Matching Array/Inverters and Energy Yield in a Grid Connected PV system.

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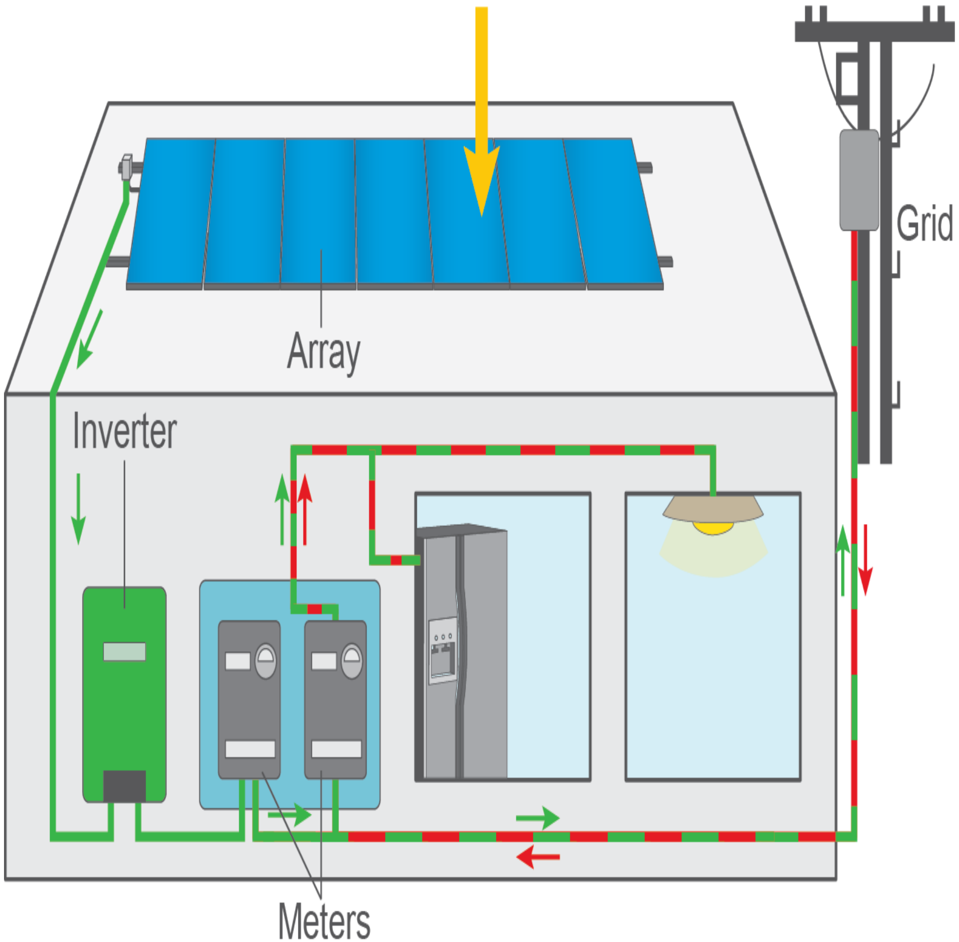
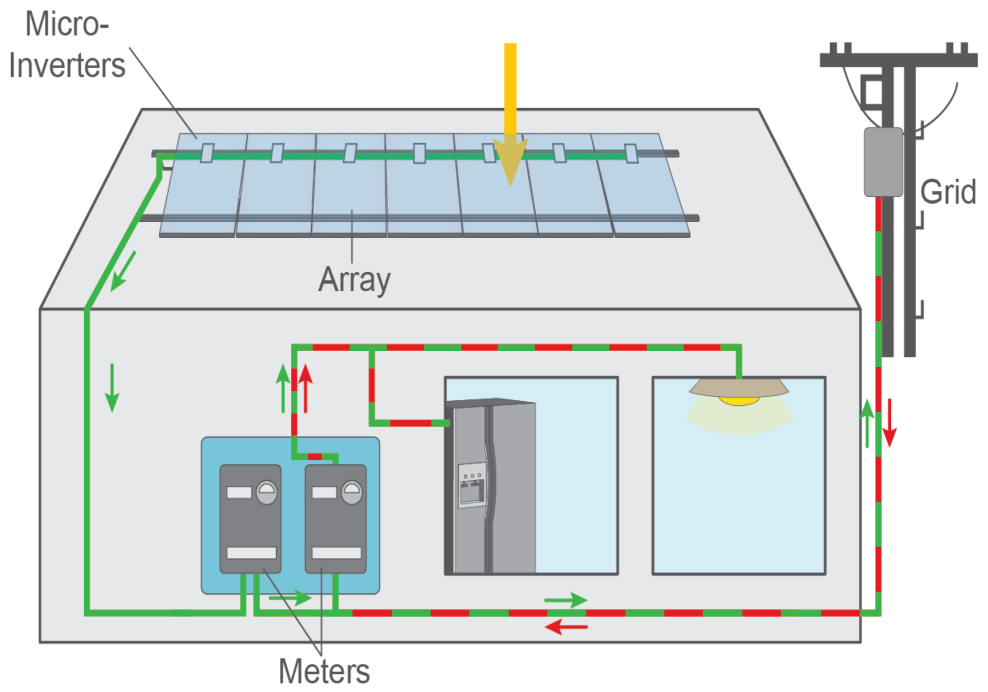
COMPONENTS OF A GRID CONNECTED PV SYSTEM – STRING INVERTER



