INTERNATIONAL JOURNAL of SMART GRID
A. A. Periola and I. E. Davidson, Vol.8, No.1, March, 2024

Bio-Inspired Design of Future Solar Power Systems for Smart Grid Applications

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Received: 26.02.2024 Accepted:30.03.2024

Abstract- Advances in the design of future solar-photovoltaic power systems should address performance constraints while maintaining a high-power output. An identified constraint is that of high tracker acquisition costs for large number of solar panels deployed in solar farms. The cost and overheads associated with solar tracker acquisition for the case of large-scale power farms should be addressed in future solar farms. This paper addresses this challenge and proposes the incorporation of the bio-inspired orientation diversity approach in future solar panel systems. In the proposed design approach, the future solar panel is realized from a solar tree that hosts multiple mini-solar panels. The mini solar panels are hosted at varying levels of deployment altitudes and orientation. The performance evaluation is carried out by scenario description and simulation in MATLAB. Performance evaluation results obtained show that the proposed mechanism enhances the power output and reduces tracker acquisition costs by an average of 35.6 %, and 65%, respectively.

Keywords: Solar Power Systems, solar farms, bio-inspired design, multidisciplinary research, system communications.

1. Introduction

The last century has demonstrated that every facet of human development including the 4th Industrial revolution is woven around a sound and stable energy supply regime [1]. Globally, renewable energy (RE) based distributed resources are being adopted and integrated into electrical power networks, using microgrids as intermediaries [2-3]. The feature of future energy shows a shift [4]:

- Towards DC power grid.
- Low carbon future.
- Carbon-neutrality (new power generation projects).
- Greenhouse gas (GHG) emissions standards.
- Universal electrification: energy access, affordability.
- Sustainability.
- Advances in cutting edge VSC-HVDC technology.
- Smart Infrastructures.

Solar energy systems have been identified as a sustainable source of renewable energy. The use of solar renewable energy systems involves the interception of solar radiation. The intercepted solar radiation is received by the solar cells and converted into electricity. The design of solar panel systems has been motivated by the necessity to intercept the highest solar radiation. Solar panels can be mounted vertically [5–7], and horizontally [8–9] to achieve this goal. The use of intelligent solar trackers also enables solar panels to change their orientation [10-11] for maximum power point tracking.

However, installing several trackers is cost prohibitive [12-13]. Therefore, using trackers in large scale solar power farms has a scalability challenge. In addition, the non-use of solar trackers may result in non-maximal energy output from solar farm. The occurrence of a non-maximal energy output is detrimental to obtaining optimum energy output. The challenge of solar radiation interception is also addressed in biological systems. Trees and other forms of vegetation access solar radiation for the purpose of photosynthesis [14–16]. The concerned vegetation forms do not include a known tracker functionality. The vegetation forms will incorporate orientation diversity. Orientation diversity implies a case where the solar radiation interception entities have variable deployment parameters. The concerned parameters are the altitude and orientation of the solar radiation intercepting entity.

Orientation diversity can be observed in nature, as trees in each area do not have the same orientation. The application of orientation diversity can be carried be out at the solar panel (in a solar farm) or at the solar cell level (in a solar panel). The implementation of orientation diversity requires configurable nano–solar cell's altitude and orientation, which is challenging and is not considered here. In addition, the implementation of the orientation diversity requires configuration at two levels. The first is at the level of the solar panel, and the second is at the level of the solar farm.

However, the focus is on the adoption of the orientation diversity approach in the presented research is at the solar panel level. The application of the diversity approach at the solar panel level is considered for two reasons, namely: (i.) Ease of implementation, and (ii.) The intersection with the horizon of varying solar radiation. This paper makes the following contributions:

The study proposes the orientation diversity as a bio–inspired model for future solar farms, to be incorporated into solar farm design. The proposed architecture describes the data computing and communication aspects, which enable monitoring of the energy output. In orientation diversity, the orientation of trees in each area is considered. The rationale for this is that tree orientation is a solution to the solar radiation interception challenge. The solar radiation interception in this case addresses the challenge of maximizing photosynthesis. The concerned solar panels do not use solar trackers.

