SuDoKu and Optimal SuDoKu Reconfiguration for TCT PV array Under Non-Uniform Irradiance Condition

Sai Krishna G.* and Tukaram Moger
Department of Electrical & Electronics Engineering
National Institute of Technology Karnataka, Surathkal, INDIA.
*Email: saikrishna240@gmail.com

***Abstract*—Power delivered by a Photovoltaic (PV) array reduces significantly due to non-uniform irradiance condition. The reduction of output power is not directly proportional to the shading area but depends on the shading pattern, array configuration and the physical location of modules in PV array. Many techniques have been reported in the literature to reduce partial shading effects. One of the effective technique is reconfiguration strategies. This paper presents the comparative study on SuDoKu and optimal SuDoKu reconfiguration techniques for 9×9 Total-Cross-Tied (TCT) PV array under partial shading condition (PSC). In this approach, the physical location of modules in TCT PV array are changing based on SuDoKu and optimal SuDoKu patterns without altering any electrical connections. In addition to this, the performance analysis is carried out by comparing the global maximum power point (GMPP) and voltage at the global maximum power (V_{GMPP}) under different shading conditions by using MATLAB-SIMULINK.**

***Key words* : PV Modelling, Partial Shading Condition, Reconfiguration strategies.**

NOMENCLATURE

$V_{cell/m/a}$	: PV cell/ module/ array voltage (V)
$I_{cell/m/a}$	: PV cell/ module/ array current (A)
T_c	: PV module operating temperature
T_{STC}	: Standard operating temperature at $298.15K$
I_{do}	: Reverse saturation current in STC
a	: Ideality factor
k	: Boltzmann's constant 1.3805×10^{-23}J/K
q	: Electron charge 1.6×10^{-19}C
R_s, R_{sh}	: Parasitic resistance of a PV cell
n_s	: No.of solar cells connected in series
G_o	: Standard PV irradiance at 1000 W/m^2

I. INTRODUCTION

The utilization of electrical energy is increasing day by day worldwide. Basically, energy is in the form of conventional and renewable energy resources (RES). Conventional sources such as coal, oil and fossil fuels. The use of conventional source causes environmental degradation due to effect of pollution and organic chemical reactions, thus increasing the need for use of renewable energies, which are solar, wind, biogas and geothermal, etc. Among all, the solar energy is the most essential and prerequisite sustainable resource because of its ubiquity and abundance in nature [1]-[2]. In short time, the PV energy is gaining more attention from the consumers due to its following advantages; fuel free, less maintenance and pollution free. The PV output power is mainly depends on the solar irradiance (G) and ambient temperature (T). These two parameters decide the maximum power point (MPP) of a PV module. Partial shading is one of the main reason to reduce efficiency of the modules. Partial shading condition (PSC), generally occurs when PV modules gets shaded by tree, passing clouds, near buildings, etc,. Under this condition, the shaded module receiving less solar irradinace as compared to unshaded modules, thus creates hot-spot problems in PV array. Further, it may lead to damage of cell or module. To overcome this, a bypass diode is connected across the PV modules in order to protect from the damage [3]. Many solutions have been reported in the literature to reduce partial shading effects [4]. One of the effective solutions is reconfiguration strategies, namely reconfigure the PV modules within the PV array in order to increase maximum power under partial shading condition(PSC). Based on the literature, these strategies can be broadly classified into 1) dynamic PV Array reconfiguration (DPVAR) techniques and 2) static PV Array reconfiguration (SPVAR) techniques. However, the dynamic technique is too expensive and it requires very complicated algorithm to achieve operation at optimum point. Whereas, in static technique, it require one time arrangement to achieve effective shading dispersion within the PV array.

In the literature, many reconfiguration approaches have been developed to reduce partial shading conditions (PSC). In [4], the authors have developed optimum TCT configuration based on mathematical formulation. This problem can be solved by using branch and bound (BB) algorithm in order reduce mismatch losses. Later, in [5], the authors have proposed optimal reconfiguration approach for shifting the shaded module locations, thereby minimizing the mismatch index (MI). In [6], they have proposed SuDoKu based puzzle pattern arrangement for TCT array to enhance maximum power. However, this arrangement have some few drawbacks; (i) requirement of additional wiring and, (b) the shading distribution is not effective under the sub-array matrix. To overcome those drawbacks the optimal SuDoKu pattern is developed in [7]. This paper presents the comparative study on SuDoKu [6] and Optimal SuDoKu [7] reconfiguration techniques for TCT PV array to enhance maximum power output under partial shading conditions. Further, the performance analysis is also carried out by comparing the GMMP and voltage at the GMPP on 9×9 PV array.