COMPONENTS OF A GRID CONNECTED PV SYSTEM – MODULE INVERTER



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SELECTING THE SIZE OF INVERTER

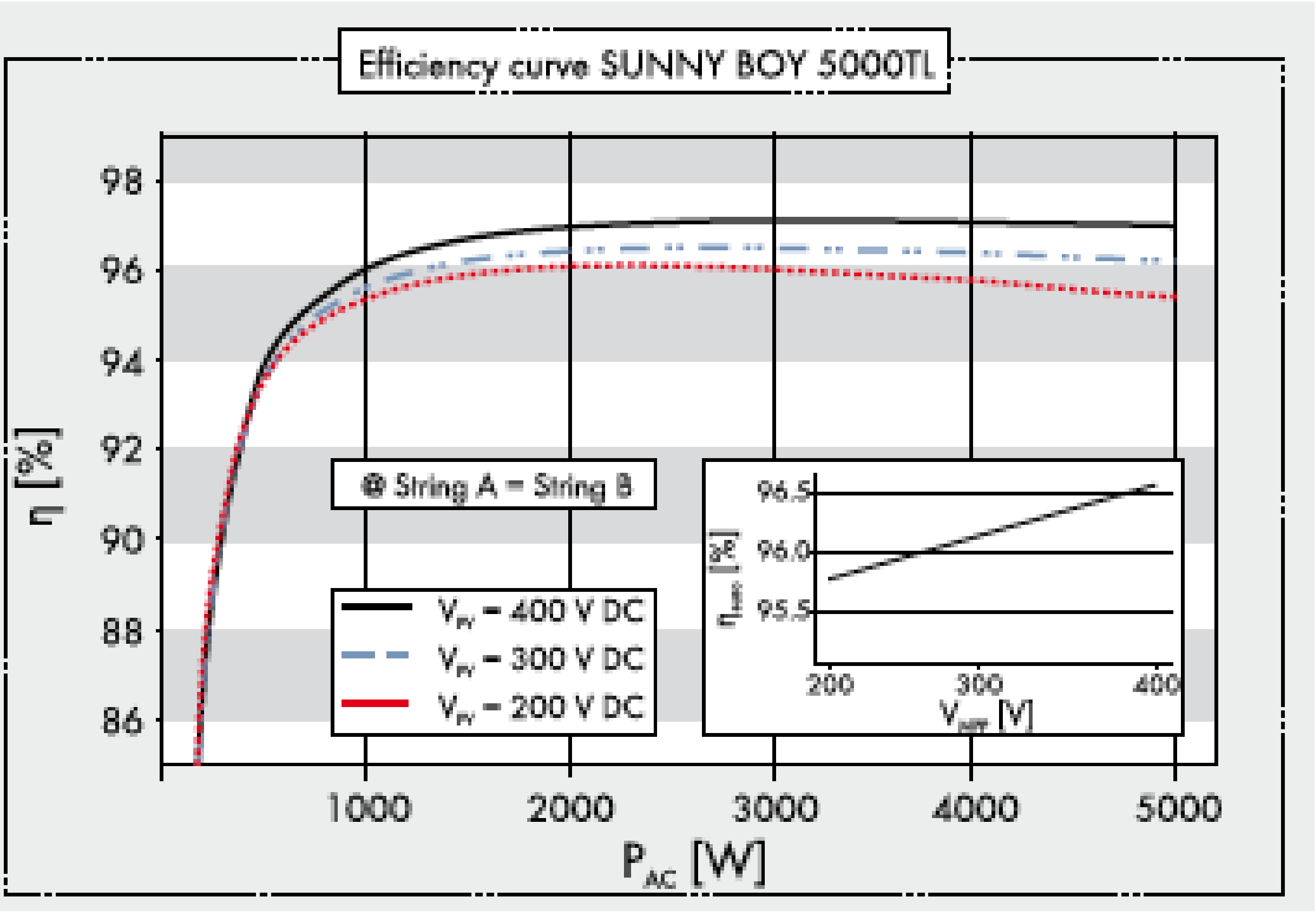
The array and the inverter must be matched to function properly. Inverters currently available are typically rated for:

- **maximum dc input power;**
- **maximum specified output ac power;**
- **maximum dc input voltage;**
- **minimum dc MPPT operating voltage;**
- **maximum dc MPPT operating voltage and**
- **maximum dc input current.**

