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Solar PV array reconfiguration using Ant Colony Optimisation for maximum power extraction under partial shading conditions

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ABSTRACT
The role of Renewable energy resources is important in the India's power sector. Due to the rapid increasing energy demand, PV (Photovoltaic) power is becoming a leading source of electrical energy. PV array suffers from the serious and unavoidable trouble called partial shading,when exposed to different level of solar irradiances. Photovoltaic (PV) array reconfiguration is an efficient dynamic rearrangement of PV modules to reduce the effect of partial shading without changing the physical location of modules. PV (photovoltaic) array reconfiguration is achieved by changing the electrical connections of the modules while the physical location remain unaltered. This paper introduces an ACS (Ant colony system) optimisation algorithm to find the best configuration of a PV array connected to maximise power output. ACS (Ant colony system) is a novel meta-heuristic inspired by the foraging behaviour of real ant. The ACS algorithm reproduces the technique used by ants to construct their food recollection path from their nest, where a set of artificial ants cooperate to find the best solution through the interchange of the information contained in the pheromone deposits of the different paths. The major objectives considered are minimization of irradiance equalisation index and minimisation of number of switching operations required in PV array reconfiguration. A mathematical model is developed to determine the equalization index and module switching count associated with PV reconfiguration problem and developed a modified multi-objective ACS (Ant Colony System) to provide optimum solution for multi-objective problem .Software based on this approach is developed in C programming and validated for different shading cases. The main advantage of this method is the low computational effort required to reconstruct the solution as compared to other existing optimisation methods. The technique found as a flexible and powerful tool for optimal PV array reconfiguration.

Keywords: Mismatch; PV (Photovoltaic modules); Optimization; Reconfiguration; ACS (Ant Colony System)

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I. INTRODUCTION

Power is one of the most crucial components for the economic growth of nations. Indian economy depends on the existence and development of adequate infrastructure is important for growth of the Indian economy. Sources of power generation are conventional sources such as coal, lignite, natural gas, oil, hydro and nuclear power to non-conventional sources such as wind, solar, and agricultural and domestic waste. In order to meet the increasing demand for electricity in the country increased installed generating capacity is required. Renewable energy resources will play a vital role in the future. India is situated in sunny belt India is endowed with vast solar energy potential. The cost of solar energy technologies are rapid decreasing in the recent past years Currently, the installed capacity of solar energy projects in India is about 4.22 GW. India is planning to produce 100 GW of solar power by 2022. PV cell convert solar energy to electricity when exposed to sunlight. In order to get required amount of current (Ampere) and voltage (volts) many PV cells are interconnected into a single unit called a PV module. Generally a PV module is composed of 36 cells which are connected in series. All the PV cells in a module are supposed to have identical electrical properties, but these properties changes when they are exposed to different levels of solar irradiance leading to mismatch losses. This mismatch causes a serious & unavoidable trouble called partial shading. Partial shading can be caused by snow, tree shadow or bird dung covering PV module surface. In a large PV system occupying a wide area of land, moving clouds is also the cause of partial shade. In building integrated PV systems, PV modules installed with different orientations as per requirements to fit the building outer wall receive different levels of irradiance, which is a situation similar to partial shading [1]. Practically all the PV cells in a module carry different current under non uniform irradiance, so the string of series connected cells carry current limits to current of the lowermost short circuit (SC) current [2]. Partial shade causes hot spots in the shaded cells which can damage the cells. PV cells protected from damage using bypass diodes [3]. The shaded cells in the PV module act as reverse biased diode so the bypass diode connected in antiparallel begins to bypass the current exceeding the SC current of the shaded cells. Bypass diodes conduct only during non-uniform condition, leads to the multiple maxima in the power- voltage (PV) curves [4], [5]. The reduction in output PV power is also due to the module interconnection scheme and different shading patterns. Different interconnection schemes such as series–parallel (SP), total cross tied (TCT), and bridge linked (BL) are introduced in the literature [6], [7] to interconnect the modules in a PV array. Study of mismatch losses in the PV array by changing the interconnection scheme of the modules in PV arrays has been studied in [8], [9],[10].In fault tolerance investigation of different interconnection schemes found that TCT and BL connections least susceptible to electrical mismatches. The study of reliability for assessing the operational life time of a PV array, has indicated that the life of an array doubled when connected with crossties [11].The fault tolerance investigation in done to compare maximum power and fill factor on PV modules with SP(series-parallel), TCT(total cross tied), BL(bridge-link), SS (simple series), and HC (honey comb) interconnection configuration using piecewise linear parallel branches model [12], [13]. The maximum possible power under partial shade is the sum of the maximum powers of the individual modules when operating independently under the same irradiance levels and shading losses. Operative techniques used to reduce partial shading losses are

i) Maximum power point tracker (MPPT).
ii) Multilevel inverters
iii) Photovoltaic array reconfiguration.

