Photovoltaic Power Systems
and
The 2005/2008 National Electrical Codes
A Presentation for
Electrical Inspectors, Electrical Contractors, and
PV Professionals

John C. Wiles
Southwest Technology Development Institute
New Mexico State University
P.O. Box 30001/MSC 3 SOLAR
Las Cruces, New Mexico  88003

http://www.nmsu.edu/~tdi
e-mail: jwiles@nmsu.edu
Phone: (575) 646-6105
Fax: (575) 646-3841
Overview

- Introduction & Background
- Introduction to PV Systems
- PV Systems & NEC Requirements
- The 2008 NEC and other material
Background and Introduction
Southwest Technology Development Institute

- Provide National & International Training
- Research & Implement NEC
- Review & Assist with UL & IEEE Standards
- Review System Designs
- Evaluate Proposals
- Design PV Balance of Systems Equipment
- Develop Prototype PV & Ground-Fault Hardware
- Test & Evaluate PV Systems
- Develop Data Acquisition Systems
- Monitor Resources & Assess System Performance
Acknowledgments

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National Fire Protection Association
Underwriters Laboratories
Objective and Method

Objective: Widespread Use of Safe, Durable, & Cost Effective Photovoltaic Power Systems

Knowledgeable People Who Can Effectively Design, Install, & Inspect PV Systems

Method: Maximum Interchange of Data Between the Research Community, the PV Community, and the Electrical Inspectors
Introduction to PV Systems

- PV Systems are like other electrical power systems
- 6 V to 1200+ V DC, 120 V - 480-12KV V AC
- 1 A to 2000+ A DC
- Low voltage/high current & high voltage/low current
- 6 W to 1megW to 14 megawatts and increasing
- All systems have potential to harm people & damage property
Introduction to PV Systems

- Simple, reliable - No sun, No energy
- DC output

Direct Connection PV System
Introduction to PV Systems

Self Regulating Stand-Alone PV System

- For constant, small loads
- Does not manage the battery state of charge
- Night/cloudy day operation possible
- DC output
Introduction to PV Systems

Typical Stand-Alone PV System

- Prevents battery overcharging
- Does not control/regulate load voltage
- May fully discharge battery
- DC output

PV Modules → Charge Controller → Battery → Load
Introduction to PV Systems

PV Modules -> Charge Controller -> Low Voltage Disconnect -> Load

Battery

Stand-Alone PV System

- Disconnects load at low battery voltage
- DC output
Introduction to PV Systems

Stand-Alone PV System

- AC & DC loads

Flowchart:

1. PV Modules
2. Charge Controller
3. Low Voltage Disconnect
4. Battery
5. Inverter
6. DC Loads
7. AC Loads
Introduction to PV Systems

- PV Modules
- Disconnect Overcurrent GFP
- Charge Controller
- Low Voltage Disconnect
  - Overcurrent Disconnect
  - Battery
  - Inverter
  - Overcurrent Disconnect
  - AC Loads
- Overcurrent Disconnect
- DC Loads

"The Real World"
Introduction to PV Systems

Grid-Connected, Utility-Interactive PV System

- Relies on Utility for Operation & Storage
Introduction to PV Systems
The PV Module

- Made up of PV cells connected in series
- PV cell voltage ($V_{mp}$) about 0.5 V under load
- PV cell current ($I_{mp}$) 0 up to ~10 A in bright light
- Module (12V) is 30-36 cells connected in series
- Typical 12-volt module - rated at 50-60 W
- Open-circuit voltage ($V_{oc}$): 18-22 V - even in dim light
- Short-circuit current ($I_{sc}$): up to ~10 A in bright light
- Can be short-circuited without damage
Introduction to PV Systems

The 12-Volt (24-Volt) Module

- 36 cells in series (72 cells in series)
- 50-60 W output: 17 V & 3 A (165 W, 34 V, 4.8 A)
- Open-circuit voltage ($V_{oc}$): ~22 V (44 V)
- Short-circuit current ($I_{sc}$): ~3.5 A (5.6 A)
- Glass front - plastic back (Tedlar) or glass/glass or glass/aluminum
- Aluminum framed, plastic framed, or unframed laminate
195 W
PV Module
Voc = 45 V
Isc = 6 A

Source Circuit (String)
10 Modules in Series
Voc = 10 x 45 V = 450 V
Isc = 6 A
Power = 10 x 195 W = 1950 W
PV Array
3 Strings In Parallel
$V_{oc} = 10 \times 45 \text{ V} = 450 \text{ V}$
$I_{sc} = 3 \times 6 \text{ A} = 18 \text{ A}$
Power = $3 \times 1950 \text{ W} = 5850 \text{ W}$
Introduction to PV Systems
Grid-Tied Systems

• Series strings of modules operate at 48-600 V.

• Each string (source circuit) usually has an overcurrent device where there are three or more strings. A very few may have blocking diodes.

• Strings are paralleled (sometimes with overcurrent devices) for greater current.
Optimal Photovoltaic Installation

- Direct Sunlight
- 9 am to 3 pm
- No shadows
- Pointed true South (fixed, non tracking array)
- Tilted at latitude above horizon
- Cooler is better
Introduction to PV Systems
Power, Voltage, & Currents

• Modules
  – Nominal 12 V and higher DC voltage
  – Connect in series & parallel for higher outputs
  – Current depends on size & sunlight intensity

• Arrays
  – Assemblies of modules
  – Provide desired levels of DC voltage & current

• Charge Controllers
  – Regulate the state of charge of storage battery

• Batteries
  – Store DC power/energy

• Inverters
  – Convert DC power to AC power

• End use appliances/load
  – Use AC or DC power
The National Electrical Code Requirements

Installation Approved by Authority (AHJ)

Equipment Examined for Safety

Listed or Labeled Equipment Required (by AHJ)
   Testing Laboratory with Jurisdictional Authorization—UL, CSA, ETL, and TUV RofA.

