Journal of the National Academy of Forensic Engineers®

NATIONAL ACADEMY OF FORENSIC ENGINEERS

http://www.nafe.org

ISSN: 2379-3252

Vol. 38 No. 1 June 2021

Forensic Engineering Analysis of a Swimming Pool Electric Shock Injury

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Abstract

This case involves a minor who received an electric shock while swimming in a membership swimming pool. Her family sued the pool association, its president, the electric utility, and others. At some time, tree trimmers had accidentally severed the service drop's neutral return wire. The electric utility made a temporary splice repair, but did not permanently replace the wire until several years later (after the incident). The forensic engineer (FE) was retained by counsel for the pool and its president to opine on electrical aspects of the plaintiff's complaints. The FE inspected the pool premises, reviewed documents, and examined the spliced service wires in storage. The FE opined that the pool association and its president were not negligent or careless — and that the electric utility failed its responsibility to maintain the service drop. This report discusses three-phase electric power, current flow, and how a severed neutral can cause a shock.

Keywords

Electric shock drowning, ESD, three-phase power, stray voltage, stray current, forensic engineering

Introduction

On the opening day of swimming pool season, a young woman was shocked while swimming in a pool owned by a paid-membership community recreation association (referred to as "Association" in this paper). Others in the pool at the same time did not receive shocks or feel tingling. The victim was taken to the hospital, examined, and released the same day. Shortly thereafter, her parents filed suit. The examining physician diagnosed electric shock based upon his visual examination. There were no debilitating physical injuries.

The plaintiffs in the case were the injured minor and her parents. The defendants were the Association, its affiliated Swim Club, the president of the Association, the supplying electric utility, the Association's electrical contractor, and an unnamed tree trimming company. (The tree trimmer was never identified.)

Discovery documents revealed that several years prior to the incident, an unnamed tree trimmer had accidentally severed the neutral wire of the four-wire, three-phase service drop from the utility pole to the pool facility. The power company made a "temporary" splice repair to that wire the following day, telling the Association representative that a permanent repair would be made "soon." The power company never returned to make the permanent repair, and the splice failed several years later. The utility did replace the entire service drop after the shock incident.

The FE was retained by counsel for the Association and its president to investigate, research, and opine on the electrical aspects of the plaintiff's complaints, which alleged that the Association and president:

1. Had exclusive control of the swimming pool.
2. Were careless in the pool's electrical maintenance.
3. Failed to provide a safe swimming pool for guests of the Swim Club.

The FE inspected the swimming pool premises and reviewed discovery documents as well as examined the failed splices on the service wires that had been removed and placed into evidence storage.

Case Timeline

In April 2014, municipal inspectors issued a bonding and grounding certificate to the Association that was valid for five years.

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DOI: 10.51501/jotnafe.v38i1.64

In June 2014, a private tree trimmer hired by the pool association inadvertently struck the bundle of four electric power wires (service drop) between the utility pole and the electric service entrance to the swimming pool utility shed. The service drop was the property of the power utility.

The chain saw severed the bare neutral wire, apparently leaving the three hot wires and their insulation intact. The power utility's repair crew arrived within a day and spliced an approximately 4-foot bare wire across the damaged neutral bare wire, using crimp sleeves at each end. The repair crew chief reported to the power utility and the Association that this was a temporary repair — and that the team would return and replace the entire service drop between the pool and the utility pole. The power utility did not return to make the permanent repair. Over the next few years, time, temperature fluctuations, humidity, and precipitation took their toll on the equipment, degrading the electrical integrity of the splices.

In April 2015, municipal inspectors issued an electrical compliance certificate to the pool association that was valid for one year. (Note: Municipal inspectors do not inspect the service drop; the service drop is the property of the power utility.) Unlike the grounding and bonding certificate, electrical compliance must be certified every year. The requirement for yearly inspection was not passed along to the newly volunteered chairman of the pool association, and nobody thought to act when certification expired before the 2016 pool season without notice.

Sometime between autumn 2015 and early spring 2016, unobserved and unreported, the splices failed. The neutral return wire, which was temporarily patched in 2014, became an open circuit.

In May 29, 2016, which was opening day of the pool season, a 14-year-old member was shocked while swimming at the association pool. There were dozens of other swimmers in the pool; however, she was the only person to sense a strong tingling. Climbing partially out of the pool and lying on the concrete pool deck, she contacted the pool ladder with one foot while the other was still in the water. While she began convulsing, the girl remained conscious (although she indicated she did not know this was in fact an electric shock). After bystanders pulled her away from the pool ladder and water, she was transported to the emergency room and later released from the hospital. The association officers closed the pool until the fault was found and corrected.

On May 31, 2016, the pool's electrical contractor investigated and immediately observed the severed neutral wire in the service drop. He reported his observation to the power utility, since only the utility may repair a service drop. Later that day, the power utility repair crew replaced the entire service drop. A pool association officer observed a "section of wire that looks like it was repaired at some point with some clamps of some sort and then the middle part is damaged and no longer connected to each other."