Second, the research formulates and investigates the savings in cost and overhead reduction due to the minimal or zero use of solar trackers. The overhead reduction arises due to the non-use of solar trackers in the proposed orientation diversity approach. The paper is organized as follows. section II: background and describes the role of bio-inspired models in solar renewable power and energy systems; section III: problem statement; section IV: problem description and proposed solution; section V: formulation of the performance model; section VI evaluates the performance analysis, while section VII is the conclusion.

2. Literature Review

The role of bio-inspired algorithms in enhancing renewable solar energy systems is discussed in [17]. Four bio–inspired algorithms were considered, namely: gray wolf, horse herd, cuckoo search, and particle swarm algorithm. The performance of these four algorithms is compared with regards to optimizing the maximum power point tracking mechanism. The influence of the manner of the solar panel deployment geometry, and tracker cost minimization on the bio–inspired algorithm performance has not been considered.

Alkahtani [18] stated that bio-inspired models such as ANN (artificial neural networks) would become widely used in solar radiation prediction. It examines the performance of different ANN models in solar radiation prediction, such as: convolution neural network (CNN); long short–term memory (LSTM), and the hybrid model (CNN–LSTM). The hybrid model was found to enhance the prediction accuracy in comparison to the CNN, and the LSTM. The study in [18] focuses on the prediction of meteorological factors affecting solar power output. Further work is required as the proposed solution is location dependent.

Sangeetha [19] proposes the use of the ANN alongside the wavelet transform to predict the solar power system energy output. The prediction of the energy output is recognized to be important to the energy developer. It enables the developer to make efficient plans for solar power system deployment. The focus here is enabling the developer to determine the best location for hosting solar farms. However, a framework that standardizes the output for different location profiles is absent.

The bio-inspired approach of ANN is identified to be used in power output and availability prediction in solar power mini-grids. Talaat [20] recognizes that the ANN has been used in monitoring voltage stability, and critical management besides the output prediction, and recommends it to be used in micro–grid integration.

Ahsan [21] says that ANNs can be used for load prediction in the smart grid, and energy resource planning. These capabilities are examined in the context of the next generation smart grid. The discussion in [17], [18], [19], [20], and [21] notes that the bio-inspired ANN has been significantly used in the renewable solar energy systems. The areas of use have been in power output, solar radiation prediction and enhancing system performance. However, they have not focused on the design of the solar panels. The discussion in [22], [23], [24], and [25] address this challenge.

The studies in [22], [23], [24], and [25] focus on the design of solar panels and considers the geometrical aspect of solar panels. Tran [22] focuses on designing the geometry of the building that hosts the solar panels. Pandya [23] examines the efficiency of different geometries of solar panels with the aim of maximizing energy output in geostationary satellites. It further notes that introducing the geometrical dimension into varying the shapes of solar panels enhances the output efficiency. In [23], the choice of the geometrical shapes is arbitrary and the motivation for the geometrical selection has not been considered. A similar perspective to the choice of geometrical shape influencing solar panel design can be found in [24]. Additional geometry types such as slightly conical, cylinder, cone, and the conventional cylinder are considered. However, a scenario examining the geometrical diversity in the case of a large-scale solar farm requires consideration.

Flexible solar panels are examined in [25] from the perspective of the material used in the design. It focuses on the manufacturing of solar panels and demonstrates the feasibility of producing flexible solar panels. This review shows that bio– inspired models find applications in renewable solar energy systems, with respect to insolation prediction and management related configuration [17–21]. The use of bio-inspired models to determine solar panel geometry is yet to significantly benefit from bio–inspired models as seen in [22–25].

Boubaker in [26] recognizes the importance of executing the task of maximum power point tracking in future solar panel systems. The study in [26] is a survey aims at studying the different approaches aimed at configuring maximum power point tracking approaches. The bio–inspired intelligent methods that have been identified are artificial neural networks and fuzzy logic control methods. The outlook of the survey in [26] is that the use of bio - inspired intelligent algorithms will be increasingly adopted in future maximum power point tracking solutions for future solar power systems. However, the survey has not considered how bio–inspired approaches can influence the geometrical structure of the solar panels.

