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Reconfiguration strategies for reducing partial shading effects in photovoltaic arrays: State of the art

G. Sai Krishna*, Tukaram Moger

Department of Electrical and Electronics Engineering, National Institute of Technology Karnataka, Surathkal, India

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ABSTRACT

Power delivered by a Photovoltaic (PV) cell reduces significantly due to non-uniform irradiance. Consequently, in the case of PV module or array, the generated output power get reduces and further deteriorates the overall system performance. The reduction of output power is not directly proportional to the shading area but depends on the shading pattern and type of array configuration chosen. Many solutions have been reported in the literature to reduce partial shadings. However, the reported solutions may fail to enhance maximum power to the possible extent. Therefore, to compensate these power losses a promising technique is required which relies on reconfiguration strategies, namely reconfigure the PV modules within the PV array in order to increase maximum power at a higher level. These strategies are classified into dynamic and static reconfiguration techniques. This paper presents the state of the art of reconfiguration strategies for PV array's to increase maximum power under partial shading and mismatch conditions. In addition to this, the challenging issues for hardware implementation of both dynamic and static reconfiguration techniques are discussed in this paper. Based on the review study, it can be concluded that the dynamic reconfiguration techniques are relatively expensive, but this can effectively compensate the partial shading and mismatch effects in PV array as compared to static technique.

1. Introduction

The utilization of electrical energy is increasing day by day worldwide. As power consumption increases, the demand for energy production from power stations also increases. As per the reports (Manju and Sagar, 2017), India is the world's third-largest energy producer and fourth largest energy consumer, and also well equipped with exhaustible as well as renewable energy sources (RES). The exhaustible energies are also known as conventional energies such as coal, oil, gas, and fossil fuels, etc. The use of conventional energies causes environmental degradation due to the 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 can be considered as the most essential and prerequisite sustainable resource because of its ubiquity and abundance in nature (Sahoo, 2016; Pandey et al., 2016). The efficiency of PV modules is very poor, even though, it is a great opportunity for several applications including residential and commercial buildings, electric vehicles, water pumping systems and rural applications. However, the generated PV power mainly depends on the solar irradiance (G) and ambient temperature (T). These two parameters decide the maximum power point (MPP) of a PV module. Due to non-linear characteristics of PV modules brings many challenges: (i) the energy provided by the sun is restricted by the low PV module conversion efficiency (Green et al., 2015; Meral and Dinçer, 2011), (ii) the cost of PV production per kW is high, (iii) the energy generated from PV is not constant because it entirely depends on the irradiance and temperature, and (d) the PV modules are not working efficiently under partial shadings. Therefore, all the factors mentioned above are creating a gap between the actual energy production and the energy extracted.

Nowadays, the scientific community is working towards further improvement to increase the conversion efficiency of PV modules and reduce the cost per kW (Parida et al., 2011; Singh, 2013). In addition, many authors are developed new maximum power point tracking (MPPT) algorithms to track maximum power of a PV system (Mellit and Kalogirou, 2014). MPPT is an algorithm embedded along with power electronic converter and load. It forces the PV module to operate at MPP in any given solar irradiance (Kamarzaman and Tan, 2014). A few years ago, the research in PV field has taken the leading edge to develop reconfiguration strategies, means 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 broadly classified into (1) dynamic PV Array reconfiguration (DPVAR) techniques and (2) static PV Array reconfiguration (SPVAR) techniques.

* Corresponding author.
E-mail address: saikrishna240@gmail.com (G. Sai Krishna).

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Notations

$V_{cell/pv}$	PV cell/ module voltage (V)
$I_{cell/pv}$	PV cell/ module current (A)
I_d	diode current of a PV cell (A)
I_{sh}	shunt current of a PV cell (A)
T_c	PV module operating temperature
T_{STC}	standard operating temperature at 298.15 K
I_{do}	reverse saturation current in STC
K_{isc}	temperature co-efficient of short circuit current
a	ideality factor
k	Boltzmann's constant 1.3805×10^{-23} J/K
q	electron charge 1.6×10^{-19} C
G	actual irradiance of PV module
R_s, R_{sh}	series and shunt resistance of a PV cell
N_s	number of cells connected in series of a PV module
G_{STC}	standard PV irradiance at 1000 W/m^2
m	number of rows
G_i	irradiance of each row

Abbreviations

STC	Standard Test Condition
PSC	Partial Shading Condition
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
GP	Global Peak
SP	Series-Parallel
TCT	Total-Cross-Tied
DPVAR	Dynamic PV Array Reconfiguration
SPVAR	Static PV Array Reconfiguration
IE	Irradiance Equalization
EI	Equalization Index

In dynamic reconfiguration, the connection layout of PV modules in the PV array is changing dynamically based on irradiance levels for increasing maximum power. The control structure of DPVAR is depicted in Fig. 1. It consists of a data acquisition system (DAQ), which requires suitable measurement devices to collect field data need for the PV mathematical model. Whereas, the mathematical model quantify the unknown parameters, then providing input to the reconfiguration algorithm. This algorithm identifies optimum configuration and accordingly gives control action to the switching matrix. In static reconfiguration, the physical location of modules in PV array are changing without altering electrical connections to distribute shading effects to increase power output. The various stages of SPVAR technique are depicted in Fig. 2. It requires only reconfigurable pattern for arranging PV modules in order to distribute shading effects over the PV array.

The reconfiguration strategies can be applied to different types of applications: (a) First case; if the PV plant is affected by the shadow projected by a fixed object. This is common for PV plants placed on roofs or integrated in buildings. As an example, in Celik et al. (2015), the dynamic reconfiguration approach has been applied to Building Integrated Photovoltaic Systems (BIPV)(Zhu et al., 2019). BIPVs are of great interests since they enable to take advantage of wide areas exposed to sunlight offered by buildings (Obane et al., 2012, 2011). In such type of applications, the static reconfiguration approach can also applied to distribute the fixed shadow into different places equally. (b) Second case; the portion of a large PV plant is affected by passing clouds. In this case, generally there is a distributed drop of the irradiance above the PV plant. Depending on the speed of the clouds producing a shade on the PV plant, the irradiance conditions can change suddenly, giving rise to a large deterioration of the PV plant efficiency that may last a long time, thus producing a reduction of the energy generated by the solar source. Finally, in the event of failure of one or many solar modules, which can be automatically disconnected by using dynamic approach (La Manna et al., 2014). However, in case of static technique, PV modules are rearranged such a way that the irradiance is equally spreading.

The partial shading issues of PV array involves many stages, which represented in a pictorial way is shown in Fig. 3. It consists of PV array, operating conditions, P-V output characteristics, moreover, partial shading reduction techniques such as PV array interconnections, distributed MPPT, multi-level inverters and reconfiguration strategies. In the following sections, each of the cited element in the diagram is discussed in detail. However, this paper is mainly focusing on the state of the art of reconfiguration strategies for PV array's to increase maximum power under partial shading and mismatch conditions.

The following sections of the paper are organized as follows. Section 2, presents the detailed modelling of PV module. In Section 3, general issues with the partial shading and mismatch effects on PV modules are outlined. In Section 4, different partial shading reduction techniques are discussed and more emphasis is given to reconfiguration strategies in Section 4.2.3. In Section 5, the challenging issues of dynamic and static reconfiguration techniques are addressed and followed by discussions and conclusion are presented in Sections 6 and 7 respectively.

2. Modelling of photovoltaic module

Modelling is the first step for analysing the behaviour of a PV system. In fact, a good and accurate mathematical model is necessary for the optimal design and simulation of PV array under partial shading. The modelling of PV array starts with a mathematical model of a single PV cell. Several models for solar cell have been reported in the literature. Two of them are single diode solar cell and two diode solar cell models. The single diode solar cell model is thoroughly analysed and its practical verification is presented in (Xiao et al., 2013; Breitenstein, 2014). In Babu and Gurjar (2014), the two diode model and the associated mathematical formulation are described. As it is mentioned in

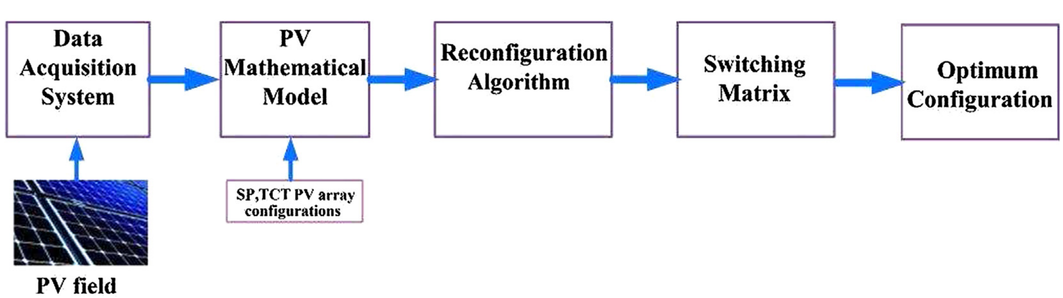


Fig. 1. Dynamic PV array reconfiguration structure.

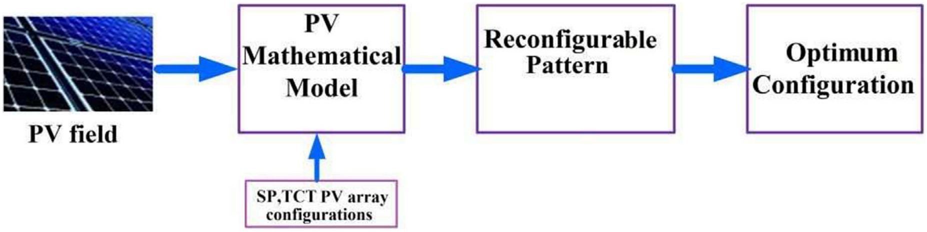


Fig. 2. Static PV array reconfiguration structure.

the literature, the single diode solar cell model is very simple and ease to modelling as compare to the two diode solar cell model (Hasan and Parida, 2016). The equivalent circuit of single diode PV cell model is shown in Fig. 4.

By applying KCL to node 'c' in Fig. 4, I_{cell} can be written as,

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

where $I_{L,cell}$ is light generated current of the PV cell. The mathematical representation of I-V characteristics for the PV cell is given in Eq. (2),

$$I_{cell} = I_{L,cell} - I_o[exp\{\frac{q(V_{cell} + I_{cell}R_s)}{kaT_c} - 1\}] - \frac{(V_{cell} + I_{cell}R_s)}{R_{sh}} \tag{2}$$

where I_o is saturation current of the diode. Eq. (2) is working only for uniform case. However, it is not suitable for the partial shadings. In the presence of shadows, where there is no exposure to sunlight, a solar cell will heat up and develop a hot spot. To reduce the overall effect of shadows, a bypass diode is to connect across the shaded cells to pass the full amount of current while preventing damage to the solar cell is shown in Fig. 5. There are two types of shadings effects can be modelled; (i) dynamic shading, and (ii) static shading. Dynamic modelling of effect of clouds on the PV system is a difficult task. Cloud conditions can dramatically change fast and the cost of such fluctuations with their effect on other systems is important to understand. One of the methods is proposed (Jewell and Unruh, 1990; Tamura et al., 2003) to measures the changes in solar irradiance over a one minute time interval. In static shading effects are assumed to be constant, which can be modelled using MATLAB/SIMULINK. Various mathematical models are reported in the literature for solving accurate I-V characteristics under partial shadings (Quaschning and Hanitsch, 1996). The mathematical expression of I-V characteristics for the PV cell under partial shading is given in Diqing et al. (2012),

$$I_{cell} = I_{L,cell} - I_o[exp\{\frac{q(V_{cell} + I_{cell}R_s)}{kaT_c} - 1\}] - \frac{(V_{cell} + I_{cell}R_s)}{R_{sh}} + I_{o,bd}[exp\{\frac{-qV_{cell}}{kaT_c} - 1\}] \tag{3}$$

where $I_{o,bd}$ is the saturation current of the bypass diode. The transition from a single PV cell to the module is by connecting number of PV cells in series. The mathematical representation of I-V characteristics for PV module under uniform case is given by Eq. (4).

$$I_{pv} = I_L - I_o[exp\{\frac{q(V_{pv} + I_{pv}R_S)}{kN_s aT_c} - 1\}] - \frac{(V_{pv} + I_{pv}R_S)}{R_{SH}} \tag{4}$$

where R_S and R_P are the series and shunt resistance of the module and I_L represents the light generated current of the module, which is referred as,

$$I_L = \frac{G}{G_{STC}}[I_{LSTC} + K_{isc}(T_c - T_{STC}))] \tag{5}$$

where I_{LSTC} is light generated current at STC.

As mentioned in Section 1, reconfiguration techniques alter the position of PV modules based on irradiance. So that, it is necessary to evaluate the irradiance of the module. By substituting Eq. (5) in Eq. (4), the obtained expression is,

$$G = \frac{G_{STC}}{[I_{LSTC} + K_{isc}(T_c - T_{STC}))]}[I_{pv} + I_o[exp\{\frac{q(V_{pv} + I_{pv}R_S)}{N_s ka(T_c/q)} - 1\}] - \frac{(V_{pv} + I_{pv}R_S)}{R_{SH}} \tag{6}$$

Eq. (6) provides a way to estimate the irradiance of the module by measuring its voltage, current, and temperature. Assuming that the other terms are given by the datasheet. However, to model the complete PV cell requires electrical data as well as physical data. The electrical data such as open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), voltage at maximum power (V_{mp}), current at maximum power (I_{mp}), and rated maximum power (P_{mp}) is provided by the manufactured companies. The physical data like R_s, R_{sh}, I_o, n, and I_L are to be evaluate by using either analytical or iterative approaches (Yadir et al., 2009; Sera et al., 2007).

3. Partial shading and mismatch effects

Generally, PV array is working under two possible conditions, such as uniform irradiance condition (UIC) and partial shading condition. In uniform condition, all PV modules in PV array receives equal irradiance. So that, each module can produce the same amount of maximum power and improves overall array performance. In uniform case, the output I-V and P-V characteristics of the array is shown in Fig. 6(a) and (b) respectively. In any case, PV array is shaded by a tree, building and passing clouds, partial shading would occur. In PSCs, the amount of irradiance received by the shaded module is less than the unshaded ones, this scenario creates a hot-spot problem in PV array. Further, it may lead to damage the PV cells or modules (Kamarzaman and Tan, 2014). However, to overcome this, a bypass diode is connected across each PV module to provide an alternative current path during partial shadings. Under this condition, each PV module would generate different I-V characteristics, which lead to mismatch losses in the PV system. The mismatch losses are categorized into internal and external mismatch loss. Internal mismatch loss is due to several factors like non-homogeneous characteristics of solar cells, manufacturing defects, faulty solar cells, malfunction of PV modules and physical effect of doping (Mäki and Valkealahti, 2012; Ramos-Paja et al., 2012). The external factors include degradation of cell material, dirt deposited on the cell surface, different temperatures and irradiance conditions (Zhao et al., 2012; Skoplaki and Palyvos, 2009). Therefore, all these factors may lead to a reduction of the modules performance in PV array. Under partial shading, the obtained maximum power is less than the maximum power of uniform condition. However, these losses cannot be avoided, but it can be minimized using effective techniques.

4. Partial shading reduction techniques

Many techniques have been reported in the literature for reducing the PS losses. These techniques are mainly classified into two types; (1) passive techniques and (2) active techniques.

4.1. Passive techniques

In passive techniques, the most commonly used passive element is the bypass diode for reducing PS effects. The role of bypass diode is already discussed in Section 3. Bypass diode protects the PV modules

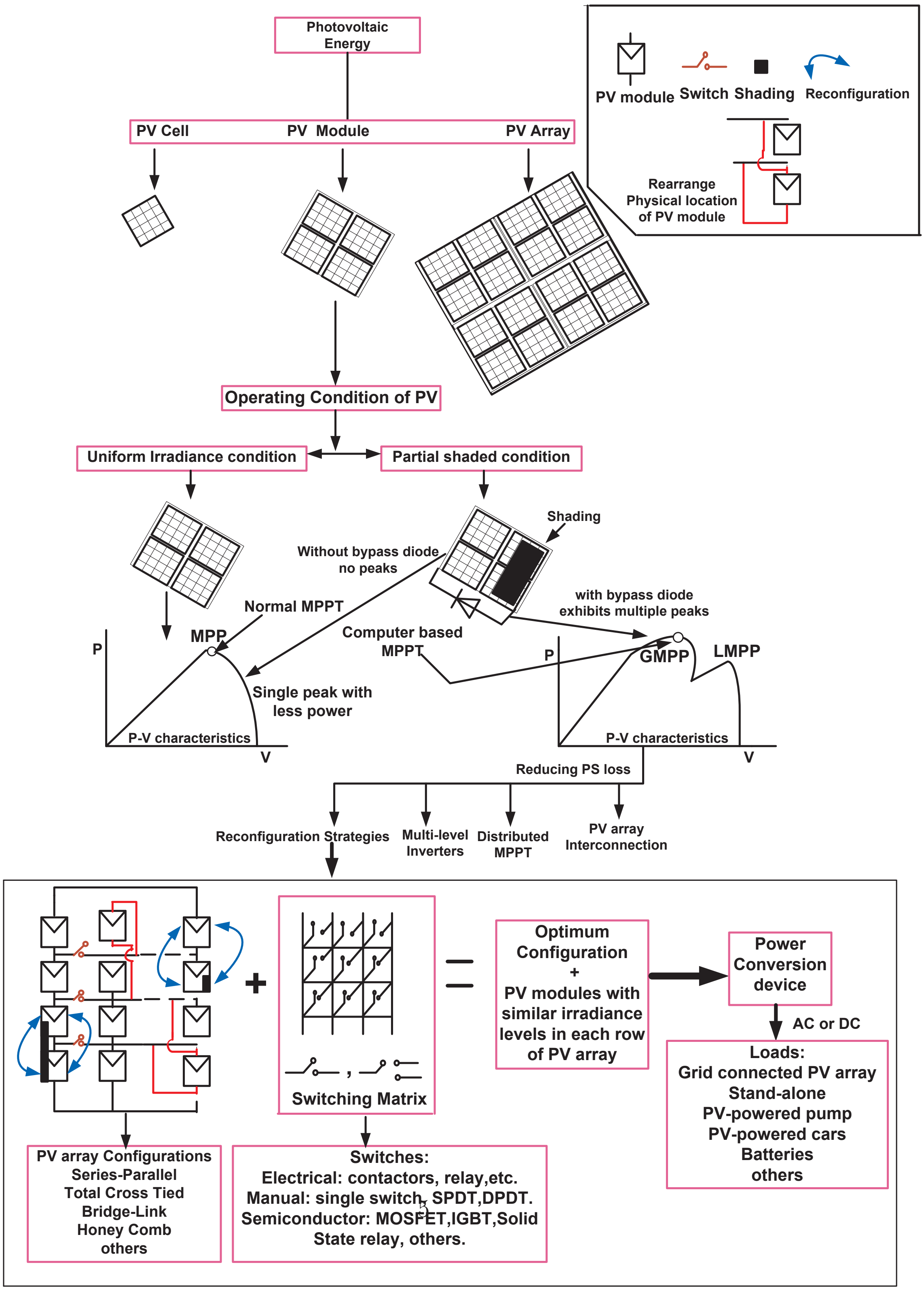


Fig. 3. Various stages of partial shading reduction in PV array: Taxonomy.

from the heating and increases overall power output under shading condition. Due to insertion of bypass diodes exhibits multiple steps in I-V and multiple peaks in P-V characteristics of the array, which can be seen in Fig. 6(a) and (b) respectively. Among the multiple peaks, there is only one global peak which produces the highest maximum power and rest all are referred to local peaks (Larbes et al., 2009; Ishaque et al., 2012).

