Modeling and Relative Research of Solar Photovoltaic Array Topologies Under Partial Shading Conditions

V. Bala Raju, Ch. Chengaiah

Abstract*- The electrical power generation from solar photo voltaic arrays increases by reducing partial shading effect due to the deposition of dust in modules, shadow of nearby buildings, cloud coverage leads to mismatching power losses. This paper gives the detailed analysis of modeling, simulation and performance analysis of different 4x4 size PV array topologies under different irradiance levels and to extract output power of panels maximum by reducing the mismatching power losses. For this analysis, a comparative study of six PV array topologies are Series, Parallel, Series-Parallel, Total-Cross-Tied, Bridge Linked and Honey-Comb are considered under various shading conditions such as one module shading, one string shading, zig-zag type partial shading and total PV array partially shaded cases. The performance of above six topologies are compare with mismatching power losses and fill-factor. For designing and simulation of different PV array configurations/topologies in MaTLab/Simulink, the LG Electronics LG215P1W PV module parameters are used in all PV modules.

***Keywords*- Solar PV cell, PV array Topologies, irradiance levels, shading effect, mismatching losses, fill-factor.**

I. INTRODUCTION

In future, electrical power from renewable energy sources increasesespecially solar and wind power systems. Solar photovoltaic systems has more advantages compare to other energy systems and play a major role in renewable sector for power generation. Worldwide the research is going on in the area of Solar PV system for improving its conversion efficiency and also reducing the cost of panels. The efficiency of pv module is less approximately 22-30% only at standard temperature conditions.Duetoshadingproblem,theefficiencywillbedecreased gradually and also it leads to shutdown the entire PV plant. Solar PV systems consists of series - parallel connected modules form PV arrays and to get required voltage, current and output power. For high currents and high voltages are obtained fromPV modules connected in parallel and series respectively altogether to improve the system output power. Normally the PV arrays are exposed to sun direction, under high irradiance the PV modules deliver maximum power. But, due to low irradiance, high temperature and partial shading the Solar PV arrays delivering low output power.[1-3]. Due to Partial shading effect where there is no exposure to sunlight, the arrays output are reduced and also decreases life-span of PV modules[4]. Partial shading caused by the deposition of dust in modules, shadowing of trees and buildings near to the PV arrays etc., that results output power from arrays are reduced gradually to zero level leads to shut-down of entire PV system [5]-[6]. The power loss occurs in a pv system due to shading effect depends on the shading pattern and array interconnection topologies but notdependonshadingarea. A shadowed pv module behaves as a load and the solar cells in a module will heat up and develop a hot spot in pv modules and these hot spots can damage the pv cells and modules, and leads to long-term decrease in annual system performance of the pv system. The bypass diodes also connected across cells for reducing the effect of shadows. The mismatching power loss can be minimized with bypass diodes connected in parallel to modules. The mismatching power losses occurs in a pv arrays due to partial shading effects are reduced in different topologies i.e., Series(S), Parallel(P), Series-Parallel(SP),Bridge-Linked(BL),Total-Cross-Tied(TCT), Honey-Comb(HC) type of array topologies [7]-[10]. By using TCT topology, the lifespan of the pv system increases by 30% which have been outlined in the literature [11].

This research paper is organized as follows: The mathematical modeling of solar PV cell, module and array described in section-2; Modeling and simulation of different topologies for various shading cases by considering different irradiance levels are presented in Section 3; the comparative and performanceanalysisofarraytopologies, and finally results and discussionsarepresentedinsection 4;conclusionsaregiveninsection5.

II. SYSTEMDESIGN

2.1.Modeling of Photovoltaic Cell, Module and Array

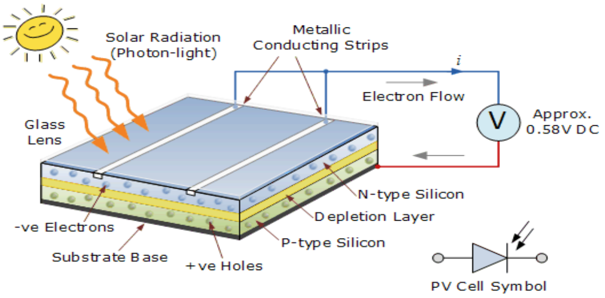
The solar cell is semiconductor device, it converts the light energy to the electrical energy. The solar module poweroutput depends on irradiance level of sunlight and ambient temperature. Solar modules are connected in series / parallel are depends on output voltage/current requirements. In uniform illumination condition, the array output power is equal to the all pv modules output power.The solar cell electrical energy conversion as shown in figure-1 (a & b).PV celloutput voltage and maximum power generation is only 0.5V and 1 to 5 W respectively because of the limitation of the process. The formation of PV module is by connecting several cells in series, and the array is formed by modules connected in series-parallel in order to satisfy the

Revised Manuscript Received on April 12, 2019.