Installation Reflects Good Workmanship
PV-Critical Issues in the NEC

- **Section 90.7: Examination of Equipment for Safety.**
  - All equipment in the *Code* shall be examined for safety. Some must be listed. Factory installed wiring internal to listed equipment is not required to be inspected.

- **Section 90.4: Enforcement.**
  - AHJ may waive or establish requirements.

- **Section 110.3: Examination, Identification, Installation, & Use of Equipment.**
  - (B) Installation & Use
    - Listed or labeled equipment shall be used or installed in accordance with any instructions included in the listing or labeling.
PV-Critical Issues in the NEC

- **Section 110.14: Electrical Connections:**
  - (C) **Temperature Limitations:** Temperature rating associated with ampacity of conductor shall be so selected & coordinated as to not exceed the lowest temperature rating of any connected termination, conductor, or device.

  - **Note:** Important because PV systems use 90°C conductors and overcurrent devices have terminals rated for only 60°C or 75°C.
Safety Issues in PV Installations

- Cable selection and ampacity
- Cable overcurrent and short-circuit protection
- Component ratings—DC, voltage, current
- Operator/User/Servicer safety
Electrical Power System Diagram

- PV Array on Roof
- DC Power Center
- Battery Bank
- DC to AC Inverter and AC to DC Battery Charger
- AC Load Center
- AC Generator
- AC Branch Circuits
- DC Branch Circuits
- Utility
- DC
- AC
Wiring Methods

Cables for Modules
  Allowed Methods & Types

Insulation Materials
  Environmental Conditions
  Terminal Ratings
  Fixed or Portable Type Conductors

Ampacity Calculations
  Short-Circuit Currents
  Enhanced Irradiance
  Temperature Derating

Connections
PV & NEC Module Cable Ampacity & Overcurrent Device Rating

• Modules are rated by UL at 1000 W/m² & 25°C (Standard Test Conditions-STC)
• Modules operate 0-1500 W/m² & -50 to +80°C
• Module short-circuit current (I_{sc}) is direct function of sun
• Module open-circuit voltage (V_{oc}) is inverse function of temperature
• UL requires $I_{sc}$ to be multiplied by 125% (before NEC Calculations)
  (Now also in NEC 690.8(A)(1))
• UL requires $V_{oc}$ to be multiplied by 125% (before NEC Calculations)
  (Now as a temperature-dependent factor in NEC 690.7)
• NEC requires $I_{sc}$ to be multiplied by second 125% (690.8(B))
• NEC requires system voltage to be highest dc voltage in system
Effects of Temperature on Conductor Ampacity

1000 W/m²
Irradiance
40 °C
Ambient Temperature

1000 W/m²
Irradiance
40 °C
Ambient Temperature

Dark Colored Roof

#10 AWG USE-2 Cable in Free Air

Maximum Short-Circuit Current is 18.1 Amps

PV Modules

No Air Circulation

75 °C
Back of Module Temperature

Ampacity = 55 * 0.41 = 22.6
22.6 ÷ 1.25 = 18.1
Effects of Temperature on Conductor Ampacity

1000 W/m²
Irradiance
40 °C
Ambient Temperature

#10 AWG USE-2 Cable in Free Air

Maximum Short-Circuit Current is 25.5 Amps

Ampacity = 55 * .58 = 31.9
31.9 ÷ 1.25 = 25.5

PV Modules

Air Circulation

65 °C
Back of Module Temperature

Southwest Technology Development Institute

NM State College of Engineering Institute for Energy & the Environment
PV & *NEC*
Module Cable Ampacity & Overcurrent Device Rating

- Typical 24 V module: \( V_{oc} = 44 \text{ V}, \quad I_{sc} = 5.3 \text{ A}, \quad \text{Power} = 200 \text{ W} \)
- 125% \( V_{oc} = 55 \text{ V} \quad 125\% \ I_{sc} = 6.6 \text{ A} \) (continuous currents) \( 1.25 \times 6.6 = 8.3 \text{ A} \)
- Module interconnecting cable must have ampacity of 6.6 A (cont current)
- Overcurrent device must be rated at or above 8.3 A (1.56 \( I_{sc} \)) but less than cable ampacity — Therefore the cable rated at 8.3 A or better
- Voltage rating of cable & overcurrent device must be 55 V DC or greater
PV & NEC
Module Cable Selection

- Single-Conductor USE-2, SE, & UF cables are allowed
- Conduit & other wiring methods are acceptable
- All exposed cables must be sunlight resistant
- 90°C cable is required
- Ampacity must be derated for conditions of use
  - Temperature and Conduit Fill
- Exposed or buried conduit requires wet-rated conductors (USE-2, XHHW-2, RHW-2, THWN-2)
PV & NEC
Module Cable Temperature Derating

- USE-2 Number 10 AWG has ampacity of 55 A in free air at 30°C
  \[\text{NEC Table 310.17}\]
  - At 65°C, ampacity is 31.9 A \((55 \times 0.58)\) (max fuse 30 A) (vented location)

- RHW-2 Number 10 AWG has ampacity of 40 A in conduit at 30°C
  \[\text{NEC Table 310.16}\]
  - At 75°C, ampacity is 16.4 A \((40 \times 0.41)\) (non vented location)

- Conductor ampacity after corrections must be equal to or greater than \(1.25 \times I_{sc}\) (continuous current)

- Conductor ampacity at 30°C must be equal to or greater than \(1.56 \times I_{sc}\) (1.25 x continuous current)

- Overcurrent Device at \(1.56 \times I_{sc}\) must protect the conductor
Wiring Methods—Modules

- Methods & Types
  - Single Conductor USE-2, **UF, SE** Cables (**PV Wire**)  
  - Sheathed Cables, Cables in Conduit  
  - Solid, Stranded, Flexible—Portable cords OK for Trackers
- Ampacity Calculations
  - 125% $I_{sc}$—Twice  
  - Temperature derating (Table 310.16, 310.17)  
  - Terminal temperature limits
- Insulation
  - Temperature Range—90°C  
  - Sunlight resistant (exposed)/wet-rated  
  - Color (white or gray for grounded conductor; **green, green/yellow**, or bare for equipment grounding)
- Connections
  - Pressure, crimped, soldered (**Fine-stranded cable limitations**)
Conductor Sizing & Overcurrent Device Rating

