

O&M Diagnosis and Testing Methods and Equipment

Outline

- Diagnosing and Testing Methods
- Thermal Imaging
- IV curve Tracer and testing procedure
- Insulation resistance testing
- Short circuit current measurement
- Earth/ground fault testing

DIAGNOSING AND TESTING METHODS

Diagonising And Testing For System Under-performance

- IR Imaging
- IV curve testing
- Megohmmeter testing
- Short circuit Current Measurements
- Fuse Checks
- V_{OC} and I_{MP} checks in dc systems
- Earthing/Grounding system integrity
- Earth/ground fault troubleshooting

Thermal Imaging

- To inspect PV modules for any hot spots
- Safest inspection method as no contact with target equipment
- The imager assigns visible graduated colour or grey scale to the image
- Hotspots are displayed as white with diminishing temperatures through red-orange-yellow-green-blue-indigo-violet to black being cold
- Range of problems including interconnection faults, defective bypass diodes and cells, mismatch and shading in modules can be analysed using the data obtained from the heat profile
- An IR imaging camera allows tagging the image with GPS data to localize a faulty module in arrays installed over large areas.

Thermal Imaging 2



Thermal Imaging 3

- ***Tools required***
  - IR Camera
- ***Favourable test conditions***
  - Irradiance > 500W/m^2. For maximum result, Irradiance > 700W/m^2
  - Clear sky as clouds produce interference and reduce irradiance
  - Calm wind conditions
  - Early morning testing as thermal contrast is higher when air temperature is cooler



Thermal Imaging Procedure

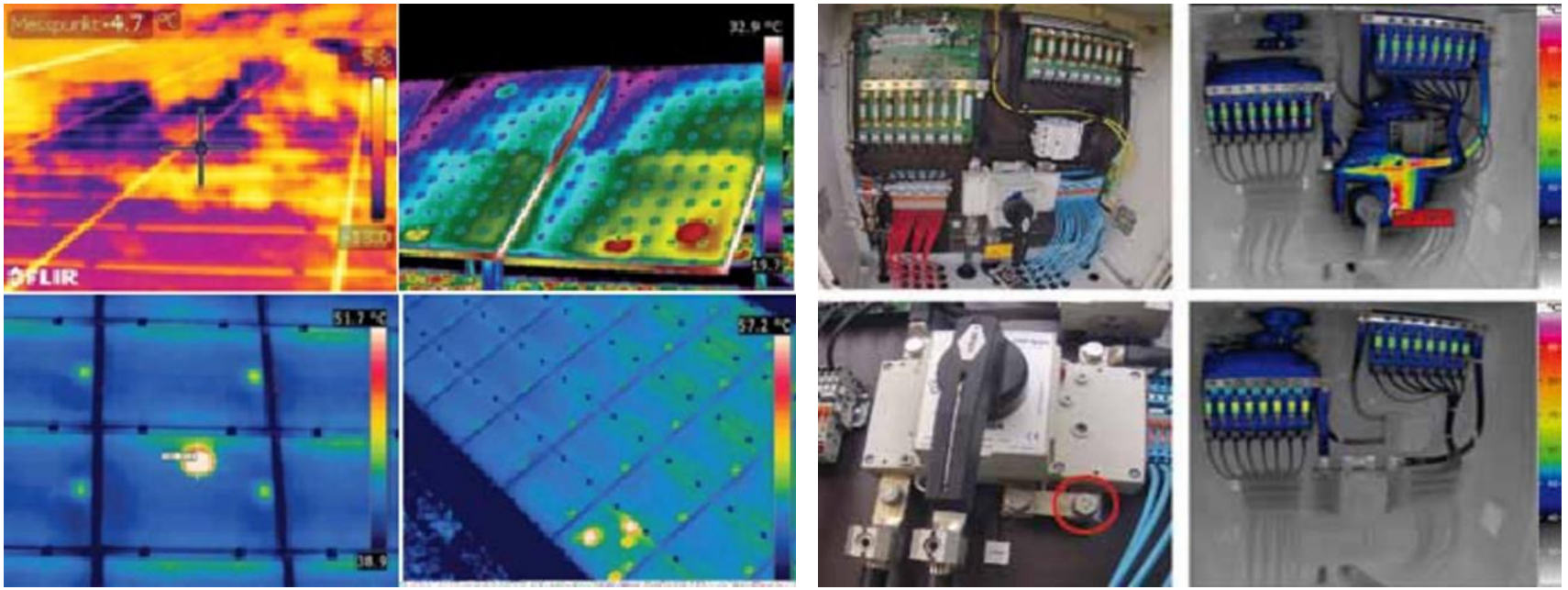
- Test shall be performed when the PV array is operating.
- Set emissivity value to 0.95 – to capture most active components like modules, combiner boxes, cables.
- If emissivity adjustment is needed, a black tape electrical tape can be fastened to the surface and emissivity can be adjusted until the taped and untapped surface show same temperature.
- Set the camera to auto scaling rather than manual scaling to allow for automatic temperature scale adjustments.
- Level and gain represent expected target temperature and the range above and below the target temperature respectively. For example, a setting with 100C level and 50C gain would have a measuring temperature range of 150 – 250C.

