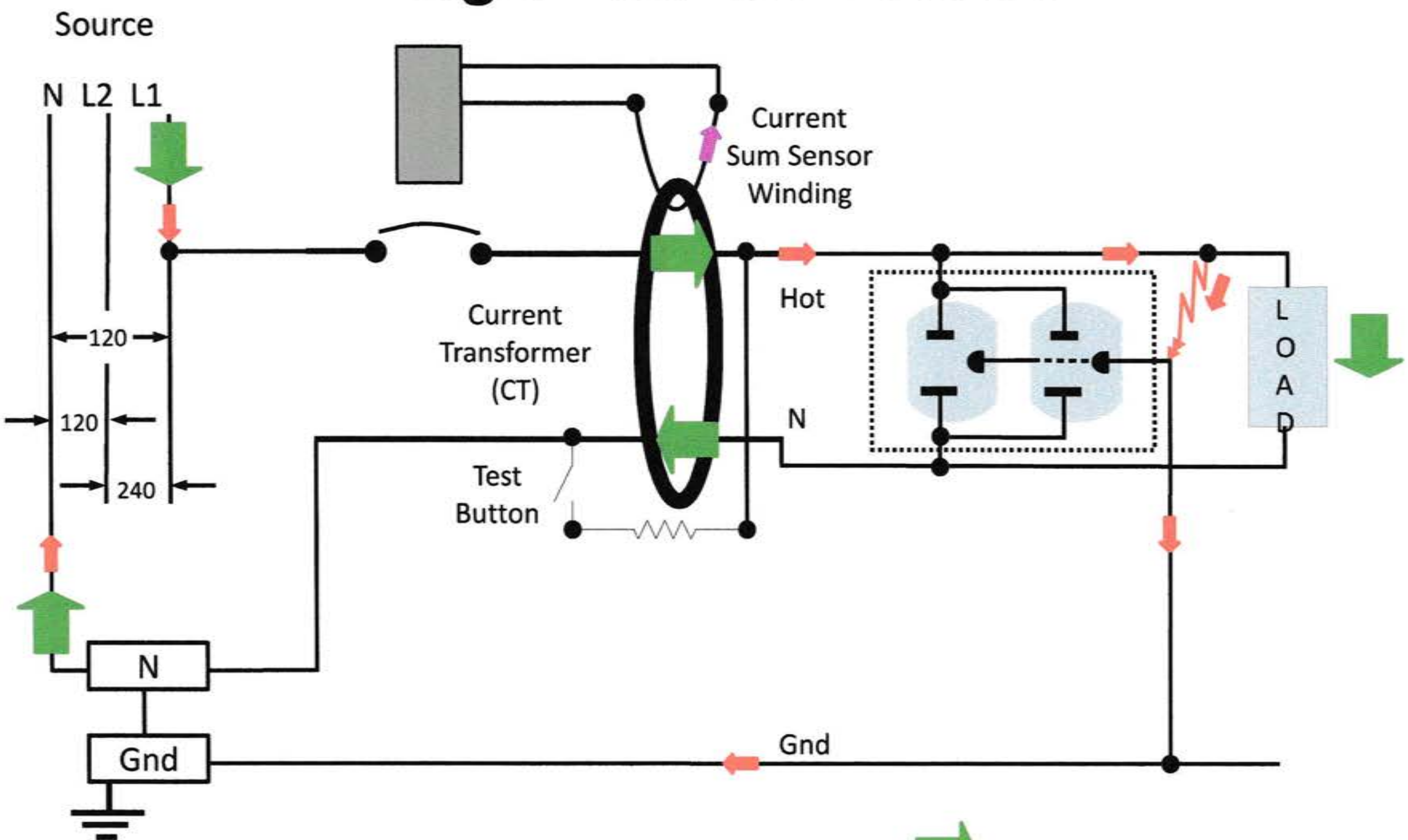
1 The number of poles properly refers to the number of conductor paths being switched. A 2-pole breaker would be expected to switch two paths. In a 120V/240V MWBC these would normally be the two hot legs, L1 and L2, with the neutral not being switched. Whether or not the neutral is switched (a 3-pole breaker) has no bearing on the effects discussed in this article. By specifying a 2-pole breaker, I am attempting to use common terminology to reference popular devices.

2 The term "fault/leak" and similar language is used throughout to emphasize that the subject current could be the result of a) an expected and sometimes allowed (UL approved) hot to ground current that is due to no fault or problem with an appliance or the circuit, or b) a fault, or c) a combination of both. Some leaks meet UL specs (0.25 - 3.5 mA, typical) and some appliances have no compulsory requirements (e.g., some directly connected appliances and all boats - the ABYC E-11 standard is voluntary).

Single Pole GFP Breaker



- All normal currents flow out on Hot (H) and return on Neutral (N) producing a zero current sum in the CT primary and no current in the sensing secondary..
- Fault/leak current flows out on Hot through the current summing transformer and returns on the Gnd without any offsetting current on Neutral.
- This imbalanced net flow in the CT primary (fault/leak current) creates a magnetic field which generates a non-zero current in the current summing secondary..