Later in 2016, the plaintiffs filed their suit against the Association and its president. A major accusation in their complaint was that by not accomplishing the annual inspection, the parties were careless in the pool's electrical maintenance — and that they failed to provide a safe swimming pool for guests of the Swim Club.

The FE investigated and submitted his report in 2019. Soon thereafter, the plaintiffs dropped the electrical aspects of their complaints against the Association and its president.

Electric Shock Drownings

AC current can "escape" its intended path when there is faulty power distribution. It can flow through land and water, including swimming pools as well as open salt and fresh water. A low-level current can shock swimmers so that they feel a tingling sensation. Current of enough magnitude can paralyze swimmers so they cannot swim or call out for help. Known as "electric shock drowning or ESD," this happens more commonly in fresh water because conductivity is higher through the human body than through fresh water[1].

Drowning caused by electric shock is a "silent killer," according to The Electric Shock Drowning Prevention Association[2], because:

- There is no visible clue as to the charged state of the water.
- The sensation of shock may not be immediately felt by the victim.
- The victim may become paralyzed and unable to call out for help.

Unless there's a witness, the swimmer's death may be reported as a common drowning. "In the vast majority of electric shock drownings, the victim's autopsy shows no signs of electrical injury, and investigators often never learn that electricity was the cause of the drowning[2].”

Of the 60 electrocutions and 50 serious electric shocks in and around swimming pools between 1990 and 2002, the causes were about equally split between end-user carelessness with radios, power tools, extension cords, and faulty pool equipment, including pool lights, pumps and vacuums[3].

Three-Phase Electrical System Overview

See “Elements of Power System Analysis”[4] for a thorough study of power generation, transmission and distribution. For a quick overview, one may turn to Wikipedia[5].

Figure 1 shows the major parts of a typical 208Y/120-volt service electrical system. The service drop wires under the “power company” label consist of three hot wires and a neutral wire. The figure will be reused for indicating current flow through an intact system, how safety grounding operates, and how stray current may escape when the system is not intact.

The neutral wire from the transformer to the meter is bare (not insulated). In **Figure 1**, neutral is indicated by the yellow color. The hot wires are insulated. The nominal voltage between any hot wire and neutral is 120V. The hot wires are colored red, black, and blue. The nominal voltage between any two hot wires is 208 volts, and there is a 60-degree phase angle between the sinusoidal waveform of each hot wire.

The transformer’s neutral terminal is held at zero volts by a grounding wire connected from the terminal to ground rods driven into the earth at the foot of the utility pole, as indicated by a green line and arrow. On the customer’s side, beneath “Your Equipment,” the neutral terminal of the service panel is held at zero volts by a grounding wire connected from the terminal to metal rods driven into the earth on the customer’s side of the meter, as indicated by a green line and arrow.

The power utility owns and is responsible for the items under the “Power Company” label — that is, high-voltage wires coming into the transformer from the substation (not shown), the transformer, the utility pole and its grounding wire and rods, the service drop wires, and the meter. The customer owns and is responsible for the items under the “Your Equipment” label — that is, the wires from the meter to the panel, the panel, the grounding wire from the panel to the earth, and the wires from the panel to all the lights, appliances, etc., within the buildings and on the property.

Current flows from the hot terminals of the transformer, through the service drop wires, through the meter, and into the building to the input side of circuit breakers on the panel. Thence, current flows from the output sides of the breakers through household wiring to light switches, permanently connected appliances, and the contact openings of electrical outlets throughout the building and property

