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MAXIMIZING POWER OUTPUT OF PARTIALLY SHADED PHOTOVOLTAIC ARRAYS USING SUDOKU CONFIGURATION

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ABSTRACT

The performance of a photovoltaic (PV) array is exaggerated by temperature, solar insolation, shading and array configuration. Often, the PV arrays get shadowed, completely or partially, by the passing clouds, neighbouring buildings & towers, trees & utility and telephone poles. Partial shading of PV arrays reduces the energy yield of PV systems and the arrays exhibit multiple peaks in the P-V characteristics. The losses due to partial shading are not proportional to the shaded area but depend on the shading pattern, array configuration and the physical location of shaded modules in the array. This paper presents a technique to configure the modules in the array so as to enhance the generated power from the array under partial shading conditions. In this approach, the physical location of the modules in a SP, BL, TCT & HC connected PV array are arranged based on the SuDoKu puzzle pattern so as to distribute the shading effect over the entire array. Further, this arrangement of modules is done without altering the electrical connection of the modules in the array. The SuDoKu arrangement reduces the effect of shading of modules in any row thereby enhancing the generated PV power. Also this paper presents a clear relationship between the interconnections of the PV modules & their power output is proposed through empirical connection laws.

Keywords: mismatch losses, interconnected pattern, partially shading, PV arrays, sudoku pattern.

1. INTRODUCTION

The intensive use of fossil fuels has triggered a worldwide discussion about their effect on the environment. As a consequence, the number of Photovoltaic (PV) power plants installed all over the world has steadily risen in the past few decades. However, experience has shown that their produced power is usually lower than their expected power [1]. There are many factors that contribute to create this difference such as cable losses, non-optimal inverter efficiency, or using PV module from different technologies in the same plant. This lower power output can be referred to as PV mismatch, although there is not a consensus in this paper.

The study of PV mismatch has followed two great tendencies for the past few decades. The mismatch due to changes in the physical conditions of the PV modules [2], [3] or to non-uniform shading (also referred to as "Partial Shading") across the PV field [4], [5].Generally, the panels are connected in series and parallel to meet the load power requirement. The output power of the PV array also decreases considerably when one or more of the panels in the array are subjected to shading [6], [7]. Partial shading can be caused by the shadows of buildings, trees and poles. In large PV systems, moving clouds also leads to partial shading [8], [9]. Partial shading complicates the PV characteristics with multiple peaks [10], [11] apart from reducing the energy yield of PV systems. The occurrence of such multiple peaks can mislead some MPPT algorithms to get trapped at local peaks [12] [13]. Different techniques have been proposed [14] [15] to track the global peak under partial shading conditions. The issue of predicting the maximum power under these conditions is reported [16].

The losses due to partial shading are not proportional to the shaded area but depend on the shading pattern, array configuration and the location of shaded module in the array. Different array configurations have been proposed in literature [17] [18] to reduce the mismatch losses in the array. Four interconnection schemes viz., Series-Parallel (SP), Bridge-Link (BL), Totally Cross Tied (TCT) and Honey-Comb (HC) are compared for their losses, maximum power, fill factor, reliability and energy yield due to mismatch caused by the manufacturer's tolerances in cell characteristics and by partial shading [19].

A study of the operational life time of PV arrays based on the probability theory indicates that the introduction of cross ties (TCT or BL schemes) in the array almost doubles the life time of the array [20]. A method [21] has been proposed to predict the maximum power production from the existing PV systems. An Electrical Array Reconfiguration (EAR) controller [22] is proposed to optimize the performance of PV powered volumetric pump under different insolation levels.

Based on the irradiance level, the EAR controller chooses a suitable configuration for different operating conditions of the pump. In adaptive reconfiguration scheme [23], a switching matrix connects a solar adaptive bank to a fixed part of the array so that less shaded modules of the adaptive part are in parallel with more shaded rows of fixed part. A large number of switches and sensors are required to implement the technique. An electrical reconfiguration technique [24] is proposed in which the connections of the modules are dynamically changed according to a switching matrix so as to maximize the current of the single string in the event of shading. Though the power loss is reduced under several

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partial shaded conditions, the technique involves high cost and greater complexity. The reconfiguration strategy [25] reported in literature ensures a minimum deviation from the PV operating voltage and the strategy is based on removing the shaded modules from the array by sensing the current through the bypass diode. A switching network is required to connect and disconnect the modules. Moreover, individual current sensors are required to sense the current through each bypass diode.

This paper presents a method to configure the physical placement of the modules in a SP, BL, TCT & HC connected PV array to enhance the PV power generation under partial shaded conditions. The modules are arranged based on the SuDoKu puzzle pattern without altering their electrical connection within the array. This pattern facilitates to distribute the effect of shading over the array thereby reducing the occurrence of shading of modules in the same row. Also, the performance of the system is investigated for different shading patterns and interconnection schemes and the result reveal that the SuDoKu configured structure exhibits superior performance under partially shaded conditions. Also, it points out, for each shading pattern, how to minimize the number of interconnections among the modules, while maximizing power output of the whole PV field.

2. PHOTOVOLTAIC SPECIFICATIONS AND ITS VARIABLES

A. Model of a PV array

A PV cell can be represented by an equivalent circuit, as shown in Figure-1.

