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Maximum Power Enhancement of Partially Shaded Photovoltaic Array by Advanced Total Cross-Tied Based Configuration

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Abstract **— Partial shading in solar photovoltaic arrays reduce the maximum power produced. Partial shading conditions in PV arrays can be caused by water, dust, tree shadows, bird-drops, nearby building, etc. Special configuration is needed to reduce the effect of partial shadings. In this study, 8 × 8 symmetric photovoltaic arrays configured in different configurations such series-parallel (SP), total cross-tied (TCT), modified complementary sudoku puzzle (MCSDKP) and symmetric matric total cross-tied (SMTCT) are studied under row shading of 25% shaded area and 50% shaded area with two different shading irradiance conditions of uniform shading irradiance and non-uniform shading irradiance. All of the performance results are carried out by MATLAB/Simulink. This study shows that advanced total cross-tied based configurations perform higher than other configurations in all conditions. The objective of this study is to understand the importance of array configurations and to get maximum power under partial shaded conditions.**

Keywords— Partial shading, SMTCT, Maximum power produced, Shaded area, Shading irradiance.

I. INTRODUCTION

In modern world, solar photovoltaic (SPV) technology is the most popular type of renewable energy because it is more reliable and effective than other types of renewable energies if it is used in correct ways. Partial shading in SPV system is one of the main problems in degradation of its performance. The most important challenge in using PV systems is to extract maximum power production from PV arrays [1]. PV array having 6 × 6 sized with various configurations of total cross-tied, honey comb, bridge link, series-parallel and series-parallel cross-tied are compared with triple-series-parallel ladder topology under shading conditions of short and wide, long and narrow, long and wide, short and narrow, middle and diagonal in literature [2]. It is found that the proposed configuration performs 0.1% to 20% better than other configurations under various partial shadings. 4 × 4 size of commercially available PV modules connected in SP and TCT configurations has been studied under two moving partial shading patterns of horizontal and vertical. It is found that TCT connected modules give the better performance [3]. The knight pattern PV array configuration scheme is proposed in literature [4]. This proposed configuration is compared with traditional series-parallel (SP), total cross-tied (TCT) configuration and sudoku-puzzle based configuration under various shading conditions. It is found that the proposed knight configuration has less mismatch losses. In literature [5], 8 × 8 TCT and SMTCT PV array configurations are examined under three shading conditions of street light lamp shading, triangular or building shape shading and single corner shape shading. For all the conditions, SMTCT configuration is noticeably perform better than TCT configuration. An extensive comparative study of traditional total cross-tied, novel total cross-tied, shape-do-ku and symmetric matrix based total cross-tied having 4 × 4 array size under three partial shading conditions is shown in literature [6]. This study shows that SMTCT configuration has less power losses and high fill factor than other configurations under partial shaded conditions. Literature [7] shows the useful knowledge in studying effect of shading in PV panel of different connections. It also shows that different configurations effect different in maximum output power.

This paper is composed of five main sections. Introduction to effective of partial shading in PV arrays is presented in section I. Section II presents different PV array configurations used in this study.

Case study of this paper is presented in section III. Results obtained from simulation is discussed in section IV. And, this paper is concluded in section V.

II. PV ARRAY CONFIGURATIONS

In this section, traditional series-parallel (SP), total cross-tied (TCT) and proposed symmetric matrix total cross-tied (SMTCT) configuration and advanced configuration of modified complementary sudoku puzzle (MCSDKP) configuration are presented.

A. Series-Parallel (SP) Configuration

In series-parallel (SP) configurations, solar modules are connected in series to become strings and all of these strings are connected in parallel to become arrays. Figure 1 presents the wiring diagram of 8 × 8 PV array connected in SP configuration.

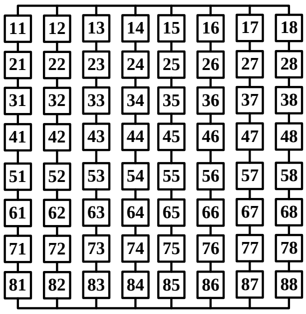


Fig. 1. Sample wiring diagram of series-parallel configuration.