This paper is organized as follows: In Section II, presents the mathematical modelling of 9×9 TCT PV array. In Section III, SuDoKu and optimal SuDoKu pattern arrangement for TCT are outlined. In section IV, result and discussions for TCT, SuDoKu and optimal SuDoKu arrangements under different shading conditions are presented and followed by conclusion is conferred in Section V.

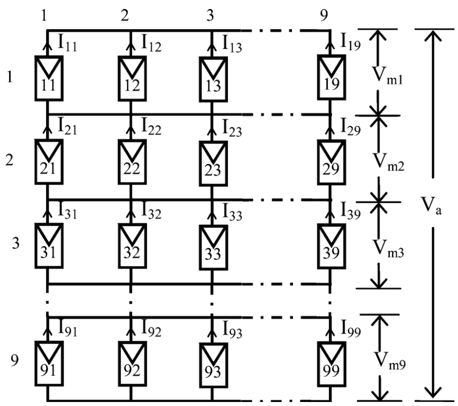

Fig. 1: 9×9 TCT PV array

II. MODELLING OF 9×9 TCT PV ARRAY

Total-Cross-Tied (TCT) is a new interconnection scheme to reduce patial shadings in PV array. In TCT, first connect the PV modules in parallel to make tiers, then all tiers are connected into series to form a string. The general layout of TCT PV array topology is shown in Fig 1. Modelling is the first step for analysing behaviour of the PV system. In fact, good and accurate mathematical models are necessary to achieve operation at optimum point under partial shadings. The modelling of PV array starts with mathematical model of a single PV cell. Several models for solar cell have been reported in the literature. Two of them are one diode PV cell and two diode PV cell models [8]. However, many researchers are widely using one diode solar cell model because it is very easy to model as compared to other models. So that, this paper is also consider single diode PV cell model for modelling. The practical one diode PV cell model is shown in Fig.2. The modelling equations are as follows:

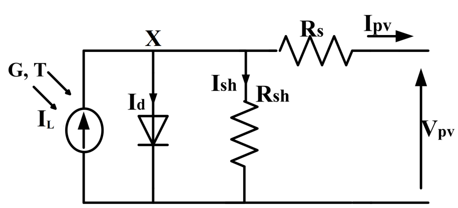

Fig. 2: Practical one diode PV cell model

By applying KCL to node 'X' in Fig.2, I_{cell} can be written as,

$$I_{cell} = I_{Lcell} - I_d - I_{sh} \tag{1}$$

where I_{Lcell} is the light generated current of the PV cell. The mathematical expression of I-V characteristics of the single PV cell can be written as,

$$I_{cell} = I_{Lcell} - I_o[exp\{\frac{q(V_{cell} + I_{cell}R_s)}{kaT} - 1\}] - (V_{cell} + I_{cell}Rs)/R_{sh} \tag{2}$$

The formation of PV module is by connecting the number of solar cells in series and then enclosed. The I-V relation for the PV module is given by,

$$I_m = I_L - I_o[exp\{\frac{q(V_m + I_mR_S)}{n_skaT} - 1\}] - (V_m + I_mR_S)/R_{SH} \tag{3}$$

where I_L is the light generated current of the PV module. It is worth to noticed that Eq.(4) is a transcendental equation and by using this, one can find the output current of the PV module. However, Eq.(4) is not restrict with one module. It can also be increased to number of modules connected in series to form string, then all strings are connected to parallel to compose PV array. Therefore, the I-V relation for the array is expressed as follows,

$$I_a = N_P.I_L - N_P.I_oexp\{\frac{q(V_a + \frac{N_S}{N_P}I_aR_S)}{N_SknT} - 1\} - (V_a + \frac{N_S}{N_P}I_aR_S)/\frac{N_S}{N_P}R_{SH} \tag{4}$$

where N_S and N_P are the modules connected in series and parallel of the array. The above set of equations are used to model the PV array with the help of data sheet parameters is presented in [9].