Thermal Imaging Procedure 2

- The camera should not be positioned perpendicular to the module or target object, so reflections of the operator and the camera itself on the target surface, especially on PV modules can be avoided.
- Position the camera as close to the module as possible to get the best results.
- Avoid shading any part of the module while scanning for thermal images.
- In ground-mounted systems, unlike roof-mounted installations, IR camera can also be used to inspect installed PV modules from rear side. The measured temperature might be higher as the cells are being directly measured and not through the glass. This method benefits from having minimal interfering reflections from the sun and clouds.
- Measure the current flowing through the circuit where hotspot is observed and make a note of it. If the current is above the rated operating range, look for the signs of short circuits or insulation damage in the circuit.
- Record module serial number, time date, image number and module or equipment location. Also, capture a visible image of the target if any issue is detected and link it to the corresponding thermal image in the record.

Thermal Imaging Interpreting Results

- The technician should be skilled enough to recognize false results (due to clouds/shadowing/reflection) and adjust the position and settings of IR camera to get accurate data
- Fault in the system is indicated as relatively hot area in the thermographic image
- These images can also be used to confirm electrical integrity in conducting cables, electrical equipment like fuses, switches, disconnects, busbars etc.



IV Curve Testing

- To measure IV curve traces in combiner boxes isolated from rest of the PV system
- Can identify the exact cause of under-performing circuits
- As the PV system need not be under inverter load during tracing, arc flash hazard is relatively reduced to other electrical testing methods

IV Curve Testing 2



- ***Tools required***
  - IV Curve Tracer
  - Wireless sensor kits to measure irradiance and temperature
  - Laptop to run IV curve tracer's application software
  - *dc* voltmeter
  - *dc* clamp-on meter



- ***Favourable test conditions***
  - Irradiance > 700W/m^2 with clear sky conditions
  - Calm wind conditions
  - Optimum test conditions would be the 4-hour window centred on solar noon