4.1.1. PV array interconnections

The efficiency of PV modules exposed to partial shading can be increased by applying interconnection to the modules. The interconnection of modules in PV array is commonly referred as

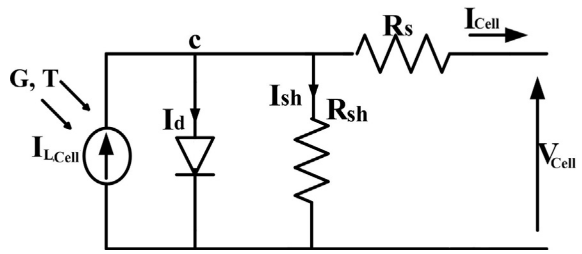


Fig. 4. Equivalent circuit of single diode PV cell model.

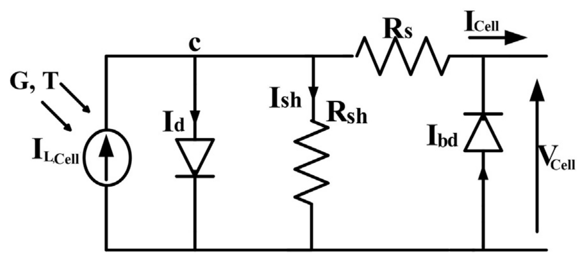


Fig. 5. Single diode PV cell with bypass diode.

configuration. Many PV array configurations have been reported in the literature, which are Simple-Series (SS), Parallel, Series-Parallel (SP), Total-Cross-Tied (TCT), Bridge-Link (BL) and Honey-Comb (HC) (Pendem and Mikkili, 2018b,a). The generic layouts of PV array configurations are shown in Fig. 7. In a series configuration, all PV modules are connected in series to increase desired output voltage, but the output current is same as module current. In parallel configuration, all PV modules are connected in parallel fashion so that the output current will be higher (Wang and Hsu, 2010; Herrmann et al., 1997). The main advantage of parallel configuration over series is that the maximum power of the parallel configuration is higher than the series configuration (Gao et al., 2009). The combination of series and parallel connection gives series-parallel configuration, which increases both output voltage and current at a time. In TCT, first PV modules are parallel tied so that voltages are equal and currents are summed up, and then many of such parallel tied are connected in series to increase the voltage. Bridge-link configuration is same as TCT but half of its connections avoided so that cable losses and wiring installation time are reduced (Roopa et al., 2011; Vengatesh and Rajan, 2016). The TCT and BL configurations have combined to form honey-comb configuration (Wang and Hsu, 2011; Satpathy et al., 2018). In the literature, it has been found that TCT and SP PV array configurations are producing same maximum power under uniform condition. Under PSCs, TCT configuration is reducing the mismatch losses and producing the highest maximum power than the other configurations(Ramaprabha and Mathur, 2012; Ramaprabha et al., 2010).

4.2. Active techniques

The active techniques are more effective than passive techniques for reducing PS effects. These techniques are classified into three categories: (1) Distributed MPPT techniques, (2) Multi-level Inverters and (3) Reconfiguration Strategies.

4.2.1. Distributed MPPT techniques

In this technique, each module or group of modules has its own MPPT, thus avoiding PS losses. Also, this technique eludes the installation of bypass diodes. As a result, the corresponding losses are neglected (Femia et al., 2008; Shmilovitz and Levron, 2012). This technique requires additional components such as DC-DC converters or DC-AC inverters for each module. Moreover, it needs a very complicated structure, which is shown in Fig. 8.

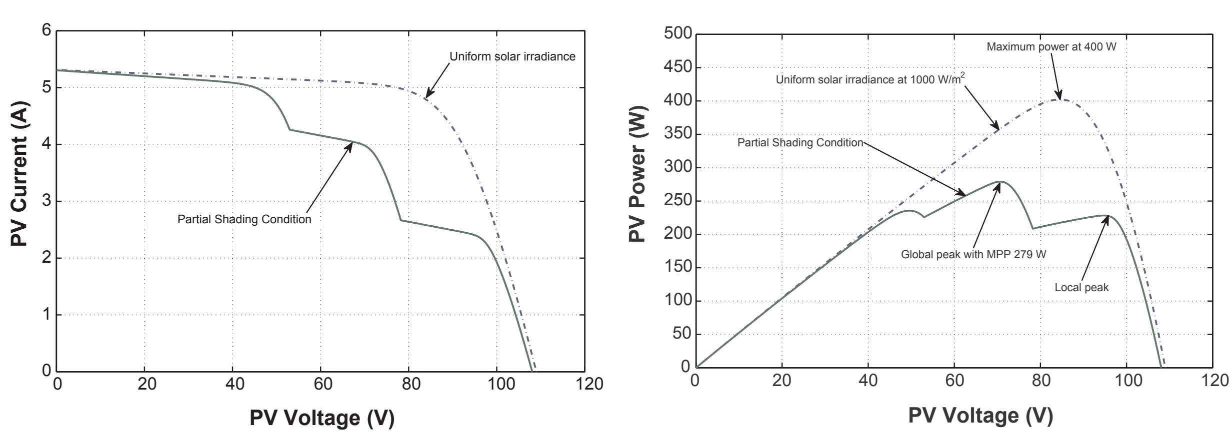
4.2.2. Multi-level inverters

Multi-level inverters (MLIs) new addition to the PV modules for reducing PS losses. MLI topologies such as diode-clamped, flyback capacitor and cascaded H-bridge are used to reduce shading effects on each module or group of modules by the controlling of individual output voltages. Moreover, these inverters reduce the voltage stress on the device and output AC voltage harmonics (Malathy and Ramaprabha, 2015a). However, it requires an effective control structure to achieve operation at the optimal power point (Busquets-Monge et al., 2008; Bratcu et al., 2011). In this approach, each module or group of modules has its own inverter (refer Fig. 9), which would increase the cost of the system. The other important active technique namely reconfiguration strategies which is extensively treated in Section 4.2.3.

4.2.3. Reconfiguration strategies

Reconfiguration strategies are most promising techniques for increasing maximum power under PSCs. In this technique, the PV modules are reconfigure based on irradiance levels, which is a function of their operating conditions or of the load request (Salameh and Dagher, 1990; Auttawaitkul et al., 1998). As mentioned in Section 1, these strategies are classified into; (1) dynamic PV array reconfiguration techniques, (2) static PV array reconfiguration techniques.

4.2.3.1. Dynamic PV array reconfiguration techniques. The dynamic reconfiguration of photovoltaic modules is a useful approach for fighting the detrimental effects of mismatching on their power



(a) I-V characteristics (b) P-V characteristics

Fig. 6. Uniform and Partial shading condition.

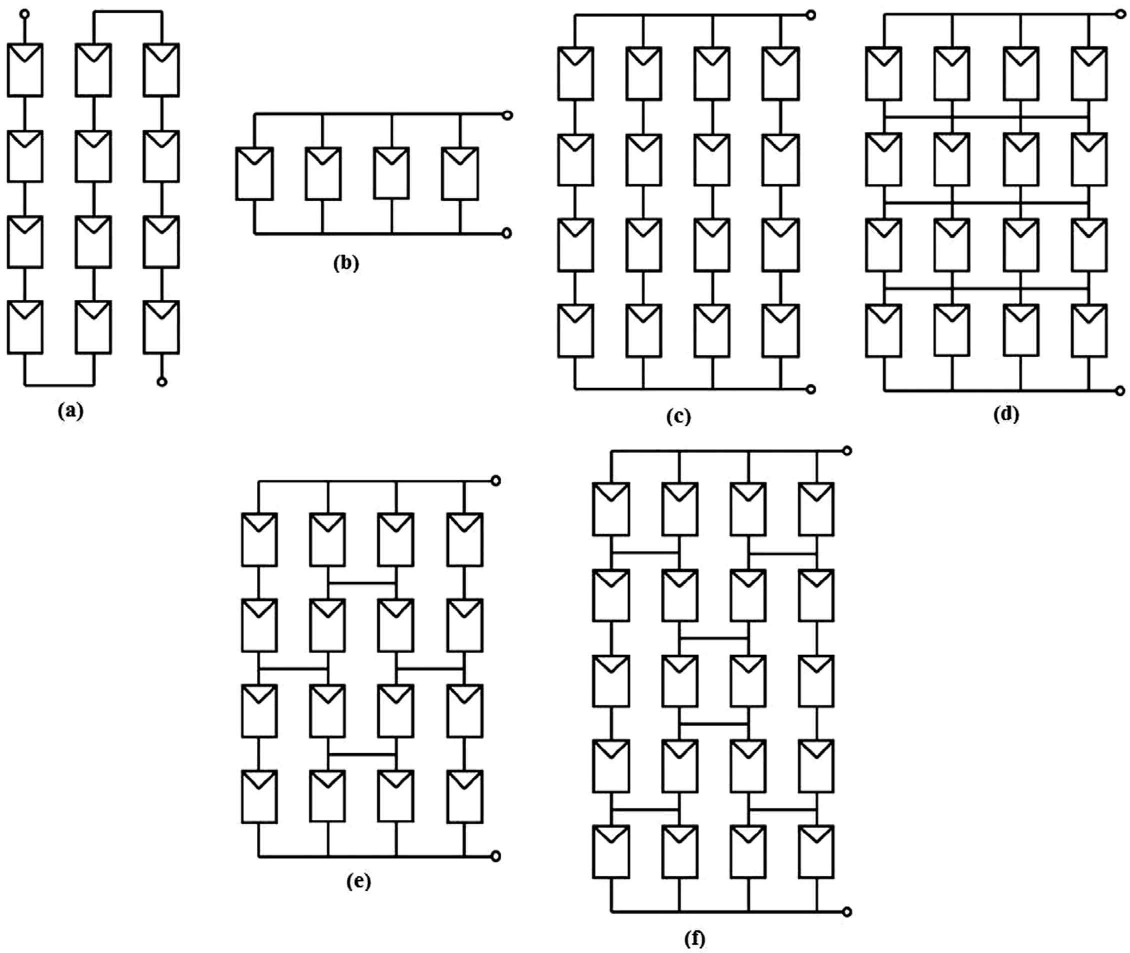


Fig. 7. Different PV array configurations: (a) Simple-Series (SS), (b) Parallel, (c) Series-Parallel (SP), (d) Total -Cross-Tied (TCT) , (e) Bridge-Link (BL) , (f) Honey-Comb (HC).

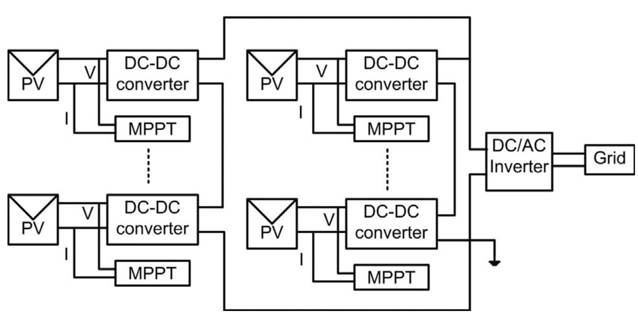


Fig. 8. PV modules with Distributed MPPT.

production. In this approach, the PV module connections are changing dynamically as it is mentioned in Section 4.1.1. However, the real dynamic reconfiguration technique has started by choosing the right PV array configuration, which has the capability of reducing mismatch effects. Many suitable PV array configurations have been reported so far, the most exploited solutions rely on the TCT and SP configurations.

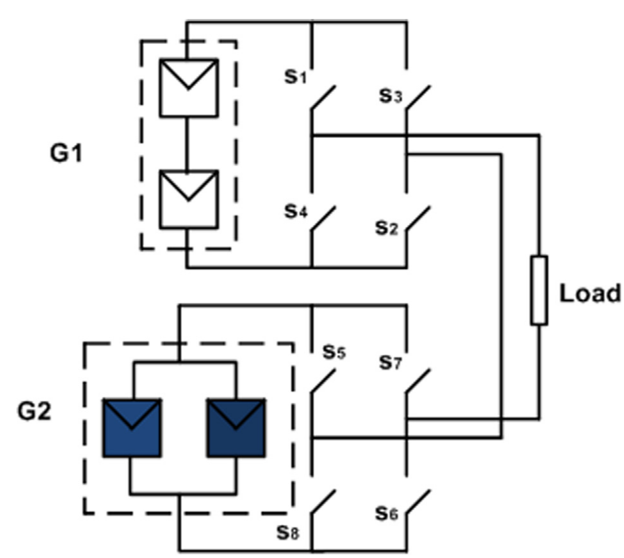


Fig. 9. Grouping of PV modules with multilevel inverters.

4.2.4. *Dynamic reconfiguration control techniques for TCT*

As mentioned in Section 4.1.1, TCT configuration reduces overall mismatch effects and increases maximum power. In TCT, the most challenging part is to connect PV modules with similar irradiance levels in each row, which is known as irradiance equalization (IE). As a result, the circulating current in a string is directly proportional to the sum of individual irradiance of the modules in a single row. In Velasco et al. (2005a,b), an optimization algorithm based on equalization index (EI) has been presented. The main aim of this algorithm is to balance the irradiance of PV modules in each row with the help of electronic switches, thereby minimizing mismatch loss. The switching between PV modules in the array is controlled by proposed algorithm. To calculate the irradiance in each row is denoted by G_i which defined as;

$$G_i = \frac{\sum_{j=1}^{m} G_{ij}}{m} \tag{7}$$

where G_{ij} is irradiance value of the module located at i^{th} row and j^{th} column, and m is the number of modules that are connected in parallel. An illustration of irradiance equalization process in TCT is shown in Fig. 10.

For each configuration, the algorithm calculates equalization index using the following expression:

$$EI = Max(G_i) - Min(G_i) \quad \forall \ i \tag{8}$$

This index quantifies the degree of current limitation of the configuration. Finally, the algorithm choose optimum configuration based on minimized EI and least switching operations.

In Velasco-Quesada et al. (2009), Velasco et al. (2008), proposed a PV generator with Electrical Array Reconfiguration (EAR) system. In EAR PV system is composed of a static part, which is necessary to meet inverter constraints and reconfigurable part is controlled by irradiance equalization (IE) algorithm. In the processes of reconfiguration, the number of configurations is identified by $(m.\ n)!$. The total configurations of interest(C), namely the configurations delivering different values of output power, are with m and n number of rows and columns.

$$C = \frac{(m.\ n)!}{m!.\ (n)!^m}$$

The possible configurations are achieved by using electronic switches. The required number of switches for this operation is given by,

$$N_{sw} = 2N_{pv}$$

where N_{sw} is number of switches of single pole m-throws type and N_{pv} is number of PV modules. It should be noted that if switches are not commercially available in the market, it is necessary to emulate switches according to the number of modules connected in parallel. In Fig. 11, shows the simplified structure of switching matrix for m = n = 3.

In El-Dein et al. (2013), an optimal reconfiguration approach is developed to minimize the Irradiance Mismatch Index (IMI). This optimal problem is formulated by using Mixed Integer Quadratic Programming (MIQP) technique and solved by branch and bound algorithm. The proposed reconfiguration approach is used to change the location of shaded module in half reconfigurable PV array (HRPVA) and full reconfigurable PV array (FRPVA). In HRPVA, first and third columns are fixed, the second and fourth columns are reconfigurable. The total number of switches are required for this operation is $m.\ n_r$. m is the number of rows and n_r is the number of reconfigurable columns. For each reconfigurable module requires double-pole m -throws type switches.

The corresponding switching matrix for a reconfigurable module is shown in Fig. 12(a). A similar approach is presented in Pareek and Dahiya (2016). In this approach, the HRPVA and FRPVA offer multiple solutions for allocation of shaded modules is shown in Fig. 12(b). Form the figure, the black box represents a shaded module. The preferred location of other shaded modules can be any of the green boxes and the non-preferred locations can be any of the blue boxes. Later, the gravitational search algorithm (GSA) is adopted for solving FRPVA is presented in Hasanien et al. (2016).

In Romano et al. (2013), a novel switching matrix is proposed, namely dynamic electrical scheme (DES) is shown in Fig. 13(a). The DES is to implement a large number of PV modules in different rows with similar irradiance levels. In this approach, two different control algorithms have been presented for computing irradiance equalization, which are deterministic and random search algorithms. The main aim of these algorithms is to create a non-equal number of PV modules in each row as shown in Fig. 13(b), thus increases the number of possible configurations. The arrangement time for a given number of PV modules is fixed for the deterministic search algorithm. Whereas, the random search algorithm depends on the ending condition. First, the minimum ($N_{Row_{min}}$) and maximum ($N_{Row_{max}}$) number of rows of the optimized PV array are set. The algorithm then looks for the optimal configuration starting with a number of rows (N_{Rows}) equal to ($N_{Row_{min}}$). The first (N_{Rows}) modules of the decreasing sequence are located one per row; then the remaining modules of the sequence are one by one connected to the row for which the sum of the irradiances of the modules already positioned is the minimum. After the last iteration, all modules are located and the total irradiations of rows are known. Then the algorithm calculates the EI (refer Eq. (8)) and stores it. The number (N_{Rows}) is thus increased and the same procedure is repeated until (N_{Rows}) equal to ($N_{Row_{max}}$). Finally, the optimal configuration is the one that minimizes the EI. The required number of switches for implementing DES is given by,

$$N_{sw} = (2mN_{pv})_{DPST} + (m)_{SPST}$$

where DPST and SPST are double-pole single-throw and single-pole single-throw type switches respectively. N_{pv} is the number of PV modules and m is the number of rows. A variation of this technique is presented in Kaliyaperumal and Chenniyappan (2016).

In Storey et al. (2013), an iterative and hierarchical sorting algorithm is proposed for identifying the optimum configuration based on irradiance equalization principle. The proposed sorting algorithm is

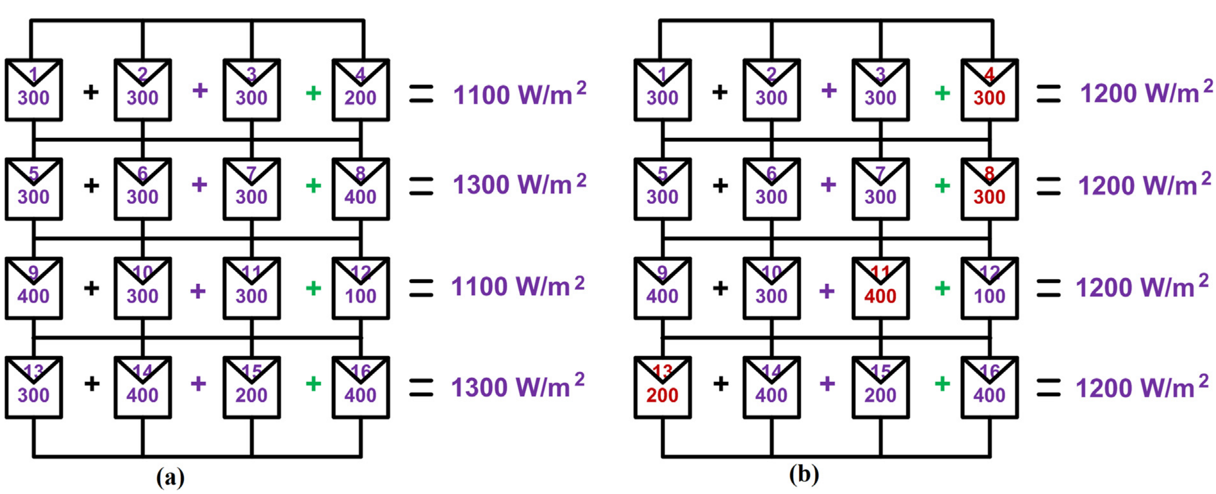


Fig. 10. Illustration of irradiance equalization in TCT: (a) before sorting the rows have different irradiance levels 1100 W/m², 1300 W/m², 1100 W/m² and 1300 W/m², (b) After applying the reconfiguration approach, the modules 4 & 13 and 8 & 11 have been switched, then irradiance in each row could be equalized as 1200 W/m².