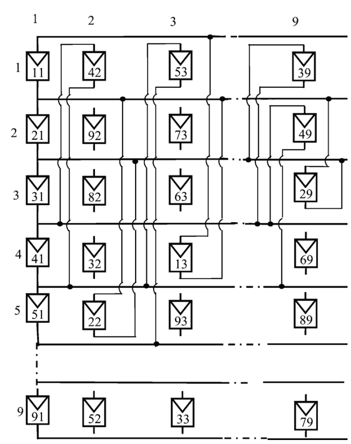

Fig. 3: SuDoKu pattern connection for TCT

III. SUDOKU PUZZLE PATTERN FOR TCT PV ARRAY

SuDoKu is a logic based puzzle pattern arrangement. In this pattern, all modules are arranged in such way that to distribute shading effects over the PV array. The advantage of this pattern is to place the digits 1 to 9 in the first column without repeating. The SuDoKu arrangement in TCT PV array is done by changing the physical location of modules without altering any electrical connections [6]. The SuDoKu pattern connection and pattern arrangement is applied to 9×9 TCT PV array are shown in Figs.3-4 respectively.

11	42	53	94	25	76	87	68	39
21	92	73	84	35	66	57	18	49
31	82	63	44	55	16	97	78	29
41	32	13	54	85	96	77	28	69
51	22	93	64	75	46	17	38	89
61	72	83	24	15	36	47	98	59
71	12	23	34	45	56	67	88	99
81	62	43	74	95	26	37	58	19
91	52	33	14	65	86	27	48	79

Fig. 4: SuDoKu pattern arrangement for TCT

11	72	43	94	65	36	87	58	29
21	82	53	14	75	46	97	68	39
31	92	63	24	85	56	17	78	49
41	12	73	34	95	66	27	88	59
51	22	83	44	15	76	37	98	69
61	32	93	54	25	86	47	18	79
71	42	13	64	35	96	57	28	89
81	52	23	74	45	16	67	38	99
91	62	33	84	55	26	77	48	19

Fig. 5: Optimal SuDoKu pattern arrangement for TCT

A. *Optimal SuDoKu Puzzle Pattern for TCT PV array*

The optimal SuDoKu is a unique number based puzzle pattern. The advantage of this pattern is it reduces the additional wiring requirement for the modules and effectively distribute the shading effects under sub array matrix in PV array. The formation of optimal SuDoKu pattern arrangement in TCT PV array is illustrated in [7] and shown in Fig.5.

IV. Results and Discussions

In this paper, SuDoKu and optimal SuDoKu pattern arrangement are compared with TCT arrangement on 9×9 PV array under different shading condition. The following shading conditions are considered in this paper; Short-Wide(SW), Long-Wide (LW), Short-Narrow (SN) and Long-Narrow (LN). In each shading case, the location of GMPP is calculated by theoretically and validated using MATLAB-SIMULINK results.

A. *Short-Wide (SW)*

In short-wide, all modules in last four rows of the TCT PV array are partially shaded with different irradiance levels is shown in Fig.6(a). In figure, it is shown that TCT, SuDoKu and optimal SuDoKu PV array shading dispersion arrangements. Under this shading, to calculate the location of GMPP, it is required to know that the output voltage and current of a PV array. However, the V_a and I_a are obtained by using kirchhoff's law.

B. *Location of GMPP for TCT*

By applying KCL to Fig.6(a). The generated output current of the $row1$ can be written as,

$$I_{row1} = B_{11}I_{11} + B_{12}I_{12} + B_{13}I_{13} + B_{14}I_{14} + -- \; +B_{19}I_{19} \tag{5}$$

where $B_{11} = \frac{G_{11}}{G_o}$, G_{11} is the solar irradiance falls on the 11^{th} PV module of the array. Then the first row current becomes,

$$I_{row1} = 9 \times 0.9 I_m \tag{6}$$

where I_m is the module current. The $row2$ to $row5$ are having same irradiance levels so that the output current is same for these rows,

$$I_{row2} = I_{row3} = I_{row4} = I_{row5} = 9 \times 0.9 I_m \tag{7}$$

In $row6$, first five modules are receiving the 900 W/m^2 and rest of all shading partially. The generated current is;

$$I_6 = 5 \times 0.6 I_m + 4 \times 0.9 I_m \tag{8}$$

In $row7$ to $row9$ are having same irradiance levels so that the output current is same for these rows,

$$I_{row7} = I_{row8} = I_{row9} = 3 \times 0.6 I_m + 3 \times 0.4 I_m + 3 \times 0.2 I_m \tag{9}$$

