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Grid-Connected PV Systems Design and Installation

Revisions to the Grid-Connected PV Systems: Design and Installation Australian Edition Version 8.6 Publication

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Following is the summary of changes to the information within Grid-Connected PV Systems Design and Installation Australian Edition Version 8.6, February 2020. Please note that the changes in this document are subject to alterations in newer editions. While all care has been taken to ensure this document is free from omission and error, no responsibility can be taken for the use of this information in the design or installation of any grid-connected PV system.

Keywords

Addition: *Adding an additional paragraph.*

Replacement: *To entirely replace something.*

Extension: *To add an additional sentence/s onto the end of a sentence or paragraph.*

Amendment: *To modify sections of a paragraph or sentence either by quote or by reviewing the referenced text.*

Removal: *To remove something altogether.*

Chapter 6

1. Introduction

Amendment:

> ***AUSTRALIAN GUIDELINES***
>
> PV modules proposed for grid connection in Australia must comply with the relevant international IEC and Australian standards. The Clean Energy Council (CEC) provides the current list of approved modules meeting these relevant standards. The CEC list is regularly revised and can be accessed via the CEC accreditation website:
>
> www.cleanenergycouncil.org.au.

Chapter 7

2. Introduction

Amendment:

> ***AUSTRALIAN STANDARDS AND GUIDELINES***
>
> ***AS/NZS 4777.1:2016***
>
> ***AS/NZS 4777.2:2015***
>
> ***AS/NZS 5033:2014*** calls up ***IEC 62109:2010*** Parts 1 & 2 and ***AS/NZS 3100: 2017***.
>
> Grid-connected inverters for use in Australia must comply with the prescribed Australian Standards. The Clean Energy Council (CEC) provides a list of these approved inverters. The CEC list is regularly updated and can be found on the CEC website:
>
> www.cleanenergycouncil.org.au

3. Section 7.8.3 - Power Rate Limit

Addition:

> ***AUSTRALIAN STANDARDS***
>
> ***AS/NZS 4777.2:2015*** Clause 7.5.2 details limitations regarding sustained operation for voltage variations.

Chapter 9

4. Section 9.1 - Cabling

Amendment:

> ***AUSTRALIAN STANDARDS***
>
> ***AS/NZS 5033:2014*** Clause 4.3.7 states that:
>
> - All connector pairings must be of the same type and from the same manufacturer
> - Cables used within the PV array shall be:
> - UV-resistant (if exposed to the environment)
> - Rated to the overcurrent protection device, or maximum normal operating current
> - Flexible, to allow for movement of the cable
> - Single core, double insulated.
>
> According to AS/NZS 5033:2014, all cables used for the PV array must meet PV1-F requirements, UL 4703, or VDE-AR-E 2283-4.

5. Section 9.2.3 - DC Disconnection Devices

Removal:

> ***AUSTRALIAN STANDARDS***
>
> ***AS/NZS 5033:2014*** Clause 4.2 states that PV array maximum voltage is calculated as follows:
>
> PV array max voltage = $V_{OC} + {}_{\gamma}V_{OC}\,(T_{MIN} - T_{STC}) \times M$
>
> Where:
>
> - V_{OC} = module open-circuit current.
> - ${}_{\gamma}V_{OC}$ = module temperature coefficient for V_{OC} in V/°C.
> - T_{MIN} = minimum cell temperature.
> - T_{STC} = cell temperature at STC (25°C).
> - M = number of modules in the array string.

Chapter 11

6. Section 11.3.4 - Assessment of the Available Installation Area

Replacement of Figure 11.14:

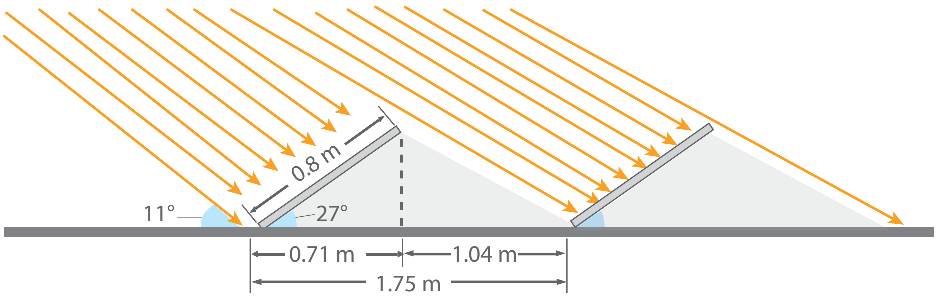


Figure 11.14: The minimum row spacing for this array (not to scale).

7. Section 11.6 - Site Assessment of the Grid Connection

Amendment:

> ***AUSTRALIAN GUIDELINES***
>
> The local **Distributed Network Service Provider** (DNSP) should be contacted about the requirements for connecting to the grid. For example, some network providers will request that voltage rise calculations are provided before approval is given (see Chapter 7 for more information on voltage rise). The replacement meter installation requirements should also be determined.

8. Section 11.9 - Designing a Site-Specific PV System

Addition:

> ***AUSTRALIAN STANDARDS***
>
> ***AS/NZS 5033:2014*** Clause 2.1.6 states that all PV modules in a single string must face the same direction (i.e. be within 5° of the same tilt and azimuth).

Amendment:

> **DID YOU KNOW?**
>
> Fronius, an inverter manufacturer, has found that there may be less than 1% loss in power when using a single-MPPT inverter with an east–west array (i.e. one string facing east and one string facing west, paralleled into a single MPPT), compared with identical east and west strings connected to separate MPPTs. As all modules in a string have the same orientation, this arrangement complies with the relevant standards.

Removal:

To achieve the highest yield in this situation, **and to meet industry guidelines,** the array may need an inverter with multiple MPPTs or to use micro-inverters.

9. Section 12.3.1 - Using Voltage Temperature Coefficients

Amendment:

> **IMPORTANT**
>
> To ensure that the string voltage doesn't fall below the minimum operating voltage, a **maximum cell temperature** of at least 75°C is recommended.

Amendment:

Where:

$$V_{MP\ at\ X°C} = V_{MP\ at\ STC} + [\gamma_{VMP} \times (T_{X°C} - T_{STC})]$$

- $V_{MP\ at\ X°C}$ = MPP voltage at the specified temperature (X°C), in volts.
- $V_{MP\ at\ STC}$ = MPP voltage at STC (i.e. the rated voltage), in volts.
- **γ_{VMP} = negative V_{MP} temperature coefficient, in V/°C.**
- $T_{X°C}$ = cell temperature, in °C.
- T_{STC} = temperature at STC, in °C (i.e. 25°C).

Amendment:

Use the temperature coefficient for V_{OC}: This is the simplest method and will give an approximate estimate.

