An Imperative Role of the Puzzle Oriented Partially Shaded PV Modules Over the Conventional Configurations: A Comprehensive Perspective

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Abstract- Dwelling upon the exploitation of solar energy is an excellent choice, but at the same time, its subsisting limitations cannot be overlooked. Partial shading is one of the major concerns that exhibit multiple peaks, due to mismatch losses (MML), in the electrical characteristics of solar photo-voltaic (PV). The presented paper, therefore, is an attempt to systematically investigate the performance of existing static and dynamic configurations (whether simulation or experimental based) of photovoltaic array. The observations and analysis is carried out in terms of optimal interconnection by puzzle based re-configurations with respect to traditional techniques facing drawbacks due to ineffective shade dispersion. Alternative puzzle based approaches are identified and taxonomized according to their attribute towards ease of use, applicability, durability and reliance. An endeavor is made to recognize the current trends of accelerated growth in the field of solar photovoltaic and the seeds of rejuvenated possibilities are sown to hope for fertile ground of future research.

Keywords- puzzle pattern, photovoltaic array, partial shading effect, renewable energy, power enhancement

1. Introduction

Sustainability is one of the vital concerns for our mother earth to keep from unbalanced energy utilization and to meet the targets of minimizing the causes of global warming. In view of the aforesaid thought, solar energy can be considered as a potential candidate to meet the required ends such that the total energy consumption ought to be optimized ensuring the eco-friendly evolution of socio-economic needs of this world. Furthermore, the need for consistent sun irradiance and solar power forecasts is a critical aspect in the optimal planning and scheduling of solar photovoltaic power plants [1]. Utilizing meteorological data, Hybrid GWO-MLP, ALO-MLP, and WOA-MLP models are used to estimate daily photovoltaic power output using air temperature, relative humidity, total horizontal sun radiation, and diffuse horizontal solar radiation parameters as multi-pled inputs [2]. The prediction of a solar system's daily total energy generation is successfully accomplished by using a

Nave Bayes classifier to examine sensitivity and accuracy measurements to create the optimal power [3]. The fundamental difficulty in the protection problem of dc micro-grids is how to develop a viable, rapid, and accurate protection method to find and isolate the problematic part. A localized protection scheme for dc microgrids with radial configuration under the impact of constant power loads (CPLs) is proposed to accurately determine the location of faults, with a maximum 3.2 percent error observed for fault locating scheme in the practical situation, and thus the proposed scheme was validated [4]. Micro-grids rely on control and communication to provide flawless operation and requirements. The impact and importance of communication degradation processes such as communication failure, noise, delay, and packet dropout on distributed control of micro-grids, as well as modelling techniques for them were thoroughly studied, as were strategies for improving the control system during communication degradation processes [5].

The interpretation of solar PV is well explained in literature either in the form of mathematical expression, depicting powerful tools (Numerical methods and iterative methods), or by the system of linear and non-linear elements connected together to yield the electrical output in the form of dc current [6]. The input to the electrical response of the PV systems may include the intensity of irradiation, the surrounding temperature, layout and selected interconnection schemes of the PV modules [7], while the output characteristics of a PV cell is directly proportional to the insolation level and inversely varies with respect to ambient temperature [8]. The discussed attributes of PVA is governed by the following fundamental equations and are mentioned in Eq. (1-3) as taken from [8, 52]:

$$I_{pv} = N_p I_{ph} - N_p I_{rs}[\exp(\frac{qV_{pv} + I_{pv}R_s N_s/N_p}{kT_{ac}N_s A})] \quad (1)$$

$$I_{ph} = G[I_{scr} + K_i(T_{ac} - T_r)]0.001 \quad (2)$$

$$I_{rs} = I_o \exp[\frac{qE_g}{kA}(\frac{1}{T_r} - \frac{1}{T_{ac}})][\frac{T_{ac}}{T_r}]^3 \quad (3)$$

1.1 Partial shading and its effects on performance characteristics of PV system

Trees, clouds, birds' pit, hoardings, nearby buildings, towers, poles, etc. are the corporeal causes of partial shading to the PV-array. The variation in I-V curve of a PV module with shaded cell is discussed via the shift of the avalanche breakdown voltage [9] of shaded PV cells, where a factor named "Shadow's transmittance" is introduced. One obvious problem of multiple peaks is quite common for the partially shaded PV modules such that it becomes difficult to track the maximum power point (MPP) of the concerned array. To the solution of this issue, [10] has intended to propose a new maximum power point tracking (MPPT) method that is individually applied to each of the PV array in a module , whereby, reducing the inner power consumption in the solar panel made with laminated film. One of the principal reasons behind this low magnitude efficiency e.g. 33.33% [11] is the scenarios of partial shading over the PV modules comprising several arrays arranged in the fashion of simple series, Series-parallel (SP), Total-cross- tied (TCT), Bridge-link (BL), Honey comb (HC), etc. [12]. Owing to study the effect of shadow on the characteristics curve of the PV array, the shadow has been considered equivalent to a descent in insolation from 1 kW/m^2 to 0.2 kW/m^2 and the ascent of cell temperature by 25 K [13,14] measuring the I-V characteristics as element of shadow's transmittance of a shaded PV cell.