To calculate output voltage of a PV array, KVL is applied to Fig.6(a),

$$V_a = 9 \times V_m \tag{10}$$

Finally, the GMPP for TCT can be written as,

$$P_{GMPP} = V_a . I_a \tag{11}$$

Similarly, the same procedure is applied to SuDoKu and optimal SuDoKu arrangements under all shading conditions to find the location of GMPP. In Table I, shown the obtained GMPP for all arrangements under short-wide shading condition. From the table, it is observed that the global peak occurs at $row1$ with 8.1I_m current and 5V_m voltage, the corresponding power is 40.5 $V_m.I_m$ for TCT. Similarly, the SuDoKu and optimal SuDoKu GMPP are 56.7$V_m.I_m$ and 57.6$V_m.I_m$ respectively. To validate theoretical GMPP by simulating P-V characteristics which is shown in Fig.10. From the figure, the simulated GMPP for TCT, SuDoKu and optimal SuDoKu PV array arrangements is given in Table V.

C. *Long-Wide (LW)*

In long-wide, all modules in last three rows and three columns of the TCT PV array are partially shaded with different irradiance levels is shown in Fig.7(a). In Fig.7(a), shows TCT, SuDoKu and optimal SuDoKu PV array shading dispersion arrangements. The location of GMPP for all PV array arrangements is given in Table II. From the table, it is observed that the global peak occurs at $row9$ with 6.6I_m current and 6V_m voltage, the corresponding power is 39.6 $V_m.I_m$ for TCT. Similarly, the SuDoKu and optimal SuDoKu GMPP are 48.6$V_m.I_m$ and 48.6$V_m.I_m$ respectively. To validate theoretical GMPP by simulating P-V characteristics which is shown in Fig.11. From the figure, the simulated GMPP for TCT, SuDoKu and optimal SuDoKu PV array arrangements is given in Table V.

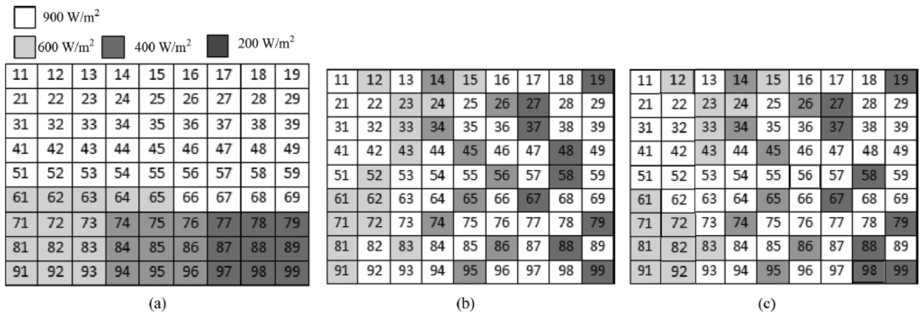

Fig. 6: Short-Wide shading dispersion arrangement for;(a) TCT, (b) SuDoKu, (c) Optimal SuDoKu

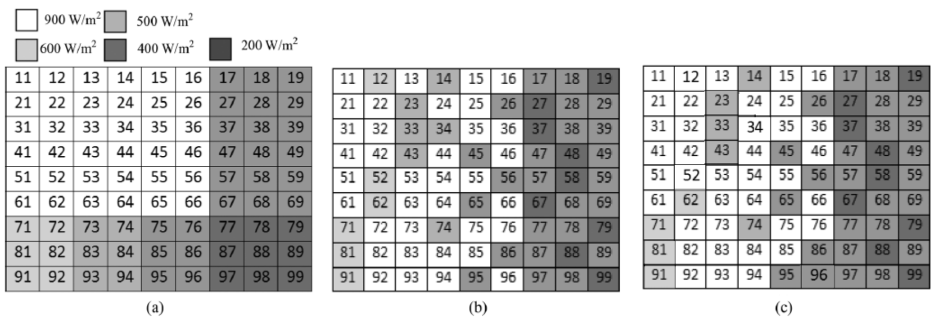

Fig. 7: Long-Wide shading dispersion arrangement for;(a) TCT,(b) SuDoKu,(c) Optimal SuDoKu