The first two operative techniques have been researched extensively in the technical literature. Photovoltaic array reconfiguration is an efficient dynamic rearrangement of PV modules in order to ensure the maximization of the power [17]. Mostly all the photovoltaic array reconfiguration techniques based on ''irradiance equalization" principle. Some optimization algorithms based on irradiance equalization have been given in the literature. An algorithm based on irradiance equalization proposed in [14] find the optimal solution only in small PV applications. The algorithm proposed in [15] BWSA (Best and Worth Sorting Algorithm) is an iterative and hierarchical sorting algorithm designed to obtain near optimum configuration within a small number of iterations. The BWSA (Best and Worth Sorting Algorithm) found very fast but its results are not optimal in most cases. In [16] the author proposed two different reconfiguration control algorithms for TCT architectures and using the irradiance equalization principle: a random search and a deterministic algorithm. The solution method build rows with an unequal number of modules, thus the number of possible interconnection configurations increases. However, the algorithms focused only on ''irradiance Equalization" without accounting for switching operations. An algorithm which allows irradiance equalization with balanced switching operations using MAA (Munkres Assignment Algorithm) proposed in [17].

In this paper, PV reconfiguration problem is formulated using ACS (Ant Colony System), algorithm, following a TCT (Total Cross Tied) layout. ACS is a multi-objective heuristic which not only focusses on irradiance equalization but also on minimizing switching operation. Thus this approach helps to maximise the power with minimum switching operations so as to preserve the lifetime of the switching matrix. The flowchart of the algorithm implementing this reconfiguration strategy is shown in Fig. 3. The paper is structured as follows. Section I discuss the need of optimisation algorithm Section II introduces PV cell modelling. Section III discusses Array topologies in brief with introduction of general approach of partial shading condition, Section IV discusses general reconfiguration strategy and its implementation with TCT layout, Section V Implementation of Proposed algorithm and summarizes the key results, and Section VI provides Validation and conclusion.

II. PV CELL MODELLING

In PV cell modelling single diode model is the most preferably used model. In this paper the single diode model of the PV cell is implemented. The PV cell current is given by (1).

$$I = [I_{\text{ph}}\text{-I}_{\text{o}}(e^{\frac{q(V+RsI)}{AKT}} - 1) - \frac{(V+RsI)}{Rsh}] \quad (1)$$

where V and I represent the PV cell output voltage and current respectively, Iph is the light generated cell current (photo current), Rs and Rsh are the solar cell series and shunt resistances, I0, the reverse saturation current, A is a dimensionless junction material factor, K is Boltzmann's constant (1.38 × 10-23 J/K), T is the temperature in Kelvin and q is the electron charge (1.6 × 10-23 C) respectively. At the Standard test conditions: Irradiance 1000W/m2, cell junction temperature 250 C, and reference air mass 1.5 solar spectral irradiance distribution definite number of such solar cells is connected in series to constitute a PV module and further into PV array.

III. RECONFIGURATION STRATAGY

The block diagram of dynamic PV reconfiguration system is shown in figure.

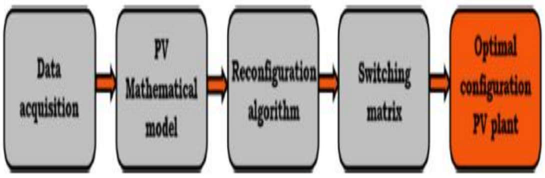


Fig 4 Dynamic PV reconfiguration System.

