

An Electrical Lab Exercise on Voltage Drop

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Lab exercises are an excellent way to give students hands on experiences. Practice by doing has been demonstrated to be one of the most effective learning methods. This paper is one of a series of papers to be published describing hands on lab activities that can be used as part of an electrical course curriculum suitable for a construction management program. Voltage drop can be a problem where long circuit lengths are necessary to supply loads in building applications. Examples include parking lot lighting, remote sewage lift stations, and even temporary construction wiring including the use of long extension cords. This lab teaches the student the fundamental theory behind the problem and uses a simple circuit arrangement to simulate a 1000 foot parking lot lighting circuit allowing the student to see the effect of voltage drop as well as take measurements to verify results of mathematical calculations.

Key words: Electrical, Construction Education, Electrical Lab, Voltage Drop

Introduction

In today's world, how students learn is just as important as what they learn. Students should be taught the basic skills in all the fundamental learning areas. They should also be taught to be active seekers of information and constructors of knowledge (Marchetti, 2002). Students have a number of intelligences beyond the language and mathematical abilities typically emphasized in learning institutions (Shunck, 1996). Some learning is simple and repeatable, other types of learning require more complex thinking and strategizing.

Do you learn better when someone tells you exactly how to do something, or do you learn better by doing it yourself? Many people are right in the middle of those two scenarios. This has led many educators to believe that the best way to learn is by having students construct their own knowledge instead of having someone construct it for them. This belief is explained by the Constructivist Learning Theory, which states that learning is an active process of creating meaning from different experiences (Brooks & Brooks, 1993). In other words, students will learn best by trying to make sense of something on their own with the teacher as a guide to help them along the way. Learning is also enhanced when educators provide students with opportunities to build understandings and practice skills by introducing a combination of several learning modes (Wankat and Oreovicz, 1993). Below is a list of different methods of learning. The percentages listed represent the average amount of information that is retained through that particular learning method (Adapted from Brooks & Brooks, 1993).

Lecture = 5%
Reading = 10%
Audiovisual = 20%
Demonstration = 30%
Discussion Group = 50%
Practice by doing = 75%
Teach others / immediate use of learning = 90%

To efficiently prepare students to integrate well into the construction industry, a comprehensive and structured construction curriculum should provide students with the necessary environment and resources. The program can facilitate students' application of what they learn by providing additional training in the form of labs as reinforcement.

The lab exercise that follows was implemented as part of an electrical course being taught at Auburn University. The background to the problem is given as part of the lab document and is self-explanatory. The lab text is condensed by leaving out blank space where students would normally perform calculations or draw diagrams. Space should be added to leave room for student work when formatting a lab handout. The expected student responses, and notes for the instructor are shown in italics and would not be included in the lab handout material. This lab would follow a classroom discussion on voltage drop that is not included here due to the limited length of the paper.

Voltage Drop Lab Exercise

Purpose

To demonstrate how the length of circuit conductors can affect the operation of equipment located long distances from a supply panel.

Materials

Four (4) 500’ rolls of #14 copper wire (1 black, 1 blue, 2 white) for long circuit connections
Approx. 10’ of #14 copper wire for short circuit connections
Eight (8) incandescent lamp holders
Eight (8) 150 watt incandescent lamps
Ten (10) octagon boxes (1/2” knockouts) for mounting lamp holders and enclosing wire splices
Two (2) blank octagon box covers
18 connectors to protect wire entering octagon box knockouts
Two (2) 120 volt heavy duty lamp cords
GFCI power supply setup

Background

Circuit conductors in building applications are usually made of copper and offer little resistance to the flow of current. The resistance of a conductor is related to the conductor size – the smaller the conductor, the higher the resistance. Resistance is also related to conductor length – the longer the conductor, the higher the resistance.

Most circuits within buildings rarely exceed 100-150 feet in length from the supply panel to the load. Conductors are sized based on their current carrying capacity (ampacity) determined from ampacity tables found in the National Electrical Code® (NEC, 2011). A given size of conductor can carry a particular amperage which can be found in the tables. Under such conditions conductors are sized to carry the amperage required by the connected load. Resistance of the conductors has a negligible effect and is not considered in the design of the circuit – the wire size is determined solely on its current carrying capacity (ampacity).

Circuits serving parking lot lighting, sewage lift stations, or other loads which may be located long distances from the supply panel, may require much longer runs of conductors than typically found within buildings. In circuits where long runs of conductors are necessary, the resistance of the conductors themselves can cause a loss of voltage (and power) due to the resistance of the conductors. This is commonly referred to as voltage drop and if severe enough, must be considered when sizing the circuit conductors.

