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String Level Optimization on Grid-Tied Solar PV Systems to Reduce Partial Shading loss

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Abstract: Partial shading, commonly observed in domestic rooftop solar photovoltaic (PV) deployments, can be highly detrimental for the Performance Ratio (PR) of a PV system. Typically, for domestic installations, string-inverter or module micro-inverter configurations are deployed. While module level micro-inverters generally present a better response to non-uniform distributions of sunlight, they are still less common and therefore, costly in many emerging markets. String-level implementations on the other hand, are widely deployed as they are less complex and cost efficient. In this work, we present an analytical and simulation framework for improving PR under partial shading conditions through alteration of string connections in a string-level inverter system. Results show up to 4.6 % higher PR in winter months for a 42.24 kW$_p$ system installed at Lahore University of Management Sciences (LUMS), Lahore, Pakistan.

1. Introduction

There is a growing shift from fossil fuels to renewable resources for electricity generation worldwide. Renewable resources, particularly solar energy has a huge potential in many countries and can contribute significantly to the overall electricity mix [1, 2]. Solar energy can be added through a) solar thermal energy extraction or b) photovoltaic extraction using solar photovoltaic (PV) modules/panels. Solar thermal process harnesses the solar energy by extracting heat from sunlight which can then be used to make steam to drive a turbine to produce electricity. On the other hand, photovoltaic technology extracts the energy of photons in sunlight through solar cells to generate electron/hole pairs which flow in the outer circuit to generate electricity. Solar PV technologies have seen a much higher growth in the last decade due to decreasing costs of solar panels and balance-of-system (BOS) components [3-5].

Most commonly found urban domestic PV systems include grid-tied topologies where many of the panels are connected to a central inverter feeding directly to the grid. Many factors affect the output of PV system; these mainly include temperature [6, 7], low irradiance [8, 9], pitch and orientation of PV panels [10], efficiency of inverters and batteries (in case of systems with backups [11], generally installed in areas with intermittent grids), wiring losses and shading [9, 12, 13]. The shadowing or shading loss can be very significant for urban settings affecting the Performance Ratio (PR) for central inverter orientation [14-16]. For instance, *Deline et al.* [16] showed that the PR of a c-Si panel based PV system could range from as little as 20% to 80% for a 30% shading.

There are various classifications of shading of which dichotomist classification, i.e. 'objective' and 'subjective' shading, is more prevalent. Objective shade is due to cloudy weather or it simply can be a time of the day when there is sparse irradiance available. Objective shading cannot be avoided as the sun gets blocked in it and whole PV installation is likely to get evenly affected. The subjective shading can be classified into 'static' and 'dynamic' shading [17]. Static shading occurs due to an anomaly in the vicinity of a PV system (such as dirt, bird droppings, etc.) and is also referred to as hard shading [9]. Dynamic (soft) shading can be in the shape of a distant buildings, structures or trees causing a shade on the PV installation. The hard shading can be improved by cleaning panels [18, 19], whereas multiple techniques are employed to reduce soft shading loss. Hard shading affects both open operating open circuit voltage and short circuit currents of a PV string. According to Zaihidee *et al.* [20] dust accumulation of 20 g/m^2 on a PV panel reduces short circuit current, open circuit voltage and efficiency by 15–21%, 2–6% and 15–35%, respectively. Typically, in case of soft shade, the MPPT algorithm of the inverter may reduce current in the entire string to take advantage of overall voltage contribution of the string to maximize the power output. In hard shades where a panel is hard shaded (bird dropping or other reasons where the input irradiance is fully blocked), the bypass diode becomes active, completely bypassing the panel/module. This lowers the overall operating voltage of the string. In this work we focus only on 'soft shading losses' (also referred as 'partial shading losses') due to structures in the vicinity of the PV deployment.

Most residential sites, where PV panels are installed, are usually surrounded by other structures or buildings and have a variable pattern of shade with respect to position of the sun. When shade(s) reach a PV installation, it decreases the output of the panels by lowering the current generation of its shaded cell as cells are connected in series. As a remedy, solar panels are equipped with bypass diodes which a) lower the losses by providing a parallel path for the shaded cells/panel and b) prevent against hot-spots which could permanently damage a panel. However, depending on the type of shade, the shading losses could still be very significant.

The PR can be improved by minimizing the effect of shading through various schemes such as modifying interconnections of modules and strings, reconfigurable arrays and string level optimization [21-30]. The possible modules and string interconnection schemes include total cross tied (TCT) and branch linked (BL) discussed in [24-26]. These schemes generally distribute the effect of partial shading evenly and minimize the power degradation due to shadows. BL and TCT are less susceptible to partial shading problems; however, large interconnection redundancy requires extra conductors, resulting in expensive cabling and a reduced Return-on-Investments (ROI) index.

Several other techniques using dynamically reconfigurable PV arrays to mitigate the effects of partial shading have been presented in literature [27-32]. These schemes utilize complex control algorithms to control the switches responsible for reconfiguration of array. Computational complexity along with real time sensing requirements along with decreasing solar module prices makes these schemes costly and largely unviable for small scale implementations. In addition, a reliability issue of switches is often an important concern for these systems. Therefore, for small and medium scale installations, a simplified, computationally less extensive and cost effective strategy with minimum hardware (switches, cables and conductors) requirements is highly desirable to mitigate the power degradation effects of shading.