In a PV plant, "PV reconfiguration" means the process of finding the best electrical connection among the modules, for the maximum power extraction. In order to find the optimal configuration, ACS (Ant Colony Optimization) approach is proposed .The implemented control algorithms adopt the irradiance equalization principle which allows to equalize the available power in each row of the TCT(Total Cross Tied) layout. The main steps of the algorithm are the following:
1) Data acquisition;
2) Search for the best configuration;
3) Reallocation of modules;
During the acquisition step, the solar irradiance of each module and its position within a configuration are read. In the second step, the algorithm performs a search of the best configuration. After the optimum configuration is determined, the control module sends the open and close commands to the switching matrix, to implement the best-calculated configuration.

1) Reconfiguration for TCT topology

The TCT configuration is obtained by connecting cross ties across each row in a simple series parallel (SP) configuration. Fig. 5 shows PV array connected in TCT configuration. The TCT topology consists of a parallel connected modules forming a tier connected in series string. Reconfiguration in TCT array is nothing but maximising the current flowing through a series string having a set of tiers (parallel-connected PV modules) by dynamically shifting the modules in an array.

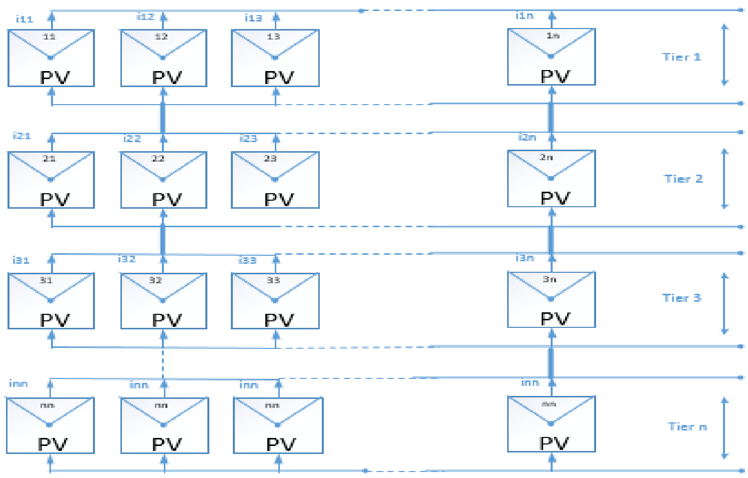


Fig 5 TCT (Total Cross Tied) layout.

In a TCT (Total Cross Tied) array total irradiance with *n* number of modules is calculated as

$$I = (i_1 + i_2 + i_3 \quad in) \qquad (1)$$

The average irradiance per tier is calculated as

$$Iavg = \frac{I}{no.of\ tiers} \qquad (2)$$

The irradiance of the tier with *m* is the number of modules parallel connected with row i, and column j, *Ii* (tire), is defined as

$$Ii(tier) = \sum_{j=1}^{m} Iij \qquad (3)$$

The equalization index is defined as measure of irradiance equalization.
Equalization Index is calculated as

$$EI = Iav - Ii(tier) \qquad (4)$$

This equalization index indicates the amount of unequilisation thus the first objective is to minimum EI such that maximum equalization can be obtained. The second objective followed by the algorithm is the minimum number of switching operations starting from the initial configuration to the optimized configuration. In this study a novel algorithms based on ACS (Ant Colony System) optimisation is proposed for optimal photovoltaic array reconfiguration ACS (Ant Colony System) Algorithm to optimize the output power and switching operation simultaneously.

IV. ACS (ANT COLONY SYSTEM) PROPOSED ALGORITHM

The ACS (Ant Colony System) algorithm is the improved version of ant colony algorithms, which system that contributes and promotes the use of the best paths [13],[14].

1) The Approach

In the study, the PV reconfiguration is considered as a multi-objective problem for solving this multi-objective problem, Ant Colony System (ACS) algorithm is found appropriate. The present approach is to determine the optimum reconfiguration of PV in minimum switching operations without violating the constraints and within the network of nodes and links. The constraints ensure that the routes correspond to a valid path.

2) Problem Formulation

For the formulation of PV reconfiguration problem, Number of solar modules in the PV array are considered as the set of N nodes, which also includes the depot (D). Depot (D) is the starting point of each ant .Every ant starts from depot and constructs its path as per pheromone depositions. The imaginary link between nodes (say node i and node j) is considered as link Xij such that $i , j \in N$ and $i \neq j$. To each link (Xij) is associated a value t_{ij} (pheromone trail value).The switching count between the modules is $Swij$. The set of nodes i.e. PV modules have initially a non-zero amount of irradiance $I= \{i_1, i_2, \dots\dots, i_n\}$. Each link Xij is also associated with a pheromone trail value τ_{ij} $(\tau_{ij} \geq 0)$. The value τ_{ij} gets updated during solution construction.

