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String level optimisation 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 to 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, the authors 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 kWp system installed at Lahore University of Management Sciences, 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 produced through (a) solar thermal energy extraction or (b) photovoltaic (PV) extraction using solar PV modules/panels. The 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, PV 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 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 the 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 distant buildings, structures or trees causing a shade on the PV installation. 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 the case of soft shade, the maximum power point tracking (MPPT) algorithm of the inverter may reduce the current in the entire string to take advantage of overall voltage contribution of the string to maximise 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 the 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 the 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/panels 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 minimising the effect of shading through various schemes such as modifying interconnections of modules and strings, reconfigurable arrays and string level optimisation [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 minimise the power degradation due to the 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 index.

Several other techniques using dynamically reconfigurable PV arrays to mitigate the effects of partial shading have been presented in the literature [27–32]. These schemes utilise complex control algorithms to control the switches responsible for reconfiguration of the 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

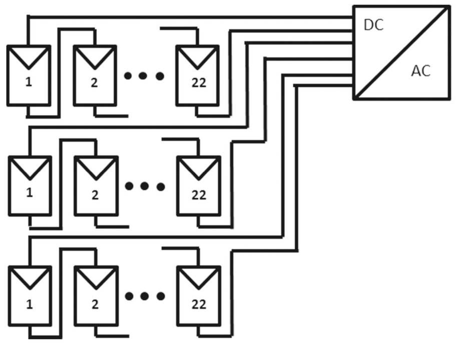

Fig. 1 *Three strings of 22 panels each connected to a central string inverter*

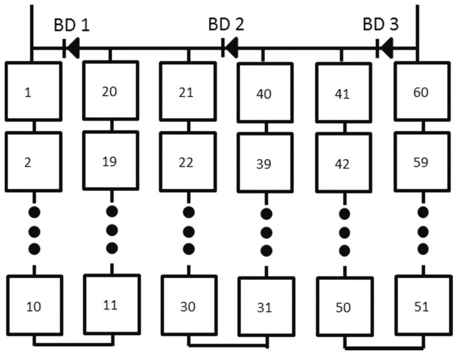

Fig. 2 *Basic schematic of a PV panel with 60 cells and three bypass diodes making three blocks of 20 cells*

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 the SU DO KU configuration of modules to enhance the power output of the 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 labour and physical resources to realise the physical relocation and (b) since electrical interconnections are unaltered, while the position of the module has been changed, therefore, an 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, the SU DO KU based method does not take the site-specific shading patterns and incident irradiance into consideration for maximising the PV array output power. In contrast, genetic algorithm (GA)-based electrical interconnection optimisation of various modules in PV arrays is utilised such that their physical location remains unaltered as discussed in [31]. Although the labour requirements associated with the relocation of panels and complexity of interconnections resulted from physical relocation may be reduced by using GA-based optimisation 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 the 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 the 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 the literature. Moreover, retrofitting of the 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 minimising shading losses. Typically, three bypass diodes are used in a panel of 60 cells, which distributes one 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 remain the same in a panel, the power output of the system is affected due to the 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 the performance of these systems and various efficient MPPT algorithms tackle this by appropriately decreasing the current levels to maximise the power output [33–35].

In this work, the key task is to analyse the system's shading pattern and evaluate possible gains through the 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 of the partially shaded system, it is important to summarise some basic PV cell parameters [36]

$$I = I_{\rm sc} - I_{01}{\rm e}^{\frac{q(V + IR_{\rm s})}{nkT}} - \frac{V + IR_{\rm s}}{R_{\rm sh}}, \tag{1}$$

$$V_{\rm oc} = \frac{kT}{q}\ln\left(\frac{I_{\rm sc}}{I_{\rm o}} + 1\right), \tag{2}$$

where I is the output current at the terminal, $I_{\rm sc}$ is the short-circuit cell current, I_{01} is the reverse saturation current, q is the charge of the electron, V is the voltage at the terminal, $R_{\rm s}$ is the series resistance of a cell, n is the ideality factor, k is the Boltzmann constant, T is the temperature under standard test conditions (STC), $R_{\rm sh}$ is the shunt resistance of a cell and $V_{\rm oc}$ is the open-circuit cell voltage.

