Voltage Drop after *NEC* Requirements

John Wiles

Sponsored by the Photovoltaic Systems Assistance Center, Sandia National Laboratories

After the *National Electrical Code (NEC)* requirements for conductor size (based on ampacity) have been met, the performance question (not a code requirement) of voltage drop should be addressed. In this *Code Corner,* I will show how voltage drops are calculated (no fancy tables), and then I'll cover some typical module wiring installations in the next issue of *Home Power.*

Voltage Drop

First of all, it should be made clear that voltage drop is not a code issue per se. It is a performance issue, not a safety issue in most cases. The code addresses voltage drop only in "Fine Print Notes" that are not part of the code, and are to be used only for added information.

I frequently get calls asking why articles published in *Home Power* and elsewhere on conductor voltage drop do not agree. Each of these articles is based on a set of assumptions that may or may not be consistent from article to article. And a few of the articles have had corrections printed in subsequent issues that may have been missed by the reader. I'll be presenting a method for calculating voltage drop that does not use short-cut tables, just plain old math.

Voltage drop is somewhat critical in PV systems operating at low voltages (12 and 24 volt systems). This is because at night under discharge, batteries have a low terminal voltage, and excessive voltage drop in the circuits causes the loads (including inverters) to operate poorly or not at all. In the PV charging circuits, excessive voltage drops cause wasted power and energy, and require longer battery charging times. In utility-interactive systems, voltage drops and the resultant power losses represent expensive energy that doesn't make it to the load or to the grid.

Current through conductors that have resistance to that current results in a voltage drop developing in a length of the conductor. The relationship is:

V = I x R

V (in volts) is the voltage drop in a conductor that has a resistance R (in ohms) and has a current of I amperes (amps). In any circuit, there are two conductors, and there is a voltage drop in each conductor. Since the two conductors are usually equal in length, the distance from source to load (as the conductors are routed) is usually doubled to get a total length that is used for determining the resistance to be used in the calculation.

Conductor resistance decreases as conductor size increases, and resistance increases as conductor temperature increases. Since we are dealing with electrical power circuits, I have selected conductor resistance values from Table 8, Chapter 9 of the 1999 *NEC.*

These DC resistance values, presented below, are for stranded, uncoated copper conductors (no tin or other coatings on the actual copper) at a temperature of 75°C (167°F). This temperature is typical of operating power circuits designed to *NEC* requirements and will not, of

Table 1: Resistance of Copper Wire

Size	*Metric Size (mm^2)*	*Ohms / 1,000 ft.*
14*	2.08	3.1400
12*	3.31	1.9800
10*	5.26	1.2400
8*	8.37	0.7780
6*	13.29	0.4910
4*	21.15	0.3080
3*	26.67	0.2450
2*	33.62	0.1940
1*	42.41	0.1540
1/0*	53.48	0.1220
2/0*	67.43	0.0967
3/0*	85.01	0.0766
4/0*	107.22	0.0608
250**	167.70	0.0515
300**	201.30	0.0429

* AWG
** kcmils

course, match similar conductor resistance values at other temperatures. AC resistance and impedance values may be significantly different, and are beyond the scope of this article. DC values may be used only as a very rough estimate for AC circuits.

To get the resistance R for the voltage drop calculation, double the one-way length of the circuit from source to load. If the circuit (source to load) length of the conductors is 40 feet (for example), the total resistance would be based on a length of 80 feet (2 x 40). If #10 (5 mm^2) conductors were being used with a resistance of 1.24 ohms per 1,000 feet, then the resistance R for the voltage drop calculation would be:

R = 1.24 x 80 ÷ 1,000 = 0.0992 ohms

Now we have to consider what current to use in the equation. As current increases, the voltage drop also increases. In utility-interactive PV source circuits, I tend to use the rated peak-power current of the module (marked on the back of the module) or group of modules connected in parallel.

In a battery-charging system, the peak-power current might also be used, but some consideration should be given to using the short-circuit current from the modules or the PV array. This higher current might be used, since at low battery states of charge, the module currents tend toward this value due to the low battery voltages.

For example, a PV module might have a short-circuit current of 3.5 amps and a peak-power operating current of 3.0 amps. For a system with ten modules or strings of modules connected in parallel, I might use 35 amps as the current in a battery charging system, and 30 amps as the current in a utility-interactive PV system.

In DC load circuits, I use the maximum steady-state currents for the DC loads or the inverter. If there are high motor starting surges on the inverter, they might cause the inverter to shut down as the surge causes the voltage at the inverter input terminals to drop to the low voltage disconnect point. I would at least calculate the voltage drop at these high surge currents.

In a battery-to-inverter circuit, the maximum steady-state DC current into the inverter might be 100 amps (for example) and I would use that current in the calculation. However, if there were well pumps or sewerage lift pumps operating at night that had peak currents of 300 amps, I would see what effect this higher current, and the resulting voltage drop, would have on the inverter operation.

With the resistance established and the current estimated, the voltage drop can be calculated.

For example, an inverter is located 20 feet (circuit length) from the batteries and is connected to a resistive load (no surges) that causes the inverter to draw 100 amps on a 24 volt system. Yes, this is a heavy AC load at about 2,200 watts. The low voltage disconnect is set at 22 volts. #4/0 (107 mm^2) conductors are being considered.

