Electrical Tech Note — 227

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Sizing Conductors to Minimize Voltage Drop

Every conductor has a finite resistance except in the case of superconductivity. When current flows on the conductors, Ohm's law governs the situation and a voltage difference will occur from one end of the conductor to the other. In the case of a single-phase circuit where the two conductors supplying a load are of the same material, size, and length, the resistance of the conductor times the current flow will give a voltage. This is the amount of voltage used up to push the current through the conductor. *Equation 227.1* can be used to determine the voltage drop due to current flowing on the circuit conductors to a load. The number 2 in *Equation 227.1* accounts for both conductors. In the case of a three-phase circuit, there will be three conductors and the current sine wave in each phase is shifted by 120° from the current in the adjacent conductors. As a result, in a three-phase circuit the multiplier used in *Equation 227.2* is 1.73. Resistance in *Equation 227.1* and *Equation 227.2* is the one-way length from the source to the load.

E_{Drop} in a single-phase circuit:

$$E_{Drop} = 2 \times I \times R \qquad \textbf{Eq. 227.1}$$

E_{Drop} in a three-phase circuit:

$$E_{Drop} = 1.73 \times I \times R \qquad \textbf{Eq. 227.2}$$

The problem that voltage drop on the conductors creates is that voltage needed to operate the load is used up getting the current to the load. Excessive voltage drop is a waste of energy as well as it may result in too low a voltage to operate equipment properly. Premature burn out of equipment such as motors is a common result of excessive voltage drop. The voltage drop may be the result of too small a conductor for the load and length of run. Excessive voltage drop may also be the result of a high resistance connection in the circuit. Improper joining of copper and aluminum conductors as well as wet aluminum connections can lead to corrosion that results in high resistance in the circuit.

Percent Voltage Drop: For general circuit wiring the *National Electrical Code* does not specify a minimum voltage drop. *The Code does recommend the maximum voltage drop from the source of power to the farthest load to not exceed **5%.*** It further suggests that it is recommended practice to allow about 2% voltage drop on feeders, and 3% voltage drop on branch circuits. There are many factors that must be considered when dealing with voltage drop, and the percentage to be allowed on different parts of a circuit are left to the person making the installation. If the amount of voltage equivalent to a particular percentage is required, simply multiply the supply voltage by the percentage converted to a decimal as shown in *Equation 227.3.* The voltage at the equipment terminals is determined by subtracting the voltage drop from the supply voltage as shown in *Equation 227.4.* If voltage at the equipment terminals is lower than expected based upon the calculated conductor voltage drop, then the obvious conclusion there is another unknown resistance at some point in the circuit.

$$E_{DROP} = \% \times E_{SUPPLY} \qquad \textbf{Eq. 227.3}$$

Where % is a decimal

$$\text{Voltage at equipment} = E_{SUPPLY} - E_{DROP} \qquad \textbf{Eq. 227.4}$$

It may be desirable in some cases to determine the percentage voltage drop on an existing circuit where voltage drop is expected to be excessive. Percent voltage drop is calculated based upon the voltage at the supply end and the load end of the conductors when the load is operating. Turn on the circuit and with the load operating measure the voltage between wires at the source of the circuit (E_{SUPPLY}) and at the load (E_{LOAD}). Subtract the load end voltage from the supply end voltage to determine the voltage drop as shown in *Equation 227.5.* Divide the voltage drop by the supply voltage and multiply by 100 as shown by *Equation 227.6* to determine percent voltage drop for the circuit. *Equation 227.7* has the previous two equations combined. This equation can be used to determine the voltage drop of a circuit.

$$E_{DROP} = E_{SUPPLY} - E_{LOAD} \qquad \textbf{Eq. 227.5}$$

$$\% \text{ Drop} = \frac{E_{DROP}}{E_{SUPPLY}} \times 100 \qquad \textbf{Eq. 227.6}$$

$$\% \text{ Drop} = \frac{E_{SUPPLY} - E_{AT\ LOAD}}{E_{SUPPLY}} \times 100 \qquad \textbf{Eq. 227.7}$$