10. Section 12.3.2 - Calculating the Minimum Number of Modules in a String

Amendment to Example:

$$V_{MP\ at\ X°C} = V_{MP\ at\ STC} + [\gamma_{VMP} \times (T_{X°C} - T_{STC})]$$
$$V_{MP\ at\ 75°C} = 35.4V + [-0.16V/°C \times (75°C - 25°C)]$$
$$V_{MP\ at\ 75°C} = 35.4V + (-0.16V°C \times 50°C)$$
$$= 35.4V + (-8V)$$
$$= 27.4\ V$$

11. Section 12.3.3 - Calculating Maximum Number of Modules in a String

Amendments:

$$V_{OC\ at\ X°C} = V_{OC\ at\ STC} + [\gamma_{VOC} \times (T_{X°C} - T_{STC})]$$

Where:

- $V_{OC\ at\ X°C}$ = open circuit voltage at the specified temperature (X°C) in volts.
- $V_{OC\ at\ STC}$ = open circuit voltage at STC, i.e. the rated voltage in volts
- γ_{Voc} = negative V_{OC} voltage temperature coefficient in V/°C.

$$V_{MP\ at\ X°C} = V_{MP\ at\ STC} + [\gamma_{VMP} \times (T_{X°C} - T_{STC})]$$

Where:

- $V_{MP\ at\ X°C}$ = MPP voltage at the specified temperature (X°C) in volts.
- $V_{MP\ at\ STC}$ = MPP voltage at STC, i.e. the rated voltage in volts.
- γ_{Vmp} = negative voltage temperature coefficient, in V/°C.

Amendments to Examples:

$$V_{OC\ at\ X°C} = V_{OC\ at\ STC} + [\gamma_{VOC} \times (T_{X°C} - T_{STC})]$$
$$V_{OC\ at\ -5°C} = 60.5 + \{-0.14 \times [(-5) - 25]\}$$
$$V_{OC\ at\ -5°C} = 60.5 + [-0.14 \times (-30)]$$
$$= 60.5 + (4.2)$$
$$= 64.7$$

$$V_{MP\ at\ X°C} = V_{MP\ at\ STC} + [\gamma_{VMP} \times (T_{X°C} - T_{STC})]$$
$$V_{MP\ at\ -5°C} = 50.2 + [-0.146 \times (-5 - 25)]$$
$$V_{MP\ at\ -5°C} = 50.2 + [-0.146 \times (-30)]$$
$$= 50.2 + (4.38)$$
$$= 54.58\ V$$

12. Section 12.7 - Multi-MPPT and Multi-input Inverters

Amendment:

DID YOU KNOW?

Multiple strings connected to a single MPPT should **have the same number of modules in series and the PV modules should have similar electrical characteristics.** However, separate MPPTs in an inverter can have different sized strings and/or different **module types** connected to them.

13. Section 12.8 - Complete Example

Amendments:

2. Convert the P_{MAX} coefficient into V/°C	**–0.41**%/°C × 30.6V = –0.125 V/°C

$$V_{MP\ at\ X°C} = V_{MP\ at\ STC} + [\gamma_{VMP} \times (T_{X°C} - T_{STC})]$$
$$V_{MP\ at\ 75°C} = 30.6\ V + [-0.125 V/°C \times (75 - 25)°C]$$
$$= 30.6 - 6.25$$
$$= 24.35\ V$$

$$V_{OC\ at\ X°C} = V_{OC\ at\ STC} + [\gamma_{VOC} \times (T_{X°C} - T_{STC})]$$
$$V_{OC\ at\ 0°C} = 38.5 + [-0.123 V/°C \times (0 - 25)]$$
$$= 38.5 + 3.08\ V$$
$$= 41.58$$

$$V_{MP\ at\ X°C} = V_{MP\ at\ STC} + [\gamma_{VMP} \times (T_{X°C} - T_{STC})]$$
$$V_{MP\ at\ 0°C} = 30.6 + [-0.125 V/°C \times (0 - 25)]$$
$$= 30.6 + 3.125\ V$$
$$= 33.725$$

14. Section 13.3 - DC Disconnection Devices

Amendment:

Load-breaking, where they can be disconnected when current is flowing through them; these devices are **switch-disconnectors** or circuit breakers, although the term 'isolators' is used for simplicity in labelling.

15. Section 13.3.1 - String Disconnection

Replacement of Australian Standards box:

AUSTRALIAN STANDARDS

According to ***AS/NZS 5033:2014*** Clause 4.2, the PV array maximum voltage is calculated using:

$$V_{MAX\_OC\_ARRAY} = V_{OC\_ARRAY} + \gamma_{OC} \times (T_{MIN} - T_{STC}) \times N_S$$

Where:

- $V_{MAX\_OC\_ARRAY}$ = PV array maximum voltage (in V)
- V_{OC_ARRAY} = PV array open circuit voltage at standard test conditions (in V)
- γ_{OC} = Negative temperature coefficient of V_{OC} per degree Celsius (in V/°C)
- T_{MIN} = Minimum cell temperature (in °C)
- T_{STC} = Cell temperature at standard test conditions (constant of 25°C)
- N_S = Number of modules in series

If the module temperature coefficient is not available, ***AS/NZS 5033:2014*** Table 4.1 contains some universal coefficients that can be used.

Amendment to Example, previously in Section 13.3.3 - Array DC Disconnection:

EXAMPLE

An array has 12 modules set up in two parallel strings of 6 modules, with VOC of 39.2 V, γ_{VOC} of –0.33%/°C and ISC of 7.4 A. Calculate the PV array maximum voltage for this array, given that the site's lowest expected temperature is 5°C.

Since there are 6 modules in each string and voltage is the same in parallel strings, the PV array maximum voltage is:

$$\begin{aligned} V_{MAX\_OC\_ARRAY} &= V_{OC\_ARRAY} + \gamma_{OC} \times (T_{MIN} - T_{STC}) \times N_S \\ &= (39.2\text{ V} \times 6) + (-0.0033/°C \times 39.2\text{ V}) \times (5°C - 25°C)] \times 6 \\ &= 235.2\text{ V} + 0.1294\text{ V}/°C \times 20°C \times 6 \\ &= 250.7\text{ V} \end{aligned}$$

16. Section 13.3.3 - Array DC Disconnection

Replacement:

A load-breaking device for disconnecting the PV array on the DC side of the inverter is essential for safety in grid-connected PV systems. Two DC disconnectors may be required: one adjacent to the array and one adjacent to the inverter (see 'Installation of Array DC Disconnectors' below).

