

ELECTRICAL GROUNDING – THEORY AND APPLICATION

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ABSTRACT

The concept of an electrical ground is pivotal to the application of all electrical circuits. In our teaching of this concept, we discuss grounding from both a theoretical and practical perspective. Practical knowledge is gained from real-life case studies on the subject. (1) A factory-based grounding plane in a large factory experiences ground looping. This is blamed for a serious accident. Our tests started with a true earth ground and concluded with a mapping of the entire factory, machine-by-machine and outlet by outlet to verify the results of ground looping in a well-constructed electrical environment. (2) A patient is being prepared for major surgery. He needs to be grounded. He is acting as an antenna for many stray signals. Also, static charge is building up on him. The result is a washing out of the data on the medical machines monitoring his physical condition. (3) Even though it is always said that a good ground is necessary for electrical safety, there are 2 cases that we report where floating a circuit (i.e. not grounding it to the earth) is the best and safest case.

INTRODUCTION

In the field of electricity, the theoretical concept known as “ground” is indispensable in solving every electric circuit. Using Gauss’s law or Maxwell’s equations, one can define an electric field of a static or moving charge in a manner that is un-ambiguous. Only one unique solution exists [1]. However, dealing with the mathematics inherent in the application of an electric field to an electrical circuit is prohibitive for most people, including electricians, technicians, and even most people with advanced degrees in Electrical Engineering. It is more efficient to introduce the concept of potential or voltage. NOTE: potential is defined as the energy-per-unit-charge (joules/coulomb) at a point in space; voltage is the potential difference between two points, i.e. subtract the potential at point A from the potential at point B to give you the voltage (V_{AB}). For any electric circuit, even one in which the current is zero, the electric field can be determined to be a single unambiguous solution in space and time. Since the negative gradient (i.e. derivative) of the voltage equals the electric field, the voltage is derived by solving an indefinite integral of the electric field. To the solution of this integral, one must always add an arbitrary constant. Hence, the voltage is a unique and unambiguous solution with an added arbitrary constant [1].

One common way to define the arbitrary constant in the solution of the voltage is to assume that there is a common point of zero voltage, aka a ground point. As an example, consider the coupling of two 9-volt batteries shown in Fig. 1. The voltage between the upper and lower plates in both Figs 1 (A) and (B) is the same, i.e. 18 volts. The 2 batteries add their voltages in series. However, in (A) the bottom connection is at zero potential (erroneously referred to by most people as zero volts). The top connection is at 18 volts, relative to the bottom. This is an 18-volt DC power supply consisting of two 9-volt sources in series. In (B), the middle point between the batteries is defined to be at zero volts. The top connection is +9 volts and the bottom is -9 volts. This is a bipolar DC supply. There is NO physical difference between (A) and (B). Yet, they can be used to perform different functions in the lab, based on the human's choice of a zero potential point, aka a ground point.

As noted already, voltage always means that 2 points in the circuit are considered, while potential refers to only one point. But with the concept of a common or ground point, everyone uses the term "voltage" even when they are referring to only one single point. The assumption they make is that the voltage is the potential referenced to the zero voltage point, aka the common point, aka the ground point. In Fig. 1 (A), the voltages are (from top to bottom) 18, 9, 0. In (B), the voltages are 9, 0, -9.



Fig. 1A: Two 9-volt batteries in series with ground chosen will have voltages 9 and 18.

Fig. 1B: Two 9-volt batteries in series will have voltages +9 and -9 with ground chosen between them.

We must next consider the concept of ground looping [2] and chassis-ground/earth-ground [3]. Chassis ground means that the "box" or container of the circuit is a metal object with zero ohms resistance in the metal, and this chassis is to be the ground point of the circuit. Earth ground refers to the fact that the earth itself is a very good conductor in many places. It is also very large (practically infinite) when compared to all human engineered electrical circuits. Even a 1000-mile long power line is small when compared to the earth. There are several important areas where the earth ground and the chassis ground are never connected. There are also cases where they MUST be connected. A flashlight is the simplest case of a chassis ground that never connects to the earth. There is absolutely no reason based on safety or practicality to do this. The metal housing

of the flashlight acts as the chassis ground for the batteries and bulb to use as their zero potential point.