The voltage lost in the conductors reduces the voltage available at the end of the circuit to power the load. The value of the voltage lost in the conductors can be determined by applying Ohm’s law where Voltage=Current x Resistance, where the resistance is the conductor resistance and the current is the amperage required by the load attached to the circuit. The NEC® suggests that the maximum voltage drop for an individual circuit should not exceed 3% of the supply voltage. For a 120 volt circuit, this would mean the voltage drop in the conductors should not exceed 3.6 volts. In order to reduce the voltage drop, the resistance of the wire must be reduced. For a given circuit length, the larger the wire, the lower the resistance.

Resistance for different conductor sizes can be found in Appendix C, Table 8 of the NEC®. The resistance found in the table is expressed in ohms/thousand feet (Ω/kFT). Knowing the length of the circuit allows the resistance of the conductors to be calculated. Using the resistance of the circuit conductors, and the current required by the load to be served, the voltage lost in the conductors can be calculated using Ohms law.

In this lab, you will be working with a circuit setup which will represent a long circuit run to power parking lot lighting. The anticipated voltage drop will be calculated using formulas and NEC® tables. The effect of voltage drop can be seen in incandescent lamps by a reduction in the intensity of the light produced by the lamps. You will connect lights to two circuits – one using short lengths of conductors and one using approximately 1000 feet of wire. You should be able to see the effects of voltage drop by observing the relative intensity of the light produced in the two circuits. The lower the voltage applied to the lamps the less light produced.

Discussion – Formulas

Ohms Law, E = I x R, is used to calculate voltage drop in conductors. A circuit serving a single load can be diagramed as shown below:

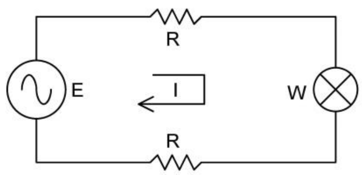

Figure 1: Full Circuit Diagram

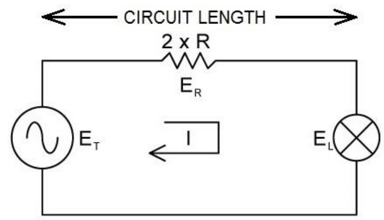

Figure 2: Simplified Diagram

In Figure 1, the resistance of the supply wire and return wire is shown separately. E is the supply voltage and W is the power requirement (in watts) of the load supplied by the circuit. Since the length of the supply wire and return wire is the same, the resistances of the two wires is the same. These two resistances can be combined in the circuit and simplified as shown in Figure 2.

In the Figure 2 circuit, the voltage drop for both supply and return conductors is combined in a single resistor shown (2 x R) and is represented by E_R. The voltage supplied to the load (E_L) is the supply voltage (E_S) less the conductor voltage drop (E_R). The NEC® formula for voltage drop uses this simplified circuit approach and can be written as:

E_{drop}= I x 2 x R

Note: The resistance (R) in the NEC® formula is NOT the total conductor resistance (out to the load and back), but the one way wire length resistance. The NEC® refers to this one way length as the "circuit length" – the simple length from the panel out to the load. The multiplier of 2 accounts for the resistance of the return conductor length.

Procedure #1 – Calculations

The diagram below represents a circuit supplying 2 parking lot lighting poles, each pole having two (2) 150 watt lights.

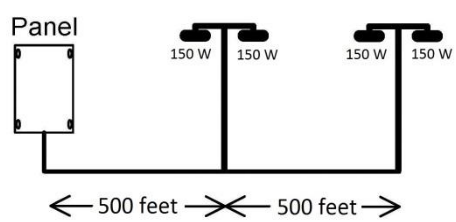

Figure 3: Parking Lot Lighting Circuit

We'll assume a 500 ft circuit length from the panel to the first 2 fixtures and a 500 ft circuit length between the first fixture pair and the second fixture pair.

- Draw a complete circuit diagram below to represent this arrangement showing the voltage source, the wire resistances, and the loads. This diagram should indicate how you will connect the actual circuit components.

The students should draw a diagram showing the connections for this arrangement similar to Figure 1 above and Figures 5 & 6 later in the lab.

This circuit can be simplified as shown below in a single line format to use the NEC® voltage drop formula. Since the pairs of fixtures are connected at the same points in the circuit, they are combined into a single 300 watt load to simplify the calculations.

