International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 04 Issue: 12 | Dec-2017 www.irjet.net p-ISSN: 2395-0072

Ant Colony optimization for optimal photovoltaic array reconfiguration under partial shading condition

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Abstract- *Renewable energy sources play a significant role in the field of energy markets over the last few years. The contribution of solar energy is total renewable energy is increasing due to rapid development in the field of photovoltaic. The wide development of PV is limited due to a very common and well discussed issue of partial shading. Partial shading causes uneven distribution of shade throughout the PV array leads to decrease in the power output of the PV array and exhibits multiple peaks in the I–V characteristics. In order to extract maximum power from PV array, the modules have to be reconfigured to get optimal PV configuration. In this paper, an optimization based approach for optimal PV array reconfiguration, following a Total Cross Tied layout, is proposed. The formulation follows the Ant colony optimization to mitigate the mismatch effect and maximize the output power of small photovoltaic plants under partial shading conditions. In this work the optimization approach consider two objectives 1) Maximization of power and 2) Minimization of switching operations. Here, the electrical connections of modules are changed by keeping the physical location unaltered.*

Keywords— Energy sources, renewable energy system, partial shading, simulation, solar photovoltaic cell

1 INTRODUCTION

The contribution of Renewable energy resources is significant in the India's energy sector. Over the last years, magnified environmental awareness leads to the development of renewable energies. The harmful effects caused by fossil fuel consumption have led to the increased interest in renewable energy sources. India situated in the sunny belt of the world map. India is endowed with tremendous amount of solar energy potential. In India, all the parts receives solar radiations approximately 300 days throughout a year [1]. Indian land area receives about 5,000 trillion kWh per year energy and 4-7 kWh per sq. meter per day [2,3]. India has total renewable energy potential of about 900 GW from sources like Wind – 102 GW, Bio-energy – 25 GW, Small Hydro – 20 GW and Solar power – 750 GW. Renewable energy shares 15.90% in total installed energy capacity in India. As of March 2017, renewable energy installed capacity totalled to 57,260 MW. Renewable energy has been showing over 20% growth in the last five years. Solar power is among the most dominant and well-established second generation renewable technologies. It has numerous ecological benefits: PV modules do not produce greenhouse gases during manufacturing as well as during operation. The modular PV systems can be built in various ranges of sizes [1]. PV technology has numerous advantages, but this technology faces various limitations in the path of wide development. The major limitation is the cost. The cost of solar energy technologies are rapid decreasing in the recent past years [1]. The other limitation with PV power generation is its dependence on the weather conditions and insufficient means of storage, resulting in stability and reliability problems for the electrical grid. The efficiency of operation of a solar array depends not only on the weather conditions but also on the array interconnection topology [4, 5].Generally a single solar cell is not capable of producing voltage and current as per given load conditions so in practice, a combination of PV modules are connected to form an array of required voltage and current [6]. These structures can be used to supply power to scalable applications known as photovoltaic plants, which may be stand-alone systems or grid-connected systems [6]. The most commonly used PV array topologies are series and parallel, total cross tied, honey comb and bridge linked [7] [8].Out of these topologies Series–parallel connections is the most common configurations used to fulfil the load requirements. These topologies work satisfactory under uniform irradiance condition but in case of non-uniform irradiance i.e. if some panels in the array are subjected to shading due to big trees, hoardings, poles, towers etc., the output power may decrease substantially. [9,10].Partial shading distributes the shadow on the solar PV array non uniformly. This causes decreased power yield from the array as well as disturbed the PV and IV characteristics creating multiple peaks. [11, 12]. Apart from maximum power, parameters like life of the array, mismatch losses and reliability playing an equally crucial role in deciding the performance of the array. As reported [13] introducing cross ties may enhance the life of an array. Results shown in [14] prove that the TCT arrangement is the best solution to accentuate the problem of mismatch losses under partial shading. This conclusion is considered in this paper and optimization approach is proposed considering total cross-tied connected modules in a PV array .The optimization approach uses an Ant colony optimization technique gives the optimal configuration of PV array giving maximum power output with minimum switching operations. This approach maintain physical locations of the

PV modules same while alter only electrical connections. This helps to disperse the shadow effect uniformly throughout the panel .The proposed reconfiguration system improve the output energy extracted by the PV array under non-uniform solar irradiation conditions. Short calculation times of the proposed control algorithms allow its use in real-time applications even where a higher number of PV modules are required.

