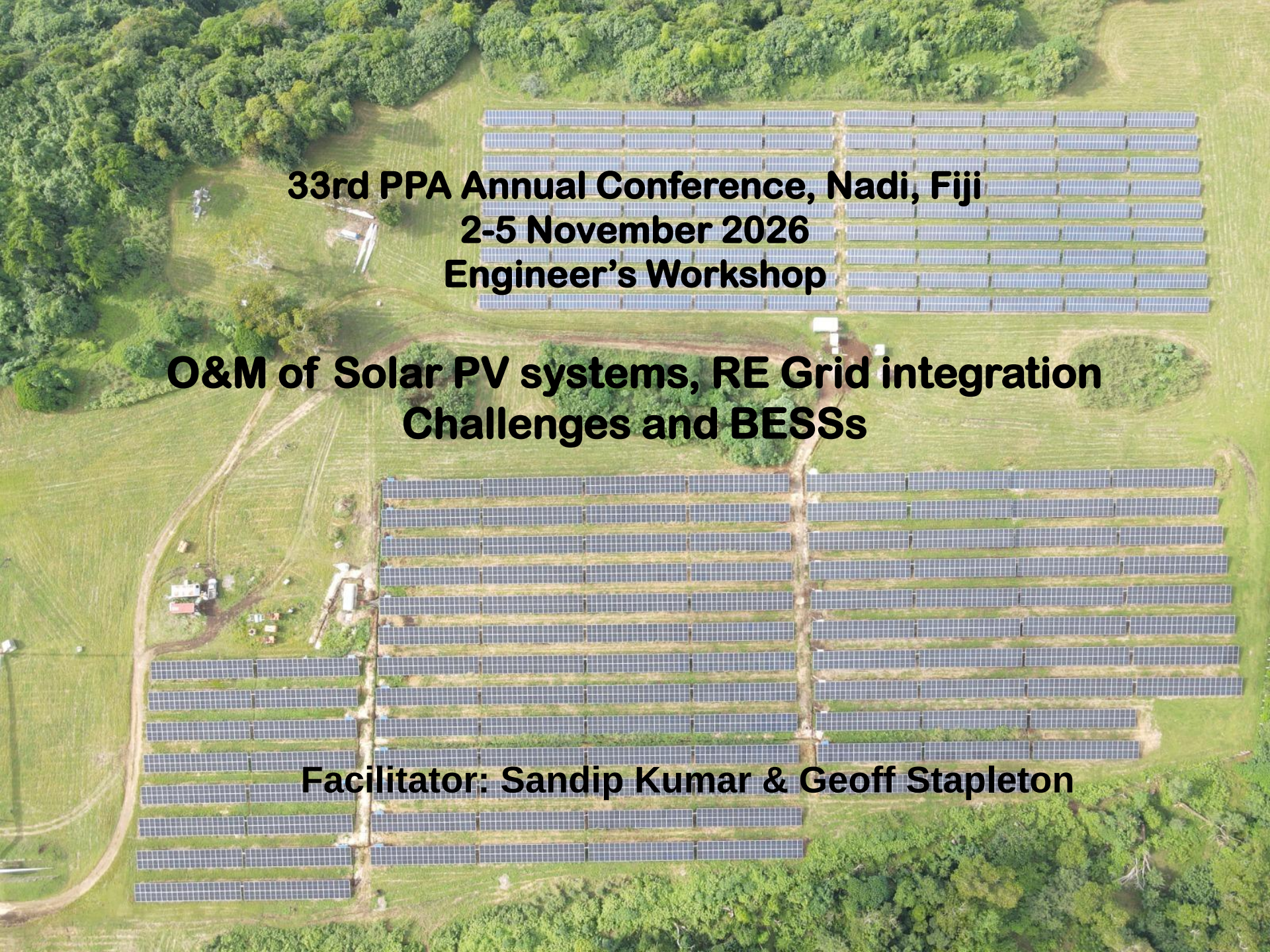


33rd PPA Annual Conference, Nadi, Fiji
2-5 November 2026
Engineer's Workshop

O&M of Solar PV systems, RE Grid integration Challenges and BESSs

Facilitator: Sandip Kumar & Geoff Stapleton

Outline

- Components of a PV system
- Common Issues
- Maintenance process, plan and procedures
- Preventive maintenance
- Corrective maintenance
- Condition-based maintenance

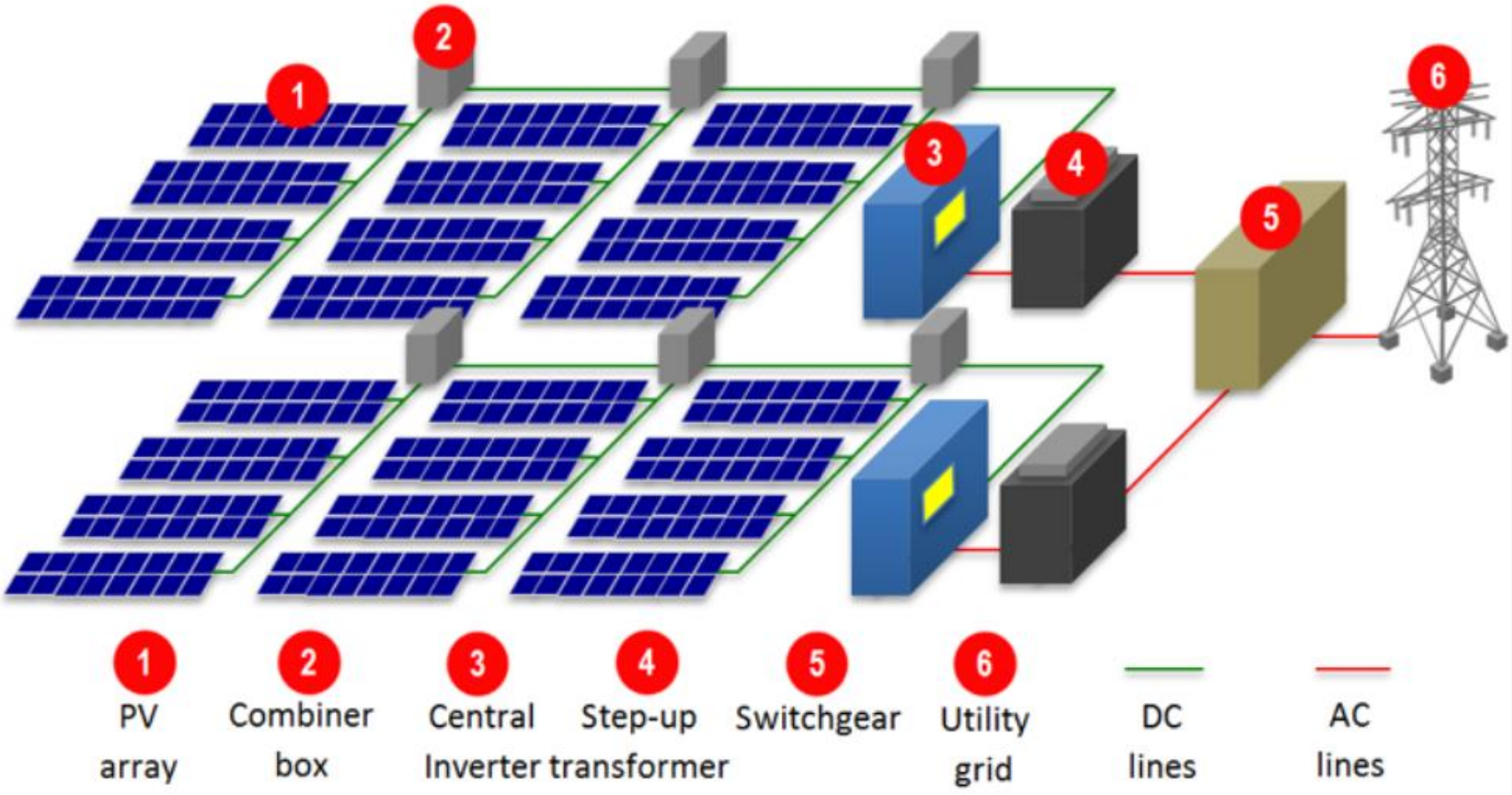
Components of a PV system

- Independent of the size of the system, there are 4 main components categories:
  - Modules;
  - Racking system;
  - Power conversion equipment; and
  - Balance of System equipment (BOS).
- The balance of system equipment refers to all of the additional equipment needed to make the system work, including but not limited to cables, connectors, electrical protection, metering, and monitoring. Meanwhile, power conversion equipment in large projects can include multiple inverters and transformers, depending on the size and design of the system.