An interesting technique based on SU DO KU configuration of modules to enhance the power output of PV array is discussed in [32], However, in such a scheme physical locations of the modules are changed, while the electrical interconnection remains unaltered. Such a scheme based upon module relocation is sub-optimal due to a) relocation of modules requires labor and physical resources to realize the physical relocation. Moreover, it might be infeasible to manipulate metal frame on which panels are mounted upon. b) Since electrical interconnections are unaltered, while the position of the module has been changed, therefore, extra conductor may be required for the module to be located at another position. This extra conductor will not only increase the cost of the system but also enhance the associated distribution and wiring losses. Moreover, SU DO KU based method does not take the site-specific shading patterns and incident irradiance in to consideration for maximizing the PV array output power. In contrary, genetic algorithm (GA) based electrical interconnection optimization of various modules in PV arrays are utilized such that their physical location remains unaltered is discussed in [31]. Although the labor requirements associated with the relocation of panels and complexity of interconnections resulted from physical relocation may be reduced by using GA based optimization of interconnections. However, such GA based schemes have the tendency to converge to local maximum rather than global maximum, which may result in reduced output power. Moreover, the convergence of GA algorithm is highly dependent on parameter selection which limits its widespread use.

In this work, we devise a method for enhancing PR in a string-level implementation through shading analysis at the time of installation or one-time rearrangement of string structures in existing PV systems to achieve a higher PR. It should be noted that the modification does not include physical relocation of the panels, but only involves re-stringing with minor alterations whereby several shaded panels in neighbouring strings are swapped with un-shaded panels to increase the combined output of two strings. In essence, the efficiency gains are achieved through allowing strings to stay shade free for larger intervals. The only cost of this alteration is the extra conductor requirement which is significantly less than TCT and BL modified reconnection schemes used in literature. Moreover, retrofitting of existing systems to TCT or BL orientation requires complex interconnections (from implementation point-of-view) may be highly challenging. Therefore, the presented framework is suitable for planning new installations as well as retrofitting of the existing installations with minor modifications in the string structure.

2. Methodology

Typically, in rooftop implementations, string level inverters are commonly implemented. A simple arrangement of this scheme with three parallel strings of 22 panels each connected to a central inverter is shown in Fig. 1. Each panel generally contains a number of bypass diodes which play a central role in minimizing shading losses. Typically, 3 bypass diodes are used in a panel of 60 cells, which distributes 1 diode per block of 20 cells as shown in Fig. 2. If one cell is shaded in a block (e.g. Cell 1-20), an alternate path for current is provided by the bypass diode (BD1). While, under partial shading condition, the current may stay the same in a panel, the power output of the system is affected due to exclusion of the ‘bypassed’ block. Further shading of cells within the same block will not affect the power output as the block is already being bypassed. However, if one cell from another block (e.g. cell 21-40) also gets shaded then two blocks from the panel are (typically) bypassed resulting in one third of the production. This is particularly critical in performance of these systems and various efficient Maximum Power Point Tracking (MPPT) algorithms tackle this by appropriately decreasing the current levels to maximize the power output [33-35].

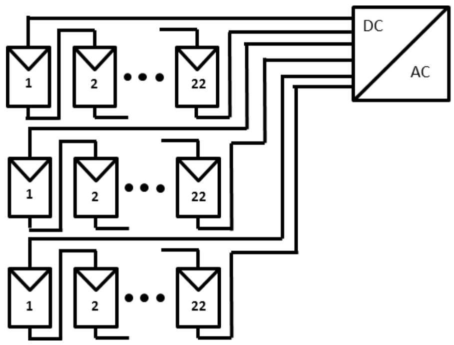

Fig. 1. *3 strings of 22 panels each connected to a central string inverter.*

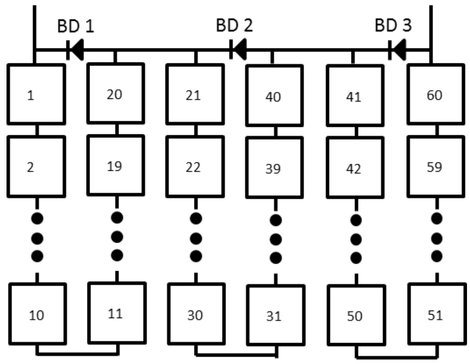

Fig. 2. *Basic schematic of a PV panel with 60 cells and 3 bypass diodes making three blocks of 20 cells*

In this work, the key task is to analyse the system’s shading pattern and evaluate possible gains through possible restructuring of the strings. The resulting gains can be analysed through a software (such as PSIM) or analytically.