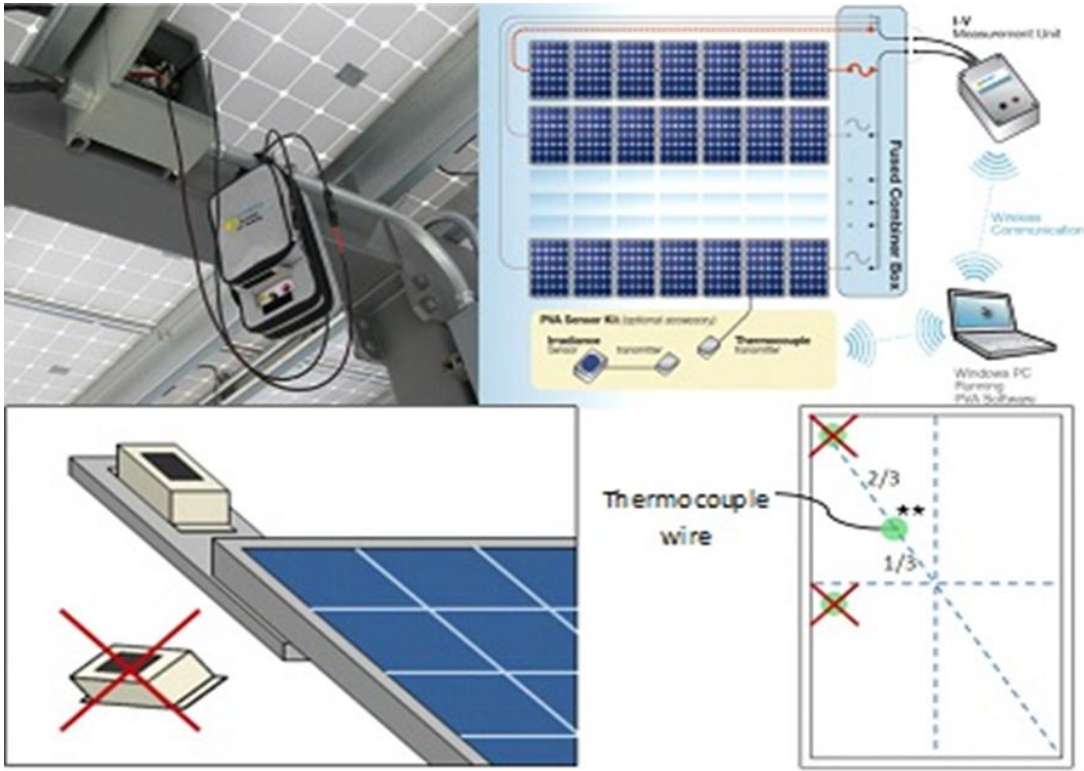
IV Curve Testing Procedure

Procedures for IV curve tracing in field is outlined in:

IEC 60904-1	Photovoltaic devices – Part 1: Measurement of photovoltaic current-voltage characteristics
IEC 60891	Photovoltaic devices – Procedures for temperature and irradiance corrections to measured IV characteristics

IV Curve Testing Procedure 2

- Safely isolate combiner box or the PV string to be tested from the inverter
- Follow LOTO (Lock Out-Tag Out) procedure to ensure it remains in disconnected state
- Use *dc* current meter to ensure there is no current present in the combiner box.

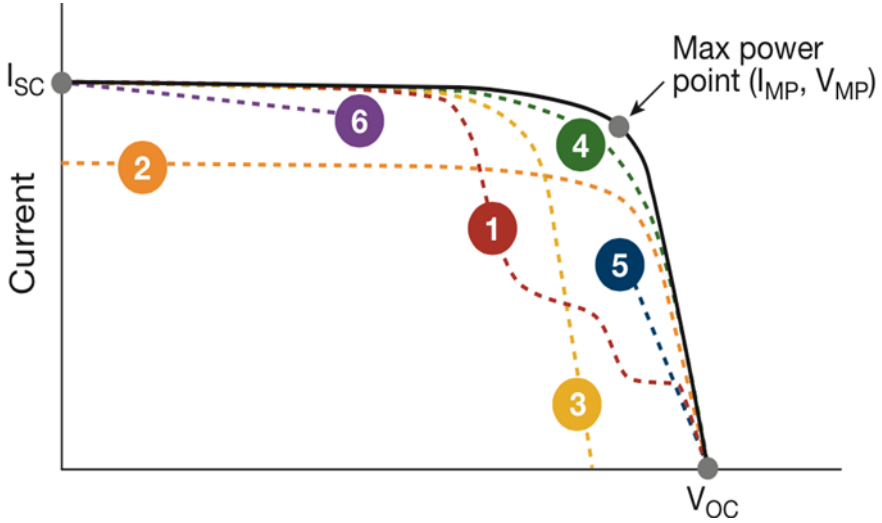


IV Curve Testing Procedure 3

- Look for any visible defects such as heat discolouration, corrosion, water intrusion, etc. in the system.
- Specify the number of modules connected in series and parallel in the PV circuit under test. Also, specify the PV module manufacturer and model number, if applicable, or manually enter the performance model parameters from manufacturer's specifications, and wire gauze and wire length.
- For calibrated performance measurements, install an irradiance sensor in the plane of the array and stick a temperature sensor, to the backside of a thermally representative module.
- Once the PV system is isolated from the load, open each fuse-holder in the combiner box.
- Connect one test lead of the tracer to positive busbar and the other to the negative busbar.
- Close appropriate fuse holder to initiate IV curve tracing of the desired circuit. Once the curve is traced, lift the fuse and interpret the curve.
- Repeat the same process for other PV circuits as well. Move the sensors if necessary to get wireless range.