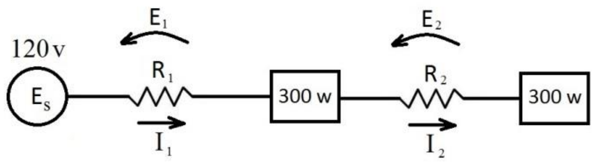

Figure 4: Simplified Parking Lot Lighting Circuit

In this circuit, R_1 and R_2 represent the one-way (circuit length) resistance of the wire. E_1 and E_2 represent the voltage drop for that circuit segment, and I_1 and I_2 represent the current passing thru that circuit segment.

Refer to Figure 7 after the end of the lab text for photos of the equipment used in the lab.

<u>Results: Show all work/calculations for credit</u>

- What is the current in the first circuit segment (I_1)?

Using the power formula: Power(watts) = volts x current (amps) i.e. P=ExI
Solving for current: I=P/E. The voltage E = 120v.
The power (and current) in the first segment supplies the total of all lamps. P = 4 x 150w= 600w
I_1 = 600w/120v = 5 amps

- What is the current in the second circuit segment (I_2)

The power (and current) in the second segment is only that supplying the last 2 lamps. P =2 x 150= 300w
I_2 = 300w/120v = 2.5 amps

- Assuming 500 foot circuit lengths, #14 stranded copper wire, what is the resistance of the two segments (R_1 and R_2)?

From the NEC® table, #14 stranded copper wire has a resistance of 3.14 ohms / 1000 ft.
Since each segment is the same length, each has the same resistance R = 3.14 x 500/1000 = 1.57 ohms.

- Using the NEC® voltage drop formula, what is the voltage drop in the first segment (E_1)?

The NEC® formula is E_{drop}= 2 x R x I_1. For segment 1: E_1 = 2 x 1.57 x 5 = 15.7 volts.

- What is the voltage drop in the second segment (E_2)?

For segment 2: E_2 = 2 x R x I_2 = 2 x 1.57 x 2.5 = 7.85 volts.

- What voltage will be present at the first fixture pair?

Voltage at the first fixture pair is the supply voltage less the voltage lost in segment 1
E = 120 – 15.7 = 104.3 volts.

- What voltage will be present at the second fixture pair?

Voltage at the second fixture pair is the supply voltage minus the voltage lost in segment #1 minus the voltage lost in segment #2. E = 120 – 15.7 – 7.85 = 96.45 volts.

- Using a maximum 3% allowable voltage drop, what is the minimum voltage that should be present at the fixtures (assuming a 120 volt source)?

3% of 120 v = 3.6 v maximum drop, therefore the minimum voltage would be 120 – 3.6 = 116.4 volts.

Conclusions

These diagrams and calculations show that circuits serving multiple loads will usually have different currents flowing through different parts of the complete circuit. Voltage drop at each point in the circuit were a load is connected must be calculated separately. The further away from the panel, the higher the voltage drop – losses are cumulative and add up as more wire is added between a load and the panel. The calculations reveal that the voltage drop at the last fixtures in the circuit is twice the drop at the first 2 fixture and the voltage at either set of fixtures would not comply with NEC® requirements.

Procedure #2 – Solution

In order to reduce the voltage drop to an allowable level, the wire size may be increased to reduce resistance of the wire, thus reducing the voltage lost in the conductors.

For this part of the problem, increase the wire size using the same size wire for the entire circuit. Different wire sizes could be used for the first and second segments of the circuit but that would only complicate the calculations and wouldn't result in significant cost savings.

Results

- Referring to Figure 4 above, write a complete formula for the voltage drop at the load farthest from the panel. Assume all wiring has the same unit resistance R_U (Ω/kFT from the table) but do not assume the circuit lengths are the same (i.e. include the circuit lengths in the equation as CL_1 and CL_2) . $R_1=R_U \times CL_1 / 1000$ and $R_2=R_U \times CL_2 / 1000$. For this problem, since Circuit Length #1 = Circuit Length #2, R_1 will equal R_2, but that won't be the case for most problems so keep them separate in the formula.

Hint: The voltage drop at the furthest point (E_{DROP2}) will be the voltage drop in the first segment plus the voltage drop in the second segment ($E_{DROP2} = E_1 + E_2$). Use the voltage drop formula to replace E_1 and E_2 with resistance and current values for those segments ($E_1 = 2 \times I \times R_U \times CL_1/1000$ ft, and similar for E_2).

$$E_{DROP2} = E_1 + E_2 = (2 \times I_1 \times R_U \times CL_1/1000) + (2 \times I_2 \times R_U \times CL_2/1000)$$

- Re-arrange the above equation to solve for the wire unit resistance R_U. Plug in the amperage and use the maximum voltage drop you calculated previously and solve the equation obtaining an answer for the unit resistance. This will be the **Maximum** resistance the wire can have and not exceed the maximum voltage drop at the furthest point in the circuit – a higher resistance would result in a higher voltage drop.