B. Total Cross-Tied (TCT) Configuration

Total Cross-Tied (TCT) configuration is the modified version of Series-Parallel (SP) configuration. It is formed by connecting cross-tied in SP configuration. It is more complex than SP configuration. Figure 2 shows the example wiring diagram of TCT configuration.

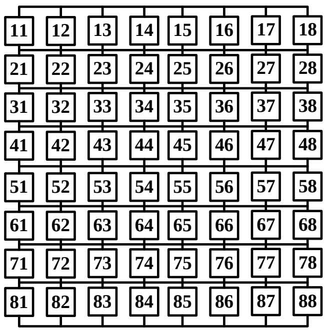


Fig. 2. Sample wiring diagram of total cross-tied configuration.

C. Symmetric Matrix Total Cross-Tied (SMTCT) Configuration

SMTCT is the modified version of TCT configuration and it has four unique properties such (a) row property, (b) column property, (c) single diagonal property and (d) repeated sub-matrix property [5, 6]. In row and column properties, numbers are sequentially in order e.g. 1, 2, 3, …, n. The last number of PV array are just in all diagonal position so it is called diagonal property. When the arrays are divided into four sub-arrays, the first two sub-arrays are repeated in last two positions. It is sub-matrix property. Figure 3(a) to 3(d) shows the four unique properties of SMTCT configuration and Fig. 4 shows the wiring diagram of SMTCT PV array configuration.

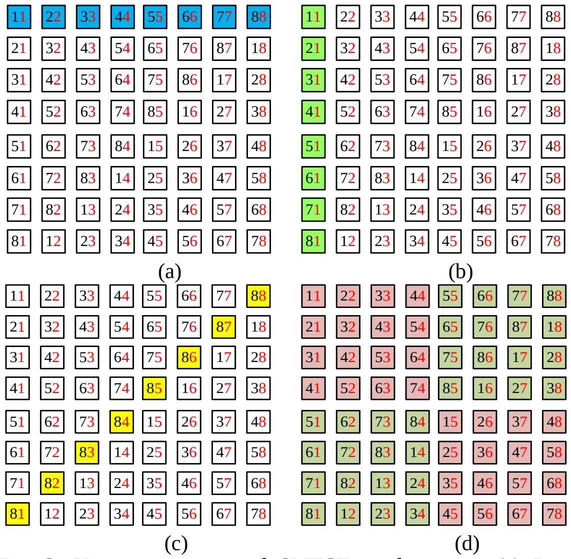


Fig. 3. Unique properties of SMTCT configuration: (a) Row Property, (b) Column Property, (c) Single Diagonal Property and (d) Repeated Sub-Matrix Property.

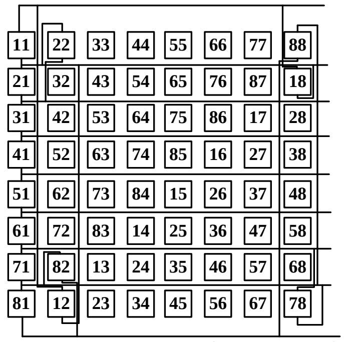


Fig. 4. Sample wiring diagram of SMTCT configuration.

D. Modified Complementary SuDoKu Puzzle (MCSDKP) Configuration

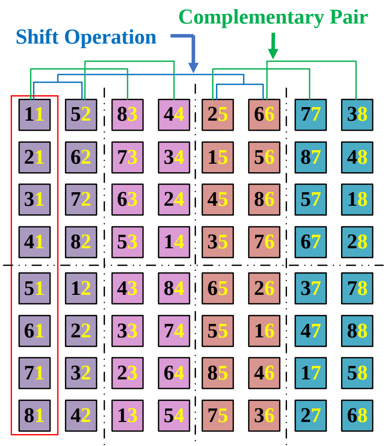


Fig. 5. Construction of 8 × 8 MCSDKP configuration.

MCSDKP is the configuration based on the rules of the sudoku puzzle. Basic rules to construct sudoku puzzle of 8 × 8 size are each row and column must contain the numbers from 1 to 8 without repetitions, the digits can only occur once per block and the sum of every single row and column must be 36. In this puzzle, numbers can be placed as randomly not in specific order. But in MCSDKP configuration, it follow these basic rules and it also has some other specific rules such as (1) The module row numbers within column 1 must be sequentially numbered, (2) The circular shift operation pair is defined as the numbers in the previous column are shifted by four. Each Pair of complementary modules must be located in the same row [8]. Figures 5 and 6 show the rules for construction of MCSDKP configuration.