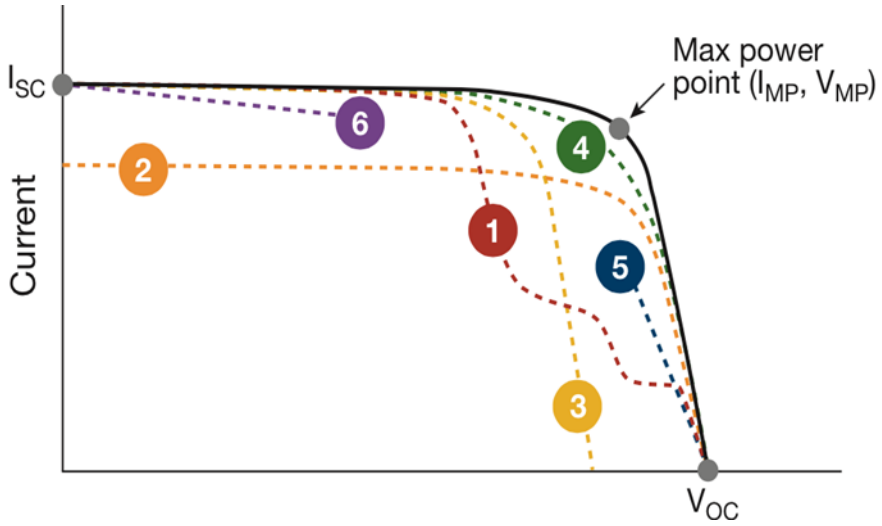
IV Curve Testing Interpreting Results

- ***Curve 1***
  - Current mismatch in the tested array
  - Such mismatch results from partial shading due to birds dropping, shadow of nearby objects, soiling, etc. Clear the shading prior to further performance tests
  - Stepped curve might also result from unequal number of modules in the strings or shorted bypass diodes or cells or even cracked cells
- ***Curve 2***
  - If there is no operator or irradiance sensor related issues, the possible causes can be uniform soiling or shading, or strip shading, or edge soiling
- ***Curve 3***
  - Check the quality of thermal connection between the temperature sensor and the back of the PV module
  - If quality of connection is good then other potential causes could be shorted bypass diodes, shorted modules or cells, missing modules, hard ground fault or potential induced degradation (PID)



IV Curve Testing Interpreting Results 2

- ***Curve 4***
  - Often a result of ageing process.
- ***Curve 5***
  - Associated with increase in series resistance and can be quantified by the voltage ratio metric as: V_{MP} /V_{OC}
  - Common cause is bad module solder joint or undersized conductors, resistive interconnections due to corrosion in terminal blocks or module junction box, and module degradation with ageing itself
- ***Curve 6***
  - Results from leakage within the PV circuit due to reduced shunt resistance and can be quantified by the current ratio metric as: I_{MP} /I_{SC}



Megohmmeter Testing

- To identify damaged or failed electrical insulation; loose wiring; faults in surge protection
- Measures insulation resistance by applying a set of test voltages using a Megger (or) Insulation Resistance Tester (IRT)
- Testing to be performed after safe isolation of the PV system from ground or any other equipment

Megohmmeter Testing

- ***Tools required***
  - Megohmmeter / Megger / Insulation Resistance Tester (IRT)
  - *dc* Current meter
  - Ohmmeter
  - *dc* clamp-on meter