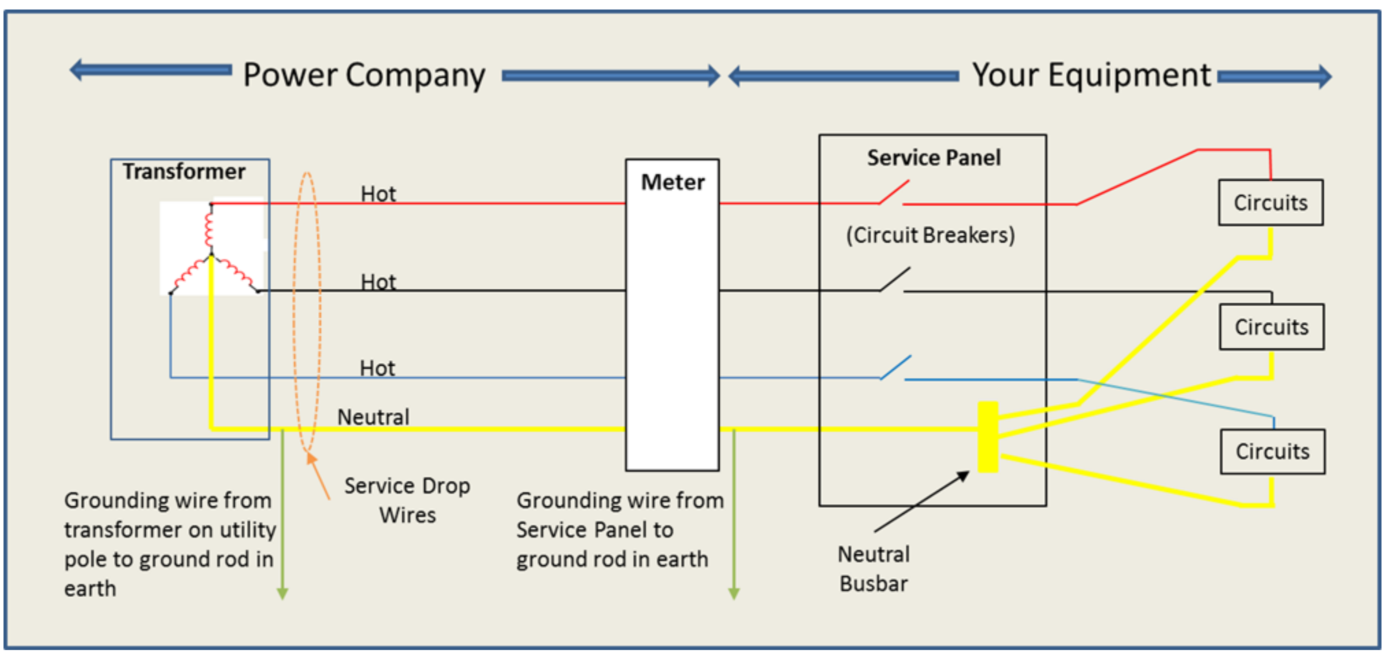

Figure 1
Typical 208Y/120V electrical system diagram.

(indicated by "Circuits").

The electric current path continues through the prongs of appliance plugs, through the wires of the appliance power cords to the hot terminals of each plugged-in 120-volt appliance.

When everything is turned off in the entire premises, no current flows to the hot terminals. The hot wires remain at 120 volts throughout the path, but no current flows.

When an appliance is plugged in and turned on, current flows through the path from the transformer into the hot terminal of the appliance and through the appliance. The current does its work inside the electric appliance and then flows out of the appliance to the return path.

Current flows through the return path from the appliance neutral terminal through the neutral wire of the building, to the neutral busbar of the service panel, through the meter, service drop wire, and into the neutral terminal of the transformer. **Figure 2** shows the current path for a single light bulb. (Ground wires are not shown for readability.)

In **Figure 2**, current flows clockwise from the upper hot terminal of the transformer, through the red service drop wire, through the meter and into the building's service panel, through the circuit breaker, and (red) building wiring ending at the hot terminal of the light bulb. The current does its work in the light bulb converting electrical energy to light and heat.

Current then flows through the return path from the light bulb's neutral contact, through the lamp fixture, neutral wiring (yellow) of the building to the neutral busbar of the service panel (yellow rectangle). From there, the return current flows back through the meter and the neutral service-drop wire (yellow), ending at the neutral terminal of the transformer.

What if there were three identical light bulbs — one each on the red, black, and blue hot wires with their neutral terminals all connected to the neutral busbar? As explained concisely in Wikipedia[5] and completely in *Elements of Power System Analysis*[4], three currents of equal magnitude, but with 60 degrees phase difference, will return from the three light bulbs and flow into the neutral busbar. The vector sum of three equal magnitude currents separated by 60 degrees is zero. The currents cancel each other out, and no current returns through the neutral wire to the transformer. What occurs is the three currents push/pull each other through the hot wires returning to the transformer.

This would be true for any three identical electrical loads on the hot wires, such as three perfect three-phase coils of an electric motor or any three identical appliance loads. This is called a balanced load and is only theoretically possible.