This paper shows formulation of the optimization problem for optimal PV array reconfiguration, using a Total Cross Tied layout (TCT). The flowchart of the algorithm implementing this reconfiguration strategy is show in Fig. 3. The formulation is based on Ant colony optimization. The proposed optimization technique is implemented on a 5_5 total cross tied PV array. This algorithm is based on reducing the shade effect by uniform distribution thought out the PV array. Thus, for given shading condition for the array, the algorithm finds out the optimal possible interconnection which extracts the maximum output power .Different application examples showing various shading patterns are used to test the performance of the approach The performance analysis shows that the ACS based approach enhanced power output as compared to the static TCT configuration. Also, P- V, I–V characteristics obtained are presented later in which shows that the proposed optimization soothes the characteristics.

2 Equivalent Circuit of PV Cell

Here the most popular single diode model of PV cell is used as shown in Figure 1. To develop a simulation model it is important to study the physical model of the system. The physical model is represented by the given equivalent electric circuit (7)(4).

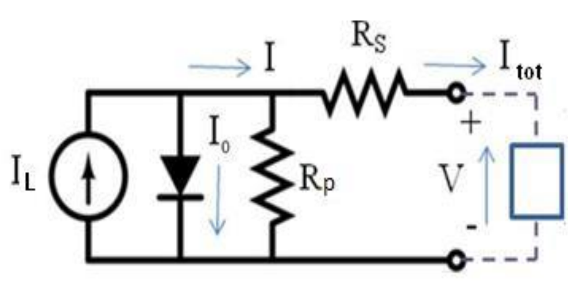


Fig 1: the equivalent electric circuit of a single PV cell

In the equivalent circuit of single PV cell model, The total current I_{tot} can be calculated as the difference of current I_L (light generated) generated by the photovoltaic effect and the diode current I_D, according to the following equation:

$$I_{tot} = I_L - I_D \qquad (1)$$

The diode current is given by

$$I_D = I_o\,[\exp(eV/kT)-1] \qquad (2)$$

Where,

I_0 is the diode saturation current, e is the electronic charge of $1.6\text{x}10^{-19}$ Coulombs, k is a Boltzmann's constant of value $1.38\text{x}10^{-23}$J/K, T is the solar cell temperature in Kelvin, and *V* is the measured solar cell voltage (4).In the equivalent circuit the p-n junction of the PV cell is denoted by a shunt diode, Rp is a shunt resistance of the leakage currents produced due to the impurities of the p-n junction (this resistance should be made as high as possible), *Rs* is a series resistance of all the ohmic resistances distributed in the semiconductor material and the resistances of the metallic contacts (ideally, this resistance should be zero). A is an ideality factor.

The following equation describes the equivalent mathematical model of the PV cell:

$$I_{tot} = I_L - I_o\left[\exp\left(\frac{e(V-IRs)}{AkT}\right)-1\right] - \left(\frac{V-IRs}{Rp}\right) \qquad (3)$$

3 Approach

The problem of PV array reconfiguration is considered as a bi-objective optimization problem. The process of selecting PV modules from any combination of modules in determining the optimum configuration. Therefore, the PV array Reconfiguration problem is a combinatorial optimization problem (COP) where the number of feasible solutions for the problem increases exponentially with the size of solar array

4 Problem Representation

1) TCT topology with optimisation point of view

In this work for optimizing PV array TCT (Total Cross tied) topology is considered. Fig. 2 shows PV array connected in TCT (Total Cross tied) (5X5) configuration.