In this work, we have used both approaches to ascertain the efficiency improvement. For analytical evaluation for the partial shaded system, it is important to summarize some basic PV cell parameters [36].

$$I = I_{sc} - I_{01} e^{\frac{q(V+IR_s)}{nkT}} - \frac{V+IR_s}{R_{sh}} \quad (1)$$

$$V_{oc} = \frac{kT}{q} \ln\left(\frac{I_{sc}}{I_o} + 1\right) \quad (2)$$

Where,
I = Output current at the terminal
I_{sc} = Short-circuit cell current
I_{01} = Reverse saturation current
q = Charge of electron
V = Voltage at the terminal
R_s = Series resistance of a cell
n = Ideality factor
k = Boltzmann constant
T = Temperature at Standard Test Conditions (STC)
R_{sh} = Shunt resistance of a cell
Voc = open-circuit cell voltage

Equations (1) and (2) evaluate the current and voltage at Standard Test Conditions (STC) for a solar cell. However, in order to incorporate the effect of changing irradiance and changing temperature, further translation equations are established. For a typical Si-based solar panel, equations are summarized [37].

$$I_{sc} = I_{sc,o}\{(1 + \alpha(T - T_o)\}\left(\frac{E}{E_o}\right) \quad (3)$$

$$V_{oc} = V_{oc,o}\left\{1 + a\ln\left(\frac{E}{E_o}\right) + \beta(T - T_o)\right\} \quad (4)$$

$$I_{mp} = I_{mp,o}\left(\frac{I_{sc}}{I_{sc,o}}\right) \quad (5)$$

$$V_{mp} = V_{mp,o} + \left(V_{oc} - V_{oc,o}\right) + R_s(I_{mp,o} - I_{mp}) \quad (6)$$

$$P_{cal} = V_{mp}.I_{mp} \quad (7)$$

Where,
$I_{sc,o}$ = Short-circuit current at STC
α = Short-circuit current temperature coefficient
T = Operating temperature
T_o = Temperature at STC
E = Instantaneous irradiance
E_o = Standard Irradiance (1000W/m^2)
$V_{oc,o}$ = Open-circuit voltage at STC
a = Irradiance correction factor of Voc
β = Open-circuit voltage temperature coefficient
I_{mp} = Instantaneous current at maximum power
$I_{mp,o}$ = Current at maximum power at STC
V_{mp} = Instantaneous voltage at maximum power
$V_{mp,o}$ = Voltage at maximum power at STC
R_s = Series resistance
P_{cal} = Calculated Maximum Power

Equations (3-7) quantify the response of a solar panel to changing parameters. As every PV installation is different due to its location, design, number of panels installed, and manufacture of the panels, the aforementioned equations cannot be linearized for MPPT operation in shaded conditions. What needed is a generic set of equations which could quantify the response of the PV system even in shaded conditions under normal MPPT operation. For instance, if some of the blocks/panels are being bypassed due to non-uniform shading then the MPPT algorithm must be able to account for that in power estimation. We therefore deduce following condition as a reference for ascertaining maximum attainable power from a string.

$$E\left(\frac{U}{N}\right) \geq E_s \quad (8)$$

Where,
U = Total number of un-shaded blocks in a string
N = Total number of blocks in a string
E_s = Irradiance in shade

'Blocks' basically represent the number of bypass diodes in a string. If a bypass is active, it will be counted as shaded block and if not it will be counted as un-shaded block. Irradiance in shade is taken to be constant factor of 0.4*E (Instantaneous irradiance) and instantaneous irradiance is taken from data logging system. This 40% is the average reduced value of irradiance taken from measured irradiance in shade and in normal condition. Basically, irradiance is found to be lower near the shadowing structure than near the edge of the shade and ambient. To reduce complexity, an average value provides a good approximation for shading in any instant.

For any string, if (8) is a true, then the instantaneous current at maximum power I^a_{mp} is same as (5) while, instantaneous voltage at maximum power V^a_{mp} is given by (10) [38]. In this case, short circuit current will vary in direct proportion with the incident irradiance E normalized over standard irradiance E_o, while open circuit voltage will show a logarithmic dependence with incident irradiance E normalized over standard irradiance E_o as shown by (3) and (4) .

$$I^a_{mp} = I_{mp,o}\left(\frac{I_{sc}}{I_{sc,o}}\right) \quad (9)$$

$$V^a_{mp} = \left\{V_{mp,o} + \left(V_{oc} - V_{oc,o}\right) + R_s\left(I_{mp,o} - I_{mp}\right)\right\} * \left(\frac{U}{N}\right) M - I^a_{mp}(S)R_{BD} - (S)V_T \quad (10)$$

Where,
S = Total number of shaded blocks in a string
R_{BD} = Forward resistance of a bypass diode
V_T = Diode threshold voltage drop
M = Total number of modules/ panels in a string

If the condition presented in equation (8) is false, then MPPT algorithm will not bypass the blocks, therefore, to attain the maximum power from the string, each block will contribute towards the net power from the string. Such a string is classified as inactive bypass string and its important parameters including short circuit current I^{ao}_{sc}, instantaneous current at maximum power point I^{ao}_{mp}, open circuit voltage V^{ao}_{oc}, and instantaneous voltage at maximum power point V^{ao}_{mp}, must be modified and are given by (11) - (14). In this case, short circuit current will vary in direct proportion with the shade irradiance E_s normalized over standard irradiance

E_o, while open circuit voltage will show a logarithmic dependence with shade irradiance E_s normalized over standard irradiance E_o as shown by (11) and (13), where shade irradiance assumption has already been explained above.

$$I_{sc}^{a^\circ} = I_{sc,o}\{(1+\alpha(T-T_o))\}\left(\frac{E_s}{E_o}\right) \quad (11)$$

$$I_{mp}^{a^\circ} = I_{mp,o}\left(\frac{I_{sc}^{a^\circ}}{I_{sc,o}}\right) \quad (12)$$

$$V_{oc}^{a^\circ} = V_{oc,o}\left\{1 + a\ln\left(\frac{E_s}{E_o}\right) + \beta(T-T_o)\right\} \quad (13)$$

$$V_{mp}^{a^\circ} = \left\{V_{mp,o} + \left(V_{oc}^{a^\circ} - V_{oc,o}\right) + R_s(I_{mp,o} - I_{mp}^{a0})\right\}M \quad (14)$$

These equations have been used in conjunction with software simulation to evaluate system performance for the observed pattern of shading.