- Determine continuous current \( (1.25 I_{sc}) \)
- Calculate \( 1.25 \times \) continuous current \( (1.56 I_{sc}) \)
- Select conductor and overcurrent device
- Evaluate conductor ampacity under conditions of use (temperature, conduit fill)
- Evaluate at Terminal Temperatures (each terminal)
- Ensure overcurrent device protects selected conductor under conditions of use
**Table 310.16**

Ampacities of conductors in conduit at 30°C (86°F)

| Temperature Rating of Conductor (See Table 310.13) |
|------------------|------------------|------------------|
| 60°C (140°F)     | 75°C (167°F)     | 90°C (194°F)     |
| Types TW, UF     | Types RHW, THHW, THW, THWN, XHHW, USE, ZW | RHH, THHN, THHW, THW-2, THWN-2, USE-2 XHH, XHHW, XHHW-2 |
| **COPPER**       |                  |                  |
| AWG or kcmil     | COPPER           | COPPER           |
| 14*              | 20               | 20               | 25               |
| 12*              | 25               | 25               | 30               |
| 10*              | 30               | 35               | 40               |
| 8                | 40               | 50               | 55               |
| 6                | 55               | 65               | 75               |
| 4                | 70               | 85               | 95               |
| 3                | 85               | 100              | 110              |
| 2                | 95               | 115              | 130              |
| 1                | 110              | 130              | 150              |

**CORRECTION FACTORS**

<table>
<thead>
<tr>
<th>Ambient Temp°C</th>
<th>Ambient temperatures other than 30°C (86°F), multiply by the factor shown.</th>
</tr>
</thead>
<tbody>
<tr>
<td>21-25</td>
<td>1.08 1.05 1.04</td>
</tr>
<tr>
<td>26-30</td>
<td>1.00 1.00 1.00</td>
</tr>
<tr>
<td>31-35</td>
<td>0.91 0.94 0.96</td>
</tr>
<tr>
<td>36-40</td>
<td>0.82 0.88 0.91</td>
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<tr>
<td>41-45</td>
<td>0.71 0.82 0.87</td>
</tr>
<tr>
<td>46-50</td>
<td>0.58 0.75 0.82</td>
</tr>
<tr>
<td>51-55</td>
<td>0.41 0.67 0.76</td>
</tr>
<tr>
<td>56-60</td>
<td>— 0.58 0.71</td>
</tr>
<tr>
<td>61-70</td>
<td>— 0.33 0.58</td>
</tr>
<tr>
<td>71-80</td>
<td>— — 0.41</td>
</tr>
</tbody>
</table>
### Table 310.17

#### Ampacities of conductors in free air at 30°C (86°F)

<table>
<thead>
<tr>
<th>COPPER</th>
<th>AWG or kcmil</th>
<th>60°C (140°F)</th>
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<tr>
<td></td>
<td>TW, UF</td>
<td>RHW, THHW, THW, THWN, XHHW</td>
<td>THHN, THHW, THW-2, THWN-2, RHH, RHW-2, USE-2, XHH, XHHW, XHHW-2</td>
<td></td>
</tr>
<tr>
<td>14*</td>
<td>25</td>
<td>30</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>12*</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>10*</td>
<td>40</td>
<td>50</td>
<td>55</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>60</td>
<td>70</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>80</td>
<td>95</td>
<td>105</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>105</td>
<td>125</td>
<td>140</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>120</td>
<td>145</td>
<td>165</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>140</td>
<td>170</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>165</td>
<td>195</td>
<td>220</td>
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#### Correction Factors

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<td>71-80</td>
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Terminal Temperature Limits
110.14(C)

Use terminal temperatures marked on equipment

No Markings:
Circuits 100A or less or 14-1 AWG, use 60 deg C limit
Circuits over 100A or greater than 1 AWG, use 75 deg C limit

Use Table 310.16
For conductor size selected, Read 60 deg C or 75 deg C Current
This Current must be greater than or equal to 1.25 continuous current.
Wiring Methods
Module Wiring Example - Number 1

Combined Output of Six Sharp 208 W Modules in Parallel
Wiring (after combiner) in conduit routed behind modules

\[ I_{sc} = 6 \times 8.13 \, A = 48.78 \, A \quad V_{oc} = 36.1 \, V \]
125% \times I_{sc} = 1.25 \times 48.78 = 60.975 \, A \, (continuous \, current)
125% \times 60.975 = 76.2 \, A \, (overcurrent \, device) >> 80 \,amps

Combiner Terminals Marked at 75°C, Fuse Terminals marked 60°C
Estimated Back-of-Module Temperature—60 - 69°C

With 76.2 A minimum fuse, select No. 2 AWG USE-2/RHW-2 (90°C column)
From Table 310.16, ampacity is 130 A x .58 temp derate factor = 75.4 A
This is greater than continuous current of 61 A—ok
Can be protected by a 80 amp fuse (240.4)—ok

**Terminal Temperature Check**
With 60°C insulation, No. 2 AWG cable has 30°C ampacity = 95 A *(Table 310.16)*
This is greater than 76.2 A (125% continuous currents)—ok.

