Study of the Effects of Smart Meter RF Transmissions on GFCI Outlets
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Abstract—Research and development are currently being performed to transform the US’s utility electric grid into a “smart grid [1], [2].” Smart meters are among the first intelligent metering devices used within the “smart grid” concept. They have been deployed in thousands of commercial and residential electrical installations around the US [3], [4]. While the wide-scale deployment of these devices has initially proven very successful, there is still much that is unknown about how they will impact the long-term operation of a large utility grid or the electrical devices sourced by them [5]. One such device, whose operation appears to be impacted by the smart meter, under specific conditions, is a ground-fault circuit interrupter (GFCI). It has been reported that the RF transmissions from smart meters can induce false tripping events on GFCI outlets installed on temporary construction poles. In an effort to understand why this may happen, a research study, which is presented here, has been performed to understand the correlation between RF transmissions and GFCI tripping events on construction poles.

Index Terms—Electromagnetic compatibility, electromagnetic interference, ferrite, ground-fault circuit interrupter (GFCI), RF, smart meter.

I. INTRODUCTION

RECENTLY, electrical contractors in North Texas have experienced repeated and uncontrollable ground-fault circuit interrupter (GFCI) tripping events, without the presence of any water or known leakage current. These events are believed to be the result of interference induced in the GFCI from the smart meter’s RF transmissions. These were observed to occur when the GFCI is located in close proximity, within 0.5 m typically, to the smart meter. Controlled investigations in the laboratory have shown that the tripping events are repeatable, and it has been found that the RF transmissions from the smart meter’s wireless radio are likely the cause of the unexpected GFCI tripping events. The tripping is caused through the coupling of the 902–928 MHz transmissions into the sense electronics within the GFCI. However, it is currently unclear if the coupling is primarily conductive or radiated coupling. This paper will describe the investigative process that has been ongoing to understand how the interference is induced and how it can be simply remedied.

A GFCI is a residual-current device that is capable of disconnecting the grid from applied loads when it detects a 5–6 mA current imbalance in the forward and return paths of the circuit to which it is connected [6]. These devices have been widely implemented in residential and commercial buildings for decades. Typically, GFCIs are required in any electrical installation where water may interfere with electronics, such as kitchens and bathrooms. One such installation includes the construction poles, which are exposed to the elements, used by workers while constructing a building on site, like the one shown in Fig. 1.

Smart meters use wireless radio frequencies (RFs) to transmit data back to the main data collection HUB of its respective company, and interact with other smart meters through a mesh network. This causes smart meters to send and receive transmissions hundreds, sometimes thousands of times per day. RF transmissions are simply ac currents which oscillate extremely fast. When current is oscillated at the extremely low frequency (ELF, designated as 1–300 Hz by OSHA [11]) range, or more, then it begins to take on new properties allowing propagation through air. If this current is put through an antenna, it can easily ionize the air around it and create a conductive path.

Fig. 1. Laboratory setup representing a construction pole with GFCI electrical panel and vertically adjustable smart meter.
Finally, the GFCI is undeniably the receiver of interference. As a cheap and easily implementable solution to mitigating them, research is to establish the reason for the faulty trips and to find a combination of both. Any of these three scenarios could cause the GFCI to detect a faulty leakage current and trip. The goal of this research is to determine the cause of the faulty trips and to find a simple schematic of the operational scenario of a GFCI being powered off of a smart meter while on the construction stand.

For this research, the smart meter has been designated the interference source, as it is the source of all RF transmissions. With that in mind, there are three possible coupling paths. First, the differential transformers found inside of GFCI devices may have a voltage induced upon them through coupling of the RF transmission signals. Second, the RF signal is being unevenly induced on to the hot or neutral line. Third, the RF signal is being induced through the power line shared by the smart meter and then conductively into the GFCI’s electronic sense board. In general, the coupling could be radiative, conductive, or a combination of both. Any of these three scenarios could cause the GFCI to detect a faulty leakage current and trip. The goal of this research is to determine the reason for the faulty trips and to find a cheap and easily implementable solution to mitigating them. Finally, the GFCI is undeniably the receiver of interference.