Some effort at load balancing is strived for and usually

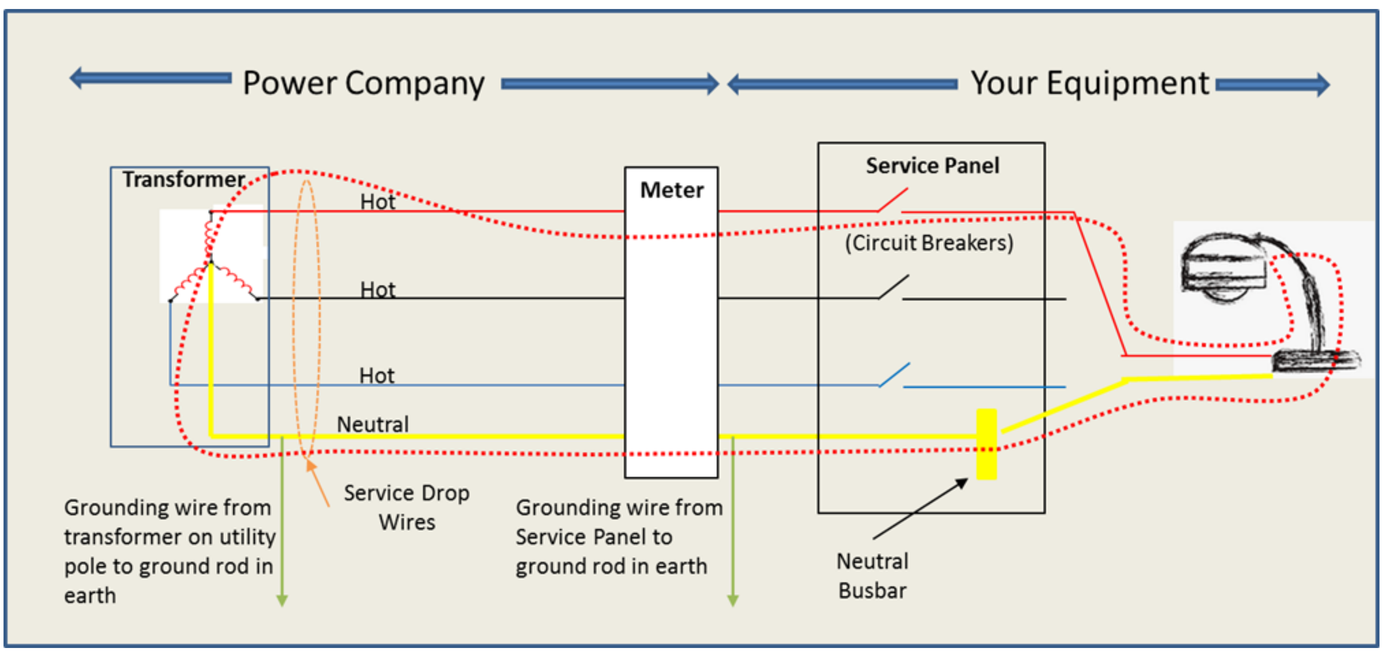

Figure 2
Current path for one light bulb.

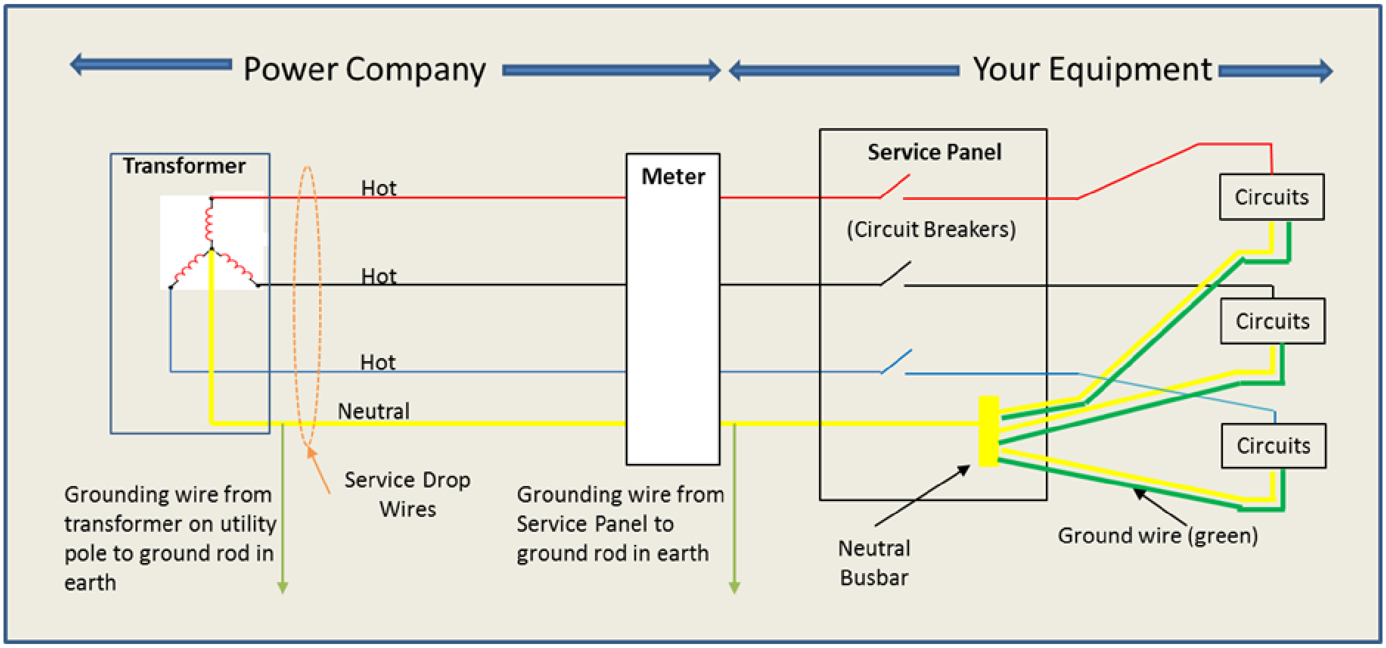

Figure 3
Electrical service diagram showing safety ground wires.

met to some extent. The current returning through the neutral wire is larger or smaller, according to the imbalance of the loads on each phase.

