June/July 2012

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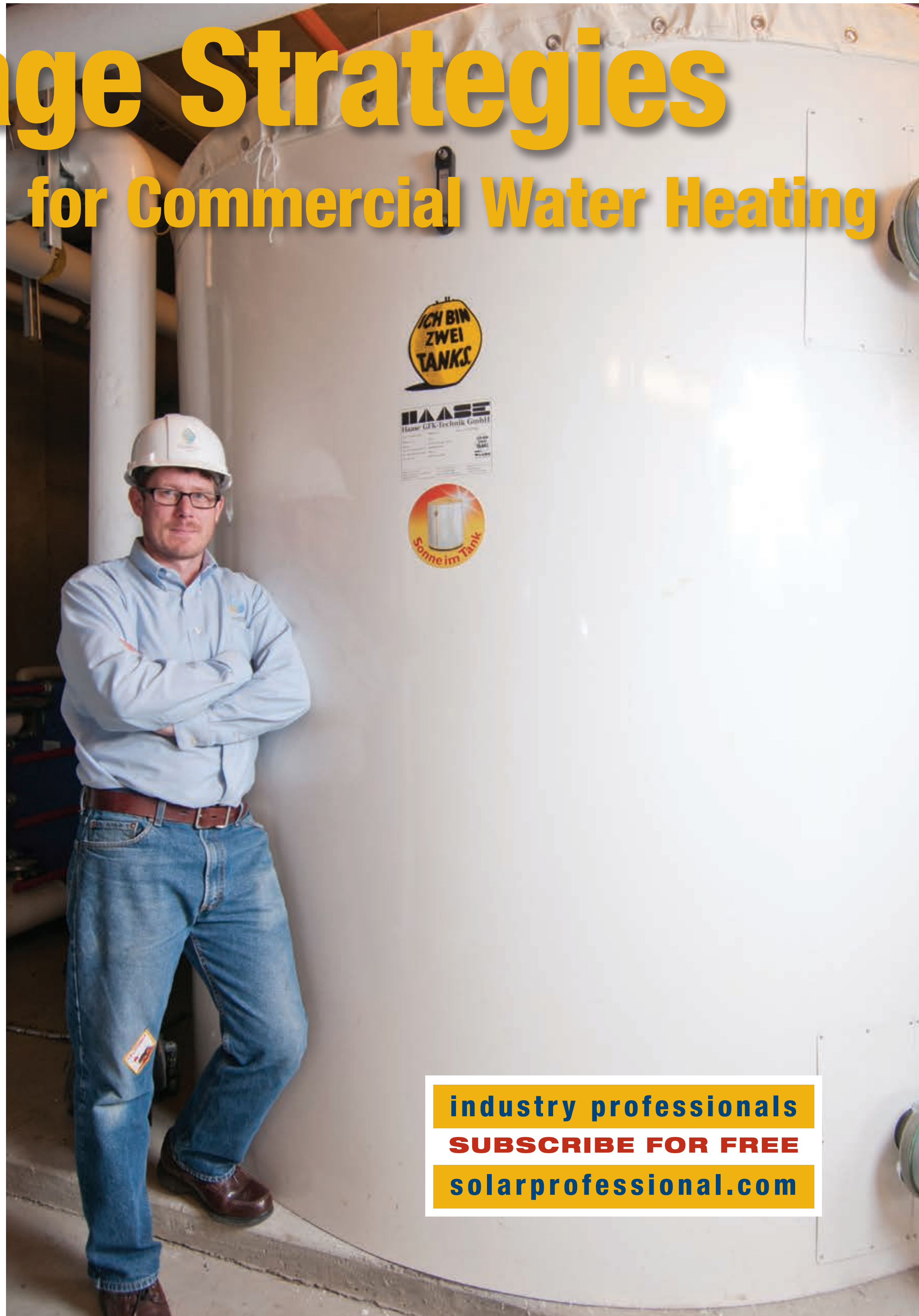

AC Module PV Systems

Understanding *NEC* Requirements for Design & Deployment

Wind Loads On Flat Roofs

Applying Building Codes to Commercial Roof-Mounted Systems

Voltage Rise Considerations

Eliminating Inverter Nuisance Tripping in Grid-Direct Systems

SunWater Solar
Station District Family Housing
Union City, CA

Contributors

Experience + Expertise

Jason Fisher has been earning his living in the PV industry for more than 15 years. From 1996 to 2006, he owned and operated the first fully licensed PV contracting firm in Maryland, where he designed and installed dozens of utility-interconnected PV systems, including his first ac PV module in 1999. Fisher is a licensed master electrician, a NABCEP Certified Solar PV Installer, a UL Certified PV System Installer and an ISPQ Certified Master Trainer with SunPower's ISPQ-accredited PV training program.