Normal current to load returning on neutral

Fault/leak current returning on ground

Current in CT secondary due to H/N imbalance

No Connection

Connection

Figure 1.

The transformer's secondary is a multi-turn winding on the toroid that functions as a sensor. It is energized when the sum of the currents in the hot and neutral primaries is non-zero. Consider current flowing through the toroid on the hot or neutral from the source toward the load, to have one sign (+ or -) and current flowing the other direction to have the opposite sign (- or +, respectively). If the current that flows from the source out on the hot wire is equal to that returning through the neutral, then a net zero primary current results, and so no magnetic field is generated, and therefore no current flows in the secondary winding. This is the case when the circuit has no leaks or faults to ground.

When Things Don't Add Up

On the other hand, if some of the current returns to the source, not on the neutral, but on the safety ground or through some environmental path (e.g., building structure, person, or the earth), then there is a current imbalance. The neutral return current will be less than the hot supply current. These opposite direction hot and neutral currents do not offset each other. The result is a non-zero net current through the primary windings which produces a magnetic field whose AC dynamics induces a current in the sensing secondary winding proportional to the imbalanced current sum. If the imbalance reaches the trip level for the breaker (e.g., 5 mA for a GFCI and 20, 30 or 100 mA for a GFPE), then the breaker is tripped by processing circuitry which opens the hot conductor path.

In order to be able to periodically test its functionality, a GFCI/GFPE breaker is equipped with a manual test circuit. A push button switch completes a path from the load side hot through a resistor to the supply side neutral, thereby providing a return path for a test current that does not flow through the toriod. The imbalance created simulates an actual fault or leak. Since the resistor is chosen so that the current is just above the trip limit, the breaker trips in the usual way. This test is to be performed monthly.

An Additional Conductor

Now let's consider the subject circuit: a 120V/240V multi-wire branch protected by a 2-pole (L1/L2/N) GFCI/GFPE breaker[3]. (See Figure 2.) A second ungrounded conductor (red in Figure 2) is added to the single pole breaker current transformer as a third primary. This conductor originates on the opposite leg (line or split-phase) of the single phase service source. It takes a switched path through the breaker and passes through the CT toroid to a load side connector. From there it is wired to a 120V circuit (L2) just as the original pole (L1) and uses the same neutral as its return path. Normal load current flows out L1 hot or L2 hot to the load and returns on L2 hot or L1 hot, respectively, or on the neutral. The current on the neutral is the difference between the L1 and L2 currents. $iN = | iL1 - iL2 |$. An L1 fault or leak to ground (red zigzag in Figure 2) flows through the current summing transformer (on L1) without any offsetting current in L2 or N. Just as in the single pole breaker, this imbalanced net flow in the primaries creates a magnetic field which generates a non-zero current in the current summing secondary and **<u>the breaker trips at the designed trip current level</u>**.

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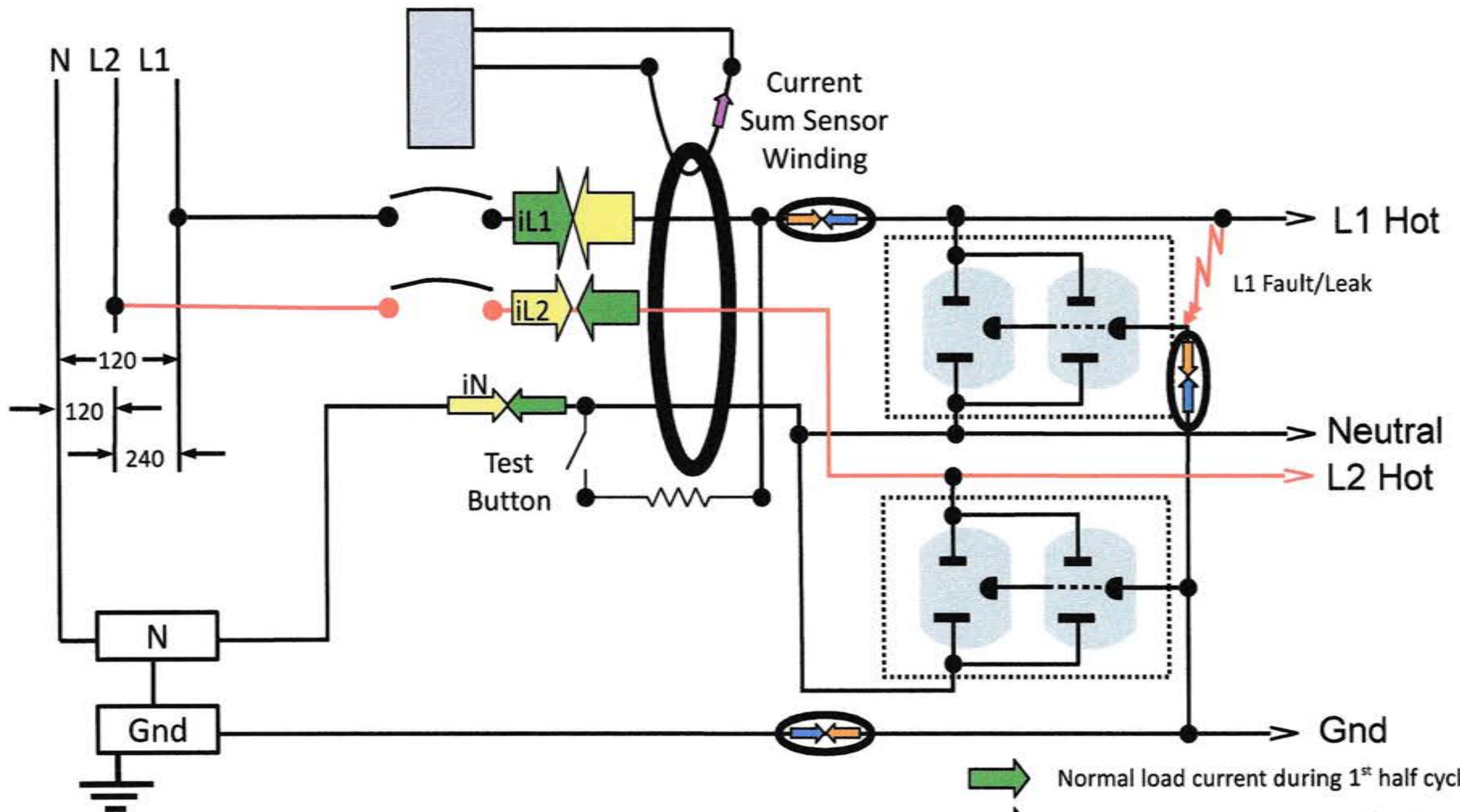
3 Multi-wire branches whose ungrounded conductors are from the same leg (either L1 "or" L2), as opposed to different legs, (L1 "and" L2) have a well defined, "as expected" behavior and are not being addressed in this article. A 2-pole breaker trips in these cases when the sum of all leaks and faults combined from both of the circuit branches exceeds the device trip level.