The objectives for optimal PV reconfiguration are

1) Minimisation of equalisation index (EI)
2) Minimize the number of switching operations thus preserve ageing of switches(*Sw*)

For the multi-objective context, let ψ is the multi-dimensional objective function, which can be stated as follows:

Minimize

$\psi=[\psi 1,\psi 2]^T$ (5)

where

ψ is the multi-objective function

$\psi 1$ is objective function of Equalisation Index

$\psi 2$ is objective function of switching operations

1) Equalization Index($\psi 1$)

Minimize the equalization index.

$$\psi 1=\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{t}((I\text{avg} - Iij))Xijk \quad (6)$$

where:

n =Total number of modules in an array.

m = Number of modules in a tier.

t = Total number of tier.

$Iavg$ =is the average irradiance per tier.

Iij =the total irradiance calculated tier $\sum_{j=1}^{m} Iij$

Xij= is the imaginary link connecting modules

Minimization of equalization index increases the irradiance equality in tiers which in turn increases the current and output power of PV plant.

2) Minimize the number of switching operations ($\psi 2$)

$$\psi 2=\sum_{j=1}^{m}\sum_{i=1}^{n}\sum_{k=1}^{t}(Swij)Xijk \quad (7)$$

Where:

$Swij$ =the switching between the modules i and j

k = number of ant visited

t =number of tier

Xij = the imaginary link connecting modules i and j

The objective function $\boldsymbol{\psi}$ to be minimized is subject to the following constraints:

(a) Solar array symmetry-Solar array should be symmetrical so that number of artificial ants produced equates number of tiers and possible candidate list (φ).

$$\sum_{k \in t}(mk) = \sqrt{N} \quad (8)$$

Where, $m\ k$ is the number of modules in k_{th} tier

(b)Nodes constraint -Every node must be visited exactly once within the network.

$$\sum_{i\ j \in N}\sum_{k \in t}(Xij) = 0 \quad (9)$$

(c) Imaginary link constraint-Each link becomes zero if module is visited else equal to1

$Xij \in (0,1)$ i,j$\in$ N (10)

(d) Switching between modules-Switching counts is 2 if modules shifted between tiers and it is 1 if modules shifted in the tier itself. This helps to calculate exact number of shifted modules.

$$Swij=1 \quad \text{if } k \in t \text{ else } 2 \quad i, j \in N \quad (11)$$

3) Solution Construction

The solution construction starts with an empty initial solution set s = ( ), at each iteration step, the current initial solution s is extended by adding a feasible solution component from the set of solution components. This set is determined at each construction step by the solution construction mechanism in such a way that the problem constraints are met. The choices performed by an ant about the feasible solution component, to be added to the initial solution, are based on a set of parameters. These parameters are τ_{ij} and η_{ij}, called as desirability, that the feasible solution (say node *j*) to be added shares with a vertex *i* on a partial solution. Each artificial ant starts from a depot and, at each step, moves to a node which is not yet visited and which does not violate the constraints. The set of available nodes in the candidate list (φ). The PV array is considered as a network of nodes (modules) connected by the imaginary link called *Xij*.The algorithm start with data acquisition i.e. collecting the irradiances of modules from different positions in an array. The irradiances are sorted in descending order to create the probable candidate list (φ). An ant k present at node i chooses the next node to move either favours exploration or go for a biased exploitation using a probabilistic rule (Eq. (11)). In case of exploitation, the ant uses the set of candidate list (φ) with the probability rule to choose the module to move to. The set φ contains preferred modules to be visited. The choice of the feasible solution component (*j*) to be added to the partial solution s is done from φ.

$$p = \begin{cases} \underset{J}{argmx}\ j \in N_i^k \{ \tau_{ij}\, [\eta_{ij}]_\varepsilon^{\alpha}\ [\eta_{ij}]_\zeta^{\beta}, & if\ q \le q_0 ; \\ & otherwise; \end{cases}$$

$$P = \{ \{ \tau_{ij}\ [\eta_{ij}]_\varepsilon^{\alpha}\ [\eta_{ij}]^{\beta} \} / \Sigma_{j \in} N_i^k\ \{\tau_{ij}\ [\eta_{ij}]_\varepsilon^{\alpha}\ \ [\eta_{ij}]_\zeta^{\beta} \} \quad (12)$$

where

q = random variable uniformly distributed in (0; 1),
q0= is a parameter (0≤q0≤1), and with probability q0 the ant makes the best possible move as indicated by the learned pheromone trails and the heuristic information (in this case, the ant is exploiting the learned knowledge), while with probability (*1-q0*) it performs a biased exploration of the links.