3. Optimization Frame-work for String Level Optimization

For a generalized solar PV system having R strings with M modules in each string as shown in Fig. 3, total number of blocks N_t can be calculated depending upon the number of bypass diodes D per module.

$$N_t = R * M * D \quad (15)$$

Based upon the incident irradiance on each block, these blocks can further be classified as shaded blocks S_i and un-shaded blocks U_i in each string i. Therefore, for each string i total number of blocks per string N, total number of un-shaded blocks N_1 and total number of shaded blocks N_2 can be represented by (16), (17) and (18) respectively.

$$N = U_i + S_i \quad \forall i \in [1, R] \quad (16)$$

$$N_1 = \sum_{i=1}^{R} U_i \quad (17)$$

$$N_2 = \sum_{i=1}^{R} S_i \quad (18)$$

While, total number of blocks N given by (15) can be represented in terms of (17) and (18) by (19)

$$N_t = \sum_{i=1}^{R}\left(U_i + S_i\right) \quad (19)$$

For a given shade pattern, S_i and U_i may vary in each string i, therefore, the output power $PS_i(t)$ of each string at any time t will vary accordingly and is given by (20)

$$PS_i(t) = \begin{cases} V_{mp,i}^{a}(t) * I_{mp,i}^{a}(t) \rightarrow E_i(t)U_i(t) \geq NE_{s,i}(t) \\ V_{mp,i}^{a\circ}(t) * I_{mp,i}^{a\circ}(t) \rightarrow E_i(t)U_i(t) < NE_{s,i}(t) \\ \quad ; \forall t \in [1, T], \forall i \in [1, R] \end{cases} \quad (20)$$

Based upon the information of U_i and S_i, in each string, connections of blocks and associated modules can be modified such that most of the un-shaded blocks are in the same string for longer intervals such that the overall output power is maximized.

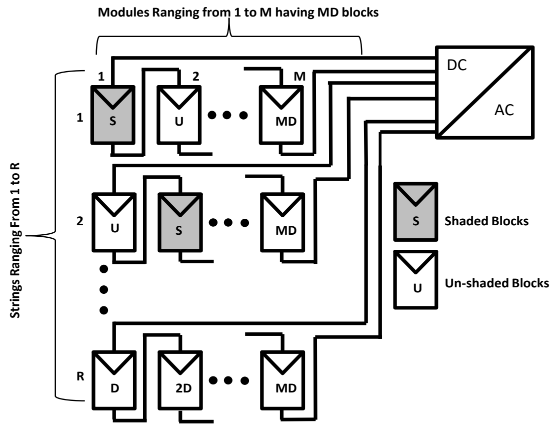

Fig. 3. *Typical grid-tied solar PV system having R strings with M modules in each string*

Theoretically, the maximum attainable power $P_{max}(t)$ at any time instant t for the installed system at a given shading profile is given by the summation of individual maximum power point operation of all the modules and is given by (21).

$$P_{\max}(t) = \sum_{i=1}^{R}\sum_{j=1}^{M} P_{cal\ i,j}(t) \quad (21)$$

The optimization function is developed to minimize the cumulative sum of the difference between the maximum attainable power and the possible attainable power through re-connections of the blocks in the strings over a defined time period T_s is

$$\underset{U_i,S_i}{Min}\left[\sum_{t=1}^{T_s} P_{\max}(t) - \sum_{t=1}^{T_s}\sum_{i=1}^{R} PS_i(t)\right] \quad (22)$$

Subject to the constraints given by (15) – (19).

This optimization problem is solved using standard linear optimization technique in MATLAB to find the values of U_i and S_i for each string i. Based upon the found values connections of modules in the strings are modified to obtain the optimized output from the installed system capacity. The schematic diagram for the system and one optimized reconnection after optimization has been shown in Fig. 3 and Fig. 4, respectively.