Resistance of Conductors The resistance of conductors depends upon the type of material (usually copper or aluminum), the length and cross-sectional area of the conductor, and the typical operating temperature of the conductor. One way to find the conductor resistance is to look up the value from a reference table such as ***Table 8*** of the *National Electrical Code*. Typical values are given as ohms per 1000 ft or ohms per kilometer. *Table 227.1* gives values of resistance for common sizes of copper and aluminum electrical wire. The resistance of the conductors for a given circuit length can be determined using *Equation 227.8.* The following example shows how to determine resistance of the wire of a circuit.

$$\text{Resistance of Wire} = \frac{\text{Circuit Length (ft)}}{\text{1000 ft}} \times \text{Resistance per 1000 ft} \qquad \textbf{Eq. 227.8}$$

As an example determine the wire resistance of a circuit where the wire is size 4 AWG aluminum supplying a single-phase 240 volt load located 300 ft from the supply. Assume the conductor will operate at 75°C. *Table 227.1* gives the resistance of common sizes of copper and aluminum electrical wire. Look up the resistance of this wire and find that it is 0.508 ohm per 1000 ft. Next insert this value into *Equation 227.8* to determine the resistance of a 300 ft length of size 4 AWG aluminum electrical wire.

$$R = \frac{\text{300 ft}}{\text{1000 ft}} \times 0.508\ \Omega = 0.1524\ \Omega$$

Another way to determine the resistance of a wire is to calculate the wire resistance using *Equation 227.9* provided the unit resistivity (K) of the wire is known. Before continuing it is necessary to understand some unique dimensions used for electrical wire in the United States. The diameter of electrical wire is given in inches and converted to mils by multiplying the diameter in inches by 1000. Area of electrical wire is given in units called circular mils (cmil) and thousands of circular mils (kcmil). Area in circular mils is determined by squaring the diameter of the wire in mils. The cross-sectional areas of common sizes of electrical wire is given in *Table 227.1.* Wire resistance also changes significantly with a change of temperature. The values of resistance in *Table 227.1* are for the wire at a temperature of 75°C. Many common circuits operate at a lower temperature such as about 50°C. These values will be about 8% lower than the values given in *Table 227.1.* This means the values of resistance in *Table 227.1* are higher than the actual resistance of the wire. A typical operating temperature for electrical wires is 50°C, and based upon this temperature the values of resistivity of the wire (K) is approximately 12 for copper wire and 19 for aluminum wire. The units are ohm circular mils per foot. *Values of electrical **wire resistivity at other temperatures** is given in Tech Note 212.* Working the previous example of a 300 ft length of size 4 AWG aluminum wire results in a value of resistance of 0.1366 ohm using *Equation 227.9.*

$$\text{Wire Resistance (ohms)} = \frac{\text{Resistivity (K)} \times \text{Wire Length (ft)}}{\text{Wire Cross-sectional Area (cmil)}} \qquad \textbf{Eq. 227.9}$$

K = 12 for copper (at 50°C)
K = 19 for aluminum (at 50°C)

Voltage Drop Formula: It is not necessary to determine voltage drop as a two step process as previously discussed. The *Equation 227.9* for resistance of a wire can be substituted into Ohm's law to give a direct formula for voltage drop expected along a conductor for a given load. This results in *Equation 227.10* for a single-phase load and *Equation 227.11* for a three-phase load.