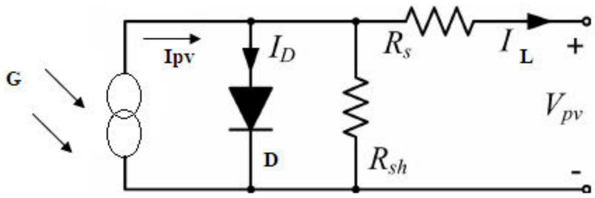

Figure-1. Equivalent circuit of a PV module.

Equation (1) describes the model [2], where I_{pv} is the photoelectric current, I_0 is the reverse saturation current, V_{pv} is the output voltage, R_{shunt} is the shunt resistance, R_{series} is the series resistance, G is the insolation on the PV module, I_L is the output current.

$$I_L = I_{PV} - I_0\left[\exp\left(\frac{V_{PV}+R_{Series}I_L}{V_t}\right) - 1\right] - \left[\frac{V_{PV}+R_{Series}I_L}{R_{Shunt}}\right] \quad (1)$$

The variable V_t is given by,

$$V_t = \frac{A.K.T_C}{q} \quad (2)$$

Where, A is the diode ideality factor, K is the Boltzmann constant, T_C is the operating temperature of the PV module, and q is the electric charge in kelvin and n is the number of cells in series.

The light generated current (I_{PV}) is obtained as the function of short circuit current as

$$I_{PV} = I_{SC}\left(\frac{G}{G_S}\right)\left(1 + \alpha_1\,(T - T_0)\right).\frac{(R_{Series} + R_{Shunt})}{R_{Shunt}} \quad (3)$$

Where, I_{SC} is the short circuit current of the module at standard insolation G_S (1000 W/m^2) and standard temperature T_0 (25^{0}C) and α_1 is the modules temperature coefficient for current. The above equations are used to model the PV modules considered for study.

B. PV Module interconnection schemes

Figure-2 shows four interconnection schemes of the 4x4 PV modules, which is considered for the study and the letters below the interconnections are the abbreviation of their names. SP represents “Series - Parallel”, with long strings. BL represents “Bridge - Link”, being inspired on a wheat stone Bridge connection. TCT represents “Totally Cross Tied”, having all its modules interconnected. HC represents “Honey Comb”, with a pattern similar to the domestic utensil.

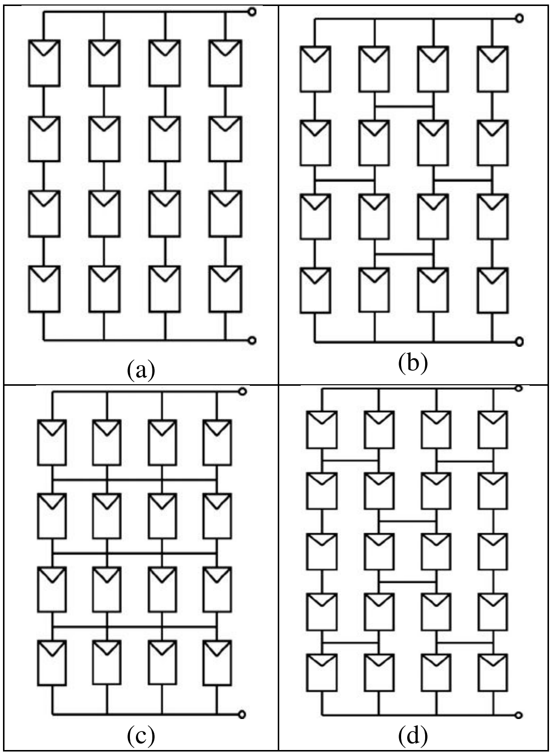

Figure-2. (a) Series-Parallel (SP), (b) Bridge – Link (BL), (c) Totally Cross Tied (TCT), (d) Honey Comb (HC).

All the modules in a column are connected in series and each module in a row has modules connected in parallel. The PV array consists of 81 modules with nine rows and nine columns. The modules are labelled as ‘mn’ where ‘m’ denotes the row and ‘n’ is the column in which the module is connected.

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C. PV Specifications

Table-1. PV Specifications at 1000 W/m^2, 25^{0}C.

PV Power	80 W
Open Circuit Voltage	22 V
Short Circuit Current	4.7 A
Nominal Voltage	18 V
Nominal Current	4.4 A

The current generated by a module at an irradiance G is given by

$$I = k\, I_L \tag{4}$$

Where I_L is the current generated by the module at standard irradiance, G_S = 1000 W/m^2 and k = G/G_S. Therefore, the current generated by the module is directly proportional to the solar irradiance on the panel. The voltage of the array is given by the sum of the voltages of the 9 rows. Applying the kirchoff's voltage law,

$$V_{PV} = \sum_{m=1}^{9} V_{Lm} \tag{5}$$

Where V_{PV} is the voltage of the PV array and V_{Lm} refers to voltage of the panels at the mth row.

Using the Kirchhoff's current law, the current at each node can be expressed as

$$I_{PV} = \sum_{n=1}^{9} (I_{mn} - I_{(m+1)n}) = 0, \quad m = 1,2,3,\ldots,8 \tag{6}$$

3. PROPOSED SUDOKU PATTERN

A. SuDoKu arrangement

Sudoku, originally called Number Place is a logic-based, combinatorial number-placement puzzle. The objective is to fill a 9×9 grid with digits so that each column, each row, and each of the nine 3×3 sub-grids that compose the grid (also called "boxes", "blocks", "regions", or "sub-squares") contains all of the digits from 1 to 9. The puzzle setter provides a partially completed grid, which for a well-posed puzzle has a unique solution.

