International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 10, October-2016

Accurate String Measurements for Solar PV Power Plants to improve the Performance and Reliability

Ramanjaneyulu Marni,
M.Tech Scholar,
B. V. Raju Institute of Technology,
Narsapur, Medak Dist,
Telangna, India-502313

Anirudh Reddy R, [3] Ramchander Nirudi,
Asst.Professor
B. V. Raju Institute of Technology,
Narsapur, Medak Dist,
Telangna, India-502313

R Harshavardhana Rao Y
[4,] Ex-CTO,
Titan Energy Systems Private Limitated,
Hyderabad, Telangana, India

Abstract: **This paper describes a new advanced string monitoring box (ASMB) with a different measurement regime i.e, with or without its own system on chip (SoC) can identify the defective string instantly for a power loss of less than 0.1% of the sub-array that results in huge improvement in reliability and higher yields of solar photovoltaic (PV) power plants by reducing mean time to repair (MTTR) substantially. ASMBs and programmable data logger combine turns out to be a stand-alone, limited but effective back up to supervisory control and data acquisition (SCADA). Its capability to audit the performance of the inverter and SCADA combine is an excellent spin off with both sets of data monitored at remote monitoring console.**

Keywords: SPV Solar Photovoltaic, String/sub-Array, By-pass diodes, Shading, String Monitoring Box, Inverter, MTTR, SCADA.

I. INTRODUCTION

Silicon PV modules are highly reliable, but performance problems do arise, and the industry needs fast and accurate ways to detect them. The stakeholders in newly built systems want to verify that all the PV modules are of consistent quality, that they were not damaged during shipment or assembly, and that the sub-arrays are producing at the contracted capacity. These stakeholders would also like to have a permanent record of the 'as-built system' performance, a benchmark for subsequent periodic comparisons of the performance of sub-arrays and the overall power plant as it ages and degrades, - particularly in cases where warranty negotiations are required [1]. Operations and Management (O&M) or Asset Management (AM) companies want to accurately evaluate the health of the arrays not only at different stages of its Life Cycle but on continual basis. To enable this, Monitoring Devices should have the ability to efficiently, positively and instantly locate defective strings leading to the ailing modules. These are all potential applications for actual I-V measurements of each string of the sub-array, which can provide a very precise quantitative measure of the performance of PV Power Plant not only to the Power Plant technicians but to Remote Monitoring Consoles even when SCADA (Supervisory Control And Data Acquisition) is down. Existing String Monitoring Box (SMB) that combines several series connected modules (string) measures the current of each string and the voltage of paralleled sub-array. It is determined that such measurement doesn't truly reflect the actual power generated by the sub-array and so won't tally with the power measured by the Inverter-SCADA combine based on the SMB inputs in most cases of defective strings. Several practical causes for the underperformance of PV sub-arrays that could not be detected with SMBs unless the power loss is more than 3% of the sub-array.

II. BACK GROUND

A. Solar Panel Construction:

Standard Solar panels for large-scale (1 MW and above) are generally constructed by 156 x 156 mm (6" x 6") standard solar cells with 60 cells in one module and have three strings, each string being a series connection of 20 cells. All the three strings are brought in to the Junction Box and each string is bypassed by a diode. The Junction Box is a 4 contact type and the 4 bussing strings are terminated maintaining correct polarity. Two cables with connectors, one marked positive and the other marked as negative, are brought out of the Junction Box for external connection. Fig 1 & 2 shows the series connection of 60 cell PV module with three bypass diodes placed in junction box.

B. Shadow Effect and Bypass Diodes:

Each PV module consisting of several cells in series, which is either a power producer when it is exposed to sunlight or a power consumer if it is not exposed to sunlight i.e. in a shadow or gets masked due to several reasons such a fallen leaves, bird droppings or dust/dirt etc. Power consumption by a solar cell is detrimental to the extent that it could burn the cell and has to be avoided. To facilitate this, bypass diodes are installed in the Junction Box of each module so that given number of PV cells are bypassed

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 10, October-2016

whenever any cell of that string is even partially not illuminated by sun light. Internal resistance of a the bypass diode is quite greater than that of a PV cell or string of PV cells when exposed to sunlight since it gets reverse biased in this condition and the same is far lower than that of the string of the cells when even a cell in the string is masked since it gets forward biased in this condition [2].