*Note: Conductors in conduit in sunlight operate 17-20°C above max ambient*

*2005 NEC FPN #2, 310.10 (+14 to +33°C in 2008 NEC—310.15(B)(2))
Wiring Methods
Module Wiring Example - Number 2

Large Direct Roof-Mount PV Module, Cables in Free Air
\[ I_{sc} = 19 \text{ A}, \quad V_{oc} = 22 \text{ V} \]
Module Terminals Rated at 90°C, Circuit Breaker (CB) rated at 75°C
Back-of-Module Temperature 60 - 68°C

125% \( I_{sc} = 23.75 \text{ A} \) — continuous current
125% \( 23.75 = 29.7 \text{ A} \) (required overcurrent device) (round up to 30 A)

From Table 310-17, select No. 12 AWG USE-2/RHW-2 cable. (90°C Column)
Derated ampacity is 40 x 0.58 = 23.2 A (can use 25 A CB)
Derated ampacity is less than 23.75 A continuous current — No Good
25 A allowed CB is less than 30 A Required CB No Good

Check No. 10 AWG USE-2/RHW-2 cable
Derated ampacity is 55 x 0.58 = 31.9 (OK for 30 A fuse) — OK
Derated ampacity is greater than 23.75 A continuous current — OK

**Terminal Temperature Check-310.16**
With 75°C insulation, No. 10 AWG: 35 A, greater than 29.7 A — OK
Module Wiring

- Any method approved by NEC (690.31, CH 3)
- Single conductor, USE-2 & PV Wire (690.31) 2008 NEC
- Ampacity—insulation, temperature, installation, terminals (310, 110.3)
- Ampacity: Based on $I_{sc}$, 125% for normal operation, 125% NEC continuous currents (690.8, UL)
- Strain relief (690.32)
- Color coding (310.12, 200.6(A) (2))
- Grounding (690.41, 42, 43, 45, 47, 250)
PV Modules

- **Marking** (690.51) - Also UL-1703
  - Polarity
  - Maximum Overcurrent Device (reverse current protection)
  - Rated Open-circuit Voltage, Operating Voltage, Maximum System Voltage, Operating Current, Short-circuit Current, Maximum Power

- **Connections** (690.33,34)
  - Concealed connectors and fittings
  - Polarized, guarded, latching, grounding, load-break rated
  - Access to Junction Boxes—Removable fasteners, flexible wiring
PV Modules

- Junction/Combiner Box (690.32, 300.15, 408)
- Metallic Frames—Grounded Directly (690.43, 45)
- *PV Source Circuits must remain outside building until first disconnect unless in metallic raceways (690.14, 31(E)—2005 NEC)*
- Up to 600 V—1 and 2-family dwellings—\( V_{oc} \) (690.7(C,D))
- Above 600 V on other than 1 and 2-family dwellings
  —See 690 Part IX
CIRCUIT BREAKERS PROTECT #14 AWG CONDUCTORS

PV ARRAY #14 AWG 15A

#14 AWG 15A

Fault

CURRENTS FLOW FROM OTHER SUBARRAYS & FROM BATTERY

BREAKER PROTECTS #6 AWG CONDUCTORS

TO CHARGE CONTROLLER AND BATTERY

#6 AWG

Module series fuse required by UL/NEC
Selecting Overcurrent Devices and Conductors in PV Systems

1. Define Continuous Currents

   The unique nature of PV power generators dictate that all ac and dc calculated currents are continuous and are based on the worst-case conditions. There are no non-continuous currents.

   A. DC currents in PV source and output circuits are 125% of the short-circuit current ($I_{sc}$) (690.8(A)(1)).

   B. AC inverter (stand-alone or utility interactive) output currents are at the rated output of the inverter (690.8(A)(3)).

   C. DC Inverter input currents from batteries are at the rated output power of the inverter at the lowest battery voltage that can maintain that output (690-8(A) (4)).
Selecting Overcurrent Devices and Conductors in PV Systems (continued)

2. Select Overcurrent Device

A. Rated at 125% of continuous current (690.8(B)(1)).

1. If listed in enclosure for 100% duty, then use 100% continuous current (690.8(B)(1) EX)—Typically circuit breakers only

2. May round up to next standard rating (\(\leq 800\text{A}\))(240.4(B)). PV circuits 1-15 A in 1 A increments (690.9(C)). 1-10, 12, 15A

B. If overcurrent device is exposed to temperatures (operating conditions) greater than 40°C, must use temperature correction factors on the device rating (110.3(B)). Manufacturer’s data
Selecting Overcurrent Devices and Conductors in PV Systems (continued)

3. Select Conductor

A. Select conductor with ampacity (at 30°C) greater than or equal to 125% of continuous current (215.2(A)(1)).

B. Conductor selected must have ampacity after corrections for conditions of use (ambient temperature and conduit fill) greater than or equal to continuous currents (no 125%).
   (1) Apply at all points of different temperatures and/or conduit fill.
   (2) Use 10%/10-foot rule where appropriate (310.15(A)(2) EX)

C. Select largest conductor from 3.A. or 3.B (310.15(A)(2))
Selecting Overcurrent Devices and Conductors in PV Systems (continued)

4. Evaluate conductor temperature at each termination

A. Find current for conductor size selected in 3.C from Table 310-16, 60°C or 75°C table depending on conductor temperature limitation of device terminals (110.14(C)).

B. Current must greater than or equal to 1.25 continuous current.

C. Increase conductor size, if necessary, to meet 4.B. at all terminations.

Note: This step may be combined with 3A.
Selecting Overcurrent Devices and Conductors in PV Systems (continued)

5. Verify That Overcurrent Device Protects Conductors

A. The rating (after any corrections for conditions of use—2.B.) of the overcurrent device selected in 2. **Must be less than or equal to** the ampacity of the conductor selected in 4.C. The ampacity used must be corrected for the conditions of use (3). Rating round-up is allowed (240.4(B))

B. Increase conductor size if not protected by the overcurrent device.
Ground-Fault Protection Device

*NEC 690.5*

- Roof mounted PV arrays on dwellings (all systems in *2008 NEC*)
- Reduce fire hazard
- *Detect fault*
  - *Interrupt fault current*
  - *Indicate the fault*
  - *Disconnect the array or turn off the equipment*
- Built in to most utility-interactive inverters (fuse on bottom)
- Listed equipment available for stand-alone systems
Overcurrent Devices

- **DC Rated (in DC Circuits), Listed/Certified to UL Standards**

- **PV Source Circuits to Inverter or Battery**
  - Listed Supplementary Fuses (Midget or Ceramic Type)
  - Listed Supplementary Circuit Protectors
  - The use of branch-circuit rated devices is preferred

