Application Note

Calculating ac line voltage drops

Purpose

This paper describes the methods for calculating the ac line voltage drop (V_{Drop}) for dedicated PV branch circuits. Calculations are provided for 240vac split-phase and 208 three phase circuits. The IEEE-1547 standard requires that utility interactive inverters cease to export power if the voltage measured at the Point of Common Connection (PCC) exceeds +10% or -12% of nominal. The point of reference for voltage measurement is at each Microinverter AC output. Since the Microinverter is located at the array, the distance to the PCC could be substantial. Undersized conductors can cause the voltage measured at the Microinverter to be outside of the IEEE limits, causing the Microinverter to enter an AC Voltage out of Range condition (ACVOOR). Proper voltage drop calculations will help to avoid nuisance trip issues due to high line voltage conditions.

Overview

All components of system wiring loss must be considered. Typically, three wire sections and several wire terminations must be quantified. There is also some resistance associated with each OCPD (OverCurrent Protective Device, typically a Circuit Breaker). As all of these resistances are in series, they add together. Since the same current is flowing through each resistance, the total voltage drop is simply the total current times the total resistance. For the 240 split-phase system, the total resistance is equal to two times the one-way resistance. For a three-phase system, each of the 3 line currents and resistances must be calculated.

Why is wire sizing so important? because improper wire size can result in nuisance tripping of the inverter's Utility Protective Functions. This results in the loss of energy harvest by the PV system. The National Electric Code requires that branch circuit conductors be sized for a maximum 3% voltage drop (Article 210.19). This is not adequate for a utility interactive inverter.

A microinverter system behavior differs significantly from a string/central inverter during marginally high utility voltage conditions. A central inverter will trip off-line and cease generation of power when a high line voltage condition is detected. When this happens, the entire array connected to the central inverter is no longer providing power. It becomes a stranded resource. Of course, once the inverter ceases production, the voltage at the inverter drops within normal range, and the inverter reconnects to the utility grid and begins exporting power typically within 5 minutes. However, if the utility voltage at the PCC is still marginally high, the inverter will trip off-line once again, and the entire process repeats itself.

A microinverter system consists of multiple inverters, each with its' own utility voltage detection circuit. Each of these circuits may have the same intended upper voltage trip level, but due to manufacturing and component variances, and due to each inverter's location in the branch circuit, each inverter will actually trip off-line at a slightly different utility voltage as measured at the PCC. This is somewhat self healing, as the line voltage declines slightly as each microinverter ceases power production. And, the entire array is not taken off-line, only a small portion of it. Wire size, circuit current, and voltage margin are the elements which must be considered. Larger wire size, lower circuit currents, shorter circuit lengths, and higher voltage margins reduce nuisance tripping due to marginally high PCC voltages.

Details

Enphase Microinverter systems are installed as dedicated branch circuits. Each dedicated branch circuit is protected by a 15A (M190, M210) or 20A (D380) OverCurrent Protective Device (i.e. circuit breaker).

Now let's analyze each of the elements that contribute to voltage rise.

Wire size – We have some control over this. There is obviously a tradeoff to be made between increased wire size and increased cost. Often, the wire size can be increased by one AWG with minimal cost impact. At some point, however, increasing wire size demands increased conduit and/or terminal sizes, resulting in significant cost increases.

Circuit current – The circuit currents will vary, depending on their position in the installation. A typical installation will contain three circuit sections.

Circuit length – There is often little choice in circuit length. Center feeding the dedicated branch circuit can help significantly to reduce voltage rise within the branch.