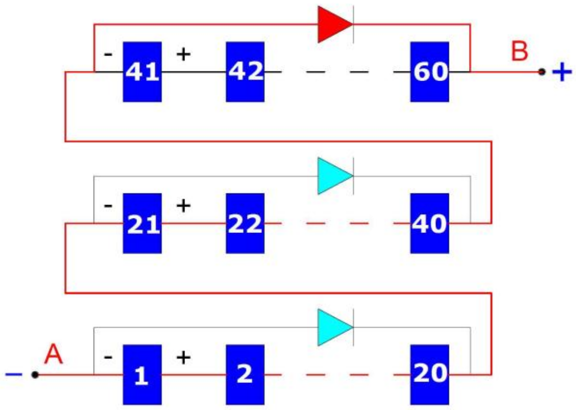


Fig 1: Bypass diode wiring and operation

The current flows through each consecutive cell following the path of least resistance. When a cell in the series string is shadowed the resistance of the string increases tremendously thus making the bypass diode the path of least resistance (ref fig 1). Hence the current flows through the diode shunting the power through the alternate path around the PV cell or string to the next power producing cell/string. The voltage loss is limited across the string that contains the inactive (shadowed) cell(s). Hence there is no change in the current of individual module while shading, whereas there is a change in the voltage i.e., reduction in voltage of the module due to loss of voltage of the total cells across the by-pass diode, which was consuming power when shaded.

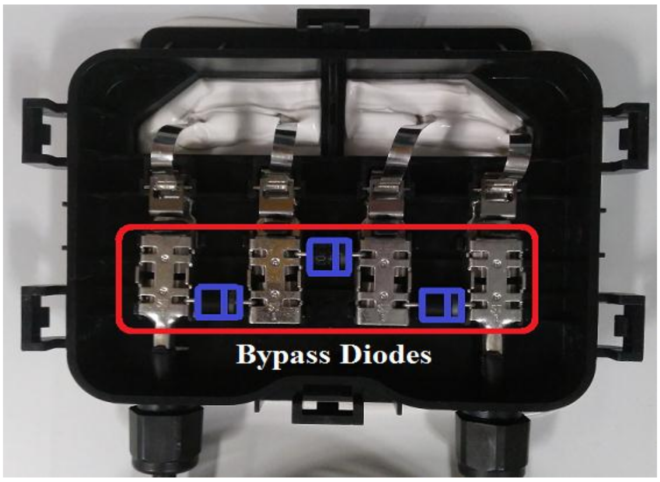


Fig 2: Bypass diodes in standard SPV modules

However, it should be noted that if the module is fully shaded (i.e., all the three strings are even partially shaded), then the module voltage would be 0 V and the current 0 A if it is a stand-alone module. If this module is one among several modules connected in series as a string, then this module will not contribute in any way, but would pass on the previous module's voltage and current to the next module by virtue of its 3 bypass diodes being forward biased [3].

C. Faults that contribute to poor yield of PV Power Plant:

It is important to note that there are many faults that can contribute for the poor yield of the power plant other than shading. PV module failures, premature aging of a few modules in several strings as well as the entire lot of modules, blown fuses or bypass diodes, uneven soiling, and poor connections [4].

III. STRING MONITORING BOX (SMB)

String Monitoring Box: Series connection of several modules is called a string and several such strings are paralleled to form a sub-array/array. String Monitoring Box aka String Combiner Box or Combiner Monitoring Box was developed by several manufacturers to combine several strings by paralleling to form a sub-array/array and to measure current of each string & paralleled voltage of the sub-array to monitor the performance of the sub-array and diagnose the faulty string(s) of the sub-array [5]. Refer Fig 3 below for its schematic that shows the measurements made by SMB.

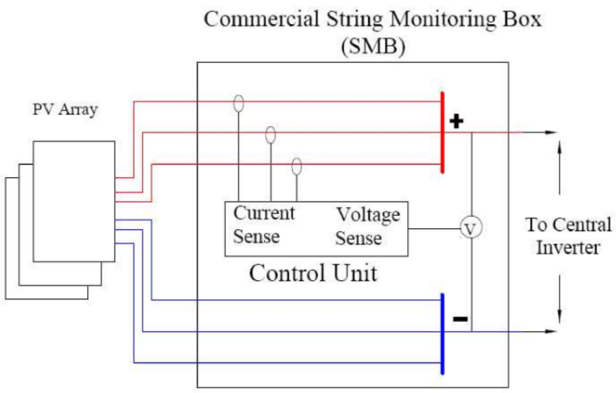


Fig 3: Commercially available String Monitoring Box (SMB)