Equations (1) and (2) evaluate the current and voltage under 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 summarised [37]

$$I_{\rm sc} = I_{\rm sc,o}\{(1 + \alpha(T - T_{\rm o}))\}\left(\frac{E}{E_{\rm o}}\right), \tag{3}$$

$$V_{\rm oc} = V_{\rm oc,o}\left\{1 + a\ln\left(\frac{E}{E_{\rm o}}\right) + \beta(T - T_{\rm o})\right\}, \tag{4}$$

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

$$V_{\rm mp} = V_{\rm mp,o} + (V_{\rm oc} - V_{\rm oc,o}) + R_{\rm s}(I_{\rm mp,o} - I_{\rm mp}), \tag{6}$$

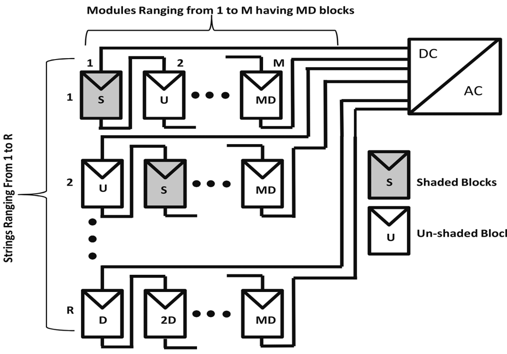

Fig. 3 *Typical grid-tied solar PV system having R strings with M modules in each string*

$$P_{\text{cal}} = V_{\text{mp}} I_{\text{mp}}, \tag{7}$$

where $I_{\text{sc,o}}$ is the short-circuit current under STC, α is the short-circuit current temperature coefficient, T is the operating temperature, T_{o} is the temperature under STC, E is the instantaneous irradiance, E_{o} is the standard Irradiance (1000 W/m^2), $V_{\text{oc,o}}$ is the open-circuit voltage under STC, a is the irradiance correction factor of V_{oc}, β is the open-circuit voltage temperature coefficient, I_{mp} is the instantaneous current at maximum power, $I_{\text{mp,o}}$ is the current at maximum power under STC, V_{mp} is the instantaneous voltage at maximum power, $V_{\text{mp,o}}$ is the voltage at maximum power under STC, R_{s} is the series resistance and P_{cal} is the 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 linearised for MPPT operation under shaded conditions. What is 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 the following condition as a reference for ascertaining maximum attainable power from a string

$$E\left(\frac{U}{N}\right) \geq E_{\text{s}}, \tag{8}$$

where U is the total number of un-shaded blocks in a string, N is the total number of blocks in a string and E_{s} is the irradiance in shade.

'Blocks' basically represent the number of bypass diodes in a string. If a bypass is active, it will be counted as a shaded block and if not it will be counted as an un-shaded block. Irradiance is measured through an irradiance sensor (SMA Sunny Sensor Box) with data-logging and provides the values of irradiance on a 15 min interval. The irradiance of shaded panels is also measured through a reference irradiance sensor (KEWTECHPV1). For any string, if (8) is true, then the instantaneous current at maximum power I^{a}_{mp} is the 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 normalised over standard irradiance E_{o}, while open circuit voltage will show a logarithmic dependence with incident irradiance E normalised over standard irradiance E_{o} as shown by (3) and (4)

$$I^{a}_{\text{mp}} = I_{\text{mp,o}}\left(\frac{I_{\text{sc}}}{I_{\text{sc,o}}}\right), \tag{9}$$

$$\begin{aligned} V^{a}_{\text{mp}} = {} & \left\{V_{\text{mp,o}} + (V_{\text{oc}} - V_{\text{oc,o}}) + R_{\text{s}}\left(I_{\text{mp,o}} - I_{\text{mp}}\right)\right\} \\ & \times \left(\frac{U}{N}\right)M - I^{a}_{\text{mp}}(S)R_{\text{BD}} - (S)V_{\text{T}}, \end{aligned} \tag{10}$$

where S is the total number of shaded blocks in a string, R_{BD} is the forward resistance of a bypass diode, V_{T} is the diode threshold voltage drop and M is the total number of modules/panels in a string.

