Wire Sizing and Voltage Drop in Low Voltage Power Systems

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Properly sized wire can make the difference between inadequate and full charging of your energy system, between dim and bright lights, and between feeble and full blast performance of your tools and appliances. Even wiring that is slightly undersized can cheat you out of a major portion of your system's energy.

Designers of low voltage systems are often confused by the implications of voltage drop and wire size. In conventional home electrical systems (120/240 volts ac), wire is sized according to its safe amperage carrying capacity know as "ampacity". The overriding concern here is fire safety. However in low voltage (12/24/48 volts DC) systems, sizing for larger wire is usually necessary to minimize power loss due to voltage drop before increased wire size is required for amperage safety.

Typically, low voltage systems are seen in Alternative Energy (AE) home systems and Recreational Vehicle (RV) systems. The heart of these systems is DC power because DC electrical power can be stored in batteries. With photovoltaic systems, the electrical power produced is also DC. DC systems are primarily low voltage because most of the DC lights and appliances have traditionally been built for the vehicular market, which is typically 12 or 24 volts. There is also increased fire danger with high voltage DC because of the high potential for arcing in switches and poor electrical connections. High voltage DC also has a high shock hazard (more than at an equivalent ac voltage).

Voltage Drop is caused by a conductor's electrical resistance (Ohms) and may be calculated according to Ohm's Law--

(1) Voltage Drop (Volts) = Electrical Resistance (Ohms) X Current (Amps)

Power Loss is calculated by--

(2) Power Loss (Watts) = Voltage Drop (Volts) X Current(Amps)

By substituting the Voltage Drop Equivalence from equation (1) into equation (2), we find--

Power Loss (Watts) = Ohms X Amps^2

If we have a 12V system with a 100 ft. wire run of 12 gauge wire (0.33 Ohms) and a 72 watt load, there will be a 6 amp current (Amps = Watts/Volts) and a power loss of 12 watts (0.33 Ohms X $[6\ \text{Amps}]^2$). If we converted this system to 24V, we would have a current of 3 amps and a power loss of 3 watts. The significance here is that by DOUBLING the system voltage, power loss is reduced by a FACTOR OF FOUR. Or for no increase in power loss, we can use ONE FOURTH the wire size by doubling the voltage. This is why the trend in AE full home systems with DC circuits is towards 24V instead 12V systems. It is also why it is important to reduce the current by using efficient loads and putting fewer loads on the same circuit. Likewise, reducing wire resistance by using large wire and shorter wire runs is important. All of these are particularly critical with AE systems, where cost per kilowatt of electrical power may be several times that of "Grid" supplied electrical power.

Wire Size Chart

Because of the significance of voltage drop in low voltage electrical systems, we have developed an easy-to-use wire sizing chart. Most previous charts published assume a 2 or 5% voltage drop for 12 and 24 volt systems and result in pages of numbers. This new chart works for any voltage and accommodates your choice of % voltage drop. You'll find it the handiest chart available. The chart applies to typical DC circuits and simple ac circuits (refer to footnote on Wire Size Chart). We recommend sizing for a 2-3% voltage drop where efficiency is important.

ac/DC Wire Size Chart

① Calculate Voltage Drop Index (VDI)

$$\text{VDI} = \frac{\text{AMPS X FEET}}{\text{\% VOLT DROP X VOLTAGE}}$$

where:
AMPS = Watts/Volts
FEET = One-way wire distance
%VOLT DROP = Percentage Volatage Drop e.g. use 2. for 2%

② Determine Appropriate Wire Size from Chart

a. Compare the "calculated VDI" with the VDIvalues for the American Wire Gauge (AWG) sizes in the chart to determine the appropriate wire size to use.
b. Circuit amperage must not exceed the indicated fire harzard AMPACITY rating for the wire gauge set by the National Electric Code.