Provensi et al., [27] address the challenge of evaluating photovoltaic module performance prior to deployment under different environmental conditions. The evaluation is done using photovoltaic modules provided in the manufacturer's data sheets. The performance simulation is done using bio–inspired algorithms of genetic algorithms, and particle swarm optimization. The bio-inspired algorithms execute the intelligent tasks of extracting equivalent circuit associated parameters. The circuit related parameters are obtained from the manufacturer's specifications.

The design and use of a bio–inspired leaf based photovoltaic module is proposed in [28]. The proposed and presented solution executes thermal management for photovoltaic based systems. The bio–inspired leaf executes the supporting task of removing heat from photovoltaic systems. The removed heat is also used for generation purposes. The proposed photovoltaic leaf is deployed as a multi-functional system. The multi-functional consideration arises because of its execution of electricity generation, heat generation, and provisioning of clean water. The proposed solution demonstrates the ability of a bio–inspired leaf design to function as an overloaded system executing multiple functions. However, additional consideration focusing on alternative design and deployment approaches in array configurations requires further research attention.

Jaksic et al., [29] explore the use of bio–inspired intelligent algorithms in designing nanostructured solar cells. In this case, the use of bio–inspired intelligent approaches such as artificial neural networks enable the determination of optical properties of nanophotonic devices i.e., small scale solar cells. The determination of the optimal property value is done with the goal of enhancing light absorption in the nano solar cell. However, the influence of using nano solar cells designed using the optimal parameters requires further research consideration.

Therefore, a study on how biological systems enables the realization of geometrical perspective with respect to solar panels is required, which is the goal of this research study. The consideration of biological inspired models in this regard is novel. This is because bio-inspired models that have been considered as seen in [17–21] have been mostly leveraged in a computational perspective. The use of a bio-inspired models from a geometrical viewpoint is yet to receive sufficient research consideration. In addition, the use of bio-inspired approaches is recognized to be useful in different aspects associated with solar cells, and solar panels as seen in [26–29]. Furthermore, the focus of the considered research is shown in Table 1.

Table 1. Appearance properties of accepted manuscripts

S/N	Author	Focus of Research	Drawbacks
1	Ahmed *et al.,* (2017) [17]	The presented research examines the performance of different intelligent algorithms with relation to enhanced power in maximum power point tracking. The outlook of the paper advocates for algorithm heterogeneity in solving the maximum power point tracking problem	Additional work is regards determining the number of algorithms that can be accommodated in the algorithm heterogeneity approach. In addition, the influence of the algorithm heterogeneity in enhancing power output requires research consideration.
2	Alkahtani *et al.,* (2023) [18]	The research advocates the use of artificial neural networks in addressing the challenge of solar radiation prediction. The architecture of the artificial neural network used are convolutional neural network, long short-term memory, and a hybrid (combining the long short term memory, and the	Additional work is required to develop a theory on the combination of different artificial neural networks to address different challenges arising in solar renewable energy systems. In addition, more work is required for multiple locations as the proposed solution is location dependent.

		convolutional neural network).	
3	Sangeetha *et al.*, (2023) [19]	The research addresses the challenge of apriori determination of solar power system output for the energy developer. It proposes using the wavelet transform to pre-process data enabling the prediction of solar power system by artificial neural networks.	The focus is enabling the developer to determine the best location for hosting solar farms. However, a framework that standardizes the output for different location profiles is absent.
4	Dallaev *et al.*, (2023) [25]	The discussion recognizes the important role of flexible solar panels in realizing robust deployment. The research discussion is presented from the perspective of material selection and design.	Additional research is required to examine how geometrical factors influence flexible solar panel power output.
5	Boubaker (2023) [26]	The research presents a survey describing the role of approaches suitable for executing maximum power point tracking in solar power systems. The outlook of the survey is that the artificial intelligence approach will be utilized for maximum power point tracking in future systems.	However, the survey has not considered how bio–inspired approaches can influence the geometrical structure of the solar panels. The conduct of research in this manner and direction extends the work of Dallaev *et al.*, (2023) [25].
6	Provensi *et al.*, (2023) [27]	The research aims to determine the power output for solar cells. The determination is done using the manufacturer's sheets as the data source.	Additional work is required to examine the effect of low extraction efficiency and accuracy from the use of artificial intelligence algorithms in the concerned data extraction.
7	Huang *et al.*, (2023) [28]	The presented research proposes a multi-functional bio-inspired leaf design. The leaf executes the tasks of power generation, and heat removal in photovoltaic systems. The tasks executed are associated with the normal functions of solar radiation interception and transpiration as found in biological vegetative systems.	However, additional details that focus on realizing alternative designs with optimal energy generation and cooling require further research consideration.
8	Jaksic *et al.*, (2023) [29]	The proposed research proposes the use of nanoscale solar cells. It is recognized that the determination of optical properties for such systems is important. The research proposes using bio-inspired approaches to determine the optical properties that maximize light absorption.	The discussion focuses on the analysis of solar cells at a micro scale. Additional research showing how optical properties may influence power output is required.