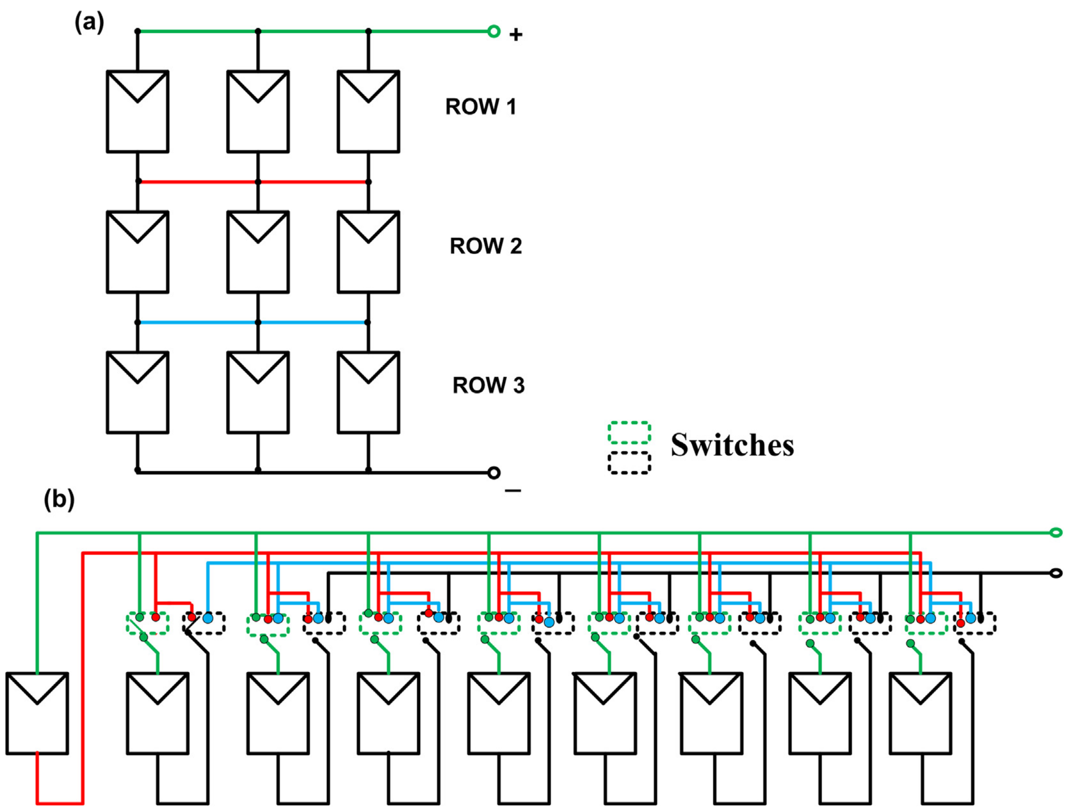


Fig. 11. (a) The simplified structure for 3 × 3 PV array, (b) Switching matrix for 3 × 3 PV array; the position of the first module is fixed to the first row, second could be connected to the first or second row; remaining modules connected to any of the rows.

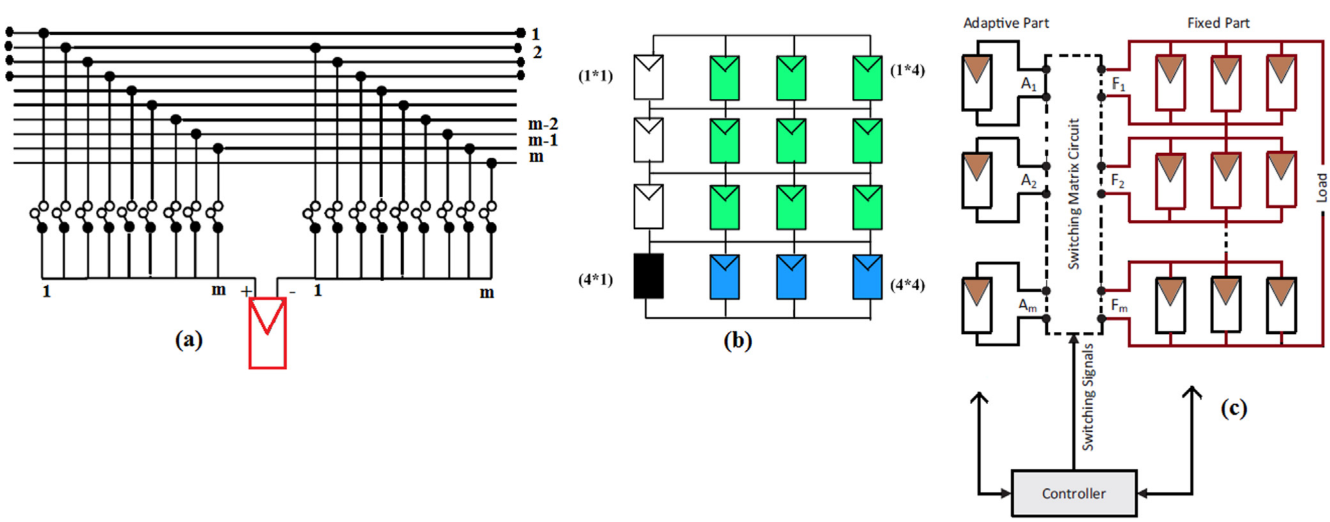


Fig. 12. (a) Switching matrix of reconfigurable PV module, (b) Optimal allocation of PV modules, (c) Adaptive reconfiguration topology.

illustrated using an example is shown in Fig. 14. First, the algorithm is to arrange the PV cells in descending order based on irradiance levels and mapped them into a matrix. In this matrix, the even rows are flipped from left to right and added to the proceeding odd row resulting in an average matrix. The same process is applied again and again until all the rows of irradiance have been considered. The advantage of this algorithm is to build the rows with an equal number of modules. The required number of single-pole single-through switches N_{sw} for operation is given by,

$N_{sw} = N_{pv}\cdot(m^2 - m)$ where m is the number of rows.

In Matam and Barry (2018a), proposed a dynamic PV (DPV) array strategy for repeating shaded conditions. In this approach, the proposed algorithm takes input as an irradiance profile, PV array voltage, and current, then optimize the reconfigurable solution, accordingly send the relevant signals to the switches. However, this approach has an advantage of minimizing the initial calculation and processing time under repeated shadings. A similar approach is presented in Matam and Barry (2018b) for the application of variable DC loads.

In Nguyen and Lehman (2008), an adaptive reconfiguration structure with fixed solar cells is presented. The switching matrix is arranged between fixed and adaptive solar cells as shown in Fig. 15. This switching matrix connects the adaptive solar cells into fixed solar cells with the help of a control algorithm in order to make identical irradiance levels in each row. In uniform condition, the fixed part is

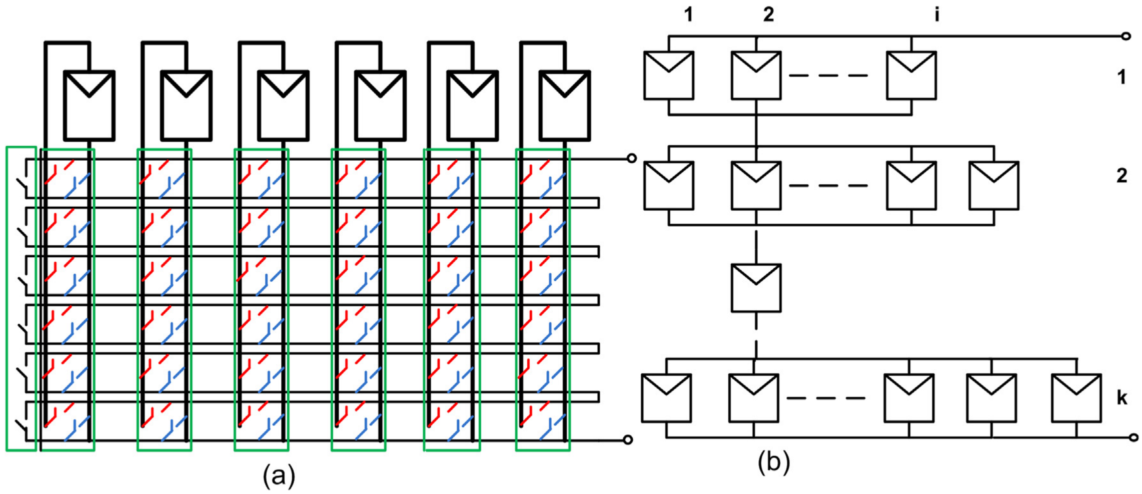


Fig. 13. (a) DES structure for PV modules, (b) non symmetrical matrix.

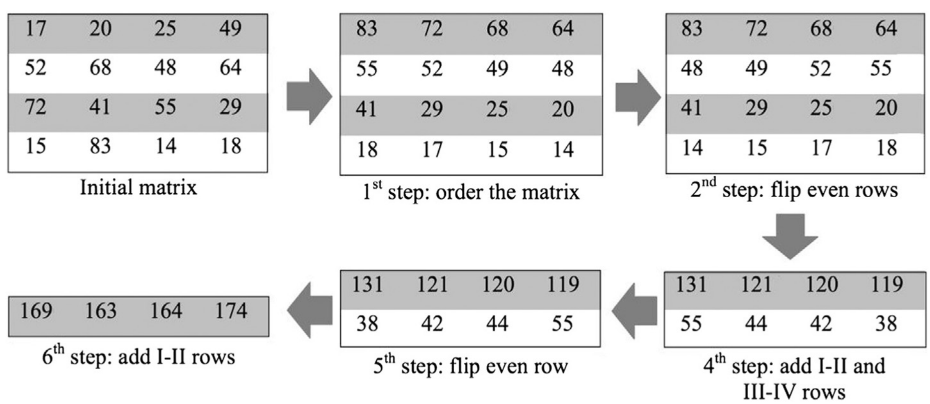


Fig. 14. Example for sorting algorithm.

connected to the adaptive part to increase maximum power. If the first row is shaded, its voltage V_1 is less than the threshold voltage. Otherwise, the output voltage is less than the quantity V_x i.e.,

$V_{out} < V_x$, (where $V_x = mV_1$), Where m is number of rows.

In this case, the adaptive part of the most irradiated solar cell is connected to the fixed part in order to compensate irradiance drop. The bubble sort and model-based algorithms are developed to control the switching matrix. Consequently, Nguyen et al. (2009) adaptive reconfiguration method based on a neural network approach has presented. The solar irradiance, ambient temperature, and sun position

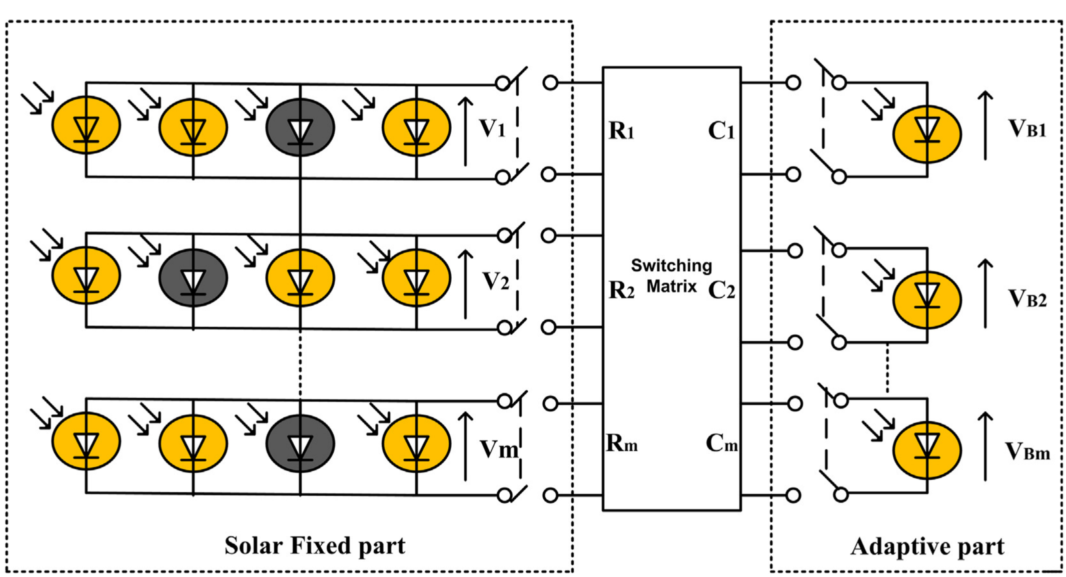


Fig. 15. Adaptive bank approach for solar cells; the low irradiance are grey-coloured, while the yellow one are full irradiated. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

angles are taken as an input to trained multilayer feed-forward neural network to estimate the output power of the solar photovoltaic array.

In Cheng et al. (2010), a self-adaptive reconfiguration method is developed based on the fuzzy logic controller. The controller looked for optimum configuration when the voltage across the first row is less than the threshold voltage. The degree of shading and derivative of irradiance are calculated and feed as an input to the fuzzy controller. Based on that, the adaptive bank of a most irradiated solar cell connects the fixed part. However, the solar cell array adaptive bank approach is extended to module PV array is shown in Fig. 12(c), and presented in Karakose et al. (2014b). In this approach, they have introduced an artificial neural network (ANN) to control the switching matrix. Later, Parlak (2014, 2013), a scanning algorithm based on current variation index (CVI) has been presented. In this approach, the algorithm enables the connections between the adaptive part and fixed part based on measurement of the output current of each row. For each possible configuration, the algorithm calculates the CVI by means of the following expression,

$$CVI = Max(i) - Min(i) \tag{9}$$

The CVI quantifies the degree of current limitation of the configuration and which has minimized CVI is selected as optimum. Similarly, the fuzzy logic controller is implemented for controlling the switching matrix in Karakose et al. (2016). The controller senses the short-circuit currents of both adaptive and fixed parts and takes them into account to generate membership function. Then, it provides control signals to switching matrix to compensate irradiance drop. In Karakose and Baygin (2014), image processing technique is adopted to establish rows of the array by using the panels whose insolation levels are as close to each other. In this approach, the shadow on PV modules are captured with help of the camera, and then it is forwarded to the shadow detection algorithm. The developed canny edge algorithm identify the optimum configuration with help of switching matrix. A similar approach is presented in Karakose et al. (2014a), Mohamed et al. (2018).

The existing reconfiguration algorithms are facing many challenges while searching for the optimum configuration. One of the main issues is, it requires more computational time while searching for the optimum one. To solve this issue, in Mahmoud and El-Saadany (2017b,a) a new adaptive reconfiguration approach is presented. In this approach, the proposed greedy algorithm is to identify the optimum configuration with less computational time. However, the verification of an algorithm is illustrated on two fixed parts with four reconfigurable parts of the array. The main advantage of this algorithm is to take very few iterations to converge an optimum as compared to other techniques.

In Tabanjat et al. (2015), proposed a dynamic reconfiguration technique for connecting PV modules in two parallel groups to satisfy the load request of 24 V. The main aim of this technique is to identify shaded, dusty or faulty modules by using the fuzzy controller and fitting tool estimator. The controller is to measure and compare the maximum and minimum voltages of the modules in order to connect or disconnect to satisfy the load request. Later, Ramasamy et al. (2016), proposed a novel PV reconfiguration structure to maintain constant output current for the load request. This reconfiguration structure is shown in Fig. 16. It consists of upper row panels (U_1, U_2, ..., U_n), which is connected to positive terminal of the string and lower row panels (L_1, L_2, ...,L_n) is connected to negative terminal of the string. Where M is the middle row panel. In this method, each module has three reconfigurable switches for connecting in either series or parallel to the other modules. These switches are operating based on the proposed adaptive algorithm in order to maintain the load request.

In Sanseverino et al. (2015), the control of irradiance equalization problem is formulated, where the sum of irradiance of each row is not equal to the value of average irradiance (S) of PV array. The formulation of a problem is acknowledged based on subset sum rules. The irradiance equalization principle is controlled by the dynamic optimization algorithm. The aim of this algorithm is to develop the rows with similar irradiance levels and each row is equal to the average irradiance of the whole PV array. The formation of IE by using dynamic algorithm is illustrated with an example; A 16 PV modules with non-identical irradiances are fed into a matrix form denoted by X as shown in Fig. 17(a), the average irradiance (S) value of the matrix is defined by:

$$S = P/m$$

where P is the irradiance of PV array and m is the number of rows.

The value of average irradiance of PV array in this case is 1675 W/m^2.This matrix has been sorted in decreasing order based on irradiance in each row. After the completion, the sorted matrix is defined by A is shown in Fig. 17(b). Then, this matrix A could be arranged in vector form as shown in Fig. 17(c). Using subset-sum rules, the values in the vector A starting from A[0] = 830, is used to fill the first row of the new matrix B as shown in Fig. 17(e). The next step consisting of deleting these already used elements from the matrix A and sorting of remaining elements of the matrix A by putting the greatest element in the first position (i.e. A[0] = 720), followed by all the elements pertaining to the same row is shown in Fig. 17(d). The identified second modified row based on subset-sum rules is shown in Fig. 17(e). The same procedure is repeating until the rows are filled with irradiances

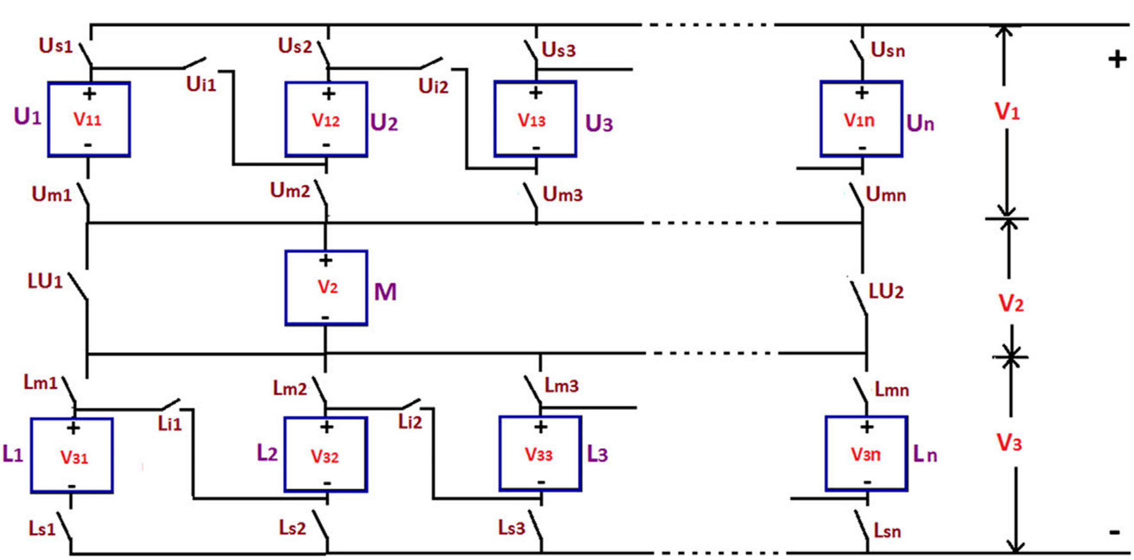


Fig. 16. PV reconfiguration structure.