V. BalaRaju,Research Scholar, Dept. of EEE, SVUCE, SV University, Tirupati, A.P, India. (vbrajuu@gmail.com)

Dr. Ch. Chengaiah,Professor, Dept. of EEE, SVUCE, SV University, Tirupati, A.P, India

high-voltage and high-power supply requirements. The total output power from the PV module depends on the solar irradiation (W/m^2) and temperature (°C).



(b)

Figure 1(a) PV Cell Construction

Figure-1(b) shows the PV Cell, module and solar farm. Connection of cells form a solar module or panel, group of modules in series form an array and many arrays make a solar farm.

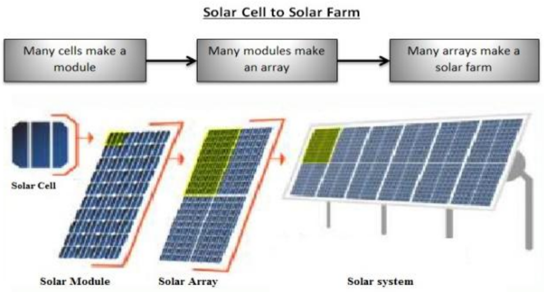


Figure 1(b). Solar cell, module and solar array

Modeling of solar PV Cell

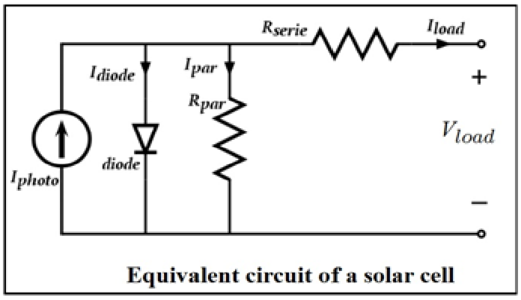


Figure1(c). Equivalent circuit of PV cell

From the above figure-1(c)[12],

$I_{photo} = I_{diode} + I_{par} + I_{load}$

$I_{load} = I_{photo} - I_{diode} - I_{par}$

$$= I_{photo} - I_{diode} - \frac{R_{serie}\, I_{load} + V_{load}}{R_{par}}$$

$$= I_{photo} - I_{sat}\left[exp\left(\frac{q(R_{serie}\, I_{load} + V_{load})}{k_B T}\right) - 1\right] - \frac{R_{serie}\, I_{load} + V_{load}}{R_{par}} \quad \text{-- (1)}$$

Equation-1 is the mathematical representation of practical PV cell model.

where, I_{load} and V_{load} are load current and load voltage, I_{photo} is photo-generated current[A], I_{diode} is diode current, I_{par} is parallel loss current, R_{par} is parallel resistance[Ω] and R_{serie} is series resistance[Ω]. I_{sat} is the constant saturation current of the diode, $k_B \approx 1.38 \times 10^{-23} JK^{-1}$(Boltzmann's constant), charge of the electron $q \approx 1.60 \times 10^{-19}$Cand T is temperature measured at the p-n junction.

Modeling of Solar PV Array

The figure-2 shows the solar PV array composed of Ns (no. of series modules) and N_P (no. of parallel modules).

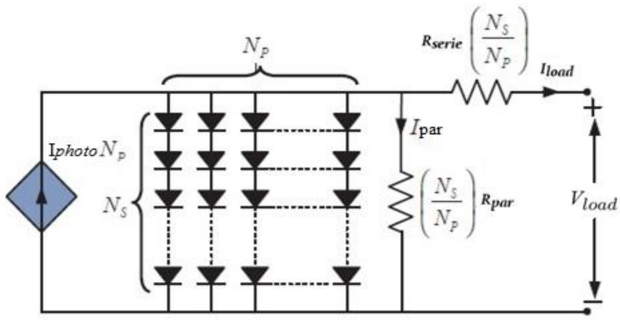


Figure 2. PV Array composed of N_S x N_P modules

$$I_{load} = I_{photo} - I_{sat}\left[exp\left(\frac{q(R_{serie}\, I_{load} + V_{load})}{N_s k_B T}\right) - 1\right] - \frac{R_{serie}\, I_{load} + V_{load}}{R_{par}} \quad \text{--- (2)}$$