- **Battery to Load (Inverters and other dc loads)**
  - Listed Branch-Circuit Rated
    - Class Type Fuses
    - Branch-Circuit rated Circuit Breakers

- **Current rating: 125% of Steady-State Currents** (unless 100% rated)

- **Voltage Rating: System $V_{oc}$ x (Temperature Dependent Factor—690.7)**
  - Battery Circuits—Highest Equalization Voltage
Disconnect Devices

• DC Rated (in DC Circuits), Listed/Certified to UL Standards

• Circuit Breakers
  - With and without current trips

• Switches
  - Load break and non-load-break operation (restricted)
  - Pull out or lever type

• Bolted Connections for Grounded Conductors
  *Never switch a grounded conductor*

• Voltage Rating: System $V_{oc} \times$ (Temperature Dependent Factor—690.7)
  - Battery Circuits—Highest Equalization Voltage
PV Disconnect
History

• Prior to 1984—PV from the start should comply with *NEC*

• 1984—Article 690 added to *NEC*
  
  – Main PV Disconnect (690.14) —> 230 Part F
    • Treat same as AC service disconnect

• 2002—NFPA rewrote 690.14
  
  – Keep the PV circuits outside building to the PV Disco

• 2005—Use of metallic raceways OK’d in building

• Will Fire Departments have any future impact?
Utility Interconnected PV
The Big Picture

PV Array → DC Disconnect → Inverter → AC Disconnect → Grid

1. Point of first penetration
2. Readily Accessible

NEC 690.14

Utility Disconnect

Backfed Breaker
1. Identified — Yes
2. Clamped — Not Required

690.64(B)(5)

Grouped
Direct Connected System - DC, No Battery

Notes:
- Block Diagram
- Typical O/D Locations
- Overcurrent/Disconnect Device
- Equipment Grounding
- Surge Suppressor

May be required if power controller is used
Stand-Alone System (AC Output Optional)

Diagram:

- PV Array
- Charge Controller
- Battery
- Optional Inverter
- DC Loads
- AC Loads

Notes:
- Overcurrent/Disconnect Device
- Surge
- Block Diagram
- Typical O/D Locations
- Equipment Grounding
Grid-Tied System

NOTES:
- BLOCK DIAGRAM
- TYPICAL O/D LOCATIONS
- SERVICE-ENTRANCE DISCONNECT
- SYSTEM GROUND
- EQUIPMENT GROUNDING
- SURGE SUPPRESSOR
- OVERCURRENT/ DISCONNECT DEVICE
Stand-Alone and Grid-Connected System

Notes: Block Diagram
- Equipment Ground
- Overcurrent/Disconnect Device
Fault Analysis

Under fault conditions, 740V+ on switch and fuse

Switch  Fuse

PV Array

Physical Separation

Switch  Fuse

+ Monopole Voc = 370

- Monopole Voc = 370

Fault
Stand-Alone PV System with Backup Generator and Utility Options

- PV Array
- Charge Controller
- Disconnect
- Battery Bank
- Inverter
- Optional Battery Charger
- Optional Backup Generator

Note: Equipment Grounds Required (not Shown)
Disconnect and Overcurrent Device

PV Array

LOAD

Ground above 50 Volts

Notes: Equipment Grounds Required (not shown)
Overcurrent protection may not be required

Direct Connected PV System
Photovoltaic Power System Ratings

*NEC Sections 690.53, 690.55*

**Photovoltaic Power Source**
- Rated Operating Current: 43.9 A
- Rated Operating Voltage: 34.6 V
- Maximum System Voltage: 55 V (Inc. temp factor)
- Rated Short-Circuit Current: 47.8 A

**Battery System**
- Maximum Voltage: 33 V
- Polarity of Grounded Conductor: Negative
Grounding

• All exposed metal surfaces that might be energized shall be grounded with *Equipment Grounding Conductors.*
  — On systems of any voltage

• One of the current-carrying conductors (*Grounded Conductor*) must be grounded if system voltage is 50 V or greater.
  - 12-volt nominal—no ground required, 24-volt nominal and up—ground usually required *(Exception: See 690.35 in 2005 NEC)*

• Only a single bonding jumper is allowed in the dc system
  - Ground-fault protection equipment and U-I inverters usually contain the bonding jumper

• Only a single bonding jumper is allowed in the ac system

• Conductor to the Ground Rod is the *Grounding Electrode Conductor*

• There are exceptions
Grounding-Details

• **Equipment-grounding Conductors**—690.45
  
  • PV Source Circuits – Sized at 1.25 $I_{sc}$ (*2005 NEC*)
  • — Use $I_{sc}$ in Table 250.122 (*2008 NEC*)
  • AC circuits – Sized per *NEC* 250.122

• **Grounding Electrode Conductor (GEC)**—690.47
  
  • Minimum 6-8 AWG — may have to be larger
  • No splices unless irreversible
  • DC GEC connected to:
    - DC grounding electrode and then bonded to AC grounding electrode
    or
    - The AC grounding electrode

*HOT Tips*

*Never use sheet metal screws to ground boxes*
*Always bond metal raceways properly over 250 volts*
PV Inverter Grounding Methods
2005 NEC Section 690.47(C)

1. PV Array
2. DC Disc
3. PV Inverter
4. AC Disc
5. Existing AC Service Equipment

690.47(C)(1)
690.47(C)(2)

Optional 250.54 Supplementary Grounding Electrode (Lightning Protection)
New DC Grounding Electrode
Existing AC Grounding Electrode
PV Inverter Grounding Methods
Alternative

- PV Array
- DC Disconnect
- PV Inverter
- AC Disconnect
- Existing AC Service Equipment

Optional 250.54 Supplementary Grounding Electrode (Lightning Protection)

Unspliced 8 AWG Conductor
Serves as (1) AC Equipment Grounding Conductor (2) DC Grounding Electrode Conductor
Irreversibly spliced GEC required Bond if conduit is metal