If the condition presented in (8) is false, then the 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 an inactive bypass string and its important parameters including short circuit current $I^{a\circ}_{\text{sc}}$, instantaneous current at maximum power point $I^{a\circ}_{\text{mp}}$, open circuit voltage $V^{a\circ}_{\text{oc}}$, and the instantaneous voltage at maximum power point $V^{a\circ}_{\text{mp}}$, 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} normalised over standard irradiance E_{o}, while open circuit voltage will show a logarithmic dependence with shade irradiance E_{s} normalised over standard irradiance E_{o} as shown by (11) and (13), where shade irradiance assumption has already been explained above

$$I^{a^\circ}_{\text{sc}} = I_{\text{sc,o}}\{(1 + \alpha(T - T_{\text{o}})\}\left(\frac{E_{\text{s}}}{E_{\text{o}}}\right), \tag{11}$$

$$I^{a^\circ}_{\text{mp}} = I_{\text{mp,o}}\left(\frac{I^{a^\circ}_{\text{sc}}}{I_{\text{sc,o}}}\right), \tag{12}$$

$$V^{a^\circ}_{\text{oc}} = V_{\text{oc,o}}\left\{1 + a\ln\left(\frac{E_{\text{s}}}{E_{\text{o}}}\right) + \beta(T - T_{\text{o}})\right\}, \tag{13}$$

$$V^{a^\circ}_{\text{mp}} = \left\{V_{\text{mp,o}} + \left(V^{a^\circ}_{\text{oc}} - V_{\text{oc,o}}\right) + R_{\text{s}}\left(I_{\text{mp,o}} - I^{a0}_{\text{mp}}\right)\right\}M\,. \tag{14}$$

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

3 Optimisation frame-work for string level optimisation

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

$$N_{\text{t}} = R \times M \times D\,. \tag{15}$$

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 the total number of blocks per string N, the total number of un-shaded blocks N_1 and the total number of shaded blocks N_2 can be represented by (16), (17) and (18), respectively

$$N = U_i + S_i \quad \forall i \in [1, R], \tag{16}$$

$$N_1 = \sum_{i=1}^{R} U_i, \tag{17}$$

$$N_2 = \sum_{i=1}^{R} S_i\,. \tag{18}$$

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

$$N_t = \sum_{i=1}^{R} (U_i + S_i)\,. \tag{19}$$

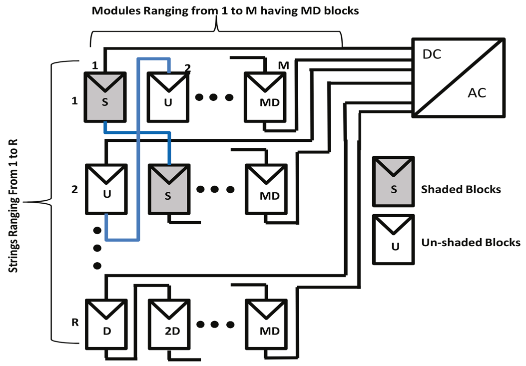

Fig. 4 *Schematic diagram for the optimized system with modified structure in neighboring strings to maximize PR*

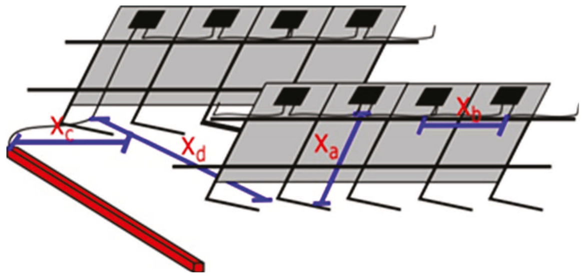

Fig. 5 *Typical series connected panels with various lengths nominated for overall conductor requirement calculations*

Table 1 Rating of installed panel BYD240P6–30

Rated maximum power (P_{max})	240 W_p
tolerance	0–5 W
voltage at P_{max} (V_{mp})	29.64 V
vurrent at P_{max} (I_{mp})	8.10 A
open-circuit voltage (V_{OC})	37.3 V
short-circuit current (I_{SC})	8.57 A
nominal operating cell temp.	45°C ± 2°C

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 as

$$PS_i(t) = \left\{ \begin{array}{r} V^{a}_{\text{mp},i}(t) I^{a}_{\text{mp},i}(t) \rightarrow E_i(t)U_i(t) \geq NE_{\text{s},i}(t) \\ V^{a*}_{\text{mp},i}(t) I^{a*}_{\text{mp},i}(t) \rightarrow E_i(t)U_i(t) < NE_{\text{s},i}(t) \\ ; \forall t \in [1, T], \forall i \in [1, R] \end{array} \right\}, \quad (20)$$

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 maximised.