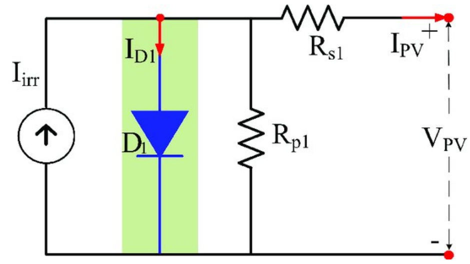

Fig.1: Single Diode model of solar cell [50]

Following parameters can be observed to replicate the effects of partial shading on PVA:

Power and voltage at GMPP/ Fill factor/ Mismatch power loss/ Performance Ratio/ Efficiency/ Power Enhancement/ Misleading Power

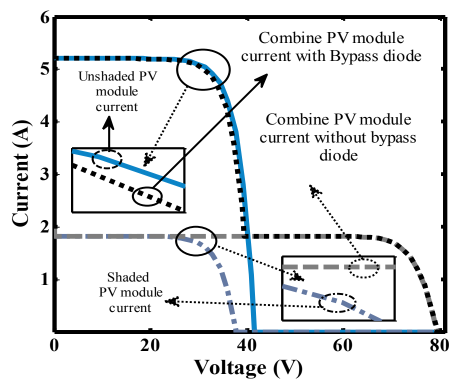

Fig.2: I-V curve under Partial Shading conditions [51]

2. Literature Review

With the accelerating popularity of the solar energy utilization in terms of electrical response, it is essentially required to maintain the quality of delivery outcomes. Hence, the current section details about the selection criterion of modelling methods of puzzle based PVA followed by the mode of extraction of parameters (to observe & analyze the performance) at reviewed scale of application i.e. array size; while the logical and mathematical computational procedures are noted to be implemented to obtain the optimal interconnection arrangement of PV configurations under the circumstance of static, dynamic as well as random shading.

2.1. PV array configurations' modelling at partial shading conditions- "Problem Formulation"

2.1.1 Modelling Method

Most widely adopted methods employ fixed electrical connections (FEC), but at the same time physical relocation of the PV modules is also observed [15, 17, 20, 22, 23, 32]. This practice of module relocation has urged the need to consider the wiring interconnections for TCT and Su-Do-Ku arrangement illustrates the cumulative difference in resistance of the overall wiring to be 72 times [16]. A wide range of shading scenario is inculcated to analyse the performance ability of PVA under consideration such that, static cum easy to predict shading circumstances are easily modeled (especially, Short-Wide, Long-Wide, Short-Narrow & Long-Narrow shading) but this does not hold one back to test under moving shadow conditions [15, 18, 30]. For the stated reason, modelling of moving cloud, assumption of progressive increment of diagonal and non-diagonal shading along with the single-row, double-row, quarter-row & oblique shading is observed [20,21,32,24]. Optimization of Su-Do-Ku dispersion scheme is carried out under mutual shading (MSH) scenario[29] where, two dedicated groups (S_L & S_H) are derived based upon the variance in number of shaded modules. All these afore-mentioned partial PSCs are eventually augmenting the magnitude of MML, limiting the actual power capacity (output) and causing multiple-local peaks in the characteristic curves of any PVA. Therefore, optimal interconnection(s) of PV modules under PSCs is essentially discussed in the literature in the form of optimization techniques (say Genetic Algorithm) [17], where global optimum is achieved 7 out of 10 trials; Mathematical formulation of algorithm [19] is carried out to develop new rules of shifting PV modules in a sub-array of any generic PVA system without violating the rules of Su-Do-Ku pattern; Magic Square (MS) configuration [22] presents a new method of arranging modules, such that non-diagonal elements are filled later than that of diagonal elements in a TCT-configured PVA; a flow chart of an algorithm is obtained[23] according to the odd & even position of the row elements of module; new rules of optimal interconnections[24] are proposed and the parallel connected shaded module is found to be the most non-preferred orientation amongst all; a general formulation is proposed such that the applied pattern can be expanded to any generic array[19, 23, 25, 32] owing to reflect the universal attribute for the assumed constraint.

2.1.2 Parameter Extraction

On the manufacturer front, the data-sheet (provided) less often contains the information about certain parameters [Utilization factor (UF), Fill factor (FF), Performance Ratio (PR), MML etc], essentially required for qualitative analysis of PVA, and therefore need to be evaluated. Most of the reviewed papers have identified these parameters initially at standard test conditions (STC) as well as to the real time ambient conditions under variable PSCs [18, 19, 20, 24, 25, 27, 29, 31, 32]. The fundamental characteristics curve (V-P curve) of [15, 22, 24, 28, 31, 32] PVA obtained for static, dynamic and random PSCs extracts the location of global maximum power point (GMPP) for the respective proposed configurations such that probability of misleading MPPT might reduce, although (in case of multiple peaks) location of global peak (GP) is identified via considering the module currents as per the order in which panels are by-passed.

Similarly, the optimization methods that are independent of any equivalent arrangement of interconnection scheme also employ a set of parameters, which majorly relies upon the population size & fitness function [17]. Other approaches, under MSH conditions, require the estimation of parameters (solar elevation angle, azimuthal angle, tilt angle, PV-azimuth angle, etc) to obtain %age annual Performance Enhancement (PE)[29]. One of the most important parameters (Power loss (P_L)) is investigated by significant number of research papers[16, 19, 20, 24, 25, 28, 32] according to the concerned element employed for P_L (say by-pass diode, parasitic resistive loss, loss due to relative power levels, resistance of the wires used in interconnection of PV modules, etc.).

2.1.3 Modelling Scale

The variation in the scale of modelling and simulation can be observed in the reviewed papers such that 81 modules(9x9 PVA) are considered to assess the performance analysis of puzzle based reconfigured and modified PVA interconnection under static and moving illumination[15, 16, 17, 19, 28, 29]. New logic based puzzle arrangements (MS, RTCT) and new-rule based optimal interconnections (HRPVA, FRPVA) are proposed and analyzed within the scale of square matrix (4x4 and 6x6) under non-uniform irradiations [20, 21, 22, 24, 27, 31]. The urge of non-square matrix evaluation is necessitated and therefore, test under panel failure, by-pass diode failure, random and fixed shading[18] is carried out for 36 panels (2x18, 3x12, 4x9, 6x6, 9x4, 12x3 and 18x2). As discussed in the literature about the wide applicability of FEC in any derived or re-configured puzzle based configuration, large PVA is designed (35x200) for illustrating[54] the dispersion of shadow over the PV array such that physical positions of PV modules alters merely once at the time of installation[23]. One can easily identify from [30, 31] that scale of simulation (2x2, 6x6) varies slightly with that of experimental validation(2x3 and 5x5) and the same is done just to check the qualitative nature of characteristic attributes of puzzle based configuration of PVA under PSCs.