Requirements of PV Array DC Disconnectors

For all systems, the PV array DC isolators must be readily available load-breaking disconnection devices and lockable in the 'off' position. They must be non-polarised and able to isolate both positive and negative active conductors simultaneously under load.

A non-polarised circuit breaker can be used as the readily available load-breaking disconnection device.

If micro-inverters are used, an array DC disconnector may not be required. The relevant standards should always be referenced when determining disconnector requirements.

Selection of the PV Array DC Disconnectors

The relevant Australian standards contain specific requirements for the array disconnection device, known as the PV Array DC Isolator. The requirements may differ for sizing and installing a PV array DC isolator that is integrated into the inverter. It is important to refer to the inverter manufacturer or installation manual to determine whether an in-built isolator is suitable for the system. An additional external isolator will be required if the in-built isolator does not meet all the requirements.

To check whether switch-disconnector is suitable for a system, perform the three steps below while referring to the isolator's datasheet. For these calculations, the maximum current is defined as $1.25 \times I_{SC\ ARRAY}$.

Step 1: Thermal effects

The maximum current must be less than or equal to I_{the} for the installation conditions:

- Indoors at 40°C ambient for isolators installed indoors.
- Outdoors at 40°C ambient for isolators installed outdoors in a location fully shaded all day (e.g. carport, verandah).
- Outdoors at 60°C ambient with solar effects for rooftop isolators or isolators
- installed externally where the enclosure or shroud will receive direct sunlight.

Step 2: Operational conditions

Consider the isolator configuration when the positive and negative conductors are operating in series. Looking at the first row where U_e is higher than the PV array max voltage, check that I_e is higher than the maximum current.

Step 3: Fault conditions

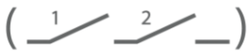
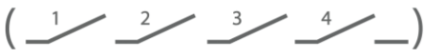
This step is for non-separated (transformerless) inverters only. Considering the isolator configuration when the positive and negative conductors are not working in series (e.g. due to an earth fault on one of the conductors), check that I_{make} and $I_{C\ (break)}$ are higher than your maximum current for the maximum voltage U_e.

When in fault conditions, the isolator must be able to withstand the maximum current using half of the poles (either the negative or the positive side only). The Imake and $I_{C\ (break)}$ is the current that one pole can withstand for very short periods of time. The isolator should be replaced after breaking this current.

EXAMPLE

The switch-disconnector with specifications given in the datasheet below will be used as the rooftop PV array isolator for an array with a transformerless inverter. The system has a PV array maximum voltage of 840 V and an array short circuit current of 17 A. The following example checks whether the isolator selected is suitable for this purpose.

Identification	Rating Data
I_{th} rated thermal current, unenclosed, at 40°C shade ambient air temperature	32 A
I_{the} rated thermal current, indoors, at 40°C shade ambient air temperature, in a specific dedicated enclosure	32 A
I_{the} rated thermal current outdoors at 40°C shade ambient air temperature without solar effects in a specific dedicated enclosure rated IP 56NW	32 A
I_{the} *solar* current value, outdoors at 60°C shade ambient air temperature, with solar effects in a specific dedicated enclosure rated IP 56NW	28 A

	U_e rated operational voltage (V)	I_e DC-PV2 rated operational current (A)	$I_{(make)}$ and $I_{c(break)}$ DC-PV2 $4 \times I_e$ (A)
2 pole 	≤500	32	128
	600	32	128
	800	27	108
	1000	13	52
4 pole 	≤500	32	128
	600	32	128
	800	32	128
	1000	32	128

Example datasheet from an isolator manufacturer. Values will differ for different brands and models.

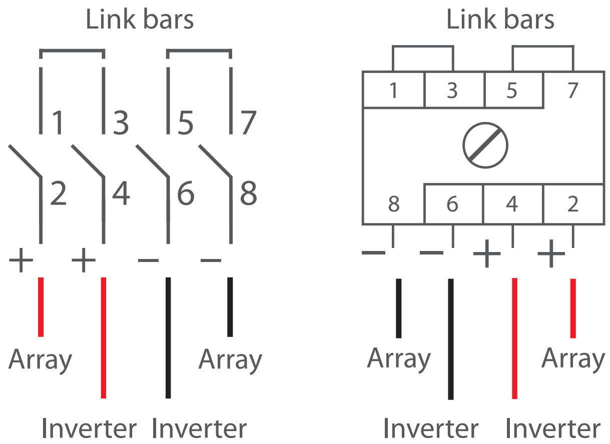
Step 1

$1.25 \times I_{SC\_ARRAY} = 1.25 \times 17$ A = 21.25 A. This isolator will be installed outdoors in direct sunlight. I_{the} under these conditions is 28 A according to the datasheet, which is higher than 21.25 A, so the rating is acceptable.

Step 2

The isolator has four poles and there is only one string to be switched, so the positive and negative conductors will each go through 2 poles (see diagram on the next page). During normal operation, these operate in series, so there are 4 poles total operating in series. Looking at the 4 pole configuration in the datasheet, the next highest U_e above 840 V is 1000 V, and the corresponding I_e is 32 A. This is higher than 21.25 A, so the rating is acceptable.

EXAMPLE (CONTINUED)



Connection diagram for the example four-pole switch-disconnector

Step 3

The positive and negative conductors each go through 2 poles. This is a transformerless inverter, so under earth fault conditions, either conductor may switch the full array current and voltage. Therefore, looking at the 2 poles in series configuration in the diagram above, at the 1000 V row, the $I_{(make)}$ and $I_{c\ (break)}$ for the chosen configuration is 52 A. This is higher than 21.25 A, so is acceptable.

The isolator meets all three sizing requirements. Therefore, this isolator and the PV array configuration are compatible.

Addition:

DC Disconnection for Inverters with Multiple Inputs

Inverters with multiple inputs connect the strings together within the inverter. This configuration determines the array disconnection device requirements, as there is no external array cable on which to install the array disconnection device. Therefore, a PV array DC **isolator** must be installed on each string, regardless of whether the strings are connected to a single MPPT or individual MPPTs.

Some inverters with multiple inputs are supplied with a DC disconnection switch that isolates all of the strings at once. Care must be taken that this disconnection switch meets all relevant standards and guidelines.

PV array DC switch-disconnectors must:

- **Comply with AS 60947.3**
- **Be supplied with dedicated individual enclosures rated at least IP56NW if installed outdoors, to ensure that water jets and rain will not enter the enclosure.**
- **Have utilization category DC-PV2.**
- **Rooftop isolators must be installed with a shroud to protect against rain and direct sunlight (Figure 13.10)**
- **Must be installed vertically, unless otherwise allowed by the manufacturer, with cables entering the lower entry face of the enclosure. Cables and conduits may enter the isolator through the side faces if allowed by the manufacturer.**

Amendment:

> ***AUSTRALIAN STANDARDS***
>
> For more information on the DC disconnection device requirements in Australia, including isolator installation and removal, consult ***AS/NZS 5033:2014*** Clause 4.4.