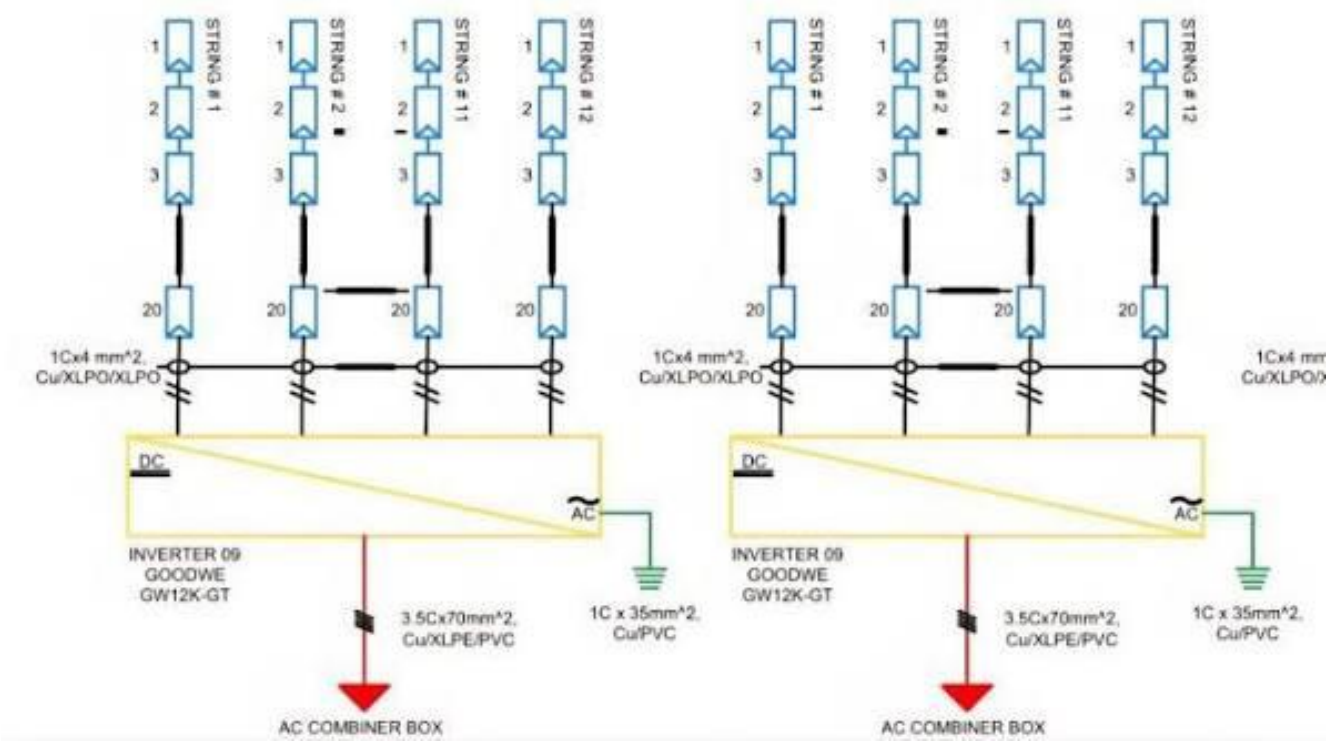
Components of a PV system 2

- The fundamental concepts and technology applied to medium and large-scale solar systems don't differ much from residential systems , however, solar farms are usually located far from customers and loads which leads to higher power losses on cables. To decrease power losses, step-up transformers are often used to increase the voltage to HV (high voltage) for distribution and transmission.

Solar farm schematics with central inverter configuration



Solar farm schematics with string inverter configuration



PV Modules

- PV modules used in commercial and utility scale projects generally comprise the same technology as those used in residential systems. As the technology develops, the market sees higher efficiencies with decreasing prices for all modules. Nonetheless, PV modules are fragile and must be maintained frequently and with methods that are technology appropriate.

PV Modules

- Some of the new technologies widely used in commercial systems include:
- New PV module technologies

Technology Name	Main advantages	Main Issues
PERC (Passive Emitter Rear Cells)	Additional layers on the back of the cell to absorb more photons (higher efficiency)	Light induced degradation (LID) (loss of performance due to light in the first few hours of exposure)
Bifacial	Absorbs light from both sides of the module; the rear can absorb the reflected light from the roof/ground	Both sides must be cleaned. More fragile than standard modules
Split Panels	Contains double the number of cells, lower internal resistance and higher shade tolerance	More expensive, higher potential for internal defects.
Dual Glass/ Frameless modules	Aesthetically pleasing, easier to clean, less earthing required, negates potential induced degradation (PID)	More fragile, heavier and harder to clamp and install

Common issues with solar modules

- PV modules are designed to withstand relevant environmental conditions, such as mechanical stresses from wind and snow.
- Despite this, they are still susceptible to fractures, thermal damage and electrical failures. A good design and installation methodology will help to mitigate these risks, however once damaged, solar cells can produce reverse currents and damage other cells and components.

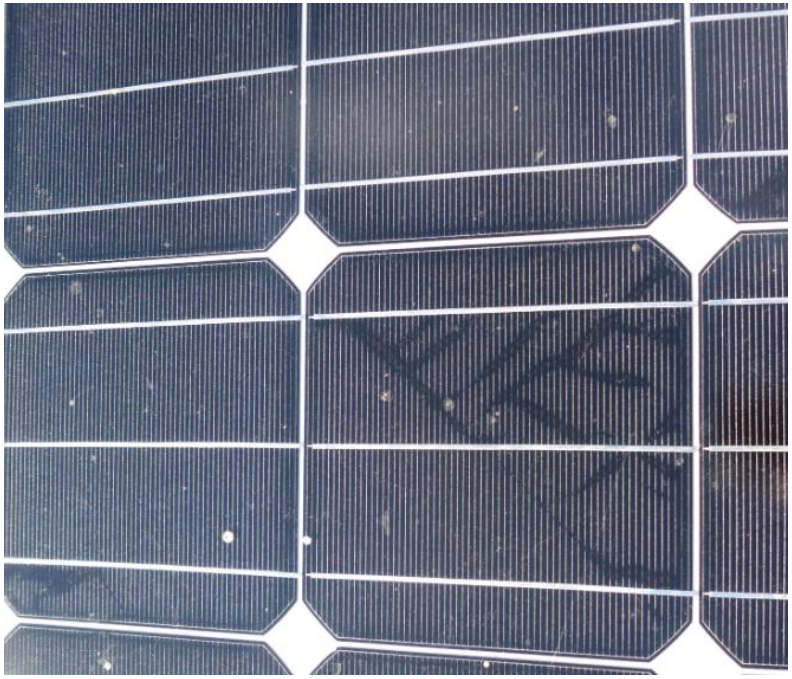
Common issues with solar modules 2

- **Yellowing**: the EVA (Ethyl Vinyl Acetate) coating inside the layers of the solar module, which are usually colourless, can yellow with age/UV exposure, reducing light transmission to the surface of the cells within the module (Figure below). In severe cases the EVA layer can become opaque, significantly reducing the output of the module.



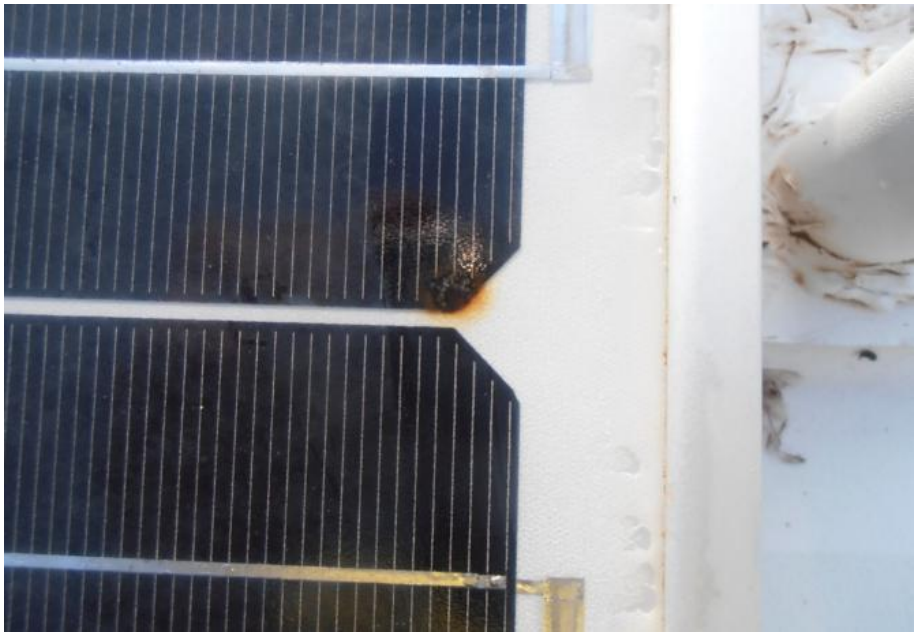
Common issues with solar modules 3

- **Micro fractures:** Discrete cracks formed in the cells in a PV module (Figure below). These cracks can be caused by localized pressure on the module, and can occur during module manufacturing or installation. They usually appear as “snail trails” on a solar module.



Common issues with solar modules 4

- **Hot spots:** A cell in a solar module may underperform due to a manufacturing defect or localised shading (Figure below). The under-performing cell will limit the overall output of the PV module, whilst power from the other cells is dissipated into the under-performing cell. This power dissipation results in overheating of the under-performing cell forming a hot spot.



Common issues with solar modules 5

- **Delamination:** Occurs when the bonding between the back plastic and the front glass separate (Figure below). This separation permits air and moisture inside the module which may lead to corrosion. Delamination typically occurs if inferior plastics are used or a low-quality manufacturing process.



Mounting Systems

- Mounting rack systems can be divided into two main categories: Roof-mount or ground mount.
- Utility scale solar farms are typically ground mounted due to a large spatial requirement.
- **Roof-mounting systems:**
  - Are more common in C&I scale as the roof can be used as the installation site;
  - Can be mounted onto or integrated into the building; and
  - May be either installed with panels flush to the roof, or raised and tilted at a specified angle.
- **Ground-mounted systems:**
  - Are more common in utility scale due to a larger spatial requirement;
  - Use a fixed tilt or adjustable tilt structure – the adjustable structure can be used with a daily tracker or a seasonal tracker; and
  - May use single or double axis tracking to maximise energy yield.

Inverters

- The main function of the inverter is to convert DC power into AC power. Unlike residential systems, large scale PV plants typically require an external step up transformer, that provides galvanic isolation between the PV system and the grid.
- Using a **centralised inverter** in a system design will involve installing a small number of large inverters often in the range of 1 -2.5 MVA power output. Central inverters do not offer MPPT flexibility to track individual strings and may have longer downtime as a skilled technician must carry out all maintenance on the inverter. Conversely, maintenance and troubleshooting may be simpler and more thorough as there are only few inverters to be maintained.



Inverters 2

- **String inverters** are typically used where greater design flexibility is required for a site, and vary in size from 5 to 175kVA (the upper limit of this range continually increases as manufacturers look to serve the C&I market). This design facilitates MPP tracking of individual strings and offers higher flexibility in PV array design as strings can have different size and orientation without being impacted by mismatch losses. Each inverter can be removed and replaced for maintenance minimizing downtime and improving monitoring and fault finding. However, if there are larger faults with multiple string inverters, this may increase the cost and downtime spent on maintaining each string inverter.