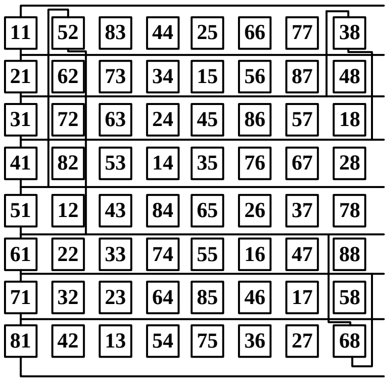


Fig. 6. Sample wiring diagram of 8 × 8 MCSDKP configuration.

III. CASE STUDY

This section shows all of the case study and results of this study.

A. PV Module Parameter and Shading Conditions

A total of sixty-four PV modules are connected in series-parallel (SP), total cross-tied (TCT) and symmetric matrix total cross-tied (SMTCT) configuration to have a maximum power of 25 kW. Table I shows the PV module parameters of SOMERA VSM.72.AAA.05 [AAA=385] monocrystalline solar PV module used in this study.

Table I. Parameters of selected PV module.

PV Module Parameters	Value
Maximum Power (P_{max})	385 W
Voltage at Maximum Power (V_{max})	40.3 V
Current at Maximum Power (I_{max})	9.56 A
Open Circuit Voltage (V_{OC})	48.9 V
Short Circuit Current (I_{SC})	10.14 A
Number of Cells	72

Table II. Conditions of Shading and Shading Irradiance.

Topology	Row Shading Condition			
	25% shaded Area with Uniform Shading Irradiance	*50% shaded Area with Uniform Shading Irradiance*	*25% shaded Area with Non-Uniform Shading Irradiance*	*50% shaded Area with Non-Uniform Shading Irradiance*
SP	Case – I	Case – II	Case – III	Case – IV
TCT				
SMTCT				
MCSDKP				

And all of the PV array configurations are examined under row shading of shaded area 25% and 50% with different shading irradiance level of uniform shading irradiance and non-uniform shading irradiance. Table II presents conditions of partial shading in this study.

Sample shading patterns with shading irradiance conditions are shown in Fig. 7.

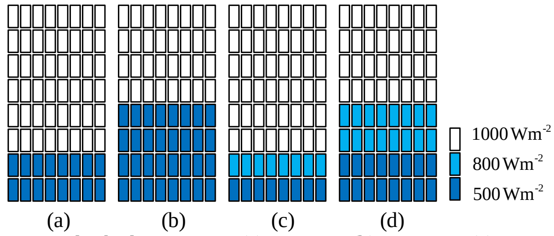


Fig. 7. Sample shading Pattern: (a) Case – I; (b) Case – II; (c) Case – III and (d) Case – IV.

B. MATLAB/Simulink Model

MATLAB/Simulink model of 8 × 8 SMTCT configuration and MCSDKP configuration are shown in Figs. 8(a) and 8(b) For Simulink model, irradiance of 1000 Wm^{-2} is set to unshaded modules and irradiance of 500 Wm^{-2} is set to shaded modules. Simulation temperature is kept at 25˚C and 45˚C for two different conditions.

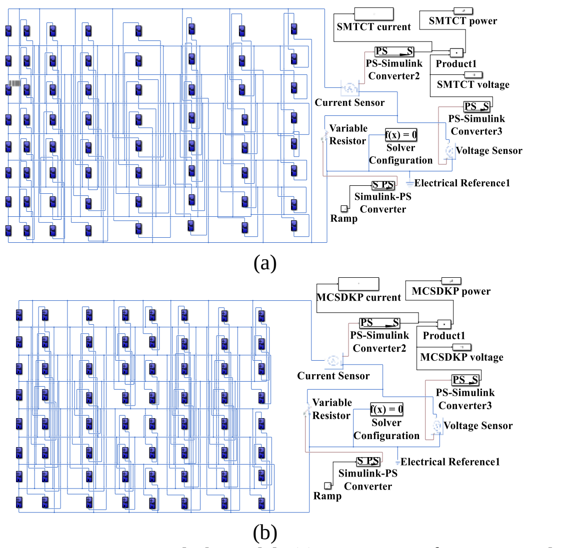


Fig. 8. MATLAB/Simulink Model: (a) SMTCT configuration and (b) MCSDKP configuration.