Double Pole GFP Breaker – Single Lug(L1) Fault/Leak



- All normal currents flow out L1 Hot or L2 Hot and return the opposite direction on L2 Hot or L1 Hot, respectively, or on N. iN = | iL1 – iL2 |
- L1 Hot fault/leak to ground flows through the CT without any offsetting current in L2 Hot or N.
- This imbalanced net flow in the CT primary (|L1 - L2| fault/leak current difference) creates a magnetic field which generates a current in the CT current sum sensing secondary.

Normal load current during 1st half cycle

Normal load current during 2nd half cycle

Fault current direction during 1st half cycle

Fault current direction during 2nd half cycle

Secondary current generated by primary imbalance

Fault/leak current from L1 Hot

Fault/leak current from L2 Hot

No Connection

Connection

Figure 2.

Ground: Where Opposite Faults Meet

That explains the case of a fault/leak on one leg (L1) or the other (L2). But suppose there are faults/leaks on both the L1 and the L2 120V branch circuits. First consider the case of equal fault/leaks. (See Figure 3.)
Current flow for equal faults/leaks is similar to that of equal loads (L1 and L2) - the return current for each uses the opposite leg. Follow the L1 fault/leak current (orange arrow, Figure 3) from the L1 source through the CT out to the L1 leg fault. It flows to ground through the L1 fault path then through the L2 fault to L2 and returns on L2 through the CT to the source. So no current returns on the ground or the neutral. The current that flows from L1 returns in L2, and vice versa. The current sum in the CT primaries is zero, therefore no magnetic field and no current in the secondary and no trip. Note that regardless of the size of the faults/leaks, **if they are equal, the breaker will not trip.**