Completed puzzles are always a type of Latin square with an additional constraint on the contents of individual regions. For example, the same single integer may not appear twice in the same row, column or in any of the nine 3×3 sub-regions of the 9x9 playing board.

To show that SuDoKu pattern will enhance the PV power generation, the modules in four interconnection schemes (Figure-2) are rearranged according to the chosen puzzle pattern and is shown in Figure-3. Here the electrical connection of the module remains the same as indicated in Fgure-2. However, the physical location of the modules is changed.

Since the electrical configuration of the array does not change, the voltage and current equations remain the same as in Figure-2. The panels belonging to the same row in Figure-2 are moved to different rows in the SuDoKu arrangement. This enables to reduce the shading of the panels in the same row and distribute the shading over the entire array. Thus, the SuDoKu arrangement increases the current entering a node under partial shading conditions and minimizes the bypassing of panels. Hence the power generated by the array for same shading pattern is increased. Also, the main advantage of the proposed SuDoKu pattern does not require any sensors or switches. Moreover no separate control algorithm is required.

1	7	4	2	8	5	3	9	6
3	9	6	4	1	7	5	2	8
8	5	2	9	6	3	1	7	4
4	1	7	5	2	8	6	3	9
6	3	9	7	4	1	8	5	2
2	8	5	3	9	6	4	1	7
7	4	1	8	5	2	9	6	3
9	6	3	1	7	4	2	8	5
5	2	8	6	3	9	7	4	1

Figure-3. Proposed SuDoKu pattern.

In large PV systems, with existing technique, the number of sensors and switches increases with array size and control circuit becomes complex. With the proposed system, the entire PV array can be divided into a 9x9 sub assembly and the proposed technique can be employed to ensure that the modules in the row are kept apart. Further, this arrangement of modules as per SuDoKu pattern needs to be made just once only since the same pattern holds effective for any shading pattern.

B. Characteristics of a shadow

The main objective of this paper is to establish a clear relationship between interconnection schemes, shadows and Maximum Power Point (MPP) of the PV array. The intensity of a shadow represents how much it can filter the power that shines over the module. This power is called *irradiance* and it is measured in watts per square meter. In this, the intensity of the shadow will be called shading factor and its value range from 0 (no shadow) to 1 (full shadow). No shadow means that the whole available irradiance shines over the module.

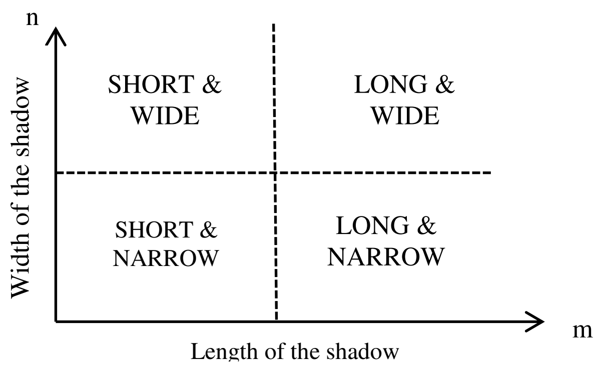

Figure-4. Types of shadow.

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The shadow shape is described by the number of strings (width) and modules per string (length) that it is cast upon. It can be classified into four different types as represented in Figure-4.

C. RESULTS AND DISCUSSIONS

To evaluate the performance of the proposed method, a 9x9 PV array connected in all interconnection schemes and it is subjected to four different shading patterns. The location of GP in both the interconnected schemes and the SuDoKu pattern are calculated theoretically. The location of GP indicates the number of rows that are bypassed to extract the maximum power. The theoretical results are verified using simulation studies in MATLAB / Simulink environment.

The PV characteristics are obtained for the SP, TCT, BL& HC and the SuDoKu pattern for each shading pattern and the results are presented.

Case - 1 (Short & Wide):

A PV array with four distinct groups is considered. The group (G_1) receives an insolation of 1000 W/m^2 while group two (G_2), group three (G_3) and group four (G_4) receives 700 W/m^2, 400 W/m^2 and 100 W/m^2 respectively and the shading pattern is described in Figure-3(a).

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

G_1 -1000 W/m^2 **G_2** - 700 W/m^2

G_3 - 400 W/m^2 **G_4** - 100 W/m^2

Figure-5(a). SuDoKu arrangement for case-1.

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

Figure-5(b). Shading dispersion with SuDoKu arrangement for case-1.

Here for interconnected pattern in row 1, four panels receive 700 W/m^2, other three panels receive 400 W/m^2 and remaining two panels are subjected to 1000 W/m^2.The current generated by the panels in row1 is given by,

$$I_{R1} = k_{11}I_{11} + k_{12}I_{12} + k_{13}I_{13} + k_{14}I_{14} + k_{15}I_{15} + k_{16}I_{16} + k_{17}I_{17} + k_{18}I_{18} + k_{19}I_{19} \quad (7)$$

Where, $k_{11} = G_{11}/G_0 = 0.7$, where G_{11} is the solar irradiance of the panel numbered 11 and I_{11} is the current generated by the panel. Let us assume the current generated by all the panels is given by,

$$I_{R1} = 4x0.7I_m + 3x0.4I_m + 2x0.1I_m = 4.2I_m \quad (8)$$

Similarly for row 2 & row 3 will have same insolation as in row 1.