Common issues with inverters

- Inverters are usually the components with the shortest lifetime of the system. While modules will have a lifetime of 20 years, most inverters have 10 years warranty and can operate for ten to twelve years fault free, provided that regular maintenance is carried out.
- Inverters are delicate components. Here are some of the issues that can be found in inverters:
  - Accumulation of dust
  - Overheating due to fans not operating as required
  - Burnt fuse
  - Software issues
  - Over and under voltage
  - Communication failures
  - Installation faults (e.g. loose cable terminations, incorrect protection settings)
  - Damage from lightning

Transformers

- Most commercial systems are designed to connect at low voltage and do not require a transformer. Where a system is to connect to the grid at high voltage, or where excessive losses would occur at low voltage, a transformer is required for the distribution and two transformer stages for transmission level voltages.
- The transformer is connected to the inverter in the low voltage sides and to the grid interface switchgear in the high voltage side.
- The transformer is not as prone to failure as the inverter. They are robust and reliable equipment with a lifespan of 20+ years.

BOS Electrical Components

Fuses

Strings connected to individual MPPTs will not require string fusing, however, when string fusing is required, each string is usually protected using an appropriately rated fuse which is designed especially for PV specific applications. In ungrounded systems both the string cables are fused while in grounded systems only the ungrounded terminal of string is connected to fuse. Each fuse should be placed in touch safe fuse holder, that is, the fuse can be replaced without touching the live parts.

Surge protection

Where implemented, a surge protection device or surge arrester is connected to both the array cables and installation earth. This protection must be connected in the circuit immediately after the point where fuses connect and before any disconnect devices to ensure that surge protection is retained in the system even when it is disconnected. They may also be installed at or inside the inverter (depending on the model) to prevent damage to the inverter.

BOS Electrical Components 2

Current monitoring

- Depending on the granularity of monitoring, current monitoring can be employed on each string or a group of strings. The corresponding electronics consists of current sensors around the cables of which the current is to be measured, current measuring board that converts the data into useful form which is transmitted by a communication equipment to central data logging equipment.
- If the system has string or multi string monitoring features, current monitoring devices will be installed inside each combiner boxes in one of the conducting terminals of each circuit under measurement. Alternately, most inverters are also capable of monitoring the current of each DC input.

BOS Electrical Components 3

Disconnect switch

- A four/two pole disconnect switch may also be present in the combiner box and can be used to isolate the combiner box and the PV system connected to it from rest of the system. The disconnect switch can be “manual” where one has to actually go to the site to operate the switch; or it can also be “remote controlled” where one can control its operation remotely by sending commands to the control system.

O & M

- The life cycle of a solar PV system can be broken down into five segments: design, installation, commissioning, operation and maintenance (O&M) and end of life.
- With most solar installations having an average lifetime of 20 to 30 years, the O&M phase is the longest and represents a significant investment to the asset holder.

O & M 2

- O&M of the solar PV system is a critical component of ensuring that the PV system operates as intended for its design lifetime. O&M activities include:
  - Mechanical checks for system safety and compliance;
  - Electrical tests and inspections to ensure safe and efficient operation;
  - Performance validation to evaluate energy yield from the system against the expected output; and
  - Component monitoring (via Supervisory Control and Data Acquisition, or SCADA) which allows the O&M provider to gather critical system metrics, find trends and understand how the system is operating in real time and historically.

Types of Maintenance

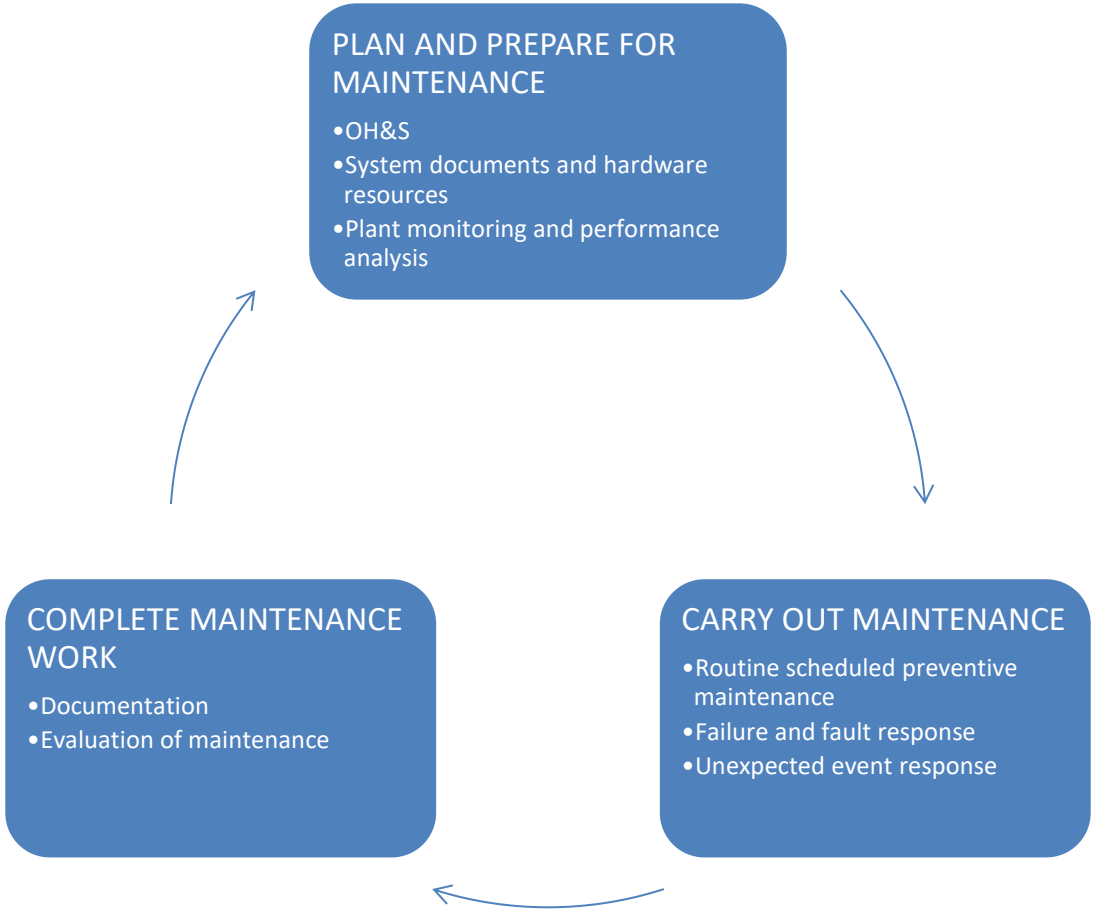
- Well planned and executed maintenance of a solar system increases the system's lifespan, energy production and safety while decreasing downtime and unexpected costs.
- There are three different types of maintenance that can be performed on a solar system:
- **Preventive** – Active maintenance that is done prior to any damage or issues with the system. Preventative maintenance is scheduled during the design phase of the project. It includes items such as cleaning, testing components and replacing parts.

Types of Maintenance 2

- **Corrective** – Reactive maintenance that is done once an unexpected issue is found. Corrective maintenance includes troubleshooting, replacing or fixing damaged components and acting upon a failure

- **Condition Based** –The monitoring system may be able to predict events that can damage the PV system such as extreme weather or performance issues with components that may cause failure in the future. The operation team can decide on the best course of action for each problem.

Maintenance Process



What is a Maintenance Plan?

- The maintenance plan is a document that details the periodicity, frequency, and actions that will need to be performed on a PV system, for example.
- The main objective of preparing a maintenance plan is to have resources for its performance in the pre-established time to occur.
- This plan may require the use of maintenance management software, which allows for the tracking of maintenance-related tasks and assists in controlling costs. There is also software that allows real-time monitoring of equipment and assets, alerting those responsible when abnormal signals are detected.

Maintenance Procedures

- Maintenance procedures include preventive maintenance, corrective maintenance and possibly condition-based maintenance activities.

- When determining the extent of these maintenance procedures, it is very important to find the optimum balance between low cost and high plant reliability and performance.

Plan and Prepare For Maintenance

- Understand and review all regulatory, industrial and enterprise occupational health and safety (OHS/WHS etc.) standards.
- Perform a risk assessment of the site (discussed in Day 1)
- Access and obtain all resources, such as manufacturer's manual, site plans and drawings, system diagrams, etc.; understand and link them to the actual site.
- Obtain all testing tools, equipment and spares needed for maintenance.
- Ensure tools are operational and properly calibrated where applicable

Plan and Prepare For Maintenance 2

- Read and understand all the maintenance manuals provided. Review past inspection reports, performance reports, and error trends, and revise the existing maintenance manual. Develop a local maintenance schedule specific to the site where required.

- Monitor the data acquisition system (DAS) in the control room, where applicable, and do a performance analysis of the system. Check for any unexpected deviations in plant's output. At the same time, look for any alarm events on the DAS to identify any fault or failure.

Example – Maintenance Manual Excerpt

6 Maintenance

6.1 Safety during Maintenance

⚠ DANGER

Danger to life from electric shock due to live voltage

High voltages are present in the live components of the product. Touching live components results in death or serious injury due to electric shock.

- Wear suitable personal protective equipment for all work on the product.
- Do not touch any live components.
- Observe all warning messages on the product and in the documentation.
- Observe all safety information of the module manufacturer.
- After switching off the inverter, wait at least 15 minutes before opening it to allow the capacitors to discharge completely (see Section 4.2, page 26).

NOTICE

Property damage due to dust intrusion and moisture penetration

Dust or moisture intrusion can damage the product and impair its functionality.

- Do not open the enclosure during rainfall or when humidity exceeds the specified thresholds. The humidity thresholds are: 15% to 95%.
- Only perform maintenance work when the environment is dry and free of dust.
- Operation of the product is only permitted when it is closed.
- Connect the external supply voltage after mounting and installing the product.
- If the installation or commissioning process is interrupted, mount all panels.
- Close and lock the enclosure.
- The product must always be closed for storage.
- Store the product in a dry and covered location.
- The temperature at the storage location must be in the specified range. The temperature range is: −25 °C to +70 °C.

