ISSN: 2278-4632
Vol-10 Issue-5 No. 9 May 2020

Performance of Series-Parallel and Total-Cross-Tied Type of Solar PV Array Configurations under Different Fault Conditions

[1*]V. Bala Raju, [2]Dr. Ch. Chengaiah
[1]Research Scholar,[2]Professor
[1,2] Dept. of EEE, SVU College of Engg., SV University, Tirupati.
[1]*vbrajuu@gmail.com

Abstract- Solar photovoltaic (SPV) cell converts solar energy directly into electrical energy. The output power of single SPV cell is less, to increase the required power by connecting solar cells in series formed as PV module. The SPV array configuration such as series-parallel, total cross tied, bridge linked and honey comb types are made by series and parallel connection of PV modules. The output power of array configuration depends on solar insolation falling on the modules. Electrical fault is the abnormal condition that occurs in any electrical circuits due to open circuit and short circuits. The output Power-Voltage characteristics of SPV array configuration or topology are affected more under faults in the PV system. In this paper, investigate the performance of 6x6 size SP and TCT array topologies under different electrical faults mainly short circuits, LG, LL, LLL, LLG, open circuits, shading faults and simulate the SPV array configurations under different fault conditions in MATLAB/ Simulink software.

Keywords- PV module and array power, configuration, Faults, Mismatch loss, Irradiances, modules in Stings.

I. INTRODUCTION

Now a day's power generation from renewable energy sources are increased due to depletion of fossil fuels, increased cost of oil and environmental conditions mainly global warming effect etc. Renewable energy sources are mainly solar, wind, biomass, geothermal etc., among these solar PV power has more advantages. In India, installation capacity of renewable energy sources has reached 10 GW and installed capacity of solar is increasing to 100 GW by 2022. Due to fast developing technology in solar PV system, increases the PV system installation around the world. To avoid the damage and shutdown of PV system due to faults, it is essential to detect and diagnosis the faults in time and minimize the damage, maintenance cost of the SPV system [1].

Faults in SPV systems leads to energy loss are often it is difficult to avoid. Fault detection in PV system is essential for improving the reliability, continuity, safety and efficiency of the SPV system. The direct current (DC) side faults of a SPV system mainly open-circuit (OC) faults, hotspot faults, short circuits (SC) faults, total and partial shading faults, degradation faults are often it is difficult to avoid it results in energy loss occurs, reduction of lifespan of PV module, fire hazards occurs due to serious fault conditions and finally shutdown occurs in entire SPV system. Generally, fault detection and protection methods mainly over current protection devices (OCPD's) i.e., fuses are used in series with the PV components. Compare to conventional power, the solar power is unique because it may have uncleared and undetectable fault current by OCPD's due to SPV arrays non-linear output characteristics, MPPT of the PV inverters, low irradiance, degradation of solar cells. However, due to the current-limiting nature, these OCPDs are may not be cleared the faults in PV system [2].

Due to uncleared faults in SPV system, causes power losses and it leads to safety issues and fire hazards. This paper investigates the performance of SPV 6x6 Series-Parallel and Total-Cross-Tied (TCT) array topologies under different faults mainly Line to ground (L-G), line to line (LL), line to line- line (LLL), line-line to ground (LL-G) faults, open circuit fault i.e., one sting is open in 6x6 array, Short circuit faults between modules in an array, inter string and intra string faults [3-4].

This research paper starts with the modeling of single diode solar cell, module and PV array are presented in section-2. Different faults in SPV array configuration and modeling, simulation of 6x6 SPV array for SP, TCT topologies are discussed in section-3 and 4 respectively. Performance analysis of SP, TCT and results, conclusions are given in section-5 and 6 respectively.

II. SYSTEM DESIGN

2.1. Modeling of Photovoltaic Array

The modeling of Single diode solar PV cell by defining the mathematical equations shown in fig-1.

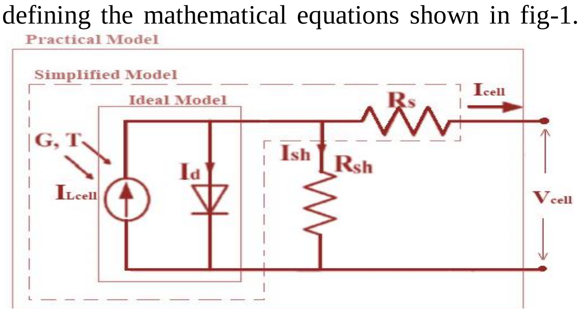

Figure-1: Single diode Solar PV cell

The mathematical representation of single diode solar PV cell is given by in equation-1[5].

$$I_{cell} = I_{Lcell} - I_0 \left[exp\left\{\frac{q(V_{cell} + I_{cell}R_S)}{KaT_c}\right\} - 1\right] - \frac{(V_{cell} + I_{cell}R_S)}{R_{SH}} \quad \dots (1)$$

The PV array consists of number of series (N_S) and parallel connected (N_P) modules shown in fig-2.

