

DISCUSSION ON HIGH VOLTAGES AND THEIR SUCCESSFUL INTRODUCTION IN TO THE ENGINEERING CLASS ROOM USING REAL LIFE ACCIDENT CASES

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Abstract

We discuss the Engineering principles of Hi-voltage (any voltage above 600 volts). We cite 3 examples that typify some of the problems facing the Engineer and technician working with Hi-voltages, including geometry considerations, the need to follow proper protocol and the laws (both scientific and political) governing Hi-voltage.

Introduction

High voltage is a source of interest to both the Engineer and to the layman. Interest ranges from the sight of speeding electrified commuter trains to horrible accidents when humans contact high voltage. In this article we cite 3 cases of high voltage accidents. Each accident teaches something different about electricity and electric safety.

Let us first begin with some clarifications. By formal definition, high voltage is defined as any voltage above 600 volts. Below 600 volts, one should consult the NEC (National Electric Code) for the rules of electrical installation and safety [1]. Above 600 volts, the better safety code is written by OSHA [2]. This should not in any way diminish the danger of low voltage circuits. People die in their homes every day from electrocution caused by 120 and 220 volt sources. Furthermore, we have personal experience of visiting factories and other sites where electricity is introduced in to an area that is frequented by many people; often these sites have prominent warning signs: HIGH VOLTAGE, even if the level is merely 220 volts.

As a key to understanding High Voltage, we must consider the human being as a resistor. Adults can be modeled successfully as a 500 ohm resistor; this represents the core of the adult and ignores the skin resistance. The core value is determined by blood, bone, and tissue and not the skin surface, which can be as little as a few ohms in most Hi-voltage cases [3, 4]

The phenomenon of arcing or flashover must also be considered. In this case, electricity leaves its source and travels through the air to connect with the human. It should be noted the insulating properties of air are extremely good. The breakdown of air (even if the air is filled with moisture) is at least twice what it is for glass. In other words, an "air" shield protects you better than a glass one. However, even this is not good enough to protect in all cases. A better insulator is Sulfur hexafluoride. The fluorine atom has a valence of -1, i.e. it is not stable until it can capture one electron in to its outer shell. Furthermore, Fluorine is the most violent reactor of all of the Halogens (i.e. elements with valence -1).

Sulfur has 6 electrons in its outer shell. Normally, Sulfur reacts to capture 2 electrons to stabilize in to a compound. For example, CdS or Cu₂S are examples of semiconductors where the Sulfur has captured two electrons from the cadmium or copper and thus formed a stable compound via valence bonding. With SF₆, the reaction expected is “backwards”. The Sulfur is stripped of all 6 of its outer electrons. The violent reacting Fluorine is subdued and remains quiet and stable. In fact the compound is so stable that it is better than air and is used as the insulating material in many very high voltage applications, including the construction of capacitors used in Hi-Pot testing [5].

Hi-Pot is another term familiar to the High Voltage engineer. Hi-Pot or hipot is an abbreviation for high potential or high voltage testing. Suppose you have a circuit breaker to be used to break the circuit in a 250,000 volt line. This might be tested with DC at a few Pico-amperes but up to 300,000 or even 500,000 volts. Often the rule-of-2 applies where possible. The rule-of-2 says that if any device (circuit breaker, capacitor, meter, inductor, etc.) is to be operated safely and without breakdown at a voltage X, then it should be stressed under test up to voltage 2X. See for instance [6].

Throughout the rest of this article, we will be talking about real life cases analyzed by us. We will identify all of the people and companies in these cases by fictitious names. Any resemblance to actual people or actual companies is pure coincidence.

