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Submodule Level Configuration for PV System Performance Improvement under Partial Shading

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***Abstract*— Photovoltaic system performance highly depends on environmental conditions. Partial shading conditions (PSC) can significantly reduce the performance of the system due to the presence of multiple peaks in P-V or I-V characteristics and increase mismatch losses. Mismatch losses depend not only on the irradiance distribution over the modules in the PV array but also on the placement and interconnection used. Various techniques are proposed to reduce the mismatch losses such as full power processing (FPP), differential power processing (DPP), and array reconfiguration mostly employed and analysed. However, the cost and control complexity greatly increase with the system size for the first two techniques hence applied in small systems. For large-size systems, static PV array interconnection is economical and easy to implement. Different PV array interconnections such as series-parallel (SP), total-cross-tied (TCT), bridge linked (BL), and honeycomb (HC) and their combinations at the module level are proposed by various researchers. This paper aimed to propose PV array interconnections at the submodule level to enhance the system performance in a simple way. A novel TCT-TCT PV array interconnection is proposed and its performance under various partial shading conditions (PSC) is analysed and compared with standard SP and TCT Interconnection used at the module level.**

***Index Terms*— Photovoltaic array, partial shading, maximum power point tracking, differential power processing, total cross-tied (TCT), series-parallel (SP), bridge-linked (BL), Honeycomb (HC).**

I. INTRODUCTION

The International Energy Agency (IEA) reports that global electricity demand climbed by 4% in 2018, the fastest since 2010. The IEA also forecasts that electricity demand will expand at a 2.1% annual pace through 2040, owing to the sustained growth of emerging countries and the rising demand for electrical power from clean and sustainable energy systems, the reliance on renewable energy sources, mainly solar and wind, will likely increase [1]–[3]. PV systems, renowned for their eco-friendly energy conversion, and widespread accessibility, will play a crucial role in meeting the future electrical energy demand [4], [5]. The significant drawbacks once linked to PV generation, including initial expenses, generation efficiency, and reliability are now of less concern [6]. PV installations have experienced substantial growth in recent years. The PV array is the main part of the PV system and comprises several PV modules connected in series and or parallel to match the voltage or current requirements. PV modules usually consist of two, three, or four strings of series connected PV cells called submodules. Shadows

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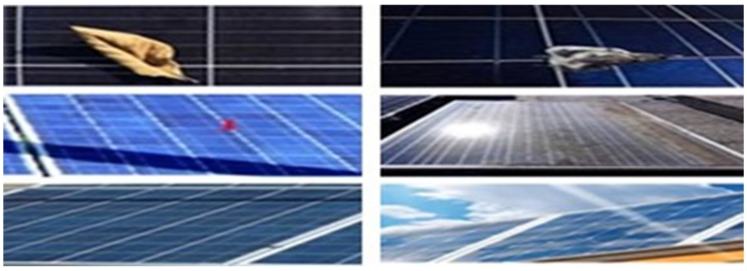
caused by nearby structures, trees, poles, and overhead wires, in addition to those from clouds, intermittently covered PV modules significantly reduce power generation and increase the PV system cost [6], [7]. Also, the hotspot phenomenon occurs in the shaded module which may lead to permanent damage. Generally, an antiparallel bypass diode is connected across each submodule to protect it from hotspots. However, the presence of a bypass diode affects the output characteristic of the PV array and creates one or more MPPs in the P-V curve. This results in misleading conventional MPPT algorithms to track the global MPP (GMPP)and hence advanced MPPT techniques are used [8], [9]. Module-level mitigation methods reduce the effects of mismatching, but may not always prevent the activation of bypass diode at the submodule level, which results in reduced power output from the module. Since, in a partially shaded PV module, the shaded submodule determines the PV module current, drawn from the terminals of the PV module, hence unshaded submodules and the whole PV string will be operating below their optimum power [10], [11].