Of course, SMB also provides several protections such as over-voltage, over-current & surge protections, replaceable fuse or MCB for each string for fault isolation etc., It comes with class IIC protection for outdoor use. DC shunt-type sensors or Hall-Effect sensors measure the current of each string and voltage of the sub-array. Few models provide Ground-Fault Detector & Interrupter (or Isolator) to detect string leakages to isolate the defective string(s) and even has its own ambient (temperature, irradiance, wind speed etc.,) sensors. SMBs are connected with shielded data cables to the SCADA (Supervisory Control and Data Acquisition) co-located with Central Inverter. SCADA gets the SMB data as well as Inverter data to analyze the health of each sub-array/array. MODBUS RTU has become de facto standard though MODBUS/RS485 or Proprietary protocols are used for transfer of data to SCADA.

Deficiencies of SMB: Few manufacturers even claim that their SMB compares the string currents to identify the faulty

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 10, October-2016

panel/module. This is definitely misleading since no SMB can identify defective module(s) based on the present set of current & voltage measurements. Let us cite one simple case. Let us assume that several or all the preceding 19 modules of a string of 20 modules are totally faulty (due to any kind of fault) and only one out of the three 20 cell strings of the last module (20th module) connected to the SMB is healthy. Even in such an eventuality, the nominal string current (same current when all the 20 modules of the string are OK) is measured. Also, SMB parallels several strings and so, even if 19 out of 20 strings are defective but just any one string of this sub-array is OK, then the voltage measurement shows normal value. So, SCADA based on this data estimates that the sub-array is healthy whereas in reality the sub-array might be producing less than 10% of its nominal power. Present day SMB can't identify the loss of power of a sub-array and how can it identify a defective string leave alone the defective module with the kind of measurements it makes.

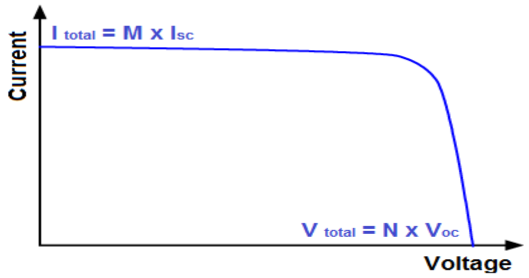
However, such a power loss could be identified by SCADA based on the data from central Inverter by measuring the actual Pmax of each sub-array and comparing the same with the Power outputs of adjacent sub-arrays. But, this has got its own limitation since even Class 1 Inverter can only identify a sub-array as defective only if it is underperforming by more than 3% of its rated Pmax in given conditions since the tolerance of Class 1 Inverter is +/- 3%. Even then, one can't identify the defective string(s) based on this since the measured values are for the entire paralleled strings/sub-array and so, time taking further tests are required to identify the defective string and thereafter, the defective modules in that string. So, the very purpose of having SMB to identify the defective string(s) is defeated despite current and voltage measurements that are obviously inappropriate [6].

IV. THEORETICAL BACKGROUND

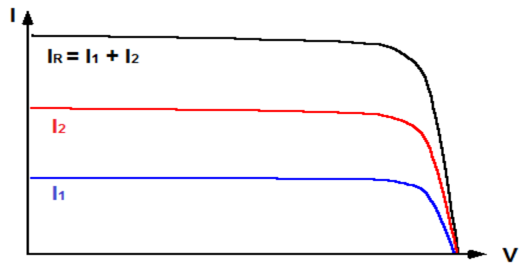
In shaded condition due to the bypass diodes connected in the module, there is no current change in module output unless it is completely dead but only the combined series voltage of the cells in the shaded string will be reduced in the voltage output of the module as shown in fig.4. Standard PV module has 60 cells package in series: Let us assume that each cell has V_{max} = 0.5 Volts and I_{max} = 8.5Amp in ideal conditions then the module is expected to deliver the voltage and current with a matched load to achieve the P_{max} of 255Watts (V_{max} = 30.0 V [0.5 x 60 cells], I_{max} = 8.5 A, P_{max}=30.0*8.5=255W).