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 as

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

The optimisation function is developed to minimise 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

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

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

This optimisation problem is solved using standard linear optimisation 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 optimised output from the installed system capacity. The schematic diagram of the system and one optimised reconnection, after optimisation has been shown in Figs. 3 and 4, respectively.

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 optimised interconnection of panels in terms of x_a, x_b, x_c and x_d can be expressed as a function of numbers of re-connections λ calculated through optimisation framework discussed in Section 3. Therefore, an extra conductor is required to obtain enhanced PR through inter string reconnections of PV modules is given as

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

The total conductor Cond_t required to ensure optimised operation is given as

$$\text{Cond}_\text{t} = (M - 1)x_b + \lambda(2x_d + 4x_a), \quad (24)$$

where x_a is the length of ground to the top pane of junction box, x_b is the length between two junction boxes of two connecting panels in series, x_c is the length of cable from a particular panel to the sheath provided for cable integrity and x_d is the 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 Lahore University of Management Sciences (LUMS), Lahore, Pakistan. In this system, three central inverters are connected to eight strings (5.28 kW_p each) with 22 modules (panel) per string. Out of three inverters, the strings connected to the second inverter remain completely shade-free, which acts as a reference for other strings (shaded) due to a 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 eight 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 characterisation. The string structure is fixed and generally optimised for best performance in summer months when the sunlight is at its maximum. However, shading pattern differs in winter and the performance of the system decline as a result. Therefore, an optimised solution with optimum string connections is key to maximise PR throughout the year.

6 Results and discussion

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

$$\text{PR} = \frac{\text{Measured AC output KWh}}{\text{Theoretical DC production without losses}}, \quad (25)$$

where theoretical direct current (DC) production is calculated by finding equivalent peak sunlight hours of the day through local measurement or through the National Renewable Energy Laboratory (NREL) data [39] which when multiplied by panel nameplate capacity and a number of panels gives the theoretical DC string production without losses. This with reference to actual

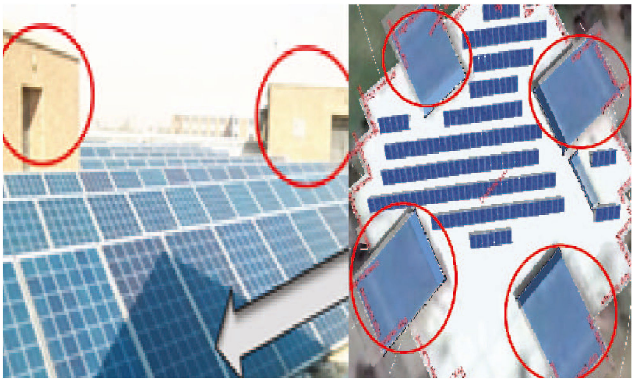

Fig. 6 *Building level view (left) and the top view (right) of the installation at LUMS library building with four obstructing structures causing soft shading at various times of the day*

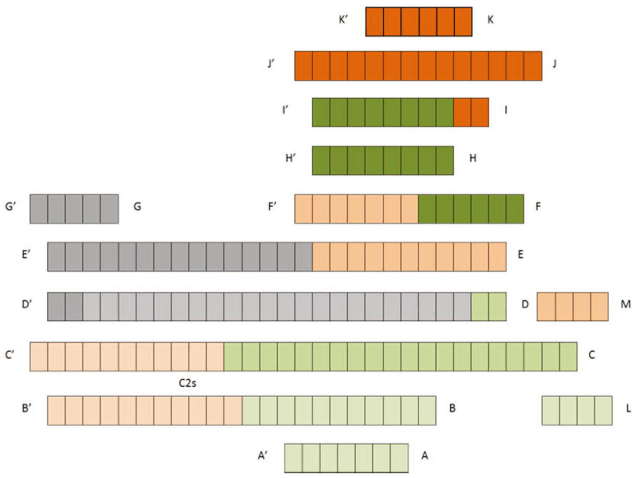

Fig. 7 *Sting level installation design for the rooftop system*

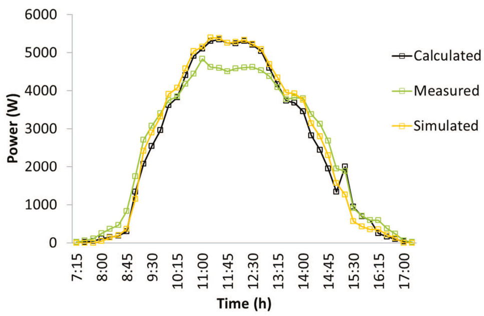

Fig. 8 *Typical winter day measured data along with simulated and calculated results*