EXAMPLE DATA SHEET

Technical data	Sunny Boy 3000TL	Sunny Boy 4000TL	Sunny Boy 4000TL/V	Sunny Boy 5000TL
Input (DC)				
Max. DC power (@ cos φ =1)	3200 W	4200 W	4200 W	5300 W
Max. DC voltage	550 V	550 V	550 V	550 V
MPP voltage range	188 V - 440 V	175 V - 440 V	175 V - 440 V	175 V - 440 V
DC nominal voltage	400 V	400 V	400 V	400 V
Min. DC voltage / start voltage	125 V / 150 V	125 V / 150 V	125 V / 150 V	125 V / 150 V
Max. input current / per string	17 A / 17 A	2 x 15 A / 15 A	2 x 15 A / 15 A	2 x 15 A / 15 A
Number of MPP trackers / strings per MPP tracker	1 / 2	2 / A: 2, B: 2	2 / A: 2, B: 2	2 / A: 2, B: 2
Output (AC)				
AC nominal power (@ 230 V, 50 Hz)	3000 W	4000 W	3680 W	4600 W
Max. AC apparent power	3000 VA	4000 VA	4000 VA	5000 VA
Nominal AC voltage; range	220, 230, 240 V; 180 - 280 V	220, 230, 240 V; 180 - 280 V	220, 230, 240 V; 180 - 280 V	220, 230, 240 V; 180 - 280 V
AC grid frequency; range	50, 60 Hz; ± 5 Hz	50, 60 Hz; ± 5 Hz	50, 60 Hz; ± 5 Hz	50, 60 Hz; ± 5 Hz
Max. output current	16 A	22 A	22 A	22 A
Power factor (cos φ)	1	1	1	1
Phase conductors / connection phases	1 / 1	1 / 1	1 / 1	1 / 1
Efficiency				

EFFICIENCY CURVE



EXAMPLE DATA SHEET

Technical data	Sunny Boy 3.0	Sunny Boy 3.6	Sunny Boy 4.0	Sunny Boy 5.0
Input (DC)				
Max. generator power	5500 Wp	5500 Wp	7500 Wp	7500 Wp
Max. input voltage	600 V			
MPP voltage range	110 V to 500 V	130 V to 500 V	140 V to 500 V	175 V to 500 V
Rated input voltage	365 V			
Min. input voltage / initial input voltage	100 V / 125 V			
Max. input current input A / input B	15 A / 15 A			
Max. input current per string input A / input B	15 A / 15 A			
Number of independent MPP inputs / strings per MPP input	2 / A:2; B:2			
Output (AC)				
Rated power (at 230 V, 50 Hz)	3000 W	3680 W	4000 W	5000 W[1)]
Max. apparent power AC	3000 VA	3680 VA	4000 VA	5000 VA[2)]
Nominal AC voltage / range	220 V, 230 V, 240 V / 180 V to 280 V			
AC power frequency / range	50 Hz, 60 Hz / −5 Hz to +5 Hz			
Rated power frequency / rated grid voltage	50 Hz / 230 V			
Max. output current	16 A	16 A	22 A[2)]	22 A[2)]
Power factor at rated power	1			
Adjustable displacement power factor	0.8 overexcited to 0.8 underexcited			
Feed-in phases / connection phases	1 / 1			
Efficiency				
Max. efficiency / European Efficiency	97.0% / 96.4%	97.0% / 96.5%	97.0% / 96.5%	97.0% / 96.5%

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SELECTING THE SIZE OF INVERTER

To reach the operating voltage of the inverter MPPT, usually a number of modules must be connected in series.

The number of modules in a string, and hence maximum and minimum voltages of the string, must be matched to the inverters:

- **maximum dc input voltage; and**
- **minimum dc MPPT operating voltage.**

SELECTING THE SIZE OF INVERTER II

- To reach the highest level of dc current that the MPPT can accept from the array it may be necessary to connect strings of modules in parallel.
- The number of parallel strings, and hence maximum dc currents must not exceed the maximum input current allowed for the MPPT that is connected to those strings.

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SELECTING THE SIZE OF INVERTER III

- The maximum power rating of the array must be matched to the power rating of the inverter.

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MATCHING ARRAY POWER TO THE INVERTER 1

- The maximum power of the array is calculated by the following formula:

Array Peak Power = Number of modules in the array x the rated maximum power (P_{mod}) of each module at STC.

MATCHING ARRAY POWER TO THE INVERTER 2

- If the inverter data sheet does specify the maximum array power, then the designer shall not design an array with rated peak power greater than the specified maximum array power.

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WORKED EXAMPLE 1

An array consists of fourteen(14) modules with a peak rating of $275W_p$.

The inverter data sheet for the SB3.0 provides the following information:

Max AC Output Power	3000W
Max Generator Power (PV Array)	$5500W_p$

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WORKED EXAMPLE 1 Solution

- The Array Peak Power = 14 x 275W = 3850Wp.

This is less than 5500W max generator power allowed.

- It is also above the AC rating of the inverter so allowing for losses (temperature effect, inverter efficiency, voltage drop, dirt etc) it could operate at its full 3000W rating at times.