As discussed above the Junction Box has 3 bypass diodes having 20 cells across each diode, if any of the cells in a given string of 20 cells within the module is either partially or fully shaded the corresponding bypass diode gets activated (forward biased) and the module output, V_{max} = 20.0 V (0.5 V x 40 cells since 20 cells are not contributing), I_{max} = 8.5 A (is constant even if one of the other two strings of the module having 20 cells each is not at all shaded and is healthy), therefore P_{max} = 20 x 8.5 = 170W. It is important to note that the difference of 85W in P_{max} due to shading or open circuiting. If two or more healthy unshaded modules connected in series which also referred as string then the total string output would be V_{max} = 60.0 V, I_{max} = 8.5 A and P_{max} = 510 W.

Further, if one string within one of the two modules is partially shaded or open circuited, then the output would be V_{max} = 50.0 V, I_{max} = 8.5 A and Pmax = 425 W, it is clearly indicating that the power loss of 85Watts, which is 16.67% nominal power output. Similarly if two or more healthy unshaded modules are connected in parallel the total output would be V_{max} = 30.0 V (constant), I_{max} = 17.0 A (8.5A x 2 modules) and P_{max} = 340 W, a loss of 170 W which is down by almost 35% of nominal power output. From the above calculations it is quite clear that in shaded conditions there is no change in current of the module at string level and there are no changes in the voltage of the module at the sub-array or array level. But there is significant Pmax loss (16.67 to 35%) in either case i.e., one of the 20 cell strings within the module gets even partially shaded connected in series or parallel.



M: No. of cells in parallel, N: No. of cells in series.



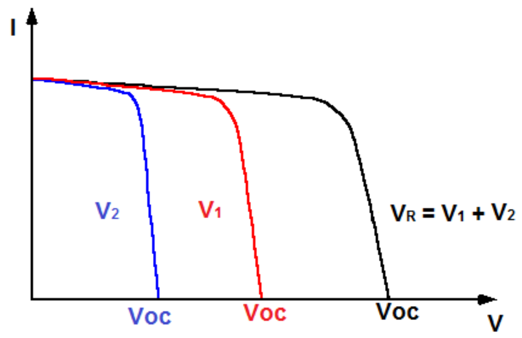


Fig 4: Representative IV curves of series and parallel connection of solar cells/modules/strings

One can imagine if more than one module in a given string or more number of strings develop similar problems in a sub-array/array. The present SMBs can't spot this Pmax loss or identify the defective string for immediate rectification of the situation before substantial power and time is lost.

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 5 Issue 10, October-2016

V. ADVANCED STRING MONITORING BOX

Fig. 5 shows the proposed Advanced String Monitoring Box (ASMB), and it is quite simple, inexpensive and elegant which can measure the voltage of each string of modules that make up the sub-array/array while retaining the current measurement of each string and provide the data string-wise to the SCADA (Supervisory Control And Data Acquisition) of the Central Inverter for accurate monitoring, logging and webcasting to the remote monitoring console. This takes the trouble shooting down to string level instantly. This can be achieved by a simple design change of adding a blocking diode for each string before paralleling them thereby enabling the measurement of the voltage of each string that make up the sub-array/array to find out the shaded/defective string in the sub-array/arrays.

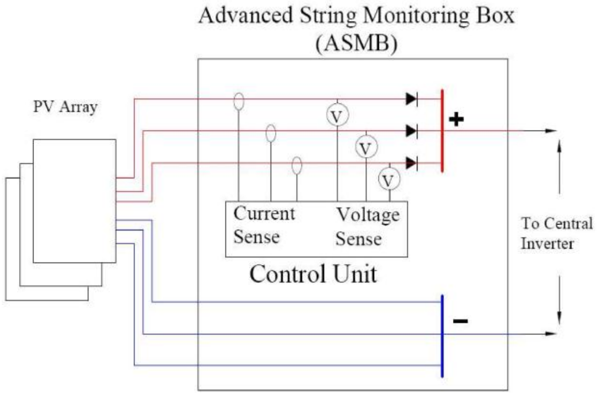


Fig 5: Advanced String Monitoring Box with blocking diodes to measure the voltages of each string prior to combining

This can be further improved into a formidable stand-alone diagnostic device by integrating a simple system on chip that multiply the voltage and current of each string and the Pmax of each string is digitally stored or transferred to a central location for remote monitoring. It will also compare the Pmax of each string with the average power of other good strings and raise an alarm/flag whenever any given string delivers less power. However, adding on such capabilities increases the initial cost of ASMB but it more than offsets the increased cost by reducing the loss of power with its quick diagnostic ability that improves the MTTR of the power plant [7].