Submodule-level mismatch mitigation techniques are recently becoming popular due to their high energy yield. Since majority of partial shadings are due to dust accumulation, bird droppings, leaves falling, and damaged cells as in fig1. responsible for nonuniform irradiance between the submodules of PV panel results in mismatch loss within the PV modules. To mitigate the impact of partial shading, different techniques such as bypass diode (BD) [12], maximum power point tracking (MPPT) [13], system reconfiguration [14], Distributed MPPT (DMPPT) [15], and differential power processing (DPP)[16] can be employed. Submodule level DMPPT used to address small scale mismatch issues to enhance the energy yield [17], [18] but increases cost and size when used at cell level or submodule level. TCT-DPP hybrid systems proposed in [19], [20] use interconnection of PV array at the panel level. It is proposed in [17], and [21] that energy yield under the partial shading condition of PV array get increased if submodule mismatch mitigation is used. The choice of mitigation technique depends on shading patterns, system cost, system size, and control complexity. In case of complex shading patterns and large system size optimizing the PV generation effectively and economically cannot be possible with a single technique. Hence a new TCT-TCT interconnection scheme to mitigate the mismatch or partial shading effect at two level is proposed and its performance is analysed for various partial shading conditions.



The paper is organized as follows, section II describes the PV cell model environmental parameter effect on performance characteristics, novel TCT-TCT two-level (TCT-2L) architecture is presented in section III, in section IV simulation results performance comparison with conventional SP and TCT architecture is presented and finally conclusion is presented in section V.

II. PV CELL MODEL AND CHARACTERISTICS

The PV cell model is a mathematical representation of the electrical behaviour of the solar cell. The model predict the performance of PV cell under different conditions such as changes in solar irradiance, temperature, and load. Among the various PV cell models, the single diode model Fig. 2 is a simple and widely used model. This model's current-voltage (I-V) equations are based on diode equation and basic circuit principles represented as in eq. (1-2)

$$I = I_{ph} - I_D - \frac{V}{R_{sh}} + I_D(e^{\frac{V+IR_S}{nkT}} - 1) \quad (1)$$

$$I_{ph} = \left[I_{sc} + K_i\left(T - T_{ref}\right)\right]\frac{G}{G_{ref}} \quad (2)$$

Where I and V are the cell current and voltage respectively, Iph is the photocurrent generated by the cell and is proportional to solar irradiance, ID is the diode current, Rs and Rsh are the series and shunt resistances of the cell, n is the diode ideality factor, k is the Boltzmann's constant, T is the absolute temperature, Isc is short circuit current of cell, Tref and Gref are the reference temperature and solar insolation (W/m2), Ki is the short circuit current temperature constant. Since PV panels generally have two or three submodules with bypass diodes. The effect of uniform and nonuniform irradiance on the performance curve, considering a single module and two submodules is shown in Fig. 3(a, b). Under normal uniform irradiance of 1000W/m2, the module output power is 250W. Under nonuniform irradiance (SM1=1000W/m2 and SM2=400W/m2) a PV module generates 118W with bypass diode and 99W without bypass diode. It is seen that generation under mismatch condition get enhanced if mismatch is mitigated within PV module at the submodule level.

In this paper a novel hybrid PV array interconnection scheme presented. Proposed system utilizes the TCT-TCT interconnection at submodule as well as at panel level. It is simple to implement, cost effective and does not require complex control.

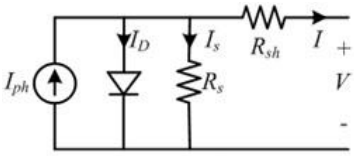
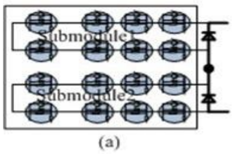


Fig 2 PV cell model



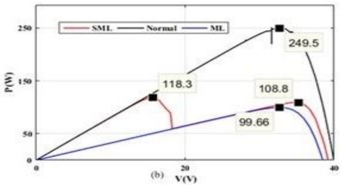


Fig. 3(a) PV panel with two submodules (SM), (b) Performance under uniform irradiance(norml), nonuniform irradiance over submodules (SML), and nonuniform irradiance at module level (ML).

IV. PROPOSED PV SYSTEM ARCHITECTURE

Fig. 4 shows the general block diagram of PV system. The main part that converts solar irradiance in electrical power is a PV array. The extent of power reduction experienced during partial shading is influenced by the specific shading patterns. Various strategies have been introduced in academic literature to mitigate the adverse consequences resulting from irregular shading. Conventionally the PV array consists of number of PV panels connected in SP, BL, HC, TCT, and or combinations of these interconnection.