2.1.4 Computational Technique

The accuracy, robustness and ease of implementation are the key parameters to be observed while seeking for any computational technique employed. The environment of MATLAB/SIMULINK software is utilized for the modelling, simulation and performance analysis of puzzle (and modified puzzle) based reconfigured PVA interconnection schemes [15-32]. This method of computation is quite useful to estimate the electrical response of the PVA, but at the same time requires the endeavor of modelling the complete circuit with long time running simulation.

Encountered with a large PV system[15, 16], PVA can be divided into 9x9 sub-assembly such that the proposed algorithm can be re-iterated until the loop completes, but the only drawback seemingly identified is the simulation time. Alternative approach of optimization (GA) is also friendly with MATLAB environment [17, 53], where, trial and error method is employed to successfully attain the global peak, but the only concern is the decision of fitness function and careful selection of population size else, the solution could be incomprehensible. Generalized coding(program) is developed facilitating the formation of array of any generic size[18] under PSCs. Analytical computing is adopted for evaluating ΔP (difference in power between two peaks) along with mathematical calculation to quantify the performance parameters[19]. P-V characteristics extract the GMPP for RTCT in MATLAB environment and 3-dimensional movement of passing cloud is shown [20]. 3-dimensional model of a home, near PVA, is designed and realistic assumption of PSC is carried out such that the PE of simulated results can be verified with that of experimental set-up [23]. Branch and Bound (BB) algorithm is applied [25] to solve Mixed Integer Quadratic programming (MIQP) which is based on evaluating the continuous quadratic model at each node, then branching on integer variables. The computational speed can be enhanced (faster) via including the linear constraints in a heuristic way, but this paper does not provide any information about the type of solver considered and the duration of simulation. Assumptions are made while carrying out a simulation i.e. voltage drop is neglected across the by-pass diode, shunt resistance is neglected in the modelling of a PV cell, etc; [26, 27] which has automatically taken the results towards the attainment of maximum power output from PVA under considered PSC(s), whereas, [28] can be observed to have its computation via actually including the aforementioned assumed parameters. Annual power output is one of the performance parameters to be investigated for the expectation of 'return of investment' and the same is reviewed in [29] such that it is calculated (for two PV solar farms) every 20 minutes from 8 a.m. to 4 p.m. daily, yielding a augmentation in PE by 20.2%. The reliability of the software simulated work is validated (although for a few cases) through the experimental set-up such that the applicability of the proposed interconnection techniques might be maximized [23, 30, 31].

2.1.5 Irradiation Levels Supported

Energy yield of PVA is significantly depends on the pattern of the shade and its duration as well. The most common type of static pattern of the shade considered in the literature are Short Wide(SW), Short Narrow(SN), Long Wide(LW), Long Narrow(LN) that is defined in [33]. Puzzle based configurations (say Su-Do-Ku and its equivalent optimized versions) has employed these four shade-pattern [15,16,17,22] to investigate for the performance analysis in terms of MML, PE, global peak,etc, such that different number of irradiation groups (ranging from 200 W/m^2 to 900 W/m^2) ,for each aforementioned pattern, are tested.

Addition to this, discontinuous shading pattern is depicted in [19] to analyse the MML for the proposed puzzle based configuration. Modelling of the moving cloud (dynamic shade) [20]is carried out to analyse the performance parameters under non-uniform and variable irradiation (200 W/m^2 to 1000 W/m^2). Experimental verification of the simulated configuration is carried out via performing the controlled experiment with different shading patterns(270 W/m^2 , 324 W/m^2 , 513 W/m^2 , 621 W/m^2 , 702 W/m^2 , 891 W/m^2) implemented with the help of transparent papers of different thickness [23] and the measurements under partial shading is taken between 1 p.m. and 3:30 p.m. [30] which has validated the proposed interconnections to be optimal such that the requirement of 'ties' between the two adjacent panels is remarked w.r.t. the type of shade confronted by the PVA, moreover, data-logger with the help of Pyranometer is used to measure the Irradiation [31]. Two stage irradiation level is also observed in the literature [21, 24, 25, 26, 27, 29] with the incorporation of single-row & double-row shading, diagonal & non-diagonal shadow movement and mutual shading scenarios.

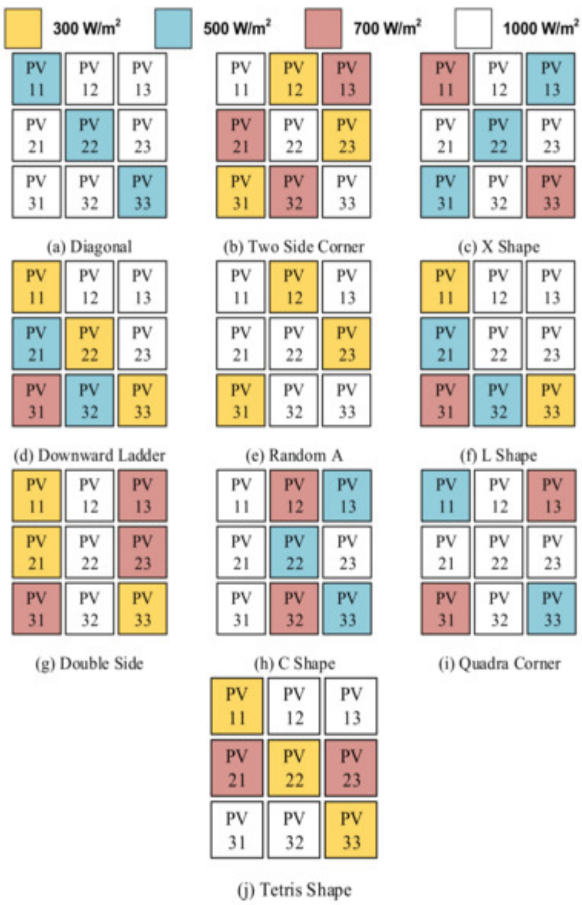

Fig.3: Poly Shade Scenario [49]