VI. EXPERIMENTAL SETUP

Four closely matched 40Wp modules are selected to simulate the array to make the measurements for ease of testing. The test results on these modules/array vary only in magnitudes from similar tests on 240 Wp high power modules. Tests on low power modules and the conclusions arrived unequivocally validate the same in sub-arrays/arrays of high power modules that make up large scale MW Power Plants.

Low Power modules such as 40 Wp are normally made up of cut cells to achieve the nominal voltage required by the end products/devices. Further, it facilitates to have at least two series connected strings of cells in the module with each string of 18 cut cells having a bypass diode.

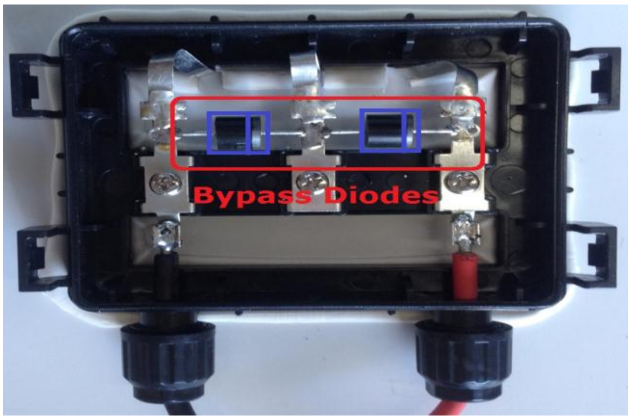


Fig 6: Bypass diodes in 40Wp modules

Main reason to choose such modules for this test is that the entire array can be placed on the testing area of Sun Simulator (SS) and so measurements can be taken by SS at array level. Array of small size modules can be tested by Sun Simulator (SS) in the Lab as per the applicable IEC standards (for the modules) to get voltage and current values quite accurate. SS uses the MPPT (Maximum Power Point Tracker) algorithm similar to the field Inverters.

Each 40 Wp module is numbered (1 through 4). Modules 1 and 2 are connected in series to make a string and two such strings are connected in parallel to simulate the sub-array/array in MW scale power plants. And each string of this array has one blocking diode.