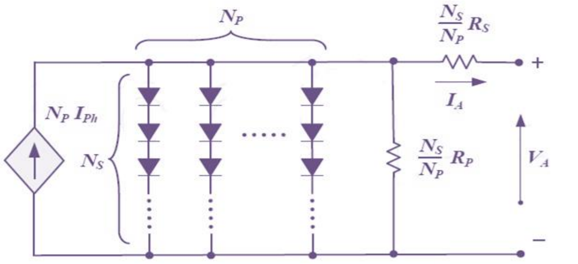

Figure-2 Solar PV Array with N_S x N_P PV modules

The solar PV array represented in mathematically as given in Equation-(2).

$$I_A = N_P.I_{ph} - N_P.I_0\left[exp\left\{\frac{q\left(V_A + \frac{N_S}{N_P}I_AR_S\right)}{N_sKaT_c} - 1\right\}\right] - \frac{\left(V_A + \frac{N_S}{N_P}I_AR_S\right)}{\frac{N_S}{N_P}.R_P} \quad \dots\dots (2)$$

Where N_P and N_S are the total number of parallel and series connected panels in SPV array, R_{SH} and R_S are parallel and series resistances of the module, V_a and I_a are the voltage and current of the SPV array. I_{Lcell} denotes the photo-electric current, I_o: reverse saturation current. V_{Th}: Thermal voltage [V] as V_{Th}= kT_C/q, where T_C: absolute operating temperature [K], q: Electron charge, k: Boltzmann's constant.

Solar PV array formation from SPV cells are shown in fig-3.

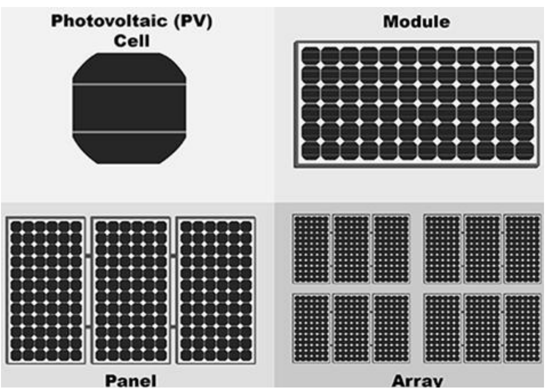

Figure-3. Solar cells to PV array formation

2.2 Simple 6x6 size Series-Parallel photovoltaic system

The PV plant consisting of 6 number of strings connected in parallel and each string has 6 number of series connection of modules. The power output of SPV array is connected to electric grid or load through power electronics devices shown in fig-4.

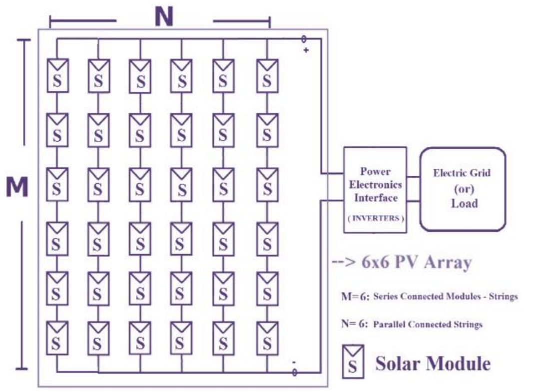

Figure-4. 6x6 Series-Parallel solar PV Plant

2.3 Specifications of PV model:

In this paper, the specifications of Vikram Solar ELDORA 270 PV module are used for designing of SP, TCT topologies are tabulated in Table-1.

Table 1: Solar ELDORA 270 PV module parameters under STC (1000 W/m^2 and 25^{o}C)

Parameters		Values
Maximum Power		270 W
Cells per module	N_{cell}	72
Open circuit voltage	V_{OC}	44 V
Short-circuit current	I_{SC}	8.1A
Voltage at maximum power point	V_{MP}	34.7 V
Current at maximum power point	I_{MP}	7.8A
Temperature coefficient of V_{oc}		-0.3583% / °C
Temperature coefficient of I_{sc}		0.0249% / °C
Light generated current	I_L	8.1924 A
Diode saturation current	I_o	2.4871e-10
Diode ideality factor		0.98223
Shunt resistance	R_{sh}	3126.5623 Ω
Series resistance	R_s	0.52303 Ω

2.4 Solar PV Array Configurations or topologies:

The Solar PV array configurations are formed by series and parallel connections of modules[8]. Based on these connections the solar array configurations are classified into,

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

In series configuration, modules are connected in series and in parallel typo modules are connected in parallel as shown in figure-5(a) and (b). In this paper mainly SP, TCT array configurations or topologies are considered for the study of performance of 6x6 size SPV arrays under different fault conditions.

i. Series(S)–Parallel (P) Configuration

In S-P array connection, first modules are connected in series called strings and then these strings are connected in parallel to form the S-P array topology as displayed in fig-5(c).

