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Chapter 12 of PV and the NEC, second edition, has been rewritten.

Here is the revised version:

Chapter 12

Wire Sizing

Wire sizing has been so complicated that many experts disagree on how to correctly size a wire and many books have conflicting methods for how to do it properly. This is also why there are no wire sizing programs on the internet that work for anything besides voltage drop. If someone was good enough at coding to make a good wire sizing program, they would be too busy at Google making $500k per year instead of making NEC wire sizing programs.

In sizing a wire there are many different checks that should be done. Some of the checks seem so obvious that they are usually skipped, while others are sometimes just given a brief statement such as “then check that the overcurrent device satisfies Article 240 Overcurrent Protection.”

We will give a few examples of wire sizing and then let you practice on your own. Practice makes perfect. Someone who sizes PV wires every day will often skip most checks, since they know from experience which check will determine the wire size in their particular situation.

It is recommended that you sit down with your NEC and use the following tables to practice these wire sizing exercises. You can also photocopy or screenshot the following tables and rules for your wire sizing kit:

310.16 Ampacities of Conductors NOT in Free Air Based on 30°C

310.17 Ampacities of Conductors in Free Air Based on 30°C (use 310.16 for terminal checks even if free air).

310.15(B)(1)(1) Ambient Temperature Correction Factors Based on 30°C

310.15(C)(1) Adjustment Factors for More than Three Current Carrying Conductors

240.4(D) Small Conductor Rule

240.6(A) Standard OCPD Sizes

110.14(C)(1) Equipment Provisions [of 110.14(C)Temperature Limitations]

Become an expert yourself or hire Bill and Sean to do your wire sizing at attorney-like prices. The difference with Sean and Bill vs. attorneys is that Sean and Bill have souls.

Legend

COU = Conditions of Use (adjustment and correction factors)

Ampacity = Conductor's ability to carry current

Imax = Maximum Circuit Current or Rated Current or Continuous Current Rating [690.8(A), 705.28(A), 706.30(A)]

Icont = required ampacity for continuous current = Imax × 1.25 [690.8(B)(1), 705.28(B)(1), 706.30(B)] This is not a current, it is an overcorrection as a safety factor. It is a pathway, which does not include adjustment and correction factors.

OCPD = Overcurrent protection device

If you are interested in looking up what the letters on the wire mean, such as THWN-2, you can go to Table 310.4. You are only allowed to use conductors in 310.4, unless you are told differently in , such as you are told with PV wire and DG cable in 690.31(C).

Wire Sizing Example 1: Inverter Output Circuit Wire Sizing

Given the following information:

- Inverter continuous rated output current = **10A**
  - If it were on a house, then 240V × 10A = 2.4kW inverter
- Number of current-carrying conductors in conduit **2**
  - Do not include ground or balanced neutral
- ASHRAE 2% high temperature from www.solarabcs.org = **40°C**
- Distance above roof conduit in sunlight = 1 inch (irrelevant info)
- Terminal temperature limits = **75°C**
  - Terminals are what we attach ends of wires to.
- Wire type to be used = THWN-2
  - **90°C** rated wire
  - We can see this in Table 310.16
  - -2 at end of wire designation means 90°C rated

Discussion

Defining current for this exercise:

690.8(A)(1)(c), 705.28(A)(1), 706.30(A) Maximum circuit current = continuous rated output current = 10A = Imax

690.8(B)(1), 705.28(B)(1), 706.30(B)

Required ampacity for continuous current = Imax × 1.25 = 12.5A = Icont

This example and these steps use a 90°C rated wire and 75°C rated terminals.

We are going to break this down into 10 steps (at least it's not 12 steps—although you might need to recover with a 12-step program after we are done). Some of the steps will seem useless in most cases, but it is possible to have a 75°C rated wire with 90°C rated terminals, although we have never seen it happen. We could make fewer steps and then find an unusual exception where the four-step process does not work.

10 Steps (almost as effective as a 12-step program—this is Ampacity Anonymous)

Step 1 is really without wires (we are powerless, and our electrical systems are unmanageable). If you end up picking a wire that is too small in one of the steps, then you go to a higher size.