II. BACKGROUND

This section will cover how a GFCI actually works in order. There are four different states that a GFCI may be in, including normal operation, the test state in which a fault is produced on demand to test the device’s integrity, ground-fault operation in which a fault is detected between hot and neutral lines, and ground-neutral fault state when a fault is detected between neutral and earth ground.

A. Normal Operation

When a GFCI device is operating normally, there is no “fault” present in the system. This means that the same amount of current flowing through the transformer on the hot line to the load is also flowing back on the neutral line. In other words, the circuit is being completed with no foreign loads, or “faults,” appearing and causing a tripping event. As can be seen in Fig. 3, it states that equal current is flowing in and out of the transformer, and thus the “trip coil” stays deenergized. The trip coil is simply a solenoid controlled by an integrated circuit that receives an input from the transformer. When the signal is received from the transformer, the electronics will apply some current to the solenoid, disconnecting the forward path to the load and inhibiting any power flowing.

B. “Test Button” State

Each GFCI has a built-in test button. The test button is something required by UL943 [13] in order to allow for consumers to test their own devices for proper functionality. When the test button is pushed, a “ground fault” occurs and the GFCI disconnects any connected loads. The test button creates this fault by creating a connection and effectively applying a resistor between the hot and neutral lines. Because this connection is done before the transformer is introduced on the forward path (hot line) and before reaching the transformer on the return path (neutral line), a change in current is sensed. This scenario can be seen in Fig. 4 for reference.

C. Ground-Fault Occurrence

Assuming a GFCI is operating correctly, it is capable of producing a “ground fault,” as discussed in the previous section. This will occur when a foreign load is introduced to the circuit, connected between the hot line and the earth ground. When this event takes place, some amount of current will flow through the foreign load rather than back through the neutral line. Since there is a difference between the current flowing on both lines through the transformer, the sense electronics will receive an input and activate the trip coil. The coil will disconnect the hot line from the foreign load in attempt to prevent any damage from occurring. There are a few specifications required by UL943 regarding the tripping requirements and trip time for a Class A GFCI. Many other specifications are required, but these are generally the ones that someone might be concerned with as it could be the difference in saving a life from electrocution. As mentioned earlier, according to UL943 a Class A GFCI is
required to trip when a 6 mA fault occurs, and it must produce this trip event within 6 ms. A ground-fault scenario can be found depicted in Fig. 5, in which a person has connected himself or herself between the hot line and earth ground, creating a foreign load and misaligning the current flowing through the GFCI.

D. Ground-Neutral Fault Occurrence

This is a special case in which a fault occurs between the neutral line and earth ground. There are two differential transformers found in GFCIs: a hot-neutral transformer and a ground-neutral transformer. In the previous figures depicting different operational scenarios, there is a hot-neutral transformer, which is the one that most people are familiar with. However, what happens if a person accidently connects himself or herself between the neutral and earth ground? At first glance, it seems like the same scenario would occur as in Figs. 2 and 3. If a person has attached himself or herself between neutral and earth ground, then the amount of current flowing in and out of the transformer should be different and trip. This is true, but the sensitivity of the transformer may not be high enough to actually activate the trip coil and disconnect the load. Due to this being potentially dangerous another coil is also found in GFCIs. This coil still contains both the hot and neutral lines, but is connected to another input of the sense electronics. Note that in the figures mentioned earlier the neutral coil is not depicted, so for reference this scenario can be seen in Figs. 3–5.

Since a ground-neutral fault is based on a slightly more complex situation, an example will now be given. This example can be followed by looking at Figs. 2–4. Say a load is connected to the GFCI unit as normal, but on the neutral side of the load, there is a fault going to ground. Then, say a person connects himself or herself between the hot side of the load and earth ground. This is the exactly same thing as a regular ground fault, so when 6 mA is detected, the GFCI should trip. When this happens, current will go through the person and back through the fault and on to the return path. Current traveling back down the return path now is different than the forward path, but since there is also a fault between neutral and earth ground, the 6 mA current will change to a lower current. This means that the GFCI will not trip since the 6 mA threshold is not reached, but electrocution is still occurring. To remedy this problem, another transformer is deployed with a different sensitivity in order to disconnect the load when this occurs.