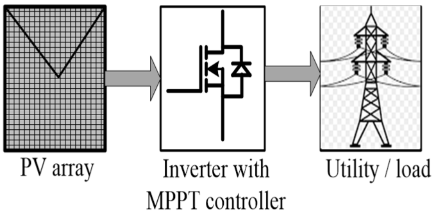


Fig. 4 General block diagram of PV system

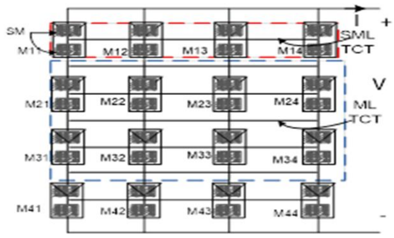


Fig. 5 Proposed PV array interconnection TCT-TCT

In this study a 4 x 4 PV array matrix is considered. It is also assumed that each PV module has two submodules with antiparallel diodes. The PV module generates a maximum power (Pp)of 250W, having maximum voltage (Vp) and current (Ip) values 31V and 8.06A respectively at 1 kW/m2 irradiance and 250C. In this paper proposed PV array interconnection scheme applies two-level mismatch mitigation in an array. Submodule-level interconnection reduce the mismatch within the module and module-level interconnection used for module-level mismatch compensation in PV array under partial shading. The proposed interconnection scheme TCT-TCT (TCT-2L) is shown in Fig. 5. The performance of this interconnection is analysed under different partial shading conditions (PS1-PS15) as in Table I.

In Fig.5 both module level (ML) and submodule level (SML) interconnections used are TCT-TCT. MATLAB simulation model Fig. 6 to test the performance of PV array interconnections under different partial shading patterns is developed. For normal uniform irradiance of 1kW/m^2 at 25^{0}C over the PV array generate 4 kW output power. The simulation results under different shading conditions are shown in Fig.7. From performance P-V curves for SP, TCT-ML, and TCT-2L it is observed that for uniform irradiance over all modules (PS1) the power generated for all three connections is the same. Also, it is noticed that for shading uniform or nonuniform irradiance over one row (PS3, PS11, and PS12) and uniform irradiance over a column and diagonal (PS7, PS8, and PS9) of PV array generates almost equal maximum power output for all three interconnections. In the case of nonuniform irradiance over a column (PS2, PS4, and PS13) and diagonal (PS5 and PS10) and random shadings (PS1 and PS15), the power output of proposed TCT-2L interconnection is more compared with SP and TCT-ML. For most of the partial shading conditions, the power generated with TCT-2L interconnection is more than that of the other interconnections

TABLE I. PARTIAL SHADING PATTERNS

PS1: Uniform irradiance

Row No		Column No (irradiance W/m^2)			
		1	2	3	4
1	1	1000	1000	1000	1000
	2	1000	1000	1000	1000
2	1	1000	1000	1000	1000
	2	1000	1000	1000	1000
3	1	1000	1000	1000	1000
	2	1000	1000	1000	1000
4	1	1000	1000	1000	1000
	2	1000	1000	1000	1000

PS2: One SM partially shaded

Row No		Column No (irradiance W/m^2)			
		1	2	3	4
1	1	500	1000	1000	1000
	2	1000	1000	1000	1000
2	1	1000	1000	1000	1000
	2	1000	1000	1000	1000
3	1	1000	1000	1000	1000
	2	1000	1000	1000	1000
4	1	1000	1000	1000	1000
	2	1000	1000	1000	1000

PS3: Row one SM shading

Row No		Column No (irradiance W/m^2)			
		1	2	3	4
1	1	500	400	300	200
	2	1000	1000	1000	1000
2	1	1000	1000	1000	1000
	2	1000	1000	1000	1000
3	1	1000	1000	1000	1000
	2	1000	1000	1000	1000
4	1	1000	1000	1000	1000
	2	1000	1000	1000	1000

PS4: column SM shading

Row No		Column No (irradiance W/m^2)			
		1	2	3	4
1	1	500	1000	1000	1000
	2	1000	1000	1000	1000
2	1	400	1000	1000	1000
	2	1000	1000	1000	1000
3	1	300	1000	1000	1000
	2	1000	1000	1000	1000
4	1	200	1000	1000	1000
	2	1000	1000	1000	1000

PS5: diagonal shading

Row No		Column No (irradiance W/m^2)			
		1	2	3	4
1	1	500	1000	1000	1000
	2	1000	1000	1000	1000
2	1	1000	400	1000	1000
	2	1000	1000	1000	1000
3	1	1000	1000	300	1000
	2	1000	1000	1000	1000