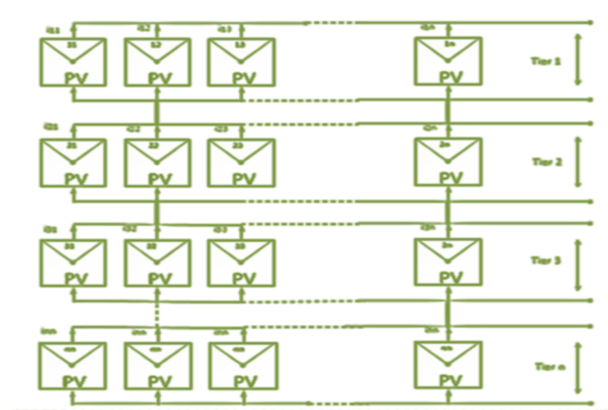


Fig 2: TCT topology with optimisation point of view

TCT topology is combination of parallel connected group of modules called tiers connected in series string as shown in above fig. In order to maximise the output power of TCT PV array the irradiance of each tiers should be equalised such that the current flowing through the string is maximum. Fig 2 shows PV array with a set of n number of modules and each tier with a set of m number of modules.

The total irradiance of the PV array is calculated as

$$I(total) = (i_1 + i_2 + i_3 - - in\ ) \qquad (4)$$

The average irradiance per tier is calculated as

$$Iavg = \frac{I(total)}{no.of\ tiers} \qquad (5)$$

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

$$Ii(tier) = \sum_{j=1}^{m} Iij \qquad (6)$$

Equalization Index is calculated as

$$EI = Iavg - Ii_{(tier)} \qquad (7)$$

The equalization index is defined as measure of irradiance equalization. Equalization Index indicates the amount of unequilisation between I_{avg} (Average irradiance per tier) and $Ii_{(tier)}$ (Actual irradiance of tier).To maximise the tier equalization EI should be minimised. Thus the first objective of optimization is to minimize EI.

The second objective is to minimize number of switching operations starting from the initial configuration to the optimized configuration.

For the mathematical formulation of these objectives, the PV array is considered as a set of *N* modules having varying irradiance, which also includes the depot and some other non-depot vertices. The available link between modules (say module *i* and module *j*) is considered as link *ij* such that *i, j ЄN* and *i≠j*, the switching between the modules *i* and *j* is *Swij*. Each link *ij* is also associated with a pheromone trail value *τij (τij≥ 0)*. The value *τij* gets updated during solution construction.

4.1 Objective Function

For the bi-objective context of the present approach the objectives framed for PV array reconfiguration are as follows:

1) Minimization of Equalization Index
2) Minimize the number of switching operations
Let *ψ* is the bi- objective function, which can be stated as follows:

Minimize

$$\psi=[\psi1,\psi2]^T \qquad (8)$$

where
ψ is the bi-objective function
ψ1 is objective function of Equalisation Index
ψ2 is objective function of switching operations

1) Equalization Index (*ψ1*) Minimize the equalization index.

$$\psi1=\sum_{i=1}^{n}\sum_{j=1}^{m}\sum_{k=1}^{t}((Iavg - Iij))Xijk \qquad (9)$$

Where:

n =Total number of modules in an array.
m = Number of modules in a tier.
t= Total number of tier.
k = number of ant visited
I_{avg} =is the average irradiance per tier.
I_{ij} =the total irradiance calculated tier
X_{ij}= 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 (*ψ2*)

$$\psi2=\sum_{j=1}^{m}\sum_{i=1}^{n}\ \sum_{k=1}^{t}(Swij)Xijk \qquad (10)$$

Where:

S_{wij} =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*
Minimization of switching operations increases the life of operating switches and reduces switching losses.

4.2 Constraints

The objective function ***ψ*** 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*).

$$\sum_{k \in t} (mk) = \sqrt{N} \qquad (11)$$

Where, *m k* is the number of modules in kth tier

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

$$\sum_{i\ j \in N} \sum_{k \in t} (Xij) = 0 \qquad (12)$$

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

$$Xij \in (0,1)\ i,j \in N \qquad (13)$$

(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.

$$Swij=1 \qquad (14)$$

if k € t else 2

i, j € N

5 Algorithm Development

Problem Formulation for PV array reconfiguration
The PV array reconfiguration problem is optimized considering all the two objectives. The problem consists of network of modules and links between the modules. The solution construction starts with an empty partial solution set s = ( ), at each construction step, the current partial solution s is extended by adding a feasible solution component from the set of solution components *Nik*. 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 partial solution, are based on a set of parameters. These parameters are *τij* and *ηij*, called as desirability, that the feasible solution (say module *j*) to be added shares with a vertex *i* on a partial solution. The process of constructing solutions is assumed as an ant moving on the construction graph of modules and links *G = (N, L)*.