E. RF Interference of GFCIs

As mentioned in paper by William D. Webb [14], common-mode currents become a problem when dealing with the RF spectrum and GFCIs. These currents are primarily caused by stray capacitance, inductive coupling, and return-loop voltage drops (thus creating mismatched currents going through the differential transformers). While these problems occur in many electronics, Webb gave the example of a GFCI since it is able to produce a visual indication of RF interference. This mention indicates that there is a problem between GFCIs and RF transmissions in general, specifically the creation of common-mode currents tripping the device when it is exposed. This also suggests that the interference is radiative; though in the scenario at hand, it does not rule out conductive interference.

III. EXPERIMENTAL WORK

A. Field Mapping

In order to better quantify the electromagnetic field strength of the smart meter’s RF transmissions, the electric and magnetic fields generated by the smart meter were mapped as a function of distance and angular position around the meter. The experimental setup used is shown in Fig. 6. The smart meter was positioned on a rotating platform, and both the electric and magnetic field were measured as a function of angle and distance away from the meter using field probes made by Beehive Electronics [10]. The output of each probe was measured using its own dedicated Agilent ESA 4403B 3 GHz spectrum analyzer. First, measurements were made with the center of the smart meter located 4.9 cm away from the center of the GFCI unit. The experiments were performed within an RF shielded room in order to eliminate any outside interference.
Fig. 6. Experimental setup consisting of a 120 V smart meter, B-field and E-field probes, UPS, two spectrum analyzers, and GFCI outlet box.

Fig. 7. Simple schematic of how testing was conducted using a UPS to isolate both devices, thus testing if radiative interference was a possible source. On the right, a GFCI is powered from a 120 V ac UPS, and on the left, a smart meter is powered from a 120 V ac wall outlet.

Angles in 45° intervals were marked on to the rotary table, along with a reference point for the smart meter to be placed upon. If the smart meter were a circle on an x- and y-axis, then the reference point would be the 0° mark on the right-hand x-axis. This allowed for the smart meter to be rotated and measurements to be taken at the various angles reliably and repeatedly. Both spectrum analyzers utilized a GPIB to USB connection, allowing them to interface with a National Instruments LabVIEW measurement program. A custom LabVIEW Visual Instrument (VI) was created for data capture across the 900 to 930 MHz spectrum. The field’s strengths were recorded for 2 min at each 1.25 cm distance interval. During that time, the program captures data upon a trigger of $-40 \text{ dBm}$. This is due to the minimum RF transmission power from the maximum distance tested being, on average, $-40 \text{ dBm}$. It is worth noting that the smart meter’s RF emission strength varies as it tries to connect with a communication HUB, which is not located within communications length of the meter. This caused variation in the measurements over the 2-min period. The highest intensity pulse recorded over the 2-min test period is used in the mapping of the magnetic field ($B$) and electric field ($E$) from 0° to 90° relative to the reference point. Those plots are shown in Figs. 7 and 8, respectively. Note that these measurements are subject to the time in which they were taken and may vary, though multiple readings were taken to minimize potential error. It can be seen in both figures that there is a “hot spot” observed around the 45° angle of the smart meter. The intensity of the field remains relatively constant up until 4.7 cm, at which point it changes by roughly 10 dBm.

The results show that the orientation of the smart meter with respect to the GFCI may impact the coupling of RF into the GFCI’s electronics. It may trip more often when subject to the “hot spot” of the fields. It may suggest that orientation of the meter on the construction stand could prevent any tripping from occurring.

B. Operation using Circuit Isolation

One hypothesis to explain the unexpected tripping events is that the shared power line conducts the RF signal from the meter into the GFCI electronics. In order to test the validity of this hypothesis, the two circuits must be electrically isolated as much as possible while still leaving them in normal operating modes. In the laboratory, two similar GFCIs, made by different manufacturers, and a single 120 V ac smart meter were each powered using a separate ac power source. A simple schematic of this setup can be found in Fig. 9.