PS6: Random shading one SM each row

Row No		Column No (irradiance W/m^2)			
		1	2	3	4
1	1	1000	1000	1000	1000
	2	1000	500	1000	1000
2	1	1000	1000	200	1000
	2	1000	1000	1000	1000
3	1	300	1000	1000	1000
	2	1000	1000	1000	1000
4	1	1000	1000	1000	400
	2	1000	1000	1000	1000

PS7: Uniform shading in row

Row No		Column No (irradiance W/m^2)			
		1	2	3	4
1	1	500	500	500	500
	2	500	500	500	500
2	1	1000	1000	1000	1000
	2	1000	1000	1000	1000
3	1	1000	1000	1000	1000
	2	1000	1000	1000	1000
4	1	1000	1000	1000	1000
	2	1000	1000	1000	1000

PS8: Uniform shading over a column

Row No		Column No (irradiance W/m^2)			
		1	2	3	4
1	1	500	1000	1000	1000
	2	500	1000	1000	1000
2	1	500	1000	1000	1000
	2	500	1000	1000	1000
3	1	500	1000	1000	1000
	2	500	1000	1000	1000
4	1	500	1000	1000	1000
	2	500	1000	1000	1000

PS9: diagonal uniform shading

Row No		Column No (irradiance W/m^2)			
		1	2	3	4
1	1	500	1000	1000	1000
	2	500	1000	1000	1000
2	1	1000	500	1000	1000
	2	1000	500	1000	1000
3	1	1000	1000	500	1000
	2	1000	1000	500	1000
4	1	1000	1000	1000	500
	2	1000	1000	1000	500

PS10: Non uniform random shading

Row No		Column No (irradiance W/m^2)			
		1	2	3	4
1	1	200	1000	1000	1000
	2	500	1000	1000	1000
2	1	1000	300	1000	1000
	2	1000	100	1000	1000
3	1	1000	1000	400	1000
	2	1000	1000	800	1000
4	1	1000	1000	1000	200
	2	1000	1000	1000	500

PS11: nonuniform row shading bottom

Row No		Column No (irradiance W/m^2)			
		1	2	3	4
1	1	1000	1000	1000	1000
	2	1000	1000	1000	1000
2	1	1000	1000	1000	1000
	2	1000	1000	1000	1000
3	1	1000	1000	1000	1000
	2	1000	1000	1000	1000
4	1	300	500	200	200
	2	100	300	100	400

PS12: Nonuniform row shading

Row No		Column No (irradiance W/m^2)			
		1	2	3	4
1	1	300	500	200	200
	2	100	300	100	400
2	1	1000	1000	1000	1000
	2	1000	1000	1000	1000
3	1	1000	1000	1000	1000
	2	1000	1000	1000	1000
4	1	1000	1000	1000	1000
	2	1000	1000	1000	1000

PS13: nonuniform column shading

Row No		Column No (irradiance W/m^2)			
		1	2	3	4
1	1	100	1000	1000	1000
	2	200	1000	1000	1000
2	1	300	1000	1000	1000
	2	400	1000	1000	1000
3	1	500	1000	1000	1000
	2	600	1000	1000	1000
4	1	700	1000	1000	1000
	2	800	1000	1000	1000

PS14: nonuniform diagonal shading

Row No		Column No (irradiance W/m^2)			
		1	2	3	4
1	1	300	800	400	1000
	2	700	200	100	500
2	1	200	100	100	300
	2	400	200	700	900
3	1	200	800	200	1000
	2	800	600	300	200
4	1	500	900	300	600
	2	100	700	1000	1000

PS15:Non uniform random shading

Row No		Column No (irradiance W/m^2)			
		1	2	3	4
1	1	1000	1000	1000	1000
	2	1000	1000	1000	1000
2	1	100	400	300	500
	2	900	800	300	200
3	1	1000	500	100	600
	2	300	400	500	1000
4	1	1000	1000	1000	1000
	2	1000	1000	1000	1000