The way Sean does it is he puts the following 10 steps in an editable document and then follows the steps as seen below. When he is consulting, he finds that over 90% of people calculate wrong and end up using a more efficient wire than the minimum required, which is probably good in the long run. This technique also works with loads.

(1) Round up Icont to fuse size

(2) Pick conductor size [perhaps from intuition, Tables 310.16, 310.17, or 240.4(D)]

(3) 75°C ampacity

(4) 75°C ampacity ≥ Icont good!

(5) 75°C ampacity ≥ OCPD good!

(6) 90°C ampacity

(7) 90°C ampacity ≥ OCPD good!

(8) 90°C ampacity × COU deratings = COU derated wire

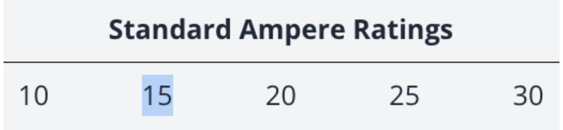
(9) COU derated wire ≥ Imax good!

(10) COU derated wire round up to OCPD ≥ OCPD from step 1 good!

Working the 10 Steps with our Example 1

(1) Round up Icont to fuse size

- 12.5A rounds up to 15A
- 240.6



Standard Ampere Ratings				
10	15	20	25	30

(2) Pick conductor size

- Educated guess or from 240.4(D)
- 14AWG copper is smallest wire for 15A OCPD 240.4(D)(4)

(4) 14 AWG Copper

15 amperes

(3) 75°C ampacity (75°C terminals)

- 14AWG = 20A
- Table **310.16 for conduit or** free air

14*	15	20	25

(4) 75°C Ampacity ≥ Icont good!

- 20A ≥ 12.5A good!
- If not good, increase the conductor size here

(5) 75°C Ampacity ≥ OCPD good!

- 20A ≥ 15A good!
- If not good, increase the conductor size

(6) 90°C ampacity (90°C rated wire)

- 14AWG = 25A
- **Table 310.16** [or Table 310.17 if free air]

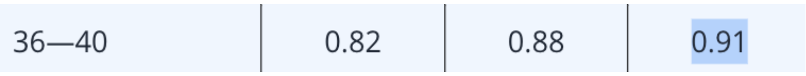
14*	15	20	25

(7) 90°C ampacity ≥ OCPD good!

    - 25A ≥ 15A good
    - If not good, increase the conductor size here

(8) 90°C ampacity × COU deratings = COU derated wire

- COU = Conditions of Use (adjustment and correction factors)
- COU deratings from 310.15(B)(1)(1) and 310.15(C)(1)
- 310.15(B)(1)(1) 40°C for 90°C rated wire = 0.91 derating



36—40	0.82	0.88	0.91

- 310.15(C)(1) no derating for two current-carrying conductors

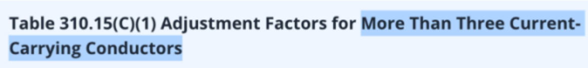


Table 310.15(C)(1) Adjustment Factors for More Than Three Current-Carrying Conductors

    - Do not count balanced neutral and ground
- 25A wire × 0.91 = 23A **rounded to nearest whole number**

(9) COU derated wire ≥ Imax good!

- 23A ≥ 10A

(10) COU derated wire round up to OCPD ≥ OCPD from step 1 good!

- 23A wire rounds up to 25A
- 25A ≥ 15A

Conclusion: 14AWG wire satisfies the requirements of the code in this case with a 10A inverter. In this case, however, most people would use a larger wire due to voltage drop.

Step 10: Rounding Up Wire to Common Overcurrent Device

One of the most difficult concepts for people to understand is that, in step 10, we **can take the ampacity of the wire and round up to the next standard overcurrent protection device size. This is not saying that the conductor has a higher ampacity**; this is just saying that a wire derated to 23A can be protected by a slightly larger sized OCPD and still be safe. This rounding up comes from 240.4(B) Overcurrent Devices Rated 800A or less. For overcurrent devices over 800A, you do not get to round up the ampacity of the conductor over the overcurrent device size, which seems to make more sense to most people. This ability to round up for the conductor's ampacity is because the conductor ampacity tables in the NEC give you numbers that are overly conservative and there is extra room in tables 310.16 and 310.17 for more current. If you look at the same conductors in other countries, you will see that they can carry more current.