Since the outlets within a room are typically on the same circuit, plugging each in to a wall outlet would not sufficiently isolate the two devices. Instead, an APC Smart-UPS SUA 1500 uninterruptable power supply (UPS), which was unplugged from the wall, was used to power the two different brands of GFCIs while the smart meter was plugged in to a normal wall outlet. This experimental setup is the same as that shown already in Fig. 6. During the experiments, the GFCIs, regardless
of brand or model, still tripped repeatedly despite not being on the same circuit as the smart meter. This eliminated the theory that the only source of RF interference is from that directly induced on the power line at the smart meter. Instead, this suggests that the RF is either directly coupled into the GFCI outlet, or the power line leading up to the GFCI acts as an antenna that picks up the RF and conducts it into the GFCI.

C. Differential Coil Measurements

Once there was evidence of the RF being wirelessly induced into the GFCI, a second test was setup in order to more accurately simulate the orientation of the GFCI outlet in relation to the smart meter. Since the distance between the two centers of the devices on the test stand was measured to be 31.75 cm, this was the distance used to separate them. Additionally, measurements of the voltage across the differential transformer needed to be made. This was accomplished by simply soldering leads on to the designated terminals of the GFCI’s printed circuit board (PCB). Utilizing the mapping of the electric and magnetic fields shown earlier, the GFCI was positioned such that it was oriented at a 45° angle, exposing it to the “hot spot.”

The wires were soldered to the test points of the differential current transformer and ground to neutral sense coil on the GFCI’s PCB. Initially, it was found that if differential voltage probes were connected to both the differential current sense coil and the ground to neutral sense coil, the GFCIs would immediately trip once connected to the oscilloscope and they could not be maintained in a nontripped state. In normal operation, a trip event cuts power to the uneven load, removing the condition on the coil, which induced the trip event to begin with.

In the laboratory experiments, the trip event is not induced by actual imbalance in the load and therefore the condition, which causes the trip, continues even after the internal solenoid has been activated. Instead the solenoid is repeatedly activated causing a steady current flow through it, which melts the solenoid within seconds since it is not designed for continuous current flow. In order to solve this problem, an isolation transformer was used to power the oscilloscope in order to isolate its power from earth ground. This effectively “floats” the oscilloscope, but allows measurements to be taken from the GFCI without any ground bouncing occurring.

In these tests, experiments were performed in which the meter directly powered the GFCIs and also in which the UPS was used to isolate the GFCIs from the smart meter. The following waveforms were recorded for both UPS and non-UPS tests: differential current transformer voltage, ground-neutral transformer voltage, and magnetic field probe waveform. Comparisons between tripping events and standard operation were made between multiple events for both differential and ground-neutral transformers, as well as between UPS and non-UPS tests. These waveforms show the exact moment the tripping event occurs, along with the B-field of the RF transmission that caused the trip. Measurements are presented for three tripping events, as well as a baseline, to show the difference in voltage during RF transmissions. For clarification, the measurements made from the differential transformer and the ground-neutral transformer were collected from separate experiments.

1) Results—Non-UPS Experiments: Waveforms measured across the differential transformer, when the GFCI was connected directly to the smart meter, are shown in Fig. 10, and the waveforms measured across the ground-neutral transformer can be seen in Fig. 11. In each plot, the pink waveform notates the “baseline” measurement taken while no RF interference was present and the GFCI devices were operating normally. This clearly shows the difference in voltage on both transformers at the same time an RF transmission occurs. The green, blue and red waveforms show tripping events from three different experiments, each corresponding with their respective color on both plots. Fig. 10 is a particularly good example of the RF interfering with the differential transformer voltage. When the RF
transmission occurs at the 0 sec point of the x-axis, a spike in voltage is recorded, and at that same moment, the GFCI tripped. This is definitive evidence of RF transmissions affecting GFCIs. The same occurrence happens with the ground-neutral transformer in Fig. 11.