Patrick O'Boyle is the director of communications at SunWater Solar, where he manages public relations and marketing efforts, and assists with project management and sales. Previously, O'Boyle managed corporate communications at a Fortune 100 company and worked for several public relations firms in the US and Hong Kong. O'Boyle strives to increase public awareness of commercial solar water heating technology while also attracting new clients to SunWater Solar.

Colleen O'Brien has worked in the PV industry since 1996. She managed the testing and reliability group at PowerLight (now SunPower), where she was responsible for the mechanical and electrical testing of PV modules and mounting hardware, including wind tunnel test programs. O'Brien now works as a principal engineer at BEW Engineering, a DNV company, where she conducts engineering reviews of PV systems. She is a California-licensed mechanical engineer.

Justin Weil, the president of SunWater Solar, has been deeply involved in the solar industry for more than 11 years. Weil specializes in commercial-scale solar water heating applications and has sold, designed, built and commissioned countless projects. A well-respected industry expert, he advises several government entities on solar heating policy issues.

Sean White is a traveling instructor who has been teaching PV design and installation since 2008 for a variety of institutions, including Diablo Valley College in Pleasant Hill, California; Solar University in Livermore, California; Krannich Solar in Mount Laurel, New Jersey; and the Solar Education Center at various locations. He also teaches in Canada and China. In his spare time, White helps private clients install and design PV systems.

Voltage Rise Considerations for Utility-Interactive PV Systems

Voltage rise is a commonly misunderstood concept among PV installers, especially those who have not worked on electrical distribution systems with parallel power supplies, such as a utility-interactive PV system. When a grid-connected inverter produces ac current, the impedance from the grid and inverter output-circuit conductors causes an increase in voltage at the inverter relative to the utility voltage. This phenomenon is commonly referred to as *voltage rise*.

Voltage rise is essentially a negative voltage drop on the circuit between the inverter and the point of common coupling (POCC) that causes the voltage to increase at the inverter ac bus. Greg Smith, technical training specialist at SMA America, points out: "It isn't that the inverter must increase the voltage to push current into the grid, but rather the voltage rises *because* the inverter pushes current into the grid." He explains, "Ohm's Law that V = I x R applies when current is pushed against the impedance of the grid."

Whether you think of this change in voltage as *voltage rise* at the inverter ac bus or *voltage drop* between the inverter ac bus and the POCC, the net effect on system performance is negative and must be considered during system design and specification. For example, the percentage of voltage lost due to voltage drop between the inverter and POCC is proportional to the percentage of power, energy and revenue lost, as illustrated by the following relationships: power = voltage x current; energy = power x time; energy = $.

> Whether you think of this change in voltage as *voltage rise* at the inverter ac bus or *voltage drop* between the inverter ac bus and the POCC, the net effect on system performance is negative and must be considered during system design and specification.

Other impacts are not as easy to quantify and predict. Voltage rise at the ac bus can also cause the inverter to disconnect from the grid if the voltage exceeds its upper ac operating voltage limit. Once the inverter trips and ceases to export current, it must monitor the utility source for at least 5 minutes before attempting to reconnect. Therefore, voltage rise is a potential cause of nuisance tripping and may result in unnecessary system losses or avoidable service calls.

Voltage Limits for Inverters

Inverter type, size and voltage	Voltage range (V)	Clearing time(s) (seconds)
Residential 240 Vac	V < 211.2	2.00
	211.2 < V < 264	operational
	264 < V	1.00
Commercial, 3-phase 208 Vac, <30 kW inverter	V < 104	0.16
	104 < V < 183	2.00
	183 < V < 228.8	operational
	228.8 < V < 249.6	1.00
	249.6 < V	0.16
Commercial, 3-phase 480 Vac, >30 kW inverter	V < 240	0.16 [1]
	240 < V < 422.4	2.00 [1]
	422.4 < V < 528	operational
	528 < V < 576	1.00 [1]
	576 < V	0.16 [1]

[1] Per IEEE 1547 these values may be adjustable in an inverter over 30 kW with utility permission.