The objective is to determine the optimal configuration with least switching operations without violating the constraints and within the PV array of modules and links. Equations (9) (10) are the objectives to be minimized. The constraints ensure that the routes correspond to a valid path. Equations (11) to (12) are constraints. Equation (13) and (14) ensures that each module is visited exactly once and ensures non-negativity of binary variable.

The detailed flowchart is given in Figure 3. An ant k present at module i chooses the next module to move either favours exploration or go for a biased exploitation using a probabilistic rule (Eq. (15)). 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 *lc (lc€ Mik)* 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.

$$p = j\in \{ \tau ij\ [\eta ij]\varepsilon\alpha\ [\eta ij]\zeta\beta\}\ ,\ if\ q \le q0\ ; \qquad (15)$$

$$J\ otherwise;$$

$$P = \{ \{ \tau ij\ [\eta ij]\varepsilon\alpha\ [\eta ij]\beta\} / \Sigma j\in \{\tau ij\ [\eta ij]\varepsilon\alpha\ [\eta ij]\zeta\beta\ \} \qquad (16)$$

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.
τij --- the pheromone trail parameters represent a stochastic desirability
Nik-- a set of not yet visited feasible modules

The heuristic desirability *[ηij]ε = 1/ (Iij)* ,

Where *Iij* is the irradiance of module

The heuristic desirability *[ηij]ζ = 1/(Swij)*,

where *Swij* is switching along link *ij* and at module *j*. The value of parameters α and β, $\alpha > 0$ and $\beta > 0$, determines the relative importance of the heuristic desirability information. The probability is calculated for all the not yet visited modules in the set of modules φ, the module with highest probability satisfying the constraints is selected by the ant.

While moving from one module to another module the pheromone value on the corresponding arc is updated using local pheromone update (Equation (17))

$$\tau p(i)new = (1-\rho)\ \tau p(i)old + \rho\ \tau 0 \qquad (17)$$

Once the ant builds a complete solution, the solution is tentatively improved using a local search procedure referred to as cross exchange [88]. The new trail pheromone value is calculated. If the new trail pheromone value ($\tau 0new$) is greater than the previous ($\tau 0$) i. e., if the new solution is better than the previous solution, global pheromone update (Eq. (18)) is applied to all the links in the set, otherwise, the global update is applied only to the visited links in the solution.

$$\tau p(i)new = (1-\rho)\ \tau p(i)old + \rho N\ \tau o \qquad (18)$$

where ρ is the evaporation coefficient, which powers exploration process by evaporating trail pheromone values for the used paths (in the Eq.(17) and Eq. (18)).

A detailed flowchart of Proposed ACS based Approach for Optimum PV reconfiguration Problem is given below in fig.3.

6 Validation

Due to the lack of standard set of real life problems on PV array reconfiguration, the proposed ACS-based algorithm has been implemented using standard shade conditions. These problems consider (5x5) TCT configured PV array used to test and validate the proposed algorithm. The standard shade conditions are set of six shades with varying irradiance. The parameters used are m =10, α = 1, β = 1, ρ = 0.1, $q0$ = 0.9

6.1 Application Examples

The following application examples solved to validate the effectiveness of the proposed algorithm. The reconfiguration problem is modelled in C++ language. The simulation model is built in MATLAB/SIMULINK environment. This model is based on the single diode model for PV .The optimization software is installed on a PC, which has an Intel Core i5 Due processor with a speed of 2.7 GHz and a RAM memory of 16 GB. Performance ratio and irradiance mismatch index are calculated for each application example to give an indication of partial shading losses. Moreover, the processing time required to solve the optimization problem in each example is given.

Standard shades

Most widely considered shades for analysis purpose are short-wide (SW), short-narrow (SN), long-wide (LW), and long-narrow (LN) PS conditions, as shown in Figures, here two special cases such as diagonal shade (DI) & random shade is also included in analysis. A (5 x 5) PV array is used to demonstrate each simulated partial shade condition. The shades are indicated by outline. The shade analysis is done using shading factor.