3. Problem Description

The scenario being considered is one comprising multiple solar panels that are deployed in a solar farm. The set of solar panels in the considered solar farm is denoted α and given as:

$$\alpha = \{\alpha_1, \ldots, \alpha_A\} \quad (1)$$

The a^{th} solar panel panel $\alpha_a, \alpha_a \in \alpha$ has the solar tracker $\beta(\alpha_a)$. The cost of the solar tracker is deemed to be time varying and denoted as:

$$C_1(\beta(\alpha_a), t_y), t_y \in t, t = \{t_1, \ldots, t_Y\}.$$

A time varying cost has been considered for the solar panel to account for various manufacturers. The consideration of different manufacturers implies that the problem description considers varying capability of the solar tracker. In addition, the amount of orientation and output related data at the time t_y is denoted $C_2(\beta(\alpha_a), t_y)$. In addition, the power output for the solar panel α_a at the time t_y is denoted $P_1(\alpha_a, t_y)$. Furthermore, the energy demand,

and threshold solar tracker cost are denoted P_{req}, and C_{thre}, respectively.

A challenge occurs in the scenario given as:

$$\sum_{a=1}^{A}\sum_{y=1}^{Y} P_1(\alpha_a, t_y) < P_{req} \qquad (2)$$

$$\sum_{a=1}^{A}\sum_{y=1}^{Y} C_1(\beta(\alpha_a), t_y) > C_{thre} \qquad (3)$$

$$\frac{1}{C_T}\sum_{a=1}^{A}\sum_{y=1}^{Y} C_2(\beta(\alpha_a), t_y) > D_{thre} \qquad (4)$$

The relation in (4) describes a case where the use of trackers for all solar panels in the solar farm results in high information overhead. This overhead arises due to the acquisition of a significant amount of data on the orientation, time, and power output. The data acquired in this scenario is associated with relevant meta-data such as the strength of solar radiation, and serial number of the solar panel. A significant information overhead arises when the data on the solar panel orientation, time of acquisition, and power output is acquired periodically. In a case where the set of high-resolution data, such as: orientation, observation time and power output have a size of 6MB. In the case where the data acquisition is every 15 mins, the size of data acquired in a day is 576MB.

Since the solar farm has 1000 solar panels, the total data acquired is 576 GB resulting in a high value for $C_2(\beta(\alpha_a), t_y)$. This is a significant amount of data given that data related to subsystem health has not been considered. Given that the network supporting the transfer of the concerned data has a finite bandwidth capacity and an expected size that can be supported being denoted as C_T. The ratio of the parameter $C_2(\beta(\alpha_a), t_y)$ to the parameter C_T has a defined threshold. This threshold describes the overhead threshold denoted as D_{thre}. In the case where additional solar panels are deployed in the farm to respond to increasing energy demand, the value of D_{thre} is exceeded as seen in equation (4).

The solution being proposed is expected to have the benefit of ensuring that the utilized solar panel architecture incorporates a design that enhances system performance i.e., power output. The desired enhanced system performance should be realized without incurring high system overhead i.e., system state descriptive data and the need to deploy a data communications network. The proposed design and architecture of the solar power system component should realize this goal while considering the capital constrained context.