Wire sizing for voltage drop is a good idea, but it is never a Code issue for PV with the NEC. We will do voltage drop calculations later in this chapter, after we focus on Code-compliant wire sizing.

Wire Sizing Example 2: PV String Circuit Wire Sizing

Sizing a PV string circuit given the following information:

- Isc = 8A
- Number of PV string circuits in conduit (over 24") = 20
- ASHRAE 2% high temperature from www.solarabcs.org = 40°C
- Distance above roof conduit in sunlight = 1 inch
- Terminal temperature limits = 75°C
- Wire type to be used = USE-2/RHW-2

Discussion

Defining current:

690.8(A)(1)(a)(1)

Maximum circuit current = Isc × 1.25 = 8A × 1.25 = 10A = Imax (Imax is different from, and not to be confused with, Imp)

Required ampacity for continuous current:

690.8(B)(1)

Required ampacity for continuous current = Imax × 1.25 = 12.5A = Icont

(Icont = Isc × 1.25 × 1.25 = Isc × 1.56)

Conductors:

USE-2/RHW-2 = 90°C rated wire and we are using 75°C terminals as mentioned.

20 PV string circuits = 40 current-carrying conductors

Working the 10 Steps with our Example 2

(1) Round up Icont to fuse size

- Icont = 12.5A rounds up to 15A fuse as per 240.6

(2) Pick conductor size

- 15A fuse requires at least 14AWG copper as per 240.4(D)

(3) 75°C ampacity (75°C terminals)

- 75°C 14AWG = 20A in Table 310.16
- For terminal check always use 310.16 and not 310.17, even if conductors are in free air according to 110.14(C)(1)]

(4) 75°C Ampacity ≥ Icont good!

- 20A ≥ 12.5A good!

(5) 75°C Ampacity ≥ OCPD good!

- 20A ≥ 15A good!

(6) 90°C ampacity (90°C rated wire)

- 14AWG = 25A per Table 310.16

(7) 90°C ampacity ≥ OCPD good!

- 25A ≥ 15A good

(8) 90°C ampacity × COU deratings = COU derated wire

- 310.15(B)(1)(1) 40°C for 90°C rated wire = 0.91 derating
- 310.15(C)(1) for 40 conductors in conduit = 40% = 0.4
- 25A wire × 0.91 × 0.4 = 9A rounded to nearest whole number

(9) COU derated wire ≥ Imax good!

- 9A is *not* ≥ 10A, so go back to use next larger wire 12AWG
- **12 AWG = 30A** per Table 310.16
- **30A** × 0.91 × 0.4 = 11A rounded to nearest whole number
- **11A ≥ 10A** (notice we are not using Icont here, which is for the terminal check and not the COU check)

(10) COU derated wire round up to OCPD ≥ OCPD from step 1 good!

- **11A wire rounds up to 15A** as per 240.6
- 15A ≥ 15A

Conclusion: **12 AWG satisfies the requirements of the Code here**. It is interesting to note that the condition of use rated wire is 11A and we can round that up to 15A and have an **11A wire protected by a 15A overcurrent protection device!** If you go to Europe, you will see that their wires can carry more current for the same size wire than AWG wires can. We have a buffer of protection built into our wires that will let us seem to deny common sense and round up a wire’s ability to carry current.

Would we use a 12AWG wire here in reality? I think I would use a 10AWG wire, just to be safe and simple, and to reduce voltage drop. Note that Bill put some tables into the NEC for conductors rated for 105°C and 125°C in 690.31(A)(3)(1) and 690.31(A)(3)(2), which would allow us to use smaller conductors to save wire money, as PV modules get less expensive than conductor costs.

Voltage Drop (Rise)

When it comes down to voltage drop (rise), what we really want to know is how much money our wire will save for us if we invest more money in the wire. There may be complex calculations, which would have to include tilt, azimuth, copper prices, aluminum prices, PV prices, soiling, labor prices, inverter prices, incentive type, PV to inverter ratio, and weather. To perform those calculations, it is recommended to use complex software and perhaps to hire a team of engineers (or do what everyone else does and use a 10AWG wire).