Equation-2 is the mathematical representation of Ns cells in module connected in series in the array.

$$I_{load} = I_{photo}\, N_P - I_{sat}\, N_P\left[exp\left(\frac{q\left(R_{serie}\left(\frac{N_s}{N_p}\right)I_{load} + V_{load}\right)}{N_s k_B T}\right) - 1\right] - \frac{R_{serie}\left(\frac{N_s}{N_p}\right)I_{load} + V_{load}}{R_{par}\left(\frac{N_s}{N_p}\right)} \quad \text{--- (3)}$$

Equation-3 is the mathematical representation of PV array composed of N_S (no. of series)andN_P(no. of parallel) connected PV modules [13] shown in figure-2.

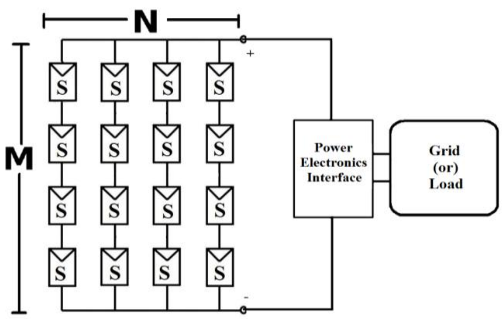


Figure 3. A Simple 4 x 4 size PV Plant

Figure-3 shows an simple PV plant connected to thegrid/load. In this plant, M is the no. of PV modules connected in one string are 4 and N is the no. of strings are 4. In this paper only 4x4 size PV array are analyzed by considering power loss and fill factor. The power electronics interface to the grid of the PV plant are not discussed in this work.

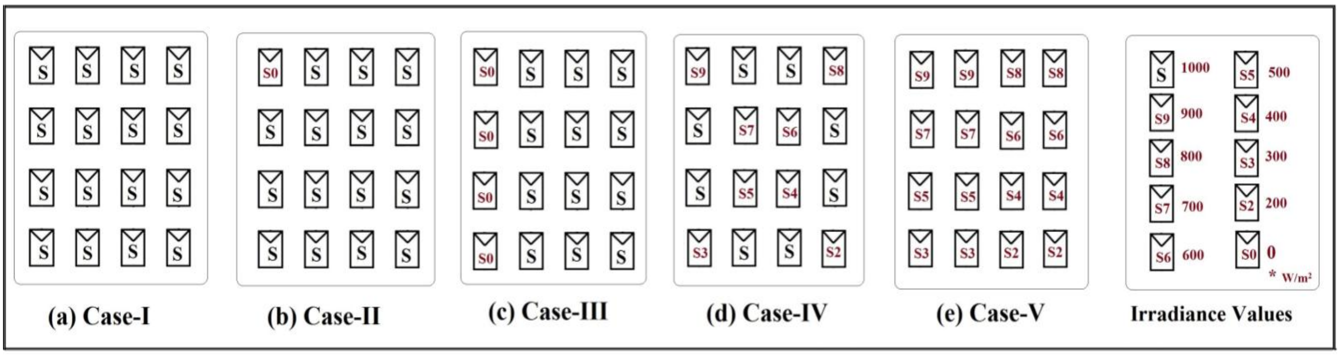


Figure 4 . Different partial shading cases of Solar PV Topologies

2.2 Uniform irradiance and Partial Shading Cases

This section describes the various Partial Shading Cases and irradiance levels of 4x4 size PV array with different configurations are described as follows: in this array, there are 4 strings and each string as 4 modules as shown in figure 4.

Case-I: Un-shading (Uniform irradiance) case- Under this case, all the PV modules in 4×4 size arrays of different topologies receives an uniform irradiance 1000 W/m^2 as shown in figure 4(a).

Case-II: One module full shading case- Under this case, the irradiance level of first PV module in first string of the array configurations receives 0 W/m^2 and remaining all modules are receives same irradiance 1000 W/m^2 as shown in figure 4(b).