Therefore, $I_{R1} = I_{R2} = I_{R3}$ (9)

In row 4, four panels receive 700 W/m^2 and remaining five panels receive 1000 W/m^2. The current generated by row 4 is given by,

$$I_{R4} = 4x0.7I_m + 3x1I_m + 2x0.4I_m = 6.6\ I_m \quad (10)$$

Similarly, from row 5 to row 9 will have same insolation of 1000 W/m^2. Hence the current generated in these rows are given by,

$$I_{R5} = 9x1I_m = 9I_m \quad (11)$$

$$I_{R5} = I_{R6} = I_{R7} = I_{R8} = I_{R9} = 9I_m \quad (12)$$

Since the current generated in different, there exist multiple peaks on the PV characteristics. Now to identify the location of GP, the module currents are noted in Table-2.

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Table-2. To find GP in interconnected patterns & SuDoKu Pattern for Case I.

Interconnected pattern				Sudoku pattern			
Row Current in the order in which the panels are bypassed		Voltage, V_a	Power, P_a	Row Current in the order in which the panels are bypassed		Voltage, V_a	Power, P_a
I_{R5}	$9I_m$	$3V_m$	$27V_mI_m$	I_{R9}	$7.5I_m$	$7\ V_m$	**$52.5\ V_mI_m$**
I_{R6}	$9I_m$	$3V_m$	$27V_mI_m$	I_{R3}	$7.5\ I_m$	$6\ V_m$	$45\ V_mI_m$
I_{R7}	$9I_m$	$3V_m$	$27V_mI_m$	I_{R6}	$7.2\ I_m$	$7\ V_m$	$50.4\ V_mI_m$
I_{R8}	$9I_m$	$4V_m$	$36V_mI_m$	I_{R5}	$7.2\ I_m$	$6\ V_m$	$45\ V_mI_m$
I_{R9}	$9I_m$	$5V_m$	$45\ V_mI_m$	I_{R4}	$7.2\ I_m$	$6\ V_m$	$45\ V_mI_m$
I_{R4}	$6.6I_m$	$7V_m$	**$46.2\ V_mI_m$**	I_{R1}	$7.2\ I_m$	$7\ V_m$	$50.4\ V_mI_m$
I_{R1}	$4.2I_m$	$9V_m$	$37.8\ V_mI_m$	I_{R2}	$6.9\ I_m$	$7\ V_m$	$48.3\ V_mI_m$
I_{R2}	$4.2I_m$	$9V_m$	$37.8\ V_mI_m$	I_{R7}	$6.9\ I_m$	$6\ V_m$	$41.4\ V_mI_m$
I_{R3}	$4.2I_m$	$9V_m$	$37.8\ V_mI_m$	I_{R8}	$6.6\ I_m$	$7\ V_m$	$46.2\ V_mI_m$

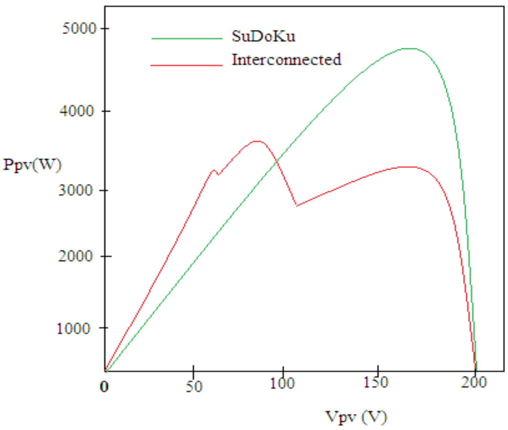

Figure-5(c). PV Characteristics of the array for Interconnected and SuDoKu pattern.

If none of the panels ae bypassed, the voltage of the array can be assumed as $V_a = 9V_m$, by neglecting the small variations in voltage across each row. If a single row is bypassed, then V_a can be assumed as $8V_m$.
The Power produced by the array,

$P_a = V_aI_m = 9V_m I_m$

If no array is bypassed. The voltage of the array and the corresponding power are calculated and are noted in Table I. To verify theoretical results, simulations are carried out in INSEL environment and PV characteristics corresponding to this array are plotted in Figure-5(d).

If shows that the maximum power generated by the array is 52.5 V_mI_m watts and the GP occurs at V which is lessthan the nominal voltage of the array.