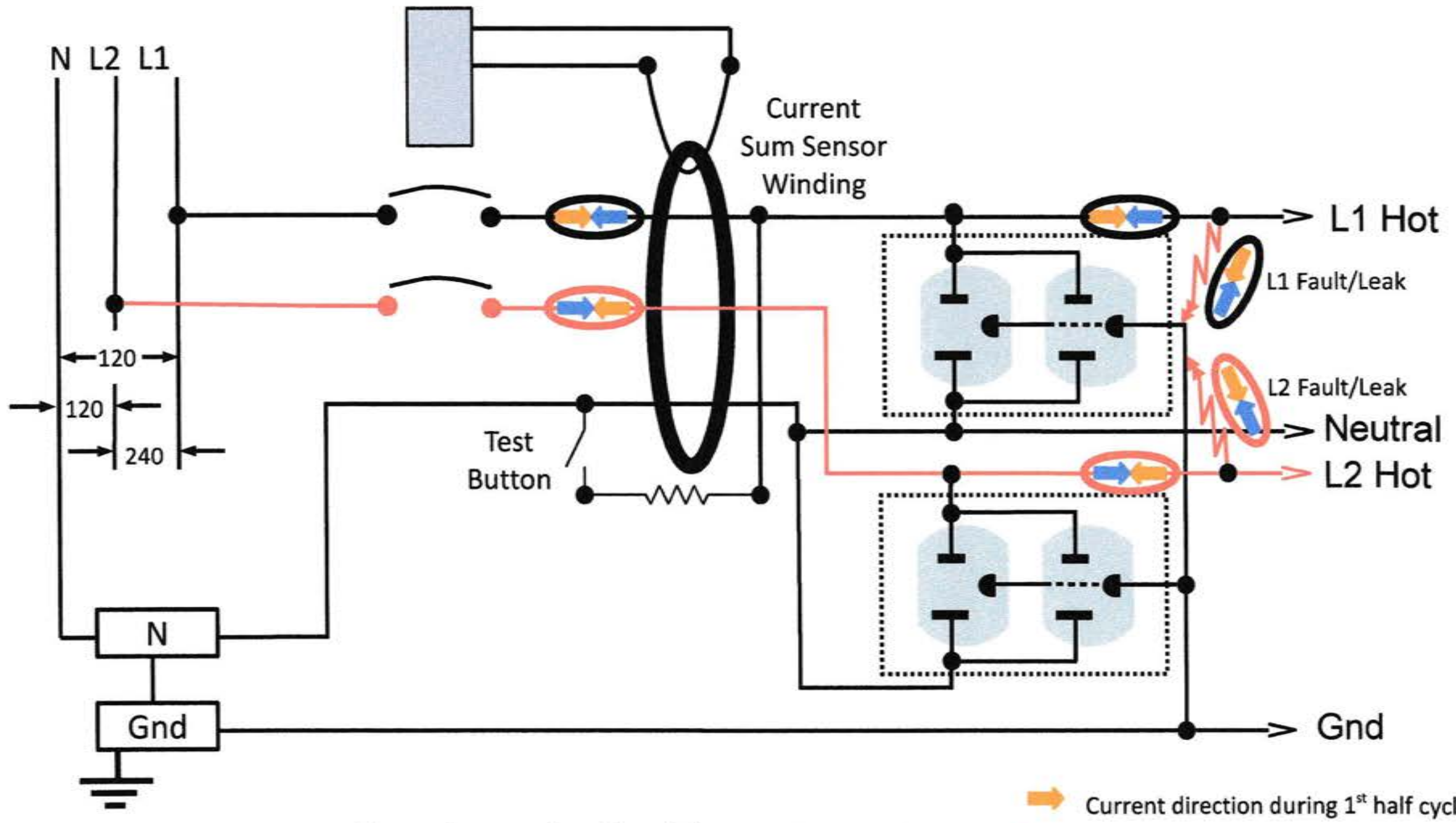
A More Likely Case

But suppose one leak is smaller than the other. (See Figure 4.) Let's say the 2-pole breaker is a GFPE with a 30 mA trip limit. Suppose the appliances connected to L1 have a total fault/leak current of 25 mA and the L2 total is 15 mA.
Normal currents (not faults/leaks) flow to and from the load on the L1/L2/N as usual and so will flow in equal amounts in both directions through the CT and will not contribute to any current imbalance measured by the secondary. They are being ignored in this analysis.

Let's trace the fault/leak currents on the positive AC half-cycle, i.e., when the instantaneous L1 voltage is greater than L2 voltage. (See the orange arrows in Figure 4.) The L1 current, 25 mA, travels from the source through the CT to the fault/leaks and then through them to ground. At the ground point, 15 mA of the 25 mA travels through L2 fault/leak path to the L2 circuit and returns through the CT to the source on the L2 circuit. The remaining 10 mA follows the ground path back to the source via the panel ground to neutral bus connection. During the negative half cycle, the currents all reverse on the same paths and in the same amounts. (Negative half-cycle is not shown in Figure 4; they would be blue arrows equal in size and head to head with each orange arrow.)

The current imbalance in the CT primaries is: 25 mA L1 source to load (+), 15 mA L2 load to source (-) and 0 through the neutral, 25 mA + (-15 mA) + 0 = 10 mA. The resulting magnetic field induces a current in the secondary indicative of a 10 mA imbalance so **the breaker will not trip.** (10 mA < the trip level of 30 mA.)

Double Pole GFP Breaker – Equal L1 & L2 Faults/Leaks



- All normal current (not shown) flows out L1 Hot or L2 Hot and returns on L2 Hot or L1 Hot, respectively, or on the Neutral without creating a CT current imbalance.
- If equal, L1 and L2 fault/leak currents return through the series connected fault/leak in the opposite line not on the Neutral.
- The current sum through the CT primary is zero so the magnetic field is zero and the current in CT secondary sensing winding is zero.