170	200	250	490
520	680	480	640
720	410	550	290
150	830	140	180

(a)

830	180	150	140
720	550	410	290
680	640	520	480
490	250	200	170

(b)

550	140	150	830		= 1670
180	490	290	720		= 1680
480	520	680			= 1680
640	250	200	170	410	= 1670

(e)

830	180	150	140	720	550	410	290	680	640	520	480	490	250	200	170
A[0]	A[1]	A[2]	A[3]	A[4]	A[5]	A[6]	A[7]	A[8]	A[9]	A[10]	A[11]	A[12]	A[13]	A[14]	A[15]

(c)

720	410	290	680	640	520	480	490	250	200	170	180
A[0]	A[1]	A[2]	A[3]	A[4]	A[5]	A[6]	A[7]	A[8]	A[9]	A[10]	A[11]

(d)

Fig. 17. (a) Starting matrix X, the irradiance values in W/m^2, (b) Sorted matrix A, (c) Equivalent vector view of matrix A, (d) Matrix A re-ordered to build the second row of matrix B, (e) Final configuration arrangement.

that should have identical value as the average irradiance of the array. After identifying the final matrix, the proposed Munkres Assignment Algorithm (MAA) allows connecting the PV modules using switching matrix. Then, the algorithm looks for the optimum one which has a minimum number of switchings could be selected. Consequently, the improved Munkres Assignment Algorithm is presented in Ngoc et al. (2017) for increasing processing speed and lifetime of the reconfigurable system. Two algorithms are proposed to operate in parallel for controlling irradiance equalization principle based on EI. These are Smart Choice (SC) and Dynamic Programming (DP). The formation of optimum configuration based on the DP algorithm is illustrated; First, initialization of 3×3 matrix with non-identical irradiance is shown in Fig. 18(a). The average irradiance of a matrix is 2433 W/m^2. The DP algorithm tries to fill the first row by summing the elements in a matrix to obtain a value that is equal or close to the average, which is shown in Fig. 18(b). For DP algorithm, the EI index is high is given by $EI_{DP} = 3000 - 2000 = 1000$. Therefore, for the better result would be obtained by improving the DP algorithm (refer Fig. 18(c)), the EI is given by $EI_{DP} = 3000 - 2150 = 850$.

The improved DP algorithm has reduced equalization index so that it produces higher maximum power. However, the further improvement of EI index the SC algorithm is used for identifying the best optimum configuration. The principle of SC algorithm is illustrated as follows; First, an initial matrix A is considered as shown in Fig. 18(d). Then algorithm should convert the starting matrix A into the vector form by using a quick sort method. Then the array can be sorted from high to low irradiance levels. Initialize the matrix B with *m*-rows, then arrange some parts of the matrix A into rows of matrix B as shown in Fig. 18(e). So that the temporary EI index (for the matrix B) is minimized for each step.

In Jazayeri et al. (2017), proposed a dynamic reconfiguration algorithm to mitigate effects of non-uniform spatial irradiance profiles on PV power production in real-time applications. Spatial irradiance is a moving cloud distributed irradiance profile, which generally occurs in real-time PV plants. These Spatially dispersed irradiance profiles (SDIPs) are modelled by taking sky images into an account, based on that the shading pattern is identified on PV plant. The proposed algorithm is controls the irradiance equalization process based on EI. The principle of algorithm is illustrated as follows; First, considered 4×4 PV array matrix with different irradiances. The irradiance profile of matrix would be $G_1 < G_2 < G_3 ... < G_{16}$ as shown in Fig. 19(a). Initially calculate the EI (refer to Eq. (8)) for each row in the PV array. Based on this index, the algorithm does not reconfigure the second and third row. Since their average irradiance values lie within the tolerable limit of 40 W/m^2. The average irradiance of the PV array, in this case, G = 801.56 W/m^2. Hence, the average irradiance values of 1st and 4th rows are exceeded the threshold value so that the algorithm is to reconfigure these two rows is shown in Figs. 19(b)–(d). The final reconfigurable matrix is shown in Fig. 19(e). In this matrix, all the rows lie within the tolerable limits. Finally, the algorithm looks for optimum

150	150	1000
1000	1000	1000
1000	1000	1000
Intial Matrix		

(a)

1000	1000	150	150	= 2300
1000	1000			= 2000
1000	1000	1000		= 3000
After using DP				

(b)

1000	1000	150	=2150
1000	1000	150	=2150
1000	1000	1000	=3000
Best Results			

(c)

620	500	600	300	= 2020
540	420	320	480	= 1760
280	460	400	560	= 1700
360	340	300	240	= 1240

Intial Matrix

(d)

620	420	400	240	= 1680
600	460	320	300	= 1680
560	480	360	280	= 1680
540	500	340	300	= 1680

Final Optimal Arrangement

(e)

Fig. 18. (a) Initial Matrix for DP algorithm, (b) Filling the matrix using DP algorithm, (c) Improved DP algorithm, (d) Initial matrix for SC algorithm, (e) Final configuration matrix.

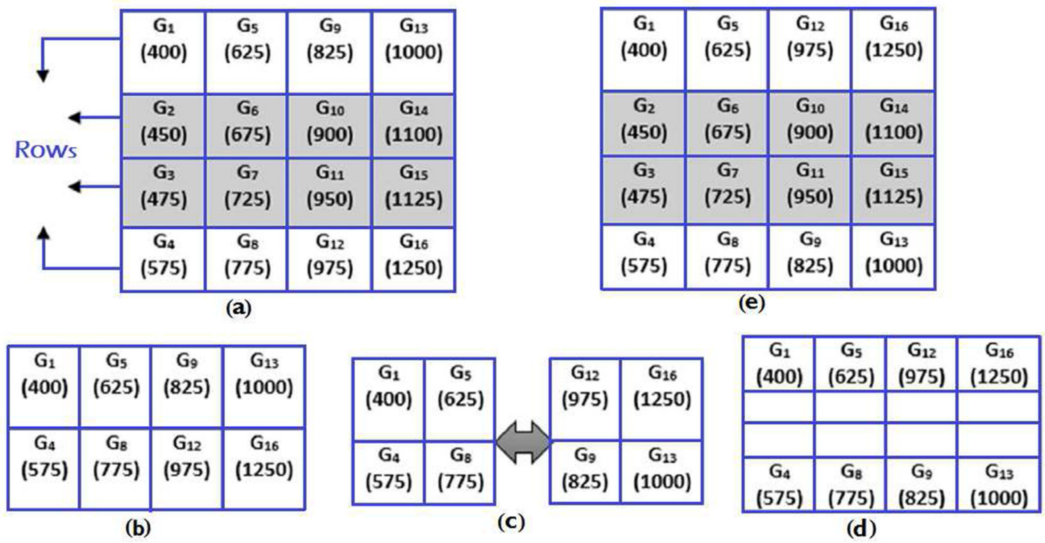


Fig. 19. (a) Initial Matrix with different irradiances, (b) Extracted first and fourth row from initial matrix, (c) Reconfiguration of PV modules using algorithm, (d) Reconfigure the modules in first and fourth row, (e) Final configuration matrix.

configuration based on minimized EI.

In Deshkar et al. (2015), Liu et al. (2016), Rajan et al. (2017), an optimization technique is proposed to distribute shading effects over the PV array. In this approach, the physical location of PV modules remains unchanged while the electrical connections are altered. The genetic algorithm (GA) is adopted for identifying the optimum configuration. This algorithm generates various switching arrangements under shading condition, which has the nearest current levels in each row should select as an optimum. A similar approach is presented in Babu et al. (2017). In this approach, the particle swarm optimization (PSO) technique is developed for identifying optimum configuration. The advantage of this technique over GA is that it requires only one time switching to achieve effective shading dispersion. A variation of this technique presented in Akrami and Pourhossein (2018). In this study, the authors have proposed novel reconfiguration technique based on a power comparison Index (PCI) to identify optimum configuration. The proposed approach compares the maximum powers of all multiple peaks in P-V characteristics of the PV array and ensures the absolute MPP.

The summary of dynamic PV array reconfiguration approach with TCT topology reported in the various literature is presented in Table 1.

4.2.5. Dynamic reconfiguration control techniques for SP

The aim of reconfiguration in SP topology is to build strings of series connected modules with similar irradiance levels, then connect all the strings in parallel. In this way, the low irradiance of modules would not be able to limit the output current in a string. In Alahmad et al. (2012), proposed an Elastic Photovoltaic structure (EPVS) using Flexible Switching Matrix (FSM) is shown in Fig. 20. This switching matrix connects the PV modules in either series or a parallel way to the other modules. In uniform condition, the EPVS is operating as a central inverter topology without using the DC-DC converter. Whenever mismatch occurs, the proposed system excludes the shaded modules, reconfigure the remaining ones with the main PV string, if necessary connected to a sub-PV string (SPV). MPV string consists of an equal number of modules which are directly connected to the input of the inverter. In SPV string has few modules so that DC-DC converter is used to connect this partial string to the inverter, thus avoiding mismatch losses. For this purpose, each module have four single-pole dual-throw (SPDT) switches are required. Two for the MPV bus and other two for the SPV. The total number of required switches *Nsw* is given by,

$$N_{sw} = (2N_{pv})_{SPDT} + (2N_{pv} + 4)_{SPST}$$

where N_{pv} is the number of modules.

In Chaaban et al. (2015, 2010), an adaptive photovoltaic system is proposed to overcome the effect of low irradiance. The proposed system is based on FSM. The FSM dynamically connects adjacent PV modules in series, parallel, series-parallel configurations or even selective element isolation. This topology is consist of mainly three subsystems is shown in Fig. 21. Subsystem-1 is FSM, subsystem-2 is flexible micro inverter modules (FMIMs), and subsystem-3 is main string-inverter modules (MSIM). These subsystems would create three flexible strings (FST) in shading condition. In normal operating condition, the FMIMs are connected to their respective micro inverter and the FSTs are connected to their respective string inverter. Both subsystems are connected in parallel to the AC bus. However, in case of shading, FSTs are connected to only one string inverter by closing parallel switch (S_{st}, *inv*), while FMIMs are also connected in parallel by closing the parallel switch (S_{mr}, *inv*). Since it reduces the number of inverters and increases the input energy of each active inverter. The required number of switches inside FSM is given by,

$$N_{switches} = 6N_{FST} + 3N_{FMIM} + (N_{FST} - 1) + (N_{FMIM} - 1)$$

where N_{FST} is the number of flexible strings and N_{FMIM} is the number of flexible micro inverter modules in the system.

Another approach is presented using the DC/DC converter, where multiple strings are connected and each contains substrings of similar power levels is created (Storey et al., 2014). All the strings are connected to a DC/DC converter and converging to a unique DC bus. A similar approach is presented in Iraji et al. (2017). In this approach, an optimized switching set (SWS) topology for PV modules is developed. This topology is to connect the PV modules which are having similar irradiance levels into a series, parallel and series-parallel by using PSO algorithm. Two binary PSO (BPSO) algorithms are employed with suitable interaction. The first BPSO is searching for a number of possible topologies are achieve and second BPSO identify the optimum one among all.

In Manjunath Matam and Govind (2018), proposed a new reconfigurable PV array (RPV) based water-pumping system. In this approach, the modules in the PV array are changes its connection layouts between series to parallel and parallel to series-parallel to run the motor at different operating conditions.

In Parlak and Karaköse (2014), developed an adaptive structure with fixed part.The switching matrix is inserted between the adaptive

Table 1
Resume of dynamic PV array reconfiguration approach with TCT topology in terms of: Reconfiguration strategy, control algorithm, number of switches, acquired parameters, application and remarks.

Author	Reconfiguration Strategy	Control Algorithm	Required Switches	Acquired Parameters	Application	Remarks
Velasco-Quesada et al. (2009)	IE	Refer Velasco-Quesada et al. (2009)	$2N_{pv}$m-throws	current, voltage	PV-Grid	static and dynamic part
El-Dein et al. (2013)	IE	Branch and Bound	$m.\ n_R$ double pole m-throw	irradiance	PV farm	fixed part along with adaptive part
Romano et al. (2013)	IE	Deterministic and Random search	$(N_{pv})_{DPST} + m_{SPS}$	irradiance	NS	supports row with different number modules
Storey et al. (2013)	IE	Best worst sorting	$N_{pv}(m^2 - m)_{spst}$	current, voltage	NS	supports row with different number modules
Matam and Barry (2018a)	IE	refer Matam and Barry (2018a)	24-DPST relays	current, voltage, irradiance	R-Load	Dynamic PV array is formed using PV modules
Matam and Barry (2018b)	Dynamic PV array	refer Matam and Barry (2018b)	15-SPST, 5-DPDT	voltage, irradiance	DC-loads	Dynamic PV array is developed for DC-loads
Nguyen and Lehman (2008)	Adaptive bank	Bubble-sort, Model based	$(2N_{AB}N_{pv})_{spst}$	voltage, temperature	R-Load	fixed part along with adaptive part
Cheng et al. (2010)	Adaptive bank	Fuzzy logic	NS	current, voltage	R-Load	fixed part along with adaptive part
Karakose et al. (2014b)	Adaptive bank	Neural Network	NS	temperature, current	R-Load	fixed part along with adaptive part
Parlak (2014)	Adaptive bank	Scanning algorithm	$2.\ m.\ m$	current	R-Load	fixed part along with adaptive part
Karakose and Baygin (2014)	Adaptive bank	Image process, canny algorithm	NS	current, voltage	R-Load	fixed part along with adaptive part
Tabanjat et al. (2015)	Adaptive Reconfiguration	Fuzzy and Fitter Estimator	$n + 6$	current, voltage	R-Load	adaptive part connects the modules automatically
Karakose et al. (2016)	Adaptive bank	Fuzzy control	NS	current	R-Load	fixed part along with adaptive part
Sanseverino et al. (2015)	IE	Refer Sanseverino et al. (2015)	NS	irradiance	NS	supports row with different number modules
Ngoc et al. (2017)	IE	DP and SC	NS	irradiance, current	NS	supports row with different number modules
Jazayeri et al. (2017)	IE	Reconfiguration algorithm	NS	irradiance	NS	supports row with different number modules
Mahmoud and El-Saadany (2017b)	IE	Greedy algorithm	NS	irradiance	NS	fixed part along with adaptive part
Ramasamy et al. (2016)	Adaptive topology	Refer Ramasamy et al. (2016)	3-switches for each module	current, voltage	R-Load	adaptive part connects the modules automatically

*NS: Not Specified.

part and the fixed part is shown in Fig. 23(a). In this approach, to connect adaptive parts into the fixed part is based on the measurement of standard irradiance of each string.

In Patnaik et al. (2011, 2012), the aim is to build strings of solar cells which are having closest irradiance levels are connected. The authors have considered three different irradiance states of solar cells, these are bright ($600 < G < 800$ W/m^2), grey ($400 < G < 600$ W/m^2) and dark ($G < 400$ W/m^2) is shown in Fig. 22. First senses the current across each bypass diode (I_d) of the solar cell. If this current is greater than zero then the cell is dark, otherwise the short-circuit current (I_{sc}) is to measure to classify the cell is bright or gray. Similar way, it calculates the derivative of short circuit current with respect to time (dI_{sc}/dt), since the grey cell can experience transitions towards dark or bright states. The proposed strategy identify the number of shaded cells, if it is more than 15% of the total, then reconfiguration occurs. Then cells have the same state is formed into a string. The proposed approach requires a number of switches N_{sw} is given by,

$$N_{sw} = (m{\cdot}n) + \frac{((m{\cdot}n) - 1){\cdot}(2 + (m{\cdot}n))}{2}$$

where m is the number of rows and n is the number of columns.

In dos Santos et al. (2011a,b), a Rough Set Theory (RST) is used for SP topology to build an Automatic Reconfiguration System (ARS). In this approach, the authors have considered different shading cases, for each case, the most convenient SP topology is selected. In such cases, the RST is identified and produce the simplified rules in the decision table. For every module in PV array is produce short-circuit current which is denoted as i_k, if this current is less than the threshold current ($i(k) < I_{ref}$), the module is considered as shaded, otherwise unshaded. Based on the simplified rules, the shaded modules can be identified. For every rule contains a switch to configuration, which sets the optimal connection for the modules (Vicente et al., 2015). A variation of this technique presented in Petrone et al. (2019). In this paper, a novel control technique is developed for selecting the possible number of configurations with less computational time.

In Picault et al. (2010), a Lambert PV model is developed to forecast real-time PV power production under different environmental conditions. The proposed model reduces the mismatch effects by changing interconnections between PV modules. A variation of this technique is presented in Villa et al. (2012). Later, in Chao et al. (2015), Tubniyom et al. (2019) an adaptive configuration method is presented based on particle swarm optimization(PSO). The algorithm identifies the optimum configuration by comparing the maximum power at the normal condition with the shaded condition. If shading or malfunction occurs in PV array, the algorithm immediately undergoes adaptive configuration and identify optimum one. This adaptive configuration structure is shown in Fig. 23(b).

In Camarillo-Peñaranda et al. (2015), a new reconfiguration approach is presented based on the genetic algorithm. In this approach, the algorithm is to connect the PV modules with closest irradiance levels of each string. In the process of reconfiguration, the number of possible interconnections is obtained by $(m + 1)^{m.n}$. where $(m.\ n)$ corresponds to the number of modules in the array. The required number of switches for each module is $(m + 1)$. where m is the number of modules in the string.

A similar approach is presented in Harrag and Messalti (2016), Carotenuto et al. (2015). In Hu et al. (2017), a novel reconfiguration approach is proposed for non-uniform aged modules. The reconfiguration is achieved by connecting many solar cells in series across with bypass diodes. These cells are investigated by the aging phenomenon of a module. The aging problem is formulated by using non-linear integer programming (NLIP) techniques. In Balato et al. (2015, 2014), a simple and fast reconfiguration algorithm has been presented to identify optimal configuration. Whenever shading occurs, the algorithm is to compose series-parallel PV array configuration within the given 24 PV modules. The advantage of algorithm is to search the nearest optimum

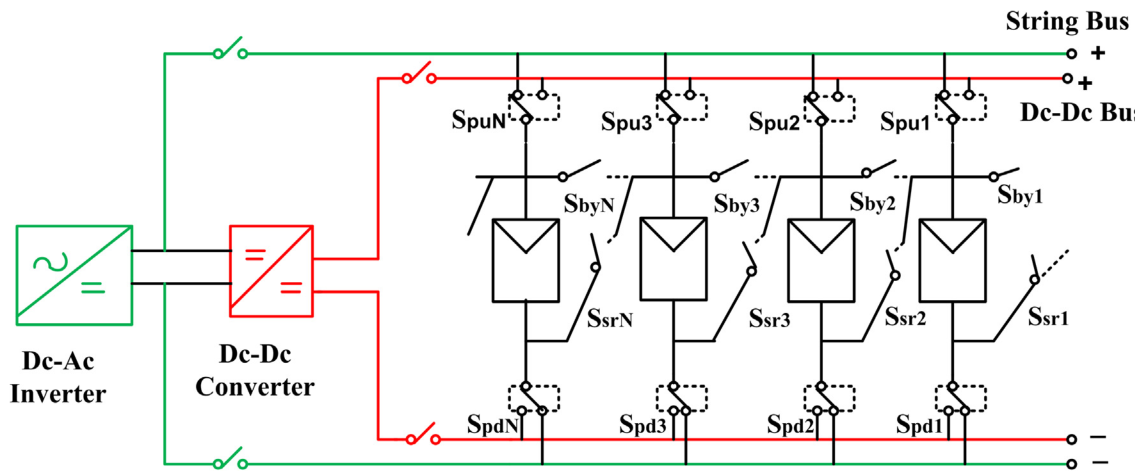


Fig. 20. Elastic Photovoltaic Structure (EPVS).

configuration with less computational time. Later, in Braun et al. (2016) an optimized reconfiguration topology is proposed to reduce mismatch effects. This topology has been implemented in SPICE circuit simulator, which can predict the best suitable configuration for irregular operating conditions. A variation of this technique is presented in Serna-Garcés et al. (2015). In this approach, the identification of optimum configuration is based on PV module I-V and P-V output characteristics.