Real life cases

Case #1: A Circuit breaker at a substation must be able to stand a stress of 250,000 volts. We start our analysis at the highest voltage normally available to an engineer. A New York State power company (NYSPC) is testing a new circuit breaker. The breaker must be able to interrupt power to 3-phase electricity with an RMS value of 250,000 volts. Hence the breaker is 3 breakers operating in parallel. Part of the breaker is a “snubber” circuit [6]. Recall that we are dealing with 3 states here: off or zero voltage state, on or 250,000 volts state, and the intermediate or transitional state. It is the intermediate state that is most dangerous. If you build a 5 volt logic circuit in the lab and leave it on at 5 volts, the circuit is relatively free of being damaged. If you turn it on and off rapidly, you can produce spikes of 10 volts or more, and this can act to destroy the circuit board. With High Voltage, the danger is much greater. If there is a spike to 500,000 volts or several million volts, the electricity can jump the ceramic insulators and travel up to 30 feet in air to electrocute someone. Therefore, a snubber is an ideal and mandatory safety feature of the circuit breaker.

In the course of testing, several “barrel” transformers were charged (along with parallel capacitors) to about 25,000 volts. These were then switched in to a “series” configuration generating the requisite 500,000 volt test voltage. A NYSPC technician was in a lift bucket when a “basketball” of light flew through the air and hit him and left him for dead. He suffered burns and muscle and organ damage as a result. He did not die, but he experienced body tremors (the “shakes”) for several years after the accident. He also suffered post traumatic stress disorder. His accident was the second such accident to occur in the past 2 years when testing this particular circuit breaker. What “gremlin” in the circuit breaker was the cause of these 2 accidents?

The circuit breaker was originally built with a single capacitor in parallel with the remaining components of the breaker. The value of the capacitor was 2 nF. This capacitor was expected to be stressed up to 500,000 volts without breakdown of the insulator. A

new design engineer later revised the circuit to employ two capacitors in series. This new series arrangement was put in parallel with the remainder of the breaker. Each capacitor was only to be stressed to 250,000 volts. Each capacitor had twice the surface area of the original capacitor they replaced. Hence, each had a value of 4 nF, and their series combination was 2nF, the same as the original capacitor. Since the voltage stress on each was to be 250,000 instead of 500,000 as it had been for the original capacitor, the need to spend money to make the capacitors “rugged” to voltage stress was reduced. As a rule, the money spent on building a capacitor to operate safely at a voltage will AT LEAST increase by 4 each time you double the maximum voltage stress of the capacitor. Consequently, there is a big savings in decreasing the voltage stress. (Note: this rule of 4 is based on the fact that the danger of high voltage varies as the power, which in turn varies at the square of the voltage.) See, for example [7].

During the testing, “barrel” transformers are used to transform ordinary electricity (single phase 120 volts) to 25,000 volts per each. These are then put in series and rectified to the DC value of voltage up to 500,000 volts. Before the circuit breaker was stressed, the capacitors were first stressed. Since the line is 3 phase, each phase was stressed to 500,000 volts. In the ideal case, two capacitors in series split the voltage evenly. But two capacitors in series is a very “bad” architecture. If two equal resistors are put in series, the voltage in the middle is always half the applied voltage, or if you include experimental error, the voltage in the middle is half the applied voltage plus/minus a small percent. Capacitors can be thought of as infinite ohm resistors. In actual fact, the resistance is many trillions of ohms. The leakage of a capacitor built as two parallel plates with air as a separator is approximately 40 trillion ohms [5]. With Sulfur Hexafluoride, this value is approximately 500 trillion ohms. This is NOT the problem. The problem is that you can not maintain strict control of the capacitor geometry. Suppose you built two resistors to be equal in value. Suppose your geometry was off by 1%. This is not a big problem for low voltages. But for high voltages, this is a tremendous problem. For 500,000 volts, 1% is 5000 volts.

