# Voltage Drop

The technical information provided herein is to assist qualified persons in planning and installing electric service to farms and residences. **Qualified person** is defined in Article 100 of the National Electrical Code (2008 edition) *as one who has the skills and knowledge related to the construction and operation of the electrical equipment and installations and has received safety training to recognize and avoid the hazards involved.* Qualified persons are encouraged to review the National Fire Protection Association (NFPA) 70-2004, Standards for Electrical Safety in the Workplace, for electrical safety training requirements. **A person who is are not qualified should not attempt the planning and installation of electric service.**



Note: Any reference to "Code" or "Code Handbook" in the following information refers to the 2008 National Electrical Code and the NEC 2008 Handbook respectively.

Everyone knows that the consumer is required to pay for the electricity supplied by the electric cooperative that is measured at the kilowatt-hour meter. But part of that electricity between the meter and the end location where it is to be used will get "lost" due to a condition called **voltage drop.**

Voltage drop can be thought of as wasted electricity. It is simply the difference between the voltage measurement at the source and the voltage measurement at the point of use. Besides paying for electricity you don't receive, voltage drop can cause other problems as well.

Due to voltage drop caused by improperly sized circuit conductors, the operating voltage at electrical equipment will be less than the output voltage of the power supply. This will result in inductive loads (i.e. motors, ballasts, etc.) operating at voltages below its rating- which in turn can cause them to overheat — resulting in shorter equipment operating life and increased cost, as well as inconvenience for the consumer. Under-voltage for sensitive electronic equipment such as computers, laser printers, copy machines, etc., can cause the equipment to lock up or suddenly power down resulting in data loss, increased cost and possible equipment failure. Resistive loads (heaters, incandescent lighting) that operate at under-voltages simply will not provide the expected rated power output.

In the fine print notes of Section 210.19(A)(1) and 215.2(A)(3) of the Code, it recommends that the maximum combined voltage drop for both the feeder and branch circuit should not exceed 5 percent. If this practice is followed, the Code says that reasonable efficiency of operation will occur. Knowing this, what's the minimum Code recommended operating voltage for a load connected to a 120V source? **Answer:** Since the maximum conductor voltage drop recommended for both the feeder and branch circuit is five percent of the voltage source, the total conductor voltage drop should not exceed (120V x 5%) or no more than 6V less than the source. So, the operating voltage should be no less than (120V – 6V) or 114V.

## Reducing Voltage Drop

It's not possible to have zero voltage drop — because some voltage loss is going to occur naturally from the resistance of the conductors themselves — simply because it takes effort (voltage) to push current through a conductor. However, the goal is to minimize the voltage drop as much as possible.

Besides wasting electricity that you are paying for, there are other reasons to keep voltage drop to a minimum when performing electrical wiring. These reasons include:

- **System efficiency.** If a circuit has much of a load, a larger conductor (that allows less voltage drop) pays for itself many times over in energy savings alone.
- **System performance.** As stated before, excessive voltage drop in a circuit can cause lights to flicker and/or burn dimly; heaters to heat poorly; and can cause overheating, inefficiency, and shorter life span of motors.
- **Troubleshooting.** When one follows the Code voltage drop recommendations, the electrician doing troubleshooting does not have to guess whether his low voltage field measurements indicate (1) a problem or (2) that voltage drop was not accounted for in the design.

## Causes of voltage drop

There are various causes of voltage drop. One of the main causes is the conductor itself that is being used. The following four factors determine the resistance found in a conductor:

- **Type of Material from which the conductor is made –** Copper conducts electricity better than aluminum and will cause less voltage drop than aluminum for a given length and conductor size.
- **Diameter of the Conductor (size or gauge of the conductors) –** Conductors with larger diameters will result in less voltage drop than conductors with smaller diameters of the same length.
- **Conductor Length –** Shorter conductors will have less voltage drop than longer conductors for the same conductor size.
- **Temperature of the Conductor –** As a general rule, most conductive materials will increase their resistance with an increase of temperature.

If you consider two more factors……..

- **Current being carried by the conductor (Ampere Load) –** Voltage drop increases on a conductor with an increase in the current flowing through the conductor.
- **Connections in the circuit –** Poor connections in splices or when connecting conductors to terminals contribute to voltage drop.

……….you now have all the primary conditions that cause voltage drop on a circuit.