4. Proposed Solution

The proposed solution incorporates the orientation diversity paradigm. The proposed orientation diversity paradigm is used in a case-study solar farm. In the proposed adoption of the orientation diversity, the solar farm comprises solar panels that have different deployment orientations. The realization of the proposed solar farm is carried out in four stages, namely: (i.) Existing solution analysis (ESA); (ii.) Solar panel design (SPD); (iii.) Design test phase (DTP); and (iv.) Solution deployment phase (SDP).

The ESA stage is one in which the geometry of the trees in the solar farm site are studied. Trees are being considered as the form of vegetation. The rationale for this choice is that trees incorporate many leaves than other vegetation. In this case, the leaves constitute the solar radiation interception entity. The bio-design and geometry of the trees and their orientation are obtained in this case. The observed bio–design is used to realize the design of solar panels to be deployed in the solar farm.

In the SPD stage, the design geometries observed in the ESA stage are used. The observed geometry for different trees is used to design the solar panels. In the proposed solar panel system, the solar radiation interception unit is a group of adaptive solar cells. The grouped solar cells form a mini-solar panel. The mini-solar panel can be adapted and inserted at different points in a solar tree. The solar tree entity has multiple interfaces enabling the insertion and turning of the proposed mini-solar panel unit.

The DTP stage involves determining the relations between the orientation configuration and the power output. The orientation configuration is described through its operational parameters. These parameters are: (i.) Number of mini-solar panel units; (ii.) Number of solar cells in each mini-solar panel unit; (iii.) Orientation of each mini-solar panel unit; and (iv.) Altitude of each mini-solar panel unit.

The values of the concerned parameters are tested, and the power output associated with each configuration is observed. The altitude and orientation of each mini-solar panel differ from each other. The use of different values in this case are different solutions to the maximum power point tracking problem. This is because the solar trackers achieve a variation of the orientation of a given solar panel. The SDP involves the execution of the deployment of a solar tree comprising multiple mini-solar panels in a solar farm site. A representation of the proposed solar panel unit is shown in Fig. 1. It shows the two-dimensional model of the proposed solar tree and its components. This is carried out exclusive of the entities executing the implied tracking and accompanying orientation changes. Each of the mini-solar panel units has a different orientation and altitude along the solar tree. In Fig. 1, the solar tree has multiple interfaces each hosting a mini solar panel unit. Each mini solar panel unit has a variable tilt and an adjustable orientation. The capability of adjusting their orientation ensures that mini solar panel units with higher altitudes in the solar tree do not shield the lower altitude mini solar panel unit. In addition, the interface supports three-dimensional motion. The incorporation of support for three-dimensional motion enables each mini solar panel unit to be adjustable in the horizontal plane. The execution of motion in the horizontal plane and adjusting the tilt prevents higher altitude mini solar panel units from occluding solar radiation incidence in the lower altitude mini solar panel units. The required interconnection of each mini solar panel unit is executed in the main frame of the solar tree. In the solar tree, each mini solar panel unit is an independent entity. The connection of mini solar panel units and their three–dimensional alignment configuration are independent.

The solar tree shown in Fig. 1 comprises of multiple mini solar panel units. Each of this mini solar panel unit is connected to the solar tree through an interface. The power output of the solar tree is the total of the power output of each of the mini solar panel unit. The connection of each mini solar panel unit to the solar tree central connection point is presented in Fig. 2. The power output of the solar tree is derived through a power output terminal. The concerned power output terminal enables the power derived from a solar tree to contribute to the power outputs of other solar trees in a solar power farm. The connection of multiple solar trees in a solar farm is shown in Fig. 3. In Fig. 3, each solar tree (and not the mini solar panel unit) is connected to a solar tree central connection point. The movement and alignment of each mini solar panel unit is localized to a given solar tree. Multiple connection points can be further connected together prior to being attached to a grid connection entity. This is shown in Fig. 4.