Wire Size	Copper Wire		Aluminum Wire	
AWG	VDI	Ampacity	VDI	Ampacity
OOOO	99	260	62	205
OOO	78	225	49	175
OO	62	195	39	150
O	49	170	31	135
2	31	130	20	100
4	20	95	12	75
6	12	75	•	•
8	8	55	•	•
10	5	30	•	•
12	3	20	•	•
14	2	15	•	•
16	1	•	•	•

• Size for a 2% to 3% Voltage Drop where efficiency is important.
• Information here applies to DC and ac circuits where the Power Factor = 1.0 and the line reactance is negligible.
• For 2-wire circuits. For more complex circuits refer to an electrical engineering handbook.

Sizing Example

We have a 12 volt system with a total one-way wire run of 40 ft. servicing three 13 watt fluorescent lights and one 20 watt quartz halogen light. Sizing for a 2% voltage drop, what wire size is needed for this circuit?

$$\text{AMPS} = \frac{\text{TOTAL WATTS ALL LOADS}}{\text{VOLTS}}$$

$$\text{AMPS} = \frac{(3 \text{ X } 13) + 20}{12} = 4.9 \text{ AMPS}$$

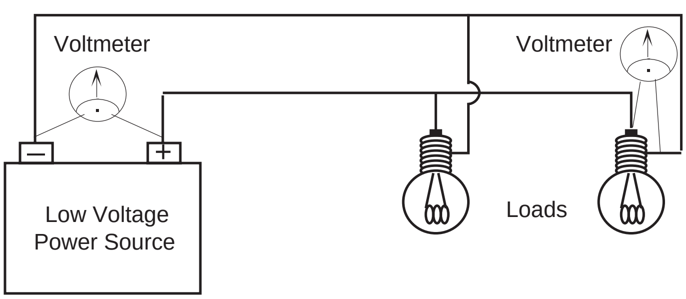
$$\text{VDI} = \frac{\text{AMPS X FEET}}{\text{\% VOLT DROP X VOLTAGE}}$$

$$\text{VDI} = \frac{4.9 \text{ X } 40}{2 \text{ X } 12} = 8.2$$

The "calculated VDI" 8.2 is between VDI values 8 and 12 on the Chart. This calls for #8 gauge wire (#12 gauge wire could be used in a 24V system). Since the "calculated VDI" is not much greater than 8, we may consider sizing-down and accepting a slightly greater voltage drop. This would be sensible because #8 gauge wire is expensive and difficult to work with. Or we might consider putting these loads on two circuits--compare wire and labor costs. If typically only one of the fluorescents and the quartz halogen are operating at the same time, we could size for this typical load, being sure not to exceed the wire ampacity for the total of all loads. In this case #12 gauge wire could be used. This is an example of some of the considerations and tradeoffs that will be discussed later in this article.

Determining Voltage Drop In Existing Circuits

You may wish to know how efficient an already existing circuit is in terms of voltage drop. There is an easy way to measure this. With a "multi-tester" or voltmeter, measure the "source voltage" for the circuit and the "load Voltage" at the end of the line, then compare the difference. Do this while the circuit is powered and all the loads are on:



Now calculate the % voltage drop with the following equation--

$$\text{\% VOLT DROP} = \frac{(\text{SOURCE VOLTS- LOAD VOLTS}) \text{ X } 100}{\text{SOURCE VOLTS}}$$

This method will total ALL voltage drops in the circuit caused by wire, connections, and switches. Because the amperage is less beyond each load in the circuit, the true % voltage drop will be somewhat less than that calculated in the above equation.

An easy way to calculate the wire voltage drop WITHOUT any measurements, if you have the information needed about the circuit, is to solve for % Voltage Drop using the VDI equation--

$$\text{\% VOLTAGE DROP} = \frac{\text{AMPS X FEET}}{\text{VDI X VOLTAGE}}$$

where:

$$\text{AMPS} = \frac{\text{TOTAL WATTS ALL LOADS}}{\text{VOLTS}}$$

FEET = one-way wire length of the circuit.