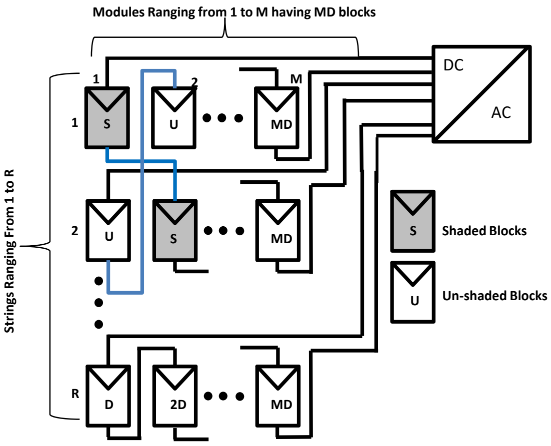

Fig. 4. *Typical grid-tied solar PV system having R strings with M modules in each string*

4. Conductor Requirements for Reconfiguration of Connections

Fig. 5 shows a typical case of PV installation with various lengths (x_a - x_d) shown. The extra conductor required $Cond_x$ for optimized interconnection of panels in terms of x_a, x_b, x_c and x_d can be expressed a function of numbers of re-connections λ calculated through optimization framework discussed in section 3. Therefore, extra conductor required to obtain enhanced PR through inter string reconnections of PV modules is given by (23).

$$Cond_x = \lambda(2x_d + 4x_a) \quad \lambda \in \left[0, \frac{M}{2}\right] \tag{23}$$

The total conductor $Cond_t$ required ensuring optimized operation is given by (24)

$$Cond_t = (M-1)x_b + \lambda(2x_d + 4x_a) \tag{24}$$

Where,
x_a = length of ground to the top pane of junction box.
x_b = length between two junction boxes of two connecting panels in series.
x_c = length of cable from particular panel to the sheath provided for cable integrity.
x_d = length from one row of panels to next row of panels in an installation.

5. System Implementation (Case Study)

The proposed methodology is tested through a 42.24 kW_p system installed at LUMS, Lahore, Pakistan. In this system, three central inverters are connected to 8 strings (5.28 kW_p each) with 22 modules (Panel) per string. Out of three inverters, the strings connected with 2nd inverter remain completely shade-free, which acts as a reference for other strings (shaded) due to neighbouring building. Specifications for installed panels are given in Table 1 and detailed system description is presented in our earlier work [14].

The top view and the building level installation design of the system are depicted in Fig. 6 with string connection design shown in Fig. 7. Different colours in Fig. 7 represent separate strings of 22 panels, for instance, IJK (orange) and FHI (dark green) are two out of 8 strings of 22 panels in series. DEG (grey) strings are the ones which stay shadow free at all times and serve as a reference for loss characterization. The string structure is fixed and generally optimized for best performance in summer months when the sunlight is at its maximum. However, shading pattern differ in winters and the performance of the system decline as a result. Therefore, an optimized solution with optimum string connections is key to maximize PR throughout the year.

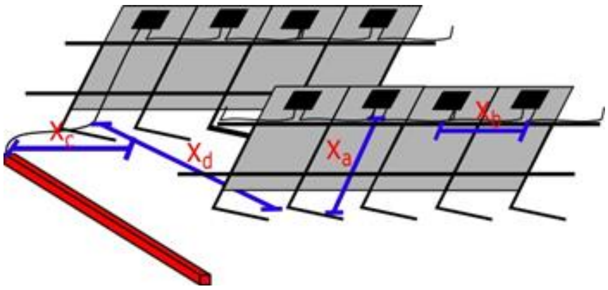

Fig. 5. *Typical series connected panels with various lengths nominated for overall conductor requirement calculations.*

Table 1 Rating of installed panel BYD240P6-30

Rated Maximum Power (P_{max})	240W_p
Tolerance	0-5W
Voltage at P_{max} (V_{mp})	29.64V
Current at P_{max} (I_{mp})	8.10A
Open-Circuit Voltage (V_{oc})	37.3V
Short-Circuit Current (I_{sc})	8.57A
Nominal Operating Cell Temp (NOCT)	45°C±2°C

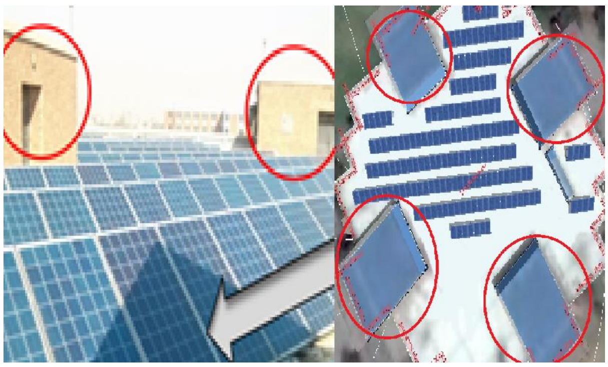

Fig. 6. *Building level view (left) and the top view (right) of the installation at LUMS library building with 4 obstructing structures causing soft shading at various times of the day*

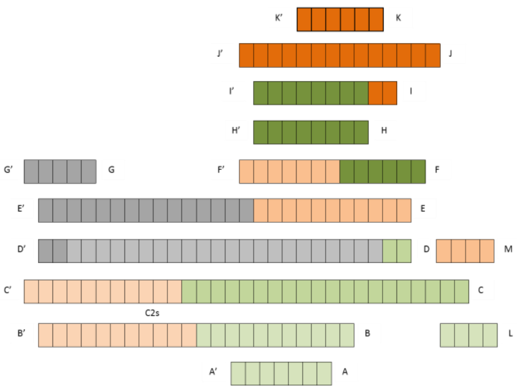

Fig. 7. *Sting level installation design for the rooftop system*

6. Results and Discussion

In order to quantify the overall gains, it is important to analyse the PR of the system which is defined as:

$$PR = \frac{\textbf{Meaured AC output KWh}}{\textbf{Theoratical DC production without losses}} \qquad (25)$$