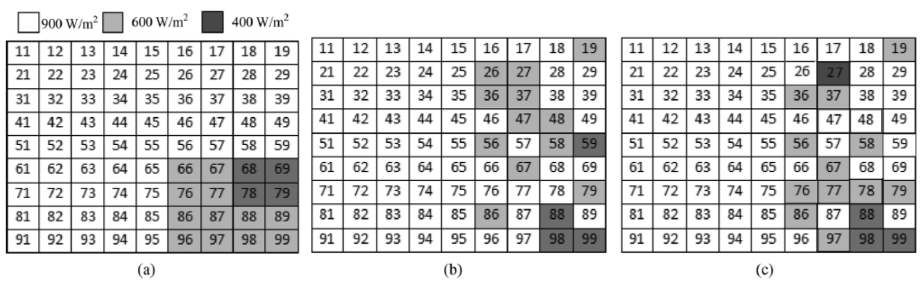

Fig. 8: Short-Narrow shading dispersion arrangement for;(a) TCT, (b) SuDoKu, (c) optimal SuDoKu

TABLE I: Location of GMPP for TCT, SuDoKu and optimal SuDoKu arrangements under SW

TCT				SuDoKu				Optimal SuDoKu			
Row bypassed	currents (A)	voltages (V)	power(P_{GMPP})	Row bypassed	currents(A)	voltages (V)	power(P_{GMPP})	Row bypassed	currents(A)	voltages (V)	power(P_{GMPP})
$Irow_9$	3.6 I_m	-	-	$Irow_9$	6.6I_m	-	-	$Irow_9$	6.4I_m	9V_m	57.6$V_m.I_m$
$Irow_8$	3.6I_m	-	-	$Irow_8$	6.3I_m	9V_m	56.7$V_m.I_m$	$Irow_8$	6.4I_m	-	-
$Irow_7$	3.6I_m	-	-	$Irow_7$	6.3I_m	-	-	$Irow_7$	6.7I_m	-	-
$Irow_6$	3.6I_m	-	-	$Irow_6$	6.3I_m	-	-	$Irow_6$	6.6I_m	-	-
$Irow_5$	8.1I_m	-	-	$Irow_5$	6.6I_m	-	-	$Irow_5$	6.6I_m	-	-
$Irow_4$	8.1I_m	-	-	$Irow_4$	6.6I_m	-	-	$Irow_4$	6.6I_m	-	-
$Irow_3$	8.1I_m	-	-	$Irow_3$	6.6I_m	-	-	$Irow_3$	6.6I_m	-	-
$Irow_2$	8.1I_m	-	-	$Irow_2$	6.3I_m	-	-	$Irow_2$	6.7I_m	-	-
$Irow_1$	8.1I_m	5V_m	40.5$V_m.I_m$	$Irow_1$	6.1I_m	-	-	$Irow_1$	6.7I_m	-	-

TABLE II: Location of GMPP for TCT, SuDoKu and optimal SuDoKu arrangements under LW