Figure 3 is the same as **Figure 1** but shows safety-ground wires, the "third prong" of electrical outlets, which are routed from the outlets to the neutral busbar (yellow rectangle) in the service panel separately from the neutral wires.

The purpose of ground terminals and wires is illustrated in **Figure 4**. For this example, a loose hot wire is contacting the exterior of a defective lamp fixture.

Current flows as usual from the transformer to the lamp fixture. Within the lamp fixture, current splits between the hot terminal of the light bulb and the loose wire contacting the lamp fixture's external surface. The loose wire electrically connecting the hot wire to the lamp's

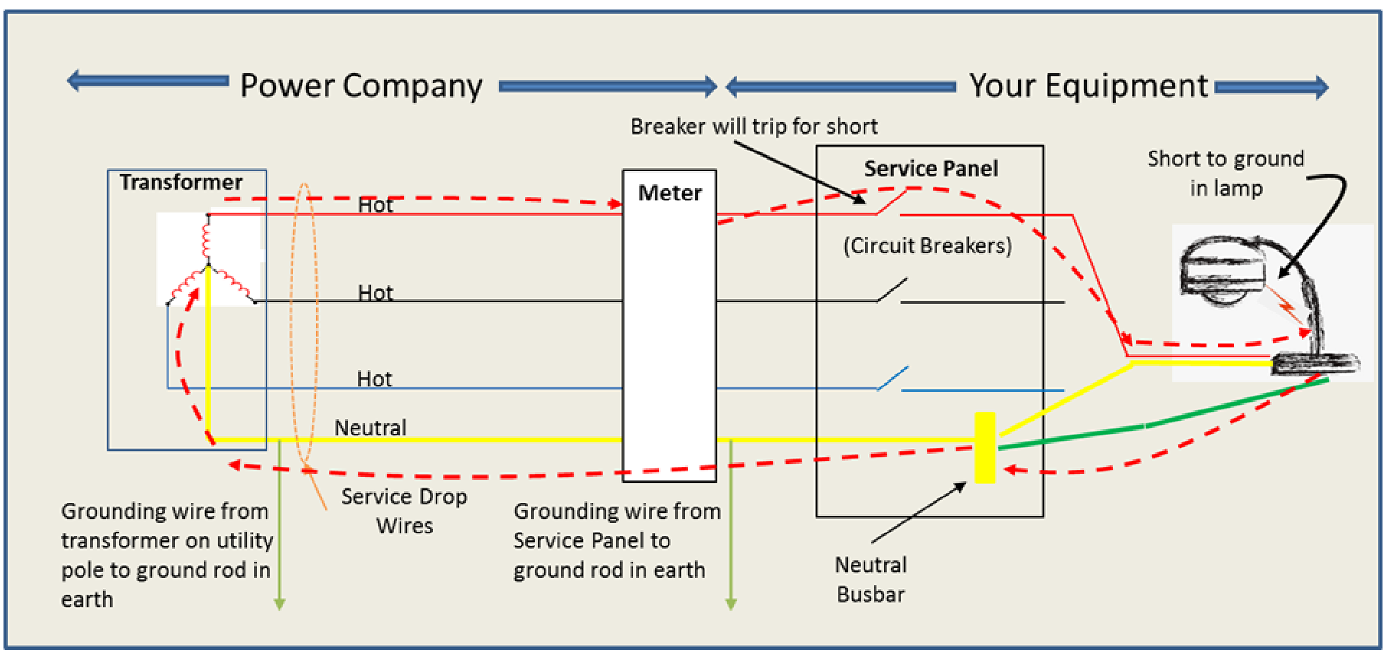

Figure 4
Current flow for one light bulb with a short to ground.

surface creates a short circuit, where, "A short circuit is a connection between two parts of an electrical circuit that you don't want to be there.[6]" The lamp's surface is energized because of the short circuit. If the lamp's surface were not grounded, the lamp would be dangerous to touch. A person touching both the lamp's surface and a conducting surface to ground could be a conducting path for current to flow, resulting in shock or electrocution.

Thanks to the proper grounding shown in **Figure 4**, the short-circuit current flows from the energized exterior lamp surface to the ground terminal of the lamp, through the ground wire of the power cord to the ground terminal of the receptacle. From the receptacle, the path flows through the building's ground wiring (green), terminating at the neutral busbar within the service panel (yellow rectangle). From the neutral busbar, the return current continues back to the neutral terminal of the transformer, as usual. If the short-circuit current is large enough, it will trip a circuit breaker in the service panel.

The low resistance of hot and neutral service-drop wires/building wires and all ground wires minimize the energy consumption that would be wasted (as heat) by current flowing through higher resistances. From the transformer to appliances, the hot voltage remains close to 120 volts with allowable current flow.

The concept of balanced three-phase power requires identical loads on each phase, so that identical current is drawn from each phase. This is a convenient abstraction but physically impossible to achieve. In the ideally balanced model, the algebraic sum of currents is zero from phase 1, phase 2, and phase 3 hot wires (red, black, and blue in **Figure 1**). Zero current returns through the neutral wire and the neutral wire remains at exactly zero volts from end to end because of the ground connections illustrated in **Figure 1** to **Figure 4**.