To validate the proposed arrangement of modules according to SuD0Ku pattern, the rearrangement pattern is subjected to the same shading pattern (Figure-5(b)) and the current in each row is calculated by,

$I_{R1} = 5x1xI_m + 2x0.7I_m + 2x0.4I_m = 7.2I_m$
$I_{R2} = 5x1xI_m + 2x0.7I_m + 1x0.1I_m + 1x0.4I_m = 6.9I_m$
$I_{R3} = 6x1xI_m + 1x0.7I_m + 2x0.4I_m = 7.5I_m$
$I_{R4} = 5x1xI_m + 3x0.7I_m + 1x0.1I_m = 7.2I_m$
$I_{R5} = 5x1xI_m + 2x0.7I_m + 2x0.4I_m = 7.2I_m$
$I_{R6} = 6x1xI_m + 1x0.7I_m + 1x0.4I_m + 1x0.1I_m = 7.2I_m$
$I_{R7} = 5x1xI_m + 2x0.7I_m + 1x0.4I_m + 1x0.1I_m = 6.9I_m$
$I_{R8} = 5x1xI_m + 1x0.7I_m + 2x0.4I_m + 1x0.1I_m = 6.6I_m$
$I_{R9} = 6x1xI_m + 2x0.7I_m + 1x0.1I_m = 7.5I_m$ (13)

The module currents, voltage and power are noted in Table-2.

Case 2: (Long & Wide)

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

G_1 -1000 W/m^2 G_2 - 700 W/m^2
G_3 - 400 W/m^2 G_4 - 100 W/m^2

Figure-6(a). SuDoKu arrangement for Case-2.

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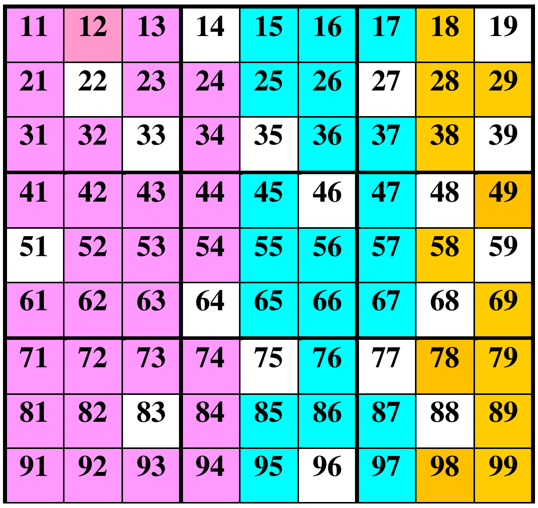

Figure-6(b). Shading dispersion with SuDoKu arrangement for Case-2.

For Interconnected Patterns:

$I_{R1} = I_{R2} = I_{R3} = I_{R4} = I_{R5} = I_{R6} = 4x0.7I_m + 3x0.4I_m + 2x0.1I_m = 4.2\ I_m$

$I_{R7} = 4x0.7I_m + 3x0.4I_m + 2x1xI_m = 6\ I_m$

$I_{R8} = 2x0.7I_m + 7x1xI_m = 8.4I_m$

$I_{R9} = 9x1xI_m = 9I_m$

For SuDoKu Pattern:

$I_{R1} = 3x0.7I_m + 3x0.4I_m + 1x0.1I_m + 2x1xI_m = 5.4\ I_m$

$I_{R2} = 3x0.7I_m + 2x0.4I_m + 2x0.1I_m + 2x1xI_m = 5.1\ I_m$

$I_{R3} = 3x0.7I_m + 2x0.4I_m + 1x0.1I_m + 3x1xI_m = 6\ I_m$

$I_{R4} = 4x0.7I_m + 2x0.4I_m + 1x0.1I_m + 2x1xI_m = 6\ I_m$

$I_{R5} = 3x0.7I_m + 3x0.4I_m + 1x0.1I_m + 2x1xI_m = 5.4\ I_m$

$I_{R6} = 3x0.7I_m + 3x0.4I_m + 1x0.1I_m + 2x1xI_m = 5.4\ I_m$

$I_{R7} = 4x0.7I_m + 1x0.4I_m + 2x0.1I_m + 2x1xI_m = 5.4\ I_m$

$I_{R8} = 3x0.7I_m + 3x0.4I_m + 1x0.1I_m + 2x1xI_m = 5.4\ I_m$

$I_{R9} = 4x0.7I_m + 2x0.4I_m + 2x0.1I_m + 1x1xI_m = 4.8\ I_m$

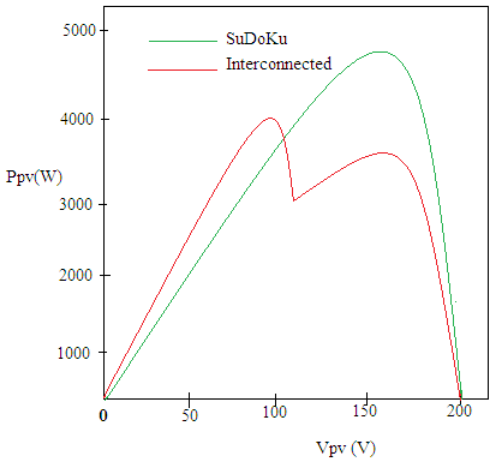

Figure-6(c). PV Characteristics of the array for Interconnected and SuDoKu pattern.

Table-3. To find GP in interconnected patterns & SuDoKu pattern for Case II.