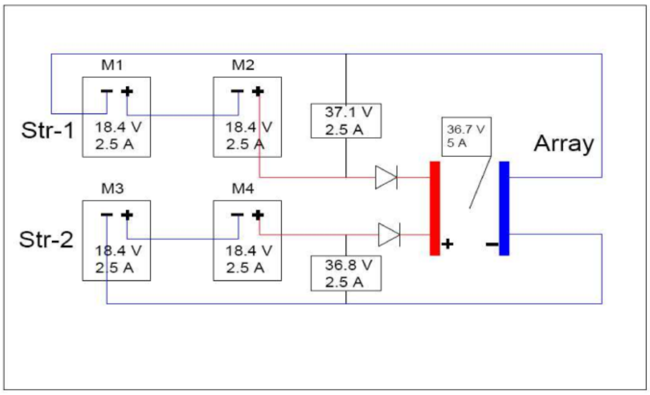


Fig 7A: Array in Normal (sun lit) condition

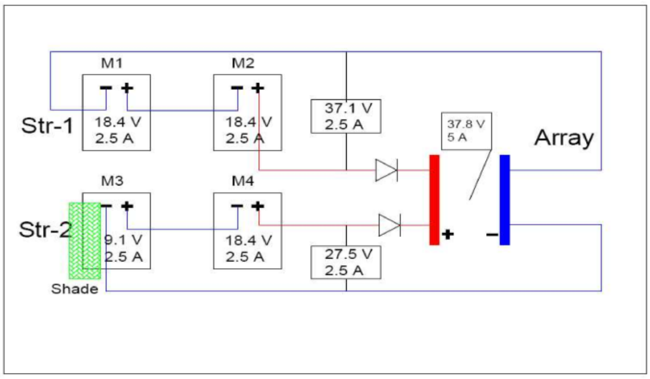


Fig 7B: Array in Shaded condition

Four modules are connected as shown in Fig.7 and measurements were taken by SS when all the four modules are in Normal (illuminated) condition. One string of Module 3 is shaded and measurements were taken before blocking diode (i.e., prior to paralleling) and after blocking diode (i.e., at the parallel junction of two strings) of each string using sun simulator. The results are shown in below tables 1-4. As discussed in earlier sections the results are matching to the theory that there is no change in the voltages and individual currents in the measurements since the voltage measured after paralleling and current measured of each array in series [8]. In commercial String monitoring boxes or String combiner boxes are measuring in the same fashion i.e., Voltage at Parallel of all arrays and currents of each string. By using Sun Simulator, same was simulated at in-house by shading one of the PV modules and taken the electrical results individual strings and after paralleling of those two strings.

VII. TEST RESULTS AND DISCUSSION

All electrical parameter tests are done by Class AAA Sun Simulator (SS) at STC (standard Test Conditions) of 1000W/m² & 25ºC as per applicable IEC standards for PV modules (IEC 60904 & IEC 61215). Test results for the parameters not relevant for the evaluation of SMB Vs ASMB are not presented here since the results of certain parameters such as FF (Fill Factor) for array, Array would be misleading because not only individual modules but the strings and array in different conditions as shown in Figs 7A & 7B are tested by SS.

Table 1: Test Results of Modules

Module ID	Voc	Isc	Pmax	Imax	Vmax	FF
Module- 1 (40Wp)	22.8	2.7	46.0	2.5	18.4	75.7
Module- 2 (40Wp)	22.8	2.7	46.1	2.5	18.4	75.7
Module- 3 (40Wp)	22.8	2.7	46.0	2.5	18.4	75.6
Module- 4 (40Wp)	22.8	2.7	46.1	2.5	18.4	75.7

Table 2: Test Results of Strings (series of two modules)

String ID	Voc	Isc	Imax	Vmax	Pmax
1st String (Mod 1& 2)	46.2	2.7	2.5	37.1	91.9
2nd String (Mod 3 & 4)	46.1	2.6	2.5	36.8	91.0
2nd String in Partially Shaded	46.1	2.7	2.5	27.5	67.6

Table 3: Test Results of the sun lit Paralleled array

Para-meter	Sun Simulator			Commercial SMB			Advanced SMB	
	Str 1	Str 2	Arr	Str 1	Str 2	Arr	Str 1	Str 2
Voc	46.2	46.1	45.9	NA	NA	NA	NA	NA
Isc	2.7	2.6	5.3	NA	NA	NA	NA	NA
Vmax	37.1	36.8	36.6	NA	NA	36.7*	37.1*	36.8*
Imax	2.5	2.5	5.0	2.5*	2.5*	NA	2.5*	2.5*
Pmax	91.9	91.0	182.4	NA	NA	182.4 *	91.9*	91.0*

Measurements that could have been done by SMB - Light Turquoise; by ASMB - Light Yellow Calculated Pmax in Tan are from the SMB & ASMB data. Results of Tables 3 & 4 clearly indicate the ineffective and misleading monitoring of Pmax by SMB whereas the measurement by ASMB represents the actual Pmax of the array.

Para-meter	Sun Simulator			Commercial SMB			Advanced SMB	
	Str 1	Str 2	Arr	Str 1	Str 2	Arr	Str 1	Str 2
Voc	46.2	46.1	45.8	NA	NA	NA	NA	NA
Isc	2.7	2.7	5.3	NA	NA	NA	NA	NA
Vmax	37.1	27.5	37.8	NA	NA	36.6*	37.1*	27.5*
Imax	2.5	2.5	4.1	2.5*	2.5*	NA	2.5*	2.5*
Pmax	91.9	67.6	155.1	NA	NA	182.0 *	91.9*	67.6*

Table 4: Test Results of the partially shaded Paralleled array

The results are graphically presented in Fig.8 and Fig.9 for easier understanding of the performance of the array in different conditions.