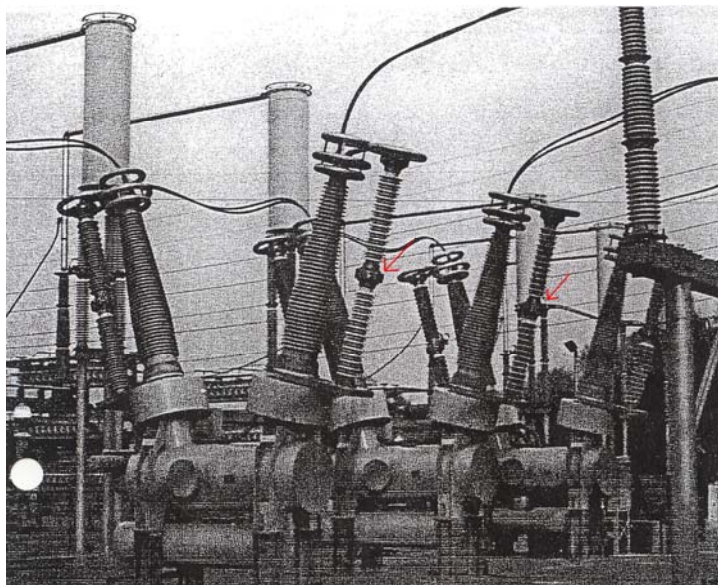


Figure 1: 3-phase circuit breaker, 250,000 Volts. Note – Capacitor that caused accident labeled with arrow.

In this accident, a NYSPC worker was in a lift bucket above ground. He was approximately 10 feet from the capacitor. The capacitor combination of phase #1 was tested up to 500,000 volts DC. It was gradually brought down. A grounding stick was placed on the high voltage end of the capacitor, while the low voltage end was at ground. But NO protocol was followed for the center point (i.e. for the point between the two caps in series). Nothing happened. The Hi-pot test continued for the #2 phase of the circuit breaker's capacitor. After 500,000 volts was reached, a grounding stick was placed on the high end. The middle point again was not involved. Suddenly, from the middle point a ball of light the size of a basketball emerged. It struck the NYSPC worker. He did not die. But he required emergency care, and his burns and muscle spasms lasted for many years, precluding him from the work for which he was trained.

Analysis of this case:

IN THEORY, the voltage at the middle point between two equal capacitors in series is zero. But geometry and other inconsistencies in design can make the capacitors unbalanced to the point of a 1% mismatch (or larger). The resistors are the bad guys, in that they allow un-equal voltages to form. But it is the capacitors charge storage ability that maintains this voltage imbalance when the high side of the capacitor is grounded. The worker thought that with the high and low sides of the capacitor at zero volts, he was safe. Also, corona discharge (aka arcing) can occur for 5000 volts up to a distance of 10 feet. Had the worker sustained a discharge of 500,000 volts, there would only be his ashes left to bury. But even so, the 5000 volts was enough to cost him massive burns, muscle pains, and the loss of his chosen career.

Conclusion:

Keep all components in a Hi voltage circuit simple and rugged, and do NOT ever put two capacitors in series, unless you are prepared to ground the middle when not in use.

Second Conclusion:

Even if the voltage levels are trivial (say 5 volts), it is always a bad idea to put 2 capacitors in series without shunting each capacitor by precision resistors. Suppose, for example, the leakage of the first capacitor is X and the leakage of the second is $10X$. Then, the voltage splits 10-to-1 and not 1-to-1 as expected. If these capacitors are shunted by very large resistors (say 100 megohm), then the voltage splits 1-to-1, since $100 \text{ meg} \ll X$ for any good capacitor.

Case #2: A sign hanger gets too near the high voltage in a telephone pole on a city street
A sign hanger is working on the outside wall of a building housing a factory in New York State. Power is supplied by another New York Power company (ANYPC). The contractor has his worker Richard Roe go up in a bucket boom (aka cherry picker). The contractor is licensed by the city. His project is near a power line that feeds power to the factory. The voltage in the power line is 13,000, 3-phase. A transformer on the pole converts this to 120 volt at 3-phase, and sends this in to the factory. Mr. Roe is very successful in completing the work on the outside wall. He finishes over 90% of the sign. Then, suddenly, he slumps over in the lift bucket. He is being electrocuted via asphyxia [3, 4]. He can not breathe. A co-worker on the factory roof attempts to lift him out of the bucket. The co-worker suddenly is struck with muscle pain and burned over the greater part of his stomach.



Figure 2: Telephone pole with 3-phase 13,000 Volt power cable near building (right) where accident occurred.