MATCHING ARRAY VOLTAGE TO THE INVERTER

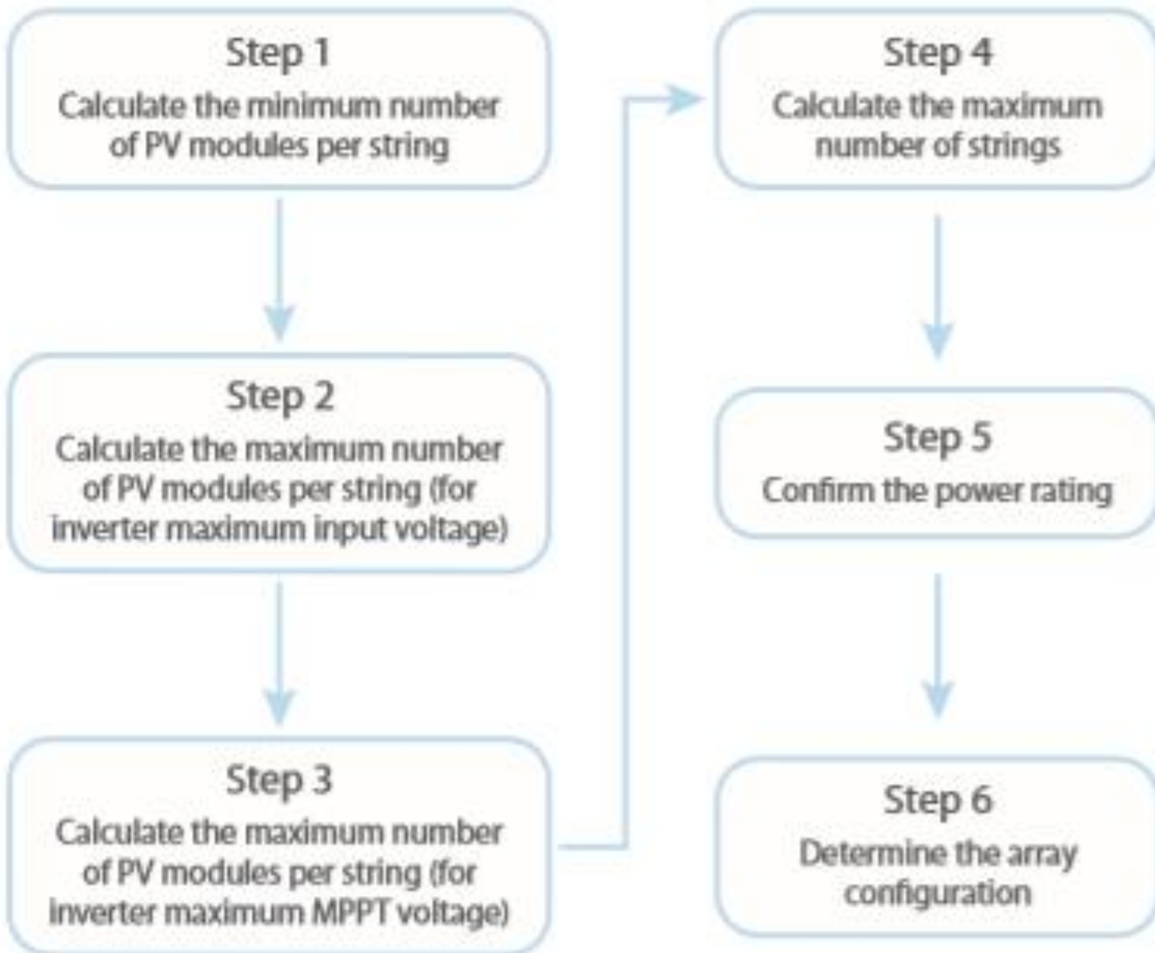
The number of modules in a string, and hence the maximum and minimum voltages of the string, must be matched to the inverters:

- Maximum dc input voltage; and
- Minimum Maximum Power Point Tracker (MPPT) operating voltage;.

OTHER INVERTER INFORMATION NOT NECESSARILY NEEDED WHEN MATCHING ARRAY VOLTAGE TO INVERTER VOLTAGES

- The inverter manufacturer on the data sheet can specify the following voltages but these are not required when matching the array to the inverter
- Minimum voltage for inverter operation; and
- Maximum Maximum Power Point Tracker (MPPT) operating voltage;

STEPS FOR MATCHING THE ARRAY AND INVERTER



MATCHING ARRAY VOLTAGE TO THE INVERTER

In practice the array should be designed such that:

- At the coldest temperature of the day (in the Pacific this will be early in the morning) the open circuit voltage of the array is less than the maximum input voltage allowed for the inverter.
- At the maximum temperature expected during the day the arrays MPP voltage is always greater than the inverters Minimum Maximum Power Point Tracker (MPPT) operating voltage.

MATCHING ARRAY VOLTAGE TO THE MIINIMUM MPPT VOLTAGE OF INVERTER 1

- When the temperature is at a maximum then the Maximum Power Point (MPP) voltage (V_{mp}) of the array should never fall below the minimum operating voltage of the MPPT of the inverter.

- The actual voltage at the input of the inverter is not just the V_{mp} of the array, the voltage drop in the dc cabling between the array and the inverter must also be included when determining the actual inverter input voltage.