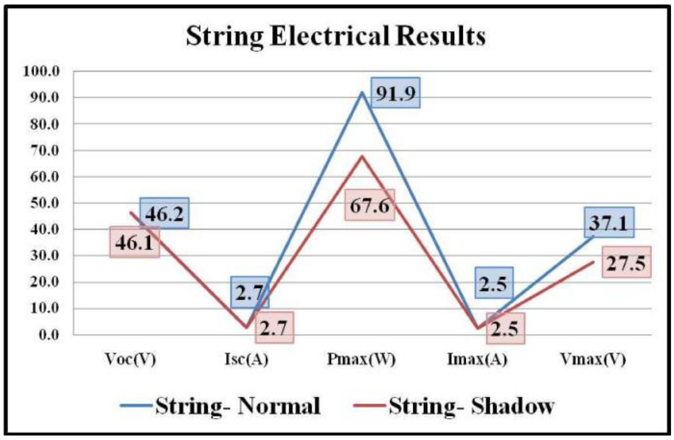


Fig 8: Test Results of strings tested by Sun Simulator in Normal condition and Shaded condition.

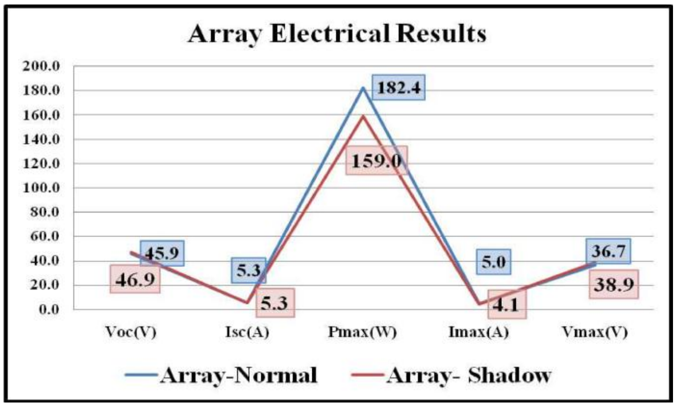


Fig.9: Test Results of Arrays in Normal and Shaded conditions. There is no change in the voltages and currents as expected when a standard SMB is used for monitoring.

CONCLUSION

As discussed in earlier sections the results are matching to the theoretical understanding since there is no change in the array voltage and individual string currents despite partial shading of the module as measured by SMB. This clearly correlates that the virtual Pmax of the array as calculated from the SMB data is mis-leading since the actual Pmax of the array is lower in shaded condition. Further, the results as measured by ASMB i.e., the string voltages and string currents confirm that the sum of the calculated Pmax of both strings (from the ASMB data) is nothing but the actual Pmax of the array.

ASMB with its instant diagnosis of defective strings far ahead of the sensing by Inverter sustains the Power Plant operation for consistently higher yield for longer periods with substantial reduction in MTTR. With due augmentation it can serve as a limited back up for SCADA and can even audit the performance of the Inverter while providing the Power Plant performance data to the Remote Monitoring Console simultaneously.

ACKNOWLDGEMENT

The team sincerely expresses the gratitude to the technical team of M/s. Topsun Energy Limited for allowing working on this paper and letting me use their facilities. Sincerely thank Mr. Radhakrishna, Mr. Bhavesh Patel, Mr. Vishal Rathore, Mr. Vishal Patel, Mr. Prashant Patel, Ms. Reema Patel, Mr. Chinatn, Mr. Narendra, and Mr. Dhaval, Mr. Lalji Thakor & Mr. Ranjit and team for their cordial contribution. We would also extend our gratitude to Sri Col.Dr.T.S. Surendra, former principal of BVRIT for his motivation towards research.

REFERENCES

[1] Field Applications for I-V Curve Tracers by Paul Hernday.

[2] Investigating the Impact of Shading Effect on the Characteristics of a Large-Scale Grid-Connected PV Power Plant in Northwest China, by Yunlin Sun - Hindawi Publishing Corporation.

[3] Performance and Reliability of photovoltaic systems (review of failures of photovoltaic modules) by Marc kontges- IEA.

[4] Monitoring of Photovoltaic systems: Good practice and Systematic Analysis by Achim Woyte.

[5] PVI-STRINGCOMB-US data sheet by PVI-Aurora.

[6] Techno-economic analysis of solar photovoltaic power plant for garment zone of Jaipur city by Mevin Chandel by Centre for Energy and Environment, Malaviya National Institute of Technology, Jaipur 302017, India

[7] Mean Time Before Failure of Photovolataic modules (MTBF-PVm) by A Realini, SUPSI, DCT, LEEE-TISO, Swiss Federal Office of Energy.

[8] Experimental Study of Shading Effect on PV Module and Improvement in Power Using Diode on Series & Parallel PV Module by Pawan Kumar- IJSR