Where, theoretical DC production is calculated by finding Equivalent Peak Sunlight Hours (EPSH) of the day through local measurement or through NREL data [39] which when multiplied by panel nameplate capacity and number of panels gives the theoretical DC string production without losses. This in relation to actual accounted energy units added to the grid (AC) gives the PR. AC output is actually energy output from inverter after effective conversion of DC into AC. This output compensates for all the losses occurring in the system. For the current implementation, for a typical winter day, the power produced by an inverter (combination of two entire strings) is shown in Fig. 8 along with the simulated (PSIM) and calculated (analytical model discussed in section 2) data. Measured output and irradiance data corresponding to the observations is taken at a 15 min interval through the data logging system. This averaging, along with shade free position of irradiance meter, accounts for the discrepancy in measured and simulated/calculated results in Fig.8. The average factor of shaded irradiance (0.4 in this case), is pivotal for simulating and calculating output as it describes the level below which the block will be bypassed.

Simulations were performed using PSIM software to evaluate the system performance for the observed pattern of shading. Variable shading was added to the simulation through C-Block generating varying irradiance to solar physical module in the software. Data for temperature was also added in the C-block. Analytical results have been achieved using the model elaborated in section 2. After performing optimization using the framework discussed in section 3 for the two shaded strings, the rearrangement gives higher power output for a typical day as shown by Fig. 9 and Fig. 10.

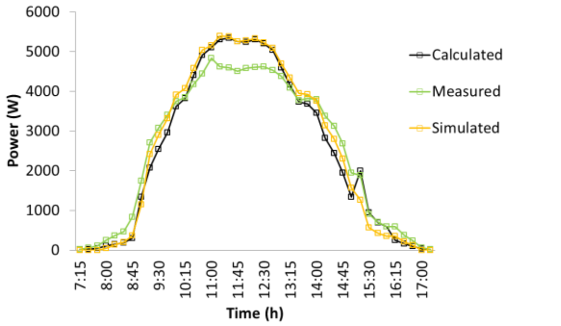

Fig. 8. *Typical winter day measured data along with simulated and calculated results*

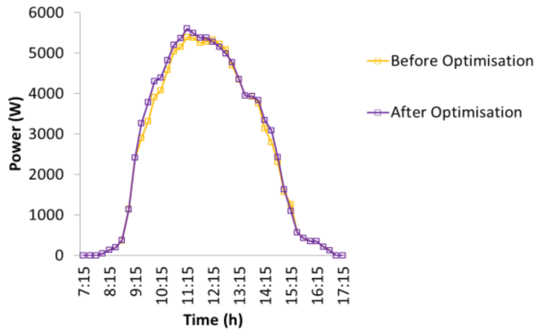

Fig. 9. *PV inverter power output (simulated) for the baseline compared with modified string structure for a typical winter day.*

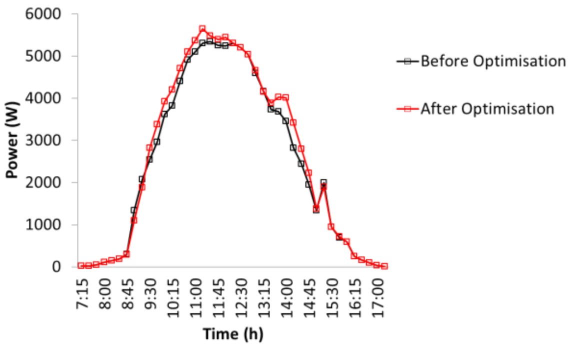

Fig. 10. *PV inverter power output (analytically calculated) for the baseline compared with modified string structure for a typical winter day.*

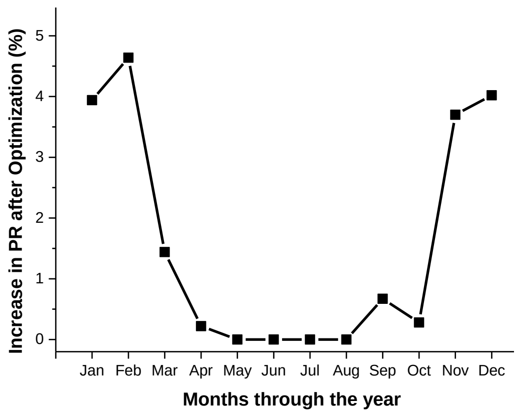

Fig. 11. *PR improvement after the proposed restringing for 12-month period.*

In order to quantify the annual gains, we evaluate the PR (on monthly basis) which is shown in Fig. 11. This is done through modelling the building structure along with obstructions in PVSOL premium and irradiance data is taken from NREL [39]. Once the shading patterns are known, the processing could be done accordingly. Unlike active schemes (such as reconfigurable arrays which require real-time information for processing), our work is based on offline processing (with standard computing resources) of the information for one-time alteration of strings. Results show a higher gain in the PR (up to 4.6%) in winter months as the system encounters large shade for these months. However, the re-stringing does not have a negative impact on the summer months largely due to the fact that the shades are minimal in these months.