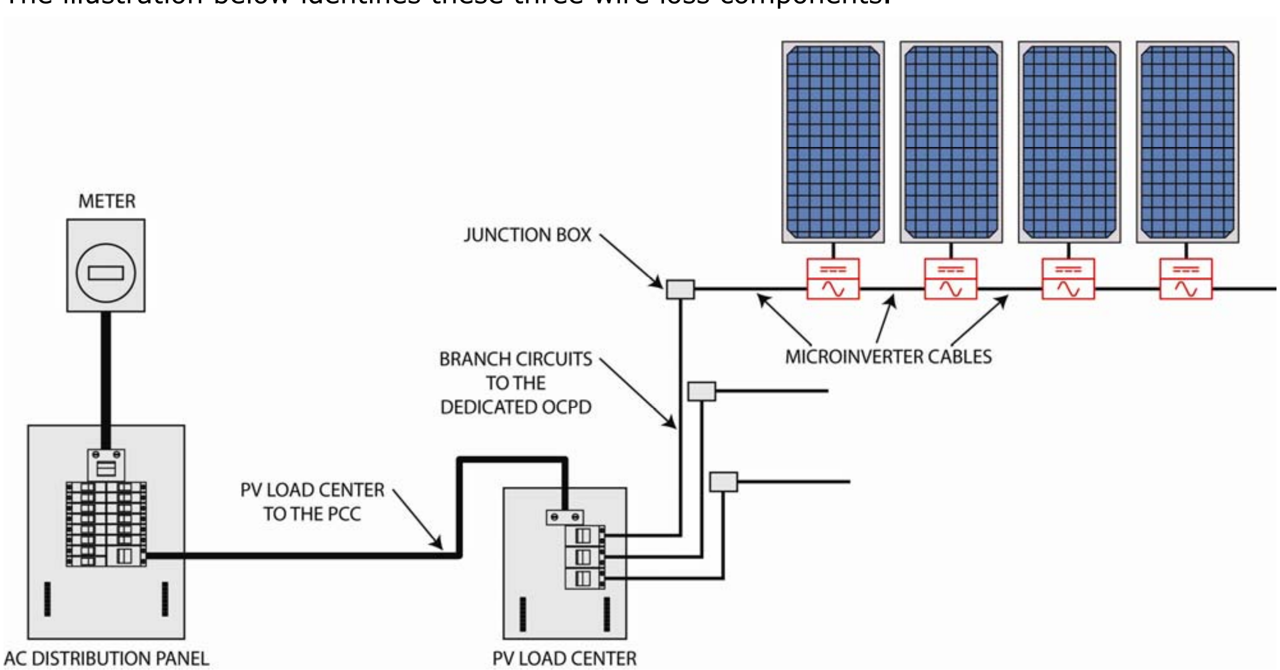
Voltage margin – Not much that the system designer or installer can do here. If the service voltage is chronically high, the utility will sometimes perform a tap change on the distribution transformer. This may provide a percent or two of additional voltage margin.

Utility Voltage – The utility strives to maintain voltage at the PCC within +/- 5% of nominal. The protective functions of the inverters are set to +10%/-12% by default. Our concern, because the inverters are a SOURCE, and not a LOAD, is at the high voltage end of the tolerance. If the utility is consistently 5% high, that leaves only 5% for all wiring and interconnection losses, and inverter measurement accuracy.

A typical installation will have three voltage loss components which must be considered:

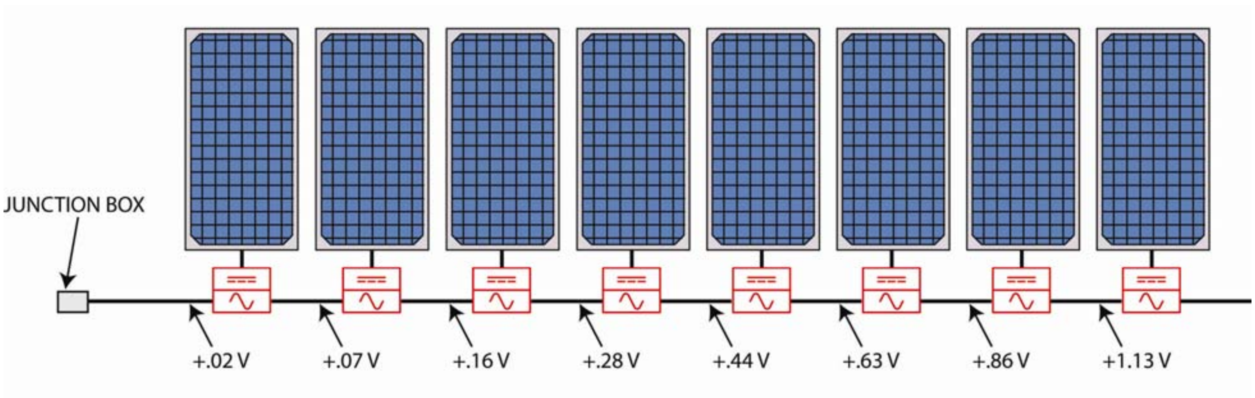
1 – Internal voltage drop within the Microinverter cables.
2 – Voltage drop from the beginning of the branch circuit to the dedicated OCPD.
3 – Voltage drop from the PV load center to the PCC.