τ_{ij} = the pheromone trail parameters represent a stochastic desirability

The heuristic desirability $[\eta_{ij}]_\varepsilon = 1/ (Te_{ij})$,

N_i^k=a set of not yet visited feasible modules

The pheromone value get updated while moving from one node to another using local pheromone update (Eq.(13))

$$\tau_{p(i)}^{new} = (1-\rho)\tau_{p(i)}^{old} + \rho\tau_0 \qquad (13)$$

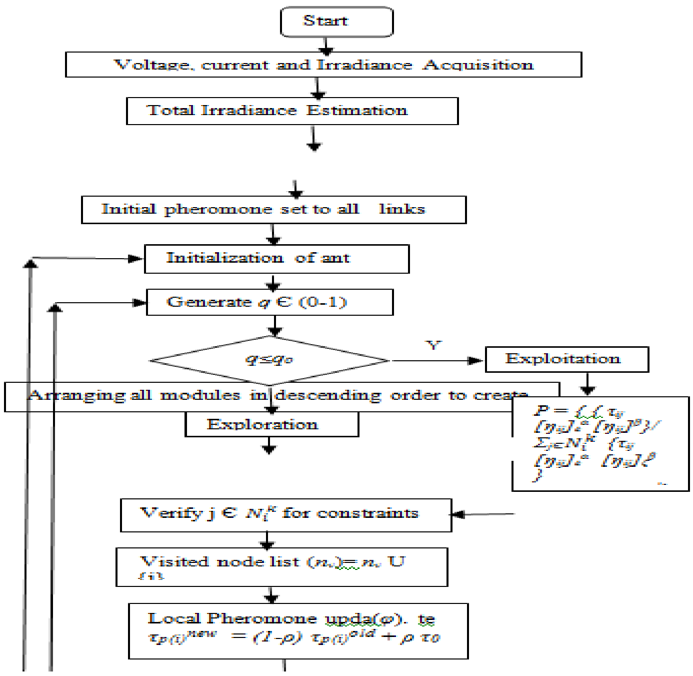
Once the ant builds a complete solution, the new trail pheromone value is calculated. If the new trail pheromone value (τ_{0new}) is greater than the previous (τ_0) i. e., if the new solution is better than the previous solution, global pheromone update (Eq. (13) is applied to all the links in the set, otherwise, the global update is applied only to the visited links in the solution.

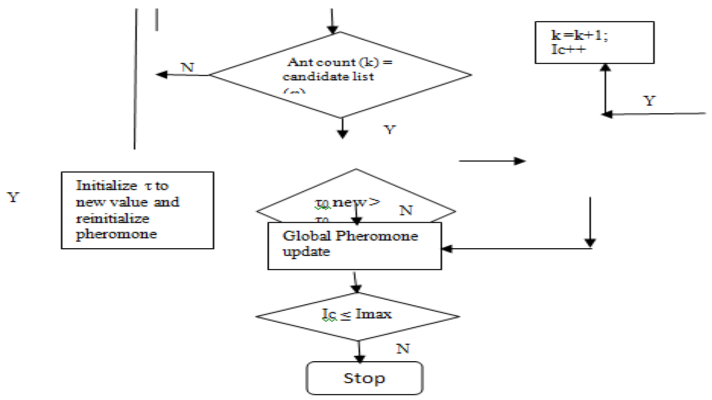
$$\tau_{p(i)}^{new} = (1-\rho)\, \tau_{p(i)}^{old} + \rho N\, \tau_o \qquad (14)$$

Where, ρ is the evaporation coefficient, which powers exploration process by evaporating trail pheromone values for the used paths (in the Eq. (13) and Eq. (14)

The total number of iterations (*Ic*) is carried out using the modified pheromone values to generate next solution up to maximum number of iterations (I_{max}). This procedure improves exploration. It also forces the ants to explore new routes and makes sure that they follow constraints.