TCT				SuDoKu				Optimal SuDoKu			
Row bypassed	currents (A)	voltages (V)	power(P_{GMPP})	Row bypassed	currents(A)	voltages (V)	power(P_{GMPP})	Row bypassed	currents(A)	voltages (V)	power(P_{GMPP})
$Irow_9$	3.6I_m	-	-	$Irow_9$	5.6I_m	-	-	$Irow_9$	5.4I_m	9V_m	48.6$V_m.I_m$
$Irow_8$	3.6I_m	-	-	$Irow_8$	5.6I_m	-	-	$Irow_8$	5.4I_m	-	-
$Irow_7$	3.6I_m	-	-	$Irow_7$	5.7I_m	-	-	$Irow_7$	5.5I_m	-	-
$Irow_6$	6.6I_m	6V_m	39.6$V_m.I_m$	$Irow_6$	5.4I_m	9V_m	48.6$V_m.I_m$	$Irow_6$	5.8I_m	-	-
$Irow_5$	6.6I_m	-	-	$Irow_5$	5.6I_m	-	-	$Irow_5$	5.8I_m	-	-
$Irow_4$	6.6I_m	-	-	$Irow_4$	5.5I_m	-	-	$Irow_4$	5.7I_m	-	-
$Irow_3$	6.6I_m	-	-	$Irow_3$	5.6I_m	-	-	$Irow_3$	5.7I_m	-	-
$Irow_2$	6.6I_m	-	-	$Irow_2$	5.5I_m	-	-	$Irow_2$	5.7I_m	-	-
$Irow_1$	6.6I_m	-	-	$Irow_1$	5.7I_m	-	-	$Irow_1$	5.5I_m	-	-

D. Short-Narrow (SN)

In short-narrow, all modules in last four rows of the TCT PV array are partially shaded with different irradiance levels is shown in Fig.8(a). In Fig.8(a), shows that TCT, SuDoKu and

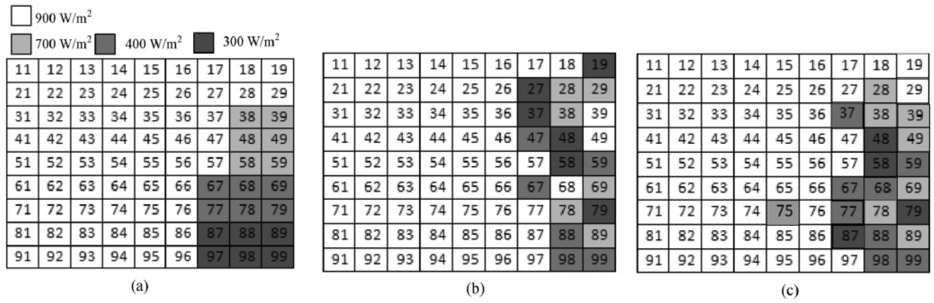

Fig. 9: Long-Narrow shading dispersion arrangement for;(a) TCT,(b) SuDoKu,(c) optimal SuDoKu