C. Power Losses and Performance Enhancement

Power losses and performance enhancement of the PV arrays configuration under partial shading conditions is also important. The lesser the power losses the better the performance of the system is.

Power losses percentage of the PV arrays configurations under partial shading can be calculated as

$$\text{Power Losses Percentage}\,(\%) = [1 - \frac{P_{shaded}}{P_{unshaded}}] \times 100\ \% \tag{1}$$

P_{shaded} = Power Production at Partially Shaded Condition

$P_{unshaded}$ = Power Production at Unshaded Condition

Performance enhancement between two PV array configurations under partial shaded condition can be calculated as

$$PE(\%) = \left(\frac{P_A}{P_B} \times 100\right) - 100 \tag{2}$$

, where

P_A = PV array giving higher power under partial shading condition

P_B = PV array giving lower power under partial shading condition

IV. SIMULATION RESULTS AND DISCUSSION

Simulation results of all PV array configurations under different conditions are discussed in this section. When PV modules receive an irradiance level of 1000 Wm^{-2} and temperature 25˚C, all of the configurations produce a maximum power of 25.06 kW each. Figure 9 shows the P-V characteristic curves for this condition.

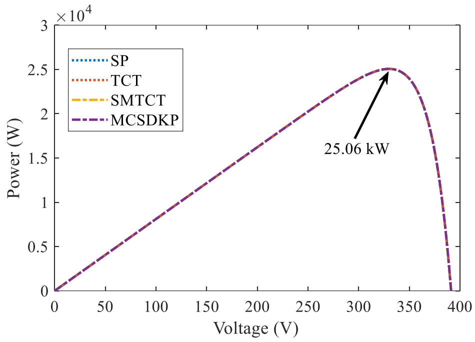
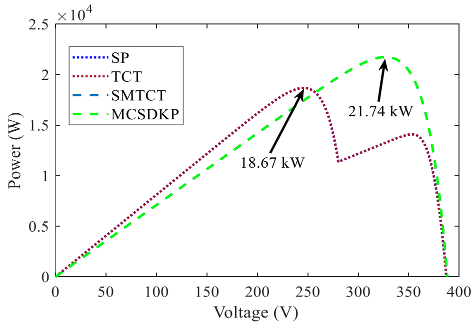
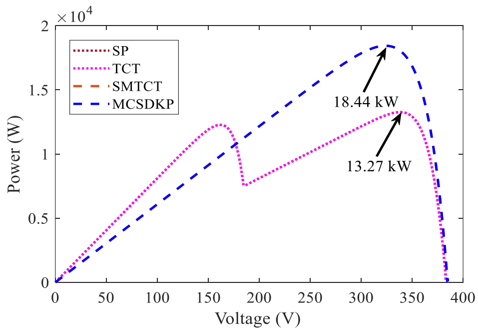


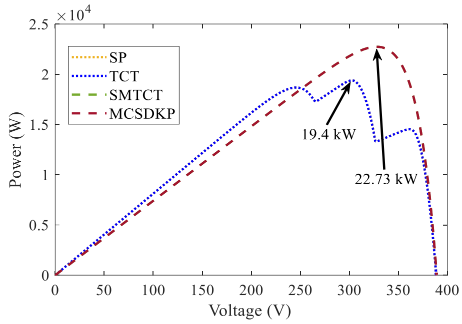
Fig. 9. P-V Characteristic curves under irradiance of 1000 Wm^{-2} and temperature of 25˚C.



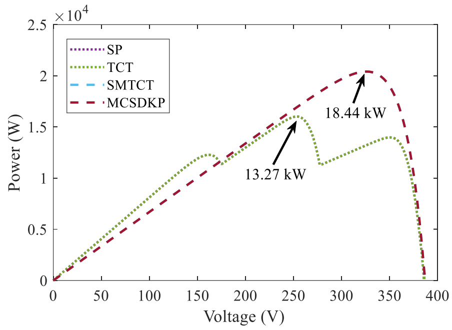
(a)



(b)



(c)



(d)

Fig. 10. P-V Characteristic curves of shading condition: (a) Case – I; (b) Case – II; (c) Case III and (d) Case – IV under temperature 25˚C.