MATCHING ARRAY VOLTAGE TO THE MIINIMUM MPPT VOLTAGE OF INVERTER 2

- The actual voltage at the input of the inverter is not just the V_{mp} of the array, the voltage drop in the dc cabling between the array and the inverter must also be included when determining the actual inverter input voltage.

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MATCHING ARRAY VOLTAGE TO THE MIINIMUM MPPT VOLTAGE OF INVERTER 3

- Since the daytime ambient temperature in some areas of the Pacific Islands can reach, or exceed, 35°C (95^{o}F) it is recommended that a maximum effective cell temperature of 75°C (167^{o}F) is used.

(Note-if this seems high, Germany specifies 70°C (158^{o}F) even though on average their summer temperatures are generally less than 35°C (95^{o}C)).

DETERMINE MINIMUM MPP VOLTAGE (V_{MP}) OF A MODULE AT THE INVERTER 1

- The minimum V_{mp} of a module is determined by calculating the reduction in V_{mp} due to the effective cell temperature.
- The reduction in V_{mp} is calculated by multiplying the voltage temperature coefficient (V/^{o}C) by the difference between the effective cell temperature and the STC temperature (25°C).

DETERMINE MINIMUM MPP VOLTAGE (V_{MP}) OF A MODULE AT THE INVERTER 2

The effective minimum V_{mp} out of the module due to the maximum temperature

= V_{mp} less the reduction in V_{mp} due to a module temperature above STC.

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DETERMINE MINIMUM MPP VOLTAGE (V_{MP}) OF A MODULE AT THE INVERTER 3

- The effective minimum V_{mp} out of the module due to the maximum temperature is then reduced by the voltage drop in the connecting wires.

DETERMINE MINIMUM MPP VOLTAGE (V_{MP}) OF A MODULE AT THE INVERTER 4

- Since voltage drop is typically expressed as a percentage (%) value then the reduction factor due to voltage drop is (1 − %voltage drop).
- So if the % voltage drop in the wires is 2%:
- voltage after wiring loses are included would be (1.00 - 0.02) = 0.98 x the operating voltage.
- That would be the voltage actually reaching the MPPT.

VOLTAGE COEFFICIENT FOR V_{MP}

Many module manufacturers do not supply the voltage coefficient for V_{mp}. It is supplied only for V_{oc} (the open circuit voltage). If the V_{mp} temperature coefficient is not available then either

- The V_{oc} temperature co-efficient can be used;

or

- P_{mp} temperature coefficient can be used in place of the V_{oc} temperature coefficient for determining the V_{mp} temperature coefficient because the current temperature coefficient is negligible so the V_{mp} temperature coefficient is very close to the P_{mp} temperature coefficient.

WORKED EXAMPLE 2 Part 1

A module data sheet provides the following information:

- P_{mp} = 275Watt
- V_{oc}= 38.4V
- V_{mp}= 31.4V
- I_{sc} = 9.24A
- I_{mp} = 8.76A
- Power temperature coefficient = -0.39%/^{o}C
- V_{oc} temperature coefficient = -0.29%/^{o}C
- No V_{mp} temperature coefficient.
- Manufacturers Tolerance 0 to + 5

WORKED EXAMPLE 2 Part 2

Based on the maximum temperature of 75°C, what is the V_{mp} at the input to the inverter

WORKED EXAMPLE 2 SOLUTION Part 1

Applying the power temperature coefficient then the V_{mp} temperature coefficient

$= 0.39/100 \times 31.4$

$= 0.1225 V/{}^{o}C$.

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WORKED EXAMPLE 2 SOLUTION Part 2

Based on the maximum temperature of 75°C then the:

Reduction in V_{mp} due to temperature

= 50° C (75° C - 25° C) times the voltage temperature coefficient (V/^{o}C).

= 50^{o} C x 0.1225V/^{o}C = 6.12V

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WORKED EXAMPLE 2 SOLUTION Part 3

So the effective V_{mp} of the module due to temperature = 31.4V - 6.12V = 25.28V

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WORKED EXAMPLE 2 SOLUTION Part 4

If we assume a maximum voltage drop in the cables of 1% then the voltage at the inverter for each module would be

$(1 – 0.01) \times 25.28 = 0.99 \times 25.28 = 25.03$ V

MATCHING ARRAY MAXIMUM V_{oc} TO THE MAXIMUM INPUT VOLTAGE OF INVERTER 1

- The critical issue is that the open circuit voltage of the array at the coldest temperature must not be above the maximum input voltage.

- There is no voltage drop included because the V_{oc} is being applied at first light before the inverter has turned on and hence no significant current is flowing

This is the effective maximum open circuit voltage input at the inverter *the array.*

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MATCHING ARRAY MAXIMUM V_{OC} TO THE MAXIMUM INPUT VOLTAGE OF INVERTER 2

- **Is** open circuit voltage at the coldest temperature is below the maximum input voltage

BUT the arrays MPP voltage at the coldest temperature is above the inverters MPPT maximum operating voltage,

then the MPPT will connect to the array at the inverters MPPT maximum operating voltage but will not track the maximum power point until the voltage falls to the MPPT maximum voltage.