Interconnected pattern				**Sudoku pattern**			
Row Current in the order in which the panels are bypassed		**Voltage, V_a**	**Power, P_a**	**Row Current in the order in which the panels are bypassed**		**Voltage, V_a**	Power, P_a
I_{R9}	$9I_m$	$3V_m$	$27V_mI_m$	I_{R9}	$7.5I_m$	$7\ V_m$	**$52.5\ V_mI_m$**
I_{R8}	$8.4I_m$	$3V_m$	$25.2V_mI_m$	I_{R3}	$7.5\ I_m$	$6\ V_m$	$45\ V_mI_m$
I_{R7}	$6I_m$	$3V_m$	$18V_mI_m$	I_{R6}	$7.2\ I_m$	$7\ V_m$	$50.4\ V_mI_m$
I_{R6}	$4.2I_m$	$3V_m$	$12.6\ V_mI_m$	I_{R5}	$7.2\ I_m$	$6\ V_m$	$45\ V_mI_m$
I_{R5}	$4.2I_m$	$3V_m$	$12.6\ V_mI_m$	I_{R4}	$7.2\ I_m$	$6\ V_m$	$45\ V_mI_m$
I_{R4}	$4.2I_m$	$3V_m$	$12.6V_mI_m$	I_{R1}	$7.2\ I_m$	$7\ V_m$	$50.4\ V_mI_m$
I_{R3}	$4.2I_m$	$4V_m$	$16.8\ V_mI_m$	I_{R2}	$6.9\ I_m$	$7\ V_m$	$48.3\ V_mI_m$
I_{R2}	$4.2I_m$	$7V_m$	$29.4\ V_mI_m$	I_{R7}	$6.9\ I_m$	$6\ V_m$	$41.4\ V_mI_m$
I_{R1}	$4.2I_m$	$9V_m$	**$37.8\ V_mI_m$**	I_{R8}	$6.6\ I_m$	$7\ V_m$	$46.2\ V_mI_m$

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Case 3: (Short & Narrow)

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

Figure-7(a). SuDoKu arrangement for Case-3.

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

Figure-7(b). Shading dispersion with SuDoKu arrangement for Case-3.

For Interconnected Patterns:

$I_{R1} = I_{R2} = I_{R3} = I_{R4} = 6x1xI_m + 1x0.7I_m + 1x0.4I_m + 1x0.1I_m = 7.2I_m$

For SuDoKu Pattern:

$I_{R1} = 1x0.7I_m + 8x1xI_m = 8.7I_m$

$I_{R2} = 1x0.1xI_m + 8x1xI_m = 8.1I_m$

$I_{R3} = 1x0.7I_m + 8x1xI_m = 8.7\ I_m$

$I_{R4} = 1x0.1I_m + 8x1xI_m = 8.1I_m$

$I_{R5} = 1x0.4I_m + 8x1xI_m = 8.4I_m$

$I_{R6} = 1x0.1xI_m + 8x1xI_m = 8.1I_m$

$I_{R7} = 1x0.4I_m + 8x1xI_m = 8.4I_m$

$I_{R8} = 1x0.7I_m + 8x1xI_m = 8.7\ I_m$

$I_{R9} = 1x0.4I_m + 8x1xI_m = 8.4\ I_m$

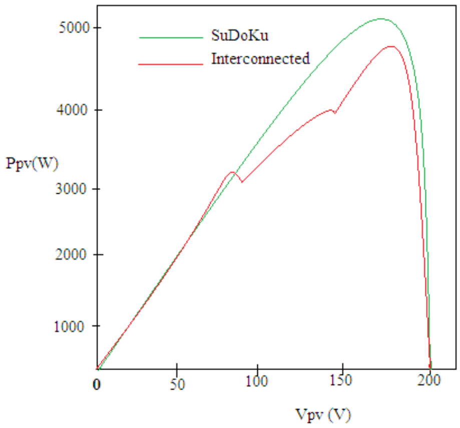

Figure-7(c). PV Characteristics of the array for Interconnected and SuDoKu pattern.

Table-4. To find GP in interconnected patterns & SuDoKu pattern for Case III.

Interconnected pattern				**Sudoku pattern**			
Row current in the order in which the panels are bypassed		**Voltage, V_a**	**Power, P_a**	**Row current in the order in which the panels are bypassed**		**Voltage, V_a**	**Power, P_a**
I_{R7}	$9I_m$	$7V_m$	$63V_mI_m$	I_{R1}	$8.7\ I_m$	$9V_m$	**$78.3V_mI_m$**
I_{R8}	$9I_m$	$7V_m$	$63\ V_mI_m$	I_{R3}	$8.7\ I_m$	$9V_m$	**$78.3V_mI_m$**
I_{R9}	$9I_m$	$7V_m$	$63\ V_mI_m$	I_{R8}	$8.7\ I_m$	$9V_m$	**$78.3V_mI_m$**
I_{R5}	$8.1I_m$	$9V_m$	**$72.9V_mI_m$**	I_{R5}	$8.4I_m$	$9V_m$	$75.6V_mI_m$
I_{R6}	$8.1I_m$	$9V_m$	**$72.9\ V_mI_m$**	I_{R7}	$8.4\ I_m$	$8V_m$	$67.2V_mI_m$
I_{R1}	$7.2I_m$	$9V_m$	$64.8V_mI_m$	I_{R9}	$8.4\ I_m$	$9V_m$	$75.6V_mI_m$
I_{R2}	$7.2I_m$	$9V_m$	$64.8\ V_mI_m$	I_{R2}	$8.1I_m$	$8V_m$	$64.8V_mI_m$
I_{R3}	$7.2I_m$	$9V_m$	$64.8\ V_mI_m$	I_{R4}	$8.1\ I_m$	$8V_m$	$64.8\ V_mI_m$
I_{R4}	$7.2I_m$	$9V_m$	$64.8\ V_mI_m$	I_{R6}	$8.1\ I_m$	$8V_m$	$64.8\ V_mI_m$

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Case 4: (Long& Narrow)

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

Figure-8(a). SuDoKu arrangement for Case-4.