The maximum voltage recorded on the differential transformer is around 60 mV, while voltages as high as 3 V were recorded across the ground-neutral coil. These higher voltages are due to the winding ratio on each transformer being different, 100:1 for the differential transformer and 1000:1 for the ground-neutral transformer. It can be seen that perturbations measured across the ground-neutral coil’s voltage are much more frequent due to the higher turns ratio and therefore sensitivity. Even slight changes in the RF transmissions are picked up much more frequently in the form of voltage spikes on the coil. Each spike of voltage on the transformer is due to another RF transmission happening, but since they are overlaid for comparison they are not completely visible.

2) Results—UPS Experiments: The previous experiments clearly show that RF transmissions affect GFCI devices due to their influence on the transformers, dictating whether a tripping event should occur or not. However, it does not dictate whether or not this interference is conductive, radiative, or both. By utilizing a UPS, the GFCI can be isolated from the smart meter on a completely separate power supply. Therefore, any interference must not be purely conductive. Note that this does not mean there is no conductive interference through the smart meter’s PCB. This is only a test to see if a portion of the interference is radiative, as opposed to purely conductive. There may very well be multiple sources of interference affecting the GFCIs and causing tripping events.

Again, each of these tests had three tripping events recorded and a baseline to show the difference in voltage during RF transmissions of the smart meter. The differential transformer and ground-neutral transformer were both tested independently of each other. The waveforms measured across the differential transformer can be found in Fig. 12, and those measured across the ground-neutral transformer can be seen in Fig. 13. One interesting note is the rapid occurrence of transmissions occurring when the voltages were measured across the ground-neutral coil. During that test, they were occurring so rapidly and since the scope was manually triggered during measurement of the ground-neutral coil, many spikes are observed before the trigger event occurs. Despite the large number of transients recorded, the GFCI only tripped after the trigger event occurred. Since both the smart meter and the GFCI device were powered off of separate electrical circuits and tripping events were still recorded, this shows that there is radiative interference from the RF transmissions. Again, this does not mean it is the sole culprit and the only source of interference, only that it is a significant factor regarding GFCIs tripping in this particular setup with smart meters. The radiative coupling may be getting coupled directly into the GFCI’s PCB/sense coils or it could be getting coupled into the power lines feeding the GFCI.

D. Distance Testing

It had been hypothesized that one possible solution that would be easy to implement on construction sites would be to simply move the smart meter farther away from the GFCI outlet box on the construction pole. Since the typical distance between the GFCI unit and smart meter on a construction pole is roughly 30 cm, this value was used as the initial separation distance. The smart meter was then installed using an adjustable sliding rail system on the construction pole. Using this method, the meter was adjustable vertically along the pole with some degree of ease and control. Using this method, the smart meter was adjusted to the maximum allowable distance (roughly 1 m) from the smart
meter. This was done with the idea that if the GFCI would trip when the smart meter was at the maximum distance, then it was not worth testing for a threshold. Once the system was powered on, the GFCI tripped within 30 s. Because of this occurrence, it was concluded that the maximum allowable distance between the two devices is not enough to fully prevent tripping events ruling out movement of the meter farther away as a possible solution. Although possibly moving the smart meter far enough away that the wavelength of the RF transmissions might not interfere with the GFCIs, this was too trivial to provide as a solution.

IV. ADDITIONAL NOTES

During all of the research and experiments conducted, there were a few points of interest noted, as well as some minimal testing done. These are discussed later.

A. Brass Versus Copper

In one manufacturer’s GFCI, the neutral conductor found inside was made of copper rather than the typical brass. The hot conductor was still made of brass. Ironically, the model with the copper neutral conductor never tripped. Only one of these types of devices was ever found available in stores. A GFCI, which uses all brass conductors, was taken apart and the conductors were covered with copper tape. This effectively stopped all tripping from occurring and suggests that GFCIs with copper conductors may be a potential solution. The only hypothesis explaining why this would matter is that somehow the difference in the skin depth between copper and brass within the frequency range of interest impacts the coupling of the RF into the device.