Case-III: One string full shading case- Under this shading case, all modules in the first string are fully shaded with an irradiance 0 W/m^2, remaining all modules receives an irradiance 1000 W/m^2 as shown in figure 4(c).

Case-IV:Zig-zag type partial shading case- Under this partial shading case, the modules in the array topologies are receives an different irradiances as shown in figure 4(d).

Case-V: Complete PV array partial shading case- Under this case, all modules in the array receives an different irradiances as shown figure 4(e).

III. MODELING AND SIMULATION OF SOLAR PHOTOVOLTAIC ARRAY TOPOLOGIES

The PV system consisting of 4×4 size array modeling, simulation of different topologies are presented in this section.For modeling of solar PV topologies, LG Electronics LG215P1W PV modules as considered for PV Array. The parameters of above model and corresponding output characteristics are shown in table 1 and figure 5 respectively.

3.1 PV model Parameters and Output Characteristics

Table 1: Parameters of LG Electronics LG215P1W PV module under STC(1000 W/m^2 and 25^{o}C)

Parameters	Values
Maximum Power	215 W
Cells per module Ncell	60
Open circuit voltage V_{OC}	36 V
Short-circuit current I_{SC}	7.99A
Voltage at maximum power point V_{MP}	29.1V
Current at maximum power point I_{MP}	7.39A
Temperature coefficient of V_{oc}	-0.339 %/deg.C
Temperature coefficient of I_{sc}	0.037997 %/deg.C
Light generated current I_L	8.027A
Diode saturation current I_o	1.225e-10
Diode ideality factor	0.93904
Shunt resistance R_{sh}	125.259 Ω
Series resistance R_s	0.34933 Ω

Output-Characteristic

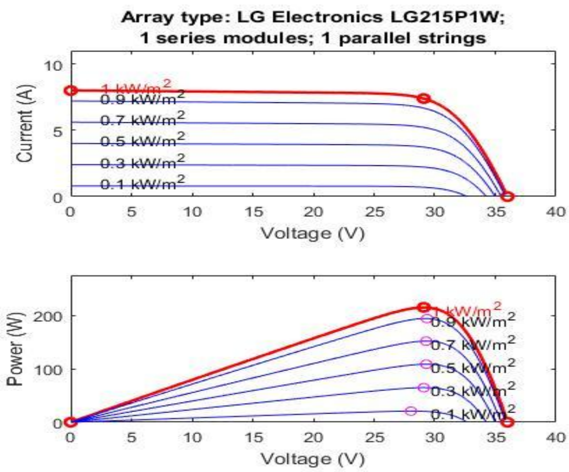


Figure 5. Output Characteristics of LG Electronics LG215P1W PV Module at different irradiances

3.2 Solar PV Array Topologies

The main Solar PV array configurations/topologies are,

a. Series (S) connection type
b. Parallel (P) connection type
c. Series-Parallel (S-P) connection type
d. Total-Cross-Tied (T-C-T) connection type
e. Bridge-Linked (B-L) connection type and
f. Honey-Comb (H-C) connection type

For the simulation of above topologies, the 4x4 size array formed with 16 PV modules and in each module total 60 PV cells in series. Each module and string in a array are protected with anti-parallel bypass diodes and series connected blocking diodes respectively.

These 4x4 size array modules are operates at STC i.e., constant temperature of 25°C and different irradiance levels are shown in figure 4. The above six solar PV topologies are shown in figure-6.

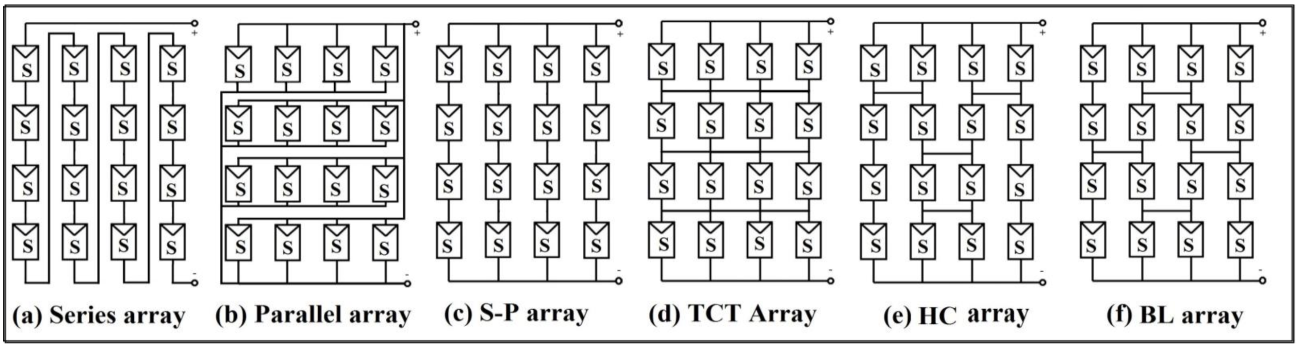


Figure 6: Schematic diagrams of Solar PV Array configurations.