The summary of dynamic PV array reconfiguration approach with SP topology is reported in the various literature is clearly presented in Table 2.

4.2.5.1. Static PV array reconfiguration techniques. In static reconfiguration, the physical location of PV modules are changing without altering electrical connections to distribute shading effects over the array as already mentioned in Section 1. Based on the literature, these techniques are classified into (1) Physical Relocation (PR) and (2) Electrical Rewiring (ER). In this technique, many authors have adopted TCT configuration due to effective shading dispersion.

4.2.6. Physical relocation

The most challenging issue of this technique is to choose the effective reconfigurable pattern to distribute shading effects over the PV array. In Rani et al. (2013), Su-Do-Ku puzzle pattern adopted for the arrangement of 9 × 9 TCT PV array is shown Fig. 24(a). Su-Do-Ku is a logic-based number placement puzzle. In Su-Do-Ku arrangement, the first digit in each box represents the logic-number and the second digit denotes the column.The advantage of this pattern is to accommodate the digits 1 to 9 without repeating. The aim of this pattern arrangement is to distribute shaded effects by changing the physical location of PV modules without altering any electrical connection. That means if the module number 53 placed at the fifth row-third column in TCT, but is physically moved to the first-row third column in Su-Do-Ku arrangement. Similar changes are done for all PV modules, thereby increasing the current in an entering node under shading conditions and minimize the bypassing of the PV modules. The output PV array voltage is defined by applying KVL to Fig. 24(a),

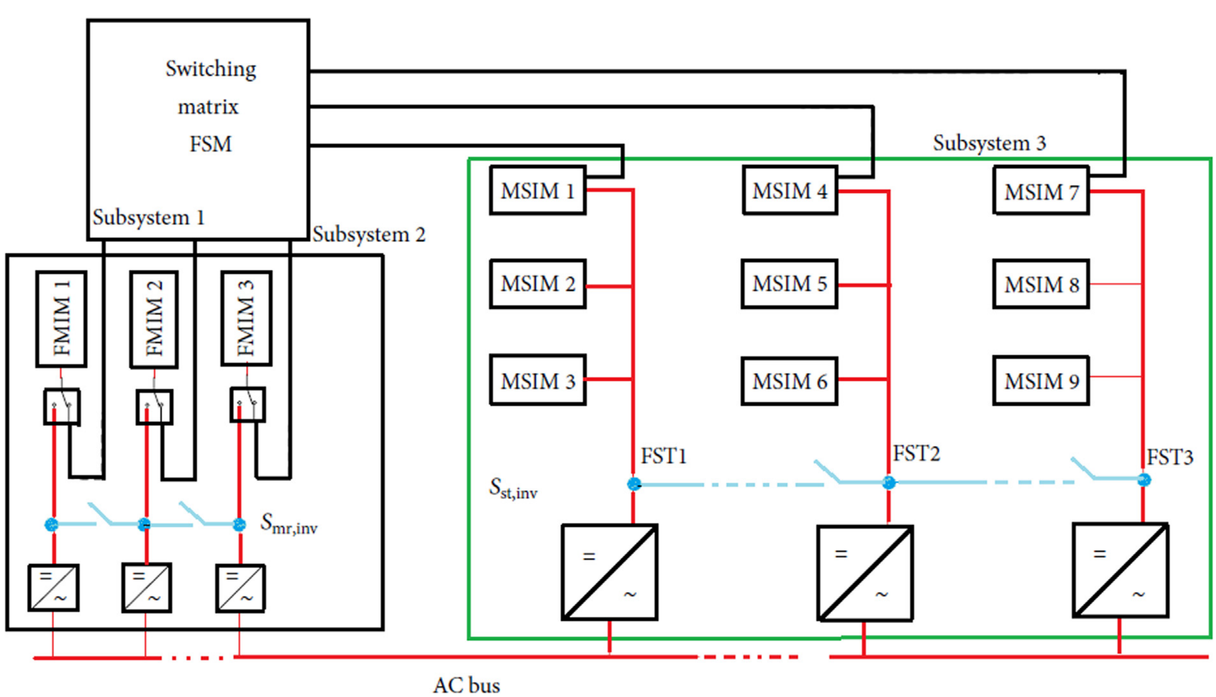


Fig. 21. Layout of the adaptive PV string-inverter configuration with three flexible strings (FST).

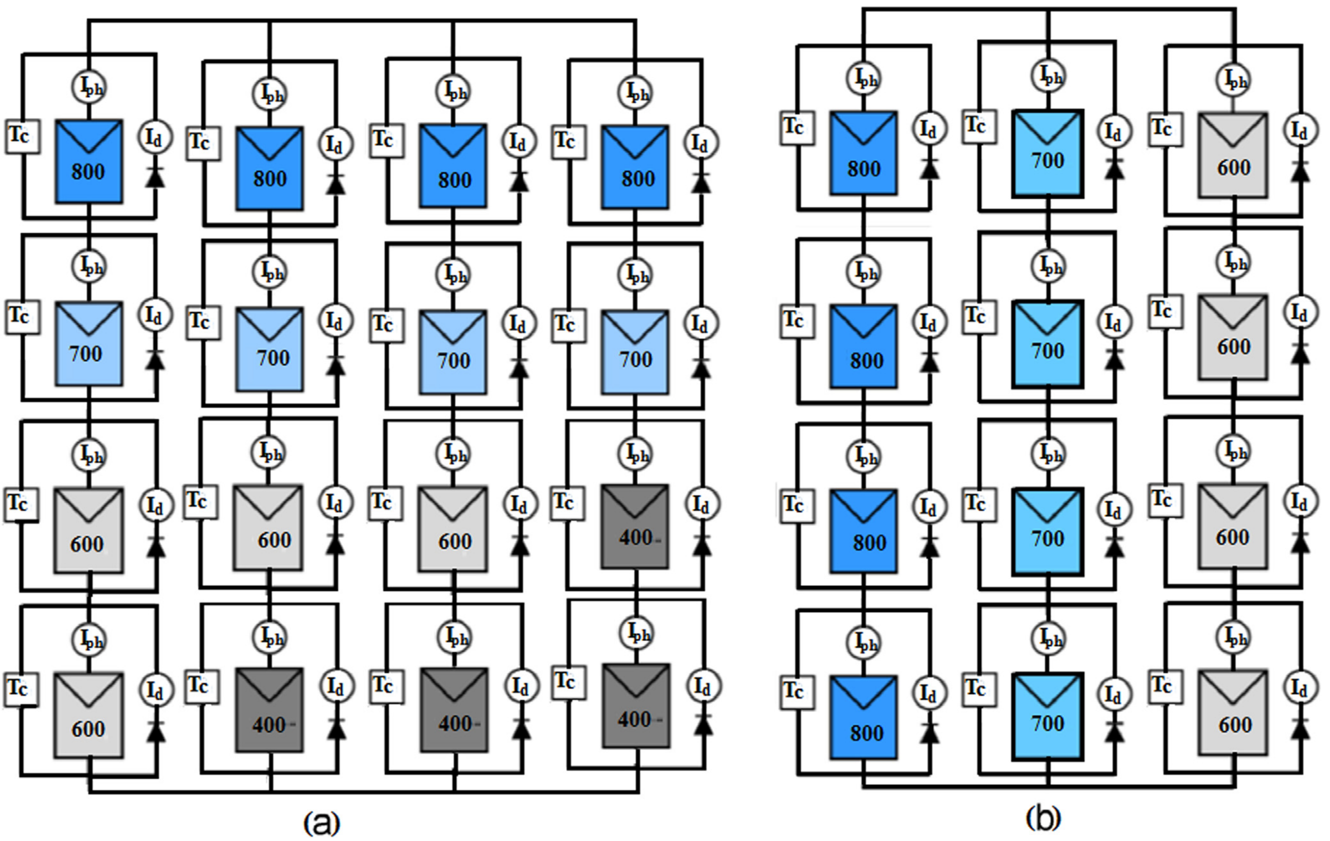


Fig. 22. Reconfiguration in SP topology: (a) four different irradiance levels of solar cells: 800, 700, 600 and 400 W/m^2, (b) after sorting, PV panels with 400 W/m^2 are excluded and composed three string with 800, 700 and 600 W/m^2.

$$V_a = \sum_{m=1}^{9} V_m \tag{10}$$

where V_a represents PV array voltage and V_m refers to voltage of the panels at the m^{th} row. The KCL is applied to find PV array current at each node.

$$I_a = \sum_{n=1}^{9} I_{mn} - I_{(m+1)n} = 0 \tag{11}$$

where I_a is the PV array current; $m = 1, 2, 3 \ldots 9$ is a rows and n is a column.

This pattern has few drawbacks; (a) it requires additional wiring, (b) the shading distribution is not effective under the sub-array. The extra wire is required for each panel depends on the relative position of before module and next module. Therefore, to arrange the modules in sequentially so that the relative position is same as the TCT. Hence, it can be minimized the additional wiring losses. Each sub-array has unique numbering within itself is to formulate to distribute the shading losses. However, these drawbacks can overcome by developing optimal Su-Do-Ku based puzzle pattern which is presented in Potnuru et al. (2015). The formation of this puzzle arrangement is shown in Fig. 24(b), and illustrated as follows: First column is filled with numbering 1 to 9 in ascending order. In order to fill the next column, each sub-array has unique numbering is required. The second column is filled by shifting the previous column by three (Sub array) and the same approach is applied to the subsequent column. The fourth column is filled with offset shifting process of the first column. Hence, the second

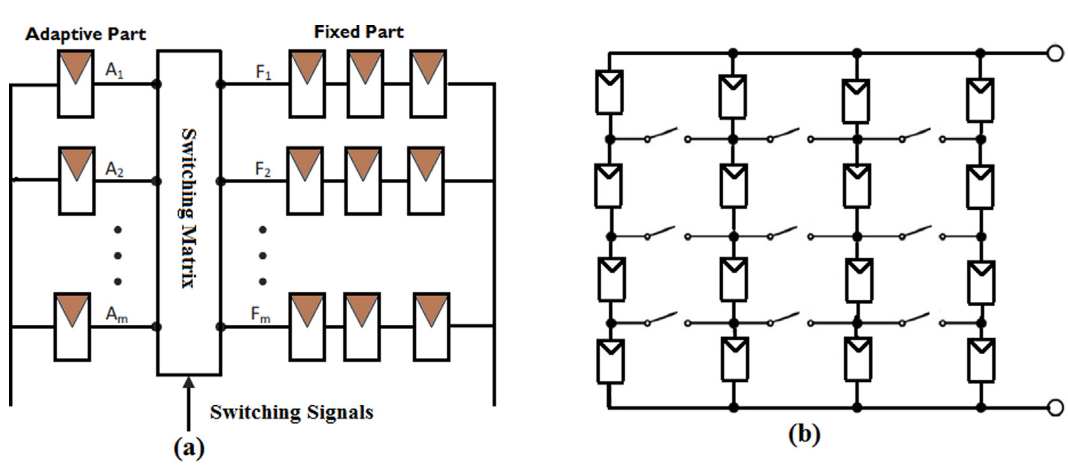


Fig. 23. (a) Adaptive bank approach for SP configuration, (b) Adaptive PV array configuration.

Table 2
Resume of the dynamic PV array reconfiguration approach with SP topology in terms of: Reconfiguration strategy, control algorithm, number of switches, acquired parameters, application and remarks

Author	Reconfigurations Strategy	Control algorithm	Required Switches	Acquired Parameters	Application	Remarks
Alahmad et al. (2012)	EPVS	Refer Alahmad et al. (2012)	$(2N_{pv})_{SPDT} + (2N_{pv} + 4)_{SPST}$	voltage, current, temperature	PV-Grid	The string with the non-equal number of modules
Chaaban et al. (2015)	adaptive	Refer Chaaban et al. (2015)	$6N_{FST} + 3N_{FMIM} + (N_{FST} - 1) + (N_{FMIM} - 1)$	current, irradiance	PV-Grid	PV modules connecting with different inverter topologies
Manjunath Matam and Govind (2018)	Reconfigurable PV array	ReferManjunath Matam and Govind (2018)	6-SPDT, 5-DPST, 4-DPDT relays	voltage, irradiance	Motor	reconfigure the modules based on irradiance
Parlak and Karaköse (2014)	adaptive bank	Optimal algorithm	NS	irradiance	R-Load	fixed part along with adaptive part
Patnaik et al. (2011)	IE	Refer Patnaik et al. (2011)	$(mn + (mn - 1)(2 + mn)_{SPST}$	current, irradiance	PV-Grid	different ranges of irradiance are classified
dos Santos et al. (2011a).	Rough set theory	Identification of optimal rule	NS	current	NS	Simplified logic rules to select optimum
Hu et al. (2017)	Reconfigurable Architecture	Kernel Algorithm	NS	irradiance, current	PV-Battery	solar cells are identify the aged condition of the module
Iraji et al. (2017)	Optimization	PSO algorithm	6-switches for each SWS	current, irradiance	Electrical loads	optimized switching set topology
Chao et al. (2015)	Adaptive technique	PSO algorithm	NS	power	NS	adaptive configuration based on switches
Camarillo-Peñaranda et al. (2015)	IE	Genetic algorithm	$(m + 1)$	irradiance	PV-field	connecting modules with similar irradiance
Harrag and Messalti (2016)	IE	Genetic algorithm	NS	irradiance	NS	connecting modules with similar irradiance
Carotenuto et al. (2015)	Optimization	Genetic algorithm	NS	current, irradiance	NS	connecting modules with similar irradiance

*NS: Not Specified.

element starts with one and the sequence continues. The subsequent two columns are filled by using a shift of three with respect to the previous column. The seventh column is filled by incrementing the offset. The following two columns, which are being filled with necessary shifts could be expressed as;

$$n^{th}column = \lceil \frac{n-1}{3} \rceil + 3((n-1)mod3) \tag{12}$$

where ⌈ ⌉ is the greatest integer function.

This optimal Su-Do-Ku arrangement is the best configuration to distribute sub array shading effects. Also, nowhere the modules are bypassed in a row.

In Vijayalekshmy et al. (2015a), Su-Do-Ku riddle puzzle pattern is presented for changing the physical location of modules under moving shadow (passing cloud) conditions. This pattern arrangement is applied to different PV array configurations which are Series-Parallel (SP), Bridge-Linked (BL), Honey-Comb (HC), Total Cross Tied (TCT) and Ladder (LDR). In LDR arrangement, the alternate rows are linked through cross ties. Consequently, in Vijayalekshmy et al. (2015b), a similar pattern arrangement is presented to distribute shading effects. A variation of this pattern is presented in Meraj and Mishra (2015).

The Su-Do-Ku based pattern has some weaknesses against Mutual Shading (MSH). The MSH usually occur in the real-time PV plant by the stationary solar collectors and mostly in places where the solar land is limited and the sun elevation angle is low. In these cases, this shading can be acceptable and the rows spacing will be reduced. However, for such conditions, the MSH can be predetermined by knowing the geographical location of the solar field, sun position, solar elevation or altitude angle (α), solar azimuth angle (γ_s) in the sky and installation characteristics. To overcome these MSH effects, the authors (Horoufiany and Ghandehari, 2017b,a) have developed fixed reconfiguration technique based on optimized Su-Do-Ku puzzle pattern. The MSH shadow is a rectangular shape and it can be predetermined by taking an account of sun position in the sky, the latitude of PVPP (Photovoltaic Power Plant), and installation characteristics. The optimized Su-Do-Ku arrangement is distributes MSH shadow effects as compare to normal Su-Do-Ku arrangement.

In Yadav et al. (2016), proposed hybrid PV array configurations and non-symmetrical patterns to distribute shading effects. The hybrid configurations such as SP-TCT and BL-TCT are shown in Figs. 25(a) and (b) respectively. The proposed pattern and arrangements of NS-1 (non-symmetrical-1) and NS-2 (non-symmetrical-2) configurations are shown in Figs. 25(c)–(f) respectively. The formation of NS-1 configuration, first arranging PV modules in the first column in ascending order and from the second column onwards number 2 is added to the previous column. The same procedure is repeated for the formation of the NS-2 pattern but 3 is added instead of 2. In this approach, it indicates that the proposed NS-1 and NS-2 configurations contain minimum power loss compare to other configurations.

In Yadav et al. (2017), a Magic-Square (MS) puzzle pattern is adopted for different hybrid PV array configurations. Magic-square is a square grids formation within the array, each square grid with the special arrangement of numbering in them. These numbers are special because of every row, column and diagonal add it gives the same number. The MS arrangement of hybrid configurations such as rearranged-total cross tied (RTCT), rearranged series parallel- total cross tied (RSP-TCT), rearranged bridge link- total cross tied (RBL-TCT) and rearranged bridge link-honey comb (RBL-HC) are shown in Figs. 26(a)–(d) respectively. Form the results, the MS configuration contains minimum power loss and higher fill factor (Reddy et al., 2018). A similar approach is presented in Rakesh et al. (2015), Rakesh and Madhavaram (2016), Samikannu et al. (2016) to distribute shading effects over the array. However, the variation of this pattern arrangement is presented in Dhanalakshmi and Rajasekar (2018a). In this approach, dominant-square (DS) based puzzle pattern is adopted for shading distribution.

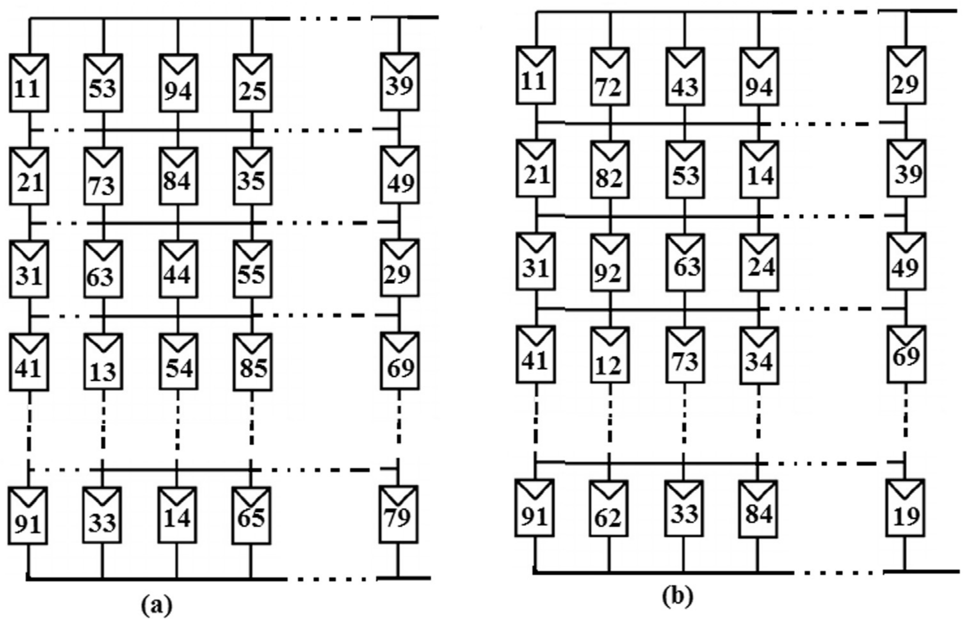


Fig. 24. Reconfigurable patterns (a) Su-Do-Ku pattern, (b) Optimal Su-Do-Ku pattern.

In Sahu et al. (2016), Sahu and Nayak (2014), authors developed Futoshiki based puzzle pattern for enhancing power generation under partial shading. The Futoshiki is a logic-based number puzzle and this pattern arrangement is done by using a linear programming (LP) approach. In this pattern, the numbers 1 to n is placed in such a way that each row and column of a square grid contains only once without repeating any number (refer Fig. 27). During the placement of the numbers in the square grid, the number must have respected the initially specified inequality constraint between two adjacent numbers. The advantage of this pattern is that, if shaded modules occur in the same row are moved to different rows.