Addition:

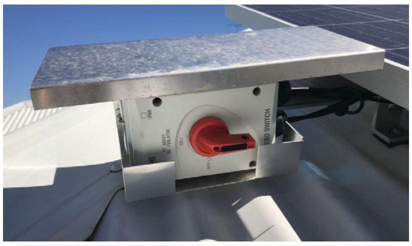


Figure 13.10: Isolator installed with shroud.

17. Section 13.3.4 - Summary of DC Disconnection Devices

Amendment:

The following table summarises the requirements for all DC protection devices for strings, sub-arrays and arrays, including overcurrent protection and disconnection. The relevant Australian standards explain how the PV array maximum voltage is calculated.

	Protection/ Disconnection Description	Protection/ Disconnection Device	Protection Sizing and Guidelines	Australian Standards
String	String overcurrent protection device (Section 13.2.1)	Fuse or circuit breaker	**Required if:** I_{SC} × *(No. of strings - 1) ≥ Module reverse current rating* **Sizing:** $1.5 \times I_{SC\_MOD} < I_{TRIP} < 2.4 \times I_{SC\_MOD}$ AND $I_{TRIP} \leq I_{MOD\_REVERSE}$	***AS/NZS 5033:2014*** Clause 3.3.4 and 3.3.5.1
	String disconnection device (Section 13.3.1)	Switch-disconnector, circuit breaker, or plug and socket	• Can be non-load-breaking • Rated for PV array maximum voltage • Current rating ≥ string overcurrent protection or, if no string overcurrent protection present, current rating ≥ CCC of string cable • No live parts may be exposed at any time	***AS/NZS 5033:2014*** Clause 4.3.5.2 and 4.4.1.3
Sub-array	Sub-array overcurrent protection device (Section 13.2.2)	Fuse or circuit breaker	**Required if:** $1.25 \times I_{SC\ ARRAY}$ > CCC of any sub-array cable, switching and connection device OR More than two sub-arrays are present within the array **Sizing:** $1.25 \times I_{SC\ SUB\text{-}ARRAY} \leq I_{TRIP} \leq 2.4 \times I_{SC\ SUB\text{-}ARRAY}$	***AS/NZS 5033:2014*** Clause 3.3.5.2
	Sub-array disconnection device (Section 13.3.2)	Switch-disconnector, circuit breaker, or plug and socket (ELV)	• Can be non-load-breaking • Recommended to be load-breaking for LV systems • Rated for PV array maximum voltage • Current rating ≥ sub-array overcurrent protection or, if no sub-array overcurrent protection present, current rating ≥ CCC of sub-array cable • No live parts may be exposed at any time	***AS/NZS 5033:2014*** Clause 4.2, 4.3.5.2 and 4.4.1.3

Array	Array overcurrent protection device (Section 13.2.3)	Fuse or circuit breaker	**Required if:** Another source of current is available that may cause damage to the PV array when under fault conditions. **Sizing:** $1.25 \times I_{SC\ ARRAY} \leq I_{TRIP} \leq 2.4 \times I_{SC\ ARRAY}$	***AS/NZS 5033:2014*** Clause 3.3.5.3
	Array disconnection device (Section 13.3.3)	Switch-disconnector or circuit breaker	• Load-breaking and lockable in off position • Non-polarised • Voltage rating outlined in Section 13.3.3 • Current rating ≥ array overcurrent protection or, if no array overcurrent protection present, current rating ≥ $1.25 \times I_{SC\text{-}ARRAY}$ • No live parts may be exposed at any time	***AS/NZS 5033:2014*** Clause 4.2, 4.4.1.3, 4.4.1.4 and 4.4.1.5

19. Chapter 13 Quiz

Replacement:

Question 5

Determine the maximum array voltage and current that would be used to check the suitability of the PV array DC isolator, given that:

Chapter 14

20. Section 14.1.2 - Voltage Drop and CSA

Amendments:

> ***AUSTRALIAN STANDARDS***
>
> The maximum AC voltage rise is addressed in **AS/NZS 4777.1:2016 and** the CEC guidelines.
>
> The Australian States and **Territories** have specific service rules relating to AC voltage rise, which must be met.

The size of the voltage rise in a cable can be calculated using the resistance of the cable and the amount of current flowing through the cable. As the resistance of a cable is proportionate to the conductor's CSA and the length of the cable, the voltage rise is a function of three parameters:

1. **Conductor CSA;**
2. **Length of the conductor; and**
3. **Current flow through the conductor.**

Voltage rise increases with higher resistance, so smaller cables (smaller CSA), longer cable runs and higher current flow in the cable increase the voltage rise. Therefore, voltage rise can be reduced by suitable cable design, including reducing the length of the cable or increasing the cable CSA.

The relationship between voltage drop, cable cross-sectional area (CSA), cable length and current flow is:

$$V_d = \frac{2 \times L \times I \times \rho \times \cos\Phi}{A_{CABLE}}$$

Where:

- V_d = Voltage drop (in V)
- L = Route length of cable (in m) Multiplying by two adjusts for total circuit cable length.
- I = Current flow (in A)†. For DC calculations, the I_{MP} current (at STC) should be used and not the I_{SC} current.
- ρ = Resistivity of the conductor (in Ω/m/mm²)
- $\cos\Phi$ = Power factor (include only for AC cables)
- A_{CABLE} = CSA of cable (in mm²)

However, resistivity depends on the material of the conductor (e.g. copper, tinned copper, aluminium) as well as temperature. For this reason, it is industry standard in Australia to state the equation in terms of V_C, voltage drop specified in millivolts per amp-metre (mV/Am), and refer to voltage drop tables specific to cable type, installation method, conductor CSA and temperature.

$$V_d = \frac{L \times I \times V_C}{1{,}000}$$

Where:

- V_d = Actual voltage drop (in V)
- L = Route length (in m)
- I = Current flow (in A)
- V_C = Millivolt drop per amp-metre route length (in mV/Am)

Tables of V_C values may be provided by the cable manufacturer, or otherwise can be found in the relevant Australian standards. The voltage drop values are typically for three-phase AC circuits, which can then be converted to single phase AC or DC values by multiplying by 1.155.

AUSTRALIAN STANDARDS

AS/NZS 3008.1.1:2017 Clause 4.2 specifies how to determine the voltage drop using V_C. Tables 40 to 51 in ***AS/NZS 3008.1.1:2017*** provide three-phase V_C values for different conductor types, sizes and temperatures.