accounted energy units added to the grid (alternating current) gives the PR. 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 are taken at a 15 min interval through the data logging system. This averaging, along with variations in the shade irradiance values due to reflections from neighbouring mumty accounts for the slight discrepancy in measured and simulated/calculated results in Fig. 8. The average factor of shade on various panels may vary due to ambient reflections and some variation is therefore observed.

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 the solar physical module in the software. Data for temperature were also added in the C-block. Analytical results have been achieved using the model elaborated in Section 2. After performing optimisation using the framework

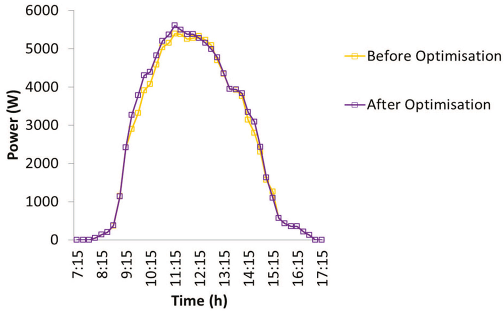

Fig. 9 *PV inverter power output (simulated) for the baseline compared with modified string structure for a typical winter day*

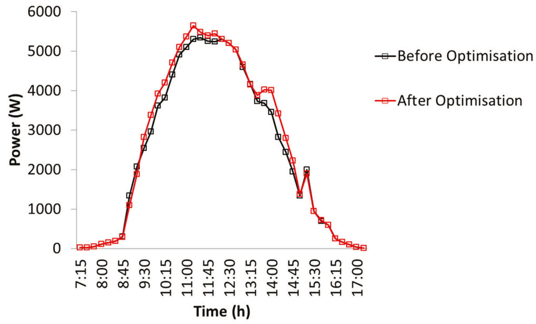

Fig. 10 *PV inverter power output (analytically calculated) for the baseline compared with modified string structure for a typical winter day*

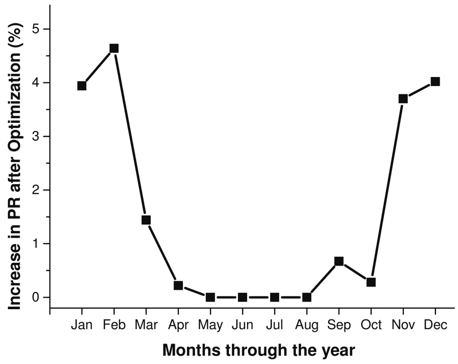

Fig. 11 *PR improvement after the proposed restringing for 12-month period*

discussed in Section 3 for the two shaded strings, the rearrangement gives higher power output for a typical day as shown by Figs. 9 and 10.

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 are taken from the 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 optimisation can be assessed through the comparison of the cost associated with the extra conductor and the savings associated with the enhanced utilisation of the grid-tied system after optimisation. The savings can be calculated by multiplying per unit cost ($/kWh) of electricity to the difference of a number of generated units after and before optimisation. Thereby, payback time for the cost of the conductor can also be calculated.

For the current installation, a 63.4 m extra conductor is required to make optimised interconnections, while approx. 114 extra units (kWh/year) would be generated after the optimisation. Thereby, taking into account the basket electricity price ($0.15/kWh), the payback time for the extra cost of the conductor (approx. 1$/m) comes out to be <4 years for this installation. Similarly, for any other installation, this analysis must be done for any possible restringing based upon the outcomes of optimisation 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 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 varies affecting the system's PR. We analyse shading losses for a central inverter PV system and evaluate gains in PR due to minor re-stringing of neighbouring panels. In our installation, this scheme produces a higher PR of up to 4.6% in winter whereas a minute increase in PR is seen in 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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