Single-phase:

$$E_{DROP(1\Phi)} = \frac{2 \times K \times I \times L}{A} \qquad \textbf{Eq. 227.10}$$

(Area of the wire is in circular mils)

Three-Phase:

$$E_{DROP(3\Phi)} = \frac{1.73 \times K \times I \times L}{A} \qquad \textbf{Eq. 227.11}$$

(Area of the wire is in circular mils)

Sizing Wires for Specific % Voltage Drop: It is recommended by the electrical code that from the electrical service to the farthest point of electrical usage the voltage drop not exceed **5%**. An electrical system for a large building or a group of buildings such as a farm will have main feeder conductors from the main service to subpanels or other buildings. Within the buildings there will be branch circuits that serve specific loads. The 5% voltage drop recommendation is divided up between the feeders and the branch circuits. In each case this is a judgement call as to what percentage should be applied to the feeders and what percentage should be applied to the branch circuits. The goal is to estimate the expected load the feeder wires or branch circuit wires will carry and the length of the feeders and branch circuit wires. In order to prevent excessive voltage drop the wire can be increased in size so there will be less resistance and thus less voltage drop. The question is what size of wire is recommended for a specific load and length of wire. *Equation 227.12* for single-phase and *Equation 227.13* for three-phase will provide the recommended cross-sectional area of the wire required to limit the voltage drop to the percentage chosen. The cross-sectional area of the wire from these equations will be in circular mils (cmil). The wire size is then determined by referring to *Table 227.1.*

Single-Phase:

$$A_{(1\Phi)} = \frac{2 \times K \times I \times L}{\% \times E_{SUPPLY}} \qquad \textbf{Eq. 227.12}$$

(% is a decimal and area (A) is in circular mils)

Three-Phase:

$$A_{(3\Phi)} = \frac{1.73 \times K \times I \times L}{\% \times E_{SUPPLY}} \qquad \textbf{Eq. 227.13}$$

(% is a decimal and area (A) is in circular mils)

All feeder wires and branch circuit wires are required to be protected by a set of fuses or a circuit breaker. This limits the current that can be drawn on the wires to a level that will not cause overheating of the wire and possibly a fire. Determination of the wire size for a specific load and choosing the rating of fuse or circuit breaker can be complex and may require the assistance from an engineer or experienced electrician. *Table 227.2* does list the sizes or wires and the maximum allowed current level for the wire. In general the fuse or circuit breaker rating is not permitted to exceed the allowed current level for the wire as given in *Table 227.2.* Some *standard* ratings of fuses and circuit breakers are 15, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 125, 150, 175, 200, 250, 300, 350, and 400 amperes. Fuses and circuit breakers with higher ratings are available. *Table 227.2* gives the maximum safe level of continuous current that can be carried by a wire for the conditions listed. Another important point is that fuses and circuit breakers should not be loaded to more than 80% of their rating. This means that if the expected load on a feeder to a building is 80 amperes the circuit breaker should be rated at least 100 amperes, and the wire must have an allowed current level of 100 amperes. The wire is sized to the rating of the circuit breaker not to the load. Assume a set of copper wires is run underground to the building, and the wires are protected at the source with a 100 ampere circuit breaker. The minimum size copper wire from *Table 227.2* would be 3 AWG. If the length of the feeder is more than 100 ft it is a good idea to check to see if the wire size needs to be increased to allow for voltage drop. This is done by either using *Equation 227.12* for a single-phase circuit, or *Equation 227.13* for a three-phase circuit.

Assume the load on the previously described feeder is 80 amperes and the length of the underground feeder is 300 ft. In this case lets allow for a 2% voltage drop for a 240 volt single-phase feeder to the building. The resistivity (K) for copper wire is 12 and using *Equation 227.12* the minimum recommended wire cross-sectional area to limit the voltage drop to not over 2% is 120,000 cmil. From *Table 227.1* the minimum size wire that has a cross-sectional area of at least 120,000 cmil is size 2/0 AWG with a cross-sectional area of 133,100 cmil. For this example the electrical code requires size 3 AWG copper wire for safety, but to limit the voltage drop to 2% when 80 amperes is flowing, the wire size will need to be increased to 2/0 AWG.

$$A = \frac{2 \times 12 \times 80\text{ A} \times 300\text{ ft}}{0.02 \times 240\text{ V}} = 120{,}000\text{ cmil}$$

Table 227.1 Cross-sectional area and resistance of standard sizes of stranded copper and aluminum electrical wire.