VDI = VDI value, from Wire Size Chart for the gauge of wire in the circuit.

VOLTAGE = System Voltage.

Practical Applications and Considerations

Here, we will consider voltage drop and wire sizing for different types of electrical loads, alternatives to the use of large wire and long wire runs, and some recommended wiring techniques. Different electrical loads (power-consuming devices) have different tolerances for voltage drop. These guidelines will help you determine how much drop is acceptable.

Lighting Circuits

Incandescent and Quartz Halogen

A voltage drop below appropriate levels results in a disproportionate loss in performance. A 10% voltage drop causes an approximate 25% loss in light output. This is because the bulb not only receives less power, but the cooler filament drops from white-hot towards red-hot, emitting far less visible light.

Fluorescent

Voltage drop here is less critical, causing a proportional drop in light output. A 10% voltage drop results in an approximate 10% loss in light output. Because fluorescents are more efficient, they use 1/2 to 1/3 the current of incandescent or QH bulbs and therefore many be used with smaller wire (including most pre-existing ac wiring). We strongly advocate use of fluorescent lights. The unpleasant qualities of flicker and poor color rendition may be eliminated by using the more advanced 12, 24, and 120 volt fluorescents now available. See our "Efficient Lighting" article in HP#9 for details. We suggest using a 2-3% voltage drop for sizing wire in lighting circuits. If several lights are on the same circuit but are rarely all on at once, see the Part-Time Loads section for an economical approach.

Motor Circuits

DC Motors

DC motors operate at 10-15% higher efficiencies than ac motors and eliminate the costs and losses associated with DC/ac inverters. DC motors have minimal surge demands when starting, unlike ac induction motors. Voltage drop results in the motor running at a proportionally slower speed and starting more gradually. We suggest using a 2-5% voltage drop under normal operating conditions for DC wire sizing.

DC motors used for hard-starting loads, particularly deep-well piston pump jacks and compressors, may have high surge demands when starting. High power demands are also seen in DC power tools when overloaded. DC refrigerators (e.g. Sun Frost) with electronically controlled (brushless) motors will fail to start if the voltage drops to 10.5 volts, in a 12V system, during the starting surge. This is due to a low voltage shut-down device in the refrigerator intended to protect your batteries from damage. We suggest sizing wire here for a 5% voltage drop at surge current (use 3X operating current).

ac Motors
Alternating Current (ac) induction motors are commonly found in large power tools, appliances and well pumps. They exhibit very high surge when starting. Significant voltage drop in these circuits may cause failure to start and possible motor damage.

Universal Motors
Brush type ac motors ("Universal Motors") are found in smaller appliances and portable tools. As with DC motors, they do not have large surge demands when staring. However, wire should still be generously sized to allow for overload and hard-starting conditions. Consult an electrician or the *National Electrical Code* for wiring standards in ac tool and appliance circuits.

Photovoltaic Battery-Charging Circuits
In PV battery charging a voltage drop can cause a disproportionately higher loss in power transfer. To charge a battery, a generating device must apply a higher voltage than exists in the battery. That's why most PV modules are designed for 16 volts or more. A voltage drop of 1 or 2 volts in wiring will negate this necessary voltage difference, and greatly reduce charge current to the battery. A 10% voltage drop in a wire run may cause a power loss of as much as 50% in extreme cases. Our general recommendation here is to size for a 2-3% voltage drop.

PV array voltage also drops in response to high temperatures. Use high voltage modules (over 17 volts peak power) in very hot climates (where module temperatures commonly exceed 117°F./47°C.). In moderate climates, high voltage modules allow for more line voltage drop, but they cost more per Amp delivered to the battery bank. Therefore, size wire for a somewhat larger voltage drop, e.g. 5%, when high voltage modules in a moderate climate.

If you think you might expand your array in the future, install wire appropriately sized for your future needs NOW, while it is easier and less costly. It never does any harm to oversize your wire.