## Calculating Voltage Drop

Since we know that it is necessary to keep voltage drop to a minimum, sometimes one may find it necessary to compute the voltage drop of an installation when the length, size of wire, and current of the load are known. The following formulas can be used to find the voltage drop of an application using either copper or aluminum conductors.

**For single-phase applications…………..Voltage Drop** $= \dfrac{2 \times K\ I\ L}{\text{cmil}}$

**For three-phase applications…………...Voltage Drop** $= \dfrac{1.732\ K\ I\ L}{\text{cmil}}$

Where

K = ohms-cmil per ft
I = current (or amperes) of load
L = length of conductor in ft. (one-way)
cmil = circular mil area of the conductor

## What is "K" in the formulas?

K is the "electrical resistivity" of the type of conductor being used. The K value is a constant and can be found in most physics tables that provide resistivity of various materials. This electrical resistivity is calculated by *(electrical resistance x cross-sectional area/ longitudinal length)* and is expressed as (ohms x cmil/ft) or simply (ohms-cmil/ft.)

**Copper has a K value of 12.9 ohms-cmil/ft and aluminum has a K value of 21.2 ohms-cmil/ft.** Other reference materials may show slightly different values, but for the purposes of this discussion, these values are acceptable. These two values are derived from the data found in Chapter 9, Table 8 of the Code. The K factor is found by multiplying the conductor's resistance (ohm/kFT) by the conductor's circular mil area and then dividing by 1000.

## What is "cmil" in the formulas?

The **circular mil** or cmil is a unit of area that's used when denoting the cross sectional size of something circular in shape — such as a wire.

Wire size can be measured in several ways such as its diameter. We could say this wire has a diameter of ½ inch. Calculating the area of the cross-section with the common formula of Area = $\pi r^2$ or Area = $[(\pi)(d/2)^2]$ — would give us $[(3.14) \times (0.50 \text{ inches}/2)^2]$ for an answer of 0.1963 square inches. As you can see, that is an extremely small number to work with and would be hard to express the wire size to others using this method.

Since it's the *cross-sectional area* that matters most when regarding current flow, we are better off designating wire size in terms of its cross-sectional area. So, another expression of wire diameter called *circular mils* is used. The formula for calculating the circular mil area of a circular wire is as follows:

$$\textbf{cmil} = \textbf{(wire diameter in decimal inches x 1000)}^2$$

So, to find the circular mil of any conductor is to take its diameter (expressed in thousands of an inch), then multiply it times 1000 and then take that answer and square it.

For example, what is the area in circular mils of a ½ inch diameter conductor? To solve, express ½ as .500, then multiply it times 1000, then take that answer and square it. $(.500 \times 1000)^2$ = **250,000 circular mils** — which is commonly written as 250 MCM — where the first M stands for 1000 and the CM stands for circular mils.

The circular mils of various conductors can be found in most electrical wiring reference materials and are listed in the table below — which was taken from Chapter 9, Table 8 of the Code.

| AWG or kcmil | Circular Mils |
|---|---|
| 14 | 4110 |
| 12 | 6530 |
| 10 | 10380 |
| 8 | 16510 |
| 6 | 26240 |
| 4 | 41740 |
| 3 | 52660 |
| 2 | 66360 |
| 1 | 83690 |
| 1/0 | 105600 |
| 2/0 | 133100 |
| 3/0 | 167800 |
| 4/0 | 211600 |
| 250 | 250,000 |
| 300 | 300,000 |
| 350 | 350,000 |
| 400 | 400,000 |
| 500 | 500,000 |

## Algebraic variations of the Voltage Drop formulas

Using basic algebra, you can use the two voltage drop formulas mentioned above to find one of the other variables if you already know the voltage drop. The tables at the end of this discussion have already done that for you and below are some examples using those formulas. The table also shows another method of calculating — called the "resistance per 1,000 ft" method — which we won't get into in this discussion.