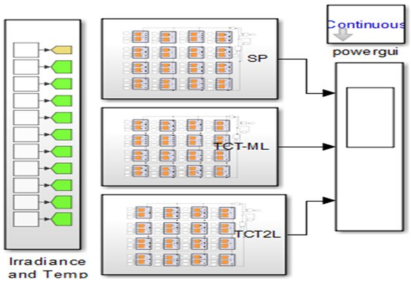


Fig.6 Simulink model of proposed PV array Interconnection

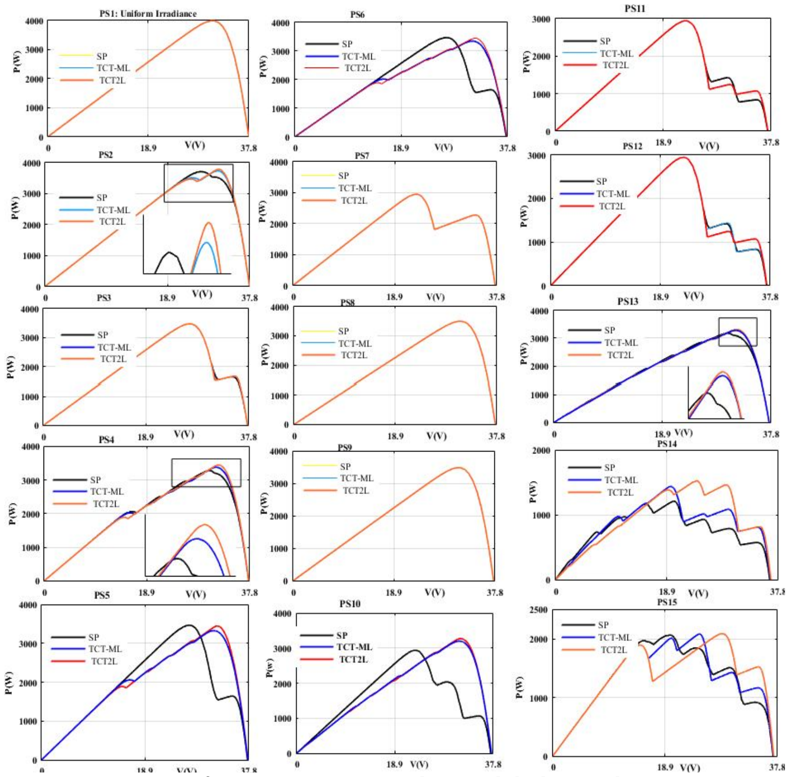


Fig. 7 Performance comparison under partial shading conditions

TABLE II. PERFORMANCE PARAMETERS

PSC	$P_{GMPP(PSC)}$			%Fill Factor (FF)			Mismatch power loss (MPL)		
	SP	TCT-ML	TCT-2L	SP	TCT-ML	TCT-2L	SP	TCT-ML	TCT-2L
PS1	4000	4000	**4000**	72	72	**72**	0	0	**0**
PS2	3705	3730	**3781**	71	72	**73**	295	280	**219**
PS3	3463	3463	**3463**	66	66	**66**	537	537	**537**
PS4	3285	3381	**3449**	63	65	**67**	715	619	**551**
PS5	3468	3341	**3448**	67	64	**66**	532	659	**552**
PS6	3468	3341	**3449**	67	64	**66**	532	659	**551**
PS7	2943	2943	**2943**	57	57	**57**	1057	1057	**1057**
PS8	3492	3492	**3492**	67	67	**67**	508	508	**508**
PS9	3492	3492	**3492**	67	67	**67**	508	508	**508**
PS10	2937	3201	**3275**	57	61	**63**	1063	799	**725**
PS11	2943	2943	**2943**	57	57	**57**	1057	1057	**1057**

PS12	2943	2943	**2943**	57	57	**57**	1057	1057	**1057**
PS13	3173	3287	**3313**	61	63	**64**	827	713	**667**
PS14	1205	1439	**1530**	23	28	**30**	2795	2561	**2470**
PS15	2063	2082	**2086**	40	40	**40**	1937	1918	**1914**

V.CONCLUSIONS

The proposed PV array interconnection is cost effective simple solution to reduce the mismatch power loss. Performance indicator Fill Factor (FF) with TCT-2L interconnection under different shading conditions get improved compared with SP and TCT-ML interconnections. Also, the MPL for TCT-2L under partial shading conditions observed minimum compared with other interconnections for same operating conditions. The only drawback of proposed interconnection is the number of wire connections required are more. This study is useful for researchers to select the proper interconnection for the PV system.

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