3.3 Simulation of Solar PV Topologies

In this paper, all available PV configurations/ topologies with one uniform case and four different partial shading cases are simulated in Matlab/Simulink. The simulink models of six topologies/configurations are grouped as sub-system with name Solar_PV_topologies and user for overall simulation purpose. The simulating model of different array topologies are shown in figure-7.

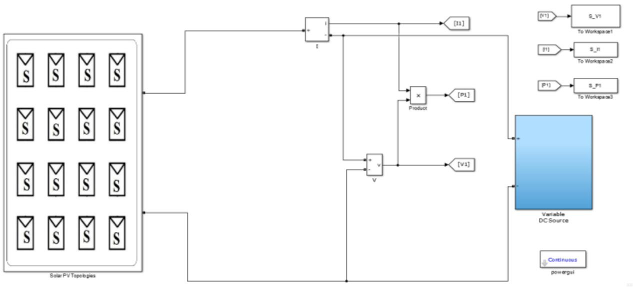


Figure 7. Simulink model of different topologies

a. Series (S) topology

The Schematic model of series topology/configuration as shown in figure.6(a).

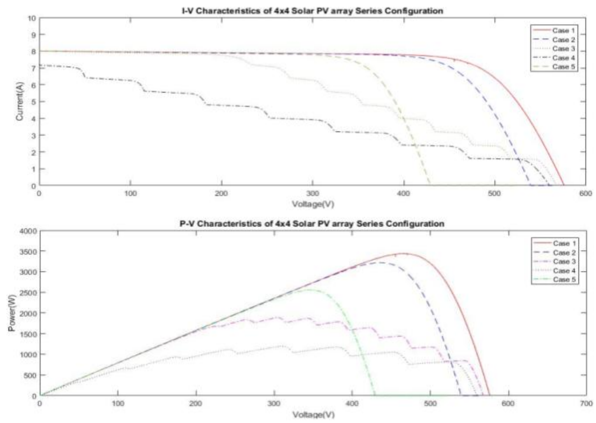


Figure 8. P-V and I-V output characteristics of 4 x 4 PV array series type of topology

In this topology, all modules in array are connected in series, so the total current from the array is same as pv module current and the total array voltage is sum of the individual PV module voltage. The output characteristics under shading cases I to V for series configuration are shown in figure-8.

b. Parallel (P) topology

The Schematic model for a Parallel topology as shown in figure.6(b).In this configuration, all the modules in array are connected in parallel, so that the total voltage of the array is same as pv module voltage and the total array current is sum of the individual currents of modules. The mismatching power losses are reduced by connecting anti parallel bypass diodes to each module.The output characteristics under different partial shading cases are shown in figure-9.

We notice that under partial shading cases, the characteristics of parallel configuration exhibit a single peak in presence of the bypass diodes, there is no effect on the maximum power in parallel case.

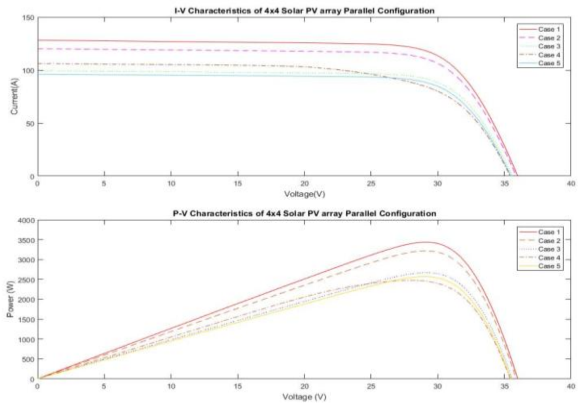


Figure 9. P-V and I-V output characteristics of 4 x 4 PV array Parallel type of *topology*

c. Series–Parallel (SP) topology

The Schematic diagram of S-P topology as shown in figure.6(c).In S-P array topology, PV strings formed by series connected modules for generating a required voltage and parallel connection of these strings for generating desired output current. The P–V and I–V characteristics under uniform and different shading cases for S–P configuration are shown in figure-10.