Current direction during 1st half cycle

Current direction during 2nd half cycle

Fault/leak current from L1 Hot

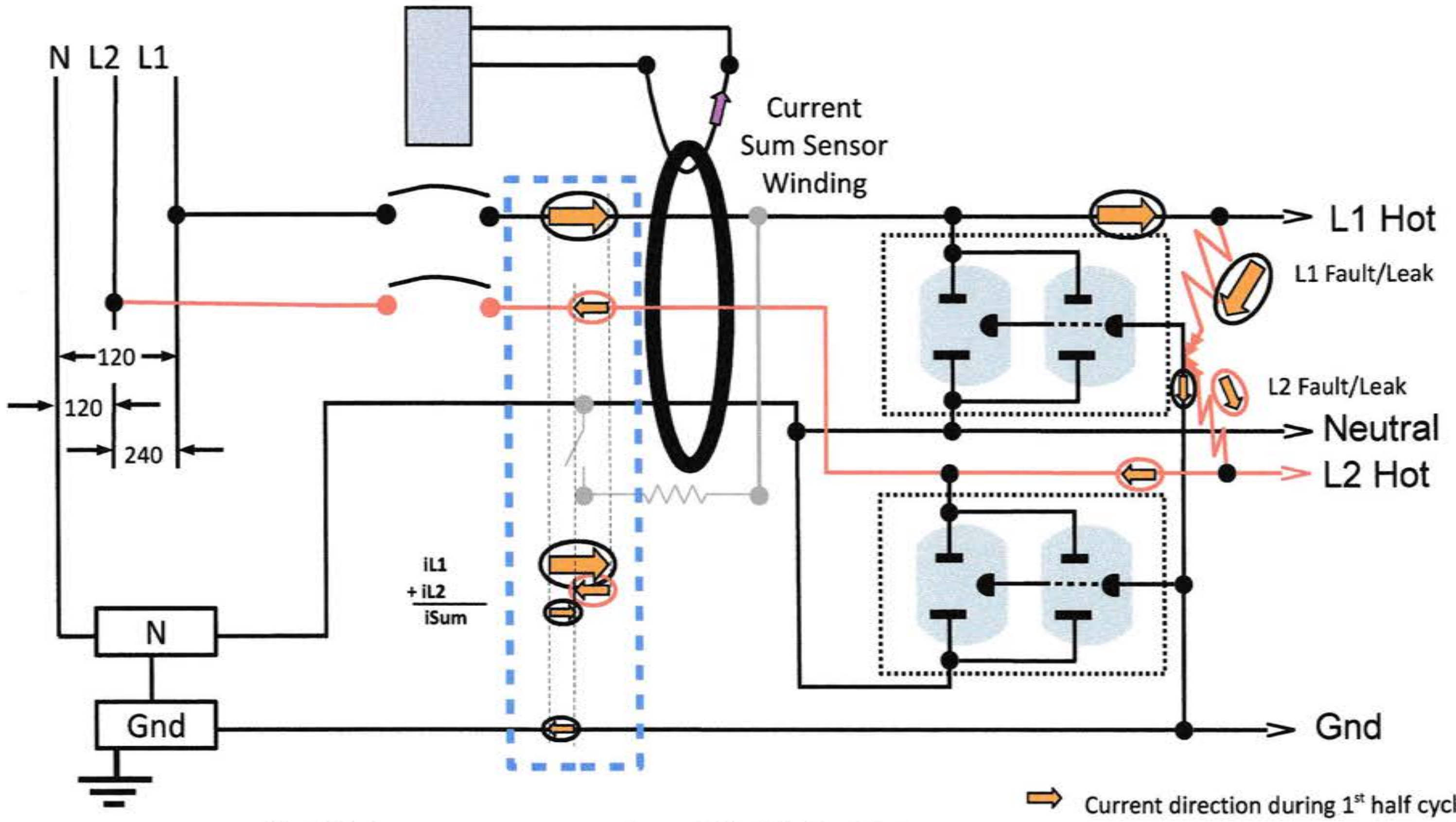
Fault/leak current from L2 Hot

No Connection

Connection

Figure 3.

Double Pole GFP Breaker – Unequal L1 & L2 Faults/Leaks



- If fault/leak currents are not equal, e.g. L1 fault/leak > L2, the part of the greater (L1) that is equal to the lesser (L2) returns through the series connected fault/leak in the opposite line (L2) and in the opposite direction through the CT creating no primary current imbalance.
- The remainder of the greater (L1) fault/leak current returns through the ground and not back through the CT.
- This imbalance is equal to the fault/leak difference between L1 and L2 and induces a proportional current in the CT sensing secondary.

Current direction during 1[st] half cycle

Current direction during 2[nd] half cycle - not shown but equal and opposite to orange arrows

Secondary current generated by primary imbalance

Fault/leak current from L1 Hot

Fault/leak current from L2 Hot

No Connection

Connection

Figure 4.

A Fault Above the Trip Limit

Let's look at another case. With L1 still leaking/faulting at 25 mA suppose L2 gets an additional 35 mA fault (5 mA in excess of the 30 mA trip limit) bringing its total fault/leak to 50 mA (15 mA + 35 mA). Using an analysis similar to the above, we can trace the fault/leak currents but using the negative AC half-cycle this time. The 50 mA L2 current flows from the source on L2 through the CT toward the load but takes a fault path to ground. From there it splits. 25 mA takes the L1 fault/leak path to the L1 circuit and returns back through the CT on the L1 conductor. The remaining 25 mA returns through the ground to the neutral bar in the panel. With 50 mA source to load on L2 and 25 mA load to source on L1, the CT imbalance is 25 mA detected by the secondary. But that is still 5 mA short of the required 30 mA to trip.

So with 75 mA flowing through leaking/faulting paths, 25 on L1 and 50 on L2, the 30 mA **breaker still will not trip.**

This Can't Be Right

But let's not give up. Suppose that 20 of the 25 mA L1 fault/leak is due to a fault in a single appliance. **If this faulty appliance is removed,** the L1 fault/leakage drops to 5 mA, the imbalance increases to 45 mA (50 L2 – 5 L1 = 45 > 30) and **the breaker trips.**

If we reconnect the faulting appliance and reset the breaker, it does not trip because the imbalance is back down to 25 mA.