Megohmmeter Pre-testing Procedure

- Follow LOTO procedures to isolate inverter from the PV circuit to be tested
- “High voltage - Testing in progress – Stay clear of photovoltaic array!” warning sign to be displayed around the testing area entry points
- Perform a visual inspection for defects such as heat discolouration, corrosion, water intrusion etc.
- For earthed/grounded PV system, isolate the earthed/grounded conductor by removing the cable from its termination.
- For tests>50Vdc, remove any SPDs (Surge Protection Devices) from test circuits
- Open all fuse holders and use a *dc* current meter to ensure that there is no current
- Verify earth/ground continuity of enclosures using an ohmmeter
- Test for current in equipment grounding conductor using clamp-on meter. If present repair ground fault by following earth/ground fault troubleshooting

Megohmmeter testing Procedure

- Connect positive lead of Megohmmeter to conductor being tested (positive or negative) and the negative lead to ground
- Set the test voltage in the meter and press and hold the test button to record the result
- For larger systems, the testing can be initially done at the busbar level of the sub-array as a whole. If measured impedance is lower than the required minimum, proceed to testing individual strings.
- Test insulation resistance on both positive and negative conductors with respect to ground at each step

MINIMUM INSULATION RESISTANCE VALUES AT STRING LEVEL AS PER IEC 62446	
Test voltage (V)	**Minimum insulation resistance (MΩ)**
250	0.5
500	1
1000	1

- For busbar level measurements, values can be as low as 500kΩ at test voltages of 1000V

Short circuit current measurement

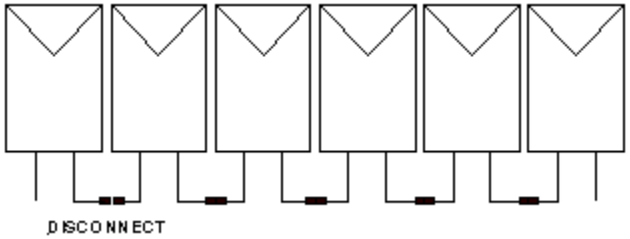
- To characterise PV array behaviour
- Can be performed in complementary to IV curve tests
- Mostly required as part of contractual commissioning requirements

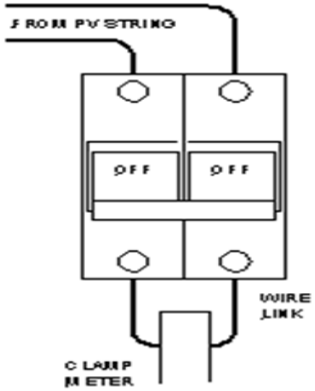
Short circuit current measurement 2

- ***Tools required***
  - Clamp-on meter
  - Pyranometer

Short circuit current measurement procedure

- The irradiance value should be recorded using a suitable pyranometer
- Turn off the PV array switch disconnector
- Ensure each string fuse is disconnected or the LV array is disconnected as follows:





- Leave array cable connected to the PV array switch disconnector
- Disconnect cable from PV array switch disconnector to inverter
- Install a wire link or small cable between the positive and negative outputs of the PV array switch disconnector
- Complete the string wiring by re-installing the string fuse or plugging the string disconnect.
- Turn on PV array switch disconnector and using a clamp-on meter, measure dc short circuit current for this string.

Short circuit current measurement interpreting results

- I_{sc} values measured when lower than expected values can be interpreted as presence of insulation faults, or sometimes even defective SPDs (Surge Protection Devices)
- The measured I_{sc} value shall be ±5% of the expected value which is determined as (AS/NZS 5033):

$$I_{SC_EXPECTED} = n \; x \; I_{SC_MOD} \; x \; \left(\frac{G_1}{1000}\right) x \; 0.95$$

where,

$I_{SC_EXPECTED}$ = expected short circuit current of the test circuit

N = number of parallel strings in the test circuit

I_{SC_MOD} = from manufacturer's datasheet

G_1 = plane of array irradiance measured using a pyranometer(W/m^2)

0.95 = factor to account for mismatch

Fuse checks

- Blown fuses are to be checked for the cause before replacing it

- ***Tools required***
  - Digital Multimeter

Fuse check Procedure

- Follow LOTO procedure and ensure system is not energised using a voltmeter
- Perform continuity test on fuse without taking it out from the fuse holder if no alternative conductive path is identified. Else remove the fuse from its holder and then perform the continuity test.
- If the fuse is tested not to be intact, then test for fuse resistance which should usually be a fraction of an ohm.
- Check product manufacturer specification as incorrect fuse rating installed may have caused the fuse to blow
- Test new fuse for continuity and correct specification before replacing

V_{OC} and I_{MP} CHECKS IN dc SYSTEMS

- Most basic and also reliable and decisive test to diagnose array underperformance
- The possible causes for underperformance in downstream circuit of *dc* system are defects in array cables, connections and disconnector switches.