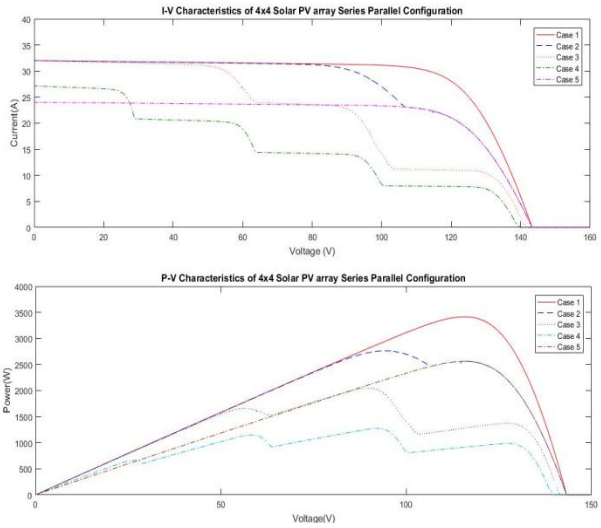


Figure 10. P-V and I-V output Characteristics of Series- Parallel type topology

d. Total-Cross-Tied (TCT) topology

The Schematic diagram of TCT topology figure 6(d). In this configuration, the open-circuit voltage of each PV module is equal to voltage across modules in each row and the total output voltage of array is the sum of voltages across all the modules in a rows. The total array current is sum of the currents of all modules in a row.The output characteristics under uniform and various shading cases shown in figure-11.

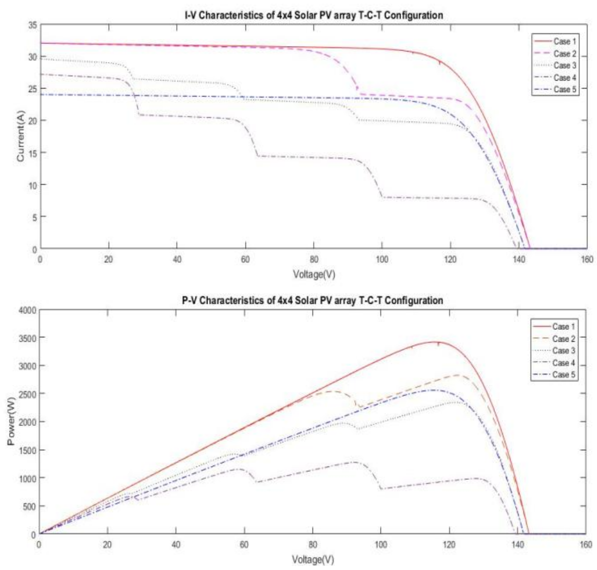


Figure 11. Output characteristics of 4 x 4 PV array Total-Cross-Tied type topology

e. Bridge-Linked (BL) topology

The Schematic diagram of BL topology figure 6(e).In this configuration, all PV modules connected in bridge rectifier type architecture for reducing the more mismatching power losses in Series and S-P type of topologies. The output characteristics under different shading cases are shown in figure-12.

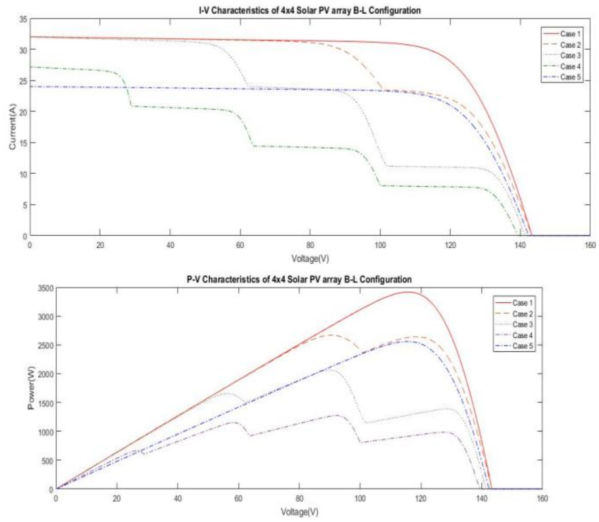


Figure 12.Output characteristics of 4 x 4 PV array B-L type topology

f. Honey-Comb (HC) topology

The Schematic diagram of HC topology as shown in figure6(f).The demerits of series and S-P array topologies can also overcome by this H-C type of configuration. In this type, all modules in array connected in the form of hexagon shape of the honey comb architecture. The output characteristics under uniform and various shading cases are shown in figure-13.