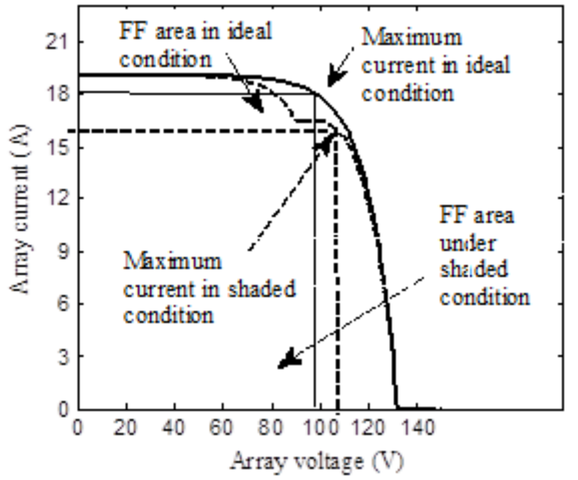

Fig.4: I-V curve during PSC

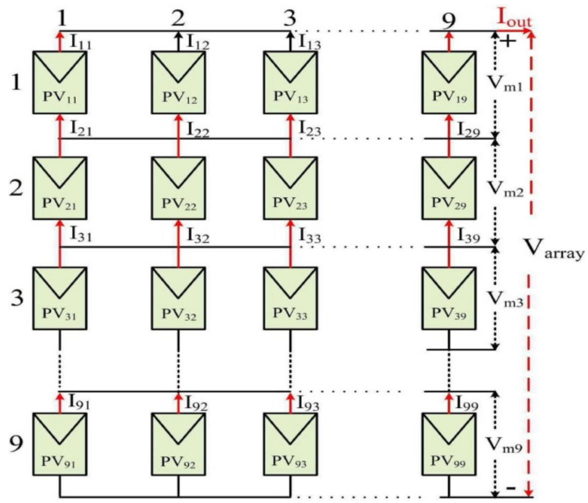

Fig.5: Electrical inter-connections of PV modules w.r.t. puzzle configuration [50]

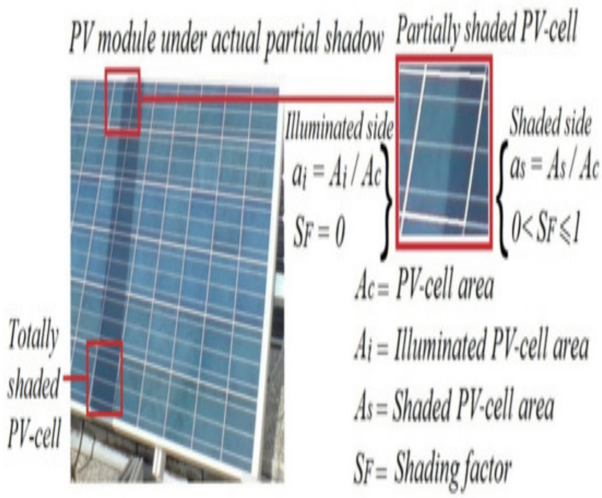

Fig.6: Partially shaded PV cell [48]

Table- 1: PV array configurations' modelling under PSCs: "Problem Formulation"

EFE REN CE	MODELLING METHOD	PARAMETER EXTRACTION	MODELLING SCALE	COMPUTA TIONAL TECHNIQU E	IRRADIAT ION LEVEL SUPPORT ED (W/m^2)	BEST CONFIGU RATION	POWER GENERAT ING CAPACITI ES (W)
[15]	• Physical relocation & electrical connection remain unaltered. • Augmentation of the incoming current at each of the node under PSC • Does not require any sensor or switch; neither a separate control algorithm • SW, SN, LW, LN shading pattern are considered	• PV characteristics is obtained for Su-Do-Ku arrangement • Row currents are theoretically calculated assuming STC • In case of multiple peaks, location of GP is identified via considering the module currents as per the order in which panels are by-passed	• Size of the PV array is 9x9 (TCT obtained from simple series-parallel configuration & Su-Do-Ku) i.e. 81 Modules	• Circuit Simulation on MATLAB/ SIMULINK environment • Even for large PV system, PVA can be divided into a 9x9 sub-assembly	200, 400, 600, 900	Su-Do-Ku	SW(4532) SN(5045) LW(4083) LN(4879)
[16]	• Resistance of the wire, used for interconnection of modules, is also given an importance • Consecutive dispersion of numbers is adopted owing to avoid the extra line-loss • Wiring diagram illustrates that the difference in cumulative resistance of the overall wiring between TCT & Su-Do-Ku configurations is evaluated as 72R • American wire gauge(AWG) rating is chosen	• R α length of the wire used for interconnection (causes additional line losses) • Power output at GMPP is same for both Su-Do-Ku and Improved Su-Do-Ku arrangements iff line losses are neglected • Length of the wire required for interconnection of modules has direct relation with the degree of dispersion of numbers in a column	• 81 modules (9x9) are analyzed	• Proposed system is designed and simulated in MATLAB/SIMULINK environment • Efficacies of various arrangements are compared • Even for large PV system, PVA can be divided into a 9x9 sub-assembly	200, 400, 600, 900	Improved Su-Do-Ku	SW(4419) SN(5168), LW(4507), LN(4850)
[17]	• KVL & KCL are applied to calculate array voltage and current at its each node respectively • Equations of TCT configuration is also valid for Su-Do-Ku pattern (due to fixed	Population size is kept constant with iteration count varies from 100 to 800. Owing to converge the algorithm at the global optimum point, parameters are constrained	• Array size is (9x9) [80 W panel]	• Trial & Error method is employed • MATLAB/SIMULINK environment is carried for Kotak PV 80 W panel	200, 400, 600, 900	GA	SW(4802) SN(5444) LN(5647)