Voltage Rise

The reason that we keep mentioning voltage rise in this book, is because the voltage must be at least slightly higher where the electricity is coming from, than where it is going to. The difference in voltage is determined by the resistance of the conductor and the current (V=IR). With a source, the voltage will be higher at the source, so with your typical interactive inverter output circuit, the voltage will be higher at the inverter than at the point of interconnection, and will rise even more as the sun gets brighter (current goes up). This is really voltage drop, but it appears as voltage rise from the inverter’s point of view as the inverter pushes current towards the grid. According to an interactive inverter, the grid is a load, unless the interactive inverter is an ESS inverter charging a battery. However, to be correct, an ESS inverter is not just an inverter (dc-to-ac), it is also a charger/rectifier (ac-to-dc).

For the purposes of this book, for voltage rise (or drop) calculations, we will use the maximum output current of the inverter, which is being very conservative, since most if not all the energy generated from a PV system is going to be less than the maximum output current. For PV source circuits, we will use current at maximum power (Imp), which is considerably less than the currents we used to calculate Code-compliant wire sizes and is more than we will often see on a PV source circuit.

Some designers will use 80% of these numbers as a rule of thumb, since most of our energy is made when it is not a cold, windy, bright summer noon (optimal PV conditions). We will use Imp and inverter maximum output current for this book, which is conservative and leads to less energy loss over the year than voltage drop percentage in the calculation. There is expensive software that engineers use for wire sizing for large projects.

If you are performing voltage drop calculations for a job that you have won a bid on or are bidding on, you should carefully read the requirements of the request for proposal.

We will use a simple calculation to arrive at an AWG wire size given the following information:

Voltage = 240V

Current = 16A

Voltage Drop Percentage = 2%

Distance from inverter to interconnection = 200 feet

Here is the formula that can be used with Chapter 9 Table 8 Conductor Properties of the NEC

$$\text{Ohms/kFT}=(5\%V)/(IL)$$

Ohms/kFT will give us an AWG wire size in Chapter 9 Table 8

5 is a constant derived from (1000FT/kFt)/100%/2 wires in a circuit)

% is the percentage, so we use 2 (not 0.02) for 2%

V is the operating voltage, which is 240V at your house

I is the current of the inverter in this case, which is 16A for a 3.8kW inverter

L is the 1-way distance in feet which is 200 FT

We will plug it in to the equation:

$$\text{Ohms/kFT}=(5\%V)/(IL)$$

$$\text{Ohms/kFT}=(52\%\times 240V)/(16A200FT)=2400/3200=0.75\ \text{ohms/kFT}$$

If we **look up 0.75 ohms/kFT in Chapter 9 Table 8** we see that an uncoated 6AWG copper wire will have a resistance of 0.491 ohms/kFT and a smaller 8AWG stranded copper wire will have a resistance of 0.778 ohms/kFT.

Since voltage drop is not a Code issue here, you can choose to round up or down from a 6AWG or an 8AWG wire.

This calculation will work for ac and dc wires because the values in Table 9 are essentially the same for ac circuits running at unity power factor. If you are using a large wire for ac and running the circuits at a power factor of 0.85 (may be required occasionally by utilities for grid support), then the values in Chapter 9 Table 9 differ from those in Table 8. It's best to get an engineer involved for larger systems as these calculations can get complicated.

To use these calculations for 3-phase power, just remember that there is a benefit to using 3-phase that is proportional to the square root of 3 (about 1.73). If we divide the square root of 3 by 2 we get 0.886, so we will have 88.6% of the resistance with 3-phase wires or we can multiply our ohms/kFT answer by 0.866. In the example we used, instead of 0.778 ohms/kFT, we could use a wire that is 0.778 × 0.866 = 0.67 ohms per kFT for 240V 3-phase.

The reason we divide the square root of 3 by 2 is because, with 3-phase, our currents are not directly opposing each other (square root of 3) and we are converting from a calculation that is from single phase power where we have to double the one-way distance of our wire to calculate the resistance of a circuit.

A circuit is a circle and if you are going to have your inverter 200 feet from the interconnection, you need to run electrons through 400 feet of wire and will have 400 feet = 0.4 kFT of resistance. With 3-phase, you will need to have current on three wires, but it will be less current, since the currents are 120 degrees out of phase with each other.