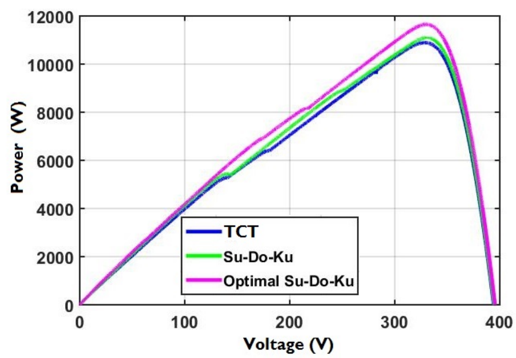

Fig. 10: P-V curve for Short-Wide

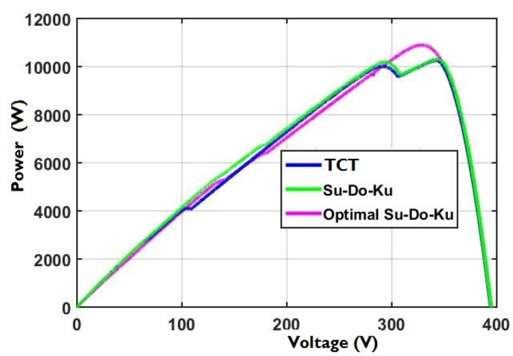

Fig. 11: P-V curve for Long-Wide

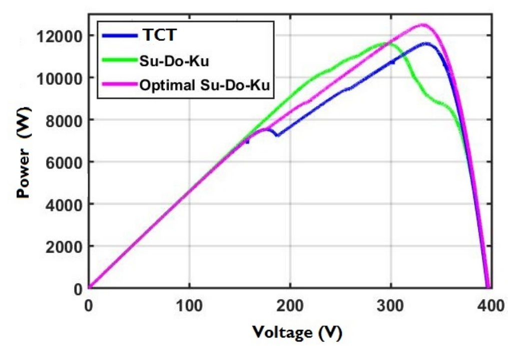

Fig. 12: P-V curve for Short-Narrow

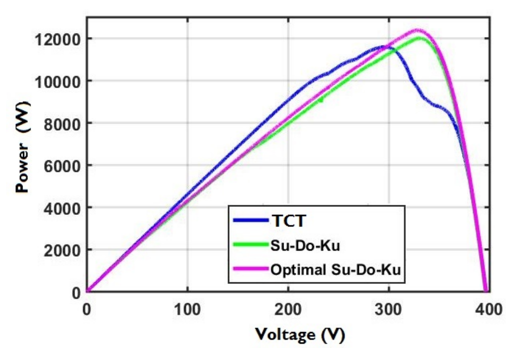

Fig. 13: P-V curve for Long-Narrow

optimal SuDoKu PV array shading dispersion arrangements. The location of GMPP for all PV array arrangements is given in Table III. From the table, it is observed that the global peak occurs at $row9$ with $6.1I_m$ current and $9V_m$ voltage, the corresponding power is 54.9 $V_m.I_m$ for TCT. Similarly, the SuDoKu and optimal SuDoKu GMPP are $61.2V_m.I_m$ and $62.1V_m.I_m$ respectively. To validate theoretical GMPP by simulating P-V characteristics which is shown in Fig.12. From the figure, the simulated GMPP for TCT, SuDoKu and optimal SuDoKu PV array arrangements is given in Table V.

E. Long-Narrow

In long-narrow, all modules in last three columns of the TCT PV array are partially shaded with different irradiance

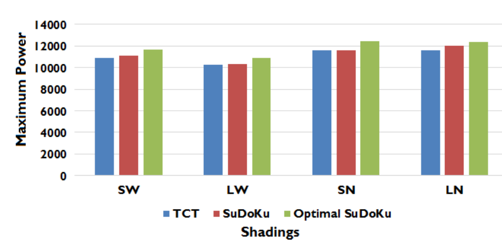

Fig. 14: GMPP under all shading conditions

levels which is shown in Fig.9(a). In Fig.9(a), it is shown that TCT, SuDoKu and optimal SuDoKu PV array shading dispersion arrangements. The location of GMPP for all PV

TABLE III: Location of GMPP for TCT, SuDoKu and optimal SuDoKu arrangements under SN

TCT				SuDoKu				Optimal SuDoKu			
Row bypassed	currents (A)	voltages (V)	power(P_{GMPP})	Row bypassed	currents(A)	voltages (V)	power(P_{GMPP})	Row bypassed	currents(A)	voltages (V)	power(P_{GMPP})
$Irow_9$	$6.1I_m$	$9V_m$	$54.9V_m.I_m$	$Irow_9$	$7.1I_m$	-	-	$Irow_9$	$7.1I_m$	-	-
$Irow_8$	$6.1I_m$	-	-	$Irow_8$	$7.3I_m$	-	-	$Irow_8$	$7.1I_m$	-	-
$Irow_7$	$7.3I_m$	-	-	$Irow_7$	$7.8I_m$	-	-	$Irow_7$	$6.9I_m$	$9V_m$	$62.1V_m.I_m$
$Irow_6$	$7.3I_m$	-	-	$Irow_6$	$7.8I_m$	-	-	$Irow_6$	$7.4I_m$	-	-
$Irow_5$	$8.1I_m$	-	-	$Irow_5$	$6.8I_m$	$9V_m$	$61.2V_m.I_m$	$Irow_5$	$7.4I_m$	-	-
$Irow_4$	$8.1I_m$	-	-	$Irow_4$	$7.5I_m$	-	-	$Irow_4$	$8.1I_m$	-	-
$Irow_3$	$8.1I_m$	-	-	$Irow_3$	$7.5I_m$	-	-	$Irow_3$	$7.1I_m$	-	-
$Irow_2$	$8.1I_m$	-	-	$Irow_2$	$7.5I_m$	-	-	$Irow_2$	$7.9I_m$	-	-
$Irow_1$	$8.1I_m$	-	-	$Irow_1$	$7.8I_m$	-	-	$Irow_1$	$7.9I_m$	-	-