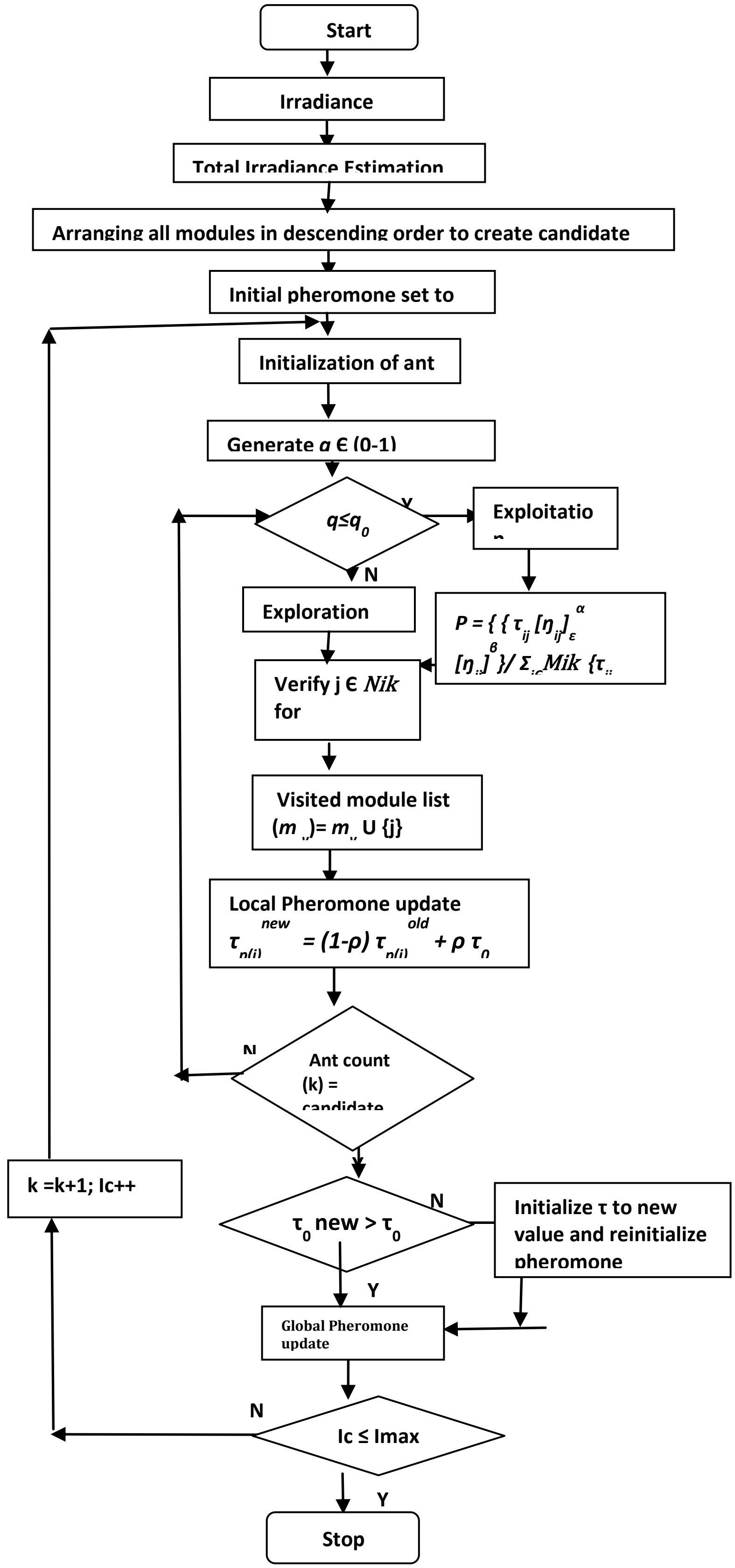


Fig 3 A detailed flowchart of Proposed ACS based Approach for Optimum PV reconfiguration Problem

Fig 4: Standard shades conditions

Table: 4.: Standard shade condition

Long Narrow				
0	0	1000	1000	1000
100	100	1000	1000	1000
200	200	1000	1000	1000
300	300	1000	1000	1000
400	400	1000	1000	1000

Long Wide				
0	100	200	300	400
100	100	200	300	400
200	200	1000	1000	1000
300	300	1000	1000	1000
400	400	1000	1000	1000