The flowchart for determining the optimal PV reconfiguration using the proposed approach (ACS) is shown in Figure 6





V. VALIDATION

A Software is developed based on this algorithm in C language and run on an Intel Core i5, 3.1GHz CPU with 4GB of RAM memory. The effectiveness of new algorithms is tested by with examples .The analytical result shows that introducing ACS algoritham in PV array reconfiguration significantly increase power output with minimization of the operating switches. The algorithm is illustrated with an example reported in Fig. 7 .Fig. 7 shows a PV generator composed of 16 modules differently irradiated. As shown in figure all the rows have different irradiance levels: 1110 W/m^2, 2320 W/m^2 and 1970 W/m^2 and 1300W/m2respectively; in (b), changing only the electrical connections of PV modules using a ACS reconfiguration approach, irradiance equalization is achieved in all rows. Fig 8 shows that the MPP (Maximum power point) before reconfiguration corresponds to 438.82 W with a misleading effect on the MPP tracking algorithm while after reconfiguration it gets to 589.53 W with a single maximum curve and without the misleading effect to the MPP tracking algorithm. This reconfiguration require only eight modules shifting using proposed approach. Fig 9 and Fig 10 shows P-I and I-V characteristic before and after reconfiguration

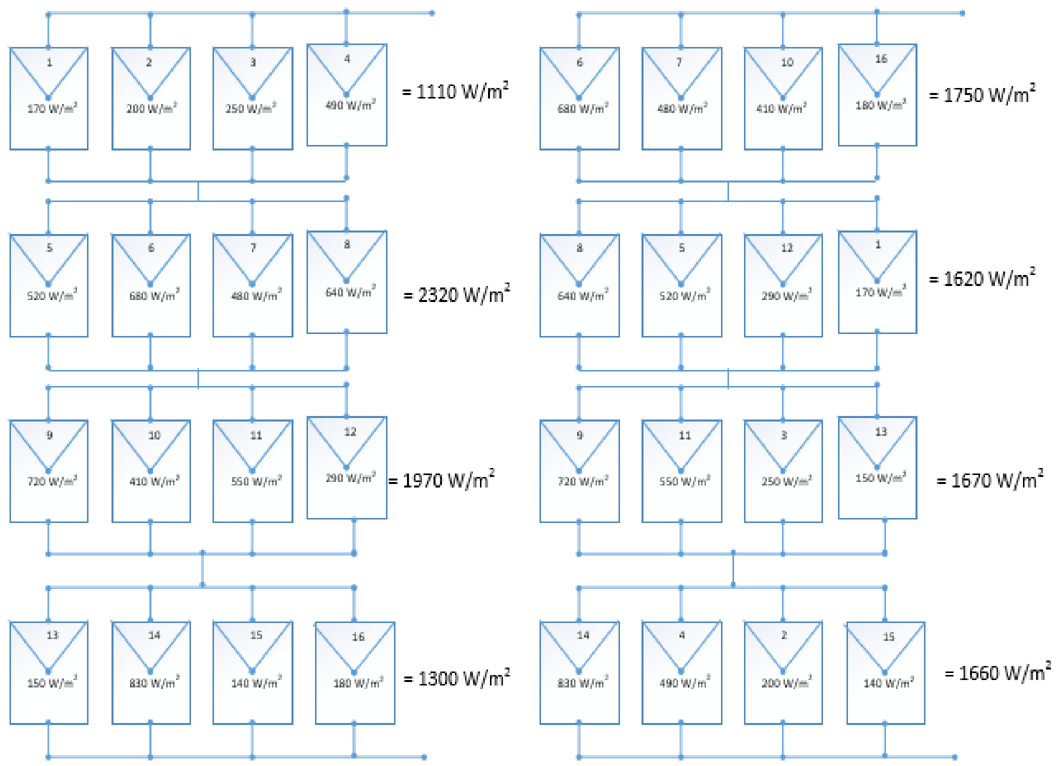


Fig 7 (a) Before Reconfiguration (b) After Reconfiguration

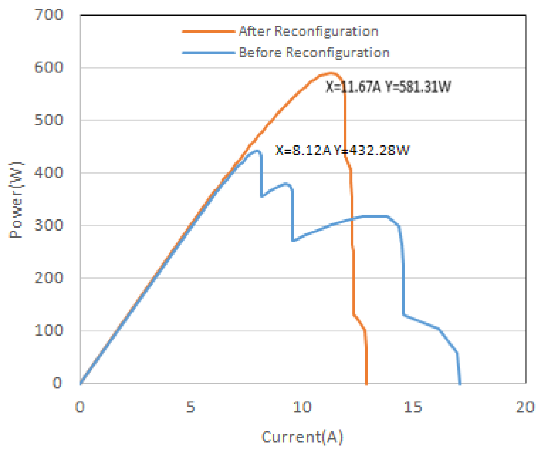


Fig 8 P-V characteristic

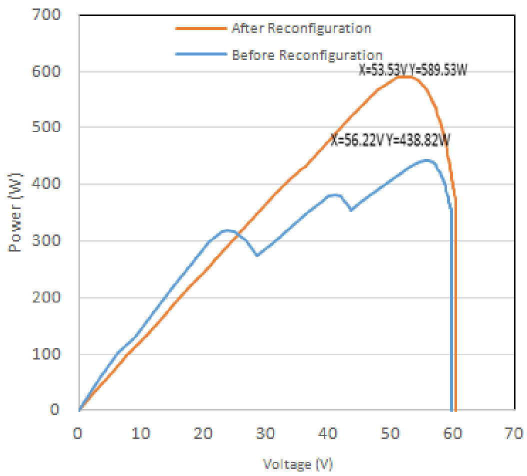


Fig 9 P-I characteristic

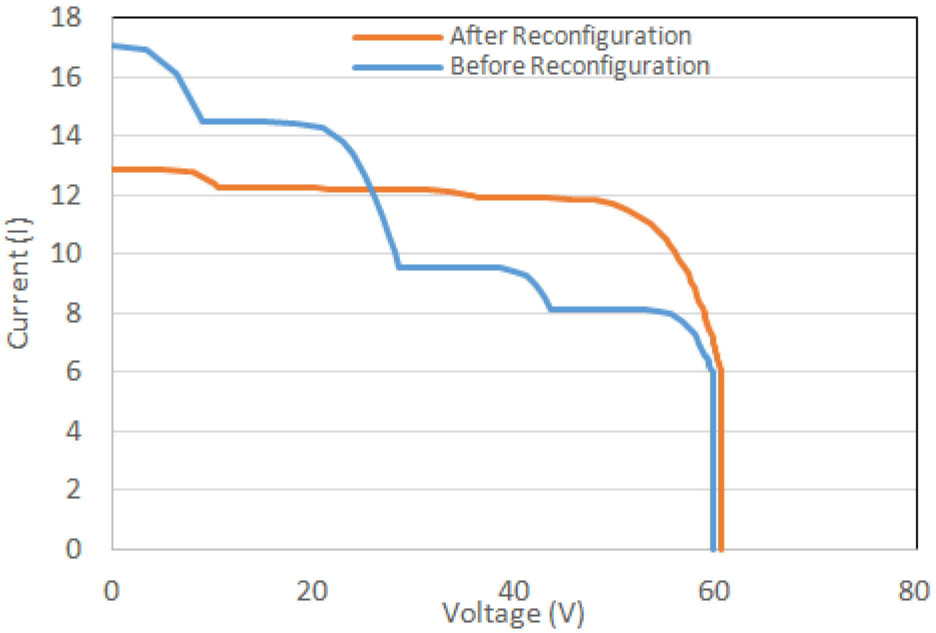


Fig 14 I-V characteristic

VI. CONCLUSION

The paper presents, an ACS optimisation technique for PV reconfiguration to increase the maximum power extracted from PV plant and avoid misleading of maximum power point .The reconfiguration consider TCT array topology. The control problem is formulated in ACS algorithm to obtain the optimal PV configuration with minimum switching operations. The proposed approach achieves a fairly uniform distribution of the shadow all over the panel thereby avoiding concentration of shadow on any one row thus equalizing the row currents to a greater extent Demonstration proves the effectiveness of ACS for solving the optimum PV array reconfiguration problem with examples. It clearly suggests such a meta-heuristic to be well worth exploring in the context of solving different reconfiguration problems.