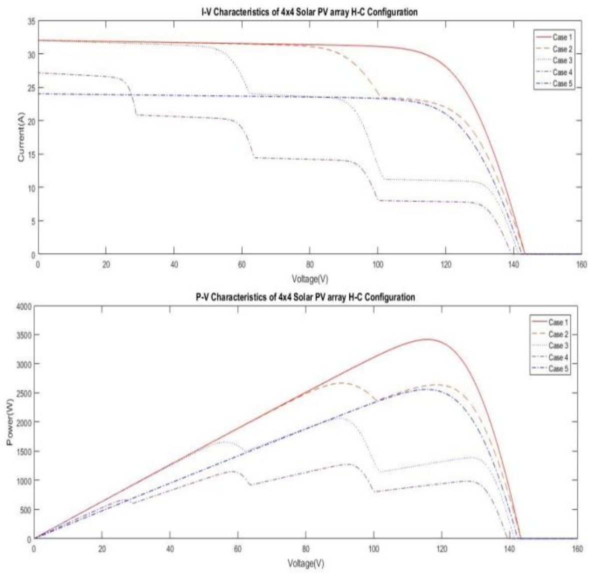


Figure 13.Output characteristics of 4 x 4 PV array H-C type topology

The simulation results of different type of topologies under uniform and partial shading cases for a 16 modules PV array topologies are summarizes in the table-2.

IV. PERFORMANCE AND COMPARATIVE ANALYSIS OF SOLAR PV ARRAY CONFIGURATIONS UNDER PARTIAL SHADING CASES& RESULTS

This section describes the performance and comparative analysis of Series, Parallel, Series-Parallel, Total-Cross-Tied, Bridge-Link and Honey-Comb type of topologies for 4x4 size PV arrays under uniform irradiance of 1000W/m^2 and different partial shading cases (II to V). From this analysis, best topology with highest performance under different irradiance levels are selected and recommended for the design of standalone/ grid connected solar PV system. The mismatching power losses and fill-factor (FF) are considered for the performance analysis of different array topologies.

The mismatching power loss and fill-factor of the solar PV system is given by,

Power loss, $\Delta P_L(\%) = \frac{P_{MPU} - P_{MPS}}{P_{MPU}} x100$ ---- (4)

Fill Factor, $FF = \frac{V_{MPP} . I_{MPP}}{V_{OC} . I_{SC}}$ ----(5)

Where P_{MPU} is the maximum generatedpower under uniform irradiance of 1000W/m^2 and P_{MPS} is the maximum generated power under different partial shading cases. The simulation values V_{mps}, I_{mps},V_{oc}, I_{sc}, P_{mps} , P_{mpu} and also calculate the mismatch power loss and fill-factors from the equations 4 and 5 respectively are tabulated in table 2.

From the simulation output results, the comparative analysis of six array topologies under five shading cases are discussed and case results are tabulated in table 2.

Table 2 : Power losses analysis of a 4x4 size solar PV array topologies under different shading cases