Simulation results of shading condition case – I to case – IV under temperature 25˚C is shown in Fig. 10(a) to 10(d). In this condition, SMTCT and MCSDKP configurations produce more maximum power than SP and TCT configurations. Power output comparison of all PV array configuration of shading condition Case – I to Case – IV under temperature 25˚C is shown Fig. 11.

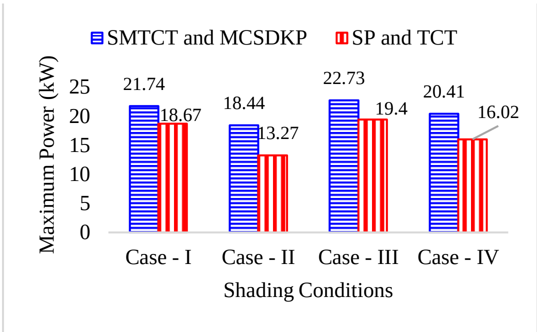


Fig. 11. Power output comparison under temperature of 25˚C.

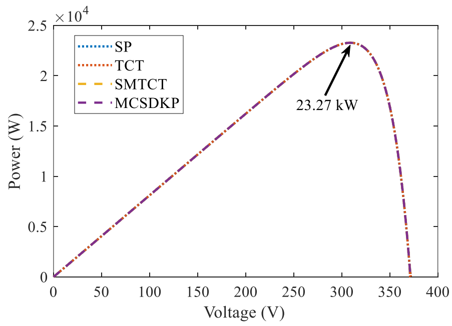
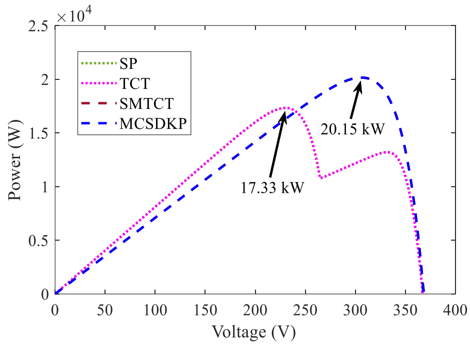
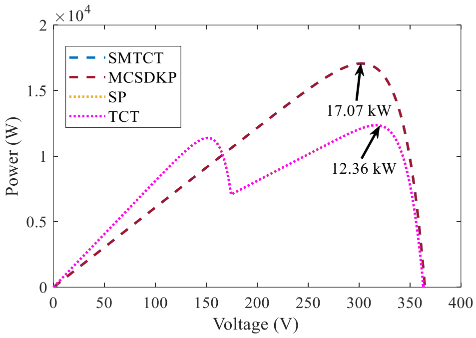


Fig. 12. P-V Characteristic curves under irradiance of 1000 Wm^{-2} and temperature of 45˚C.

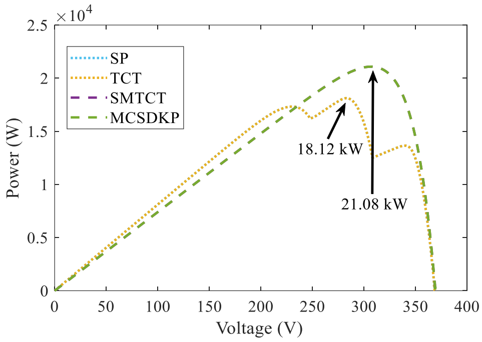
When PV modules receive an irradiance level of 1000 Wm^{-2} and temperature 45˚C, all of the configurations produce a maximum power of 23.27 kW each. Figure 12 shows the P-V characteristic curves for this condition.