In Vijayalekshmy et al. (2016a), Zig-Zag scheme arrangement is adopted for novel configuration to distribute different shading effects. Later, Belhaouas et al. (2017), a new physical arrangement of PV array scheme is presented. This arrangement is mainly based on maximizing the distance between adjacent PV modules within the PV array.

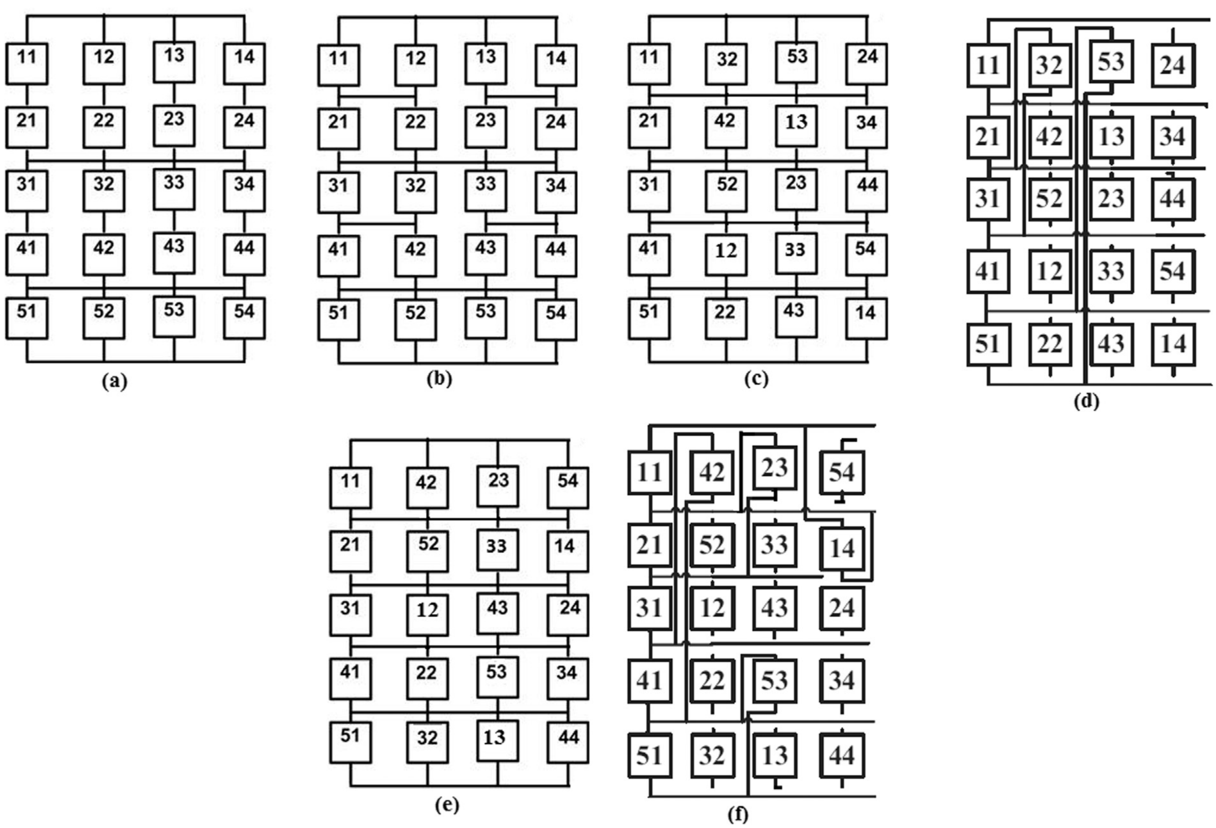


Fig. 25. Hybrid PV arrays and non-symmetrical pattern arrangement: (a) Hybrid SP-TCT , (b) Hybrid BL-TCT , (c) NS-1 Pattern, (d) NS-1 pattern arrangement, (e) NS-2 Pattern , (f) NS-2 pattern arrangement.

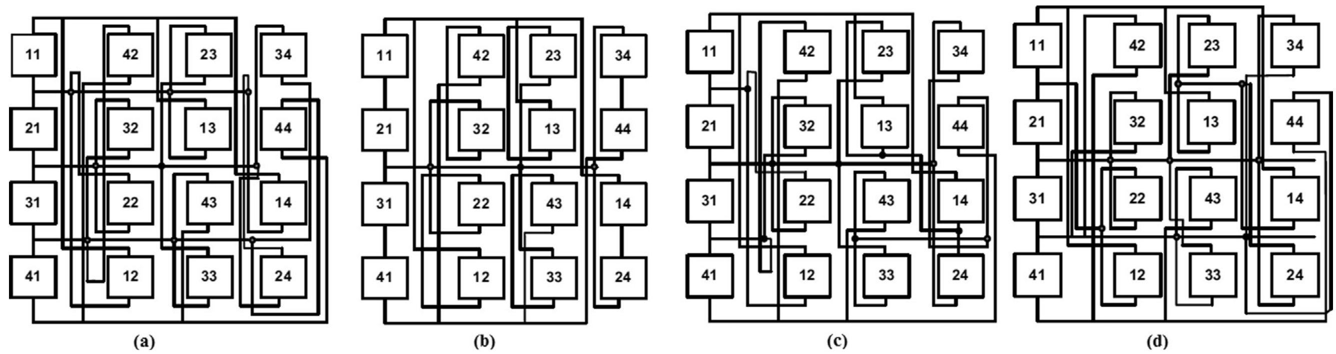


Fig. 26. PV array with MS reconfigurable patterns: (a) RTCT pattern, (b) RSP-TCT pattern, (c) RBL-TCT pattern, (d) RBL-HC pattern.

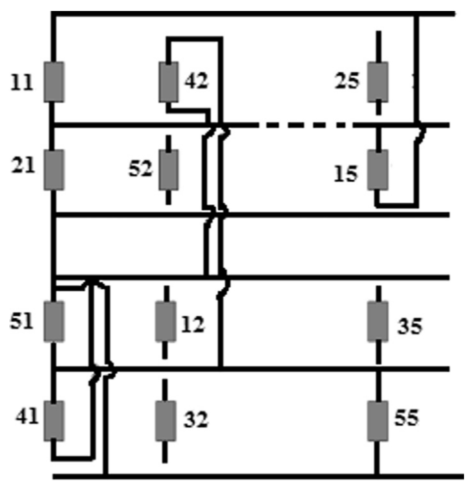


Fig. 27. Futoshiki Puzzle Pattern for TCT PV array.

4.2.7. Electrical rewiring

In this technique, the electrical connections are made after renumbering the position of PV modules. The most challenging part is to assign renumbering to the modules in such way that to distribute shading effects over the PV array. In Rao et al. (2014), the fixed interconnection scheme is presented. In this scheme, the connections are made after the renumbering the modules. The algorithm is developed for renumbering the PV modules in order to disperse the shading effects over the PV array. A similar approach is presented in Pachauri et al. (2018), Satpathy et al. (2017), Satpathy et al. (2018).

Later, the static shade tolerant scheme is developed in Malathy and Ramaprabha (2015b). The proposed algorithm for renumbering of the modules is presented in Malathy and Ramaprabha (2017). This algorithm is tested for three PV array cases where $m = n$, $m < n$ and $m > n$. The advantage of this algorithm is that it can be used for any size of the PV array to enhance power generation under different shading pattern.

The summary of static PV array reconfiguration approach with TCT topology is reported in the various literature is clearly presented in Table 3.

5. Challenging issues

5.1. Dynamic PV array reconfiguration techniques

In dynamic reconfiguration technique, the most challenging parts are monitoring (DAQ) system, reconfiguration algorithm and switching matrix which can be seen from Fig. 1.

5.1.1. Monitoring system

Monitoring the PV system is essential due to unpredictable weather conditions. The monitored data can help full to predict the power production in the PV field. This data also enables to track the working condition of each module, which identifies faulty or shaded condition. The monitoring system consists of sensors, transducers, and hardware programme embedded with a PC (personal computer). Sensors are the most crucial part in a monitoring system, which is used to sense the environmental parameters such as irradiance, temperature, humidity, and wind speed as well as electrical parameters like voltage, current, and power. The majority of monitoring systems collect data at the plant level and sensing the parameters with respect to each module, which is necessary when the reconfiguration approach is adopted. However, this approach requires knowledge of the irradiance for every PV module. The most common way to sense the irradiance of modules is using a pyranometer. In order to have a good understanding of the spatial irradiance, one pyranometer per PV module is used, which would increase the cost of the system. The other way to estimate the irradiance is by measuring the module voltage, current, and temperature, along with the physical parameters of the given solar module (refer Eq. (6)). The experimental setup is also developed to measure the irradiance of PV modules in Vigni et al. (2015).

5.1.2. Complexity of reconfiguration algorithm

Reconfiguration algorithm (RA) optimizes the maximum power from the PV array and introduce the best configuration which can satisfy the output constraints. The process of reconfiguration in PV array gives a very large number of possible combinations of configurations. So that, the number of combinations to be examined must be reduced by introducing some operating constraints (Laudani et al., 2018). However, the optimal solution is determined by using heuristic, intuitive, or mathematical approaches (Petrone et al., 2015; Carotenuto et al., 2013). Based on the literature, these algorithms are broadly classified into different categories:

1. Programmed Reconfiguration Algorithm (PRA): These type of algorithms are required a training phase to create a relationship between the different operating conditions for optimal connection among the PV modules. These algorithms usually determine the connections among the PV modules by seeing lookup tables. In Salameh and Dagher (1990), Salameh and Liang (1990), reported the way of changing the connections among PV modules based on irradiance and to meet the output constraints. In Faldella et al. (1991), Vaidya and Wilson (2013) authors have used analog comparators for predetermining the optimum configurations by connecting PV modules on basis of irradiance.
2. Exhaustive Evaluation Reconfiguration Algorithm (EERA): These type of algorithms are used to identify the all possible PV configuration for some particular applications. In Obane et al. (2012), the algorithm is testing all the possible configuration in reconfigurable SP (RSP) topology without excluding any failure modules to fulfill the voltage constraint at the inverter input. In Velasco-Quesada et al. (2009), the algorithm decides the module connection, after

Table 3
Resume of the static PV array reconfiguration approach with different topology in terms of: Reconfigurable pattern, Array size, study of shading patterns, the complexity of implementation, type of configuration is chosen and remarks

Author	Reconfigurable Pattern	Implemented Array Size	Types of Shadings	Complexity	Configurations	Remarks
Rao et al. (2014)	Renumbering pattern	5×5, 6×6	SW, LW, SN, LN	High	TCT	renumber before connection
Sahu et al. (2016)	Futoshiki puzzle pattern	5×5	SW, LW, SN, LN	Medium	TCT	Futoshiki arrangement
Rani et al. (2013)	Su-Do-Ku puzzle	9×9	SW, LW, SN, LN	High	TCT	Su-Do-Ku arrangement
Rao et al. (2015)	Improved Su-Do-Ku Pattern	9×9	SW, LW, SN, LN	High	TCT	improved Su-Do-Ku arrangement
Yadav et al. (2016)	Non-symmetrical patterns	5×4	vertical horizontal diagonal	High	TCT	Non-symmetrical arrangement
Yadav et al. (2017)	Magic Square Puzzle	4×4	vertical horizontal diagonal	High	TCT	Magic-square arrangement
Yadav and Mukherjee (2018)	SuDoKu, Latin-Square and Ken-Ken Square	6×6	SW, LW, SN, LN	High	TCT	Proposed three different arrangements
Pachauri et al. (2018), Madhusudanan et al. (2018)	Latin Square Puzzle	4×4	vertical horizontal diagonal	High	TCT	Latin-square arrangement
Vijayalekshmy et al. (2015a), Vijayalekshmy et al. (2016b)	Su-Do-Ku	$6 \times 6 gridwith 3 \times 2$	Different shadings	High	SP, TCT, BL, HC, LDR	Su-Do-Ku arrangement
Horoufiany and Ghandehari (2017b)	Optimal Su-Do-Ku	9×9	Horizontal diagonal bottom left bottom right	High	TCT	Optimal Su-Do-Ku arrangement
Malathy and Ramaprabha (2015b)	static shade tolerant scheme	3×3, 5×5	Horizontal, vertical, etc.	High	TCT	renumber before connection
Satpathy et al. (2017)	Shadow Dispersion Scheme	7×7	SW, LN, center, L, one module patterns	High	TCT	renumber before connection
Satpathy et al. (2018)	shade dispersion positioning Scheme	3×3	different shadings	Low	TCT	renumber before connection
Vijayalekshmy et al. (2016a)	Zig-Zag scheme	4×4	Double row, single row, corner, oblique	High	TCT	Zig-Zag arrangement
Rakesh et al. (2015)	Magic square	4×4	SW, LW, SN, LN	High	TCT	Magic square arrangement
Belhaouas et al. (2017)	Adjacent shifting pattern	9×9	SW, LW, SN, LN	High	TCT	Adjacent shifting arrangement
Dhanalakshmi and Rajasekar (2018a)	dominance square pattern	5×5	SW, LW, SN, LN	High	TCT	dominance square arrangement
Pillai et al. (2018b)	Column Index (CI) arrangement	9×9	SW, LW, SN, LN	High	TCT	Proposed column index (CI) arrangement
Bosco and Mabel (2017)	Cross Diagonal View (CDV)	9×9	Inner and diagonal shadings	High	TCT	proposed CDV arrangement
Pillai et al. (2018a)	Two phase reconfiguration	9×9	SW, LW, SN, LN	High	TCT	Two phase reconfiguration for shaded dispersion
Tatabhatla et al. (2019)	Arrow SuDoKu Puzzle	6×6	step by step rows and columns	High	TCT	Arrow SuDoKu arrangement for shaded dispersion
Dhanalakshmi and Rajasekar (2018b)	Competence Square Pattern	9×9	SW, LW, SN, LN	High	TCT	Competence Square Pattern for shaded dispersion

identifying the irradiance of each row in reconfigurable TCT (RTCT) topology. In Bastidas-Rodriguez et al. (2013), the algorithm exclusively measures the strings current and the voltage to calculate the modules irradiance and other parameters. The advantage of this algorithm is, search space can be reduced by fixing the number of modules per row, thus decrease the calculation time for optimum.

3. Sorting Reconfiguration Algorithm (SRA): These type of algorithms are composed of PV modules into a matrix based on the irradiance. Then, a sorting algorithm is applied to search an acceptable solution. In general, the algorithm is to search for the configuration that meets a given condition based on sorting. In Nguyen and Lehman (2008), Chaaban et al. (2010), the algorithm is used to decide the connection between the adaptive part and fixed part based on irradiance. In Storey et al. (2013), the algorithm is used to create PV array into a matrix, the sorting selection criterion is applied to speed up the selection of a configuration.
4. Classical Optimization Algorithm (COA): These algorithms are based on the classical optimization theory, where the value of a mathematical cost function is optimized by using classical methods. Moreover, the constraints are introduced to limit the width of the search space based on possible connections of the solar modules. In El-Dein et al. (2013), proposed branch and bound (BB) algorithm to reduces the cost function and irradiance difference among the modules in each row
5. Computational Intelligence Algorithm (CIA): These type of algorithms calculates the optimum configuration is based on fuzzy sets, neural networks, and evolutionary methods. In general, a designer's knowledge or large amounts of data are required to define or train the algorithm rules. In Auttawaitkul et al. (1998), a fuzzy algorithm is designed using a small set of rules to search for the best configuration based on the irradiance and the torque-velocity of a car.

Table 4 comparing the main features of reconfiguration algorithms in terms of; type of implementation analog or digital, convergence speed, complexities and performance in identification of best configuration (Petrone et al., 2015).

5.1.3. Switching matrix

The switching matrix is the most crucial part in dynamic reconfiguration technique. It takes input signals from the control algorithm accordingly, the switches are operated to identify best optimum configuration. In the switching matrix may use different kinds of switches, which include solid-state relays, contactors, MOSFETs, IGBTs, and SCRs. MOSFET switches are widely used in this type of applications due to its advantages of low cost, high efficiency, and high power availability. A solution based on MOSFETs is presented in Salameh and Dagher (1990). Relays are also used in many cases, as it is the most effective choice in the mechanical version. However, the main constraints to design switching matrix is that it must provide strong reliability, low cost, low maintenance and its lifetime should be the same as that of the PV generator itself.

5.2. Static PV array reconfiguration techniques

Static reconfiguration utilizes a fixed interconnection scheme to enhance maximum output power under partial shading conditions. It means the modules positions are fixed for all shading patterns. In other words, it can be termed as a one-time arrangement. This technique doesn't require any sensors, switching matrix and no separate control algorithm as in case of dynamic technique. In this technique, the most challenging part is to choose an effective reconfigurable pattern to distribute the shading effects from one row into different rows, thereby minimizing the mismatch losses and operation of bypass diodes.

5.3. Economical convenience

This section aims to establish the economical convenience of reconfiguration of the PV system. Reconfiguration is a process of changing the structure of existing PV system is either by modifying the electrical connections or physical positions of the PV modules. In dynamic technique, the PV modules are selfly reconfigured based on irradiance levels with the help of switches (i.e., SPST, DPST, relays, etc.). Also, each PV module has a facility that it can connect with any of the rows in the PV system; this would increase the cost of this technique. However, the overall cost of this technique mainly depends on the area of PV plant, data acquisition system, PV array size, number of switches per module, wiring, and implementation of an algorithm, etc. There are few papers have been presented regarding the economic study of dynamic reconfiguration approach in European Union (EU) countries for evaluation of annual cost/kWh of a PV system (Schettino et al., 2016; Baka et al., 2019). They have used Net Present Value (NPV) method to evaluate the cost of the PV system. This method allows to obtain the result from a sum of cash flows actualized at time zero with a rate equal to the opportunity cost of the financial capital:

$$NPV = -C_0 + \sum_{k=1}^{n} \frac{C_k}{(1+i)^k} \tag{13}$$

where C_0 is the original investment (cost of the PV plants), C_k is the cash flow at the year k, i is the interest rate, and k is the period of net cash flow. Whereas, in static technique, the physical location of PV modules are assembled by manually based on the reconfigurable arrangement. In this technique, the expenditure of the cost would be the area of the PV plant, pyranometer/ PV module, array size, labor cost, and wiring. The maximum power of the PV system under reconfiguration is directly proportional to the cost of the system. The cost becomes inferior if the power generation of the PV system becomes higher (Viola et al., 2017; Miceli and Viola, 2017). In this article, few reconfiguration schemes are compared by estimate the total energy extracted per day kW-h and total energy extracted per year kW-h that corresponds to TCT, SuDoKu Rani et al., 2013, GADeshkar et al., 2015 and PSO Babu et al., 2017 methods, are made for the full effective sun hours. Moreover, the revenue generated by the plant is estimated by considering the tariff as Rs.15 per unit and the computed data is presented in Table 5. Note: The various cost components of the system that have been taken into account are: PV array ($5,167), electric switches ($ 3,229) and data acquisition system ($11,503). From the table, it can understood that the PSO reconfiguration scheme contributes maximum energy yield with the highest income of $ 2689 compared to TCT, Su Do Ku and GA schemes.