MATCHING ARRAY MAXIMUM V_{OC} TO THE MAXIMUM INPUT VOLTAGE OF INVERTER 3

- This would only happen first thing in the morning when the power output is small.
- As the temperature increases the array's MPP voltage will decrease soon to the point where the MPPT voltage will enter the operating voltage window and the MPPT unit will become operational until late in the day when the voltage falls below the minimum MPPT voltage

MATCHING ARRAY MAXIMUM V_{OC} TO THE MAXIMUM INPUT VOLTAGE OF THE INVERTER 4

- Therefore the maximum open circuit voltage of a module must be determined for the coldest temperature.

MATCHING ARRAY MAXIMUM V_{OC} TO THE MAXIMUM INPUT VOLTAGE OF THE INVERTER 5

- In some areas of the Pacific the minimum daytime ambient temperature can reach 15°C (59°F) but In some mountainous areas of the Pacific it might fall below this.

- It is recommended that 15°C (59°F). is used unless you know that your area has a lower historical minimum temperature for your location, if so use that

DETERMINE MAXIMUM V_{OC} OF A MODULE AT THE INVERTER 1

- The lowest daytime temperature for the area where the system is installed shall be used to determine the maximum V_{oc} of the module

DETERMINE MAXIMUM V_{oc} OF A MODULE AT THE INVERTER 2

- The maximum V_{oc} of a module is determined by calculating the increase in V_{oc} due to the minimum cell temperature. (This is assuming the minimum temperature is less than the STC temperature of 25°C)
- The increase in V_{oc} is calculated by multiplying the voltage temperature coefficient (V/°C) by the difference between the minimum cell temperature and the STC temperature (25°C).

DETERMINE MAXIMUM V_{OC} OF A MODULE AT THE INVERTER 3

The maximum V_{oc} out of the module due to the coldest/minimum temperature

= V_{oc} plus the increase in V_{oc} due to a module temperature below STC.

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WORKED EXAMPLE 3 Part 1

A module data sheet provides the following information:

- P_{mp} = 275Watt
- V_{oc}= 38.4V
- V_{mp}= 31.4V
- I_{sc} = 9.24A
- I_{mp} = 8.76A
- Power temperature coefficient = -0.39%/^{o}C
- V_{oc} temperature coefficient = -0.29%/^{o}C
- No V_{mp} temperature coefficient.
- Manufacturers Tolerance 0 to + 5

WORKED EXAMPLE 3 part 2

Based on the minimum temperature of 15°C, what is the V_{oc} at the input to the inverter

WORKED EXAMPLE 3 SOLUTION Part 1

V_{oc} temperature coefficient

$= 0.29/100 \times 38.4$

$= 0.1114 V/^{o}C$.

WORKED EXAMPLE 3 SOLUTION Part 2

Assume a minimum temperature of 15°C then the:

Change in V_{oc} due to temperature

= -10° C (15° C - 25° C) times the voltage temperature coefficient (V/°C).

= - 10° C x 0.1114V/°C = - 1.11V

WORKED EXAMPLE 3 SOLUTION Part 3

The negative implies the voltage increases

So the effective V_{oc} of the module due to temperature = 38.4V + 1.11V = 39.51V

MINIMUM MPPT OPERATING VOLTAGE OF THE INVERTER

The inverter data sheet specifies actual minimum MPPT operating voltage.

But what is the voltage we use when determining the minimum number of modules in a string?

SHOULD WE INCREASE THE MINIMUM MPPT VOLTAGE OF INVERTER?

- The MPP voltage of a solar module rises with increases in irradiance.
- The array is typically operating with irradiance levels less than 1kW/m^2 (the STC value) when the effective cell temperature is still high so the actual effective MPP voltage of the module (and hence array) will be reduced.
- The exact variation is dependent on the quality of the solar cell so it is recommended that a safety margin of 10% is added to the minimum MPPT operating voltage of the inverter.

DETERMINE MINIMUM NUMBER OF MODULES IN THE STRING

- The minimum number of modules in a string is determined by dividing the effective minimum operating voltage of the MPPT of the inverter (that is allowing safety margin) by the effective minimum MPP voltage input at the inverter for each module.

- Since it is the *minimum* number it should always be rounded up when a fraction of a module is indicated by the calculations.

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WORKED EXAMPLE 4

The inverter data sheet states the Minimum MPP operating voltage is 110 V

The module is that same as used in worked examples 1 and 2.

Determine the minimum number of modules in a string?

WORKED EXAMPLE 4 Solution Part 1

The minimum operating voltage of the MPPT is 110V

Allowing for the safety margin of 10% the effective minimum operating voltage of the MPPT (1 + 10%) x 110V = 1.1 x 110V = 121V

WORKED EXAMPLE 4 Solution Part 2

- The effective minimum operating voltage of the MPPT = 121V
- The effective minimum MPP voltage input at the inverter for each module =25.03V
- Therefore, the minimum number of modules in a string = 121V/25.03V = 4.83
- This would have to be rounded up to 5 since rounding down to 4 would sometimes cause the input voltages to be too low for the inverter to function.