In real systems, there is always some imbalance. Considering **Figure 2**, there are no loads on the black or blue phases, so all the current from the red phase through the lamp returns through the neutral wire. Because of the low resistance of the neutral return wire — and the ground connections shown in **Figure 1** to **Figure 4** — the neutral voltage remains close to zero volts. However, in some unbalanced load situations, neutral-to-ground voltage of up to 25 volts is acceptable[7].

Service Drop Neutral Wire Drop

For the case at hand, the neutral wire of the service drop was severed, resulting in a dangerous condition. If the neutral wire of the service drop is severed as shown in **Figure 5**, the return current finds a different path back to the transformer. This alternative flow is from the service panel's neutral busbar (yellow rectangle) through the grounding wire and ground rods, through the earth, through the utility pole ground rods and grounding wire, back up to the transformer's neutral terminal. This path is not low resistance and is not intended to be a useful alternative to the neutral wire. "The earth shall not be considered as an effective ground-fault current path[8]." The ground rods and wires are intended only to provide a voltage reference for the low-resistance neutral wire from the service panel to the transformer.

A severed or impaired neutral wire allows stray current flow through surface and voltage gradients across the surface. **Figure 5** illustrates an electrical system where the neutral return wire from the meter to the utility transformer has been severed or impaired (indicated by the large X). "Impaired" means the wire is partially severed or corroded and its resistance is much greater than it should be.

By Kirchhoff's current and voltage laws[4], all current from the transformer hot terminals must return to the transformer. The amount of current flowing depends on which appliances are operating.

Assume the meter, panel, and all circuitry are operating perfectly, but the neutral is severed. No current can flow through the neutral service drop wire, so the returning current finds an alternate path back to the transformer. If the neutral is only impaired, the return current will divide between the neutral return wire and alternative paths according to the resistance of each path. When earth is the only path for the ground fault current, it's called an "earth fault."[9]

Multiple earth fault paths are possible, and the current flowing through the alternative paths depends on factors including how much current is being consumed by appliances on the red versus black versus blue hot lines — and on the resistance of the earth fault paths at any given time.

One such current path is indicated by the red dashed-arrows on **Figure 5**, flowing from the hot red terminal of the transformer through the meter, panel, wiring, and appliances. Return current cannot flow through the severed neutral. As the arrows indicate, the current flows from the neutral busbar, through the grounding wires and ground rods, through the earth, through the utility pole's ground