Case-I : Uniform irradiance of 1000 W/m^2							
Topology	**P_{MPU} (w)**	**V_{MP} (V)**	**I_{MP} (A)**	**V_{OC} (V)**	**I_{SC} (A)**	**ΔP_L (%)**	**FF**
S	3437	465.5	7.38	574.6	8.0	0	0.747
P	3437	29.09	118.2	35.86	128	0	0.749
SP	3416	115.7	29.52	142.8	32.01	0	0.747
TCT	3416	115.7	29.52	142.8	32.01	0	0.747
BL	3416	115.7	29.52	142.8	32.01	0	0.747
HC	3416	115.7	29.52	143.1	32.01	0	0.745
Different Partial Shading Conditions							
Topology	**P_{MPS} (w)**	**V_{MPS} (V)**	**I_{MPS} (A)**	**V_{OCS} (V)**	**I_{SCS} (A)**	**ΔP_L (%)**	**FF**
Case-I: One module full shading in 1st string condition							
S	3217	435.8	7.38	538.8	8.0	6.40	0.74
P	3221	29.09	110.7	35.75	120.1	6.28	0.75
SP	2762	94.58	29.29	142.7	32.1	19.14	0.60
TCT	**2823**	**122.3**	**23.08**	**142.7**	**31.96**	**17.36**	**0.61**
BL	2667	90.54	29.46	142.8	32.01	21.92	0.58
HC	2693	120.7	22.31	142.8	32.01	21.16	0.59
Case III : 1st string fully shading condition							
S	2557	346.5	7.38	428.3	8.0	25.60	0.74
P	2571	29.02	88.6	35.39	96.31	25.19	0.75
SP	2562	115.7	22.14	143	24.01	25.14	0.74
TCT	**2557**	**115.5**	**22.15**	**141.6**	**24.01**	**25.08**	**0.75**
BL	2559	115.5	22.15	141.8	24.0	25.08	0.75
HC	2557	115.5	22.15	142.2	24.08	25.08	0.74
Case IV : Zig-Zag Type partial shading condition							
S	1889	304.1	6.21	566.3	7.99	45.03	0.41
P	2970	29.16	91.58	35.53	99.29	13.58	0.75
SP	2048	89.75	22.82	141	32.11	40.04	0.45
TCT	**2343**	**121.9**	**19.23**	**142.5**	**29.53**	**31.41**	**0.55**
BL	2064	90.04	22.92	143.3	31.96	39.57	0.45
HC	2180	87.98	24.77	141.6	31.96	36.18	0.48
Case V : Complete PV array partial shading condition							
S	1196	309.4	3.86	557.8	7.22	65.20	0.29
P	2476	27.96	88.53	35.32	106.7	27.96	0.65
SP	1273	92.16	13.81	139.5	27.28	62.73	0.33
TCT	**1274**	**92.2**	**13.81**	**139.2**	**27.28**	**62.70**	**0.33**
BL	1273	92.16	13.82	139.4	27.15	62.73	0.32
HC	1273	92.16	13.82	139.4	27.14	62.73	0.33

From the comparative analysis, it can be concluded that:

- In all cases, the Parallel configuration produces highest maximum power, least mismatching power losses and high value of fill-factor and also high currents and low voltages are generated. Due to this reason, the parallel topology is not suitable for many PV system applications. In this paper for the performance analysis, only S, SP, TCT, BL and HC type of PV array topologies are considered.
- In Case-I: Uniform irradiance of 1000W/m^2, all PV array configurations generates approximately same maximum power, there is no mismatching power losses and the fill-factor approximately 0.75.
- In Case-II: One module in 1st string fully shaded at an irradiance 0 W/m^2: The S, P configurations has produces approximately same maximum power and also same relative power losses. Compare to SP, BL, HC configurations T-C-T topology has less power losses and high fill-factor.
- In Case-III: 1st string fully shaded condition, in this case the TCT configuration produces maximum power and less relative power losses. So in case 3, the TCT has best performance.
- In Case-IV: Under Zig-zag type partial shading condition, compare to S,SP,BL,HC configurations the TCT topology generates maximum power and less mismatching power losses, high fill-factor.
- In Case-V, Under all PV modules are completely partial shading condition, the SP,TCT,BL,HC type of configurations generates same maximum power and less mismatching losses.
- When entire PV array are partially shaded, in all cases the TCT configuration provides the best performance in terms of highest maximum generating power and least relative power losses, it is usually followed by the HC or BL or SP configurations/ topologies.

V. CONCLUSIONS

In this paper, the comparative and performance analysis of available different PV array topologies Series(S), Series-Parallel(SP), Parallel(P), Total-Cross-Tied(TCT), Bridge Linked (BL), Honey-Comb(HC) types are presented. This research article has investigated the performance of available six PV array configurations under uniform and various shading cases such as; one module shading, one string shading, zig-zag partial shading, complete array partial shading cases and the output characteristics of above topologiesare analyzed. The comparative and performance analysis of arrays are determined by considering mismatching power losses and fill factors. From this analysis, it is observed that the parallel array topology generates highest maximum power due to its high currents and low voltage, this parallel type topology is not suitable for many PV applications so that other PV topologies are considered for performance analysis. Under the partial shading cases II to V, compare to S,SP,HC,BL configurations the T-C-T topology has the highest output power and least mismatching power losses as followed by the BL or HC or SP topologies.

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