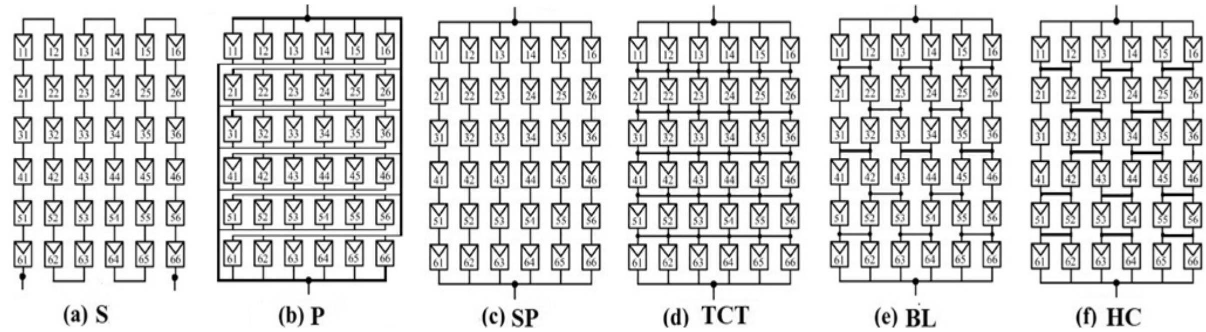

Figure-5: 6x6 Solar PV Array Conventional Configurations

The entire array current I_{PV} in S-P topology is equal to the sum of six string currents.

$$i.e.,\quad I_{PV} = I_1 + I_2 + I_3 + I_4 + I_5 + I_6 \qquad --(3)$$

Where I_1, I_2, I_3, I_4, I_5 *and* I_6 are the 1st, 2nd, 3rd, 4th, 5th and 6th string currents respectively. The six parallel string voltages are equal to the array voltage. Apply KVL at parallel strings, then the equations are given by,

$$\sum_{n=1}^{6} V_n = \sum_{n=7}^{12} V_n = \sum_{n=13}^{18} V_n = \sum_{n=19}^{24} V_n = \sum_{n=25}^{30} V_n = \sum_{n=31}^{36} V_n = V_{PV} \quad --(4)$$

Array power of SP topology is, $P_{PV} = V_{PV}.I_{PV} \quad --(5)$

ii. Total(T)-Cross(C)-Tied (T) Configuration

In TCT type, the modified the S-P topology by connecting ties among the all PV modules in SP array topology as displayed in figure-5(d). The total output voltage of TCT array is equal to sum of the voltages across modules in all six rows and total output current of array is sum of currents in the modules in a row. For the 6x6 size SPV array, total array voltage V_{PV} is equal to the sum of six rows individual module voltages:

$$V_{PV} = \sum_{m=1}^{6} V_m \qquad ----(6)$$

The array current I_{PV} is given by,

$$I_{PV} = \sum_{m=1}^{6} I_m \qquad ----(7)$$

Where V_m, I_m are the maximum voltage and current of each PV module respectively.

Array power of TCT topology is,

$$P_{PV} = V_{PV}.I_{PV} \qquad ----(8)$$

III. FAULTS IN PHOTOVOLTAIC SYSTEM

3.1 Different faults in PV array

Solar PV system can be affected due to various types of faults that can results energy loss occurs in a SPV system [6-7]. Faults in solar PV system decreases the power output, reduces reliability and leads to damage of entire PV system. To maximize the output power, identifying the faults in SPV system is very important. The typical classification of faults occurs in PV system as presented in figure-6. Depending upon the duration of fault, there are temporary faults such as shading (it disappear after a certain period of time or after being manually cleared in cases of dust, bird dropping then the PV system returns to its normal operation) and permanent type of faults mainly short circuits, open circuits and partial shading faults commonly occurred in the DC side of PV systems [9-10].

3.2. Classification of Faults

3.2.1 Short circuit faults:

The short-circuit faults are PV cells/modules cracking, interconnections between the modules in PV array and it affect the solar cells, bypass diodes, modules. Main sources of short circuits are due to the infiltration of water into modules, bad wiring among modules and aging of PV modules. Short circuits occur between modules in 1st string as shown in fig-8(a) and 8(b) for SP and TCT array topologies.