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

Figure-8(b). Shading dispersion with SuDoKu arrangement for Case-4.

For Interconnected Patterns:

$I_{R1} = I_{R2} = I_{R3} = I_{R4} = I_{R5} = I_{R6} = I_{R7} = 6x1xI_m + 1x0.7I_m + 1x0.4I_m + 1x0.1I_m = 7.2I_m$

$I_{R8} = 7x1xI_m + 1x0.7I_m + 1x0.4I_m = 8.1I_m$

$I_{R9} = 8x1xI_m + 1x0.7I_m = 8.7I_m$

For SuDoKu Pattern:

$I_{R1} = 6x1xI_m + 1x0.7I_m + 1x0.4I_m + 1x0.1I_m = 7.2\ I_m$

$I_{R2} = 7x1xI_m + 1x0.7I_m + 1x0.4I_m = 7.8I_m$

$I_{R3} = 7x1xI_m + 1x0.7I_m + 1x0.4I_m = 8.1\ I_m$

$I_{R4} = 6x1xI_m + 1x0.7I_m + 1x0.4I_m + 1x0.1I_m = 7.2I_m$

$I_{R5} = 6x1xI_m + 1x0.7I_m + 1x0.4I_m + 1x0.1I_m = 7.2\ I_m$

$I_{R6} = 6x1xI_m + 1x0.7I_m + 1x0.4I_m + 1x0.1I_m = 7.2\ I_m$

$I_{R7} = 6x1xI_m + 1x0.7I_m + 1x0.4I_m + 1x0.1I_m = 7.2\ I_m$

$I_{R8} = 7x1xI_m + 1x0.7I_m + 1x0.4I_m = 8.1I_m$

$I_{R9} = 6x1xI_m + 1x0.7I_m + 1x0.4I_m + 1x0.1I_m = 7.2\ I_m$

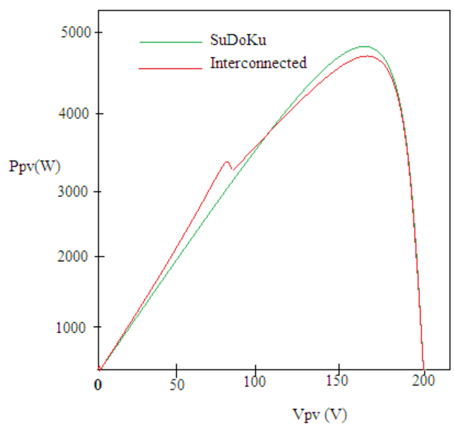

Figure-8(c). PV Characteristics of the array for interconnected and SuDoKu pattern.

Table-5. To find GP in interconnected patterns & SuDoKu pattern for Case IV.

Interconnected pattern				**Sudoku pattern**			
Row current in the order in which the panels are bypassed		**Voltage, V_a**	**Power, P_a**	**Row current in the order in which the panels are bypassed**		**Voltage, V_a**	**Power, P_a**
I_{R9}	8.7 I_m	$6V_m$	$52.2V_mI_m$	I_{R3}	$8.1I_m$	$7V_m$	$56.7V_mI_m$
I_{R8}	8.1 I_m	$6V_m$	$48.6V_mI_m$	I_{R8}	$8.1I_m$	$8V_m$	**$64.8V_mI_m$**
I_{R1}	7.2 I_m	$6V_m$	$43.2V_mI_m$	I_{R2}	$7.8I_m$	$8V_m$	$62.4V_mI_m$
I_{R2}	7.2 I_m	$6V_m$	43.2 V_mI_m	I_{R1}	$7.2I_m$	$7V_m$	$50.4V_mI_m$
I_{R3}	7.2 I_m	$6V_m$	43.2 V_mI_m	I_{R4}	7.2 I_m	$7V_m$	$50.4V_mI_m$
I_{R4}	$7.2I_m$	$6V_m$	43.2 V_mI_m	I_{R5}	7.2 I_m	$7V_m$	$50.4V_mI_m$
I_{R5}	$7.2I_m$	$6V_m$	43.2 V_mI_m	I_{R6}	7.2 I_m	$7V_m$	$50.4V_mI_m$
I_{R6}	$7.2I_m$	$7V_m$	$50.4V_mI_m$	I_{R7}	7.2 I_m	8 V_m	$57.6V_mI_m$
I_{R7}	$7.2I_m$	$8V_m$	**$57.6V_mI_m$**	I_{R9}	7.2 I_m	$7V_m$	*$50.4V_mI_m$*

Table-6. Comparison of output power for various shading pattern.

Shading pattern	Interconnected pattern	Su-Do-Ku pattern
Short & Wide	$46.4V_mI_m$	$50.4V_mI_m$
Long & Wide	$36.8V_mI_m$	$42V_mI_m$
Short & Narrow	$72.9\ V_mI_m$	$78.3V_mI_m$
Long & Narrow	$57.6V_mI_m$	$64.8V_mI_m$

As shown in the Table-6, in all the four cases the power generated by the SuDoKu pattern is greater compared to the previous arrangement. It is also noted that when most of the modules in a row are shaded or under wide shading conditions (Case 1 and Case 2), the output obtained in the SuDoKu arrangement is higher.