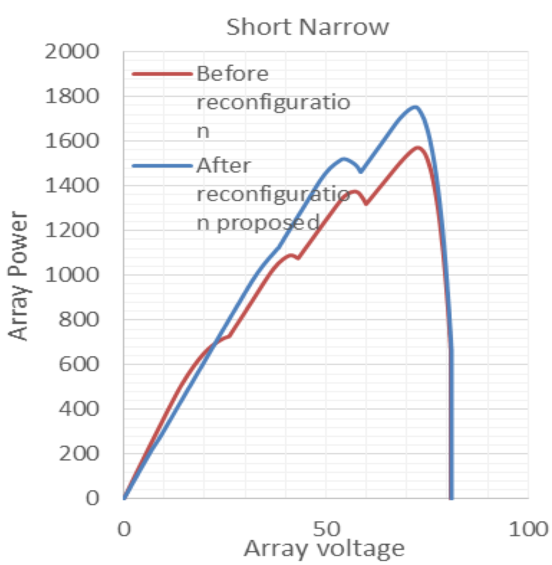
Short Narrow				
0	0	1000	1000	1000
200	200	1000	1000	1000
400	400	1000	1000	1000
1000	1000	1000	1000	1000
1000	1000	1000	1000	1000

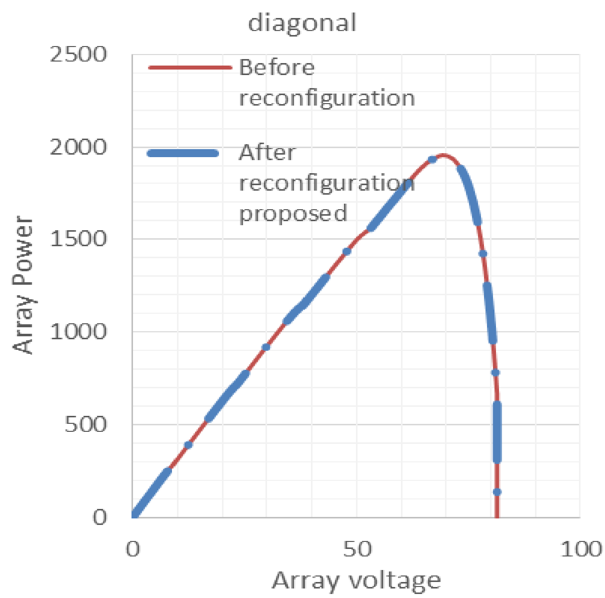
Short Wide				
0	100	200	300	400
0	100	200	300	400
1000	1000	1000	1000	1000
1000	1000	1000	1000	1000
1000	1000	1000	1000	1000

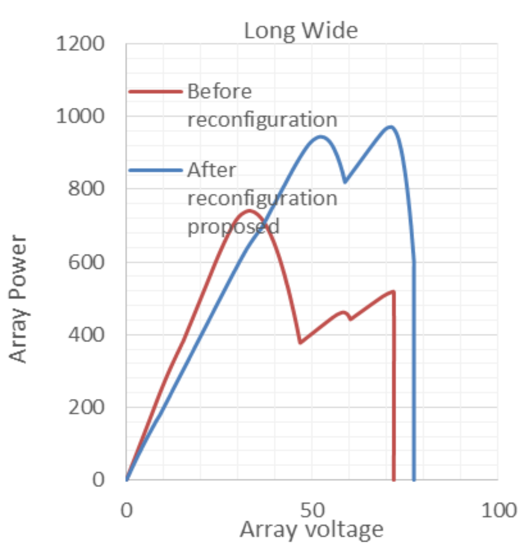
Diagonal				
0	1000	1000	1000	1000
1000	100	1000	1000	1000
1000	1000	200	1000	1000
1000	1000	1000	300	1000
1000	1000	1000	1000	400