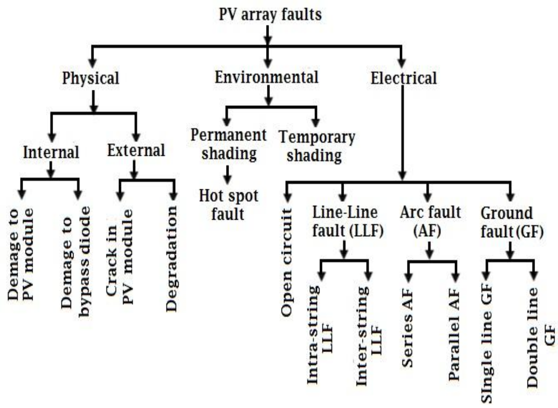

Figure-6 Classification of Faults in Solar PV arrays

3.2.2 Open circuit faults:

The open-circuit faults are due to disconnection inside the PV module conductor, discontinuity between PV modules or solar cells wiring connection. The open circuit fault occurs in 1st string of PV array as shown in fig-7(a) and 7(b) for SP and TCT topologies.

3.2.3 Shading Fault:

Shading fault means solar irradiances received by the PV modules in an array is less than the standard value of 1000 W/m^2. Due to this shading, decreases the output power of array configuration. Shading fault occurs at 6th string of PV array as shown in fig-7(a) and 7(b) for SP and TCT topologies respectively.

3.2.4 Line to Ground Fault:

In this type of fault, fault occurs between any string module and ground connection as shown in figure-7.

ISSN: 2278-4632
Vol-10 Issue-5 No. 9 May 2020

3.2.5 Line to Line Fault between strings 3 and 4:
In this type of fault, fault occurs (i.e., Line to Line fault) in between strings 3 and 4 as shown in figure-7.

3.2.6 Line to Line Fault between strings 3 and 5:
In this type of fault, fault occurs (i.e., Line to Line fault) in between strings 3 and 5 as shown in figure-7.

3.2.7 Line-Line to Ground Fault:
In this type, fault occurs (i.e., Line to Line fault) between strings 1, 2 and ground as shown in figure-7.

3.2.8 Line to Line to Line Fault:
In this type, LL fault occurs in 1st, 2nd and 3rd strings of SPV modules as shown in figure-7.

3.2.9 Short circuit Fault: In this type, faults occurs across modules in any string in an array. Figure-8 (a) and 8 (b) shows the short circuit fault occurs in 1st string of 6x6 array of SP and TCT configurations respectively.

Table-2 represents the fault type and corresponding symbol of fault used in modeling of SP and TCT array topologies represents in figure-7 & 8. Where V_{PV} and I_{PV} are the total array voltage and current respectively.

Table-2: Different Faults occurs in the 6x6 PV arrays

Fault Type	Symbol
Normal operation (No Fault)	F0
One module short circuit in PV array	1M-F
Two modules short circuit in PV array	2M-F
Three modules short circuit in PV array	3M-F
Four modules short circuit in PV array	4M-F
Five modules short circuit in PV array	5M-F
Six modules short circuit in PV array (One String Short circuit)	6M-F
Line to Ground(L-G) Fault	F-1
Line to Line Fault-1 between strings 3&4	F-2
Line to Line Fault-2 between strings 3&5	F-3
Line-Line-Line Fault between strings 1,2&3	F-4
Line-Line to Ground Fault (LL-G)	F-5
Short Circuit of one module	F-6
Open Circuit of one string module	F-7
Shading Fault in 6th Strings	F-8