NOTICE

Damage to electronic components due to electrostatic discharge

Electrostatic discharge can damage or destroy electronic components.

- Observe the ESD safety regulations when working on the product.
- Wear suitable personal protective equipment for all work on the product.
- Discharge electrostatic charge by touching grounded enclosure parts or other grounded elements. Only then is it safe to touch electronic components.

Plan And Prepare For Maintenance 3

- Before starting on-site maintenance activities, prepare the work area in accordance with work and site requirements.

- This includes requesting for or carrying out necessary isolations, transporting all necessary equipment to site, job allocation etc.

Carry Out Maintenance

- Follow all OH&S control measures and procedures for carrying out the work.
- Confirm the required isolation of equipment.
- Perform general inspections of the site area and all equipment of the PV system. This includes visual inspection, noting down performance parameters and errors, minor modifications such as tightening loose screws, and other manufacturer and equipment specific maintenance activities.

Carry Out Maintenance 2

- In the case of fault or failure, inform all stakeholders about the problem. Repair or replace any failed equipment or faults using the established procedures. In some cases, it may be necessary to call the manufacturer or installer to assist in the repair of damage.

- Be careful not to void any warranty conditions while servicing the system.

- Any unexpected situation, such as grid failure or fire, should be dealt with according to established procedures and/or discussions with appropriate persons.

Completing Maintenance Work

- Follow OH & S work completion risk control measures. Lock all equipment so access is allowed only to authorized personnel.
- Clear the work area of waste, tools, etc. then reconnect and secure the system to restore it to its proper operational condition.
- Document all work completed. This should include a description of the problems identified and, if needed, justification for the solutions used to solve those problems.
- Evaluate the maintenance program and make recommendations for future improvement.

System Maintenance Personnel

- Responsible for visual and mechanical inspections such as:
  - Ensuring switched devices are operational
  - String IV curve testing
  - Switchgear replacement
- Some personnel are required to be qualified with special skills such as having participated in trainings for working with high voltage equipment, equipment calibration, relay calibration, transformer maintenance etc.

Preventive Maintenance

- Includes scheduled activities carried out to prevent issues occurring with the system equipment that may lead to reduction in performance and loss of revenue.

Date	Name of Maintenance Technician	PV Module Clean		Array Frame			Array Cabling	Array Output voltage
		Yes	No	Good	Fair	Bad		

PV Module Maintenance log sheet

Solar System Maintenance Checklist

Task	Frequency	Description
Monitor energy production	Monthly	Use monitoring tools (e.g. app) to check system performance and identify irregularities.
Inspect inverter lights	Monthly	Ensure indicator lights show normal operation; address any error messages or warnings.
Check panels for debris	Quarterly	Remove visible debris like leaves; schedule cleaning if necessary.
Inspect for damage	Quarterly	Look for cracks, chips, or discoloration on panels; check mounting hardware for corrosion.
Professional system check	Every 3 years or as required	Hire a licensed professional to inspect electrical connections, inverters, and mounting systems.

Preventive Maintenance 2

- The extent and period of preventive maintenance activities will depend on:
  - The manufacturers' recommendations and the equipment warranty requirements
  - The specific environmental conditions, such as the type of vegetation on site, the level of rainfall, the dustiness or saltiness of the area etc.
  - The climatic conditions and seasonable climatic variability
  - The optimum balance between the cost of preventive maintenance activities and the increased revenue from the increased yield over the system lifetime.

Preventive Maintenance 3

Activities may include:

- Module cleaning
- Vegetation management
- Wildlife access prevention
- Water drainage / erosion control
- Upkeep of data acquisition and monitoring systems
  - Servicing of electronics and sensors

Preventive Maintenance 4

Upkeep of major components

- Inverter inspection and servicing
- Transformer inspection and servicing
- Checking module connection integrity
- Checking for hotspots
- Checking junction/combiner boxes for water ingress, dirt or dust accumulation and integrity of the connections within the boxes

Preventive Maintenance 5

Upkeep of balance of system components

- Racking system maintenance
- Check and all wiring and schedule repairs if needed
- Checking and servicing security system
- Check signal strength and connection of communication systems.

Preventive Maintenance of Equipment

Cleaning PV Modules

- Depositions on modules like dirt, dust, debris, salt, pollens and bird droppings can significantly reduce system efficiency



Boost in system's performance ratio in a 900kW roof-mounted PV plant in Fetzer Winery in Hopland, California after array cleaning

Image source: Williams D., Large-scale PV operations and maintenance, Solar Pro magazine, July 2010

Cleaning PV Modules 2

Frequency and need for cleaning determined majorly by:

- Site conditions
  - If regular rainfall at site, regular cleaning not required
  - Proper cleaning schedule required in dry or desert environment
- Array specifics
  - Flat PV arrays highly prone to soiling and not effectively cleaned during rainfall
  - Designs should consider a minimum of 10 degree tilt to facilitate cleaning by rain
  - Modules with standard frames may have build-up of soil/debris in the frame edges unlike frameless modules

Cleaning PV Modules 3

- Water supply/Storm water run-off
  - Costs can increase if insufficient water supply is available for cleaning
  - The stormwater management system can include collection and treatment of water run-off to be used for array cleaning
- Operating priorities
  - Cleaning priority decided by comparing the actual energy production with the projected production adjusted for degradation over time. If loss of production exceeds cost of array cleaning, cleaning crew can be dispatched
- Budget constraints

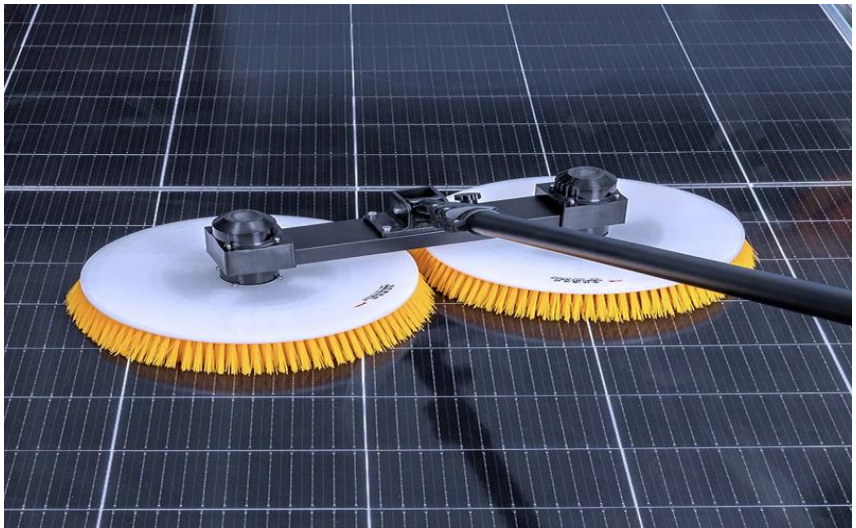
Cleaning PV Modules Procedure

- Modules if identified to be broken or faulty, replace after isolating the module. Can lead to an electrical spark hazard if water is sprayed on broken modules
- Record system energy production before and after cleaning
- Plan for collection and disposal of runoff if the site has any Storm Water Prevention plan
- Identify a water source near array. Sometimes water has to be brought from outside in a tank or water truck

Cleaning PV Modules Procedure

- Use hoses with non-conductive handles and non-conductive tools. Avoid walking on modules.
- De-ionised water is preferred for washing to avoid spotting or calcium build-up
- Water pressure for cleaning should be within the limits specified by the manufacturer.
- Use a soft-bristled brush with extension tools to remove stubborn dirt. Squeegee modules dry where required

Source:
https://www.zhendabrush.com/solar-panel-cleaning-brush-dual-brush.html



Cleaning PV Modules Procedure

- Do not walk or crawl on panels or their mounting frames. Develop and use cleaning equipment that can work from the access lanes between array mounts.



Sample Maintenance schedule of PV modules and mounting system

Frequency	General inspection Activities	Remedial actions
Quarterly	Check modules for excessive soiling from dirt build-up, debris or bird droppings.	Clean small traces of soiling by spraying demineralized water. Follow array washing procedure if array cleaning is decided by the O&M management.
Annually	Inspect PV modules for defects such as burn marks, discoloration, delamination, or broken glass	Replace any defective PV module with an appropriate substitute
Annually	Confirm that the module wiring is not hanging loose, resting on the surface, bent to an unapproved radius, stretched across sharp or abrasive surface. Check for any visible damage to wire insulation	Rearrange the wires to proper wiring condition. Repair or replace any damaged wires
Annually	Inspect racking system for defects including corrosion (rust or pitting), sagging, and missing or broken clips or bolts	Repair/replace defective parts, apply gal-spray to areas at risk of accelerated corrosion
Annually	Check conduits for proper support, bushings, and expansion joints, where needed	Replace or add as required
Annually	Check the integrity of penetrations/fixings in roof mounted systems, verify torque is within acceptable range (refer manufacturer's documentation)	Repair/rectify as required
Annually	Check for the signs of corrosion near the supports in ground mounted systems	Repair or replace as required
Annually	Check the continuity of equipment grounding randomly throughout the array, mounting frames and lightning protection termination	Locate any discontinuities in grounding system and repair as required

DC Combiner Boxes maintenance

Frequency	General inspection activities	Remedial actions
Annually	•Inspect the DC isolator enclosure, including lock and seal for any signs of excessive cracking, discoloration, wear, or corrosion. •Confirm that the enclosure is securely fastened and appropriately sheltered from rain, and direct UV exposure (for non-metallic enclosures)	Repair any such damage
Annually	Check for any vegetation growth or debris around the enclosure	Remove vegetation or debris
Annually	Look for the signs of dust, water or any foreign body ingress into the enclosure	Clean inside the enclosure, repair/replace enclosure or glands where necessary
Annually	Check for the torque marks in terminals	Tighten the loose connectors
Annually	Confirm the continuity of equipment grounding and system grounding	Locate and repair any discontinuity in grounding
	Perform maintenance of DC disconnect per manufacturer's instructions	

Site Maintenance

Site maintenance includes:

- Vegetation management;
- Cleaning and dust control;
- Weather damage control; and
- Theft and vandalism control.