	electrical connections) • Optimization by GA is proposed, which majorly depends on: Population generation & Fitness function design. • Global optimum is achieved 7/10 trials; (*Suitable labelling is done to identify the individual module)	Row currents are calculated to determine the location of the GP PV array extracts maximum power at reduced nominal voltage Despite of the same limiting coefficient, current extracted at a specific voltage is higher in magnitude than that of Su-Do-Ku arrangement;					
[18]	• Test under panel failures • Test under shaded condition • Test under bypass diode failures • Test under random shading • Test under fixed shading	A significant decline is observed in the magnitude of Utilization factor when tested for failure in By-pass diode No. of ties in the proposed configuration is lesser than that of TCT The Utilization factor of NEW configuration is comparable to TCT except for diagonal shading	• 36 panels are taken into consideration • Test under shaded condition is performed for [2x18, 3x12, 4x9, 6x6, 9x4, 12x3 and 18x2]	• Generalized programming is developed, using MATLAB software, facilitating the formation of array (any size), configuration & shading pattern	300, 500, 700, 800 1000	TCT/NEW	1285.3
[19]	• A general formulation is proposed • Logic sequence is followed to develop the puzzle • Allowing the unique number orientation in a sub-array via shifting the numbers in the previous column by maximum sub-array size (3) • Mathematical formulation of the algorithm is carried out;	• Indirect descent in mismatch losses is observed via directly reducing the wire length • Total wire resistance is optimized to 209 times 'R' in the optimal Su-Do-Ku • Improvisation in Energy yield is presented & computed to be 80 kWh/year;	• 9x9 PVA	• Analytical computing is adopted for evaluating ΔP (difference in power between two peaks) at STC • Mathematical calculations are involved to evaluate the performance parameters • MATLAB/SIMULINK environment is utilized to simulate the system model	100, 200 300-900 1000	Optimal Su-Do-Ku	SW(5011) SN(5700) LW(3038) LN(5461) Discontinuous(5488)
[20]	• By-pass diodes are connected across each module • Physical relocation is done	• The %age improvement in FF, %age reduction in power loss for	• 36 modules (6x6) PV array is considered	• 3-D Graphical representation of Moving Shadow and respective P-V characteristics is depicted in	Variable from 200-1000	RTCT	1348

	of RTCT as per the Su-Do-Ku pattern • Modelling of a moving cloud is adopted	RTCT configuration • %age MML of TCT & RTCT configuration is depicted in the graphical scene		MATLAB environment			
[21]	• Puzzle shade dispersion pattern is used to share out the dispersion effect • Progressive increase in shadow movement (diagonal & non-diagonal) is assumed;	• Row current is calculated for shade dispersion pattern of Su-Do-Ku arrangement • Power and voltage at GMPP is observed to predict the performance analysis of 3 different PVA configuration	• 4x4 PVA is considered	• Extensive simulation is carried out for three configurations in MATLAB/SIMULINK environment	350, 1000	Su-Do-Ku	2279
[22]	• Magic Square configuration is presented • all the diagonal elements of TCT is filled up first and then filling the remaining position • each number occurring exactly once, such that the sum of the entries of any row, any column, or any main diagonal is the same	• Maximum power is extracted from the P-V characteristics of the PVA • Performance enhancement, in terms of Power Loss, is quantified	• 4x4 PVA is considered	• Results are verified with the simulations in MATLAB/ SIMULINK environment	200 400 600 900	MS	SW(898) SN(960) LW(791) LN(920)
[23]	• An algorithm is proposed for PRM-FEC arrangement in a TCT configuration of (mxn) PV array [m=n & m!=n] such that a flow chart is obtained considering, whether the row number is even or odd • Rearrangement of the PV modules in an array under PSC depends on the row length of an array	• Power and Energy production is extracted for the hourly basis during sun-shine hours • 3-Dimensional modelling tool for home construction(near PVA) is utilized to replicate the realistic assumption of PSC on a PVA	• 7x5 array of TCT configuration • 35x200 large PV array is designed to illustrate PRM-FEC configuration	• Comparison between PRM-FEC & EAR techniques is performed using MATLAB/SIMULINK environment for 85W PV-module	270, 324 432, 513 621 702, 891	PRM-FEC	73.55(Simulation) 61.56(Experimental)
[24]	• New rules of optimal interconnections are proposed • shaded modules are placed diagonally	• ON resistance of the by-pass diodes has zero loss observed for HRPVA & FRPVA • Increment of Performance	• 4x4 TCT configured PVA	• MATLAB/SIMULINK environment	500 1000	FRPVA	4234 (Shaded) 4857.4 (Non-shaded)

	opposite to each other • Non-preferred orientation of the shaded module is the parallel connection • Applications of Single-row, double row, quarter row and oblique shading is considered	Ratio (PR), by 0.077, is extracted for HRPVA & FRPVA • generated power is augmented by 22.37% (HRPVA & FRPVA) • Power-Voltage curve of HRPVA & FRPVA is much smoother than that of TCT configuration					
[25]	• Zig-Zag arrangement of modules in TCT configuration is proposed • NTCT configuration: modules in the first row (of conventional TCT)are reconnected as a diagonal element(4x3 array) • The modules which were connected in succession in conventional TCT are now occupy alternate cells in NTCT;	• Losses due to relative power levels (due to multiple MPPs) is identified & minimized • FF is affected by the presence of parasitic resistive loss • "PR" is well defined with the help of relation among "AE, GMPP, t, IRA, P_{dc}, G_{ST}; • Power Enhancement (PE) remains the same for both OTCT & NTCT configuration	• 12 Modules (4x3)	• [OTCT] Branch & Bound (BB) algorithm is applied to solve the stated optimization problem (MIQP) • Theoretical calculations are verified by MATLAB/SIMULINK environment	500, 1000	NTCT	567.7
[26]	• Digit based positioning of rows and column for proposed puzzle based configuration is adapted • Mathematical elaboration of proposed Shading cases	• FF/ Power mismatch/ Power loss • Temperature effect on characteristics curve	• 5x4 • 9x4	• Simulation is carried out in MATLAB/ SIMULINK	350-1000	NS-1/ NS-2	3265
[27]	• Magic Square configuration is proposed (logic based number placement puzzle 4x4) • Every row, column & diagonal adds up to the same number • Rules for Row-wise, column wise and diagonal addition is observed	• Row currents are obtained essentially employing the shading factor and module current • No local MPP is observed • Power losses mismatch shows the lower elevations • "FF" is graphically represented (showing shadow movement)	• 4x4 PVA	• MATLAB/SIMULINK	350, 1000	MS based Configurations	2279