An automobile is another example of a case where the chassis and earth ground are generally not connected. The chassis of the car is insulated from ground by the rubber tires. In an accident where a power line or a lightning bolt contacts the chassis, there is generally no danger to the human inside. Moreover, there is a case when it is good to ground a motor vehicle. Suppose that you are driving a truck with gasoline in it. The tires should conduct electricity. In this way, as you build up charge on the gas tank, the charge dissipates from the chassis to the earth ground. Otherwise, it could build up to several thousand volts on the chassis and then arc to ground through the air. This would cause a spark, which could ignite the gasoline.

By contrast, to these first 2 examples, the refrigerator in your house must be grounded to the earth; this is mandated by law [4]. In general, a refrigerator consumes a great deal of power, and thus it draws a large current. The metal “box” that makes up the outside of the fridge is required by law to have a voltage of zero when referenced to the earth. This is done for safety reasons. Since the refrigerator draws a large load current, simple leakage can be of the order of 10³’s of milliamps, which is more than enough to electrocute a human being [4].

The rest of this paper covers some real-life cases that show the application and/or misunderstanding of grounding in an electrical circuit.

CASE I

In a factory, a man’s hand is ripped off due to suspected ground plane problems

A large milling machine drew 3-phase electricity at 240 volts RMS per phase with respect to neutral/ground. Current was approximately 100 amps per phase.

The machine ran hot. It drew an excessive amount of electric current (approximately 20% above that specified for normal operation). A repairman was summoned by the company to repair and/or clean up the machine internally. With the back of the machine off, the repairman bent over to touch the motor in order to see if it was the motor that was running hot. He anticipated that if the motor felt cool or warm, he would then move on to other parts of the machine to see if they might be responsible for the excess current draw. As the repairman’s hand got near the motor, he felt an extreme pain. He later described this as an electric shock. This caused him to jerk his hand away suddenly. In the process, his hand was caught by the large belt around the pulley being driven by the motor. His hand was torn off violently.

The repairman sued the electrical contractor who had wired up the machine. He claimed there was ground looping. Each machine and each electrical outlet were tied to earth ground. But, if there was resistance between these connections, there could be a simple Ohmic (IR) voltage built up as current passed through the ground plane, such that one point on the plane could be many volts higher than another. This might not kill the repairman, but it would shock him and cause the accident.

Our investigation showed that there was “ground-looping” in all of the machines in the company. The problem is caused by the fact that ground connections as well as the ground itself have some non-zero resistance between them. In the ideal case, all

resistance in the earth is zero, and there is no ground looping. But what if we consider soil that is wet and consists of dirt – it may have less than one ohm of resistance between points that are hundreds of feet apart, but even this value of resistance is greater than zero (ideal case). Furthermore, what if the soil is sandy and dry? The resistance could be quite large. If an electric current is shunted in one place, it can produce a significant voltage at a point several hundred feet away [2].