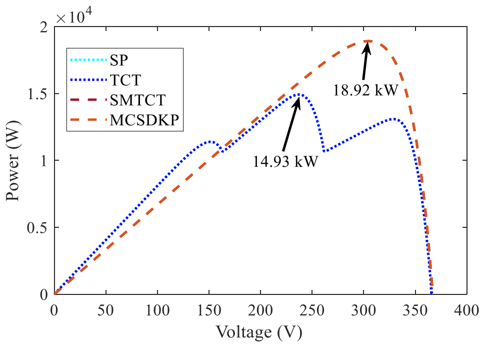
(a)



(b)



(c)



(d)

Fig. 13. P-V Characteristic curves of shading condition: (a) Case – I, (b) Case – II, (c) Case III and (d) Case – IV under temperature 45˚C.

Simulation results of shading condition case – I to case – IV under temperature 45˚C is shown in Fig. 13(a) to 13(d).

In this condition, SMTCT and MCSDKP configurations also produce more maximum power than SP and TCT configurations. Power output comparison of all PV array configuration of shading condition Case – I to Case – IV under temperature 45˚C is shown Fig. 14.

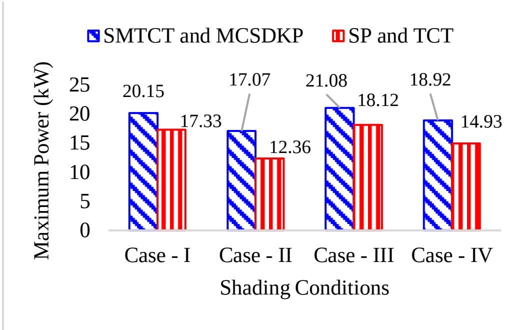


Fig. 14. Power output comparison under temperature of 45˚C.

Power losses of SMTCT and MCSDKP configurations under both 25˚C and 45˚C is lesser than SP and TCT configurations for all shading conditions. Figure 15 shows the power losses percentage of all PV array configurations under temperature of both 25˚C and 45˚C for all shading conditions.

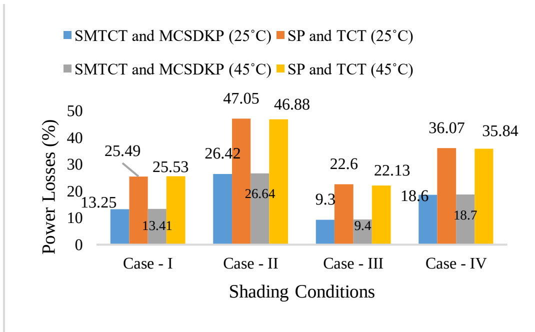


Fig. 15. Power losses percentage of PV array under different temperature and shading conditions.

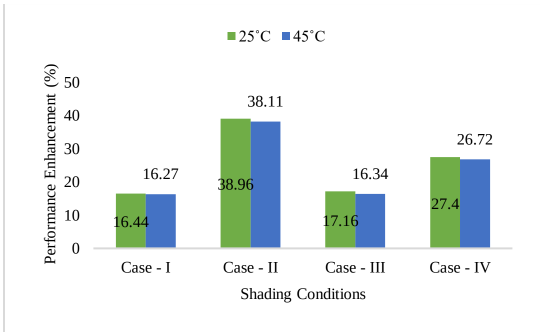


Fig. 16. Performance enhancement of SMTCT and MCSDKP configurations.

And then, SMTCT and MCSDKP configuration perform better than SP and TCT configuration under all shading conditions of different temperature. Performance enhancement percentage of SMTCT and

MCSDKP configurations over SP and TCT configurations is shown in Fig. 16.

V. CONCLUSION

Advanced total cross-tied based configurations of SMTCT and MCSDKP configurations produce more 3.07 kW in Case – I, 5.17 kW in Case – II, 3.3 kW in Case – III and 4.39 kW in Case – IV under temperature of 25˚C and more 2.82 kW in Case – I, 4.71 kW in Case – II, 2.96 kW in Case – III and 3.99 kW in Case – IV under temperature of 45˚C. This shows SMTCT and MCSDKP outperform SP and TCT under all shading conditions with different temperature. For PV array size of larger than 8 × 8, it is difficult to build MCSDKP configuration than SMTCT because of its complex complementary and shift operation pairs. In this study, SMTCT and MCSDKP configuration give same performance under all shading conditions of different temperature. So, symmetric PV array should be configured as SMTCT configuration rather than tradition SP and TCT configurations and one of the advanced total cross-tied configurations of MCSDKP.

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