Courtesy Solectria Renewables

Table 1 This table shows the grid voltage limits for utility-interactive inverters as required by UL 1741 and IEEE 1547.

Nuisance Tripping

Understanding the interaction between inverter and utility operating-voltage ranges is key to understanding how, when and why nuisance tripping occurs due to voltage rise.

Inverter operating voltage. The UL 1741 safety standard, which is based on IEEE 1547 requirements, defines ac operating voltage range for a utility-interactive inverter as 12% to 10% of the nominal grid voltage. Table 1 shows the voltage trip point according to inverter capacity and service voltage. Per this standard, an inverter must disconnect from the grid when the voltage at the inverter ac bus is outside this range.

For example, consider the typical residential service in the US, which has a nominal voltage of 240 V. Per UL 1741, the minimum inverter ac operating voltage on this service is 12% less than nominal, or 211.2 V (240 V x 0.88), and the maximum inverter ac operating voltage is 10% above nominal, or 264 V (240 x 1.1).

While 211 V to 264 V is the maximum inverter operating range for a 240 V interconnection, the effective range may be somewhat narrower. Some manufacturers intentionally set the upper limit of their inverter operating-voltage range 9% above nominal to ensure that their inverters do not fail UL compliance tests. Therefore, to be conservative, designers may want to assume that the effective upper voltage limit for a 240 V service is actually 109% of nominal, or 261.6 V (240 V x 1.09).

Service voltage range. While the inverter operating-voltage range is set by the manufacturer in relation to the nominal service voltage, the actual grid voltage maintained by the utility fluctuates. The American National Standards Institute (ANSI) defines the voltage tolerance for electric power systems in ANSI C84.1. There are two voltage ranges defined in this standard: Range A is the optimal service voltage range, and Range B is the acceptable service voltage range. According to ANSI C84.1, the maximum Range A service voltage is 105% of nominal, and the maximum Range B service voltage is 105.8% of nominal.

Compound effects. When the utility service voltage is at the high end of its operating range, the likelihood of inverter nuisance tripping due to voltage rise increases. Again, consider a 240 V nominal residential interconnection. If the utility is operating at the high end of ANSI Range A, then the service voltage that the inverter is interconnecting to could be as high as 252 V (240 V x 1.05). Since occasional "voltage excursions" are allowed into Range B, the utility would consider a service voltage of 254 V (240 V x 1.058) to be acceptable. Under these circumstances, 3% or 4% of voltage rise at the ac input bus could cause the inverter to disconnect from the utility grid.

Fortunately, most PV systems are designed to have less than 3% to 4% voltage rise on the inverter output-circuit conductors. This is in part due to the relatively high cost of PV-generated kilowatt-hours, which incentivizes system designers to optimize system efficiency. In addition, Informational Notes found in *NEC* Sections 210.19(A) and 215.2(A) suggest that "reasonable efficiency of operation" is achieved if voltage drop is kept under 3% in branch circuits and feeders, and under 5% overall.

However, the inverter output circuits are not the only source of resistance in a grid-connected PV system. John Berdner, general manager for North America at SolarBridge, explains: "The resistance is the sum of impedance of the wire plus the impedance of the grid." He continues, "In our testing, we have found that grid impedances range from a high of around 0.4 Ω in an older 100 A residential service to 0.1 Ω or less in larger services."

The potential for increased grid impedance is of particular interest. Following the 120% allowance found in Section 705.12(D)(2), a 100 A–rated residential service accommodates a 20 A circuit breaker on the inverter output circuit. Since this overcurrent protection device needs to be rated to carry 125% of the inverter continuous output current, the interconnected inverter can be capable of exporting 16 A (20 A x 0.8) at full power. Therefore, on a residential service with relatively high impedance, like the one tested by SolarEdge, the voltage rise (V = I x R) could be as high as 6.4 V (16 A x 0.4 Ω), or 2.67%, before wire losses in the inverter output circuit are factored into the equation.