Failure of Push To Test

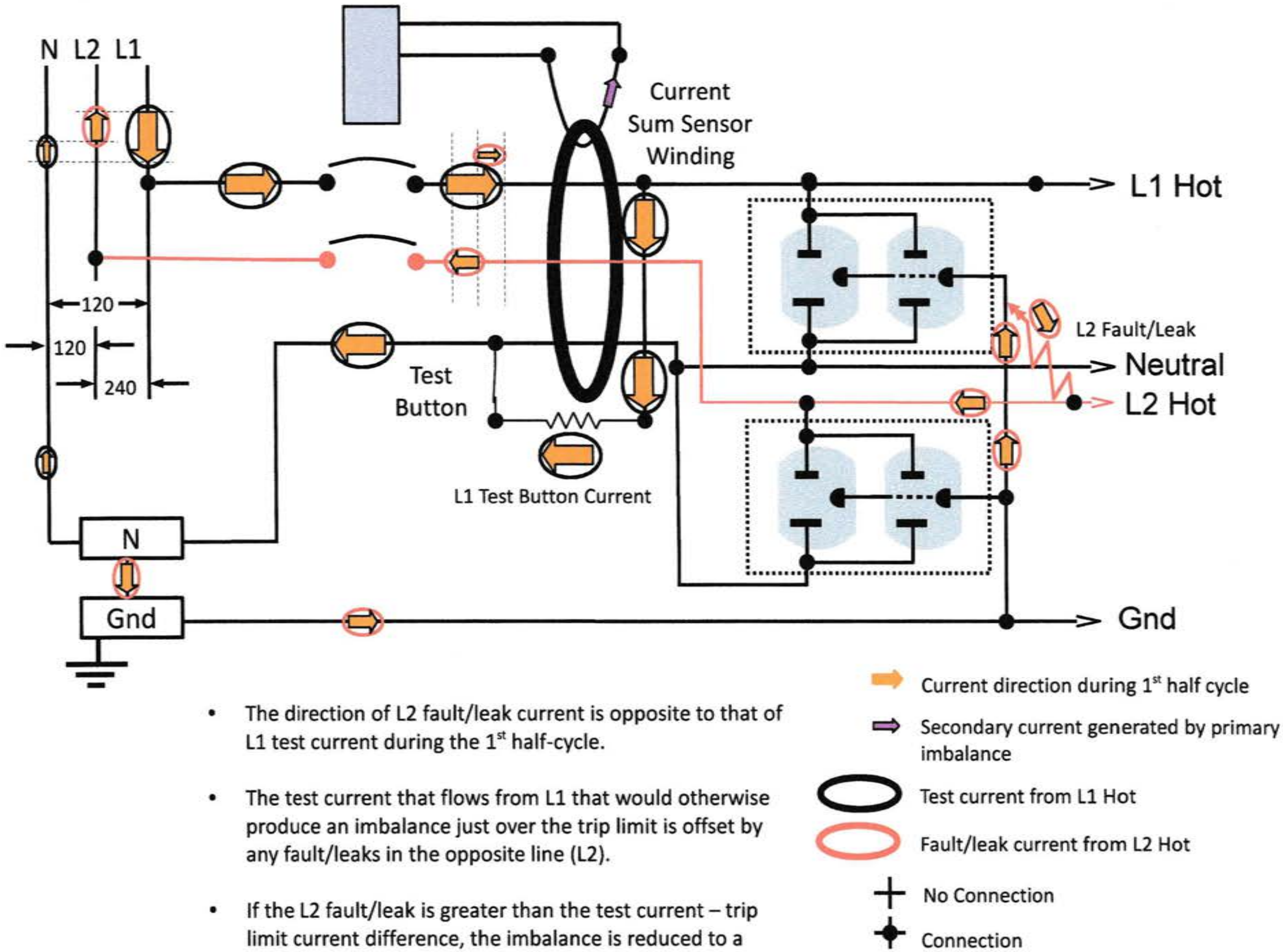
One of the most troublesome and unhelpful consequences of 2-pole ground fault protection of a MWBC is the effect on the push to test feature. (See Figure 5.) As described earlier, the test button produces a current imbalance just above the trip limit. Let's suppose in the case of our 30 mA trip example GFPE, the test circuit draws 31 mA from L1 (shown in Figure 5 by large orange arrows circled in black).

Provided there is no leak or fault on L2, the breaker will trip when the test button is pressed, since the entire 31 mA will be an imbalance. But if there is a leak or fault on L2 (shown in Figure 5 by mid-sized orange arrows circled in red), a portion of the test current flows through the neutral-ground connection in the panel, then through the L2 fault/leak and onto the load side of L2 and then back through the CT to the source, thus reducing the 31 mA imbalance by the amount of the L2 leak. If the L2 leak is more than 1 or 2 mA the test button imbalance will not be enough to trip the breaker (31 mA - 2 mA < 30 mA). Unless L2 is essentially free of faults/leaks[4] the **push to test button will misidentify a good breaker as faulty**.