Size	Area		dc Resistance at 75°C			
AWG or			**copper**		**aluminum**	
kcmil	mm^2	**cmil**	Ω/km	**Ω/kft**	Ω/km	***Ω/kft***
18	0.82	1,620	26.1	7.95	42.8	13.1
16	1.31	2,580	16.4	4.99	26.9	8.21
14	2.08	4,110	10.3	3.14	16.9	5.17
12	3.31	6,530	6.50	1.98	10.6	3.25
10	5.26	10,380	4.07	1.24	6.67	2.04
8	8.37	16,510	2.55	0.778	4.20	1.28
6	13.3	26,240	1.61	0.491	2.65	0.808
4	21.2	41,740	1.01	0.308	1.67	0.508
3	26.7	52,620	0.802	0.245	1.32	0.403
2	33.6	66,360	0.634	0.194	1.05	0.319
1	42.4	83,690	0.505	0.154	0.829	0.253
1/0	53.5	105,600	0.399	0.122	0.660	0.201
2/0	67.4	133,100	0.317	0.0967	0.523	0.159
3/0	85.0	167,800	0.251	0.0766	0.413	0.126
4/0	107	211,600	0.200	0.0608	0.328	0.100
250	127	250,000	0.169	0.0515	0.278	0.0847
300	152	300,000	0.141	0.0429	0.232	0.0707
350	177	350,000	0.121	0.0367	0.198	0.0605
400	203	400,000	0.105	0.0321	0.174	0.0529
500	253	500,000	0.085	0.0258	0.139	0.0424

Table 227.2 Ampere rating of electrical wire with 75°C insulation and terminations where no

abnormal heating conditions exist that would require adjustment of wire size.

Size AWG or kcmil	Allowable Ampere Rating: Cable, conduit or direct burial (*Table 310.16*) copper	aluminum	Multiplex cable in open air (*Table 310.20*) copper	aluminum	Single conductor on insulators in open air (*Table 310.17*) copper	aluminum
18	7	—	—	—	—	—
16	10	—	—	—	—	—
14	15	—	—	—	—	—
12	20	15	—	—	—	—
10	30	20	—	—	—	—
8	50	40	57	44	70	55
6	65	50	76	59	95	75
4	85	65	101	78	125	100
3	100	75	118	92	145	115
2	115	90	135	106	170	135
1	130	100	158	123	195	155
1/0	150	120	183	143	230	180
2/0	175	135	212	165	265	210
3/0	200	155	245	192	340	240
4/0	230	180	287	224	360	280
250	255	205	320	251	405	315
300	285	230	359	282	455	350
350	310	250	397	312	505	395
400	335	270	430	339	545	425
500	380	310	496	392	620	485

Conclusions: The electrical code requires that all electrical wires be protected with a set of fuses or a circuit breaker with a rating not exceeding the maximum allowed current rating for the wire. This is to prevent overheating of the wire due to excessive current flow. When the wire supplying a load is greater than 100 ft in length it is a good idea to check to see if the voltage drop caused by the load current is too high. *A voltage drop of 5% from the main service to the farthest load is recommended as a maximum.* Excessive voltage drop is a waste of energy as well as a problem that can cause poor performance of lighting and equipment as well as premature failure of equipment such as motors. The expected voltage drop for a given load and length of wire can be calculated and if necessary the size of the wire serving the load can be increased to minimize this voltage drop.

Note: Sizing a wire for a circuit is not always an easy task. *Table 227.2* does not allow for conditions that may require adjustment of wire size to serve a load. Rules for sizing branch circuit and feeder wires can be found in the latest edition of the *National Electrical Code* which can be obtained from the National Fire Protection Association, 1 Batterymarch Park, Quincy, MA. The most recent edition of the National Electrical Code has the date 2023.