NOTE

In some cases, V_C tables are only available for three-phase values. Multiply the three-phase values by 1.155 to convert to single-phase values Similarly, divide the maximum V_C in single phase AC or DC values by 1.155 to convert to three-phase values.

EXAMPLE

The cable route between a battery inverter and main switchboard is 4 metres. The inverter has a maximum current output of 13 A, single phase AC. The cable manufacturer provides the following three-phase VC values at 60°C for various conductor CSAs:

2.5 mm2 copper multicore cable: 14.9 mV/Am

4 mm2 copper multicore cable: 9.24 mV/Am

6 mm2 copper multicore cable: 6.18 mV/Am

Since these values are for a three-phase circuit, they will need to be multiplied by 1.155 to find the single-phase voltage drop.

If using 2.5 mm2 cable, the actual voltage drop will be:

$$V_d = \frac{4\text{ m} \times 13\text{ A} \times (14.9\text{ mV/Am} \times 1.155)}{1{,}000}$$

$$= 0.89\text{ V}$$

However, if a larger 6 mm2 cable were to be used, the voltage drop would be:

$$V_d = \frac{4\text{ m} \times 13\text{ A} \times (6.18\text{ mV/Am} \times 1.155)}{1{,}000}$$

$$= 0.37\text{ V}$$

To find the voltage drop as a loss percentage, simply divide the voltage drop in volts by the system voltage:

$$Loss = \frac{V_d}{V_{DC}}$$

Where:

- ***Loss*** = Voltage drop in the cable (dimensionless, i.e. 5% = 0.05)
- V_d = Voltage drop (in V)
- V_{DC} = System voltage (in V)

Alternatively, the previous formulae can be rearranged to give the maximum permitted V_c for a given voltage drop:

$$V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$

Where:

- V_C = Millivolt drop per amp-metre route length (in mV/Am)
- ***Loss*** = Maximum permissible voltage drop in the cable (dimensionless, i.e. 5% = 0.05)
- ***VDC*** = System voltage (in V)
- ***L*** = Route length (in m)
- ***I*** = Current flow through the cable (in A)

In conjunction with tabulated V_C values for a variety of cable sizes, the minimum required conductor CSA to meet the voltage drop requirements can then be determined.

Table 14.1 shows tabulated three-phase V_C values for a particular cable. Similar tables can be obtained from local standards or cable manufacturers.

Table 14.1: Three-phase V_C for single-core flexible cable in touching formation (mV/Am).

Conductor CSA (mm^2)	Conductor temperature (°C)				
	45	60	75	90	110
0.5	74.2	78.2	82.2	86.1	91.4
1.0	37.1	39.1	41.1	43.1	45.7
1.5	25.3	26.7	28.0	29.4	31.2
2.5	15.2	16.0	16.8	17.6	18.7
4	9.42	9.92	10.4	10.9	11.6
6	6.28	6.62	6.96	7.29	7.74
10	3.64	3.84	4.03	4.22	4.48
16	2.31	2.43	2.56	2.68	2.85
25	1.50	1.58	1.66	1.74	1.84
35	1.07	1.13	1.18	1.24	1.31
50	0.760	0.798	0.837	0.875	0.926
70	0.551	0.577	0.603	0.630	0.665

EXAMPLE
Using Table 14.1, determine the minimum cable size required for an array where:
Route length = 20 m,
Maximum current = 15 A,
System voltage = 24 V, and
Maximum allowable voltage drop = 5%.

$$Maximum\ V_C = \frac{1{,}000 \times 0.05 \times 24\ V}{20\ m \times 15\ A} = 4\ \text{mV/Am (DC)}$$

Converting to three-phase:

$$4\ mV/Am \div 1.155 = 3.46\ mV/Am\ (three\text{-}phase\ AC)$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a 16 mm² cable.

DID YOU KNOW

Most commercial PV modules are manufactured with 4 mm² cables preattached.

AUSTRALIAN STANDARDS

AS/NZS 3000:2018 Clause 3.4 provides guidance on sizing cables according to CCC.

21. Section 14.2.1 - String Cables

Amendments:

Where:

- **CCC = Current carrying capacity rating of the cable (in A);**
- I_n = Downstream overcurrent protection **(in A);**
- **I_{SC} = Short circuit current of the module (in A); and**
- ***Number of strings*** = Total number of parallel connected strings protected by the nearest overcurrent device.

To keep the voltage drop below the maximum threshold, the minimum CSA of the string cables should be calculated. It is calculated **using the method outlined** in Section 14.1.2.

As discussed in Section 14.1.2, the modules in a string should be connected such that the area of inductive loops is minimised. This means that the positive string cable and the negative string cable may be different lengths.

According to the standards, the maximum permissible DC voltage drop is 3%: this number is a combined limit across all cabling on the DC side, including the string cabling and the array cabling. Therefore, it is reasonable to allocate different amounts of the maximum permissible voltage drop to different parts of the DC side. For example, if the string cabling has a 1% voltage drop then the remainder of the DC cabling can have a maximum of 2% voltage drop to keep below the combined permissible maximum of 3%.

EXAMPLE:

The MPP voltage of a string at STC is 216 V and the string current is 5 A. The length of the positive cable is 18 m and the length of the negative cable is 18 m from the furthest module to the inverter.

As per the applicable standards, the maximum permissible voltage drop between the furthest module and the inverter is 3%. This figure also needs to include the array cable voltage drop, so the string cable should have a maximum permissible voltage drop of 1.5%.

Typical CSAs for PV module cables are 1.5 mm², 2.5 mm², 4 mm² and 6 mm². For this system, 1.5 mm² is satisfactory. A larger cable could also be selected, resulting in reduced power loss (but increased cost).

Using Table 14.1, determine the minimum cable size required for the string cables.

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$

$$= \frac{1{,}000 \times 0.015 \times 216\text{ V}}{18\text{ m} \times 5\text{ A}}$$

$$= 36\text{ mV/Am } (DC)$$

Converting to three-phase:

$$\frac{36\text{ mV/Am}}{1.155} = 31.17\text{ mV/Am } (three\text{-}phase\ AC)$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated VC requirement is a 1.5mm² cable.

22. Section 14.2.2 - Sub-array Cables

Amendments:

To keep the voltage drop below the maximum threshold, the minimum CSA of the sub-array cables should be calculated. It is calculated using the **method outlined in Section 14.1.2.**

EXAMPLE

An array has two sub-arrays, each one comprised of four strings.

The V_{MPP} at STC of each string is 216 V and the current in the string is 5 A.

The V_{MPP} of the sub-array cable remains at 216 V, but the current is multiplied by 4 (four parallel strings) to give 20 A.

The sub-array cables will be 5 m long and the permissible voltage drop is set at 1%, as per the principles outlined in this section.