It is important to note that the extra conductor required to achieve this enhanced PR is calculated through (23). In general, the viability of the proposed optimization can be assessed through the comparison of cost associated with the extra conductor and the savings associated with the enhanced utilization of grid-tied system after optimization. The savings can be calculated by multiplying per unit cost ($/kWh) of electricity to the difference of number of generated units after and before optimization. Thereby, payback time for the cost of conductor can also be calculated. For the current installation, 63.4 m extra conductor is required to make optimized interconnections, while 133.3 extra units (kWh/year) would be generated after the optimization. Thereby, taking into account the basket electricity price (0.12$/kWh), the payback time for the extra cost of the conductor (approx. 1 $/m) comes out to be less than 4 years for this installation. Similarly, for any other installation this analysis must be done for any possible restringing based upon the outcomes of optimization discussed in section 3 to get the maximum efficiency from the system.

7. Conclusion

The losses due to partial shading are not proportional to the shaded area but depend on the shading pattern, array configuration and the physical location of shaded modules in the array. As shading patterns vary throughout the year, due to relative sun position, the shading on the panels vary affecting the system's PR. In this paper we analyse shading losses for a central inverter PV system and evaluate gains in performance ratio due to minor re-stringing of neighbouring panels. In our installation, this scheme produces a higher PR of up to 4.6% in winters whereas a minute increase in PR is seen for summer months. This work is particularly relevant for domestic rooftop deployments where PR reduction is commonly observed due to partial shading losses.

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9. References

[1] K. Harijan, M. A. Uqaili, and U. K. Mirza, "Assessment of solar PV power generation potential in Pakistan," *J. Clean Energy Technol*, vol. 3, pp. 54-56, 2015.

[2] D. Li, G. Liu, and S. Liao, "Solar potential in urban residential buildings," *Solar Energy*, vol. 111, pp. 225-235, 2015.

[3] B. K. Sahu, "A study on global solar PV energy developments and policies with special focus on the top ten solar PV power producing countries," *Renewable and Sustainable Energy Reviews*, vol. 43, pp. 621-634, 2015.

[4] J. Khan and M. H. Arsalan, "Solar power technologies for sustainable electricity generation – A review," *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 414-425, 2016.

[5] L. Hirth, "Market value of solar power: Is photovoltaics cost-competitive?," *IET Renewable Power Generation*, vol. 9, pp. 37-45, 2015.

[6] T. Nordmann and L. Clavadetscher, "Understanding temperature effects on PV system performance," in *Photovoltaic Energy Conversion, 2003. Proceedings of 3rd World Conference on*, 2003, pp. 2243-2246.

[7] H. A. Khan and S. Pervaiz, "Technological review on solar PV in Pakistan: Scope, practices and recommendations for optimized system design," *Renewable and Sustainable Energy Reviews*, vol. 23, pp. 147-154, 2013.

[8] S. Pervaiz and H. A. Khan, "Low irradiance loss quantification in c-Si panels for photovoltaic systems," *Journal of Renewable and Sustainable Energy*, vol. 7, p. 013129, 2015.

[9] D. Thevenard and S. Pelland, "Estimating the uncertainty in long-term photovoltaic yield predictions," *Solar Energy*, vol. 91, pp. 432-445, 2013.

[10] M. de Wild-Scholten, E. Alsema, E. Ter Horst, M. Bächler, and V. Fthenakis, "A cost and environmental impact comparison of grid-connected rooftop and ground-based PV systems," in *21st European Photovoltaic Solar Energy Conference*, 2006, pp. 3167-73.

[11] A. S. Mundada, K. K. Shah, and J. Pearce, "Levelized cost of electricity for solar photovoltaic, battery and cogen hybrid systems," *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 692-703, 2016.