V_{OC} and I_{MP} CHECKS IN dc SYSTEMS

- ***Tools required***
  - *dc* voltmeter
  - *dc* clamp-on meter
  - Ohmmeter
  - Irradiance meter / pyranometer
  - Temperature sensor
- ***Favourable test conditions***
  - For best results, clear sky conditions with Irradiance > 700W/m^2
  - Comparison among string is still possible in stable conditions with Irradiance > 200W/m^2 for V_{OC} test and Irradiance > 500W/m^2 for I_{MP} tests

V_{OC} and I_{MP} Pre-test Procedure

- Follow LOTO procedures to isolate inverter from the PV system
- Record test conditions including ambient and module temperature and irradiance. Calculate expected temperature compensated V_{OC} and irradiance compensated I_{MP} as reference values.
- Open disconnect switch and fuse holders in combiner box
- Carry out visual inspection for defects such as heat discolouration, corrosion, water intrusion etc.
- Verify continuity of enclosure to ground using ohmmeter
- Test for current in equipment earthing/grounding conductor using clamp-on meter. If present repair ground fault by following earth/ground fault troubleshooting

V_{OC} Check Procedure

- Measure and record V_{OC} of strings using *dc* voltmeter. If incorrect polarity, investigate the problem before switching the conductors and re-label the conductors
- The measured values for identical strings should be ±5% of each other. Lower than expected values can be due to disconnected cable or plug failure, loose connections, failed bypass diode or modules
- Use IR camera to precisely locate the fault
- Incorrect string connections where one or more modules from a string are wrongly wired to another string can be easily identified by deviations from expected results by the multiple/s of V_{OC} of a module
- In large systems, one string will have to be used as the test comparison string. All other are compared with this string because V_{OC} will decrease during the day as cell temperatures increases
- Close fuse holders and disconnects in combiner box and torque all terminals
- Measure V_{OC} of subarray at busbars. If low voltage is measured, check fuses and connections

I_{MP} Check Procedure

- Re-energise the system by closing the *dc* disconnect.
- Measure and record I_{MP} using *dc* clamp-on meter around each string
- Low performing strings i.e. strings with low I_{MP} value should be further investigated for any soiling or shading.
- Additional tests involving IR imaging and I-V curve tracing may be required to further identify and locate the fault.

Earthing/Grounding System Integrity

- All exposed non-current carrying metal parts in the PV plants must be connected to the equipment earthing/grounding all the time
- This equipotential bonding provides path to any unwanted surges or fault current to ground and mitigates the risk of potential damage to equipment, electric shocks or fire
- the equipment earthing/grounding should not be compromised even during removal of any component, such as during module replacement
- If it does, a jumper of suitable capacity must be used as a temporary connection

Earthing/Grounding System Integrity Test Procedure

- This test is simply a continuity test using an ohmmeter between two nearby metal surfaces or earth/ground wire.
- This process shall be repeated at random zones in the array and at every electrical enclosure in the field.

Earthing/Ground Fault Troubleshooting

- To detect earth/ground fault which when undetected can lead to high fault currents and dangerous situations for field personnel

- On the event of earth/ground fault, the earth/ground fault monitoring unit sets off some kind of alarm to alert the concerned personnel.

- However, the earth/ground fault in grounded conductors cannot be reliably detected by most of the inverters in today's market. To address this issue, it is recommended to check for earth/ground fault at each inverter stage at least once a year during routine inspection.