Using Table 14.1, determine the minimum cable size required for the sub-array cables.

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$

$$= \frac{1{,}000 \times 0.01 \times 216\text{ V}}{5\text{ m} \times 20\text{ A}}$$

$$= 21.6\text{ mV/Am } (DC)$$

Converting to three-phase:

$$\frac{21.6\text{ mV/Am}}{1.155} = 18.7\text{ mV/Am } (three\text{-}phase\ AC)$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a 2.5mm² cable.

23. Section 14.2.3 - Array Cables

Amendments:

To keep the voltage drop below the maximum threshold, the minimum CSA of the array cables should be calculated. This figure is calculated using the **method outlined in Section 14.1.2.**

EXAMPLE

An array comprises four strings. The V_{MPP} at STC of each string is 216 V and the string current is 5 A. The V_{MPP} of the array cable remains at 216 V; the array current is 20 A: 4 parallel strings at 5 A.

The array cables will be **10m long and** the permissible voltage drop is set at 1.5% as per the principles outlined in this section.

Using Table 14.1, determine the minimum cable size required for the array cables.

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$

$$= \frac{1{,}000 \times 0.015 \times 216\ \text{V}}{10\ \text{m} \times 20\ \text{A}}$$

$$= 16.2\ \text{mV/Am}\ (DC)$$

Converting to three-phase:

$$\frac{16.2\ \text{mV/Am}}{1.155} = 14.03\ \text{mV/Am}\ (\textit{three-phase AC})$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a 4mm^2 cable.

24. Section 14.3 - AC Cable Design

Amendment:

AUSTRALIAN STANDARDS

AS/NZS 3008.1.1:2017 states the DC and AC de-rated CCC for different cables.

AS/NZS 4777.1:2016 outlines the AC cable requirements in a grid-connected PV system.

25. Section 14.3.1 - AC Inverter Cable

Amendment:

The minimum CSA of a single phase AC cable is calculated by adjusting the formula given in **Section 14.1.2:**

$$V_C = \frac{1{,}000 \times Loss \times V_{AC}}{L \times I}$$

Where:

- **V_C = Millivolt drop per amp-metre route length (in mV/Am)**
- **Loss = Maximum voltage drop in the cable (dimensionless, i.e. 5% = 0.05)**
- **V_{AC} = AC voltage of the grid (in V)**
- **L = Route length (in m)**
- **I = Current flow through the cable (in A)**

EXAMPLE:

The inverter for use with a 2 kWp PV array is to be installed so that the AC cabling route will be 30 m between the inverter and the main switchboard. What is the minimum CSA required for the AC cabling to ensure that the voltage rise will be less than 1%?

Assume the following:

Maximum inverter output current = 11 A

Single phase supply: AC voltage = 230 V_{RMS}

Using Table 14.1,

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{AC}}{L \times I}$$

$$= \frac{1{,}000 \times 0.01 \times 230\ \text{V}}{30\ \text{m} \times 11\ \text{A}}$$

$$= 6.97\ \text{mV/Am}\ (\textit{single-phase AC})$$

Converting to three-phase:

$$\frac{6.97\ \text{mV/Am}}{1.155} = 6.03\ \text{mV/Am}\ (\textit{three-phase AC})$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a 10mm² cable.

26. Extension Material: Calculating Power Loss

Removal:

Cable design for a grid-connected PV system should ensure that there are no excessive voltage drops throughout the system. The voltage drop calculation, expressed as a percentage, is also used to represent the cable power losses for the purposes of calculating the system efficiency (Chapter 15). The voltage drop and power loss at STC are proportional according to Ohm's law P = I × V.

However, it might be useful to be able to calculate the actual power loss experienced by the system. Calculating the power loss in real terms uses Ohm's law, multiplying the voltage drop by the current at STC. This results in the following formula:

Where:

- A_{CABLE} = CSA of cable in mm².
- L_{CABLE} = route length of cable in metres (multiplying by two adjusts for total circuit cable length).
- IMP = maximum power current in amperes*†.
- ρ = resistivity of the conductor in Ω/m/mm².

  Note:

  *For AC calculations, the current should also account for the power factor:

  †For DC calculations, the I_{MP} current should be used and not the I_{SC} current.

27. Chapter 14 Quiz

Amendments:

Question 3

An array has four strings of nine modules and the following specifications:

- Module I_{MP} = 5.2 A
- Module V_{MPP} = 35.1 V
- String cable length = 14 m
- Array cable length = 22 m

Assume the cable has the same specifications as in AS/NZS 3008.1.*1:2017* Table 47 and a maximum conductor temperature of 90°C.

The cables should be sized to have a maximum 1.5% voltage drop on the string cables and a 1.5% voltage drop on the array cables.

a. Calculate the minimum string cable CSA.

b. Calculate the minimum array cable CSA.

Question 4

You are supplied with a reel of 4 mm^2 cable to use as the array cable for a solar PV installation. The array has five strings of ten modules and the following specifications:

- Module I_{MP} = 7.9 A
- Module V_{MPP} = 36.1 V
- String cable length = 20 m
- Array cable length = 11 m

Assume the cable has the same specifications as in AS/NZS 3008.1.*1:2017* Table 47 and a maximum conductor temperature of 60°C.

a. Calculate the % voltage drop on the array cable.

b. Calculate the maximum allowable % voltage drop on the string cables.

c. Calculate the minimum string cable CSA.

Question 5

The distance between an inverter and the main switchboard is 26 m. What is the minimum cable CSA that will ensure the voltage drop will be less than 1%?

Assume the following:

- I_{AC} = 12 A
- V = Single-phase 230 V_{RMS}

Assume the cable has the same specifications as in AS/NZS 3008.*1.1:2017* Table 47 and a maximum conductor temperature of 90°C.