DETERMINE MAXIMUM OPERATING VOLTAGE OF THE INVERTER

The inverter data sheet specifies actual Maximum operating voltage.

DETERMINE MAXIMUM NUMBER OF MODULES IN THE STRING

- The maximum number of modules in a string is determined by dividing the maximum allowable input voltage of the inverter by the effective maximum open circuit voltage for each module.

- Since it is the maximum number it should always be rounded *down* when an exact number of modules is not the result.

WORKED EXAMPLE 5

The maximum voltage of the inverter = 600V

The module is that same as used in worked examples 1 and 2.

Determine the maximum number of modules in a string?

WORKED EXAMPLE 5 Solution

From worked example 2, the effective maximum V_{oc} input at the inverter for each module = 39.51V

Therefore, the maximum number of modules in a string = 600V/39.51V = 15.18

This would be rounded down to 15 modules in a string.

WORKED EXAMPLES 4 and 5 Solution

So in the worked example we can have between 5 (the minimum number) and 15 (the maximum number) of modules in a string and the inverter will function properly.

HOW MANY STRINGS?

- Depending on how many modules have been selected to meet the client's requirements and the characteristics of the inverter to be used, the array could include one string or could be divided into multiple strings.
- The final configuration can be determined by matching the output currents of the array to the maximum input current of the inverter

WORKED EXAMPLE 6

- Worked Example 1 the array comprised of 14 modules
- Worked Example 2,3,4 and 5 determined the string could comprise between 5 and 15 modules.
- So how many modules in a string and how many strings?

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WORKED EXAMPLE 6 Solution

- Two solutions:
  - as one string of 14 modules; or
  - two strings of 7 modules.
- The inverter has two MPPT's so each string of 7 could be connected to one MPPT input of the inverter.
- Matching the output currents of the array with the maximum input currents can help determine the final string arrangement.

MATCHING ARRAY CURRENT TO THE INVERTER

- Inverters have a maximum input current. However, since many inverter now have multiple MPPT's and can have multiple connections, often plugs, for the PV array dc wiring to the inverter, these also have a maximum current specified.

- The final configuration of the array must ensure that no strings or array connection to the inverter has an output current greater than that specified for that inverter input.

WORKED EXAMPLE 7

The inverter data sheet provides the following information:

Max. input current input A / input B 15 A / 15 A

Max. input current per string input A / input B 15 A / 15 A

Number of independent MPP inputs / strings per MPP input 2 / A:2; B:2

Could both solutions as determined in worked example 6 be suitable; that is :

- as one string of 14 modules; or
- two strings of 7 modules.

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WORKED EXAMPLE 7 Solution Part 1

The inverter allows maximum input current (generally the Isc) 15A for input A and 15A for input B.

It allows a maximum input current for each string of 15A for A and 15A for B.

WORKED EXAMPLE 7 Solution Part 2

The module data sheet provides the following information:

- Isc = 9.24A
- Imp = 8.76A

If there are two parallel strings on either MPPT input, then the maximum currents would be greater than that allowed. So only one string per MPPT is allowed for this inverter.

WORKED EXAMPLE 7 Solution Part 3

- So there are still two solutions that will work: one long string of 14 modules or two short strings of 7 modules with each string connected to a separate MPPT.
- Either approach will stay within the acceptable voltage and current range of the inverter inputs.
- Which is better?

WORKED EXAMPLE 7 Solution Part 4

- Generally using shorter strings is preferred because of the lower voltages that are present in the module circuits.
- A 14 module string will have double the voltage of a 7 module string
- Also if there is partial shading of the array and the array is split over two MPPT units, the overall array output may be somewhat better than if a single MPPT connection is used since the shading will affect the whole array if there is only one string but may affect only half the array if there are two strings with one in the shade and one staying in the sun.