Site Maintenance 2

- This maintenance is highly site dependent. It is important to set a preventative maintenance schedule that is reflective of the site conditions.

- Ground mounted systems can be prone to theft and vandalism. Preventive maintenance must also include a procedure to be followed in case the system suffers from vandalism. It should also include measures such as CCTV cameras, security fences and permanent guard stations in sites where this is a possible issue.

Vegetation Control

- Vegetation growth is particularly relevant for ground-mounted systems, due to the proximity of the absorbing surfaces of the panels to the ground, and the tendency of water runoff to concentrate on the areas directly in front of the panels during rain events.

Vegetation control 2

- Causes shading, problems with array wiring
- Causes ventilation obstruction for pad mounted equipment like inverters, transformer. This could damage these equipment.
- Performance issues may arise when a substrate grows on accumulated debris on the module



Solar farm near Markranstädt, Germany
showing highly unmanaged vegetation growth





Vegetation control methods

- Spraying chemicals to prevent growth
  - Can lead to environmental and health issues
  - Could render the area barren and result in more dust to be deposited on the modules
- Mowing or trimming plants
  - But can become expensive due to ongoing labour costs
  - Has a risk of debris like grass, pollen or dust splitting off the mower and depositing on the modules causing shading
  - Could be difficult to mow beneath the arrays
- Planting low growing ground cover under the system
  - Can help retain moisture and prevents heat radiation from the ground onto back of the modules, which can produce cooling effect hence enhancing system performance
  - Less expensive compared to mowing or spraying chemicals

Vegetation control methods 2

- Using animals to graze
  - Ecofriendly method
  - Opportunity to incorporate agri-business with energy production
  - But clearance under the array should be about 200-300 mm (8’ to 12”) higher than the animal
  - Goats are not recommended as they will jump or climb onto the array scratching and damaging the modules. They also tend to chew on everything including wires
  - Horses and cattle are not recommended as they are too large and can damage the system while scratching against the posts
  - Sheep, geese, emu have been used with some success





Erosion Control

- Excavation for the footing installation can leave soil exposed that may be vulnerable to erosion due to run-off from the panels

- Run-off or flooding after storm surges when not channeled adequately to the stormwater drain can cause major top soil erosion and endanger the stability of the PV array foundations. Erosion can also expose conductors buried underground with associated dangers and fault problems



Source: https://www.madisoncourier.com/north_vernon/water-drainage-at-tripton-causing-erosion-around-solar-panels/article_68a60da0-e1dc-59f4-8af5-e75816ef208e.html

Erosion Control Methods

- Recommended to construct specific pathways (e.g. rock lined flow channels, berms to direct flow) for water run-off to discharge into the site's stormwater retaining basin or external drainage system.

- Using soil conditioners, e.g. polymers, that can be sprayed on dry soil surface before the rainy season. The type of soil and other site conditions determine the type of soil conditioner and the amount to be sprayed

Inverter And Protection Devices

- Maintenance procedures provided by the manufacturer must be followed to meet the product warranty obligations

- Depending on site conditions and the type of the installation, the maintenance frequency can be scheduled

- The down-time of inverters for maintenance and repair should always be taken into account before scheduling. Consider scheduling for times with low solar input to minimise lost revenue.

Inverter And Protection Devices 2

- Central inverters typically require more regular, strict inspections and maintenance than the string inverters on field as their down-time revenue loss is high

- Central inverters usually will have sub-system repair support from the manufacturer and users are typically supplied with spare parts such as control cards, driver cards, IGBT matrix, capacitors.

- It may make economic sense to replace failed string inverters with spare units and make repairs later rather than repairing them on site.

Maintenance schedule of inverters

Frequency	General inspection activities	Remedial actions
Annually	•Inspect the exterior of inverter mounting structure/pad for any signs of excessive cracking, wear, or corrosion. •Confirm that all equipment is securely fixed in place	Repair any such damage
Annually	Check for any vegetation growth or debris or equipment around the inverters that may obstruct airflow or otherwise encroach on electrical equipment	Remove vegetation where required
Annually	•Look for signs of ingress of dust, water or any foreign body into the inverter •Check for dust accumulation in and around filters, air exhausts and ventilation/heat sinks	Clean and clear accumulated dust where required
Annually	Check for any abnormal operating noise	Talk to the service providers/manufacturer for guidance
Annually	•Record and validate all voltages and production values from the human- machine interface (HMI) display. •Check all status indicators and record last logged system error	Follow instructions per error message
Annually	Ensure fans are properly operating	Repair or replace as required
Annually	Check torque on terminations	Tighten the loose connectors
Annually	Check gasket seal	Replace as required
Annually	Look for discoloration or damage due to excessive heat build-up	Confirm if fans, heat sinks and filters are in proper condition and call for service
Annually or after each trip	Look for the end of life indicators in surge arresters	Replace where necessary
Annually	Check fuses	Investigate the cause for blown fuse. Replace fuse as per the instruction manual
Annually	Confirm the continuity of equipment grounding and system grounding	Locate and repair any discontinuity in grounding
Annually	Check for operation of ground fault monitoring unit	Troubleshoot ground fault and replace component in ground fault monitoring unit as per manufacturer's instructions
Annually	Confirm that current software is installed	Update as required
Annually	Check the operation of DC disconnect on inverter	Replace as required or call for service
Per manufacturer's instruction	Maintenance of internal DC disconnect and AC circuit breaker	

Maintenance schedule of step-up transformers

Frequency	General inspection activities	Remedial actions
Quarterly	•Inspect the exterior of transformer pad for any signs of excessive cracking, wear, or corrosion •Confirm that the equipment is properly bolted to the pad	Repair any such damage
Quarterly	Check for any vegetation growth or debris or equipment around the pad	Remove excessive vegetation around the pad
Quarterly	Check for any abnormal operating noise	Talk to the service providers
Quarterly	Check the tank exterior for signs of leak	Repair any such leaks
Quarterly	Check for the proper operation of gauges and controls	Repair or replace defective equipment
Quarterly	•Look for the signs of dust or water ingress, or rodent intrusion into the transformer •Check for dust accumulation in filters and ventilation area	Clean inside of cabinet, filters and ventilation area

Maintenance schedule of step-up transformers 2

Quarterly	Inspect fuse mountings and switches. Look for signs of any liquid seepage around gaskets, seals, etc.	Repair or replace as required
Quarterly	Check oil level gauge	Check for the signs of leaks if oil level is below the nominal level. If not, refill oil to normal level.
Quarterly	Ensure the tank pressure and fluid temperature are within the operating range	If tank pressure is below the nominal level for long time, check for the signs of leaks and repair. If the fluid temperature is elevated, call for transformer service immediately.
Quarterly or after each trip	Check for damaged lightening arresters	Replace damaged arresters

Maintenance schedule of step-up transformers 3

Quarterly	Look for any signs of dirt or damage in LV and HV bushings	Clean any dirt in the bushings. Call for service from a qualified technician to repair any damage
Quarterly	Check the torque marks on all connectors	Tighten any loose connector
Quarterly	Confirm the continuity of equipment grounding and system grounding	Locate and repair any discontinuity in grounding
As per manufacturer's instructions	Perform maintenance of AC circuit breaker	

Data acquisition system

- The monitoring system is fundamental to operate a large solar system. Corrective and conditional-based maintenance are fully dependent on warnings given by the monitoring. It is important that the SCADA and other monitoring devices are regularly checked and kept in an optimal condition during the preventative maintenance stage.

- An example of the importance of this is that the irradiation monitor will be set up to record the weather conditions of the site to compare against actual PV generation. If irradiation data was not recorded, it would be difficult to verify that the actual system output satisfies its performance guarantee, which typically stipulate a minimum performance ratio (ratio of real to estimated generation, corrected based on measured irradiation).

Data acquisition system 2

Frequency	General inspection activities	Remedial actions
Annually	Record the status of all indicators and/or error messages in data acquisition system	Follow the instructions per error message
Annually	Check for dust, water or any foreign body intrusion inside the electronics	Clean the equipment, rectify any points of ingress/replace equipment if required.
Annually	Measure voltages of power supplies	Replace power supply if abnormal voltage is measured
Annually	Validate all readings, if applicable, including temperature, irradiance and voltage measurements by comparing to calibrated equipment.	Recalibrate or replace sensors as required. Call for service is if the problem persists.
Annually	If a weather station is present, ensure that the sensors are in the correct location and at the correct tilt and direction.	A global irradiance sensor must be flat, and an array plane irradiance sensor must be tilted in the plane of array. A module surface temperature sensor should be mounted on the back surface of the module, away from the frame.
Dependent on site - as required	Check that irradiation and temperature sensors are clean and free of soiling	Clean the sensors



System Maintenance: Corrective Maintenance

Corrective Maintenance

- Corrective maintenance, or unscheduled maintenance, addresses any equipment breakdowns after their occurrence.

- If preventative maintenance is properly designed and implemented frequently, corrective maintenance requirements should decrease in frequency and cost. However, if preventative maintenance is not implemented or incomplete, there is a safety hazard or if there is an error resulting in production loss, the business case cost may be much higher than preventative maintenance., and are mostly inverter faults

Corrective Maintenance 2

- Faults can be categorized into three general categories, in order from most to least critical:

1. Total system failure, i.e. the system is not working, with no generation.
2. Partial system failure, i.e. the system is working but underperforming, not producing the expected output.
3. System non-compliance, i.e. the system is working and performing as expected, but requires some rectification work (e.g. restoring of communications)

- Corrective maintenance is based on troubleshooting and fault finding/correcting. Many things can go wrong on a medium to large scale system. Faults must be attended by specialized personal and in accordance with the manufacturer's recommendations.