The illustration below identifies these three wire loss components.

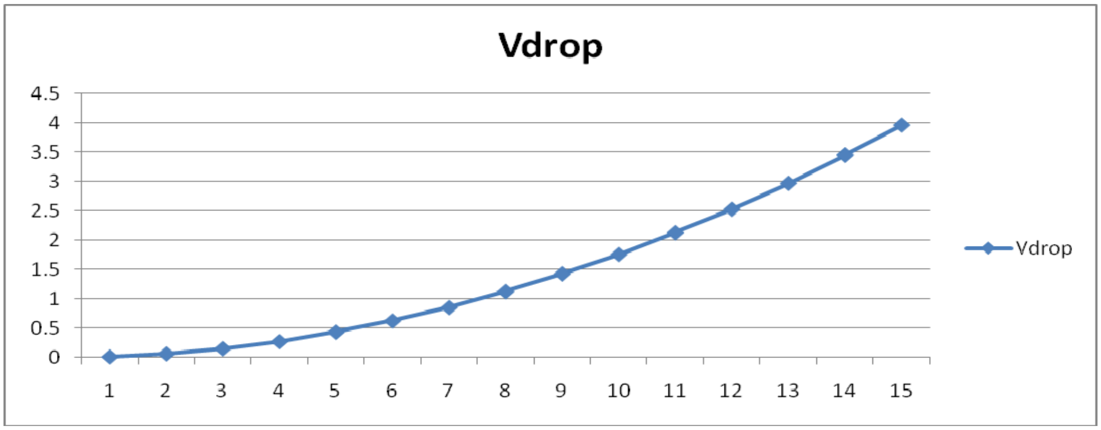


Internal voltage drop within the Microinverter cables

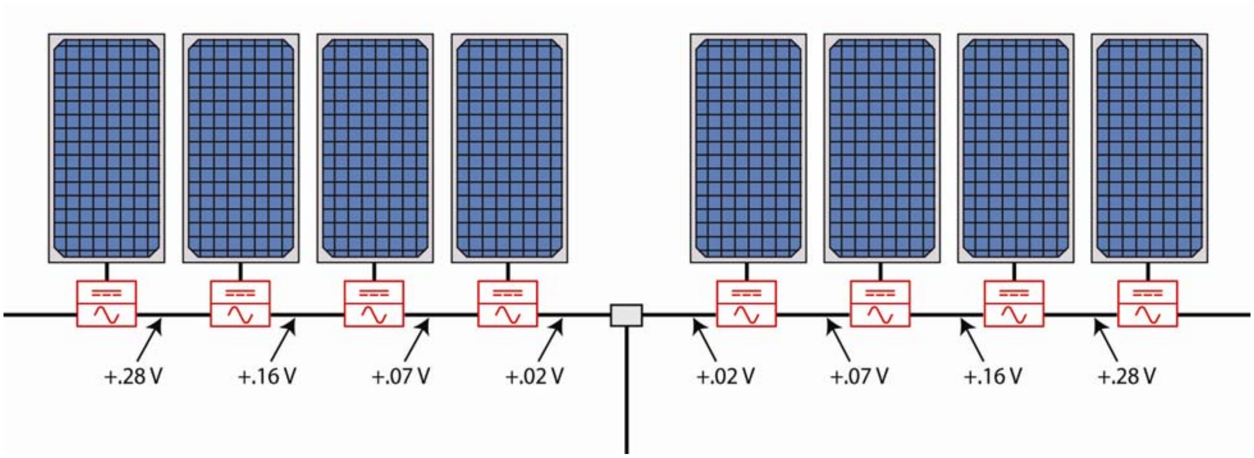
Voltage drop within the microinverter branch circuit can be easily determined. The diagram below represents a branch circuit that is "end fed" and illustrates how the voltages measured at the individual Microinverters increase with their position in the branch circuit.