[28]	• 2-diode model of a PV cell is considered • A *Shifting* is introduced in modified-TCT (M-TCT) arrangement such that maximized spatial gap between adjacent PV modules, in different columns and rows , is achieved • Sub-arrays of S-MTCT arrangement is connected in parallel owing to reduce the power dissipation by protection diodes	• GMPP is improvised by 54% for 2x2 PVA & 100% of GMPP is attained for 3x3 PVA • P-V curve not only shows a single peak but also exhibit the highest MPP • Efficiency of SMTCT is augmented by inserting blocking diodes for each PV module • Lower energy dissipation (//S-M-TCT configuration)	• 9x9 PVA divided into 3x3 sub-array	• MATLAB/SIMULINK environment is utilized to analyze and assess the proposed PVA arrangement in terms of GMPP & the extent to which the number of peaks are minimized in P-V characteristics	200, 400 500, 600 700, 900 1000	//S-M-TCT	4081 (//S-M-TCT) 4077 (S-M-TCT+ BLK)
[29]	• New rules are presented for optimizing the Su-Do-Ku dispersion scheme in mutual shading conditions (MSH) • Two groups (S_L & S_H) are derived based upon the variance in number of shaded modules in one or more rows from OSBAs;	• Mutual Shadowing is indirectly relies upon the following parameters: *Solar elevation angle, Solar Azimuthal angle, tilt angle, PV-azimuth angle, row spacing, height & weight of the collectors* • PE for S_H members is more than that of S_L members • Annual power enhancement is carried out	• 9x9 PVA	• MATLAB/SIMULINK model is set up to prove the efficiency of the proposed scheme	200, 1000	OSBA	NA
[30]	• Single-diode module is used & simulated with STC (1000W/m^2, 1.5 air mass & 25^{0}C) and PVA (lumped altogether) • Switching between two mentioned configuration is depicted like an ON-OFF concept • PS due to 'easy to predict sources' is considered • 7 shading scenarios are observed for predicting the	• Under all shading scenarios, MPP power is observed (irrespective of the 'tie' connected) • Energy production is maximized due to increased coherence between modules' MPPs power & array's MPP power	• 2x2 PVA [Simulation] • 2x3 PVA [Experimental verification]	• MATLAB/ SIMULINK • Experimental set-up is prepared to verify the Simulated work	200, 500, 800, 1000	Proposed (in terms of NIR)	4419.3

	MPP power, moreover, necessity to omit spare interconnection (among modules)is realized						
[31]	• Static shade tolerant scheme is proposed • Modelling of Algorithm is carried out such that panels associated with the concerned row are not to be placed next to each other (but separated by a minimum distance governed by the size of the array) • Equation is developed to locate the orientation of panels	• Magnitude of Utilization factor clearly depicts the uniform shade dispersion • Output power in the V-P characteristics curve not only extracts the maximum value, but also presents the absence of multiple peaks under PSC	• Experimental verification [5x5] • [6x6 PVA is considered for calculation]	• MATLAB/ SIMULINK • Experimental set-up is prepared [Pyranometer, DSO, data-logger]	200, 300, 400, 500, 600, 700, 800, 900, 1000	PSA	280.2
[32]	• Correction factor(of Irradiation & temperature) is considered for proposed NS-puzzle configuration • Diagonal movement of shadow is considered • Physical relocation & electrical connection remain unaltered	• Effect of temperature variation over the row currents is observed • P-V characteristics is represented under various shadow movements at STC • Graphical analysis (BAR-chart) is done to depict the effect of diagonally shadow movement on Power loss& FF • Probability of false tracking to GMPP (caused by LMPP) for PV-characteristics is reduced	• 6x4 sized PVA is tested for the proposed NS-puzzle configuration	• MATLAB/SIMULINK modelling of PV module is performed against the specification of "BP3170N" (commercially available)	350, 500,800, 1000	NS	3457
[34]	• Each row has one shaded panel • Does not require sensor, switches and adaptive banks	• DSO is employed for fundamental curves of current and power	• 5x5 PVA is considered	• Experimental Setup	500 to 1000	FRPVA (under applied set of rules)	98.54(Modules of 500W/m^2); 202.44(Modules of 500W/m^2); 4234;
[35]	• Single Diode model is adopted • Connection matrix is used to	• Current Sensor, Oscilloscope are utilized to	• 3x3 Array size is employed	• Experimental validation	70 to 960	N/A	52.11