Some people say that 3-phase power takes more than a lifetime to truly understand, but if Tesla (a crazy genius) could figure out how 3-phase power worked all on his own, you can too!

Thank you for reading this book! Sean and Bill.

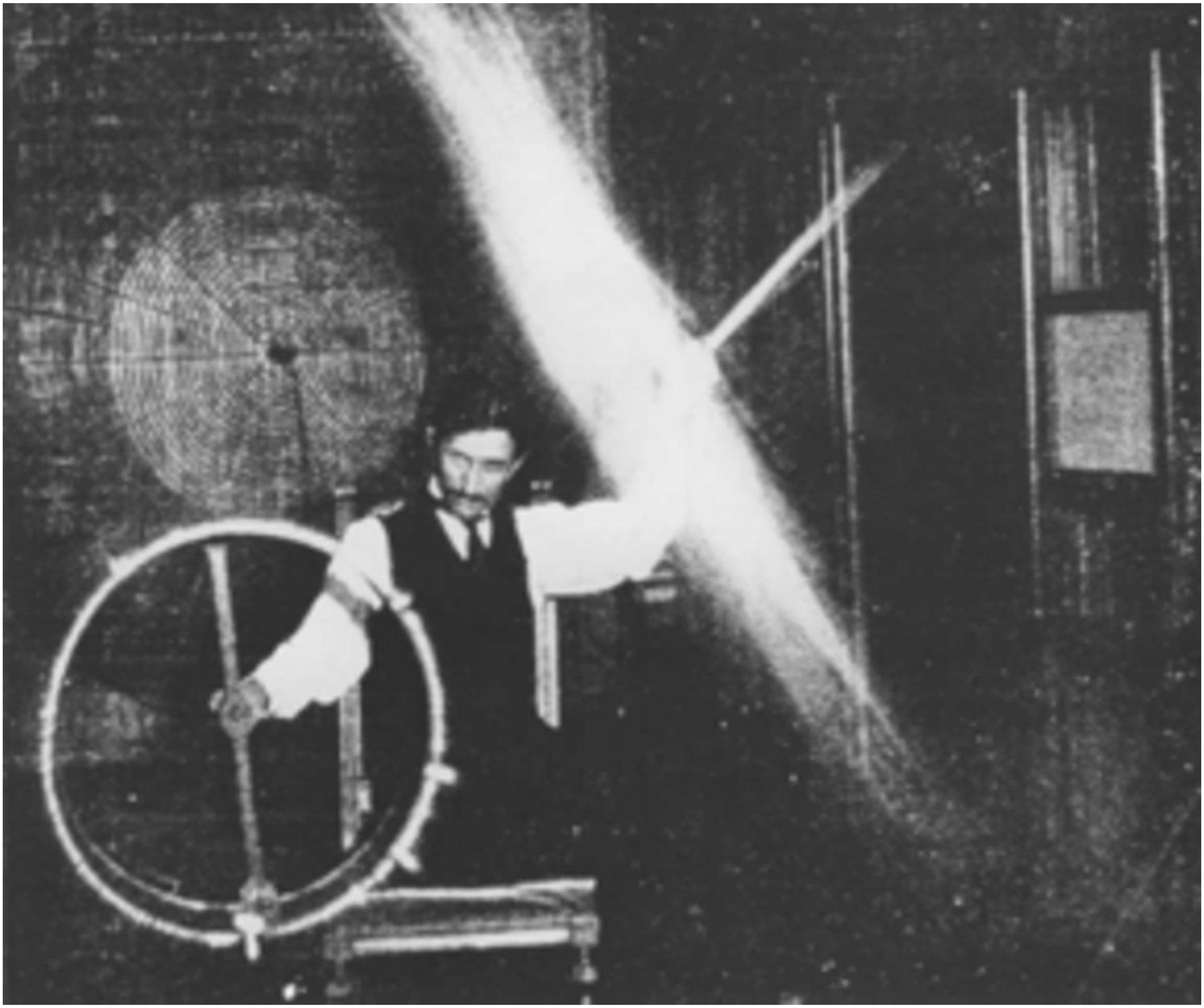


Figure 12.1 Nikola Tesla demonstrates how to truly understand 3-phase in 1899