B. Antenna Testing

In this test, aluminum foil was used to completely cover the smart meter in order to mitigate the RF signals emanating from the case. The GFCI was powered normally using the same source as the smart meter. The B-field probe was hooked up to the spectrum analyzer in order to measure the intensity of the frequencies transmitted by the smart meter. First, the probe was used to take a sample reading of the signal outside of the aluminum foil in order to ensure that the signal was being relatively suppressed, about half the intensity as normal. Once this was concluded, the probe was then placed directly on the power line being shared between the GFCI outlet box and the smart meter. The intensity of the signal was significantly higher than previous signal recorded outside, roughly 10–20 dB.

These results suggest that the power line is indeed acting as an antenna and is picking up the RF signal from inside the smart meter where nothing is shielded. However, while measuring the field strength near the power line the GFCI would not always trip. This most likely means that the RF is inducing just enough current to trip the differential transformer, but not consistently. This is why when the power line is oriented in a “loop,” it picks up the signal much better—just like the loop antennas used for RFID tags—and thus the GFCI trips more often.

V. PROPOSED SOLUTION

In order to develop a solution that is as simple and user-friendly as possible for construction sites, ferrite beads were proposed. This was the initial “go-to” solution purely from intuition, but with thoroughness in mind, it was decided to evaluate its impact through similar experimentation to that already discussed.

In these tests, two ferrite beads were used in an attempt to “choke” the RF signal from being picked up by the power lines. Two power lines (each containing a hot, neutral, and earth ground wire) are carried from the smart meter up to the metal enclosure where the GFCI outlets are located. Two different types of GFCIs from two different manufactures are housed on the stand. In the first set of tests performed, ferrite beads made of Fair-Rite 61 material (200–1000 MHz, part 0461178281) put placed around the entire power line connecting the smart meter to the GFCIs. When this was done, the system was powered on and the GFCI tripped within 1 min of activity. This means that the placement was not at a sufficient choke point, thus not able to effectively eliminate the RF interference. Next, instead of having the ferrite beads located close to the smart meter, it was decided to put them closer to the GFCIs. Also, instead of having one ferrite bead around the entire power line, individual beads were placed around the hot, neutral, and earth ground terminals feeding each GFCI. This is shown in Fig. 14.

The system was then powered on and left for a total of 108 h in multiple configurations with no trips occurring. Due to this, it is believed that ferrite beads placed upon the hot and neutral lines near the GFCI devices are the best solution regarding effectiveness combined with user-friendly installation. In a final set of tests, ferrite was also applied within the smart meter itself, as depicted in Fig. 15, and the same results were recorded. A summary of these results is listed in Table I.

It is important to note that while the GFCIs did trip when no ferrite was applied to the test stand setup, they did not trip nearly as much as in previous tests when the stand was not used. This
is due to the metal containments around each device acting as an RF shield.

VI. CONCLUSION

Based upon the research and experiments conducted, it is believed that the power line being shared between the smart meter and GFCI devices is acting as an antenna for the RF transmissions. Whether or not the power line is shared between the two devices, or they are independent of each other, tripping still occurs. One of the most important things to regard is that the power line when arranged in a “loop” appears to create a better antenna for picking up the RF signal. The possible distance between the two devices on the test stand was not far enough to create a difference taking this away increasing the separation between the devices as an easy solution to the problem. Lastly, the typical metal enclosures used in the test stand act as a shield from some but not all of the radiated interference; although the shared power line between the smart meter and GFCIs acts as an antenna, this is not consistent. The ferrite beads used for testing cost roughly 2 dollars each. This cost is minimal compared to that of having a filter designed for the GFCI’s PCB, assuming each stand is using the same model and then hiring a professional to install this device at each construction site. Not to mention, this would void the warranty of every GFCI device, which may not be desirable. The addition of ferrite beads around all of the conductors appears to be the most practical, user-friendly solution available, along with having wires cut as short as possible. These two suggestions, when combined, have resulted in successfully negating enough RF interference such that the GFCI devices do not trip.

REFERENCES


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