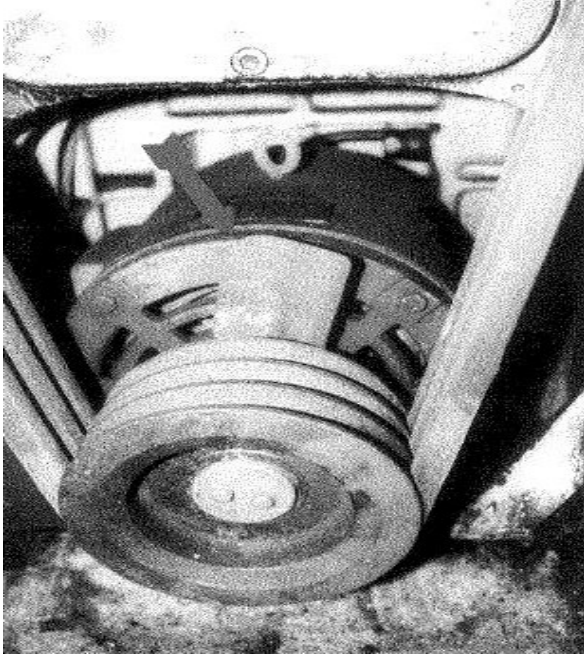


Fig. 2: The arrow shows tight clearance between motor and the fan blade

In the case under investigation, the ground was concrete and dirt and steel (rebar). This turned out to be a very good grounding system. We started with an absolute grounding point, established by a metal pipe sunk over 10 feet into the ground. This compared very well to the ground wire coming off the pole from the power company, with less than one mV difference. We then measured many different points on the machine and around the machine to establish a pattern of ground looping. Ground looping produced several different values of voltage, depending on the places we measured and depending on which other machines in the shop were on during the measurement and depending on what speed the suspect machine ran at. But the maximum voltage that was produced was 40 mV. This could produce a shock current for the human of $40\text{m}/500 = 80$ micro Amps [4]. This is too small for a normal human to even feel. Thus, the repairman did NOT feel an electric shock when his hand neared the motor. The electric contractor and the power company and company owner were not liable for his accident. They could not be sued. It turns out that the reason for the accident was a problem with the motor design. The motor was 12 inches in diameter. To help cool it while it ran the manufacturer had placed a fan blade on the motor shaft. The fan blade was 13 inches in diameter. With the motor running, the fan blade was invisible to the eye. As the repairperson's hand was within a half inch above the motor, the fan blade was already touching his hand and cutting off one finger. This finger was later found; the cut was clean (as if cut by a surgeon); the

finger was located 20 feet from the accident site. In the confusion, the repairman thought the finger was receiving an electric shock. He did not realize it was being cut off. He pulled his hand away suddenly, it caught in the pulley, it was ripped off, and it was later found near the motor. Two separate accidents occurred, but they were the result of poor machine design by the motor/machine manufacturer. Fig. 2 shows the motor and fan blade. It also shows how the tight clearance resulted in the repairman cutting off his finger. The pulley belts are also shown, where the repairman's hand was ripped off. Most ground-looping investigations do not end in so frightening a fashion, but ground looping remains a serious problem. Small ground-loop voltages can wreak havoc with the "intelligence" portion of a machine, and thus control the mechanical and electrical and power of the machine in an improper way. The next case discusses how grounding problems led to surgical problems in a hospital.

CASE II

Improper grounding of a patient in a hospital causes chaos.

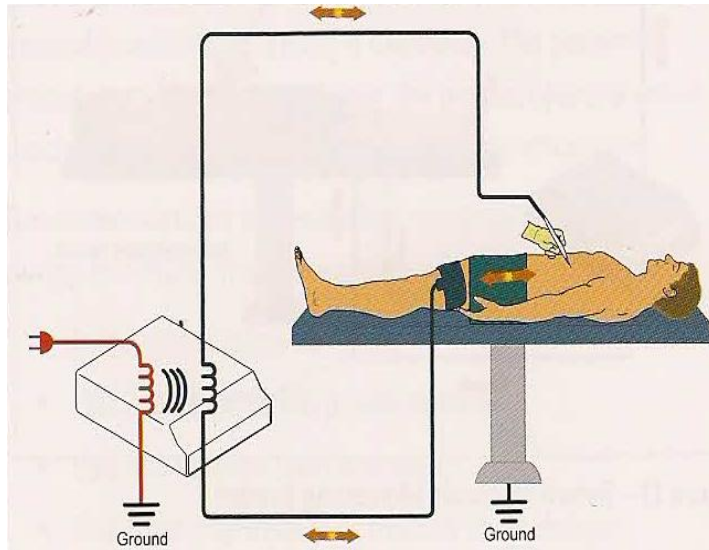
In the pre-op area of a large hospital operating room, a man was prepared for surgery. He was sedated, and all looked like it would follow a normal path of progress. But as the man was wheeled closer to the operating room, all of the medical machines attached to his body began giving strange readings. His EKG (to measure his heart voltage) showed a high degree of noise. At first, the attendants thought the man's heart was going into arrhythmia. But his breathing was slow and consistent with his sedation. Other machines also exhibited a great deal of noise. It was hard to tell what the man's blood pressure and heart rate actually were, though visual indicators showed him to be resting comfortably. One attendant was well versed in the theory of radiation and electromagnetic waves. On a hunch, he took the patient's arm and touched it to the metal "bed" on which he was being wheeled. At this point, the noise stopped completely. All readings for EKG, pulse, and blood pressure were normal. The patient had somehow become an antenna for stray radiation. By grounding the patient to the bed rail, the radiation found a path to ground, and the patient became neutral, except for the normal electric potentials generated by his body.