Chapter 15

28. Section 15.1.1 - Effect of Temperature on PV Module Efficiency

Amendment:

$$T_{CELL\ EFF} = T_{AMB} + T_r$$

Where:

- $T_{CELL\ EFF}$ = effective cell temperature, in °C.
- T_{AMB} = ambient temperature, in °C.
- **T_r = temperature rise dependent on the mounting type, in °C.**

Addition:

> ***AUSTRALIAN STANDARDS***
>
> According to ***AS/NZS 5033:2014***, T_r is expected to be approximately 25°C with very good ventilation. However, the CEC design guidelines recommend the following temperature rise values for different mounting arrangements:
>
> - 35°C when parallel to the roof with less than 150mm standoff
> - 30°C when using a rack-type mount with more than 150mm standoff
> - 25°C for freestanding frames and where there is a 20 degree or greater angle between the modules and the roof

Amendment:

Question

Calculate the efficiency (f_{TEMP}) for a 175 Wp poly-crystalline module at an ambient temperature is 23°C. The temperature coefficient for this particular module is –0.5%/°C (or in absolute terms, –0.005/°C). **Assume T_r = 25°C.**

Answer

The steps for calculating f_{TEMP} are as follows:

Calculate the cell temperature:

$$\begin{aligned} T_{CELL\ EFF} &= T_{AMB} + T_r \\ &= 23^\circ C + 25^\circ C \\ &= 48^\circ C \end{aligned}$$

29. Section 15.1.3 - Orientation and Tilt Angle of the Modules

Removal:

> **RESOURCES**
>
> Sources of solar irradiation data for different tilts and orientations for locations in Australia include:
>
> - **Clean Energy Council monthly irradiation tables (www.solaraccreditation.com.au/).**
> - The Australian Solar Radiation Data Handbook – Exemplary Energy.
> - NASA POWER Data Access Viewer (power.larc.nasa.gov/data-access-viewer).

Amendment:

To calculate the annual irradiation received by the array installed with a tilt of 40° and an orientation of 50° from true north, the average monthly horizontal irradiation levels are required. The adjusted annual irradiation calculations are shown in Table 15.4.

Table 15.4: *Annual irradiation calculations for PV modules at different tilts and orientations in Brisbane.*

Month	Days per month	Average daily irradiation on horizontal plane (kWh/m²/day)	Average monthly irradiation on horizontal plane (kWh/m²/month)	Percentage received by modules tilted 40° and orientated 50° (%)	Monthly irradiation received by modules tilted 40° and orientated 50° (kWh/m²/month)
Jan	31	6.6	204.6	88	180.0
Feb	28	5.9	165.2	95	156.9
Mar	31	5.3	164.3	105	172.5
Apr	30	4.6	138.0	117	161.5
May	31	3.7	114.7	130	149.1
Jun	30	3.2	96.0	137	131.5
Jul	31	3.6	111.6	134	149.5
Aug	31	4.4	136.4	123	167.8
Sep	30	5.4	162.0	109	176.6
Oct	31	6.0	186.0	97	180.4
Nov	30	6.5	195.0	90	175.5
Dec	31	6.7	207.7	87	180.7
Average annual irradiation (kWh/m²/year)			1881.5		1982.0

An array mounted in Brisbane with a tilt of 40° and an orientation of 50° from true north will receive an average irradiation of 1982.0 kWh/m2/year, compared to 1881.5 kWh/m2/year received on a horizontal plane.

Addition:

REMEMBER

A PV module that is perpendicular to the Sun will receive the most radiation, as outlined in Section 3.3.1. As a result, tilted modules will often receive more solar radiation (>100% of the horizontal plane irradiation) in comparison to flat-mounted modules.

30. Chapter 15 Quiz

Amendments:

Question 2

Calculate the resulting efficiency (f_{TEMP}) for a 250 Wp module at an ambient temperature of 26°C and a temperature coefficient of 905 mW/°C. Assume temperature rise due to module mounting method is 25°C.

Question 3

Calculate the system operating efficiency for a solar PV system with the following losses:

- Manufacturer's tolerance = ±2%

Assume the ambient temperature at the location **is 24°C, T_r is 25°C, and the temperature coefficient of the modules** is −0.6%/°C.

Question 4

Temperature coefficient	**–0.45**%/°C

Chapter 16

31. Section 16.1 - Standards and Best Practice

Amendment:

RESOURCE

Australian Capital Territory:
https://www.legislation.act.gov.au/DownloadFile/di/2013-220/current/PDF/2013-220.PDF

CEC Guidelines:
https://www.cleanenergycouncil.org.au

New South Wales:
https://energy.nsw.gov.au/government-and-regulation/legislative-and-regulatory-requirements/service-installation-rules

32. Section 16.1.2 - Industry Guidelines and Best Practice

Amendment:

Applying standards and best practice guidelines can ensure a high-quality design **and installation (Figure 16.5).**

33. Section 16.5.2 - DC Disconnection Devices

Amendment:

Figure 16.20: *Example of application of AS/NZS 5033:2014* ***Section 3.1****, showing enclosure for inverter/disconnector for non-domestic systems >600VDC.*

Domestic DC disconnectors must be readily available; therefore:

- There should be no need to dismantle anything to access or operate the disconnector.
- A domestic rooftop disconnector should be installed on a section of the roof that can be safely accessed by a person on the roof. If it is underneath a module, it needs to be easily reached to operate without removing any modules first. Non-domestic >600 V installation disconnectors should be readily available but not readily accessible:
- The inverter and disconnector could be in a lockable room that is accessible only to authorised personnel.
- The inverter and disconnector could be inside an enclosure with a padlock (Figure 16.20).
- The inverter and disconnector could be on a commercial roof with locked roof access.

Chapter 20

34. Section 20.3 - Large-Scale Grid-Connected PV System Design Process

Removal:

High-efficiency 300 W monocrystalline modules

Replacement:

$$V_{MP\ at\ X°C} = \{V_{MP\ at\ STC} + [\gamma_{VMP} \times (T_{X°C} - T_{STC})]\} \times (1 - voltage\ drop\ decimal)$$
$$V_{MP\ at\ 75°C} = \{32.0\ V + [(-0.42\%/°C \times 32.0\ V) \times (75°C - 25°C)]\} \times (1 - 0.03) = 24.52\ V$$
$$V_{MP\ at\ 0°C} = \{32.0\ V + [(-0.42\%/°C \times 32.0\ V) \times (0°C - 25°C)]\} \times (1 - 0.03) = 34.29\ V$$
$$V_{OC\ at\ 0°C} = 39.5\ V + [(-0.31\%/°C \times 39.5\ V) \times (0°C - 25°C)] = 42.56\ V$$

Amendment:

Min. inverter operating voltage 16 V < Min. module operating voltage 24.52 V (at 75°C)

Min. inverter start voltage 22 V < Min. module operating voltage 24.52 V (at 75°C)

However, the minimum operating voltage of the modules is not greater than the minimum operating voltage of the MPPT:

Min. peak power tracking voltage 27 V > Min. module operating voltage 24.52 V (at 75°C)

Appendices

35. Appendix 2: Shadow Tables

Amendment:

*Distances that a shadow would be cast by a 1 metre high object **on the winter solstice** in Adelaide, Alice Springs, Brisbane, Cairns and Canberra.*

36. Appendix 3: Formulae Summary

Replacement:

Chapter 14

Calculating Voltage Drop

$$V_d = \frac{2 \times L \times I \times \rho \times \cos\Phi}{A_{CABLE}}$$

Where:

- V_d = voltage drop in volts.
- L = route length of cable in metres (multiplying by two adjusts for total circuit wire length).
- I = current flow in amperes (for DC calculations, the I_{MP} at STC current should be used).
- ρ = resistivity of the wire in Ω/m/mm².
- $\cos\Phi$ = power factor (include only for AC cables).
- A_{CABLE} = CSA of cable in mm².