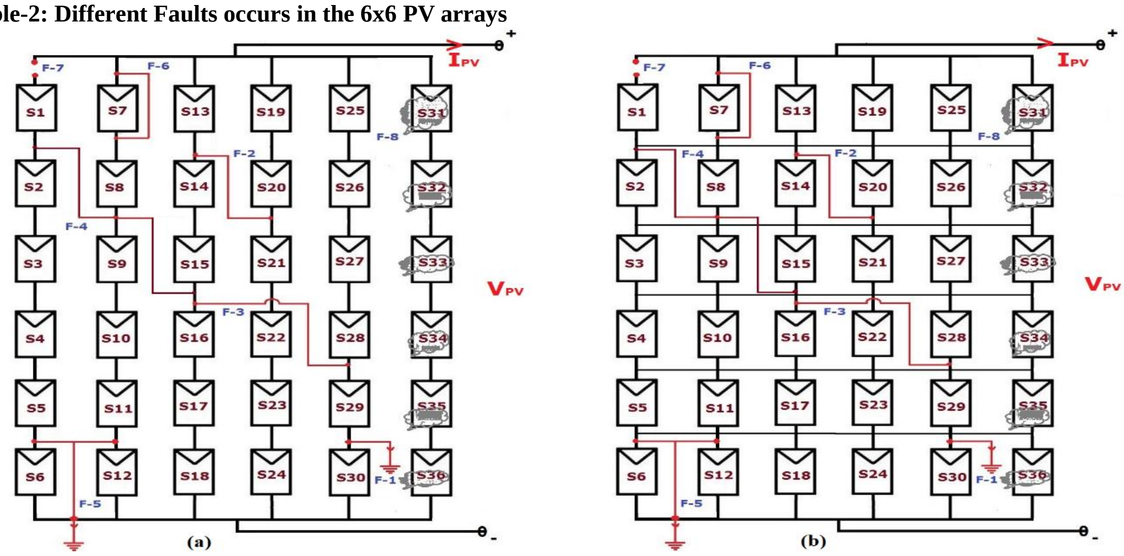

Figure-7: Solar PV array configurations showing possible faults in (a) SP (b) TCT

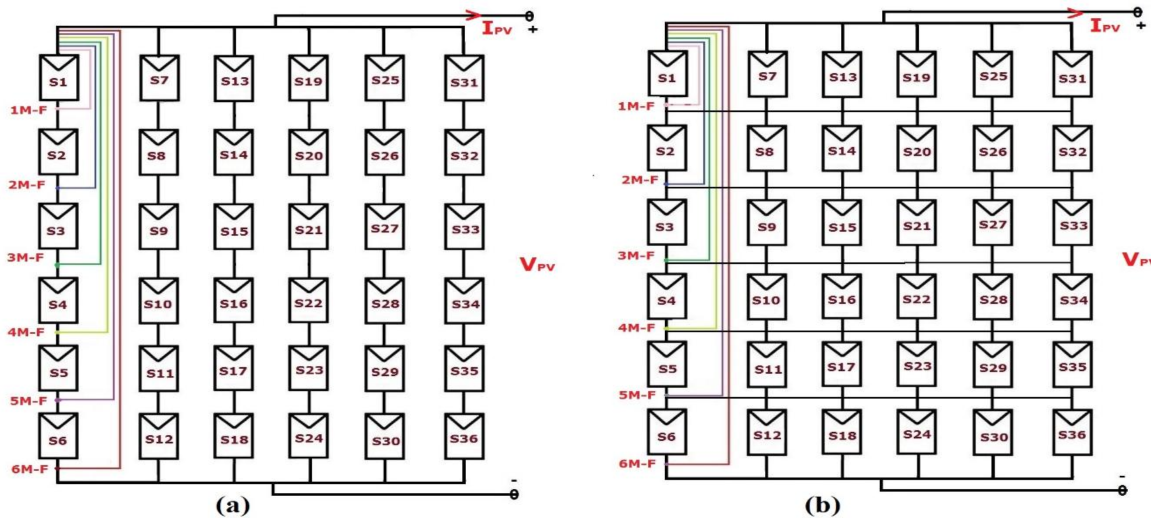

Figure-8: Solar PV array configuration showing possible short circuit faults in 1st string modules (a) SP (b) TCT

IV. Modeling and Simulation of Solar PV array topologies under fault conditions:

The modeling of 6x6 size SP and TCT topologies under proposed different faults occurs in SPV array shown in figure-7 and 8 are presented in this section and their output P-V characteristics are examined in detail to analyze the performance of array under proposed fault cases. The vikram solar eldora 270 PV modules are used for modeling and simulation of 6x6 SPV array with S-P and TCT topologies. Figure-9 represents the simulink model of S-P topology with different fault conditions and figure-10 represents the simulink model of TCT array topology with different faults,