Earthing/Ground Fault Troubleshooting

- ***Tools required***
  - *dc* voltmeter/multimeter
  - Megohmmeter

Earthing/Ground Fault Troubleshooting Procedure

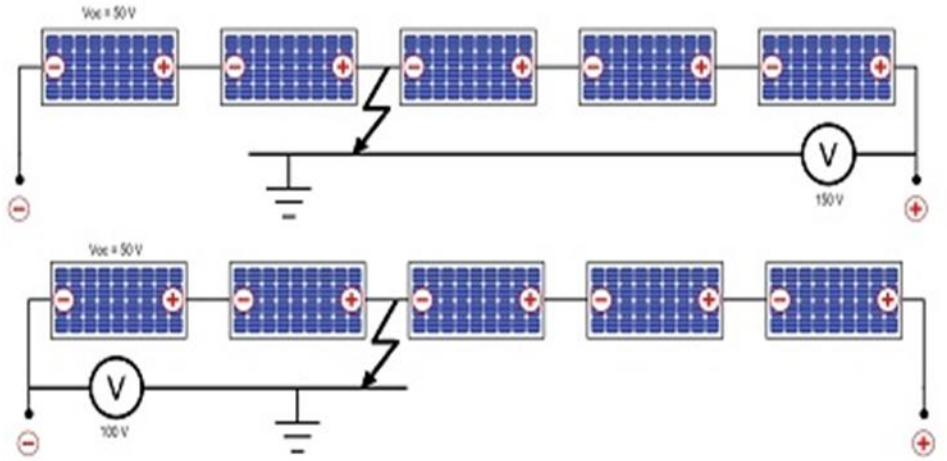
- Follow LOTO procedure to isolate inverter from the PV system
- Carry out visual inspection of the system starting at the inverter and moving to the array. Look for any signs of fire or electric arc, or melted or scorched components.
- In functionally earthed/grounded PV array, check continuity of earth/ground Fault Detect Interruption (EFDI or GFDI) fuse at inverter. Also check the fuse for correct rating type and size. If the fuse is blown, it is an indication of ground fault.
- Remove the EFDI/GFDI fuse. Under non-fault conditions, this would convert the grounded PV system into an ungrounded PV system.
- Measure voltage between positive conductor and ground, and negative conductor and ground at the line side of *dc* disconnect.
- Under non fault conditions, the voltage measured between line conductors and ground should not be well-defined. The measured voltage is often around half of V_{OC} due to capacitive coupling between the conductors and ground and slowly decays to zero.

Earthing/Ground Fault Troubleshooting Procedure 2

- If a consistent voltage is measured, it indicates earth/ground fault
- In the case of single ground fault, the sum of voltages – positive line conductor to ground and negative line conductor to ground – is equal to the voltage between both line conductors, i.e. V_{OC}
- When fault is detected, isolate combiner boxes from inverter by taking out the cables or switching off the *dc* disconnects
- Check voltages at both the +e and -ve busbars with respect to ground in each combiner box and narrow down the fault to a subarray
- Also test the insulation resistance in homerun wires from combiner box to inverter for any fault in that section using a Megohmmeter.
- In unearthed/ungrounded systems, test voltages to find fault at the line side of fuses
- In earthed/grounded systems, remove earthed/grounded conductors one at a time, test the voltage to earth/ground, and then put a wire nut or electrical tape around the exposed end of the conductor before testing another conductor

Earthing/Ground Fault Troubleshooting Procedure 3

- Once the faulty string is identified, the voltages measured at both ends of the string to ground can be used to locate the fault in string
- This method is extremely useful in quickly locating fault in long strings.



Inverter Troubleshooting

- Most common faults and failures identified in inverters.
- Most large-scale inverters today can report the type of error in the equipment and procedures are available for troubleshooting most errors.