6. Discussions

In this paper, the authors highlighted PV array reconfiguration strategies for reducing partial shading conditions which are presented in the literature. These strategies classified into dynamic and static techniques. The dynamic technique is an alternative to the distributed MPPT, which used to increase the power production in the PV plants under the mismatch phenomenon. However, this technique requires a monitoring system to monitor the physical and electrical parameters of

Table 4
Comparison the features of Reconfiguration Algorithms

Type of RA	Analog or Digital	Convergence Speed	Complexity of Implementation	Tracking Performance for Best Solution
PRA	Both	Fast	Low	Low
EERA	Digital	Slow	Medium	High
SRA	Digital	Medium	Medium	Medium
COA	Digital	Medium/Slow	High	High
CIA	Digital	Medium/Slow	Medium	High

Table 5
Energy calculations for Reconfiguration schemes

Energy Index	TCT	SuDoKu	GA	PSO
Total energy extracted per day Kw-h	21.6	31.0	32.2	33.1
Total energy extracted per year Kw-h	7876.8	11316.3	11743.4	12065.4
Total income generated per year Rs.15/kW-h	118151.5	169745.1	176151.7	180981.6
Total income in $ per year	1755.6	2522.2	2617.4	2689.2

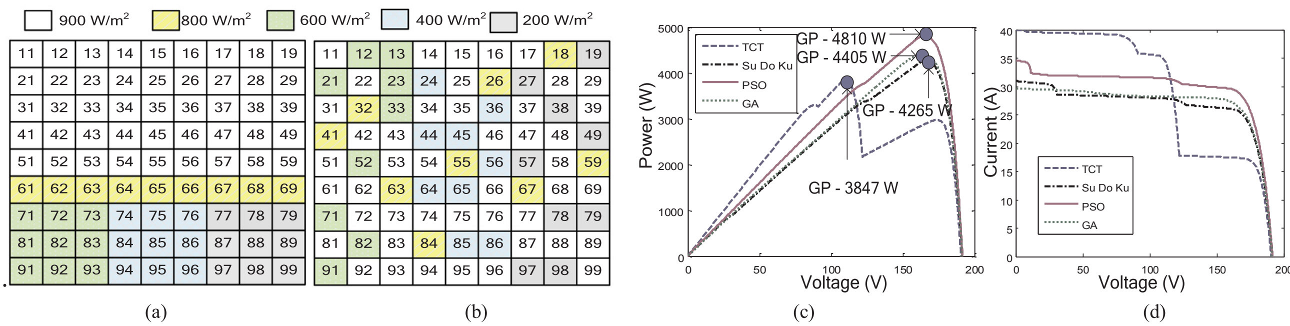


Fig. 28. Shading condition-I; (a) TCT interconnection scheme, (b) Shade dispersion with PSO arrangement, (c) & (d) P-V and I-V characteristics for TCT, Su-Do-Ku (Rani et al. (2013)), GA (Deshkar et al. (2015)) and PSO (Babu et al. (2017)) arrangement.

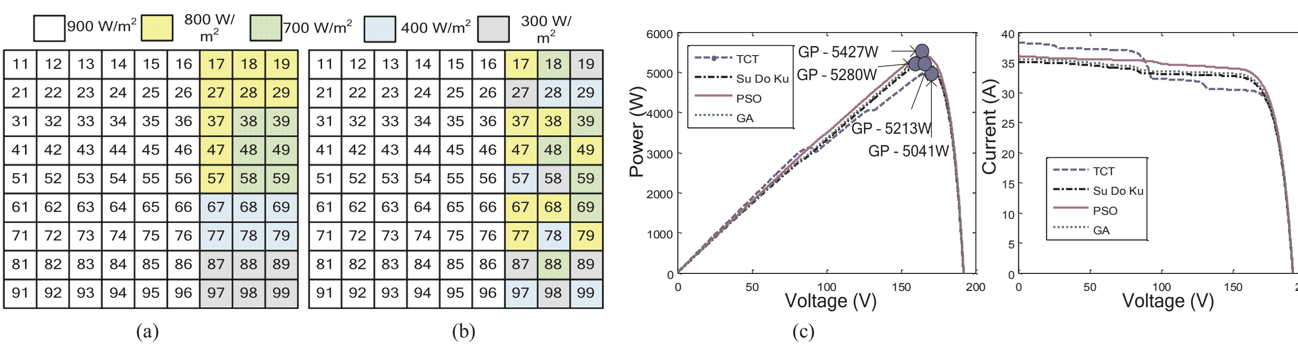


Fig. 29. Shading condition-II; (a) TCT interconnection scheme, (b) Shade dispersion with PSO arrangement, (c) & (d) P-V and I-V characteristics for TCT, Su-Do-Ku (Rani et al. (2013)), GA (Deshkar et al. (2015)) and PSO (Babu et al. (2017)) arrangement.

the PV module, reconfiguration algorithm to identify the optimum configuration and the switching matrix to make connections between PV modules. Hence, this will increases the cost of the dynamic technique, which can compensate by generating the highest maximum power from the PV array. In this technique, to find the suitable electrical switching combination is a complex and challenging task. Therefore, one of the possible alternative ways to suitably address the above issues is the application of optimization technique. Since optimization techniques show the superiority in handling multi-modal objective function, they always remain as the best choice to identify the suitable switching combination to distribute shading effects over the array (Babu et al., 2017; Deshkar et al., 2015). The dynamic technique is mainly recommended for the real-time applications because which employ a microprocessor-based or field-programmable gate array-based system that modifies the layout of the PV plant through the change of the connections among PV modules. The main advantage of the dynamic technique is preventing the hot-spot effect, thereby neglecting the multiple peaks under shading conditions. Further, it suggests the standard MPPT technique for tracking the maximum power output of a PV system.

In the static technique, it requires only an array pattern arrangement to distribute partial shading effects. Several arrangement schemes are addressed in the literature which are Su-Do-Ku, optimal Su-Do-Ku, Magic square, Futoshiki, and Dominant-Square, etc. However, each arrangement has its own advantages and disadvantages. In static technique has a few shortcomings. First, it requires physical labor and excessive wires for rearrangement of PV modules. Second, in all arrangement schemes, the first column of the array remains unaltered. It means, if the shadow is falling on the left side of the array will remain undistributed, which leads the reduction in power output and exhibits multiple peaks in P-V characteristics. Also, some special cases like mutual shadow and fast-moving clouds, this technique may fail to distribute the shading effects. Apart from all, the main drawback of this technique is, it cannot self-reconfigured (Horoufiany and Ghandehari, 2017a).

In summary, earlier attempts to handle partial shading problem in a PV array involves (1) dynamic techniques, and (2) static techniques. Among both, the dynamic method is a self-reconfigure approach, which can effectively distribute the shading effects under any shading issues other than the static method. However, to portray the dynamic technique is enhancing the global maximum power than the static, a simulation study is carried out for three reconfiguration schemes on 9×9 PV array such as PSO (Babu et al., 2017), GA (Deshkar et al., 2015) and Su-Do-Ku (Rani et al., 2013) under two different shading scenarios. The PSO and GA belong to dynamic technique, it means the physical location of PV modules are fixed, but the electrical connections are altered. Whereas, Su-Do-Ku is a static based technique, the physical location of PV modules are changing without altering electrical connections. In each shading condition, the I-V and P-V characteristics are plotted for three reconfiguration schemes as shown in Figs. 28 and 29.

The observation from the results mentioned above, the PSO and GA reconfiguration schemes are effectively distribute the shading effects over the PV array and increasing the global maximum power as compared to Su-Do-Ku scheme.

7. Conclusion

Partial shading is one of the major drawbacks which deteriorates the maximum power from the PV array. Various techniques are reported in the literature to reduce these effects, namely bypass diodes, PV modules interconnection, distributed MPPT, multilevel inverters, and reconfiguration strategies. However, this paper is mainly focused on reconfiguration strategies for increasing maximum power under partial shading and mismatch issues. These strategies are divided into dynamic and static reconfiguration techniques. Based on the review study, mainly two observations carried out in this paper are as follows. Firstly, the dynamic reconfiguration techniques are more effective than the static technique for reducing the partial shading or any other issues. Secondly, among the PV array configurations, the Total-Cross-Tied (TCT) configuration is found to be superior as it offered an effective optimization and higher flexibility for reconfiguration approach.The reconfiguration strategies bring new challenges to the industries aiming at the production of higher maximum power. Marketing target in the next few years could be the conversion of fixed PV plants into reconfigurable one.

References

Akrami, M., Pourhossein, K., 2018. A novel reconfiguration procedure to extract maximum power from partially-shaded photovoltaic arrays. Sol. Energy 173, 110–119.
Alahmad, M., Chaaban, M.A., kit Lau, S., Shi, J., Neal, J., 2012. An adaptive utility interactive photovoltaic system based on a flexible switch matrix to optimize performance in real-time. Sol. Energy 86 (3), 951–963.
Auttawaitkul, Y., Pungsiri, B., Chammongthai, K., Okuda, M., 1998. A method of appropriate electrical array reconfiguration management for photovoltaic powered car 201–204.
Babu, B.C., Gurjar, S., 2014. A novel simplified two-diode model of photovoltaic (pv) module. IEEE J. Photovoltaics 4 (4), 1156–1161.
Babu, T.S., Ram, J.P., Dragicevic, T., Miyatake, M., Blaabjerg, F., Rajasekar, N., 2017. Particle swarm optimization based solar pv array reconfiguration of the maximum power extraction under partial shading conditions. IEEE Trans. Sustain. Energy.
Baka, M., Manganiello, P., Soudris, D., Catthoor, F., 2019. A cost-benefit analysis for reconfigurable pv modules under shading. Sol. Energy 178, 69–78.
Balato, M., Costanzo, L., Vitelli, M., 2015. Series–parallel pv array re-configuration: maximization of the extraction of energy and much more. Appl. Energy 159, 145–160.
Balato, M., Manganiello, P., Vitelli, M., 2014. Fast dynamical reconfiguration algorithm of pv arrays 1–8.
Bastidas-Rodriguez, J.D., Ramos-Paja, C.A., Saavedra-Montes, A.J., 2013. Reconfiguration analysis of photovoltaic arrays based on parameters estimation. Simul. Model. Pract. Theory 35, 50–68.
Belhaouas, N., Cheikh, M.-S.A., Agathoklis, P., Oularbi, M.-R., Amrouche, B., Sedraoui, K., Djilali, N., 2017. Pv array power output maximization under partial shading using new shifted pv array arrangements. Appl. Energy 187, 326–337.
Bosco, M.J., Mabel, M.C., 2017. A novel cross diagonal view configuration of a pv system under partial shading condition. Sol. Energy 158, 760–773.
Bratcu, A.I., Munteanu, I., Bacha, S., Picault, D., Raison, B., 2011. Cascaded dc–dc converter photovoltaic systems: power optimization issues. IEEE Trans. Industr. Electron. 58 (2), 403–411.
Braun, H., Buddha, S., Krishnan, V., Tepedelenlioglu, C., Spanias, A., Banavar, M., Srinivasan, D., 2016. Topology reconfiguration for optimization of photovoltaic array output. Sustain. Energy Grids Netw. 6, 58–69.
Breitenstein, O., 2014. An alternative one-diode model for illuminated solar cells. Energy Procedia 55, 30–37.
Busquets-Monge, S., Rocabert, J., Rodríguez, P., Alepuz, S., Bordonau, J., 2008. Multilevel diode-clamped converter for photovoltaic generators with independent voltage control of each solar array. IEEE Trans. Industr. Electron. 55 (7), 2713–2723.
Camarillo-Peñaranda, J.R., Ramírez-Quiroz, F.A., González-Montoya, D., Bolaños-Martínez, F., Ramos-Paja, C.A., 2015. Reconfiguration of photovoltaic arrays based on genetic algorithm. Revista Facultad de Ingeniería Universidad de Antioquia (75), 95–107.
Carotenuto, P.L., Curcio, S., Manganiello, P., Petrone, G., Spagnuolo, G., Vitelli, M., 2013. Algorithms and devices for the dynamical reconfiguration of pv arrays. PCIM Europe-2013 765–772.
Carotenuto, P.L., Della Cioppa, A., Marcelli, A., Spagnuolo, G., 2015. An evolutionary approach to the dynamical reconfiguration of photovoltaic fields. Neurocomputing 170, 393–405.
Celik, B., Karatepe, E., Silvestre, S., Gokmen, N., Chouder, A., 2015. Analysis of spatial fixed pv arrays configurations to maximize energy harvesting in bipv applications. Renew. Energy 75, 534–540.
Chaaban, M.A., Alahmad, M., Neal, J., Shi, J., Berryman, C., Cho, Y., Lau, S., Li, H., Schwer, A., Shen, Z., et al., 2010. Adaptive photovoltaic system 3192–3197.
Chaaban, M.A., El Chaar, L., Alahmad, M., 2015. An adaptive photovoltaic topology to overcome shading effect in pv systems. Int. J. Photoenergy 2015.
Chao, K.-H., Lai, P.-L., Liao, B.-J., 2015. The optimal configuration of photovoltaic module arrays based on adaptive switching controls. Energy Convers. Manage. 100, 157–167.
Cheng, Z., Pang, Z., Liu, Y., Xue, P., 2010. An adaptive solar photovoltaic array reconfiguration method based on fuzzy control 176–181.
Deshkar, S.N., Dhale, S.B., Mukherjee, J.S., Babu, T.S., Rajasekar, N., 2015. Solar pv array reconfiguration under partial shading conditions for maximum power extraction using genetic algorithm. Renew. Sustain. Energy Rev. 43, 102–110.
Dhanalakshmi, B., Rajasekar, N., 2018a. Dominance square based array reconfiguration scheme for power loss reduction in solar photovoltaic (pv) systems. Energy Convers. Manage. 156, 84–102.
Dhanalakshmi, B., Rajasekar, N., 2018b. A novel competence square based pv array reconfiguration technique for solar pv maximum power extraction. Energy Convers. Manage. 174, 897–912.
Diqing, Z., Wu, C., Li, Z., 2012. Modeling and simulation of partial shaded pv modules. In: System Simulation and Scientific Computing. Springer, pp. 124–134.
dos Santos, P., Vicente, E.M., Ribeiro, E.R., 2011a. Reconfiguration methodology of shaded photovoltaic panels to maximize the produced energy 700–706.
dos Santos, P., Vicente, E.M., Ribeiro, E.R., 2011b. Relationship between the shading position and the output power of a photovoltaic panel. In: Power Electronics Conference (COBEP), 2011 Brazilian. IEEE, pp. 676–681.
El-Dein, M.S., Kazerani, M., Salama, M., 2013. Optimal photovoltaic array reconfiguration to reduce partial shading losses. IEEE Trans. Sustain. Energy 4 (1), 145–153.
Faldella, E., Cardinali, G.C., Calzolari, P.U., 1991. Architectural and design issues on optimal management of photovoltaic pumping systems. IEEE Trans. Industr. Electron. 38 (5), 385–392.
Femia, N., Lisi, G., Petrone, G., Spagnuolo, G., Vitelli, M., 2008. Distributed maximum power point tracking of photovoltaic arrays: novel approach and system analysis. IEEE Trans. Industr. Electron. 55 (7), 2610–2621.
Gao, L., Dougal, R.A., Liu, S., Iotova, A.P., 2009. Parallel-connected solar pv system to address partial and rapidly fluctuating shadow conditions. IEEE Trans. Industr. Electron. 56 (5), 1548–1556.
Green, M.A., Emery, K., Hishikawa, Y., Warta, W., Dunlop, E.D., 2015. Solar cell efficiency tables (version 45). Prog. Photovoltaics: Res. Appl. 23 (1), 1–9.
Harrag, A., Messalti, S., 2016. Adaptive ga-based reconfiguration of photovoltaic array combating partial shading conditions. Neural Comput. Appl. 1–26.
Hasan, M., Parida, S., 2016. An overview of solar photovoltaic panel modeling based on analytical and experimental viewpoint. Renew. Sustain. Energy Rev. 60, 75–83.
Hasanien, H.M., Al-Durra, A., Muyeen, S., 2016. Gravitational search algorithm-based photovoltaic array reconfiguration for partial shading losses reduction.
Herrmann, W., Wiesner, W., Vaassen, W., 1997. Hot spot investigations on pv modules-new concepts for a test standard and consequences for module design with respect to bypass diodes. In: Photovoltaic Specialists Conference, 1997. Conference Record of the Twenty-Sixth IEEE. IEEE, pp. 1129–1132.
Horoufiany, M., Ghandehari, R., 2017a. Optimal fixed reconfiguration scheme for pv arrays power enhancement under mutual shading conditions. IET Renew. Power Gener. 11 (11), 1456–1463.
Horoufiany, M., Ghandehari, R., 2017b. Optimization of the sudoku based reconfiguration technique for pv arrays power enhancement under mutual shading conditions. Sol. Energy.
Hu, Y., Zhang, J., Li, P., Yu, D., Jiang, L., 2017. Non-uniform aged modules reconfiguration for large-scale pv array. IEEE Trans. Dev. Mater. Reliab. 17 (3), 560–569.
Iraji, F., Farjah, E., Ghanbari, T., 2017. Optimisation method to find the best switch set topology for reconfiguration of photovoltaic panels. IET Renew. Power Gener.
Ishaque, K., Salam, Z., Amjad, M., Mekhilef, S., 2012. An improved particle swarm optimization (pso)–based mppt for pv with reduced steady-state oscillation. IEEE Trans. Power Electron. 27 (8), 3627–3638.
Jazayeri, M., Jazayeri, K., Uysal, S., 2017. Adaptive photovoltaic array reconfiguration based on real cloud patterns to mitigate effects of non-uniform spatial irradiance profiles. Sol. Energy 155, 506–516.
Jewell, W.T., Unruh, T.D., 1990. Limits on cloud-induced fluctuation in photovoltaic generation. IEEE Trans. Energy Convers. 5 (1), 8–14.
Kaliyaperumal, S., Chenniyappan, S., 2016. Low cost dynamic switching technique for improving the power in partially shaded photo voltaic array. Int. J. Control Autom. 9 (2), 61–70.
Kamarzaman, N.A., Tan, C.W., 2014. A comprehensive review of maximum power point tracking algorithms for photovoltaic systems. Renew. Sustain. Energy Rev. 37, 585–598.
Karakose, M., Baygin, M., 2014. Image processing based analysis of moving shadow effects for reconfiguration in pv arrays 683–687.
Karakose, M., Baygin, M., Baygin, N., 2014a. An analysis approach for optimization based reconfiguration in photovoltaic arrays 954–959.
Karakose, M., Baygin, M., Murat, K., Baygin, N., Akin, E., 2016. Fuzzy based reconfiguration method using intelligent partial shadow detection in pv arrays. Int. J. Comput. Intell. Syst. 9 (2), 202–212.
Karakose, M., Baygin, M., Parlak, K.S., 2014b. A new real-time reconfiguration approach based on neural network in partial shading for pv arrays 633–637.
La Manna, D., Vigni, V.L., Sanseverino, E.R., Di Dio, V., Romano, P., 2014. Reconfigurable electrical interconnection strategies for photovoltaic arrays: a review. Renew. Sustain. Energy Rev. 33, 412–426.
Larbes, C., Cheikh, S.A., Obeidi, T., Zerguerras, A., 2009. Genetic algorithms optimized