Great care is generally taken to make sure that hospital machinery is well grounded in order to avoid electric shocks. Whereas a normal person can sustain an electric shock without harm, a person in a weakened and susceptible physical state can suffer severe damage or even death from even a mild shock [4]. But a shock was not the problem here. Evidently, grounding had the beneficial effect of precluding any possibility of shocking the patient. Nevertheless, the grounding was not sufficient to prevent the patient from picking up stray radiation. Apart from this case, there has been growing concern that not one but 2 or more grounds need to be attached to any machine, with the intent that the first shunts away stray electric power, while the second shunts away the electric currents caused by weak electromagnetic radiation. This latter ground is not a direct safety guard but an indirect guard against electric currents that can damage intelligence gathering and utilization [5].

The man in this case had one of his arms free. His hand was taped to the metal bed frame during his operation. All medical equipment worked well, and the surgery was a success.

The problem solved here was not ground looping, but rather the lack of “cleanliness” of most grounding point. A dirty ground shunted the majority of the power, while a clean ground shunted the small high frequency noise. The power ground point had approximately 0.1 ohm between it and earth ground contact. The clean ground had approximately 10,000 ohms between it and earth ground. By using the high resistance of 10,000 in parallel with 0.1 ohm, the dirty ground shunted the “power” through itself and not through the 10,000. By contrast, the noise in the patient was very low power and moderately high voltage generated by charging and discharging within the patient himself. This charge discharge cycle was shunted by the large RC value, i.e. the low

capacitance of the patient and the high resistance feeding the clean ground.



CASE III

When a ground is bad

Fig. 3: Electric power into a transformer is earth grounded. The transformer secondary is floating. Hence, there is no leakage of current entering the patient -- all current must return via a pad on the patient's back or thigh. None will leak

into the earth ground of the operating table. This eliminates shorts and shocks to the patient and other people.

Many Electricians and Electrical Engineers have the mistaken notion that a ground is always a good thing. There have been many court cases won by the plaintiff who claimed the defendant did not adequately ground the machine he was working on. But there are some notable cases when grounding an appliance/machine/environment is a very bad thing to do.

Let us start with a hospital. A hospital requires all machinery to be grounded with a permitted leakage current of 80 micro-amps or less [6]. Appliances in the home as well as machinery in the workplace are considered safe with a leakage of 1 milliamp or 1000 micro-amps. The value of 80 micro-amps is enforced for the sake of the sicker people who may contact machinery in a hospital.

However, there is one major case where grounding in a hospital is not safe. Over 80% of major surgeries are electro-surgeries [7]. Electricity emits from a pen or wand in such a fashion, that skin can be cut or cauterized. This electricity is collected in a pad on the patient's back or thigh. See Fig. 3. First generation electro-surgical units had the collection pad tied to earth ground. Any leakage not collected at the pad shunted to

ground by another route, such as the operating table or machines or people-nurses-doctors. This leakage was kept as low as possible by careful machine design. Modern electro-surgical units, however, are safer because input electricity is first passed through an isolation transformer. Although the input electrical wires must include a ground wire, all points past the isolation transformer are floating. See Fig. 3. Shocks to doctors/nurses are eliminated, even though they may be electrically grounded. Shorts that can cause leakage into the patient's feet or head to ground are also eliminated. A second example of when a well-grounded machine is a bad thing can be found in a case we worked on that involved a man putting up a sign on the side of a building. Electricity from a nearby telephone pole was at 13,000 volts. The man got too close. The electricity arced through the air 8 feet and killed the man. The electricity on the telephone pole was earth ground. The man putting up the sign was approximately 20 feet above the ground in a "cherry picker" or lift bucket. A later investigation showed some interesting things. The lift bucket was part of a truck driven to the site. In order to stabilize the truck mechanically, "feet" pads were lowered to the sidewalk. Each pad was metal and approximately one foot in area. After the electrocution of the man in the lift bucket, there were burn marks on the sidewalk where the pads had been holding the truck steady. This was proof of the path that the electricity had taken through the air, through the man, through the truck, through the sidewalk, and to earth ground. More modern lift trucks are ground isolated, insofar as the bucket is concerned. The truck must be grounded simply because the feet pads must be lowered to stabilize it while the lift arm is in operation. But the bucket that holds the man is floating with respect to ground.

CONCLUSION

We have stressed the importance of grounding machinery. Poor grounding can lead to death, or it can mess up the intelligence required for proper analysis and control. On the other hand, there are some clear cut occasions where a floating (non-grounded) architecture is not only easier, but much better for the safety of both man and machine.

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