Let's return to our continuing example and actuate the test button. After reconnecting the faulting appliance, L1 has 25 mA of fault/leak current and L2 has 50 mA. If the test button is pushed, ~31 mA is added to the 25 mA L1 leakage path, bringing the L1 total fault/leak up to 56 mA. With L2 fault/leak current at 50 mA, there is a 6 mA imbalance, 56 mA + (- 50 mA) + 0 = 6 mA, which is less than the trip

4 More precisely, unless the L2 fault/leak current is less than an amount equal to the L1 fault/leak current increased by the difference between the test current and the trip limit, since the effective L1 fault/leak current during the test will be the leg fault/leak current plus the test current.

Double Pole GFP Breaker – The Test Button



- The direction of L2 fault/leak current is opposite to that of L1 test current during the 1st half-cycle.
- The test current that flows from L1 that would otherwise produce an imbalance just over the trip limit is offset by any fault/leaks in the opposite line (L2).
- If the L2 fault/leak is greater than the test current – trip limit current difference, the imbalance is reduced to a value below the trip limit and the breaker will not trip when tested..

Figure 5.

limit. The breaker does not trip[5], thus indicating a bad breaker. **A good breaker fails the push button test**.

Let's Call the Doctor

Note how difficult this circuit would be to diagnose. If all appliances were removed, the breaker would test good. Then as the devices are reconnected, the point at which the breaker would test bad, or trip, or even **if it would trip at all, would depend on the order of reconnection**. If L2 were disconnected or all L2 loads removed (only L1 connected), the breaker would not trip and the test button would trip the breaker. If L1 were disconnected from the breaker or all L1 loads removed (only L2 connected), the L2 fault/leaks would trip the breaker, but they are only an accumulation of allowable leaks[6]. We could multiply similar examples of unnecessary confusion when trying to track down problems. Confusion which would not exist if 120V circuits requiring ground fault protection were provided their own neutral return rather than share a neutral with another circuit on a multi-wire branch. Before dismissing this musical connections scenario as unlikely, consider the marina where connecting and disconnecting with varying and uncertain order is the norm.

Bottom Line Effects

In a nutshell, then, what we find is that when feeding a MWBC, the 2-pole ground fault protection breaker trips when the imbalance caused by the difference in the L1 vs. L2 faults/leaks exceeds the trip limit. In other words, it trips when:

| (L1 leaks & faults) – (L2 leaks & faults) | > Trip Limit.

It is incapable of tripping on an L1 fault at the trip limit unless the leakage and fault current of L2 is equal to that of the pre-fault L1 circuit. In order for the faults or leaks on one leg (L1) to cause a trip, they must exceed the total faults and leaks on the other leg (L2) by at least the trip limit.

To put it another way, the common, **multi-wire branch circuit cannot be protected against ground faults** to the same degree and with the same precision, the same measures of protection, expectation of behavior, etc. **as a branch with its own neutral**. This is not all that surprising when you consider that by sharing a neutral, the return current of each branch is made anonymous as to its origin (L1 vs. L2).

Here are some of the effects of using a 2-pole ground fault protection on a MWBC:

1. **Fault current on one leg in excess of the rated ground fault protection level** is required to trip the breaker in the presence of the inevitable leakage/fault current difference (I.e., when L1_leakage - L2_leakage is not = 0) – thus decreasing fault detection sensitivity.

2. The manual test button will not consistently perform a valid test. - i.e., **a good breaker will test bad -**

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5 Notice that at 6 mA, a Type A GFCI would just barely trip.

6 See footnote 2.

when L1 fault/leakage current is greater than that of L2 (plus test current margin[7]) or when L2 fault/leakage current is greater than that of L1 (plus margin), depending on whether or not the current for the test button is drawn from L1 or L2.

3. L1 and L2 circuits may be able to sustain leakage/fault currents well in excess of the rated ground fault protection level. I.e., **leakages/faults my be arbitrarily high** without tripping the breaker so long as their fault/leakage difference (L1 vs. L2) is less than the rated ground fault protection level. E.g.,**a faulty/leaky boat** which trips a 2-pole GFCI/GFPE when connected to a 120V/30A, L1 circuit **could work just fine** if moved to an adjacent L2 powered receptacle.

4. The **removal of an appliance or device from a circuit could cause a trip**. This happens when the fault/leak in the removed device is of such value that, when removed, it increases the L1 vs. L2 difference up to the trip level. The order of appliance connection and disconnection determines the possible, trip/non-trip, circuit states.

5. The **likelihood of so-called nuisance trips is increased.** A very small added fault or leakage can cause the breaker to trip since lop-sided L1 vs. L2 fault/leak current increases the trip sensitivity on one leg while decreased sensitivity on the other.

What Circuits Are Affected

These effects apply to virtually every 120V multi-wire branch that consists of two ungrounded conductors from opposite legs (L1 and L2) of the 240V source[8]. However, the implications in some cases are decidedly more significant than in others.