	develop sub-Array • ERDM PV panels are employed	demonstrate I-V and P-V curves • Infrared Thermometer measures Temperature					
[36]	• LS-TCT configuration is proposed and tested for 4 shading pattern	• Power, V_{oc}, I_{sc}, V_{mpp}, $I_{mpp}$are extracted	• 4x4 [LS-TCT]	• Simulation	350 to 1000	LS-TCT	2279
[37]	• New column index method is proposed • One time relocation(physically)	• Mismatch and power loss are measured • FF for 4 shading condition is calculated	• 9x9	• Simulation	200-900	Proposed(column index method)	4647(SW) 4089(LW) 5582(SN) 5338(LN)
[38]	• PVA are arranged in SP and TCT configuration to be investigared via ARDUINO [ATmega 2560]	• Power loss and FF are extracted • Current sensor, Arduino and DAS are deployed	• 3x3	• UEOS based Experimental Set up and Simulation	380-710	TCT	24.78 25.06
[39]	• Improved SuDoKu without altering Electrical inter-connections • Backtracking and Recursive checking is implied	• Mismatch Losses/Fill Factor/Efficiency/ GMPP	• 9x9 TCT PVA	• Simulation in the environment of MATLAB/SIMULINK	100-1000	Improved SuDoKu	60.3V_m I_m
[40]	• Permanent Structuring technique [TCT connection] • Cost Effective technique based on ODD-EVEN methodology	• Row wise current • Voltage and Power of PVA/P_{max} of PV modules • Current and voltage sensor and ARDUINO	• 4x4	• Simulation and Experimental	300, 600, 1000	Proposed OE	2338(DBSP) 2166(TBSP) 2774(DNSP 2512(TNSP)
[41]	• Skyscraper puzzle apt for symmetrical and non-symmetrical PVA • 3-D representation	• Mismatch Loss/ Row current calculation/ GMPP/ Power loss/ FF • Income generation	• 5x5, 9x9	• Simulation and real time-Experiment	200-800	Proposed Skyscraper puzzle	4127(9-10 am) 5658(10-11am) 5280(11-12pm) 4127(12-1pm) 5658(1-2 pm) 5280(2-3 pm)
[42]	• Shading Faults scenarios are primarily concerned in PVA of polycrystalline and CIGS	• Reduced P-V peaks/ Row current estimation • Power, V_{oc}, I_{sc}, V_{mpp}, I_{mpp} are extracted	• 6x6	• Simulation	400-1000	CIGS PV Technology	4940(TCT) 4720(BL) 4680(SP) 5210(RM)
[43]	• Discuss hybrid PVA topology • Mathematical analysis of Honey Combed PVA	• FF/ ML/ I-V, P-V/ Local and Global peaks • V_{oc}, I_{sc}, V_{mpp}, I_{mpp} are extracted	• 4x4	• Simulation • Employed SPR-200-BLK-U PV modules	300-1000	HC (when shading spread across half of the string)	2859(HC)[Maximum power generated under PSC]
[44]	• SRBL-TCT configuration	• Irradiance Density	• 6x6 solar PVA	• Simulation and Experimental	200-1000	(SRBL-TCT)	8118-Instant T1

	using single-diode model • Moving clouds are modelled	• GMPP/ Power loss/ FF/ Performance Ratio • Effect of Temperature					5829-Instant T2 6209-Instant T3 8117-Instant T4 5059-Instant T5
[45]	• Hybrid Reconfiguration Algo • Splitting of 4x4 array into two sets of 2x4 PVA • Implementation of switching matrix circuit	• Performance parameters like: Cost/Complexity/ Controller speed/ No. of Sensors and Switches	• 4x4 TCT connected PVA	• Experimental	200-950	Reconfigured SuDoKu	104.1
[46]	• Lo-Shu grid based reconfiguration • Nine hall arrangement	• Power enhancement/ FF/ Capacity factor/ PR/ Capture loss/ Execution Ratio	• 9x9 • Subarrays of 3x3	• imulation	300-900	Lo-Shu Technique based Configuration	5783(SW) 5738 (LW) 5558 (SN) 5548 (LN)
[47]	• Thorough analysis of Faults over PV system under PSCs • Investigation is carried out for multiple faults for no-uniform shading	• V_{oc}, I_{sc}, V_{mp}, I_{mp} • Light generated current • Efficiency/ $Power_{max}$ • Reduction in Power Generation(while Grid-tied)	• 6x6 PVA	• imulation	400, 500, 1000	Thin film (a Si-type) Technology	4530(SP) 4640(HC) 4910(TCT)

3. Summarized discussion based on comparative assessment of the methods reviewed

3.1 Quanti-qualitative assessment

3.1.1 Power Generating Capacities

The puzzle based Su-Do-Ku arrangement of the PVA configuration is known for its ability to reduce the effect of partial shading via dispersing the shadow over the entire array without altering the electrical connections amongst the modules such that maximum output power can be procured[15]. But this feature merely does not seems enough to reduce the MML and the effect of sub-array shading to the PVA and hence, the authors [19] realized to come up with optimal form of Su-Do-Ku such that the aforementioned drawbacks can be eliminated and the highest output power (8118 W) among [15, 16, 17, 19, 44] is achieved under static cum continuous shade and test for discontinuous shade yielded the generation of 5488 W. The optimization technique has also contributed [17] to the maximum power extraction (5647 W) at a point where voltage of the PVA is much less than that of its nominal voltage. During the sun-shine hours, hourly based power extraction can be observed [23] for the PRM-FEC configuration, where by, experimental results deviated with that of the simulation power output by 11.99 W. ON resistance loss of the by-pass diodes in TCT configuration are found to be vanished in HRPVA & FRPVA configurations [24] and applying the proposed interconnection rules guarantee the augmentation in generated power by 22.37%.

Affected by partial shading, the multiple MPPs (identified) contribute towards the losses due to relative power levels which can mislead the perception of GMPP. This problem is minimized by [25] employing the Zig-Zag pattern of modules in TCT configuration which can be applied to array of any dimension, moreover the power enhancement remained equal in both OTCT and NTCT configuration due to the attainment of same GMPP. In few papers [26, 27, 28, 30, 31, 32] power generation capacity is observed and understood in the form of 'Energy yield'[52], 'Elevations of power loss', 'Efficiency', 'Energy dissipation' and 'V-P characteristics of PVA

3.1.2 Potential Configurations and Why?

Out of the reviewed papers comprising of puzzle based PV configurations under the PSC(s)[15-32], only 16 distinguished configurations qualifies as the potential candidates on the ground of their respective performance analyzed via profoundly observing the behavior of associated performance parameters. As already discussed in previous sub-headings, one of the widely adopted approaches is to not to alter the electrical connections (used for interconnection) amongst the modules of a PV array owing to effectively apply the shade dispersion technique because the fundamental equations used for TCT (in most of the cases) remains valid for the proposed configurations [15, 16, 17, 20, 21, 22, 23, 25, 29, 32].