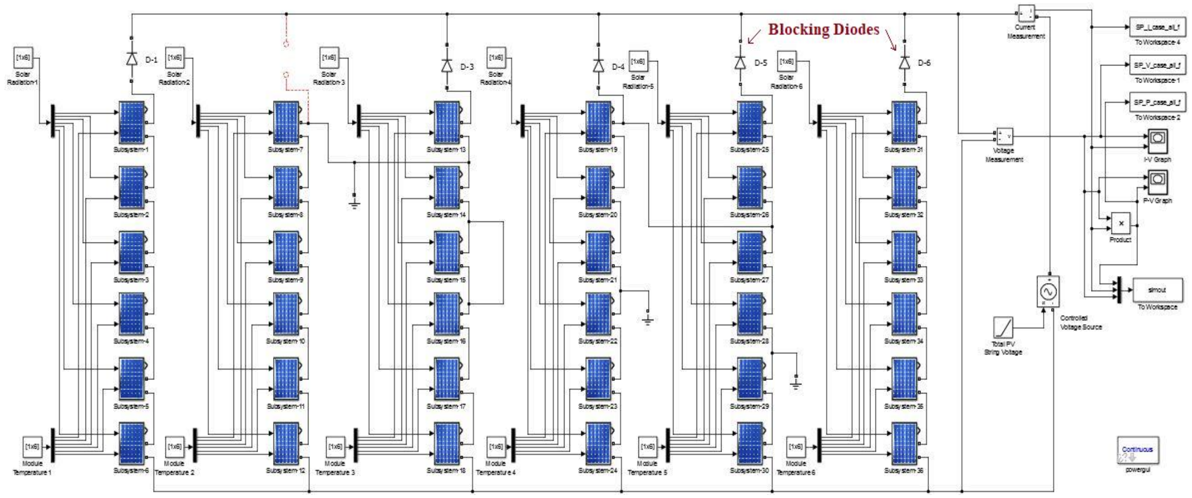

Figure-9. Matlab/Simulink model of 6x6 Series-Parallel topology under different fault conditions

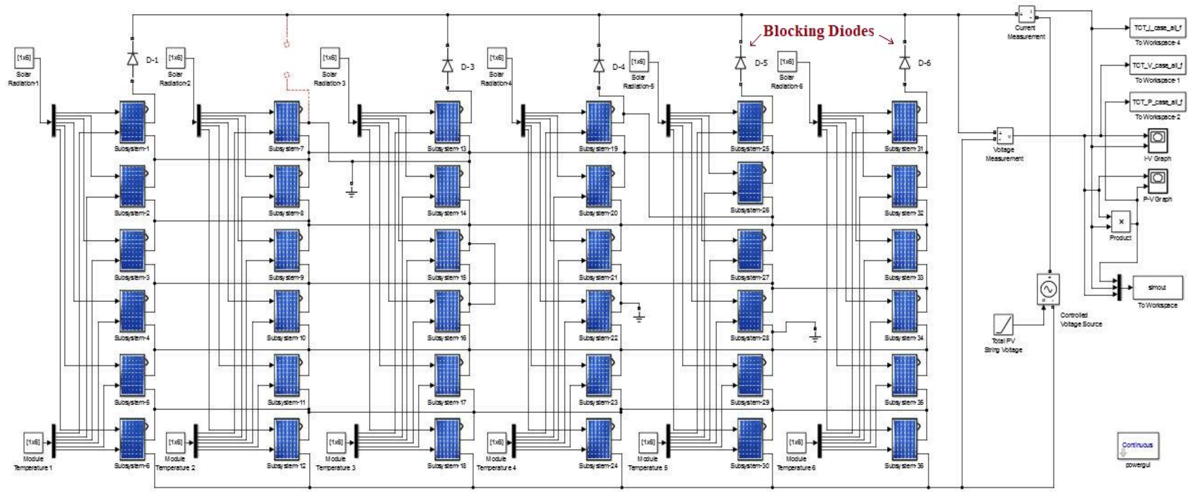

Figure-10. Matlab/Simulink model of 6x6 TCT topology under different fault condition

4.2 Performance analysis of SP and TCT type of solar PV arrays under faults:

In this section, the performance such as output power of array considers global maximum power (GMPP), mismatch power losses under different fault conditions of SP, TCT connection arrays are analyzed by investigation of output P-V characteristics of 6x6 SPV array. The Mismatch array power loss are given by [8],

$$P_{mpl} = P_{mu} - P_{msc} \qquad --(9)$$

Where P_{mu}: global maximum power at uniform solar insolation of 1000 W/m^2 and P_{msc} is the global maximum power at different fault conditions.

V. RESULTS AND DISCUSSION

From the simulation results presented in Table-3, it can be concluded that

* Under No fault condition, the output power of SP, TCT arrays are same i.e., 9620W and no mismatch losses. In this case, no fault occur in array and all modules in the PV array configuration receives solar insolation of 1000 W/m^2.

* Under short circuit faults across PV modules in 1st string, the mismatch loss is 732W in one S1 module is short circuited (means line to line fault across module-1) case and remaining 2,3,4,5,6 modules short circuited case the array output power is 8017W and mismatch power loss is 1603W. Total 6 modules short circuit means complete string-1 is short circuited. In this case performance of SP configuration is better compared to TCT array

ISSN: 2278-4632
Vol-10 Issue-5 No. 9 May 2020

configuration as shown in figure-11 & 12.
* Under line to ground fault (F-1), SP connection has less mismatch loss of 732W.
* Under line to line faults between strings (F-2 and F-3) case, SP connection has least mismatch losses of 713W and 704W respectively.
* Under line-line-line fault (F-4), SP connection has least mismatch loss of 1635W.
* Under line-line to ground fault (F-5), SP has least power loss of 2289 W and TCT has highest loss of 4826W.
* Under short circuit fault across one module (F-6) case, the SP configuration has least power loss of 732W.
* Under open circuit of one string (F-7) case, the TCT connection has least power loss of 1026W.
* Under shading fault in string-6 (F-8) case, The TCT type of array configuration has least mismatch power loss of 616W.