Putting in known values $E_{DROP2} = 7.5\ R_U$
Solving for the unit Resistance of the wire: $R_U = E_{DROP2} / 7.5$
Putting in the maximum desired voltage drop of 3.5 volts: $R_U = 3.5 / 7.5 = 0.467$ *ohms per 1000 ft.*

- Using the NEC® resistance table, what size wire would be required to reduce the voltage drop at the furthest fixtures below the maximum allowed 3% drop?

From the NEC® table, #4 wire is the smallest wire that has less than 0.467 Ω/kFT resistance. Actual resistance for #4 is 0.308 Ω/kFT.

- Using the resistance value for the wire selected above, calculate the voltage drop at the furthest set of fixtures (located at the end of circuit segment #2).

Using formulas above, $E_{DROP2} = E_1 + E_2 = (2 \times I_1 \times R_U \times CL_1/1000) + (2 \times I2 \times R_U \times CL_2/1000) = (2 \times 5 \times 0.308 \times 0.5) + (2 \times 2.5 \times 0.308 \times 0.5) = 2.31$ *volts.*

- Is this value less than the maximum allowable voltage drop?

Yes, the maximum allowable (3%) drop is 3.6 volts.

Conclusions

Increasing the wire size results in lowering the voltage drop. The voltage drop at the furthest point is a worst case – if the wire is sized to lower the voltage drop at the furthest point to within limits then the voltage at fixtures that are on the same circuit closer to the panel will be acceptable.

Procedure #3 - Mock-up and Testing

- Using the provided materials, construct two (2) separate lighting circuits. One circuit will have short wire lengths where voltage drop should be negligible and the second circuit will have 500 ft wire lengths for segments #1 and #2.

The circuit with short wiring should be constructed as in Figure 5 below:

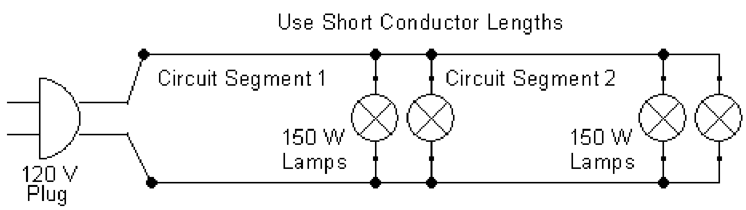

Figure 5: Circuit diagram for Mock-up with Short Circuit Lengths

NOTE: Use wire nuts to connect/splice wires in the octagon boxes. Use crimp-on wire terminals (spade connectors) to connect stranded wire to the lamp holders.

- Construct a second circuit making circuit segments 1 & 2 long by using 500 ft rolls of wire as shown below:

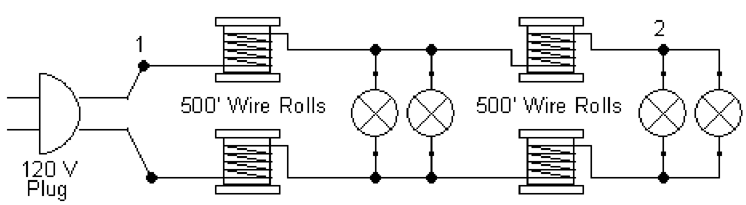

Figure 6: Circuit diagram for Mock-up with Long Circuit Lengths

Wire can be purchased as 500 foot rolls. Make sure both ends of the wire are accessible on the roll for connection to prevent having to unroll and re-roll the wire. This makes implementing a 1000 foot circuit in the lab easy!

Results:

- Before plugging the circuits in, measure the total resistance of the wire in between points 1 and 2 in Figure 6. You're measuring the resistance of approximately 1000 feet of wire. What is the resistance in ohms?

Students use a multi-meter set to measure resistance. The resistance can be measured by connecting the meter leads to one plug prong and the receptacle at the furthest lamp base. Do this with bulbs removed to make sure the correct plug prong and receptacle slot are used. With the bulbs removed, resistance will only be measured when the leads are attached correctly.

- From the NEC® tables, what is the resistance for 1000 ft of #14 stranded copper wire?

As found previously this value is 3.14 Ω/kFT. This should match what was found with the meter.

- **AFTER THE LAB INSTRUCTOR HAS INSPECTED THE CIRCUITS -** Plug both circuits into the 120 volt GFCI protected supply outlet. Switch the outlet on and observe the brightness of the incandescent lamps. Was there a noticeable difference in brightness?