On the less troublesome end of the spectrum might be the dishwasher and garbage disposal split outlet connection that is fed by a 2-pole Type A GFCI breaker. In the first place the Class A GFCI trip point is low (~5 mA)[9] Even with a leakage difference of 4.9 mA, the trip limit for the lower fault/leakage leg would still be only ~10 mA – a fairly safe level. Secondly, the test button dead zone for a test current of 7 mA would be only about 3 mA wide, i.e., for fault/leak differences of greater than about 2 mA and less than 5 mA. Thirdly, there is only one appliance connected to either leg (L1/L2) and there are no available additional receptacles and for much of the time, only one appliance is switched on. Lastly, but perhaps most importantly, both are subject to mandatory standards and codes.

At the other end might be a 2-pole (L1/L2/N), 100 mA GFPE multi-wire circuit at a marina that feeds 120V/240V as well as and both L1 and L2 120V shore power receptacles. This configuration is consistent with the 2014 NEC - 555.3 which requires the main or feeder to have ground fault protection not to exceeded 100 mA. The circuit connections – the boats – vary widely both as to the mix of appliances on board and also with time (here today, gone tonight, in a different slip tomorrow) and are subject to no mandatory codes[10]. In addition the likelihood of lethal exposure is greater since the circuit faults/leaks

7 Test current margin is amount that the test current exceeds the trip limit – a small number, typically 1 or 2 mA.

8 See footnote 3

9 The effective minimum guaranteed trip limit of a 2-pole GFCI/GFPE feeding a MWBC is twice the nominal trip limit. That being the case, twice the Class A GFCI limit is still very low and provides some level of personnel protection.

10 The ABYC E-11 standard is not mandatory.

could far exceed a safe limit and could be flowing into the water.

Other Devices

GFCI/GFPE breakers are the focus of this article, but what other devices might be subject to some of these same effects when used on shared neutral circuits (L1/L2/N)? Any of the alphabet soup of ground fault protection devices which employ a residual current summing transformer are suspect.

For example, the ELCI used on board boats that is called for in the American Boat and Yacht Council (ABYC) E-11 standard is another ground fault protection device that uses residual current detection. If it is protecting a 120V branch of a 120V/240V (L1/L2/N) multi-wire branch circuit, then it too is subject to these same issues.[11]

What about the AFCI? Some AFCI breakers implement unadvertised ground fault detection as a component of its AFCI functionality using a current summing transformer[12]. So a 2-pole (L1/L2/N) AFCI feeding a multi-wire branch circuit could be subject to some of the same problematic behaviors as are GFCI/GFPE devices depending on its implementation[13].

So What?

The question is, for circuits requiring ground fault protection (personnel or equipment) do the savings of the MWBC justify the additional safety and usability costs? And secondly, although not secondarily, are these safety and usability costs sufficiently understood by those who design, construct, and maintain them?

Each of us operates in his/her own sphere of activity and influence, whether that of standards and code making, engineering, construction, maintenance, or simply property owner. We should all look for ways to combat the confusion and problems of the GFCI/GFPE-MWBC union. Some might be:

1. Advance awareness and understanding of this behavior in forums, presentations, and continuing education.

2. Consider limiting the use of the MWBC where protection is required. Restrict the use of 2-pole devices for ground fault protection to small, well defined, or stable circuits with small numbers of appliances and few, if any, open receptacles (sockets). For example:

   a. Allow garbage disposal and dishwasher in a split duplex receptacle (single receptacle with one

11 Note that what is significant is not the number of switched conductors (poles), but which conductors pass through the current transformer. For example, the neutral is switched in some marine RCDs.

12 I am not referring to "Dual Function" breakers which advertise GFCI plus AFCI functionality. I am addressing standard "combination" AFCIs. See Roberts, Earl W. *Overcurrents and Undercurrents: All about GFCIs, AFCIs and Similar Devices Plus New Safety Product Ideas.* 4th Ed. Mystic, CT : Reptic, 2009. Print.

13 One I tested happily supplied two 40-watt bulbs wired from each of L1 and L2 to ground. Granted it was not a "Dual Function" device and, as an AFCI, had no requirement to provide any level of ground fault protection, but it is at least an interesting observation.

L1 outlet and one L2 outlet.

b. Phase out 120/240 (L1/L2/N) shore cord power on docks and marinas and provide separately protected 120V (single pole) and 240V (double pole) power to boats.

3. If protection of a large or complex MWBC is necessary, consider calculating the expected leakage and then measuring post installation leakage on each leg (L1/L2). Consider the use of a ballast resistor to zero the current imbalance due to expected (predicted and verified) leakage, thereby increasing the likelihood that an additional fault/leak on either leg will exceed the trip limit and cause a trip.

4. Equip ground fault protection devices with both L1 and L2 test functions – either two separate buttons (one for L1 and one for L2) or a clever single button that tests one circuit (L1) when depressed and another circuit (L2) when released.

The multi-wire branch is here to stay and so is ground fault protection. But we should unite these technologies only if it's a good match. Let's not disturb Edison in his grave by insisting on too much of a good thing.[14]

14 The original multi-wire branch circuit was for DC wiring. Thomas Edison was issued a patent for it (U.S. Patent 274,290) in 1882.