CONCLUSIONS

This paper proposes SuDoKu Configuration as a onetime arrangement for the PV modules in the array and demonstrates the improvement in the PV power generation under partial shaded conditions. In this technique, the panels are arranged in a pattern without altering their electrical connection within the array. This SuDoKu structure distributes the effect of shading over the array and reducing the occurrence of shading of modules in array one row thereby increasing the generated PV power. The performance of the system for different shading patterns was examined and it shows that positioning the modules in the array in SuDoKu pattern shows better performance under partially shading conditions.

REFERENCES

[1] M. Sadok and A. Mehdaoui. 2008. Outdoor testing of photovoltaic arrays in the Saharan region. Renew. Energy. 33(12): 2516-2524.

[2] N. Kaushika and A. K Rai. 2007. An investigation of mismatch losses in solar photovoltaic cell networks. Energy. 32(5): 755-759.

[3] J. Appelbaum, A. Chait and D.A. Thompson. 1995. A method for screening solar cells. Solid - State lectron. 38(1): 246-248.

[4] E. Karatepe, M. Boztepe, and M. Colak. 2007. Development of a suitable model for characterizing photovoltaic arrays with shaded solar cell. Solar energy. 81(8): 977-992.

[5] N. D. Kaushika and N. K. Gautam. 2003. Energy yield simulations of interconnected solar PV arrays. in Proc. IEEE power eng. Soc. General Meet. pp. 127-134.

[6] R. A. Mastromauro, M. Liserre and A. Dell Aquila. 2012. Control issues in single - Stage photovoltaic systems: MPPT, current and voltage control. IEEE Trans. Ind. Inform. 8(2): 241-254.

[7] Y. J. Wang and P. C. Hsu. 2010. Analytical Modeling of partial shading and different orientation of photovoltaic models. IET Renew. Power Gener. 4(3): 272-282.

[8] L. Gao, R. A. Dougal, S. Liu, and A. P. Iotova. 2009. Parallel – Connected solar PV system to address partial and rapidly fluctuating shadow conditions. IEEE Trans. Ind. Electron. 56(5): 1548-1556.

[9] H. Patel and V. Agarwal. 2008. Maximum power point tracking scheme for pv systems operating under partially shaded conditions. IEEE Trans. Ind. Electron. 55(4): 1689-1698.

[10] H. Patel and V. Agarwal. 2008. M Atlab based modelling to study the effects of partial shading on pv array characteristics. IEEE Trans. Energy Convers. 23(1): 302-310.

[11] T. Esram, J. W. Kimball, P. T. Krein, P. L. Chapman and P. Midya. 2006. Dynamic maximum power point tracking of photovoltaic arrays using ripple correlation control. IEEE Trans. Power Electron. 21(5): 1282-1291.

[12] Y. H. JI, D. Y. Jung, J. G. Kim, T. W. Lee and C. Y. Won. 2011. A real maximum power point tracking method for mismatching compensation in PV array partially shaded conditions. IEEE Trans. Power Electron. 26(4): 1001-1009.

[13] N. Femia, G. Lisi, G. Petrone, G. Spagnuolo and M. Vitelli. 2008. Distributed maximum power point tracking of photovoltaic arrays: Novel approach and system analysis. IEEE Trans. Ind. Electron. 55(7): 2610-2621.

[14] E. Koutroulis and F. Blaabjerg. 2012. A new technique for tracking the global maximum power point of PV arrays operating under partial-shading conditions. IEEE J. Photovol. 2(2): 184-190.

[15] T. L. Nguyen and K. S. Low. 2010. A global, aximum power point tracking scheme employing direct search algorithm for photovoltaic system. IEEE Trans. Ind. Electron. 57(10): 3456-3467.

[16] E. V. Paraskevadaki and S.A. Papathanassiou. 2011. Evaluation of MPP voltage and power of mc-si PV modules in partial shading conditions. IEEE Trans. Energy Convers. 26(3): 923-932.

[17] A. Woytea, J. Nijsa and R. Belmansa. 2003. Partial Shadowing of photovoltaic arrays with different system configurations: Literature review and field test results. Solar Energy. 74(3): 217-233.

[18] E. Karatepe, M. Boztepe and M. Colak. 2007. Development of a suitable model for characterizing photovoltaic arrays with shaded solar cells. Solar Energy. 81: 977-992.

[19] N. K. Gautam and N.D. Kaushika. 2002. An efficient algorithm to stimulate the electrical performance of solar photovoltaic arrays. Energy. 27(4): 347-361.

[20] N. K. Gautam and N. D Kaushika. 2002. Reliability evaluation of solar photovoltaic arrays. Solar Energy. 72(2): 129-141.

[21] D. Picault, B. Raison, S, Bacha, J.de la casa and J, Aguilera. 2010. Forecasting photovoltaic array power production subject to mismatch losses. Solar Energy. 84(7): 1301-1309.

[22] Z.M. Salameh and F. Dagher. 1990. The effects of electrical array reconfiguration on the performance of a PV-powered volumetric water pump. IEEE Trans. Energy Convers. 5(4): 653-658.