Example 1 — A single-phase motor is located 250 feet from its power source and is supplied with 10 AWG copper. The motor has a full load current draw of 24 amps. What is the voltage drop when the motor is in operation? *(Please note that for motors or continuous loads, the total current of the load in question is at 100%, not at 125%).*
**Answer:** Applying the single-phase formula for voltage drop, where: K = 12.9 ohms-cmil/ft for copper; I = 24 amps; D = 250 ft; cmil for 10 AWG = 10,380 cmil. So, VD = 2 x 12.9 x 24 x 250/10,380 = **14.9 Voltage Drop**

Example 2 — A three-phase, 100 ampere load rated 208V is wired to the panelboard with 80 ft lengths of #1 AWG THHN aluminum. What is the approximate voltage drop of the feeder circuit conductors?
**Answer:** Applying the three-phase formula for voltage drop, where: K = 21.2 ohms-cmil/ft for aluminum; I = 100 amps; D = 80 ft; cmil = 83,690 cmil. So, VD = 1.732 x 21.2 x 100 x 80/83,690 = **3.51 Voltage Drop**

Example 3 — Find the size of copper wire needed in a single-phase application to carry a load of 40 amperes at 240 volts a distance of 500 feet with a 2% voltage drop.

**Answer:** First, calculate the total voltage drop allowed in the circuit. This is done by (240 volts x 2%) or 4.8 Voltage Drop. Then use the single-phase formula for circular mils where: K = 12.9 ohms-cmil/ft for copper; I = 40 amps; L = 500 ft.; and voltage drop = 4.8 volts. So, cmil = 2 x 12.9 x 40 x 500/4.8 = 107,500 cmils. Referring to above chart, we would have to select **2/0 for the wire size,** since 1/0 AWG wire has less than the cmils needed.

Example 4 — Suppose you have a 3-phase, 18-ampere load rated 480V with 390 ft of conductor. What size aluminum conductor will prevent the voltage drop from exceeding 3%?
**Answer:** First, calculate the total voltage drop allowed in the circuit. This is done by (480 volts x 3%) or 14.4 volts. Then use the three-phase formula for circular mils where K = 21.2 ohms-cmil/ft for aluminum; I = 18 amps; L = 390 ft; and VD= 14.4. So, cmils = 1.732 x 21.2 x 18 x 390/14.4V = 17,900 cmils. Referring to above chart, we would select **6 AWG.**

## Voltage Drop Calculators

The Internet has some online calculators that will calculate the voltage drop and its percentage. There are calculators at this location http://www.electrician2.com/calculators/vd_calculator.html that will provide this information if one enters in the:

- type of material used (copper or aluminum)
- conductor size
- supply voltage and phase
- length of the run
- load amperage.

These calculators use the same K values of 12.9 and 21.2 for copper and aluminum, respectively, as was used in this discussion.

The above website also has a minimum conductor size voltage drop calculator to help one select the proper wire size.

The following two tables use these designations.

VD = Voltage drop (volts)
L = Length (feet) of conductor from source to load
I = Connected load current (Amperes)
cmil = conductor cross-sectional area in circular mils
R = Resistance of conductor per 1000 feet expressed in Ohms per 1000 feet.
K = Constant (12.9 for copper; 21.2 for Aluminum)
VD max = Line voltage x 0.03 (3% of line voltage)

Note: Reference Chapter 9 Table 8 of the Code for CM and R.

| Formulas for Single Phase | | |
|---|---|---|
| | Circular Mil method | Resistance per 1000 ft. method |
| To calculate Voltage Drop | $VD = \frac{2 \times K \times I \times L}{cmil}$ | $VD = \frac{2 \times L \times R \times I}{1000}$ |
| To determine conductor size | $cmil = \frac{2 \times K \times I \times L}{VD}$ | $R = \frac{VD \times 1000}{2 \times L \times I}$ |
| To calculate length of conductor | $L = \frac{cmil \times VD}{2 \times K \times I}$ | $L = \frac{VD \times 1000}{2 \times R \times I}$ |
| To calculate current | $I = \frac{cmil \times VD}{2 \times K \times L}$ | $I = \frac{VD \times 1000}{2 \times R \times L}$ |

| Formulas for Three Phase | | |
|---|---|---|
| | Circular Mil method | Resistance per 1000 ft. method |
| To calculate voltage drop | $VD = \frac{1.732 \times K \times I \times L}{cmil}$ | $VD = \frac{1.732 \times L \times R \times I}{1000}$ |
| To determine conductor size | $cmil = \frac{1.732 \times K \times I \times L}{VD}$ | $R = \frac{VD \times 1000}{1.732 \times L \times I}$ |
| To calculate length of conductor | $L = \frac{cmil \times VD}{1.732 \times K \times I}$ | $L = \frac{VD \times 1000}{1.732 \times R \times I}$ |
| To calculate current | $I = \frac{cmil \times VD}{1.732 \times K \times L}$ | $I = \frac{VD \times 1000}{1.732 \times R \times L}$ |