REFERENCES

[1]. G. Petronea and C. A. Ramos-Pajab, "Modeling of photovoltaic fields in mismatched conditions for energy yield evaluations," Elect. Power Syst. Res., vol. 81, no. 4, pp. 1003– 1013, Apr. 2011.

[2]. A. K. Abdelsalam, A. M. Massoud, S. Ahmed, and P. N. Enjeti, "High-performance adaptive perturb and observe MPPT technique for photovoltaic-based microgrids," IEEE Trans. Power Electron., vol. 26,no. 4, pp. 1010–1021, Apr. 2011.

[3]. N. Mutoh, M. Ohno, and T. Inoue, "A method for MPPT control while searching for

parameters corresponding to weather conditions for PV generation systems," IEEE Trans. Ind. Electron., vol. 53, no. 4, pp. 1055–1065, Jul. 2008.

[4]. D. Nguyen and B. Lehman, "An adaptive solar photovoltaic array using model-based reconfiguration algorithm," IEEE Trans. Ind. Electron., vol. 55, no. 7, pp. 2644–2654, Jul. 2008.

[5]. H. Patel and V. Agarwal, "Maximum power point tracking scheme for PV systems operating under partially shaded conditions," IEEE Trans. Ind. Electron., vol. 55, no. 4, pp. 1689– 1698, Apr. 2008.

[6]. D. Picault, B. Raison, S. Bacha, J. de la Casa, and J. Aguilera, "Forecasting photovoltaic array power production subject to mismatch losses," Sol.Energy, vol. 84, no. 7, pp. 1301–1309, July. 2010.

[7]. H. Patel andV. Agarwal,"MATLAB based modeling to study the effects of partial shading on PV array characteristics," IEEE Trans. EnergyConvers., vol. 23, no. 1, pp. 302–310, Mar. 2008.

[8]. N. D. Kaushika and N. K. Gautam, "Energy yield simulations of interconnected\ solar PV arrays," IEEE Trans. Energy Convers., vol. 18, no. 1, pp. 127–134, Mar. 2003.

[9]. Z.M Salamehand and F. Dagher, "The effect of electrical array reconfiguration on the performance of a PV-powered volumetric water pump," IEEE Trans. EnergyConvers., vol. 5, no. 4, Mar. 2008.

[10]. A. Woyte, J. Nijs, and R. Belmansa, "Partial shadowing of photovoltaic arrays with different system configurations: Literature review and field test results," Sol. Energy, vol. 74, no. 3, pp. 217–233,Mar. 2003.

[11]. N. K. Gautam and N. D. Kaushika, "An efficient algorithm to simulate the electrical performance of solar photovoltaic arrays," Energy, vol. 27, no. 4, pp. 347–361, Apr. 2002.

[12]. N. K. Gautam and N. D. Kaushika, "Reliability evaluation of solar photovoltaic arrays," Sol. Energy, vol. 72, no. 2, pp. 129–141, Feb. 2002.

[13]. Y.-J. Wang and P.-C. Hsu, "An investigation on partial shading of PV modules with different connection configurations of PV cells," Energy, vol. 36, no. 5, pp. 3069–3078, May 2011.

[14]. Velasco-Quesada". Electrical PV array reconfiguration strategy for energy extraction improvement in grid-connected PV systems". IEEE Trans. Indust. Electron. 56 (11), 4319–4331.2009

[15]. Storey, J.P., Wilson, P.R., Bagnall, D." Improved optimization strategy for irradiance equalization in dynamic photovoltaic arrays". IEEE Trans. Power Electron. 28 (6), 2946–2956.2013

[16]. Romano, P., Candela, R., Cardinale, M., Li Vigni, V., Musso, D., Riva Sanseverino, E. Optimization of photovoltaic energy production through an efficient switching matrix". J. Sustain. Develop. Energy, Water Environ. Syst. 1 (3), 227–236.2013

[17]. Eleonora Riva Sanseverino a, Thanh Ngo Ngoc a,b, Marzia Cardinale a, Vincenzo Li Vigni a, Domenico Musso a, Pietro Romano a, Fabio Viola" Dynamic programming and Munkres algorithm for optimal photovoltaic arrays reconfiguration" Solar Energy 122 (2015) 347–358.

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