[12] S. Pervaiz, H. A. Khan, and M. A. Qureshi, "A practical perspective on grid-tied PV systems in low reliability grids," in *Photovoltaic Specialist Conference (PVSC), 2014 IEEE 40th*, 2014, pp. 1969-1972.
[13] Y. J. Wang and P. C. Hsu, "Analytical modelling of partial shading and different orientation of photovoltaic modules," *IET Renewable Power Generation*, vol. 4, pp. 272-282, 2010.
[14] J. Ahmed and Z. Salam, "A critical evaluation on maximum power point tracking methods for partial shading in PV systems," *Renewable and Sustainable Energy Reviews*, vol. 47, pp. 933-953, 2015.
[15] E. I. Batzelis, P. S. Georgilakis, and S. A. Papathanassiou, "Energy models for photovoltaic systems under partial shading conditions: a comprehensive review," *IET Renewable Power Generation*, vol. 9, pp. 340-349, 2015.
[16] C. Deline, "Partially shaded operation of a grid-tied PV system," in *Photovoltaic Specialists Conference (PVSC), 2009 34th IEEE*, 2009, pp. 001268-001273.
[17] P. B. a. R. Zhang, "Shading Analysis & Improvement for Distributed Residential Grid-Connected Photovoltaics Systems," *Solar 2014*, 2014.
[18] L. A. Lamont and L. El Chaar, "Enhancement of a stand-alone photovoltaic system's performance: Reduction of soft and hard shading," *Renewable Energy*, vol. 36, pp. 1306-1310, 2011.
[19] M. A. Ramli, E. Prasetyono, R. W. Wicaksana, N. A. Windarko, K. Sedraoui, and Y. A. Al-Turki, "On the investigation of photovoltaic output power reduction due to dust accumulation and weather conditions," *Renewable Energy*, vol. 99, pp. 836-844, 2016.
[20] F. M. Zaihidee, S. Mekhilef, M. Seyedmahmoudian, and B. Horan, "Dust as an unalterable deteriorative factor affecting PV panel's efficiency: Why and how," *Renewable and Sustainable Energy Reviews*, vol. 65, pp. 1267-1278, 2016.
[21] M. A. Chaaban, L. El Chaar, and M. Alahmad, "An Adaptive Photovoltaic Topology to Overcome Shading Effect in PV Systems," *International Journal of Photoenergy*, vol. 2015, 2015.
[22] M. Hasan and S. Parida, "An overview of solar photovoltaic panel modeling based on analytical and experimental viewpoint," *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 75-83, 2016.
[23] D. La Manna, V. L. Vigni, E. R. Sanseverino, V. Di Dio, and P. Romano, "Reconfigurable electrical interconnection strategies for photovoltaic arrays: A review," *Renewable and Sustainable Energy Reviews*, vol. 33, pp. 412-426, 2014.
[24] N. D. Kaushika and N. K. Gautam, "Energy yield simulations of interconnected solar PV arrays," *IEEE Transactions on Energy Conversion*, vol. 18, pp. 127-134, 2003.
[25] M. S. El-Dein, M. Kazerani, and M. Salama, "An optimal total cross tied interconnection for reducing mismatch losses in photovoltaic arrays," *IEEE Transactions on Sustainable Energy*, vol. 4, pp. 99-107, 2013.
[26] Y.-J. Wang and S.-S. Lin, "Analysis of a partially shaded PV array considering different module connection schemes and effects of bypass diodes," in *Utility Exhibition on Power and Energy Systems: Issues & Prospects for Asia (ICUE), 2011 International Conference and*, 2011, pp. 1-7.
[27] M. S. El-Dein, M. Kazerani, and M. Salama, "Optimal photovoltaic array reconfiguration to reduce partial shading losses," *IEEE Transactions on Sustainable Energy*, vol. 4, pp. 145-153, 2013.
[28] D. Nguyen and B. Lehman, "An adaptive solar photovoltaic array using model-based reconfiguration algorithm," *IEEE Transactions on Industrial Electronics*, vol. 55, pp. 2644-2654, 2008.
[29] G. Spagnuolo, G. Petrone, B. Lehman, C. A. R. Paja, Y. Zhao, and M. L. O. Gutierrez, "Control of photovoltaic arrays: Dynamical reconfiguration for fighting mismatched conditions and meeting load requests," *IEEE Industrial Electronics Magazine*, vol. 9, pp. 62-76, 2015.

[30] J. P. Storey, P. R. Wilson, and D. Bagnall, "Improved optimization strategy for irradiance equalization in dynamic photovoltaic arrays," *IEEE Transactions on Power Electronics*, vol. 28, pp. 2946-2956, 2013.

[31] D. S. Niranjan, S. Dhale, J. Mukherjee, T. SudhakarBabu, and N. Rajasekar, "Solar PV array reconfiguration under partial shading conditions for maximum power extraction using genetic algorithm," *Renew. Sustain. Energy Rev*, vol. 43, pp. 102-110, 2015.

[32] B. I. Rani, G. S. Ilango, and C. Nagamani, "Enhanced power generation from PV array under partial shading conditions by Shade dispersion using Su Do Ku configuration," *IEEE Transactions on Sustainable Energy*, vol. 4, pp. 594-601, 2013.

[33] C. S. Chin, P. Neelakantan, S. S. Yang, B. L. Chua, and K. K. Teo, "Effect of Partially Shaded Conditions on Photovoltaic Array's Maximum Power Point Tracking," *Modelling, Simulation and Computing Laboratory, School of Engineering and Information Technology*, vol. 12, pp. 52-59, 2011.

[34] Y. Wang, Y. Li, and X. Ruan, "High-Accuracy and Fast-Speed MPPT Methods for PV String Under Partially Shaded Conditions," *Industrial Electronics, IEEE Transactions on*, vol. 63, pp. 235-245, 2016.

[35] M. Nasir and M. F. Zia, "Global maximum power point tracking algorithm for photovoltaic systems under partial shading conditions," in *Power Electronics and Motion Control Conference and Exposition (PEMC), 2014 16th International*, 2014, pp. 667-672.

[36] C. S. Solanki, *Solar photovoltaics: fundamentals, technologies and applications*: PHI Learning Pvt. Ltd., 2015.

[37] K. Ding, J. Zhang, X. Bian, and J. Xu, "A simplified model for photovoltaic modules based on improved translation equations," *Solar Energy*, vol. 101, pp. 40-52, 2014.

[38] A. S. Rana and H. A. Khan, "String level optimization on grid-tied solar PV systems for minimizing soft shading power loss," in *5th Renewable Power Generation Conferencet, IET Conference Proceedings*, 2016.

[39] National Solar Radiation Database (NSRDB) [Online]. Available: https://nsrdb.nrel.gov/