Berdner points out that the compound effects of high service voltage (+5% to 6%) and voltage rise between the inverter and the utility grid at full power (+3% to 4%) are such that everything could be designed and operating correctly, and yet the system could be on the verge of nuisance tripping—especially if the inverter is conservatively set to trip at 109% of the nominal service voltage. CONTINUED ON PAGE 18

> "Wire size is low-hanging fruit when it comes to improving system performance. The best inverters today are approaching 99% peak efficiency and have CEC-weighted efficiencies of 97.5% to 98%. This means that wire losses in the system can exceed inverter losses."
>
> **—John Berdner, SolarEdge**

Getting down to the Wire

With the formulas shown in this article, you can calculate the percentage of voltage drop in a circuit based on the conductor size used. However, this is backward. Designers often know what percentage of voltage drop they want in the circuit and are instead solving for the conductor size needed to achieve this goal.

Here is a shortcut to solve directly for the desired conductor resistance in a single-phase application:

$$R = (5 \times \%V_{drop} \times V_{nom}) \div (I \times D)$$

where R is the conductor resistance in Ω/kFT as found in *NEC* Chapter 9, Table 8; $\%V_{drop}$ is the desired maximum voltage drop or voltage rise percentage; V_{nom} is the nominal service voltage; I is the maximum circuit current; and D is the one-way distance of the circuit in feet.

This is a derived equation based on the Ohm's Law method of calculating the percentage of voltage drop in a circuit. With this formula, you can quickly select a conductor based on specific voltage drop goals. This formula works for both dc and single-phase ac circuits.

Here is an example based on the percentage of voltage rise desired in a 6 kW residential inverter output circuit:

Inverter: 6 kW, 240 Vac 1Ø, 25 A
Inverter-to-POCC distance: 225 feet
Percent voltage drop: 1.0%

R = (5 x 1.0 x 240) ÷ (25 x 225)
= (1,200) ÷ (5,625)
= 0.21 Ω/kFT

You then use this result to look up a conductor in *NEC* Chapter 9, Table 8. In this case, you are looking for a coated copper conductor with a resistance less than or equal to 0.21 Ω/kFT. The following values are closest:

3 AWG = 0.25 Ω/kFT
2 AWG = 0.20 Ω/kFT

Since 2 AWG has resistance less than 0.21 Ω/kFT, using this size conductor ensures that the voltage rise remains less than 1% under full power conditions.

Unlike wire losses in general, the impacts of nuisance tripping due to high-grid–voltage errors are not linear and predictable. Utility-interactive systems with long ac wire runs are particularly vulnerable.

Design Recommendations

While it is difficult for system designers and installers to change the grid impedance or maximum service voltage at a site, other variables such as inverter location, inverter output-circuit length and conductor size are within their control. In many cases, the negative performance impacts of voltage rise can be mitigated or effectively eliminated by minimizing the length of and resistance in the ac output conductor.

Reduce conductor length. To the extent that it is possible or practical to do so, locate inverters close to the point of service. According to Berdner, "Reducing the length of the inverter output conductor minimizes the voltage rise in the ac wiring and therefore reduces nuisance tripping due to high ac voltage." This is often the simplest and most cost-effective solution to potential voltage rise problems.

Increase conductor area. System designers can also oversize the inverter output-circuit conductor to further minimize voltage rise. Berdner recommends that designers limit voltage rise in the ac output circuit of residential and small commercial PV systems to 1.5% or less, rather than the typical 3%. However, he notes, "In a large system, you would probably do an LCOE analysis to determine the optimal wire size."

You can find additional principles and design strategies for minimizing voltage drop and controlling associated costs in Blake Gleason's QA article "Voltage Drop in PV Systems" (February/March 2010, *SolarPro* magazine). While these are good general guidelines, inverter output-circuit specification deserves careful consideration with regard to voltage rise.