Existing AC Grounding Electrode
Grounding Multiple Small Inverters

Inverter 1 → Inverter 2 → Inverter 3 → Inverter 4

Irreversible Splices
Utility Interconnections

- **NEC Requirements**
- **Utility Requirements**
  - Safety (inverter only or full protective relaying)
  - Metering (one to three)
  - Outside Disconnect
  - Contract (net metering/buy back?)
- **Insurance Requirements**
Utility Interconnections
NEC Requirements

• De-energize on Loss of Power [690.61]

• Neutral Conductor Ampacity [690.62]
  Minimum: Equipment grounding conductor

• Unbalanced Interconnections [690.63]

• Point of Connection [690.64]
Utility Interconnections
Point of Connection (690.64/705.12(A))

690.64(A)

• Supply Side of Service Disconnect (230.82(6))
  - NFPA considers this a second service entrance (See Appendix M, PV/NEC Manual)
Supply Side Point of Connection
Service Entrance Tap
NEC 690.64(A)

Tap Location Depends on Equipment

Utility Service Entrance

Revenue Meter

60 A Min (Suggest: Same size as SE conductors, RMC, shortest distance possible)

Optional REC Meter

Service-Entrance-Rated Disconnect (60A Min) (May also serve as utility-required PV disconnect)

From PV Inverter (Rated output no larger than ampacity of SE conductors)

Existing Load Center

Overcurrent Protection (Less than 60A OK Not greater than SE conductors)
Supply Side Taps

Combination Meter/Main or Meter/Panel
- Don’t tap internally—violates the listing
- Replace with separate meter and main disconnect or panel
- Add new meter base on utility side of existing meter/main
  - Tap between meters, move meter to new base, jumper old base

Zero Sequence CT/PT
- Add new service disconnect, tap on load side or CT/PT
- Install special meter CT/PT disconnect, move CT/PT to supply side
Utility Interconnections
Point of Connection

690.64(B)/705.12(D)

- Load Side of Service Disconnect
  - Dedicated Circuit
  - Sufficient Ampacity (Load Center Rating)
  - Line Side of GFCI/GFP
  - Sufficient Marking
  - Backfed Breakers—identified (690.64(B)(5)-2005 NEC)
Utility Interconnections
690.64(B)(2)

“The sum of the ampere ratings of overcurrent devices in circuits supplying power to a busbar or conductor shall not exceed the rating of the busbar or conductor. Exception: 120% for dwelling units.”
Utility Interconnections
690.64(B)(2)

Commercial Installation:

Main Breaker + PV Breaker \( \leq \) Rating of Load Center, etc.

For PV on Non-Dwellings:

- Increase load center and retain same main breaker
- Carefully assess all circuits back to service entrance
- Use supply (utility) side tap
Commercial Utility Interactive Systems
690.64(B)(2)
PV + Main ≤ Panel

1. If load permits, reduce main breaker by x: Add x PV Breaker
2. Connect to feeder at panel input
3. Increase panel size to meet requirements

After applying 690.64(B)(2) to all of these panels and feeders, it may be cheaper and easier to just add a second service to the building.
2005 *NEC* Requirements
Commercial Utility Interactive Systems
690.64(B)

Backfed PV Breaker + Main Breaker ≤ Panel Rating
Count only backfed breaker directly connected to panel

- **100 A**
  - 10th Floor Panel
  - Must increase panel to at least 115A (15 + 100 ≤ 100)

- **15A**
  - 4th Floor Panel
  - Must increase panel to at least 500A (100 + 400 ≤ 400)

- **100 A**
  - Main Panel Service Entrance
  - Must increase panel to at least 1400A (400 + 1000 ≤ 1000)

- **400 A**
  - Grid

---

Southwest Technology Development Institute

NM State Institute for Energy & the Environment
2008 NEC Requirements
All Utility Interactive Systems
690.64(B)
Backfed PV Breaker + Main Breaker ≤ 120% Panel Rating
Count only the first backfed breaker connected to the inverter
Backfed breaker(s) must be at opposite ends of panel from main breaker

PV Inverter

100 A
10th Floor Panel

15A

No change 15 + 100 < 120% of 100

400 A
4th Floor Panel

100 A

No change 15 + 400 < 120% of 400

1000 A
Main Panel Service Entrance

400 A

No change 15 + 1000 < 120% of 1000

400 A

Grid

1000 A
Load Side Taps--More Details

Meter/Main feeding a main-lug subpanel(s)
• Cannot backfeed breaker in meter/main panel
• Backfed PV breaker must be at “bottom” of subpanel
• Install main breaker in subpanel. Can then backfeed main panel at bottom

Article 240 Tap rules were not developed for multiple sources
• Use 690.64(B)/705.12(D) instead—conductors and bus bars
• Overcurrent device must normally be at the tap point

Center-Fed Panels and multiple-ampacity bus works not covered
• Engineering assessments required
Utility Interconnections
690.64(B)(2)

Dwelling Units Installation:
Main Breaker + PV Breaker <= 120% Rating of Load Center, etc.

For PV on Dwellings:

100 A Load Center/100 A Main Breaker—20 A PV
2 x 2400 W, 120 V Inverters
or 4800 W, 240 V Inverter
Limited by 80% rating on breakers to 3840 W total

200 A Load Center/200 A Main Breaker—40 A PV
2 x 4800 W, 120 V Inverters
or 9600 W, 240 V Inverter
Limited to 7680 W total by breaker ratings
### AC Overcurrent Devices

<table>
<thead>
<tr>
<th>V&lt;sub&gt;nom&lt;/sub&gt;</th>
<th>I&lt;sub&gt;nom&lt;/sub&gt;</th>
<th>X 1.25</th>
<th>Breaker</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB 2500</td>
<td>240 V</td>
<td>10.4</td>
<td>13 A</td>
</tr>
<tr>
<td>SB 2500</td>
<td>208 V</td>
<td>12.0</td>
<td>15.0</td>
</tr>
<tr>
<td>SB 1800</td>
<td>120</td>
<td>15</td>
<td>18.75</td>
</tr>
<tr>
<td>SB 1100</td>
<td>240</td>
<td>4.6</td>
<td>5.75</td>
</tr>
</tbody>
</table>

*10 A available on special order
Residential Utility Installations
690-64(B)(2)

The sum of O/C devices supplying power to conductor or busbar must not exceed the rating of that busbar or conductor: Ex: 120% dwelling unit.