Table-3: PV array configuration GMPP

Type of Faults	Configurations	Array Power P_{PV} (W)	Mismatch Power loss (W)
No Fault	SP	9620	0
	TCT	9620	0
Short circuit Faults across PV Modules in 1st String			
1 M-F	SP	8888	***732***
	TCT	8796	824
2 M-F	SP	8017	***1603***
	TCT	7321	2299
3 M-F	SP	8017	***1603***
	TCT	5816	3804
4 M-F	SP	8017	***1603***
	TCT	4315	5305
5 M-F	SP	8017	***1603***
	TCT	2821	6799
6 M-F (String fault)	SP	8017	***1603***
	TCT	1344	8276
LG, LL, LLL, LL-G, OC and SC Faults			
L-G Fault (F-1)	SP	8888	***732***
	TCT	8011	1609
L-L Fault 1 (F-2)	SP	8907	***713***
	TCT	8011	1609
L-L Fault 2 (F-3)	SP	8916	***704***
	TCT	8011	1609
L-L-L Fault (F-4)	SP	7985	***1635***
	TCT	6402	3218
LL-G Fault (F-5)	SP	7331	***2289***
	TCT	4794	4826
SC Fault (F-6)	SP	8888	***732***
	TCT	8796	824
OC Fault (F-7)	SP	8017	1603
	TCT	8594	***1026***
Shading Fault in 6th String			
Shading Fault (F-8)	SP	8698	922
	TCT	9004	***616***

5.1 Matlab/Simulation Results:

In this section, Matlab/simulink results of 6x6 SP and TCT SPV array topologies under different fault conditions are presented.

a. P-V Characteristics of Series-Parallel(S-P) Configuration under different faults:

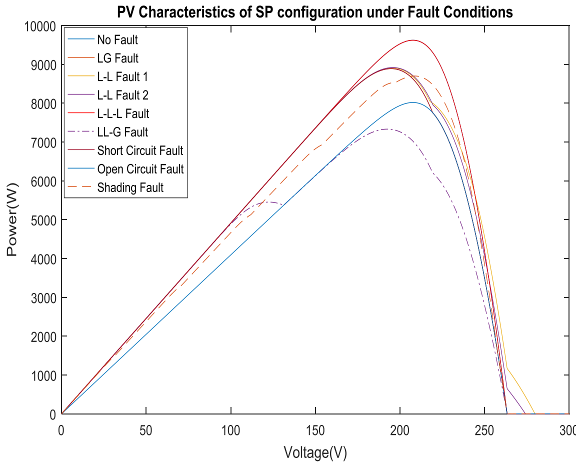

Fig-11: PV curves for SP connection under faults in array strings

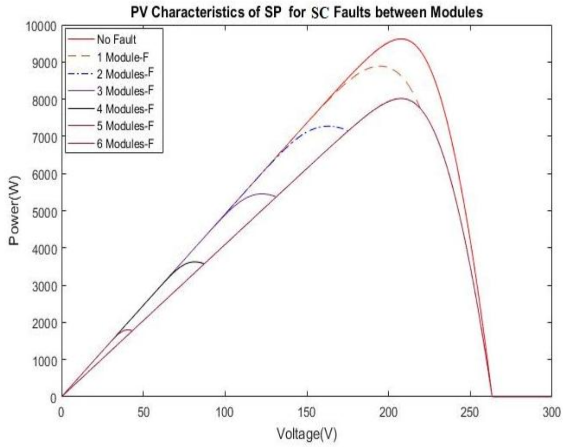

Fig-12: PV curves for SP connection under faults in 1st string

b. PV characteristics of Total(T)-Cross(C)-Tied(T) Configuration under different faults:

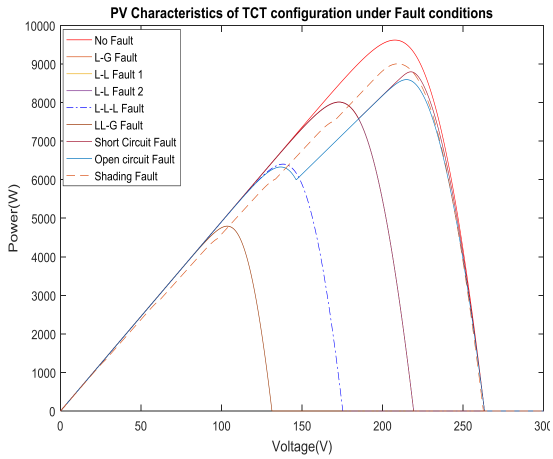

Fig-13: PV curves for TCT connection under faults in array strings

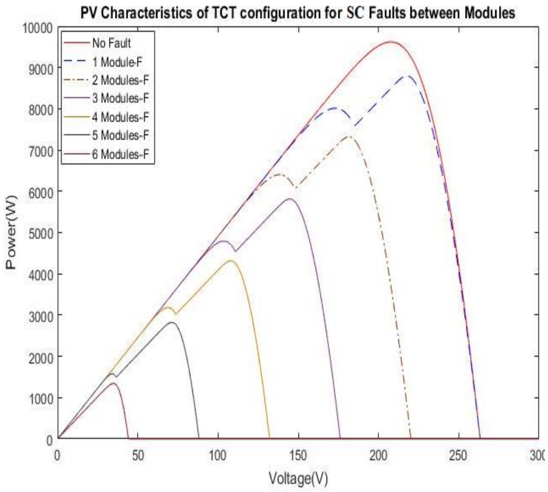

Fig-14: PV curves for TCT connection under faults in 1st string

VI. CONCLUSIONS

The performance of SPV array configuration depends up on the solar insolation falling on the PV modules, temperature, shading patterns due to shadows and fault occurs due to short circuit, open circuits in the array connections. More energy loss due to faults and it may results safety issues leads to fire hazards occurs in SPV system. So, the detection and prevention of faults within less time is important for reliable and continuity of electrical power to the loads. In this paper, the performance of 6x6 SP, TCT solar PV array configurations are analyzed by investigation of output characteristics under different proposed fault conditions with respect to the global maximum power and mismatch power loss. From the simulation results, it can be concluded that the performance of Series-Parallel PV array configuration has least power loss and highest global maximum power under most proposed fault conditions compare to TCT configuration. In partial shading cases the TCT PV connection has better performance but in fault conditions the SP configuration has better performance compared to TCT solar PV array configuration

VII. REFERENCES

[1] Taylor M, Ralon, Ilas A. “The power to change: solar and wind cost reduction potential to 2025”. International Renewable Energy Agency (IRENA) 2016, http://www.irena.org/.

[2] S. K. Firth, K. J. Lomas, and S. J. Rees, “A simple model of PV system performance and its use in fault detection”, *Solar Energy*, vol. 84, no. 4, pp. 624–635, Jan. 2010.

[3]. Ferrara C, Philipp D. Why do PV modules fail? *Energy Procedia*. 2012;15(2011):379-387.

[4] A.T. Lahiania, A. B. Abdelghani, I. S. Belkhodja, “Fault detection and monitoring systems for photovoltaic installations: A review”, Renewable and Sustainable Energy Review, 82, 12 (2018)

[5] Colli A. “Failure mode and effect analysis for photovoltaic systems”. Renew Sustain Energy Rev 2015; 50:804–9.

[6] Y. Zhao, J. F. de Palma, J. Mosesian, R. Lyons, “Line–line fault analysis and protection challenges in solar photovoltaic arrays”, *IEEE Trans. Ind. Electron.*, vol. 60, no. 9, pp. 3784–3795, Sep. 2013.

[7] Y. Zhao, “Fault analysis in solar photovoltaic arrays”, M.S. thesis, ECE Department, Northeastern Univ., Boston, MA, 2011.

[8] V. Balaraju, Dr. Ch.Chengaiah "Performance Analysis of Conventional, Hybrid and Optimal PV Array Configurations of Partially Shaded Modules", International Journal of Engineering and Advanced Technology, 2019.

[9] Patel H, Agarwal V. “Matlab based modeling to study the effects of partial shading on pv array characteristics”. IEEE Trans Energy Convers 2008;23(1):302-310.

[10] P. Xuejun, N. Songsong, C. Yu, and K. Yong, "Open-Circuit Fault Diagnosis and Fault-Tolerant Strategies for Full-Bridge DC-DC Converters," IEEE Trans. Power Electron., vol. 27, pp. 2550-2565,2012.

Authors’ Profiles

Mr. V.Balaraju received B.Tech degree in 2010 from SV University, Tirupati and M.Tech degree in 2013 from JNTU Anantapur. Currently pursuing Ph.D in Department of Electrical and Electronics Engineering, SV University, Tirupati. His research interests include Reconfigurations of Solar PV arrays, Power quality and grid integration of renewable energy systems.

Dr. Ch.Chengaiah is a Professor of the Department of Electrical and Electronics Engineering in SV University college of Engineering, Tirupati. He completed his Ph.D in power system operation and control from SV University, Tirupati in 2013. He obtained his ME in power systems from NIT Trichy in 2000 and B.Tech in Electrical and Electronic Engineering from SV University in 1999. His research interests include Renewable energy systems, power system operation and control.