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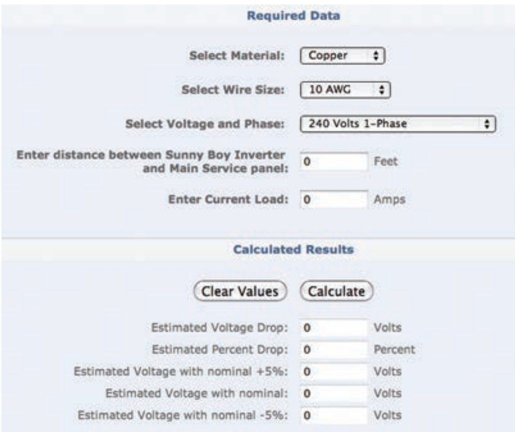
Courtesy Calculated Industries and SMA America



Design aids Products like SMA's free online Voltage Drop Calculator (left) or the Electri-Calc Pro from Calculated Industries (right) allow system designers and installers to quickly estimate maximum voltage drop in ac circuits.

tripping exists, best practice is to design conservatively.

Design Calculations

Veteran system designers have the design tools necessary for determining voltage drop—and hence voltage rise—on inverter output circuits. If you do not have a preferred design tool, you can choose among several free online tools, such as SMA America's Voltage Drop Calculator (america .sma.de/vdropcalculator.html). Calculated Industries (calculated.com) offers the ElectricCalc Pro, an electrical code calculator, that can solve for voltage drop either in volts or as a percentage; alternately, if a desired percentage of voltage drop is specified, the calculator can solve for the required conductor size. Wire sizing software programs are also available commercially.

Even if you are using online tools, it is helpful to know how to manually calculate voltage drop in a circuit. Ohm's Law describes the basic formula as V = I x R. In the article "Don't Let Voltage Drop Get Your System Down" (June 2004, *EC&M* magazine), *NEC* consultant Mike Holt illustrates how Ohm's Law can be applied to single-phase ac circuits with 1/0 AWG and smaller conductors. To do so, refer to the dc resistance values found in *NEC* Chapter 9, Table 8. Since these values are listed in ohms per 1,000 feet (Ω/kFT) of conductor, you can use simple algebra to determine the resistance based on the round-trip circuit length.

If, for example, the previously mentioned 240 V utility-interactive inverter with a 16 A continuous output current was installed 100 feet from the POCC—for a roundtrip distance of 200 feet—using 12 AWG copper conductors, the voltage drop in the wires would be calculated using Ohm's Law as follows:

$$
\begin{aligned}
V_{drop} &= I \times R \\
&= 16\ A \times (2.01\ \Omega/kFT \times 0.2\ kFT) \\
&= 16\ A \times 0.4\ \Omega \\
&= 6.4\ V
\end{aligned}
$$

To convert this result to a percentage, divide the voltage drop by the nominal service voltage and multiply by 100:

$$
\begin{aligned}
\%V_{drop} &= (6.4\ V \div 240\ V) \times 100 \\
&= 2.7\%
\end{aligned}
$$

Even though 2.7% voltage drop is within the *NEC* recommendations, this design could result in nuisance tripping if coupled with high service voltage at a site with higher-grid impedance. Increasing the inverter output-circuit conductors to 10 AWG reduces the voltage drop to 1.7%.

Holt also provides more-descriptive formulas for single-phase and 3-phase voltage drop:

$$1Ø\ V_{drop} = (2 \times K \times Q \times I \times D) \div CM$$
$$3Ø\ V_{drop} = (\sqrt{3} \times K \times Q \times I \times D) \div CM$$

where *K* is a constant that represents the dc resistance for a 1,000-foot conductor with an area of 1,000 circular mils at 75°C (K = 12.9 Ω for copper and 21.2 Ω for aluminum); *Q* is an alternating current adjustment factor that must be applied to conductors 2/0 AWG and larger to account for self-induction (the "skin effect"); *D* is the one-way distance of the circuit in feet; and *CM* is the circular mils of the conductor as listed in *NEC* Chapter 9, Table 8. When using these formulas with conductors 2/0 AWG and larger, the ac adjustment factor, *Q*, is calculated by dividing the ohms-to-neutral impedance found in *NEC* Chapter 9, Table 9, by the dc resistance from Chapter 9, Table 8.

Since inverters operate with a power factor near unity (PF = 1.0) and have relatively small output-circuit conductors (1/0 AWG or less), the Ohm's Law method of calculating voltage drop is applicable in many instances.

—Sean White / Solar Education Center/ Lafayette, CA / pvstudent.com

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