Dwelling Unit

100 A panel: PV + main = 120 A →
1 SB 2500 (240 V)
2 SB 1800 (120 V)
1 (15 A) or 2 (10 A) SB 1100

200 A panel: PV + main = 240 A →
2 SB 2500 (240 V)
4 SB 1800 (120 V)
2 (15 A) or 4 (10 A) SB 1100
How to put 3 SB 2500’s on a 200 A panel
Use a 100 A Subpanel

- Subpanel Inverter Breakers
  Three SB 2500 → Three 15 A Breakers
- Subpanel Main Breaker
  Main must be 3x10.4x1.25 = 39 → use 40 A main breaker on subpanel. Could also use main-lug panel.
- Subpanel Rating
  45 + 40 ≤ 1.2 x panel rating
  85/1.2 ≤ panel rating 71 A → 100 A subpanel
- Main Panel Rating
  Main panel must be 200 A with a 40 A backfed breaker
  40 + 200 ≤ 1.2 x 200 = 240
Three SB 2500’s on a 200 Amp Service

100 Amp Panel

Utility Disconnect

Grid

200 Amp Panel
Main Service Entrance

SB 2500
15A

SB 2500
15A

SB 2500
15A

40A
2500 Watt Inverter
AC Voltage Drop/Rise

- Utility must maintain voltage within 240 V +10%/-12%.
- Voltage drop between inverter and meter is seen as voltage rise.
- Keep to 0.5% (1.2 V) - 1.0% (2.4 V) or less.

2500 w @ 240 v = 10.42 A

240 X .005 = 1.2 V
240 X .01 = 2.4 V

R = E/I = 1.2/10.4 = .1154 ohms

2.4/10.4 = .2308 ohms

<table>
<thead>
<tr>
<th>AWG</th>
<th>Ohms/1000 ft</th>
<th>0.5 % VD</th>
<th>1.0% VD</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>3.14</td>
<td>37 ft</td>
<td>74 ft</td>
</tr>
<tr>
<td>12</td>
<td>1.98</td>
<td>58 ft</td>
<td>117 ft</td>
</tr>
<tr>
<td>10</td>
<td>1.24</td>
<td>93 ft</td>
<td>186 ft</td>
</tr>
</tbody>
</table>

Total of Both Conductors

Southwest Technology Development Institute
12 AWG USE-2/RHW-2

12 Sharp 208W Modules
Voc = 36.1V
Isc = 8.13A

System Voltage
433.2 * Cold Weather Factor

Revenue Meter
100A

Utility

2500 W Inverter
240V AC

GEC

Square D
HU361RB
10 AWG
THHN/THWN-2
1/2 in EMT

Square D
H221NRB

12 AWG
THHN/THWN-2
3/4 in EMT

Residential Load Center

GE1
Battery Circuits
Observed Problems

- No overcurrent protection
- Improper fuses
  - AC supplemental
  - Automotive
  - Not listed
  - Sizes
- Circuit breakers protecting circuit breakers
  - Not current limiting/limited AIC/AIR
- No short-circuit protection
- Improper cable sizes
Battery Circuits
Complicating Factors

- High short-circuit currents
- No listed DC current-limiting circuit breakers
- Listed DC fuses & breakers with high AIC
- Fuses must be serviced “Cold” (no voltage)
- Rated inverter input currents not available
PV & NEC
Batteries - Cable Selection

- Battery cables may be 4/0 AWG & higher
- Cables must be run in conduit
- PV industry has limited experience/equipment
- "Battery cables" (Automotive/Marine) are not recognized by NEC
- Welding cables are listed by UL only for welders
- **Flexible** USE, RHH, RHW, and THW cables are available & acceptable *but must be used with special terminals.*
PV & NEC
Batteries - High Short-Circuit Currents

- Deep-Cycle storage batteries can deliver high short-circuit currents
- One 220-A·h, 6 V golf cart battery can deliver 6000-8000 A into a short circuit
- Some DC-rated overcurrent devices have limited short-circuit interrupting capabilities
- Current-limiting fuses (types RK-5, RK-1, T) are required on all circuits leaving battery—High AIC circuit breakers throughout are a substitute
  - *Current limiting fuses cannot protect dc breakers*
- Disconnect switch must be between battery & fuse
Cables, Disconnects, Overcurrent Protection
Trace SW4024
Battery-to-Inverter Cables (from Factory Specs)

- Rated AC Output Power: 4000 W (Listed)
- Lowest Battery Voltage: 22 V
- Efficiency: 85% at rated power
- Calculated DC Input Current (with external charger)
  \[ \frac{4000}{22} \div 0.85 = 214 \text{ A} \]
- NEC 125% Factor: \[ 214 \times 1.25 = 267 \text{ A} \]
Cables, Disconnects, Overcurrent Protection
Trace SW4024 (continued)
Battery-to-Inverter Cables

• Assume: 30°C Temperature and 75°C Terminals
• Conduit Required (NEC Table 310.16)
• 300 Kcmil 75°C cable carries 285 A at 30°C
• Parallel 2/0 AWG carries 175 x 2 = 350 A at 30°C
  - 4 conductors in conduit: 80% derating
  - 350 x .8 = 282 A
• Manual suggests single 4/0 AWG cable @ 230 A
Cables, Disconnects, Overcurrent Protection
Trace SW4024 (continued)
DC Overcurrent Devices

- **300 A Fuse**
  - Fused Disconnect
  - Pull-Out Fuse Holder (must be load-break rated—or marked)
  - Use High-AIR fuses throughout the system

- **250-300 A Circuit Breaker** (rated for 100% operation in the enclosure)
  - Cannot protect other overcurrent devices

- **Mounted Near Battery**
Sunwize SW-1200 Hybrid PV System
Inverter Current Waveform (DC Side)

Load Power = 4000 Watts
Battery Voltage = 22.0 Volts

Current Average = -254.2 Amperes
Current RMS = 311.3 Amperes

Southwest Technology Development Institute
Trace SW4024 (continued)
Large Systems

Test Data: At 22 V and 4000 W Resistive Load

Measured Inverter DC Input Current:

Average  254 A
RMS      311 A

RMS currents should be used for sizing cables and overcurrent devices.