Mathematical formulation of algorithm based new interconnection shemes is reviewed and noted for their contributions towards generalization of application to any generic array (either a square matrix or a non-square matrix) under the effect of non-uniform irradiation[19, 23, 24, 23, 29, 31]. These new rules of optimal interconnections of the modules of PVA under PSC(s) are serving to obtain the maximum power output from the considered array size in the form of one or the other performance parameter(FF (%), PR, MML (%), P_{loss} (%) , I_{sc} , V_{oc} , U.F., shading factor, power difference, GMPP). Once applicable to the decided array size, it can be extended to the larger array (LA) provided the LA is further subdivided into the smaller arrays of the decided pattern under all types of static as well as dynamic shading conditions, moreover, their advantages like omission of spare interconnections, attainment of uniform dispersion, annual power enhancement, optimization of spatial gap between adjacent PV modules, indirect decline in the graph of MML, resistance optimization of the wire, etc clarily sort them for the nomination of potential configuration.

4. Expected scope of future work: “Possible-recommendations”

The systematically investigated performance of existing static and dynamic configurations (whether simulation or experimental based) of puzzle based PV system has proved its potentiality for robustness, reliability and easy to implementation; but still this detailed review has observed the scope of improvisation in the area as enlisted here under:

- Physical relocation of the PV modules is a time-consuming and laborious task;
- Fault analysis is yet to be thoroughly explored for augmenting PVA interconnection strategies under PSCs.
- Generalized interconnection laws for large partially shaded PV-fields still need attention;
- A few interconnection scheme is specifically developed (although guidelines are mentioned) for ‘difficult to predict’ shadow conditions (dust, clouds, snow, etc);

Author(s) feel motivated to recommend the possible solution to the aforementioned issues. Computational methods can be improvised for the attainment of maximum power output (having non-linear nature) out of a reconfigured PV system via adopting the Soft Computing techniques to achieve an optimal interconnection strategy in the expectation of enhanced computational speed, real time identification of global MPP etc.

MATLAB/SIMULINK environment is widely used throughout the reviewed papers to come to the theoretical results, wherefrom the parameters (required for analysis) are extracted in the graphical fashion. One can also extract these parameters utilizing new softwares like “PV-Syst”, “SAM” (System Advisor Model), that offers an advantageous use of exporting its result to be served as an input data for other related softwares (say MATLAB) for further qualitative analysis. However, real-time weather input can be incorporated, from NSRD (National Solar Radiation Database), for solar resources data and ambient weather conditions along with de-rating factors for PV systems can be included for analysis purpose. Many studies have applied just 3 or 4 patterns of static shade, which is a common scene but not the generally applicable scenario, which ultimately constraints the applicability of the respective configurations, moreover this issue deserves thoughtful attention and investigation owing to congregate practical applicability and computational efficacy such that this study could face wider embrace.

5. Conclusion

This paper details the comprehensive perspective of the state of the art puzzle based PV array configurations for all the known categories of PSC(s). Problem formulation is classified according to the methods of modelling, mode of parameter extraction and complexity of computational procedures along with other worthy attributes are discussed. Quanti-qualitative comparative assessment perceive the faculty of adequacy, robustness, degree of accuracy as well as applicability of the reviewed configurations under static, dynamic and random partial shading scenarios. Most of the interconnection schemes provided for puzzle based re-configuration arrangement work well for only ‘easy to predict’ sources of shadowing, but at the same time also claims for reduced initial capital and essential maintenance owing to the passive participation of sensors & switches aided by simplified control algorithms. Logical computation is observed to be realized in the environment of **MATLAB/SIMULINK** either via coding (programming) or optimization technique (GA) [53] or by applying special algorithm (BB). Certain drawbacks are identified, although minor, that require attention while prosecuting the future research in this area and that’s the reason for author(s) to summarize this study highlighting the scope of improvisation (with possible recommendations) with available alternatives.

Nomenclature

I_{sc}	Short circuit current of PVA	I_o	reverse saturation current at reference temperature T_r
V_{oc}	Open circuited voltage of PVA	I_{pv}	output current of the PVA
I_{mpp}	array current at maximum power point	V_{pv}	output voltage of the PVA
I_{row}	row current of PVA	K_i	temperature coefficient of short circuit current
P_{max}	– maximum power output of the PVA	K_v	temperature coefficient of open circuit voltage
I_{scr}	short circuit current of the cell at	k	Boltzmann’s constant
G	irradiation level (kW/m^2)	q	unit charge
E_g	band gap energy of the cell (eV)	A	p-n junction ideality factor
T_{ac}	actual cell temperature	R_s	series resistance of each cell
I_{rs}	reverse saturation current of the cell	I_{ph}	photo current of the PVA
N_s	number of PV modules connected in series	N_p	number of N_s connections connected in parallel

Abbreviations

PVA	Photovoltaic array	PRM FEC	Physical relocation of modules with fixed electrical connection
SP	Series Parallel	OSBA	Optimal Su Do Ku based arrangement
TCT	Total Cross Tied	NOSB A	Non optimal based arrangement
RTCT	Reconfigured TCT	EAR	Electrical array reconfigurati on
NTCT	Novel TCT	PSA	Proposed static arrangement
SPTC T	Series Parallel TCT	NS	Novel Structure
RSPT CT	Reconfigured SPTCT	NS1, NS2	Non symmetrical 1, 2
SMTC T	Shift modified TCT	NIR	Number of interconnecti ons required
//SMT CT	Parallel SMTCT	BLHC	Bridge linked HC
HC	Honey Comb	RBLH C	Reconfigured BL
BLTC T	Bridge linked TCT	BL-	Bridge Link
HRPV A	Half reconfigured photovoltaic array	FRPV A	Fully reconfigured photovoltaic array

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