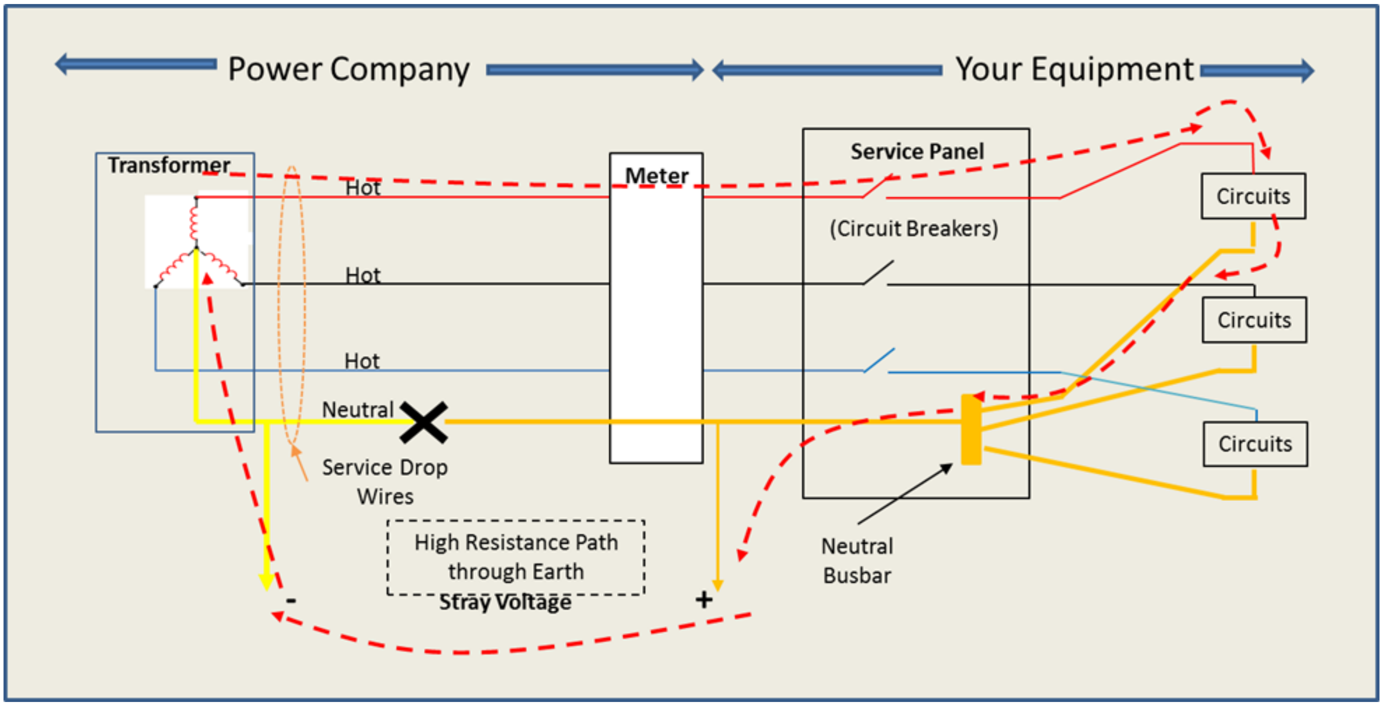

Figure 5
Current flow with severed neutral in the service drop.

rod, and back to the transformer's neutral terminal. **Figure 5** shows the wires in this path as orange.

Current flowing through the earth between the consumer and utility ground rods develops stray voltage. This magnitude of the stray voltage is determined by the magnitude of the current and resistance of the earth fault path from the pool ground rod to the utility pole ground rod.

The magnitude of the current through the earth — and thus the magnitude of the stray voltage across the surface — depends upon which appliances are operating by the balance of the load and resistance of the entire alternate path. Earth resistance is dynamic: It changes from moment to moment because of moisture, temperature, and other factors. The resistivity of soil decreases with moisture content from about 300kOhms per cubic centimeter to about 10kOhms per cubic centimeter, as moisture content increases from 10% to 20%[10].

In the theoretical case of total balance, there is no stray current or stray voltage. By elementary trigonometric identities:

$$I_{Neutral} = \sin(wt) + \sin(wt + 120^o) + \sin(wt + 240^o)$$
$$=$$
$$\sin(wt)[\cos(0)+\cos(120^o)+\cos(240^o)] + \cos(wt)[\sin(0)+\sin(120^o)+\sin(240^o)]$$
$$=$$
$$\sin(wt)[\ 1 - ½ - ½\ ] + \cos(wt)[\ 0 + \mathrm{sqrt}(3)/2 - \mathrm{sqrt}(3)/2]$$
$$=$$
$$\sin(wt)[\ 0] + \cos(wt)[\ 0] = 0.$$

Therefore, $I_{Neutral} = 0$ when the loads on all 3 phases are perfectly balanced, and there is no stray current to escape into the earth. But switching on an appliance results in an increasingly unbalanced load and stray current and voltage increase.

Consequences of Stray Voltage and Stray Current

"Stray voltage is the occurrence of electrical potential between two objects that ideally should not have any voltage difference between them[11]."

"Stray current refers to the electricity flow via buildings, ground or equipment due to electrical supply system imbalances or wiring flaws. It refers to an existence of electrical potential that can be found between objects that should not be subjected to voltage[12]."

Because of the severed neutral wire, the excess current that should have returned through it instead finds its way back to the transformer, as it must, as described in Kirchhoff's laws[4], choosing the path of least resistance. The stray current changes over time, as appliances are switched on and off, changing the total current drawn from the electric utility as well as the imbalance of the three-phase system. The current passes through the various material of the earth surface in the earth fault path found because of the severed neutral. Stray voltage develops between points along these current paths.

Stray voltage is a problem everywhere — in urban, suburban, and rural settings. Consolidated Edison of New York City, N.Y., for example, reported finding 1,214 instances of stray voltage after a yearlong test of electrical equipment on city streets. The tests were ordered after several occurrences of fatal pedestrian electrocutions[13].

A young girl in the Perth (Australia) suburb of Beldon, received a massive electric shock when she touched a tap outside her house while attempting to turn off a garden hose. A damaged neutral wire was suspected of causing the tap to become electrified. Anything plugged into a wall socket (pipes and water taps) can become electrified when the neutral wire of the service drop is severed[14]. In rural areas, livestock can be electrocuted when they stand aligned with the direction of the stray electric field and current flow. The relatively long distance between front and hind hooves of cattle allows a significant stray voltage across an animal's body. Animal flesh is a better conductor than soil, so the favored current path is through the animal — sometimes electrocuting it[15,16].

Referring to **Figure 5** for the case at hand, since return current could not flow through the severed neutral, the current flowed from the neutral busbar, through the grounding wires and ground rods, through the earth. This stray current took whatever path offered the least impedance to get back to the utility pole's ground rod, and ultimately back to the transformer's neutral terminal. That path in general will change from moment to moment according to changes in impedance due to moisture, temperature, and other factors. A likely path would have included the swimming pool and its surrounding fixtures and soil. As discussed in the section on ESD, conductivity is higher through the human body than through fresh water. Persons entering the pool lower the overall impedance of the path through the pool. Depending on a person's size, depth in the pool, and orientation versus the stray electric field across the pool, they may become part of the stray current path and receive a shock.