Number Of Circuits
If circuits are designed with numerous loads requiring large wire, overall wire cost may be adding additional circuits and putting fewer loads on each circuit. Fewer loads per circuit reduces circuit current which in turn allows for the use of smaller wire.

More Than One Size Of Wire In A DC Circuit
If you size wire for the loads on "End Branches" of a circuit, smaller wire may be used. For instance, voltage drop sizing may specify 10 gauge wire for a circuit but a light on an "End Branch" of the circuit, when sized separately, may allow for the use of 12 gauge wire from the switch to the light. Using smaller wire for "End Branches", may also make your electrical connections faster and easier because it is physically difficult to make connections to standard household switches, receptacles, and fixtures with wire larger than 12 gauge.

BE SURE THAT THE AMPACITY RATING OF ALL WIRE IN A CIRCUIT MEETS OR EXCEEDS THE FUSE PROTECTION RATING OF THE CIRCUIT.

Part-Time Loads
If a number of loads are on the same circuit but are rarely all operating at the same time, you can size the wire for voltage drop according to the TYPICAL load demand. AGAIN, BE CERTAIN THAT THE AMPACITY RATING OF ALL WIRE IN THE CIRCUIT MEETS OR EXCEEDS THE FUSE PROTECTION RATING OF THE CIRCUIT.

System Voltage
Consider 24 volt DC instead of 12 volt where feasible. Use 120 volt ac from inverter to loads where 10-20% conversion loss is not a major comprise. See our article "Selecting System Voltage" in HP#4.

Location Of System Components
Locate batteries, inverter, ac battery charger, and distribution panel near each other. Also, locate the distribution panel as close as possible to very large loads and as central as possible to all other loads. This will shorten wire runs and for some circuits, reduce the wire size required.

Water Well Pumps
Consider a slow-pumping, low power system with a storage tank to accumulate water. This reduces both wire and pipe sizes where long lifts or runs are involved. An ARRAY-DIRECT pumping system may eliminate a long wire run by using a separate PV array located close to the pump. (For more about water system design, see our article "Solar Powered Pumping", HP#11.)

Soldering vs. Mechanical Connections
Soldering is recommended around battery and inverter terminals (see "Build Your Own Battery/Inverter Cables" in HP#7) and in other corrosive, high-current environments OR at the discretion of the installer. Soldering requires skill and has numerous pitfalls--too much or too little heat, oxidized or dirty metal, the wrong solder or flux, or just lack of experience will GUARANTEE poor solder joints. Do not attempt to solder connections in your system unless you have learned do it properly. A tight mechanical joint is far safer than a questionable solder joint.

Grounding And Lightning Protection
We've seen thousands of dollars of damage to electrical equipment from lightning. In one PV home a lightning bolt entered the house via the PV wiring and exited the other side of the house, popping plaster and light bulbs, and burning wire along the way. Proper grounding PREVENTS nearly all such occurrences. For a more thorough discussion, see our article "Grounding and Lightning Protection", HP#6.

Audio Signal Wires
Wires that carry audio signals (telephones, intercom, speakers) may pick up buzzing noise if run alongside ac wiring. This is especially true when the ac power is from an inverter. Avoid this problem by running audio wires along a separate path (or in a separate trench) from the ac wires. Keep then as far apart as possible, especially on long runs. Proper grounding also helps. Audio wires will NOT pick up noise from DC lines.

Wiring Design And Installation Book
We recommend *The Solar Electrical Independent Home Book* to familiarize you and your PV installer/electrician with safe up-to-code installation procedure (available from Flowlight Solar Power).

About the Authors
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***Editor's Note**: I have reprinted the first section of this article which appeared in HP#13. This is because I introduced serious errors when typesetting the equations in this article for HP#13. My sincere apologies to John, Windy & any reader who tried to make sense of the hash I made of the data. This version contains the straight info. Richard Perez*