fuzzy logic control for the maximum power point tracking in photovoltaic system. Renew. Energy 34 (10), 2093–2100.
Laudani, A., Lozito, G.M., Lucaferri, V., Radicioni, M., Fulginei, F.R., 2018. On circuital topologies and reconfiguration strategies for pv systems in partial shading conditions: A review. AIMS Energy 6 (5), 735–763.
Liu, H., Wan, L., Pei, B., 2016. Optimal scheme of pv array in partial shading: a reconfiguration algorithm 2105–2109.
Madhusudanan, G., Senthilkumar, S., Anand, I., Sanjeevikumar, P., 2018. A shade dispersion scheme using latin square arrangement to enhance power production in solar photovoltaic array under partial shading conditions. J. Renew. Sustain. Energy 10 (5), 053506.
Mahmoud, Y., El-Saadany, E., 2017a. Fast reconfiguration algorithm for improving the efficiency of pv systems. In: Renewable Energy Congress (IREC), 2017 8th International. IEEE, pp. 1–5.
Mahmoud, Y., El-Saadany, E.F., 2017b. Enhanced reconfiguration method for reducing mismatch losses in pv systems. IEEE J. Photovoltaics 7 (6), 1746–1754.
Mäki, A., Valkealahti, S., 2012. Power losses in long string and parallel-connected short strings of series-connected silicon-based photovoltaic modules due to partial shading conditions. IEEE Trans. Energy Convers. 27 (1), 173–183.
Malathy, S., Ramaprabha, R., 2015a. Performance enhancement of partially shaded solar photovoltaic array using grouping technique. J. Sol.Energy Eng. 137 (3), 034505.
Malathy, S., Ramaprabha, R., 2015b. A static pv array architecture to enhance power generation under partial shaded conditions 341–346.
Malathy, S., Ramaprabha, R., 2017. Reconfiguration strategies to extract maximum power from photovoltaic array under partially shaded conditions. Renew. Sustain. Energy Rev.
Manju, S., Sagar, N., 2017. Progressing towards the development of sustainable energy: a critical review on the current status, applications, developmental barriers and prospects of solar photovoltaic systems in India. Renew. Sustain. Energy Rev. 70, 298–313.
Manjunath Matam, V.R.B., Govind, A.R., 2018. Optimized reconfigurable pv array based photovoltaic water-pumping system. Sol. Energy 170, 1063–1073.
Matam, M., Barry, V.R., 2018a. Improved performance of dynamic photovoltaic array under repeating shade conditions. Energy Convers. Manage. 168, 639–650.
Matam, M., Barry, V.R., 2018b. Variable size dynamic pv array for small and various dc loads. Sol. Energy 163, 581–590.
Mellit, A., Kalogirou, S.A., 2014. Mppt-based artificial intelligence techniques for photovoltaic systems and its implementation into field programmable gate array chips: review of current status and future perspectives. Energy 70, 1–21.
Meraj, W., Mishra, S., 2015. An approach to increase power in partial shading condition by reconfiguration. In: India Conference (INDICON), 2015 Annual IEEE. IEEE, pp. 1–6.
Meral, M.E., Dinçer, F., 2011. A review of the factors affecting operation and efficiency of photovoltaic based electricity generation systems. Renew. Sustain. Energy Rev. 15 (5), 2176–2184.
Miceli, R., Viola, F., 2017. Designing a sustainable university recharge area for electric vehicles: technical and economic analysis. Energies 10 (10), 1604.
Mohamed, A.M., Saafan, S.M., Attalla, A.M., Elgohary, H., 2018. Reconfiguration technique for optimization of the photovoltaic array output power under partial shading conditions. Trends Renew. Energy 4 (2), 111–124.
Ngoc, T.N., Phung, Q.N., Tung, L.N., Sanseverino, E.R., Romano, P., Viola, F., 2017. Increasing efficiency of photovoltaic systems under non-homogeneous solar irradiation using improved dynamic programming methods. Sol. Energy 150, 325–334.
Nguyen, D., Lehman, B., 2008. An adaptive solar photovoltaic array using model-based reconfiguration algorithm. IEEE Trans. Industr. Electron. 55 (7), 2644–2654.
Nguyen, D.D., Lehman, B., Kamarthi, S., 2009. Performance evaluation of solar photovoltaic arrays including shadow effects using neural network 3357–3362.
Obane, H., Okajima, K., Oozeki, T., Ishii, T., 2012. Pv system with reconnection to improve output under nonuniform illumination. IEEE J. Photovoltaics 2 (3), 341–347.
Obane, H., Okajima, K., Ozeki, T., Yamada, T., Ishi, T., 2011. Minimizing mismatch loss in bipv system by reconnection. In: Photovoltaic Specialists Conference (PVSC), 2011 37th IEEE. IEEE, pp. 002406–002411.
Pachauri, R., Yadav, A.S., Chauhan, Y.K., Sharma, A., Kumar, V., 2018. Shade dispersion-based photovoltaic array configurations for performance enhancement under partial shading conditions. Int. Trans. Electr. Energy Syst.
Pandey, A., Tyagi, V., Jeyraj, A., Selvaraj, L., Rahim, N., Tyagi, S., 2016. Recent advances in solar photovoltaic systems for emerging trends and advanced applications. Renew. Sustain. Energy Rev. 53, 859–884.
Pareek, S., Dahiya, R., 2016. Enhanced power generation of partial shaded photovoltaic fields by forecasting the interconnection of modules. Energy 95, 561–572.
Parida, B., Iniyan, S., Goic, R., 2011. A review of solar photovoltaic technologies. Renew. Sustain. Energy Rev. 15 (3), 1625–1636.
Parlak, K.S., 2013. A new reconfiguration method for pv array system. In: Industrial Electronics Society, IECON 2013-39th Annual Conference of the IEEE. IEEE, pp. 1478–1483.
Parlak, K.Ş., 2014. Pv array reconfiguration method under partial shading conditions. Int. J. Electr. Power Energy Syst. 63, 713–721.
Parlak, K.Ş., Karaköse, M., 2014. An efficient reconfiguration method based on standard deviation for series and parallel connected pv arrays 457–461.
Patnaik, B., Mohod, J., Duttagupta, S., 2012. Distributed multi-sensor network for real time monitoring of illumination states for a reconfigurable solar photovoltaic array. In: Physics and Technology of Sensors (ISPTS), 2012 1st International Symposium on. IEEE, pp. 106–109.
Patnaik, B., Sharma, P., Trimurthulu, E., Duttagupta, S., Agarwal, V., 2011. Reconfiguration strategy for optimization of solar photovoltaic array under non-uniform illumination conditions 001859–001864.
Pendem, S.R., Mikkili, S., 2018a. Modeling, simulation and performance analysis of solar pv array configurations (series, series–parallel and honey-comb) to extract maximum power under partial shading conditions. Energy Rep. 4, 274–287.
Pendem, S.R., Mikkili, S., 2018b. Modelling and performance assessment of pv array topologies under partial shading conditions to mitigate the mismatching power losses. Sol. Energy 160, 303–321.
Petrone, G., Serra, F., Spagnuolo, G., Monmasson, E., 2019. Soc implementation of a photovoltaic reconfiguration algorithm by exploiting a hls-based architecture. Math. Comput. Simul.
Petrone, G., Spagnuolo, G., Zhao, Y., Lehman, B., Ramos, C., Orozco, M., 2015. Dynamical reconfiguration for fighting mismatched conditions and meeting load requests.
Picault, D., Raison, B., Bacha, S., De La Casa, J., Aguilera, J., 2010. Forecasting photovoltaic array power production subject to mismatch losses. Sol. Energy 84 (7), 1301–1309.
Pillai, D.S., Rajasekar, N., Ram, J.P., Chinnaiyan, V.K., 2018a. Design and testing of two phase array reconfiguration procedure for maximizing power in solar pv systems under partial shade conditions (psc). Energy Convers. Manage. 178, 92–110.
Pillai, D.S., Ram, J.P., Nihanth, M.S.S., Rajasekar, N., 2018b. A simple, sensorless and fixed reconfiguration scheme for maximum power enhancement in pv systems. Energy Convers. Manage. 172, 402–417.
Potnuru, S.R., Pattabiraman, D., Ganesan, S.I., Chilakapati, N., 2015. Positioning of pv panels for reduction in line losses and mismatch losses in pv array. Renew. Energy 78, 264–275.
Quaschning, V., Hanitsch, R., 1996. Numerical simulation of current-voltage characteristics of photovoltaic systems with shaded solar cells. Sol. Energy 56 (6), 513–520.
Rajan, N.A., Shrikant, K.D., Dhanalakshmi, B., Rajasekar, N., 2017. Solar pv array reconfiguration using the concept of standard deviation and genetic algorithm. Energy Procedia 117, 1062–1069.
Rakesh, N., Madhavaram, T.V., 2016. Performance enhancement of partially shaded solar pv array using novel shade dispersion technique. Front. Energy 10 (2), 227.
Rakesh, N., Madhavaram, T.V., Ajith, K., Naik, G.R., Reddy, P.N., 2015. A new technique to enhance output power from solar pv array under different partial shaded conditions 345–348.
Ramaprabha, R., Mathur, B., 2012. A comprehensive review and analysis of solar photovoltaic array configurations under partial shaded conditions. Int. J. Photoenergy 2012.
Ramaprabha, R., Mathur, B., Murthy, M., Madhumitha, S., 2010. New configuration of solar photo voltaic array to address partial shaded conditions 328–333.
Ramasamy, S., Seenithangam, J., Dash, S.S., Chaitanya, K., 2016. A dodging algorithm to reconfigure photovoltaic array to negate partial shading effect. Prog. Photovoltaics Res. Appl. 24 (2), 200–210.
Ramos-Paja, C.A., Bastidas, J.D., Saavedra-Montes, A.J., Guinjoan-Gispert, F., Goez, M., 2012. Mathematical model of total cross-tied photovoltaic arrays in mismatching conditions. In: Circuits and Systems (CWCAS), 2012 IEEE 4th Colombian Workshop on. IEEE, pp. 1–6.
Rani, B.I., Ilango, G.S., Nagamani, C., 2013. Enhanced power generation from pv array under partial shading conditions by shade dispersion using su do ku configuration. IEEE Trans. Sustain. Energy 4 (3), 594–601.
Rao, P.S., Dinesh, P., Ilango, G.S., Nagamani, C., 2015. Optimal su-do-ku based interconnection scheme for increased power output from pv array under partial shading conditions. Front. Energy 9 (2), 199–210.
Rao, P.S., Ilango, G.S., Nagamani, C., 2014. Maximum power from pv arrays using a fixed configuration under different shading conditions. IEEE J. Photovoltaics 4 (2), 679–686.
Reddy, G.S., Reddy, T.B., Kumar, M.V., 2018. Shadow dispersion of pv array under variable irradiance for superior power generation by magic square configuration. Int. J. Eng. Technol. 7 (1.8), 172–177.
Romano, P., Candela, R., Cardinale, M., Li Vigni, V., Musso, D., Riva Sanseverino, E., 2013. Optimization of photovoltaic energy production through an efficient switching matrix. J. Sustain. Develop. Energy Water Environ. Syst. 1 (3), 227–236.
Roopa, P., Rajan, S.E., Vengatesh, R.P., 2011. Performance analysis of pv module connected in various configurations under uniform and non-uniform solar radiation conditions. In: Recent Advancements in Electrical, Electronics and Control Engineering (ICONRAEeCE), 2011 International Conference on. IEEE, pp. 142–149.
Sahoo, S.K., 2016. Renewable and sustainable energy reviews solar photovoltaic energy progress in India: a review. Renew. Sustain. Energy Rev. 59, 927–939.
Sahu, H.S., Nayak, S.K., 2014. Power enhancement of partially shaded pv array by using a novel approach for shade dispersion. In: Innovative Smart Grid Technologies-Asia (ISGT Asia), 2014 IEEE. IEEE, pp. 498–503.
Sahu, H.S., Nayak, S.K., Mishra, S., 2016. Maximizing the power generation of a partially shaded pv array. IEEE J. Emerg. Sel. Top. Power Electron. 4 (2), 626–637.
Salameh, Z.M., Dagher, F., 1990. The effect of electrical array reconfiguration on the performance of a pv-powered volumetric water pump. IEEE Trans. Energy Convers. 5 (4), 653–658.
Salameh, Z.M., Liang, C., 1990. Optimum switching points for array reconfiguration controller 971–976.
Samikannu, S.M., Namani, R., Subramaniam, S.K., 2016. Power enhancement of partially shaded pv arrays through shade dispersion using magic square configuration. J. Renew. Sustain. Energy 8 (6), 063503.
Sanseverino, E.R., Ngoc, T.N., Cardinale, M., Vigni, V.L., Musso, D., Romano, P., Viola, F., 2015. Dynamic programming and munkres algorithm for optimal photovoltaic arrays reconfiguration. Sol. Energy 122, 347–358.
Satpathy, P.R., Jena, S., Sharma, R., 2018. Power enhancement from partially shaded modules of solar pv arrays through various interconnections among modules. Energy 144, 839–850.
Satpathy, P.R., Sharma, R., Jena, S., 2017. A shade dispersion interconnection scheme for

partially shaded modules in a solar pv array network. Energy 139, 350–365.
Schettino, G., Caruso, M., Miceli, R., Romano, P., Viola, F., 2016. Economic evaluation on the use of reconfiguration systems for increase of energy production in pv plants 384–387.
Sera, D., Teodorescu, R., Rodriguez, P., 2007. Pv panel model based on datasheet values. In: Industrial Electronics, 2007. ISIE 2007. IEEE International Symposium on. IEEE, pp. 2392–2396.
Serna-Garcés, S.I., Bastidas-Rodríguez, J.D., Ramos-Paja, C.A., 2015. Reconfiguration of urban photovoltaic arrays using commercial devices. Energies 9 (1), 2.
Shmilovitz, D., Levron, Y., 2012. Distributed maximum power point tracking in photovoltaic systems?emerging architectures and control methods. Automatika 53 (2), 142–155.
Singh, G.K., 2013. Solar power generation by pv (photovoltaic) technology: a review. Energy 53, 1–13.
Skoplaki, E., Palyvos, J., 2009. On the temperature dependence of photovoltaic module electrical performance: a review of efficiency/power correlations. Sol. Energy 83 (5), 614–624.
Storey, J., Wilson, P.R., Bagnall, D., 2014. The optimized-string dynamic photovoltaic array. IEEE Trans. Power Electron. 29 (4), 1768–1776.
Storey, J.P., Wilson, P.R., Bagnall, D., 2013. Improved optimization strategy for irradiance equalization in dynamic photovoltaic arrays. IEEE Trans. Power Electron. 28 (6), 2946–2956.
Tabanjat, A., Becherif, M., Hissel, D., 2015. Reconfiguration solution for shaded pv panels using switching control. Renew. Energy 82, 4–13.
Tamura, J., Nakamura, H., Inoue, Y., Otani, K., Kurokawa, K., 2003. A new method of calculating in-plane irradiation by one-minute local solar irradiance. In: Photovoltaic Energy Conversion, 2003. Proceedings of 3rd World Conference on Vol. 3. IEEE, pp. 2265–2268.
Tatabhatla, V.M.R., Agarwal, A., Kanumuri, T., 2019. Performance enhancement by shade dispersion of solar photo-voltaic array under continuous dynamic partial shading conditions. J. Clean. Prod. 213, 462–479.
Tubniyom, C., Chatthaworn, R., Suksri, A., Wongwuttanasatian, T., 2019. Minimization of losses in solar photovoltaic modules by reconfiguration under various patterns of partial shading. Energies 12 (1), 24.
Vaidya, V., Wilson, D., 2013. Maximum power tracking in solar cell arrays using time-based reconfiguration. Renew. Energy 50, 74–81.
Velasco, G., Guinjoan, F., Pique, R., 2008. Grid-connected pv systems energy extraction improvement by means of an electric array reconfiguration (ear) strategy: operating principle and experimental results 1983–1988.
Velasco, G., Negroni, J., Guinjoan, F., Pique, R., 2005a. Energy generation in pv grid-connected systems: power extraction optimization for plant oriented pv generators 3, 1025–1030.
Velasco, G., Negroni, J., Guinjoan, F., Pique, R., 2005b. Irradiance equalization method for output power optimization in plant oriented grid-connected pv generators, 10 pp.
Velasco-Quesada, G., Guinjoan-Gispert, F., Piqué-López, R., Román-Lumbreras, M., Conesa-Roca, A., 2009. Electrical pv array reconfiguration strategy for energy extraction improvement in grid-connected pv systems. IEEE Trans. Industr. Electron. 56 (11), 4319–4331.
Vengatesh, R.P., Rajan, S.E., 2016. Analysis of pv module connected in different configurations under uniform and non-uniform solar radiations. Int. J. Green Energy 13 (14), 1507–1516.
Vicente, P.d.S., Pimenta, T.C., Ribeiro, E.R., 2015. Photovoltaic array reconfiguration strategy for maximization of energy production. Int. J. Photoenergy 2015.
Vigni, V.L., Manna, D.L., Sanseverino, E.R., di Dio, V., Romano, P., di Buono, P., Pinto, M., Miceli, R., Giaconia, C., 2015. Proof of concept of an irradiance estimation system for reconfigurable photovoltaic arrays. Energies 8 (7), 6641–6657.
Vijayalekshmy, S., Bindu, G., Iyer, S.R., 2015a. Analysis of various photovoltaic array configurations under shade dispersion by su do ku arrangement during passing cloud conditions. Indian J. Sci. Technol. 8 (35).
Vijayalekshmy, S., Bindu, G., Iyer, S.R., 2016a. A novel zig-zag scheme for power enhancement of partially shaded solar arrays. Sol. Energy 135, 92–102.
Vijayalekshmy, S., Bindu, G., Iyer, S.R., 2016b. Performance improvement of partially shaded photovoltaic arrays under moving shadow conditions through shade dispersion. J. Inst. Eng. (India): Ser. B 97 (4), 569–575.
Vijayalekshmy, S., Bindu, G., RamaIyer, S., 2015b. Power enhancement of partially shaded solar arrays under moving illumination conditions through shade dispersion. In: Signal Processing, Informatics, Communication and Energy Systems (SPICES). 2015 IEEE International Conference on. IEEE, pp. 1–5.
Villa, L.F.L., Picault, D., Raison, B., Bacha, S., Labonne, A., 2012. Maximizing the power output of partially shaded photovoltaic plants through optimization of the interconnections among its modules. IEEE J. Photovoltaics 2 (2), 154–163.
Viola, F., Romano, P., Miceli, R., Spataro, C., Schettino, G., 2017. Technical and economical evaluation on the use of reconfiguration systems in some eu countries for pv plants. IEEE Trans. Indust. Appl. 53 (2), 1308–1315.
Wang, Y.-J., Hsu, P.-C., 2010. Analytical modelling of partial shading and different orientation of photovoltaic modules. IET Renew. Power Gener. 4 (3), 272–282.
Wang, Y.-J., Hsu, P.-C., 2011. An investigation on partial shading of pv modules with different connection configurations of pv cells. Energy 36 (5), 3069–3078.
Xiao, W., Edwin, F.F., Spagnuolo, G., Jatskevich, J., 2013. Efficient approaches for modeling and simulating photovoltaic power systems. IEEE J. Photovoltaics 3 (1), 500–508.
Yadav, A.S., Mukherjee, V., 2018. Line losses reduction techniques in puzzled pv array configuration under different shading conditions. Sol. Energy 171, 774–783.
Yadav, A.S., Pachauri, R.K., Chauhan, Y.K., 2016. Comprehensive investigation of pv arrays with puzzle shade dispersion for improved performance. Sol. Energy 129, 256–285.
Yadav, A.S., Pachauri, R.K., Chauhan, Y.K., Choudhury, S., Singh, R., 2017. Performance enhancement of partially shaded pv array using novel shade dispersion effect on magic-square puzzle configuration. Sol. Energy 144, 780–797.
Yadir, S., Benhmida, M., Sidki, M., Assaid, E., Khaidar, M., 2009. New method for extracting the model physical parameters of solar cells using explicit analytic solutions of current-voltage equation. In: Microelectronics (ICM). 2009 International Conference on. IEEE, pp. 390–393.
Zhao, Y., Yang, L., Lehman, B., de Palma, J.-F., Mosesian, J., Lyons, R., 2012. Decision tree-based fault detection and classification in solar photovoltaic arrays. In: Applied Power Electronics Conference and Exposition (APEC), 2012 Twenty-Seventh Annual IEEE. IEEE, pp. 93–99.
Zhu, L., Li, Q., Chen, M., Cao, K., Sun, Y., 2019. A simplified mathematical model for power output predicting of building integrated photovoltaic under partial shading conditions. Energy Convers. Manage. 180, 831–843.