As Microinverters are added to the branch circuit, the voltage drop increase is non-linear. The graph below illustrates how the voltages measured at the individual Microinverters increase in a fully populated branch circuit of 15 M190 Microinverters.



Since the voltage drop is non-linear, reducing the number of Microinverters in the branch circuit greatly reduces the voltage measured at the last Microinverter in the branch. One way to minimize this voltage drop is to "center feed" the branch. The diagram below illustrates the "center fed" method.



A fully populated "center fed" branch circuit could still have 15 M190 Microinverters with 8 connected end to end and 7 connected end to end meeting in the same junction box. The longest portion would be 8 microinverters, the last Microinverter in the branch circuit would measure a 1.13 volt increase instead of a 3.96 volt increase measured with 15 Microinverters end to end. Center feeding requires 2 AC interconnect cables per branch circuit. The AC Interconnect cables would be connected in parallel in each junction box, all.L1s connected together, all L2s connected together, etc.

Single Phase Calculations

Internal voltage drop within the Microinverter cables, M190, 240 Vac, single phase

	Microinverters per branch														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Vdrop	.02	.07	.16	.28	.44	.63	.86	1.13	1.43	1.76	2.13	2.53	2.97	3.45	3.96
%	.01	.03	.07	.12	.18	.26	.36	.47	.59	.73	.89	1.06	1.24	1.44	1.65

Internal voltage drop within the Microinverter cables, M210, 240 Vac, single phase

	Microinverters per branch												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Vdrop	.02	.08	.17	.31	.48	.7	.95	1.24	1.57	1.94	2.34	2.79	3.27
%	.01	.03	.07	.13	.2	.29	.4	.52	.65	.81	.98	1.16	1.36

Internal voltage drop within the Microinverter cables, D380, 240 Vac, single phase

	Microinverters per branch									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Vdrop	.02	.09	.2	.35	.55	.79	1.08	1.41	1.79	2.21
%	.01	.04	.08	.15	.23	.33	.45	.59	.75	.92

Voltage drop from the beginning of the branch circuit to the dedicated OCPD.

Calculating the voltage drop in this portion of the circuit is determined by multiplying the combined current of the Microinverters in the branch by the total resistance of the wire run.

Vdrop = (amps/inverter x # of inverters) x (Ω/ft x length)

The example below is for a fully populated branch circuit of 15 M190 Microinverters.

M190 full load current = .8 amps
Wire gauge for individual branch circuit = 10 AWG
10 AWG resistance = .00124/ft
Length of individual branch circuit = 40 feet

Vdrop = (.8 x 15) x (.00124 x 40)
= 12 x .0496
= .59 volts

In a single phase circuit the voltage drop needs to be considered for both current carrying conductors, so the total voltage drop would be .59 volts x 2 or 1.18 volts.

Voltage drop from the PV load center to the PCC.

Calculating the voltage drop in this portion of the circuit is determined by multiplying the combined current of all the Microinverters in the array by the total resistance of the wire run.

Vdrop = (amps/inverter x # of inverters) x (Ω/ft x length)

The example below is for 3 fully populated branch circuits of 15 M190 Microinverters.

M190 full load current = .8 amps
Wire gauge for individual branch circuit = 4 AWG
4 AWG resistance = .000308/ft
Length of individual branch circuit = 80 feet

Vdrop = (.8 x 45) x (.000308 x 80)
= 36 x .0246
= .88 volts

In a single phase circuit the voltage drop needs to be considered for both current carrying conductors, so the total voltage drop would be .88 x 2 or 1.77 volts.

Single Phase Summary

With the utility operating at the upper limit of their allowable tolerance or +5% and the microinverters having a measurement accuracy of 2.5%, we are left with a voltage drop budget of 5.4 volts for all wiring to the PCC. The calculated voltage drops for all 3 portions the system must be 5.4 volts or less. For systems with long branch circuit runs and or long runs from the PV load center to the PCC it is best to make the Vdrop in the microinverter cabling as small as possible. The best way to reduce Vdrop in the microinverter cabling is to center feed the branch circuits to allow for larger Vdrop in the home run circuits.