Inverter Troubleshooting

COMMON INVERTER ERRORS AND REMEDIAL ACTIONS	
Inverter error	**Remedial action**
Low dc voltage	Follow steps to diagnose underperformance
High dc voltage	Immediately disconnect array from the inverter. Perform V_{OC} tests in strings
High input current	Immediately disconnect array from the inverter. Check string wiring
Low input power	Normal if sunshine is low. If it is sunny, follow steps to diagnose underperformance
dc earth (ground) fault	Follow steps to troubleshoot earth (ground) fault
Defective surge arrester	Replace damaged surge arresters
Low ac voltage	Confirm all breakers are on and test ac voltage with voltmeter. If within range, perform a manual restart, otherwise, contact network provider
High ac voltage	Test ac voltage with voltmeter. If within range, perform a manual restart, otherwise, contact network provider
Out of range power frequency	Check power frequency. Check grid monitoring relay display. Make sure the fuses in the load circuit function properly. If the problem persists, contact network provider
High line impedance	Check that none of the connections on ac side are loose, contact network provider if fault persists
High temperature – Fan not operating	Check power supply to fan. If good, replace fan; if bad, replace power supply.
High temperature – Fan operating	Check to confirm sensor readings. If bad, replace sensor, if good, investigate further
High temperature – Fan operating, sensors accurate	Check intake and filters for excessive build-up
Communication failure	Check indicators and error message in communication equipment and follow instructions. If good, check power supply. Contact manufacturer if the problem persists
Software error	Contact manufacturer

SAFE SHUTDOWN OF SYSTEM

Safe Shutdown For Troubleshooting And Maintenance

- Some equipment require maintenance and testing when the system or a zone of the system is energised.
  - e.g., string current testing is performed when the string circuit is live
- Only qualified personnel (at least 2 people) shall work on energised electric circuits and equipment.
- It is recommended to follow the manufacturer's instructions to isolate any equipment if applicable.

Inverter Pad Equipment Isolation

- Follow LOTO (Lock Out-Tag Out) procedures during the entire process.
- Follow the inverter manufacturer's guideline for a controlled shutdown using HMI keypad, if applicable.
- Turn off *ac* disconnect switch on inverter.
- Turn off *dc* disconnect switch on inverter. It is important to turn off the *ac* side prior to the *dc* side to prevent arcing and save lifetime of *dc* disconnect.
- Turn off any remaining external disconnect switches connected to the inverter.
- If applicable, check for readings and indicators on inverters to confirm that both *ac* and *dc* sides are disconnected.
- Turn off the switches corresponding to the inverter in control and supply panel, if applicable.
- Install lockout devices on all disconnects.
- Always wear appropriate PPE and ensure that the system is completely isolated by testing voltage with a proper meter.
- Repeat the same for all inverters and switches, as required, to completely isolate the entire inverter layer from both PV system and grid.

Transformer Isolation

- Follow LOTO (Lock Out-Tag Out) procedures during the entire process.
- Follow the general isolation procedure for inverters to disconnect inverters from the system.
- Turn off the switches corresponding to the transformer on control and supply panel, if applicable.
- Turn off the transformer switch on secondary side, which is either a stand-alone switch or is located in the switchgear.
- Install a lockout device on the transformer switch.
- Always wear appropriate PPE and ensure that the system is completely isolated by testing voltage with a proper meter.
- Repeat the same for all transformers, as required, to completely isolate them from switchgear.

Field Combiner Box Isolation

- Turn off the inverters as described in previous slides.
- Turn off the switch of combiner box, if applicable.
- Ensure that there is no current through the conductors in the combiner box using a *dc* clamp meter, and then open all fuses.
- If further isolation is needed, use the string wiring diagram to locate the homeruns (end connectors of PV strings). Confirm that the homeruns are not carrying any current using *dc* clamp meter. Disconnect the homerun positive and negative connectors and put caps on the source circuit connectors.
- Measure voltage on terminals of string combiner box using a voltmeter to confirm that each string has been successfully disconnected.
- Repeat the same process on each combiner box to be isolated.

Modules And String Wiring Isolation

- Turn off the inverter, switches and isolate the combiner boxes from the array as described.
- Ensure no current is passing through the string.
- Disconnect the module connector using appropriate unlocking tool.
- It should be confirmed that the equipment earthing/grounding remains intact, even if the module is being removed temporarily. If removing the module compromises the earthing/grounding, a bypass should be used before removing the module.
- Repeat the same for each module to be isolated.