ENERGY YIELD

ELECTRICAL LOSSES IN THE GRID CONNECTED PV SYSTEM

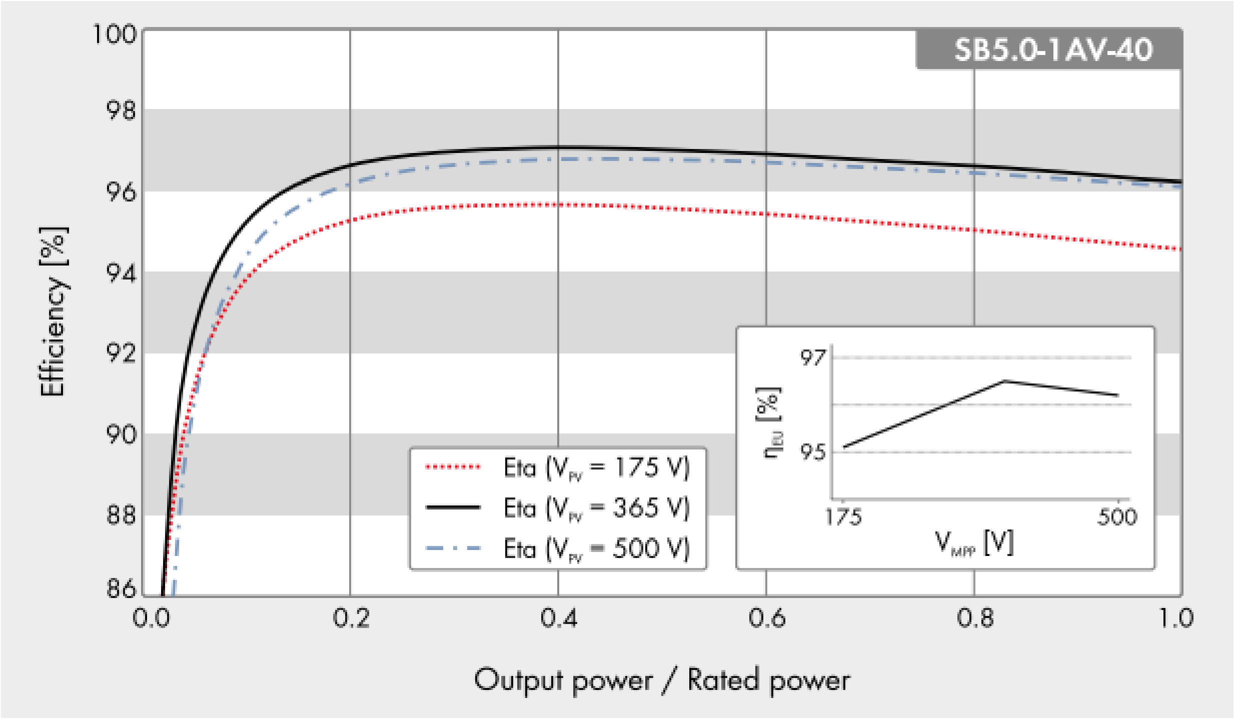
The electrical losses in the grid connected system include all the losses between the PV array and the point of connection to the grid.

The losses typically include:

- Power loss due to voltage drop between the PV array and inverter. This should not exceed 3%.
- Power loss resulting from inverter efficiency. This is typically supplied on the Inverters data sheet as a curve showing efficiency vs inverter output. (see next slide)
- Power loss due to voltage drop between the PV inverter and the interconnection to the grid. This should not exceed 1%.

INVERTER DATA SHEET

The data sheet states that the maximum inverter efficiency is 97% and provides the following efficiency curve.



- This curve indicates that the inverter is above 96% efficiency for most of its operating range so using 96% would be good conservative figure.

ENERGY YIELD

- For a specified peak power rating (kW_p) for a solar array a designer can determine the systems energy output over the whole year. The system energy output over a whole year is known as the systems "Energy Yield"
- The average yearly energy yield can be determined as follows

$$E_{sys} = P_{array\_STC} \times f_{temp} \times f_{mm} \times f_{dirt} \times H_{tilt} \times \eta_{pv\_inv} \times \eta_{inv} x \eta_{inv-sb}$$

ENERGY YIELD Cont'd

Where:

E_{sys} = average yearly energy output of the PV array, in watthours

P_{array}-stc = rated output power of the array under standard test conditions, in watts

f_{temp} = temperature de-rating factor, dimensionless

f_{man} = de-rating factor for manufacturing tolerance, dimensionless

f_{dirt} = de-rating factor for dirt, dimensionless

H_{tilt} = yearly irradiation value (kWh/m^2) for the selected site (allowing for tilt, orientation and shading)

h_{inv} = efficiency of the inverter dimensionless

h_{pv_inv} = efficiency of the subsystem (cables) between the PV array and the inverter

h_{inv-sb} = efficiency of the subsystem (cables) between the inverter and the switchboard

Note: The efficiency of solar modules reduce efficiency over time. This can result in a loss of rated power of 0.5% to 1.0% per year. The above formula determines the expected energy yield in the first year of operation. The expected energy yield will reduce each year due to the effect of the reduction in the solar modules efficiency.

EFFECT OF SHADING

- Care should be taken when selecting the number of modules in a string because the shading could result in the maximum power point voltage at high temperatures being below the minimum operating voltage of the inverter causing the inverter to shut down until the shading is reduced.
- Determining the effect of shading on the energy yield can be difficult to predict exactly and the designers should use a suitable program or be conservative when providing the energy yield to the client.

WORKED EXAMPLE 8

You are provided with information of the sample system:

P_{array}-stc = 3850 W_p

f_{temp} =0.828

f_{man} =0.97

f_{dirt} =0.9

H_{tilt} =1846.9kWh/m^2

h_{inv} = 0.96 (96%)

h_{pv_inv} = 0.97 (97%)

h_{inv-sb} = 0.99(99%)

Determine the average yearly energy yield.

WORKED EXAMPLE 8 SOLUTION

$$E_{sys} = P_{array\_STC} \times f_{temp} \times f_{mm} \times f_{dirt} \times H_{tilt} \times \eta_{pv\_inv} \times \eta_{inv} x \eta_{inv-sb}$$

E_{sys} = 3850 x 0.828 x 0.97 x 0.9 x 1846.9x 0.96 x 0.97 x 0.99

E_{sys} =4,738,347 Wh or 4,738.35kWh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