All lamps in the mock-up with short conductors should be of equal brightness. In the mock-up with the long circuit conductors, all lamps should be dimmer than the mock-up with short conductors, and the lamps at the end of segment#2 should be noticeably dimmer than those at the end of segment #1.

- The lamp holders have a 120 volt outlet at the base of the bulb. Measure the voltage at the last fixture (furthest from the plug). What is the measured voltage?

With the multi-meter set to measure voltage, the voltage should agree with previous calculations.

- How does the measured voltage at the last fixture compare with the calculated voltage?

Procedure #4 – Alternatives

The allowable voltage drop is a percentage of the supply voltage. The voltage developed in the conductors is due to the current flowing thru the conductors. The higher the current the more voltage is developed across the conductors.

- Turn off the circuit and give the lamps a chance to cool. Unscrew all lamps from their holders so no current is required to flow to any loads. Turn on the circuit and measure the source voltage and the voltage at the last lamp holder (using the receptacle on the last lamp holder). Is there any voltage drop in the conductors when there is no load applied?

With no current flow there is no voltage drop in the conductors.

Look back at the equations and calculations under Procedure #1. Assume you could change the Lamps to operate at 480 volts and connect the circuit to a 480 V supply. Recalculate using the higher voltage.

- What is the current in the first circuit segment (I_1)?

Calculations are not shown for this section of the lab to reduce overall article size. They parallel previous calculations and result in a voltage drop that falls within the maximum 3%.

- What is the current in the second circuit segment (I_2) ?

Assuming the same 500 foot circuit lengths, #14 stranded copper wire, the resistance of the two segments (R_1 and R_2) would not change.

- Using the NEC® voltage drop formula, what is the voltage drop in the first segment (E_1)?

- What is the voltage drop in the second segment (E_2)?

- What voltage will be present at the second fixture pair?

- Using the maximum 3% allowable voltage drop, what is the minimum voltage that should be present at the fixtures (assuming a 480 volt source)?

Note the differences in increasing the voltage: the current was reduced, thus reducing the voltage drop. With the higher source voltage the allowable drop (3% of a larger number) is also increased.

Conclusions:

From these last calculations, it should be apparent that increasing the voltage of the supply (and loads), the effects of voltage drop can be reduced. While the resistance of the wire does not change, the current required to supply a given load is reduced when the voltage is increased (Power=Volts x Amps). The reduced current required by the load at higher voltages reduces the voltage developed across the conductor resistance (E = I x R).

Either one or both of these techniques may be applied to circuits where long conductor lengths create a voltage drop problem. It is not uncommon to see large wires connected to relatively small circuit breakers supplying site lighting. The wire size may exceed the necessary ampacity required for the circuit to reduce the wire resistance, resulting in lower voltage drop for the circuit. Typically, higher voltages are used in buildings for large equipment to reduce the current requirement and thus reduce wire and circuit breaker size. It is not uncommon to find site lighting fixtures that operate at 480 volts to reduce voltage drop effects!

Using Ohm's law (E=I x R) and he power formula (P = E x I), power can also be expressed as $P = I^2 \times R$. For a given load, increasing the voltage in a circuit, reduces the current required to supply the same wattage. This results in less power loss in the conductors (sometimes called I^2R losses).

End of Lab Text

Equipment

Due to the limited length of this paper, additional details of the equipment used will be provided as part of the paper presentation. The author may also be contacted for additional details.

Figure 7 below shows a photo of the assembled components for a circuit with short conductor lengths and long conductors (the two 500 foot rolls make a 1000 foot long circuit). Using lights as the load allows the students to see the effects of voltage drop. Less voltage means the lights are not a bright. Try and use lamps with as high of a wattage as possible. While this type of lighting does not generally consume much power, the more current in the circuit, the higher the voltage drop and the more evident the effect of voltage drop. . A cord/plug is connected to apply power from a ground fault (GFI) switch/receptacle setup shown on the right (GFI and switch not part of this lab).

Lamp bases can be purchased that have a built in receptacle outlet. While these photos do not show this type of base, the outlet allows easy and safe measurement of voltage using probes and a digital multi-meter.

Figure 7: Photo of Completed Circuits Simulating Parking Lot Lighting Installations

A cord/plug is connected to the circuits so power can be obtained from a ground fault (GFI) switch/receptacle setup shown in Figure 8 below. The switch and GFI receptacle setup is used for other lab activities and is not part of this lab assignment.

Figure 8: Ground Fault Protected Arrange to Apply Power to Lighting Circuits.

References

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