The stray current's magnitude varies over time as well. An appliance that draws a single-phase large current from the severed-neutral system would increase the unbalance of the system. The unbalanced current, which would return through the neutral in an intact system, now increases the magnitude of the stray current. When that appliance turns off, the stray current would decrease. The dynamic nature of stray current in time (as well as position) explains why others in the pool were not shocked — and why a staff member was able to reach into the pool and say, "See, I'm not getting a shock!"

Conclusion

After reading all the provided documents, researching further into municipality, county, and state regulations, visiting the scene of the incident, and inspecting the damaged power lines that were stored as evidence, the FE submitted an expert report opining that:

1. The Association and its president did not have control over the service drop. The utility was responsible for maintaining the service drop, including the return wire, its failed splices, and the stray electric field and stray currents that resulted.

2. The Association and its president were not careless in the pool's electrical maintenance with respect to the faulty condition that led to the incident.

3. The Association and its president were not responsible for the unsafe swimming pool condition resulting from the failed service drop wires.

Furthermore, the report concluded that neither the Association's hired electrical contractor nor the municipality's electrical inspector had responsibility for the service drop wires. Only the power utility had the authority and responsibility to inspect and repair the equipment it owned. The utility was at fault for not returning to permanently repair the service drop; it was the only entity authorized to make the repair or obligated to monitor the condition of the service drop.

References

1. G. M. Dworkin and K. Doheny, "Electric Shock Drowning: A Silent Killer," Lifesaving and Rescue, 15 June 2017. [Online]. Available: https://lifesaving.com/in-the-news/electric-shock-drowning-a-silent-killer/. [Accessed 29 October 2019].

2. Electric Shock Drowning Prevention Association, "The Electric Shock Drowning Prevention Association," The Electric Shock Drowning

Prevention Association, 2019. [Online]. Available: https://www.electricshockdrowning.org/esd--faq.html. [Accessed 29 October 2019].

3. M. Dibreli, "A Review of Electric-Shock Drowning Incidents," Service Industry News, 28 November 2017. [Online]. Available: http://www.serviceindustrynews.net/featurestories/2017/11/28/h0tpjdwvvb3dr89mq16d9uaeevt179. [Accessed 29 October 2019].

4. J. William D. Stevenson, Elements of Power System Analysis, Third Edition, New York: McGraw-Hill, 1975.

5. W. Contributors, "Three-Phase Electric Power," Wikipedia, The Free Encyclopedia, 18 October 2019. [Online]. Available: https://en.wikipedia.org/w/index.php?title=Three-phase_electric_power&oldid=921812602. [Accessed 31 October 2019].

6. M. Murphy, "Ask An Engineer," MIT School of Engineering, 11 November 2017. [Online]. Available: https://engineering.mit.edu/engage/ask-an-engineer/what-is-a-short-circuit/. [Accessed 31 October 2019].

7. T. Shaughnessy, "Clearing Up Neutral-to-Ground Voltage Confusion," EC&M, 1 February 2007. [Online]. Available: https://www.ecmweb.com/power-quality/clearing-neutral-ground-voltage-confusion#close-olyticsmodal. [Accessed 31 October 2019].

8. M. W. Earley, C. D. Coache, M. Cloutier, G. Moniz and D. Vigstol, National Electrical Code Handbook, Fourteenth Edition, Quincy, MA: National Fire Protection Association, 2017.

9. P. Paul Ortmann, "Advanced Topics in Stray Voltage - Why is that voltage there?," Idaho Power Company, 2015.

10. T. M. Shoemaker and J. E. Mack, The Linemans's and Cableman's Field Manual, Second Edition, New York: McGraw Hill, 2009.

11. Definitions.net, "Definitions for stray voltage," Definitions.com, [Online]. Available: https://www.definitions.net/definition/stray+voltage. [Accessed 4 November 2019].

12. CORROSIONPEDIA, "Definition - What does Stray Current mean?," corrosionpedia.com, [Online]. Available: https://www.corrosionpedia.com/definition/1032/stray-current. [Accessed 4 November 2019].

13. S. Chan, "Con Ed Finds 1,214 Stray Voltage Sites in One Year," The New York Times, 4 March 2006. [Online]. Available: https://www.nytimes.com/2006/03/04/nyregion/con-ed-finds-1214-stray-voltage-sites-in-one-year.html. [Accessed 4 November 2019].

14. R. Trigger and G. Powell, "Warning after Denishar Woods receives near-fatal electric shock from garden tap," ABC News, 5 March 2018. [Online]. Available: https://www.abc.net.au/news/2018-03-05/what-causes-taps-to-be-electrified/9508664. [Accessed 4 November 2019].

15. D. Lanera, "Stray Voltage Facts, Straight and Simple," Stray Voltage, [Online]. Available: http://www.lanera.com/strayvoltage/strayvolt/sect1/index.html. [Accessed 4 November 2019].

16. P. Douglas J. Reinemann, "Stray Voltage Field Guide," University of Wisconsin, Madison, 2009.