TABLE IV: Location of GMPP for TCT, SuDoKu and optimal SuDoKu arrangements under LN

TCT				SuDoKu				Optimal SuDoKu			
Row bypassed	currents (A)	voltages (V)	power(P_{GMPP})	Row bypassed	currents(A)	voltages (V)	power(P_{GMPP})	Row bypassed	currents(A)	voltages (V)	power(P_{GMPP})
$Irow_9$	$6.3I_m$	$9V_m$	$56.7V_m.I_m$	$Irow_9$	$7.0I_m$	$9V_m$	$63.0V_m.I_m$	$Irow_9$	$7.0I_m$	$9V_m$	$63.0V_m.I_m$
$Irow_8$	$6.3I_m$	-	-	$Irow_8$	$7.4I_m$	-	-	$Irow_8$	$7.4I_m$	-	-
$Irow_7$	$6.6I_m$	-	-	$Irow_7$	$7.3I_m$	-	-	$Irow_7$	$7.1I_m$	-	-
$Irow_6$	$6.6I_m$	-	-	$Irow_6$	$7.4I_m$	-	-	$Irow_6$	$7.4I_m$	-	-
$Irow_5$	$7.7I_m$	-	-	$Irow_5$	$7I_m$	-	-	$Irow_5$	$7.3I_m$	-	-
$Irow_4$	$7.7I_m$	-	-	$Irow_4$	$7.0I_m$	-	-	$Irow_4$	$7.4I_m$	-	-
$Irow_3$	$7.7I_m$	-	-	$Irow_3$	$7.3I_m$	-	-	$Irow_3$	$7.4I_m$	-	-
$Irow_2$	$8.1I_m$	-	-	$Irow_2$	$7.1I_m$	-	-	$Irow_2$	$7.9I_m$	-	-
$Irow_1$	$8.1I_m$	-	-	$Irow_1$	$7.5I_m$	-	-	$Irow_1$	$8.1I_m$	-	-

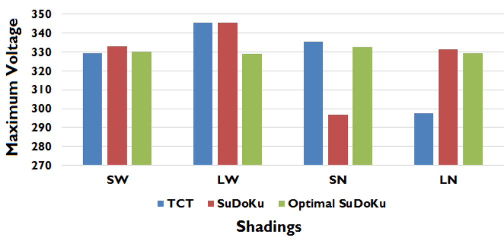

Fig. 15: voltage at the GMPP under all shading conditions

array arrangements is given in Table IV. From the table, it is observed that the global peak occurs at $row9$ with $6.3I_m$ current and $9V_m$ voltage, the corresponding power is 56.7 $V_m.I_m$ for TCT. Similarly, the SuDoKu and optimal SuDoKu GMPP are $63.0V_m.I_m$ and $63.0V_m.I_m$ respectively. To validate theoretical GMPP by simulating P-V characteristics which is shown in Fig.13. From the figure, the simulated GMPP for TCT, SuDoKu and optimal SuDoKu PV array arrangements is given in Table V.

For all shading conditions, the obtained parameters of GMPP and voltage at the GMPP are graphically represented in Figs.14-15. In all aforementioned studies, it is cleared that the optimal SuDoKu PV array arrangement is producing highest global maximum power compared to TCT and SuDoKu arrangements which is given in Table V.

TABLE V: GMPP from the simulation for all arrangements

Shading case	TCT	SuDoKu	Optimal SuDoKu
SW	10890 W	11080 W	11650 W
LW	10280 W	10300 W	10890 W
SN	11600 W	11590 W	12480 W
LN	11610 W	12000 W	12380 W

V. CONCLUSION

This paper presents the performance of SuDoKu and optimum SuDoKu reconfiguration techniques on 9×9 Total-Cross-Tied (TCT) PV array under partial shading condition (PSC). In this approach, the physical locations of modules in TCT PV array are changing based on SuDoKu and optimum SuDoKu pattern arrangements without altering any electrical connections. The conclusion made from this paper is that, the optimal SuDoKu arrangement effectively distributes the shading effects over the PV array. And also, it enhances the average global maximum power by 7.03% and 5.2% as compared to TCT and SuDoKu PV arrays under all shading conditions.

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