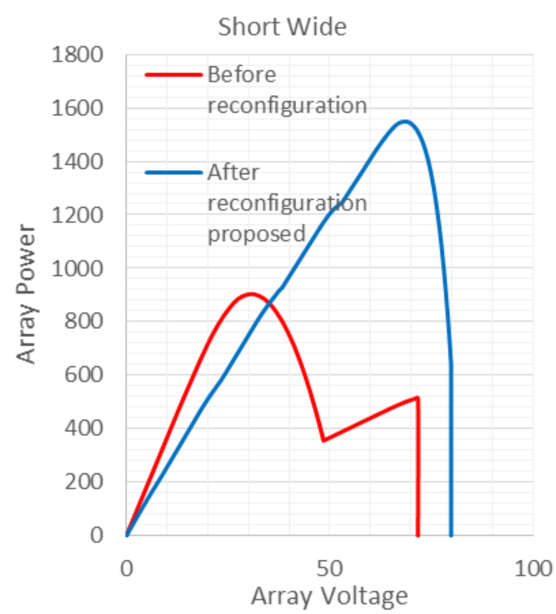
Random				
750	250	750	1000	1000
500	100	700	1000	1000
1000	1000	1000	1000	1000
1000	900	0	750	1000
1000	700	0	750	1000

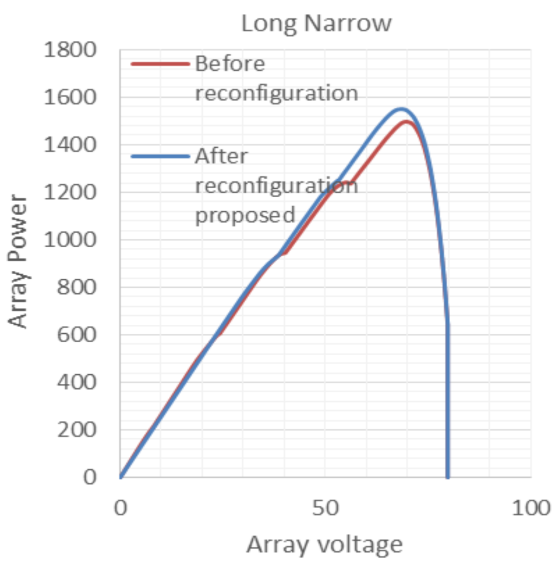
In this analysis static TCT topology (before reconfiguration) is compared with the proposed (ACS) approach TCT topology (After reconfiguration)











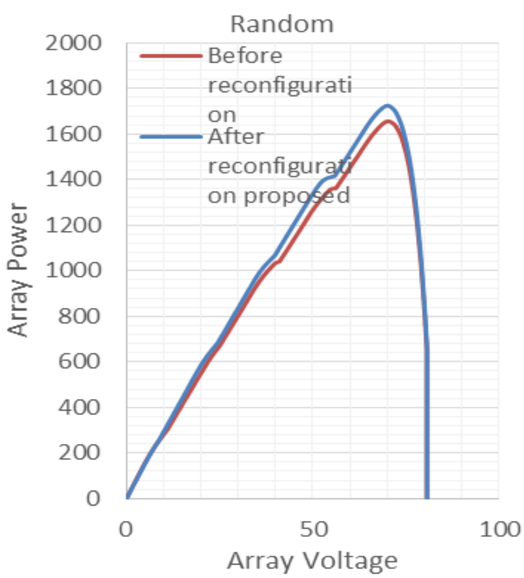


Fig 5: Standard shade analysis

Table 2 Comparative Shade analysis of standard shades

Various Shading	Pmax (TCT)	Pmax Proposed (ACS)	% Improvement
Diagonal	1950.9	1950.9	0
Short Narrow	1511.7	1754.3	16.04
Long Narrow	1499.2	1531.9	2.18
Short Wide	896.01	1531.6	70.93
Long Wide	713.6	962.50	34.87
Random	1667.6	1723	3.32

7 Conclusion

In this paper, a new algorithm for optimized PV modules reconfiguration maximizing the performances of a PV array in shading conditions has been presented. The reconfiguration is here referred to the TCT connection. The representation of the problem as a ACS to obtain the sub-optimal final configuration allows to obtain also the configuration that give rise to a minimum number of switching operations.

In this paper, a mathematical formulation for photovoltaic array reconfiguration using an Ant colony optimization problem was proposed. This formulation can be used for a fully reconfigurable and symmetric array. It was shown that the application of the proposed reconfiguration approach can result in considerable reduction in partial shading losses, thus increasing the generated power output of arrays in the range of 10% to 70-80% . The lead advantage is the smoother P-V characteristic without multiple peaks for the array, making the MPPT tracking task much simpler.

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