Nuisance tripping of circuit breakers rated at 250 A is possible.

If 350-amp fuses are used, cables must be sized appropriately.
Cables, Disconnects, Overcurrent Protection
Trace SW4024 (continued)
AC Output Circuits

- Rated feed through from AC-1 or AC-2: 60 A
- Maximum steady-state output current: 60 A
- Required cable ampacity $60 \times 1.25 = 75$ A
- 4 AWG cable at $30^\circ$C and $75^\circ$C insulation = 85 A
- SW4024 can take 6 AWG maximum: 65 A
- Unusual to have these outputs for hours at a time
- Use 6 AWG, $90^\circ$C cable (65 A at $75^\circ$C)
  - Protect with 70 A breaker rated for 100% duty
No. 8 AWG USE-2 in Free Air

Junction Box
No 2 AWG XHHW-2 in Conduit

50 feet
Control Panel Internal Cables are 6 AWG

No. 2 AWG

Ground Rod

Charge Controller

45 Amp

DC Loads
No. 10-2 with gnd NM

Fused
Disconnet

350 A-H 6-Volt Batteries

---

Equipment Grounding

Surge Arrestor

** Overcurrent Device may be required by UL 1703
Pole-Mounted 30-Amp Circuit Breaker

Current Booster Controller

Pump Motor

No. 8 AWG XHHW-2 in Conduit

System Grounding

No. 10 AWG USE-2 in Free Air

Equipment Grounds

Surge Arrestor

Overcurrent device may be required by UL 1703
No. 8 AWG USE-2 in Free Air

No. 2 AWG XHHW-2 in Conduit

50 feet

Control Panel Internal Cables are 6 AWG

45 Amp

Charge Controller

DC Loads No. 10-2 w/ gnd NM

No. 6 AWG

350 A-H 6-Volt Batteries

--- Equipment Grounding

Surge Arrester

** Overcurrent Device may be required by UL 1703
51W, Isc = 3.25

65°C Module Temperature
No. 10 AWG USE-2 in Free Air

30 Amp Fuses in Pull-Out Holders

60A

Charge Controller

No. 6 AWG THHN

No. 4 AWG THHN

15 A

Inverter

AC Loads

6 V @ 200 A-H each

** Overcurrent Device may be required by UL 1703
All Source Circuit Wiring is No. 10 AWG USE-2

All dc Components must be rated for 600 Volts or Higher.
Equipment Grounds not shown.

Source Circuit #1

Source Circuit #2

No. 10 AWG XHHW-2 in Conduit

Inverter
4000 Watts
120 VAC

No. 8 AWG RHW-2 In Conduit

AC Load Center

12 Modules

22W
Isc=1.8a

12 Modules

3A

30 A

50 A

50 A
Safety Alert
Multiwire Branch Circuits and PV Systems

- Inverters—250 W - 8 kW @ 120 V
- Load Centers—120/240 V @ 100 - 200 A
- Multiwire Branch Circuits—common
- Neutral Overload Possible
Multiwire Branch Circuits
Section 690.10(C)

(c) Single 120-Volt Supply. The inverter output of a stand-alone solar photovoltaic system shall be permitted to supply 120 V to single-phase, 3-wire 120/240 V service equipment or distribution panels where there are no 240 V outlets and where there are no multiwire branch circuits. In all installations, the rating of the overcurrent device connected to the output of the inverter shall be less than the rating of the neutral bus in the service equipment. This equipment shall be marked with the following words:

**WARNING—SINGLE 120 VOLT SUPPLY
DO NOT CONNECT MULTIWIRE BRANCH CIRCUITS!**
Multiwire Branch Circuits
How to Correct the Problem

- Rewire multiwire circuit as separate home runs.
- Connect both ungrounded conductors to a single circuit breaker—wire nut may be required.
- Limit output breaker on inverter to ampacity of multiwire branch circuit neutral. Add warning.
- Add second inverter to get 120/240 V system.
- Use transformer to get 120/240 V output from single inverter.
2008 NEC

- 120% on 690.64(B) for non-dwelling installations
- Revisions to grounding
- Clarification of 250.166, size of DC GEC
- Ground-fault protection on all systems
- “PV Wire” for ungrounded systems
- 5°C Table for 690.7 or use manufacturer’s data
- No requirements for batteries or generators, except…
- Inverter or generator must serve largest connected load
- DC/PV Metallic cable assemblies NOT allowed inside buildings
- Must use proper terminals on fine-stranded, flexible cables
- Grounding electrode required for PV array grounding
PV & NEC
Summary

- NEC applies to most PV systems
- DC-rated equipment is required
- Most wiring methods are familiar
- Cable selection & sizing require added consideration
- Battery circuits need attention to high currents

- The Trinity:
  - PV Designer
  - "Code Familiar" Person
  - The Inspector/Plan Reviewer

- RESULT: Safe, Durable, Reliable and Cost Effective PV SYSTEMS
FOR MORE INFORMATION on
PHOTOVOLTAIC POWER SYSTEMS and the NATIONAL ELECTRICAL CODE

Southwest Technology Development Institute, New Mexico State University
web site: http://www.nmsu.edu/~tdi Go to PV, then Codes and Standards


2008 NEC and NEC Handbook available from NFPA: custserv@nfpa.org http://www.nfpa.org


Home Power Magazine—web site: http://www.homepower.com
Conduit temp data:


Conduit Temperature data:
http://www.copper.org/applications/electrical/building/derating_table.html