Corrective Maintenance 3

- When designing the corrective maintenance plan it is important to consider:
  - How the problem will be diagnosed
  - How fast the response will be
  - How long the repair is expected to take.
  - The balance between the increased cost of achieving shorter response times with the increase in revenue from increased yield.

Corrective Maintenance 4

Made up of:

- On-site monitoring/mitigation
- Critical reactive repair
- Address production losses
- Non-critical reactive repair
- Address production degradation
- Warranty enforcement (as needed)

Apart from inverter faults, it may also relate to:

- Tightening cable connections that have loosened
- Replacing blown fuses
- Repairing lightning damage
- Repairing equipment damaged by intruders or during module cleaning
- Rectifying SCADA faults
- Repairing mounting structure faults
- Rectifying tracking system faults.

Response Time

- Corrective maintenance almost certainly requires site visits to diagnose and rectify the cause of the fault, leading to partial or total generation loss in the meantime – all of which incurs costs to the project.
- Because the cost of correction can be so much higher, response time is one of the most important aspects of corrective maintenance. Response time is the time taken to find the issue, decide on the course of action and implement the solution.
- Response time can be as short as seconds for simple issues such as one panel being shaded and no urgent action is required. More serious issues, such as electrical damage to an inverter from a lightning strike, can take days to rectify as replacement components or specialised technicians are sourced.
- Delayed responses are also permissible for issues with minimal impact on generation, e.g. a module that has microcracks doesn't need to be replaced immediately, and the response can be delayed.

Locating the Fault

- System troubleshooting involves identifying the source of a problem and how to rectify it; the attending technician will need a thorough understanding of the system and its components to complete this process (system design drawings and calculations as a minimum).

- To troubleshoot the PV System, there are four key steps:

  - Identify and record the symptoms (non-standard or unexpected behaviour)
  - Use relevant and accessible information to locate the source
  - Investigate the source to determine the cause of the symptoms
  - Propose a solution

  The specifics of the troubleshooting procedure will vary widely based on the particulars of the site.

Commissioning Tests

Any system must undergo commissioning testing as per AS/NZS 5033. Perform the following general tests as required to identify problems:

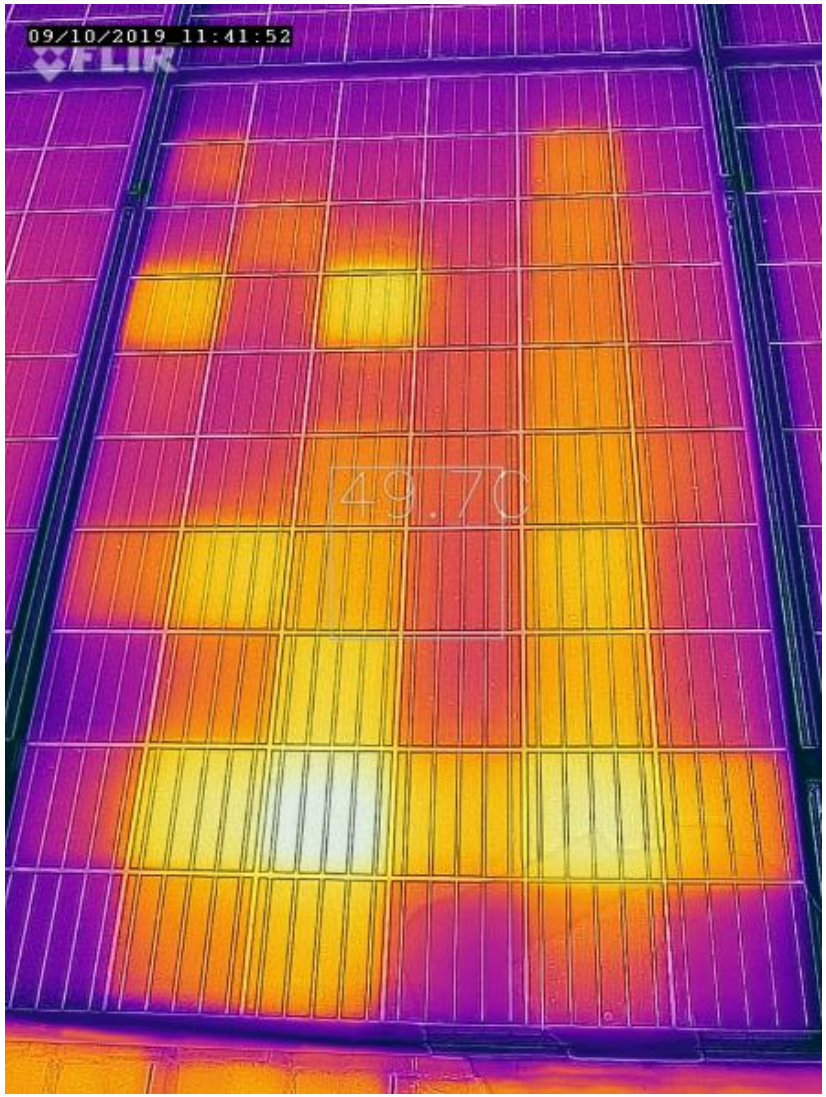
- Check all the fuses at the inverter and work out to the combiner boxes
- Perform V_{OC} string testing.
- Perform I_{MP} string testing.
- Validate weather sensors.
- Look for soiling. If soiling might be a problem, test an individual string (V_{OC}, I_{MP}, IV curve), clean the string following array washing procedure, and then retest.
- Perform I-V curve tracing.
- Take infrared (IR) images of the PV cells.



Thermal imaging devices

- Thermal imaging devices use infrared sensors to scan and represent visually the relative and absolute temperatures in an image. This is an economical, safe and quick way to locate faults without any contact with the actual component (i.e. electrical measurements).

- As a general rule, hotspots are displayed as white, while the range of other temperatures are shown as red (hot) to blue (cold), as in Figure below. With this method it is possible to locate areas of high electrical resistance, defective bypass diodes and cells, mismatch and shading in modules and other issues.



Infrared photo of a solar module with hotspots

Thermal Imaging

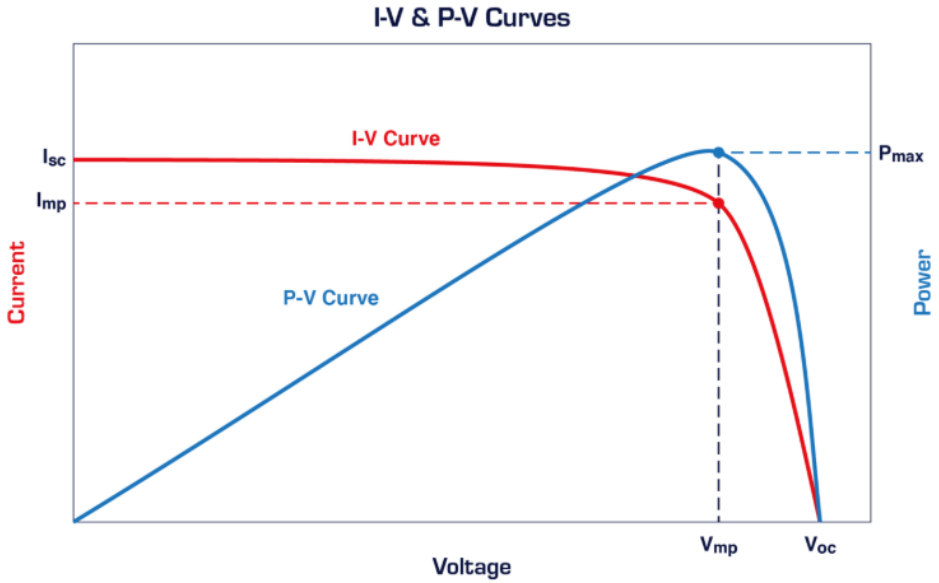
Reading the pattern

Pattern	Likely cause
One third of the module hot	A substring is out. Bypass diode conducting or shorted.
A column of cells hot	Short circuit in a cell string
Patchwork of hot cells	Defective diode, internal short, or mismatch
One cell bright	Cell rupture, or a shadow on that cell
Whole module or row hotter	Wiring, a worn cable, or a bad connection

I-V curve tracing

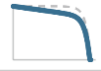
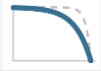
- I-V curve tracing is excellent for identifying underperforming strings/panels when system monitoring, visual inspection and conventional electrical tests cannot point out the exact cause. This method is generally used in combiner boxes isolated from the rest of the PV system. The PV doesn't need to be under inverter load during tracing which leads to a relatively safer inspection, reducing arc flash hazard.

- For best results, clear skies with irradiance over 700 W/m2 with no clouds is preferred. The test should be done within a 4 hour window around solar noon with low wind and no rain.



I-V Curves

Seven shapes

Curve shape	Likely cause
 Normal, over 90 %	Nothing to do. Record it as the baseline for next time.
 Stepped	Part of the string is bypassed and its diode is conducting: partial shade, module mismatch, a shorted bypass diode, or cracked cells.
 Low Isc	Less light is reaching the cells. Check the tracer's irradiance input first, then look for uniform soiling or shading across the whole string.
 Low Voc	Series voltage is missing. Check the tracer's temperature sensor first, then look for shorted bypass diodes, modules missing from the string, or PID.
 Sloping vertical leg, near Voc	Series resistance: a poor connection, an undersized or damaged cable, a corroded terminal.
 Sloping horizontal leg, near Isc	Shunt resistance: cell damage, PID (potential induced degradation), or a single shaded or soiled cell.
 Rounder knee	Fill factor falling (knee less square). Normal with age, but if early, check both slopes above.

Source: SEIAPI, Grid-Connected PV Operations and Maintenance Guideline, Section 4

Inverter

As a central point of failure in a system, inverters tend to be the major contributor to system downtime. A short response time is critical in achieving a high degree of system availability. If dealing with string inverters, the faulty inverter can be replaced with a spare inverter for as long as needed.

Some examples of inverter error displays are:

- Grid Voltage and/or frequency too high or too low;
- PV array voltage too low;
- PV array voltage too high;
- Line Impedance too high; and
- Ground fault detected

Inverter 2

- In some cases, the inverter might not display comprehensive error message, in which case further investigation would be required.