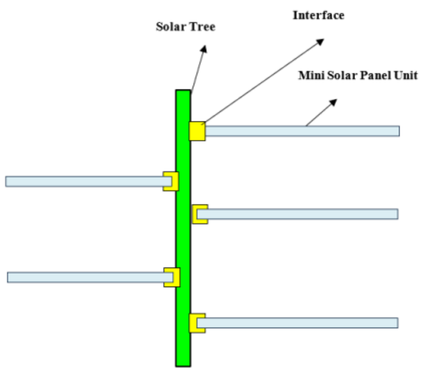

Fig. 1. Structure of the Proposed Solar Tree.

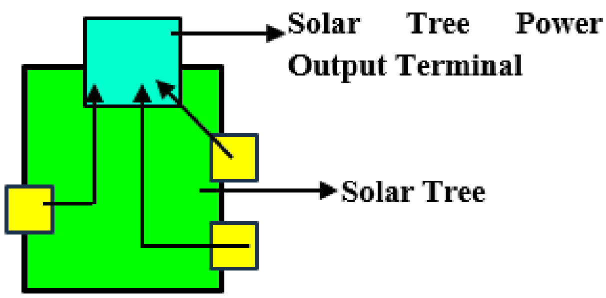

Fig. 2. Connection of the power output from each interface to the solar tree power output terminal.

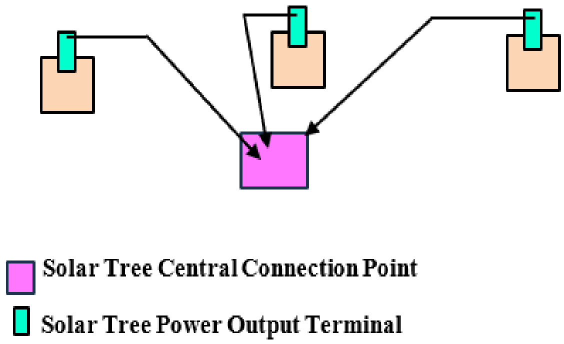

Fig. 3. Interconnection of solar trees to a central point.

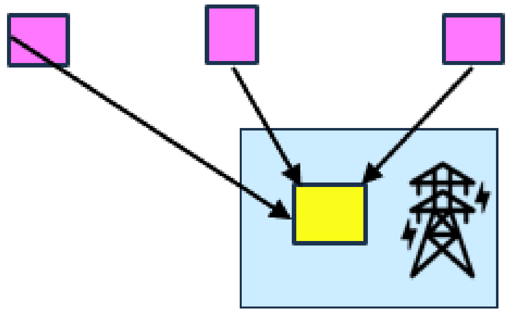

Fig. 4. Interconnection of central points to the grid.

5. Performance Formulation

The performance metric being formulated in this section are the tracker associated overhead, and solar farm power output. The associated overhead is described further by the cost and computing overhead. In the formulation, the inclusion of a tracker to solve the maximum power point tracking challenge realizes a sub-optimal solution. A sub-optimal solution has been considered since not all maximizing orientations can be executed by a solar panel, due to the inability of the solar panel to execute an all manoeuvre with regards to orientation. The power output in the existing case and proposed case are denoted denoted θ_1, and θ_2, respectively.

$$\theta_1 = \sum_{a=1}^{A}\sum_{y=1}^{Y} P_{max}(\alpha_a, t_y)\varsigma_1(\alpha_a, t_y) \tag{5}$$

$$\theta_2 = \sum_{a=1}^{A}\sum_{b=1}^{B}\sum_{y=1}^{Y} P_1(\phi_a^b, t_y)\varsigma_2(\phi_a^b, t_y) \tag{6}$$

$P_{max}(\alpha_a, t_y)$ is the maximum power output from the a^{th}solar panel α_a at the y^{th} time t_y. $P_1(\phi_a^b, t_y)$ is the power output of the b^{th} mini-solar panel unit in the a^{th}solar tree α_a at the y^{th}time t_y. $\varsigma_1(\alpha_a, t_y)$ is the deviation from the achievable maximum solar power output for the a^{th} solar panel α_a at the y^{th} time t_y. The value of $\varsigma_1(\alpha_a, t_y)$ is such that $0 < \varsigma_1(\alpha_a, t_y) < 1$. $\varsigma_2(\phi_a^b, t_y)$ is the deviation from the achievable maximum solar power output for the b^{th} mini-solar panel unit in the a^{th} solar tree α_a at the y^{th} time t_y. The value of $\varsigma_2(\phi_a^b, t_y)$ is such that that $0 < \varsigma_2(\phi_a^b, t_y) < 1$.