The resistance R is calculated as:

R = 0.0608 x 40 ÷ 1,000 = 0.00243 ohms

The voltage drop is 0.00243 x 100 = 0.243 volts.

The operating voltage of the inverter is 24 - 0.243 = 23.76 volts when the batteries are at the nominal system voltage of 24 volts.

Now let's see what happens when there is a well pump on the inverter output that causes the inverter to require a surge current of 300 amps from the batteries. The conductor resistance will cause the voltage drop to increase to 0.729 volts. This drop alone would cause the inverter terminal voltage to drop to 23.27 volts in a good battery bank.

However, the internal resistance of the batteries and other resistances in the circuit will also cause a voltage drop. The total voltage drop may cause the low voltage disconnect point of 22 volts to be reached, shutting down the inverter.

Finer Points

Ah yes, batteries have an internal resistance that varies all over the place depending on the type of battery and the state of charge. These are very hard numbers to pin down and verify. For golf cart batteries and L-16 style batteries, I use 0.00075 ohms per 6 volt battery. I just add the number of 6 volt batteries in series and use that number times 0.00075 and add this to the conductor resistance. That comes out to 0.0015 for a 12 volt system, 0.003 for a 24 volt system, and 0.006 ohms for a 48 volt system. Remember that these are just ballpark numbers—your mileage will vary.

Contacts in connectors and switchgear also have resistances. I use 0.0002 ohms for each good battery terminal, power block terminal, split-bolt, or twist-on wire connection. I use a resistance of 0.002 ohms for each circuit breaker pole and a resistance of 0.006 for each fused disconnect switch pole (this accounts for the resistance of two terminals, the switch blade, the moving contact, the fuse element, and the two fuse blades).

Again, these are very rough estimates for well-made connections and devices, and the actual numbers will vary widely. High-current devices will usually have lower resistances than low-current devices. The resistances

Table 2: Example Circuit Resistances

Type of Resistance	Ohms*
Battery internal resistance	0.0030
Battery contacts (8)	0.0016
Inverter contacts (2)	0.0004
Circuit breaker	0.0020
Conductors	0.0024
Total	0.0094

* Very rough estimates.

for each circuit are composed of the conductor resistance plus the battery internal resistances, plus all contact and switchgear resistances.

In the preceding inverter example, let us assume that the #4/0 (107 mm^2) cables are routed through a single 250 amp circuit breaker. The circuit resistances are now as shown in Table 2.

At 100 amps, the voltage drop is 0.94 volts. During a 300 amp surge, the voltage drop is 2.82 volts, which might just cause problems. Some of this voltage drop, but not all of it, can be reduced by using larger conductors. This is one of the reasons that getting good, tight, quality connections is necessary in a PV system. Every milliohm counts.

Percentage voltage drop may be expressed as the voltage drop divided by the nominal system voltage and then multiplied by 100. In this example, the voltage drop is 0.94 ÷ 24 x 100 = 3.9 percent for the 100 amp load, and three times that for the 300 amp surge.

I try to keep the voltage drop below 2 percent for 12 and 24 volt systems and below 3 percent for 48 volt systems. Higher voltage systems can sometimes carry higher voltage drops. But the operating points and losses of power should be compared with the costs of increasing the conductor sizes to reduce those losses.

In many cases, the resistance of switchgear, poor connections, and aging batteries may cause far more voltage drop than the conductors alone do. Increasing conductors above the code ampacity requirements won't help much, but may be necessary.

In many cases, long distances between the PV array and the batteries might indicate that the conductors may require oversizing to lower the voltage drop. If the circuit conductors are increased above minimum ampacity requirements, the equipment-grounding conductor for these circuits may also have to be increased. See previous *Code Corners* and *NEC* Section 250-122 for details.

Summary

After the code-required ampacity calculations are made to determine the size of the conductors, additional calculations should be made for the voltage drops in the system. If these voltage drops are excessive, increasing the conductor size may help to reduce them.

If you have questions about the *NEC* or the implementation of PV systems following the requirements of the *NEC,* feel free to call, fax, email, or write me. Sandia National Laboratories sponsors my activities in this area as a support function to the PV Industry. This work was supported by the United States Department of Energy under Contract DE-FC04-00AL66794. Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy.

Access

John C. Wiles • Southwest Technology Development Institute, New Mexico State University, Box 30,001/ MSC 3 SOLAR, Las Cruces, NM 88003 • 505-646-6105
Fax: 505-646-3841 • jwiles@nmsu.edu
www.nmsu.edu/~tdi

Sponsor: Sandia National Laboratories, Ward Bower, Department 6218, PO Box 5800 MS 0753, Albuquerque, NM 87185 • 505-844-5206
Fax: 505-844-6541 • wibower@sandia.gov
www.sandia.gov/pv

National Electrical Code® and *NEC*® are registered trademarks of the National Fire Protection Association. The 1999 *NEC* and the *NEC Handbook* are available from the NFPA, 11 Tracy Dr., Avon, MA 02322
800-344-3555 or 508-895-8300 • Fax: 800-593-6372 or 508-895-8301 • custserv@nfpa.org • www.nfpa.org

National Renewable Energy Laboratory solar radiation and weather database: http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/sum^2