Voltage drop from the beginning of the branch circuit to the dedicated OCPD = 1.18 volts
Voltage drop from the PV load center to the PCC = 1.77 volts

Voltage drop in the wiring external to the Microinverter equals 2.95 volts in the example above, so the voltage drop in the Microinverter cabling would need to be 2.45 volts or less. The number of Microinverters could not exceed 11 for an “end=fed” branch circuit.

Three Phase Calculations

Internal voltage drop within the Microinverter cables, M190, 208 Vac, 3 Phase

	Microinverters per branch						
	3	**6**	**9**	**12**	**15**	**18**	**21**
Vdrop	.05	.1	.31	.63	1.04	1.57	2.19
%	.02	.05	.15	.3	.5	.75	1.05

Internal voltage drop within the Microinverter cables, M210, 208 Vac, 3 Phase

	Microinverters per branch					
	3	**6**	**9**	**12**	**15**	**18**
Vdrop	.05	.11	.34	.69	1.14	1.71
%	.02	.05	.16	.33	.55	.82

Internal voltage drop within the Microinverter cables, D380, 208 Vac, 3 Phase

	Microinverters per branch				
	3	**6**	**9**	**12**	**15**
Vdrop	.06	.13	.39	.77	1.29
%	.03	.06	.19	.37	.62

Voltage drop from the beginning of the branch circuit to the dedicated OCPD.

Calculating the voltage drop in this portion of the circuit is determined by multiplying the combined current of the Microinverters per phase in the branch by the total resistance of the wire run. The microinverter cabling rotates the microinverters around the phase conductors. If the total number of inverters on a branch circuit is evenly divisible by 3, the currents will be balanced. For a fully populated branch circuit of 21 M190 Microinverters, there would be 7 per phase. Since the phase currents are out of phase with each other by 120°, the phase currents would be multiplied by the square root of 3 or 1.73 to obtain the line currents.

$$\text{Vdrop} = (\text{amps/inverter} \times \text{\# of inverters/phase} \times \sqrt{3}) \times (\Omega/\text{ft} \times \text{length})$$

The example below is for a fully populated branch circuit of 21 M190 Microinverters.

M190 full load current = .92 amps
Wire gauge for individual branch circuit = 10 AWG
10 AWG resistance = .00124/ft
Length of individual branch circuit = 40 feet

Vdrop = (.92 x 7 x 1.73) x (.00124 x 40)
= 11.14 x .0496
= .55 volts

Voltage drop from the PV load center to the PCC.

Calculating the voltage drop in this portion of the circuit is determined by multiplying the combined current of all the Microinverters per phase in the array by the total resistance of the wire run. Three fully populated branch circuit of 21 Microinverters would each have 7 microinverters per phase for a total of 21 per phase.

Vdrop = (amps/inverter x # of inverters/phase x √3) x (Ω/ft x length)

The example below is for 3 fully populated branch circuits of 21 M190 Microinverters.

M190 full load current = .92 amps
Wire gauge for individual branch circuit = 4 AWG
4 AWG resistance = .000308/ft
Length of individual branch circuit = 80 feet

Vdrop = (.92 x 21 x 1.73) x (.000308 x 80)
= 33.4 x .0246
= .82 volts

Three Phase Summary

With the utility operating at the upper limit of their allowable tolerance or +5% and the microinverters having a measurement accuracy of 2.5%, we are left with a voltage drop budget of 4.88 volts for all wiring to the PCC. The calculated voltage drops for all 3 portions the system must be 4.88 volts or less. For systems with long branch circuit runs and or long runs from the PV load center to the PCC it is best to make the Vdrop in the microinverter cabling as small as possible. The best way to reduce Vdrop in the microinverter cabling is to center feed the branch circuits to allow for larger Vdrop in the home run circuits.

Voltage drop from the beginning of the branch circuit to the dedicated OCPD = .55 volts
Voltage drop from the PV load center to the PCC = .82 volts

Voltage drop in the wiring external to the Microinverter equals 1.37 volts in the example above, so the voltage drop in the Microinverter cabling would need to be 3.51 volts or less. An “end=fed” branch circuit should work well in this example.

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