Analysis of this case:

Simply stated, Mr. Roe was too close to the power source. His boss (a licensed sign hanger) failed to measure the proper and safe distance to keep from the power line. Alternatively, Mr. Roe's boss could have contacted the power company, and he did not. The power company had the power wires close to the factory because the wall nearby was a non-maintenance wall, i.e. there was no indication of any activity that was to be carried on near that wall. As an example, a wall with a door or window is a maintenance wall. Similarly, after the sign was installed, it too became a maintenance wall. But these facts should have been reported to the power company beforehand.

Conclusion:

Contact the power company before you work near a hi-voltage line (any line with voltages of 600 volts and up).

Case #3: Master Electrician uses ordinary handheld voltmeter to measure 4000 volts

This case is very sad. It was totally avoidable. It produced only minor injury, but this in turn led to the death of a young man with a wife and children.

John Doe is a Master Electrician. Note: he can train someone who has no knowledge of electricity and turn that person in to an electrician like himself. He is the Master of his trade.

John is hired to work on staff at a large factory in New Jersey (ALFINJ). The factory is undergoing change. There are almost 100 different electric closets, and each closet has a multiple of different voltages in each of them. All of the voltages are low voltage (nominal 120, 240, and 480 volts, either single phase or 3-phase) with one exception. There is a 3-phase source of 2300 volts. It is located apart from the factory. There is a chain link fence around it. It is not the type of place that you can just wander in to.

The power from this source is fed to one particular closet, almost identical to dozens of other electrical closets near it. There is a large sign that reads: "Danger 2300 volts". There is a small sign (about one inch square) that reads the same thing. The closet is locked with a padlock. This dangerous voltage obeys the Lock-Out-Tag-Out protocol enforced on all dangerous voltages.

John is comfortable with all of the low voltages. His Fluke meter has a maximum rating of 1000 volts (DC/RMS AC). With no concern about what he is doing, he randomly opens many different electric closets and measures a host of voltages. There is NO set of master schematics for the factory. John is putting together his own master set.

Over time, the large sign that reads "Danger 2300 volts" either falls off the cabinet or is removed. The padlock is opened on the cabinet and later disappears. This sloppiness has now left 2300 volts inside a cabinet that anyone can open. The small sign (one inch square) remains.

One day, John is testing various voltages when he comes to the cabinet. As a master electrician, he is duty bound to read all he can before he enters the cabinet. Because he is sloppy, he does not take notice of the one inch square sign. He assumes that the voltages inside are low. He hooks his Fluke meter to the first leg of a 3-phase arrangement. At this point, he could still come out of this okay. Protocol dictates that you measure each UNKNOWN voltage with respect to ground. If John had done this, he would have 2300 volts sitting across his multimeter. The rule of 2 applies. John's meter is capable of safely measuring 1000 volts. It can go up to 2000 volts without breaking. Beyond 2000, there is the real chance of serious damage. At 2300 volts, his meter should "smoke" and cause problems, but that is all. We can verify this from first hand testing in the laboratory.

Instead of hooking his meter leads between ground and one leg of the 3 phases, John hooks his two meter leads across two different phases. This is a shortcut. By doing so, John can cut his testing time in half; if the voltage is proper, he can verify 2 phases with one measurement. But this is dangerous, if the voltage is unknown.



Figure 3: Bright yellow fluke multi-meter is badly blackened (burnt) out a result of measuring 4000 Volts.



Figure 4: A sampling of the more than 300 electrical closets at a very large food warehouse in New Jersey.

Analysis of this case:

A voltage of approximately 4000 volts travels in to John's meter. Note: for any two phases in a 3 phase system, the difference in voltage is 2300 volts (the voltage of one leg) multiplied by the square root of 3. This large voltage causes a massive current to travel down the leads to the meter. The meter is instantly burned and on fire. The current does not stop there. It continues to travel into John's work gloves and in to his hands and chest. He is severely burned. Eventually after a very long illness, he will die.

Conclusion:

Follow the proper protocol when measuring any unknown voltage. Do not assume that your measurements are safe for the voltage you think you are measuring.

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Biography

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