- If working, the inverter's display screen should be used to gather preliminary electrical measurements, such as the voltage and current readings on the AC and the DC sides of the inverter, and the power output of the array. If there is a 'zero' voltage or current reading on the AC or DC side, the system on each respective side should be investigated further.

- If the inverter is not operating because the AC breaker to the inverter at the switchboard has tripped, it is recommended to investigate why it has tripped (e.g. overheating within the switchboard) before turning back on.

Troubleshooting the AC side

Below are few reasons why the AC side of the system must be investigated:

- If the inverter reading has indicated that there is a zero AC voltage or current;
- If the inverter error code has indicated a grid voltage or frequency issue;
- If the inverter code has indicated that the line impedance is too high; and
- If the inverter is not operational, with no readings or error codes.



Operate and Maintain Grid-Connected PV Systems

Session 13C: System Maintenance: Condition-based Maintenance

Condition-based Maintenance

- The third type of maintenance is called condition-based maintenance, and it usually happens when a potential issue is flagged by a monitoring system and the response can be scheduled.

- Once an issue has been identified a decision has to be made. Conducting condition-based maintenance is not time sensitive in comparison to corrective maintenance. However, a lack of response can increase operational costs, or increase the risk and/or severity of the possible fault.

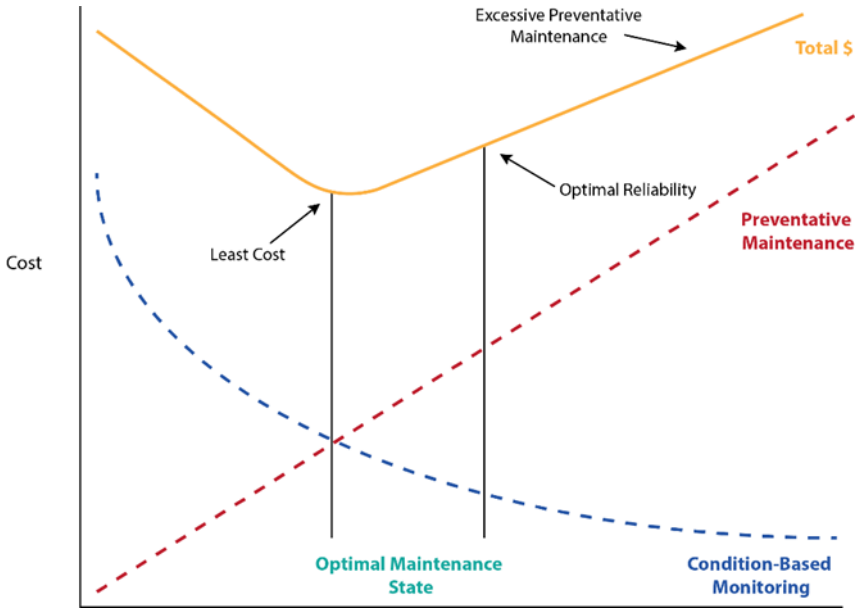
- For example, if a weather monitoring system triggers a warning to the operators that a dust storm will reach the site in a few weeks' time. The cleaning of the modules and other scheduled maintenance might need to be rescheduled to be carried out right after the dust storm. A corrective maintenance team might also need to be in alert for the dust storm in case it damages any components.

- The main maintenance issues to be solved with condition-based maintenance are: Weather conditions, grid conditions, and component failure.

Condition-based Maintenance

- Condition-based maintenance employs real-time data to prioritise and optimise maintenance and resources.
  - Important to find the right balance between condition-based maintenance and preventive/scheduled maintenance activities.

- The plant operator will schedule O&M activities when deemed necessary based on the monitored data.
  - Higher O&M efficiency.
  - High upfront costs due to communication and monitoring systems required.



Weather related conditions

- Weather related conditions are detected by the system so that cleaning; downtime for maintenance and site visits can be rescheduled or matched with an already scheduled site visit.

- Examples:

  - The weather monitoring system identifies that a dust storm is approaching the site within the next week, whilst module cleaning is scheduled to occur during the same week. This scheduled activity can be changed until after the dust storm passes over the site.
  - A central inverter was scheduled for maintenance. However, weather monitoring shows that it will be a clear sunny day while next week it will be rainy and cloudy. The maintenance can be rescheduled to a cloudy day to decrease loss of output from downtime.

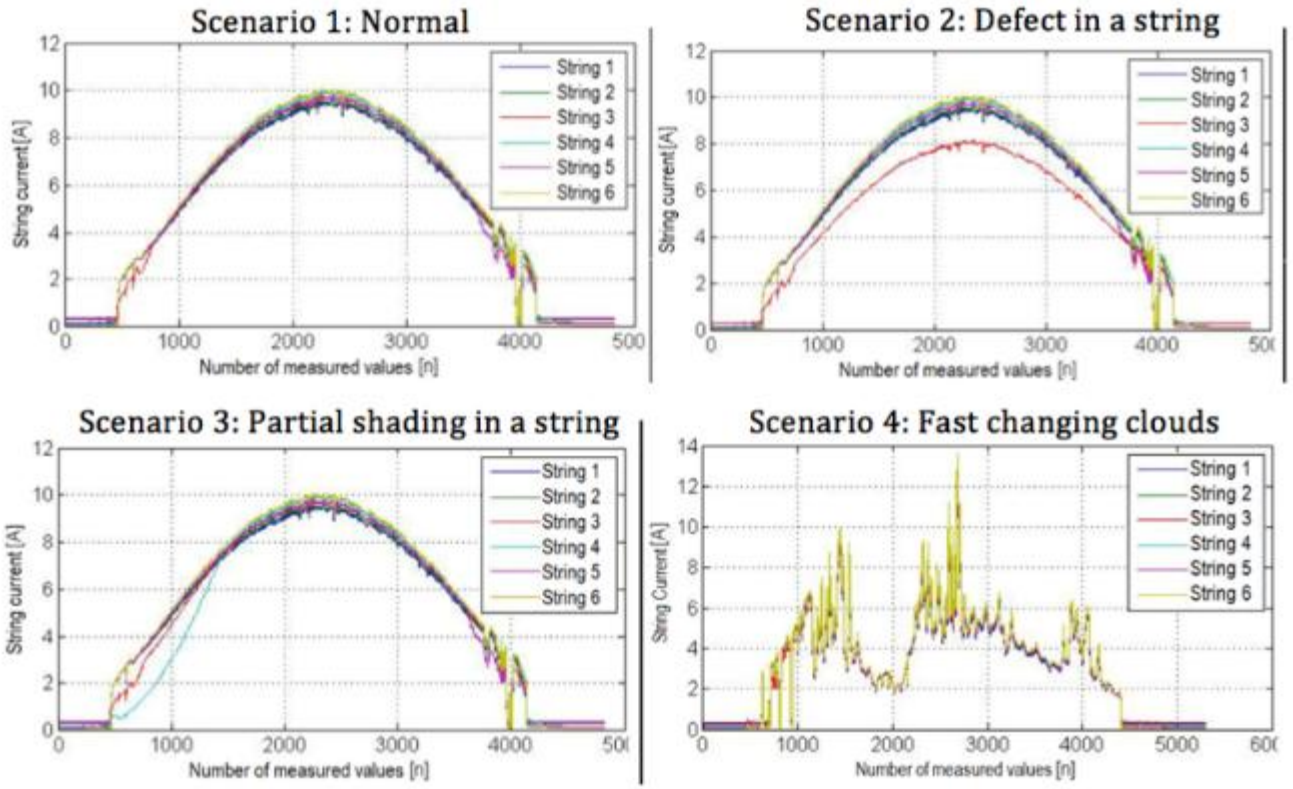
Real Data Monitoring

- Monitoring systems can be used for systems across the range of residential, commercial and utility scale. Data monitoring software helps in providing real time energy generation and fault alerts which can occur in the system.

- For residential scale PV systems, it is generally suitable to use proprietary monitoring systems provided by the inverter manufacturer – alternately, there are many third-party products which can integrate real time data monitoring into the existing system.

- For commercial or utility scale PV system, higher levels of monitoring and control are often required. These monitoring and control requirements are imposed on the system either by the system owner or the service provider of the network to which the system is connected. Supervisory control and data acquisition (SCADA) is the term used for the communication systems used to monitor and control PV system.

Real Data Monitoring 2

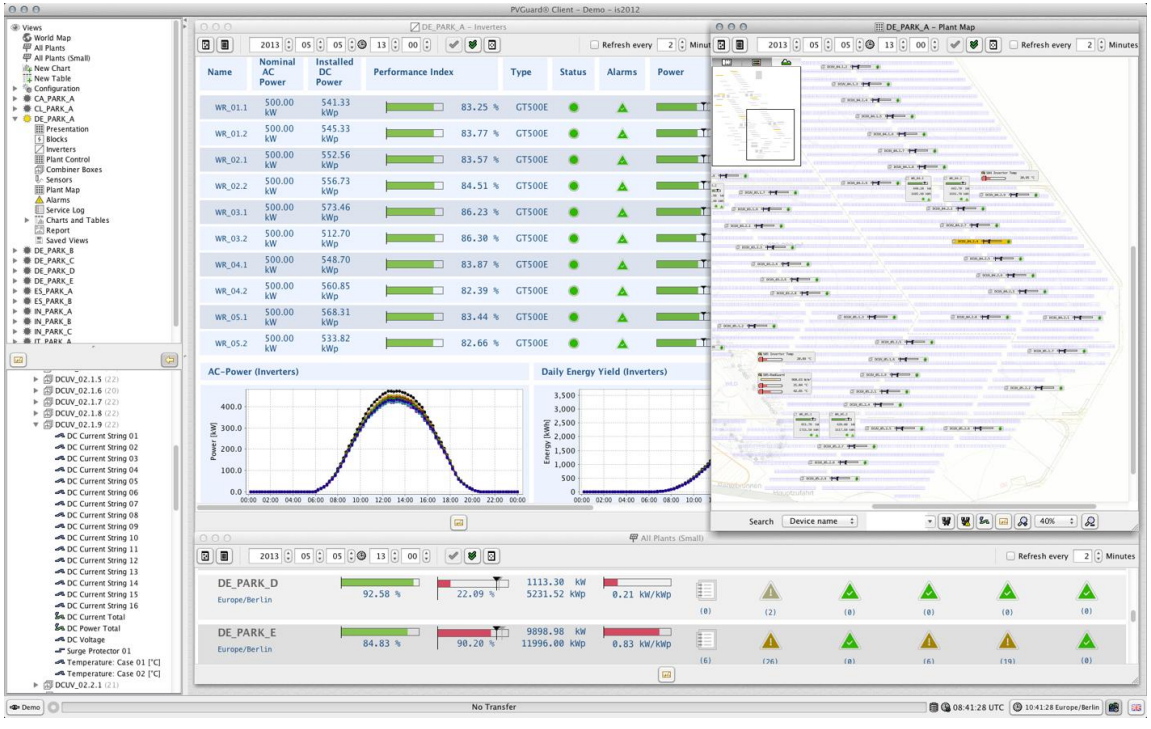


Shading scenarios revealed from string monitoring (Source: SMA)