Using V_C Tables to Calculate Voltage Drop

$$V_d = \frac{L \times I \times V_C}{1{,}000}$$

Where:

- V_d = voltage drop in volts.
- L = route length of cable in metres.
- I = current flow in amperes.
- V_C = millivolt drop per amp-metre route length in millivolts per amp-metre.

Calculating Voltage Drop as Percentage

$$Loss = \frac{V_d}{V_{DC}}$$

- *Loss* = voltage drop in the conductor expressed as a decimal, e.g. 3% = 0.03.
- V_d = voltage drop in volts.
- V_{DC} = system voltage in volts.

Calculating the Maximum Permitted V_C

$$V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$

Where:

- V_C = millivolt drop per amp-metre route length in millivolts per amp-metre.
- *Loss* = maximum permissible voltage loss in the conductor, expressed as a decimal, e.g. 3% = 0.03.
- V_{DC} = system voltage in volts.
- L = route length of cable in metres.
- I = current flow in amperes.

String Cables: Calculating the Required CCC
If string overcurrent protection will be installed:

$$CCC \geq Rating\ of\ string\ overcurrent\ protection$$

If string overcurrent protection will not be installed:

$$CCC \geq I_n + (1.25 \times I_{SC\ MOD}) \times (Number\ of\ strings - 1)$$

Where:

- I_n = downstream overcurrent protection.
- *Number of strings* = total number of parallel connected strings protected by the nearest overcurrent device.

Sub-array Cables: Calculating the Required CCC

If sub-array overcurrent protection will be installed:

$$CCC \geq Rating\ of\ sub\text{-}array\ overcurrent\ protection$$

If sub-array overcurrent protection will not be installed:

$$CCC \geq 1.25 \times sub\text{-}array\ short\ circuit\ current$$

OR

$$CCC \geq I_n + (1.25 \times Sum\ of\ I_{SC}\ from\ other\ sub\text{-}arrays)$$

Where

- I_n = downstream overcurrent protection.

Array Cables: Calculating the Required CCC

1. The array short circuit current (with safety margin):

$$CCC \geq 1.25 \times array\ short\ circuit\ current$$

OR

The inverter back-feed current:

$$CCC \geq inverter\ backfeed\ current$$

Amendment:

Chapter 15

Calculating the Effective Cell Temperature

$$T_{\text{CELL EFF}} = T_{\text{AMB}} + T_{\text{r}}$$

Where:

- $T_{\text{CELL EFF}}$ = effective cell temperature, in °C.
- T_{AMB} = ambient temperature, in °C.
- T_{r} = temperature rise dependent on the mounting type, in °C.

37. Appendix 5: Quiz Answers

Amendment to Chapter 13 Question 5:

$$PV\ array\ maximum\ voltage = 47.3567\ \text{V} \times 7$$

$$PV\ array\ maximum\ voltage = 331.49\ \text{V}$$

A maximum array voltage of 331.49 V will be used to check the suitability of the PV array DC isolator.

Current

The maximum array short circuit current is:

$$1.25 \times I_{SC\ array} = 1.25 \times 3 \times 8.1\ A = 30.375\ A$$

A maximum array current of 30.38 A will be used to check the suitability of the PV array DC isolator.

Amendment to Chapter 15 Question 2:

$$T_{\text{CELL EFF}} = T_{\text{AMB}} + T_{\text{r}}$$

$$T_{\text{CELL EFF}} = 26°\text{C} + 25°\text{C} = 51°\text{C}$$

Replacement for Chapter 14:

Question 3

String cable:

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$
$$= \frac{1{,}000 \times 0.015 \times (9 \times 35.1)\ \text{V}}{14\ \text{m} \times 5.2\ \text{A}}$$
$$= 65.09\ \text{mV/Am}\ (DC)$$

Converting to three-phase:

$$\frac{65.09\ \text{mV/Am}}{1.155} = 56.35\ \text{mV/Am}\ (\textit{three-phase AC})$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a 1 mm^2 cable.

Array cable:

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$
$$= \frac{1{,}000 \times 0.015 \times (9 \times 35.1)\ \text{V}}{22\ \text{m} \times (4 \times 5.2\ \text{A})}$$
$$= 10.36\ \text{mV/Am}\ (DC)$$

Converting to three-phase:

$$\frac{10.36\ \text{mV/Am}}{1.155} = 8.97\ \text{mV/Am}\ (\textit{three-phase AC})$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a 6 mm^2 cable.

Question 4

a. Array cable:

$$V_d = \frac{L \times I \times V_C}{1{,}000}$$
$$= \frac{11\ \text{m} \times (5 \times 7.9)\ \text{A} \times (10.9 \times 1.155)\ \text{mV/Am}}{1{,}000}$$
$$= 5.47\ \text{V}$$
$$Loss = \frac{V_d}{V_{DC}}$$
$$= \frac{5.47\ \text{V}}{(10 \times 36.1)\ \text{V}}$$
$$= 0.015 = 1.5\ \%$$

b. $V_{DROP\ ALLOWABLE\ STRING\ CABLE} = V_{DROP\ MAX} - V_{DROP\ ARRAY\ CABLE}$

$= 3.0\ \% - 1.5\% = 1.5\%$

c. String cable:

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{DC}}{L \times I}$$
$$= \frac{1{,}000 \times 0.015 \times (10 \times 36.1)\ \text{V}}{20\ \text{m} \times 7.9\ \text{A}}$$
$$= 34.27\ \text{mV/Am}\ (DC)$$

Assuming the selected cable may operate up to its rated insulation temperature of 60°C, the minimum conductor CSA that meets the calculated V_C requirement is a 1.5 mm^2 cable.

Question 5
AC cable:

$$Maximum\ V_C = \frac{1{,}000 \times Loss \times V_{AC}}{L \times I}$$
$$= \frac{1{,}000 \times 0.01 \times 230\ \text{V}}{26\ \text{m} \times 12\ \text{A}}$$
$$= 7.37\ \text{mV/Am}\ (DC)$$

Converting to three-phase:

$$\frac{7.37\ \text{mV/Am}}{1.155} = 6.38\ \text{mV/Am}\ (three\text{-}phase\ AC)$$

Assuming the selected cable may operate up to its rated insulation temperature of 90°C, the minimum conductor CSA that meets the calculated V_C requirement is a 10 mm^2 cable.