SCADA

SCADA can be achieved in different ways using different equipment but generally the purpose of SCADA is the same. Some of the goals that are usually achieved with a SCADA system are:

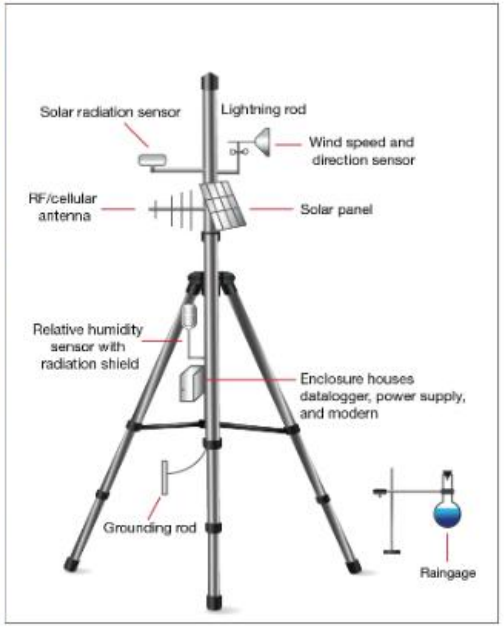
- Fault monitoring;
- String monitoring (for power discontinuity);
- Grid tolerance and grid quality;
- Dynamic grid support (power factor, and real or reactive power attenuation); and
- Remote control (from the system owner, power purchaser or network).



Weather Monitoring

- Weather monitoring is essential in order to evaluate and predict the PV plant's performance throughout its lifetime.
- The output data from the plant should be measured continually and adjusted with the actual weather parameters before comparing with the design values. This is because the output of PV systems constantly changes depending on the meteorological conditions like solar radiation and temperature.
- Weather data is also essential for analysing the weather pattern at the site in order to extrapolate future power generation trends. Such analyses are valuable for scheduling of O&M activities, setting control parameters for grid support and evaluating performance.





Electrical parameter monitoring

- The electrical parameters of large-scale PV plants are monitored and logged at several power conversion stages. The power conversion chain in PV plants can be divided into two parts: DC side, the core generation unit, and AC side, the grid integration facilitating unit. By monitoring the electrical parameters, faults and underperformance can be identified and corrected with minimum disruptions on the system.

Electrical parameters on DC side
PV voltage (per string)
PV current (per string)
PV power
PV energy yield
Insulation resistance

Electrical parameters on AC side
Voltage (Inverter and grid)
Current (Inverter and grid)
Frequency (Inverter and grid)
Power factor (Inverter and grid)
Inverter and grid synchronization
Harmonics (Inverter and grid)
Daily power and energy (Each inverter and the whole power plant)
Total power and energy (Each inverter and the whole power plant)

Inverter monitoring

- In most PV plants, inverters are at the core of the monitoring system, as they have the unique ability of offering insights into both AC and DC circuits, inverter status (and faults), adjustable parameters and historical operating data.

- Large scale systems with central inverters will be limited in their ability to monitor individual modules and strings; faults on this level can easily go unnoticed until the next scheduled maintenance.

- Once a fault is detected by the central inverter the process of locating the fault can also be time consuming and labour intensive. Nonetheless, the losses incurred due to a string failure are low compared to the total cost of adding string level monitoring.

- Microinverters and DC optimizers are only commonly used in residential to commercial scale systems, due to their higher cost per watt and additional installation requirements. Where they are installed, however, they bring a number of benefits including elimination of DC wire loss while reducing panel mismatch loss.

PV array and string monitoring

- Array monitoring or zone monitoring collects information from DC sub-array circuits – generally the voltage and current. This dramatically increases visibility of an array's DC performance and can aid in the detection and locating of DC faults. Additional current sensors can be located inside the major combiner box or the inverter itself.

- In the case that more decentralised monitoring is necessary, string monitoring can be applied. Each string can have current and voltage monitoring to improve fault finding including performance degradation, module failure or shading of one module in a string

Monitoring of faults and failures

- The inbuilt monitoring systems in inverters and other equipment employed in utility-scale segment are generally “smart”; they can report and activate trips in the event of failure of most system components including power systems, embedded electronics, communication systems and even the monitoring systems themselves.

- Such applications are usually equipped with sufficient redundancy to ensure reliable reporting and trips in the event of failures. If the system fails to report any component failure, it should be identified and corrected during routine inspection visits.

- Apart from equipment failures, several unexpected faults in PV plants can create extended periods of downtime or increased risk of fire.

Ground fault monitoring

- A ground fault is defined as:
  - A condition of current flow through the grounding conductor due to an unintentional electrical connection between a current carrying conductor and the equipment ground conductor; or
  - A condition where the resistance in a conductor falls bellow a certain threshold providing a pathway for current to flow between the current carrying conductor and ground.

- Such faults can cause the PV system to shut down as a safety precaution, and in extreme cases can result in electric arcs and reverse current flow resulting in severe damage to the system.

- Common examples of ground faults include:
  - Damage to cable insulation - made worse in humid or wet conditions;
  - Damaged PV modules;
  - Incorrect electrical connections;
  - Incorrect mounting of the PV modules - inserting the mounting screw through the PV module;
  - Bonding the PV ground conductor outside the inverter; and
  - Lightning strikes.

Ground fault monitoring 2

- In order to check the PV system for ground faults, the following methods can be taken:

  - Check the PV system for ground faults by measuring the voltage; or
  - If voltage measurement was not successful, check the PV system via insulation resistance measurement for ground faults.

Ground fault monitoring 3

Conducting ground fault monitoring - Resistance Testing

- A PV generator has a non-infinite insulation resistance (RIS) distributed along the installation that creates resistive leakage currents.

- The insulation resistance can only be measured with a suitable devices (such as a megaohmmeter) for safe disconnection and short-circuiting of the PV array. If no suitable device is available, the insulation measurement must not be carried out.

Ground fault monitoring 4

Conducting earth fault connection testing

Appendix F7 of AS/NZS 5033 outlines the steps that must be performed to verify that the earth fault protection system and earth fault alarms operating correctly

Surge Protection Device

- Lightning is a major cause of downtime in PV plants due to overvoltage. To protect the system from surge events two methods are used: protective earth (PE) of the exposed metal parts, and installation of surge protection devices between each conductive line and PE.

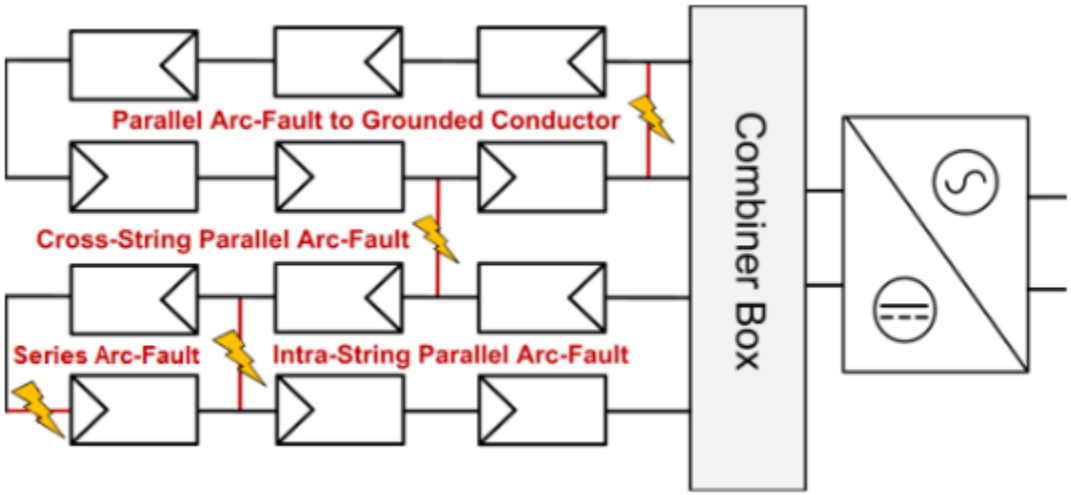
- SPDs protect components by providing an alternate path for surges to ground. Recommended locations for SPD installation are:

    1. At PV array (<10m)
    2. DC input to Inverter (<10m)
    3. AC output of inverter/connecting switchboard

- Induction loops can also attract lighting and must be avoided. It is recommended to visit the plant at after every thunderstorm or every six months to ensure that the protection devices are in operating order.

Arc Fault Detection

- Some faults can generate electric arcs which can cause fire in PV systems. The temperature of a damaged conductor rises due to excessive current, eventually melting it and creating an air gap in the conductor. This may create a “series arc” due to ionisation of the air in the region and subsequently, “parallel arc” once two energised conductors of opposite polarity or between an energised ungrounded conductor and ground.



Schematic showing the different types of arc-faults in a PV system