The inclusion of the tracker has cost implications. The formulation of the tracker cost is done considering a scenario where solar panels and the proposed solar trees co-exist. Let $I_S(x, t_y) \in \{0,1\}, x \in \{\alpha_a, \phi_a^b\}$ denote the tracker indicator of the entity x at the y^{th} time t_y. The entity x uses and does not use a tracker at the y^{th} time y^{th} when $I_S(x, t_y) = 0$, and $I_S(x, t_y) = 1$, respectively. The tracker associated costs in the proposed and existing case are denoted Γ_1 and Γ_2, respectively.

$$\Gamma_1 = \sum_{a=1}^{A}\sum_{y=1}^{Y} C_1(\beta(\alpha_a), t_y) I_S(\alpha_a, t_y) \tag{7}$$

$$\Gamma_2 = \sum_{a=1}^{A}\sum_{b=1}^{B}\sum_{y=1}^{Y} C_1(\beta(\phi_a^b), t_y) I_S(\phi_a^b, t_y) \tag{8}$$

The computing i.e., data overhead associated with the existing case and proposed case are denoted η_1 and η_2, respectively.

$$\eta_1 = \sum_{a=1}^{A}\sum_{y=1}^{Y} C_2(\beta(\alpha_a), t_y)\, I_S(\alpha_a, t_y) \tag{9}$$

$$\eta_2 = \sum_{a=1}^{A}\sum_{b=1}^{B}\sum_{y=1}^{Y} C_2(\beta(\phi_a^b), t_y)(1 + \vartheta(\phi_a^b, t_y)) I_S(\phi_a^b, t_y) \tag{10}$$

$C_2(\beta(\phi_a^b), t_y)$ is the size of the computing data enabling reconfiguration and transmitted over the associated communication network for the b^{th} mini-solar panel unit in the a^{th} solar tree α_a at the y^{th} time t_y.

$\vartheta(\phi_a^b, t_y)$ is the additional configuration data arising from the use of the b^{th} mini-solar panel unit in the a^{th} solar tree α_a at the y^{th} time t_y.

6. Performance Evaluation

The simulation is carried out within a context comprising solar panel arrays deployed in a solar farm. Hence, each solar panel has solar trackers for maximum power point tracking. The use of solar trackers is deemed applicable to the context of a solar farm. The inclusion of solar trackers in this case is recognized to be cost prohibitive especially for the case of large-scale solar farms. The use of solar trackers in the solar tree is inapplicable. This implies that there is minimal need to acquire solar trackers. Furthermore, the inclusion of trackers in the existing case and proposed case considers the case of solar tracker heterogeneity. Each of the solar panel i.e., solar radiation interception entity uses a different tracker model. Each of the concerned tracker models has a varying cost. Hence, there is a minimum, mean and maximum value for the cost of considered solar trackers as seen in the simulation parameters presented in Table 1. In addition, the solar tracker costs in the proposed case are lower than that considered in the existing case. The justification for this is the reduced need for the role of solar trackers when orientation diversity is included. In addition, the role of the solar tracker is described through the solar tracker deployment ratio. The solar tracker deployment ratio describes the use of solar trackers in the existing case and proposed case. The reduced need for the use of solar trackers in the proposed case leads to the solar tracker deployment ratio being lower than in the proposed case than in the existing case.

The performance evaluation results obtained by simulation are presented. The simulation is carried out using MATLAB. The considered simulation parameters are presented in Table 1. The simulation parameter concerns the existing case and proposed case. The simulation procedure has focused on the number of solar radiation interception entities. The rationale for this consideration is that the solar radiation interception entities constitute a solar farm. However, a solar farm consideration has not received focus in the simulation, because the solar farm comprises multiple solar radiation interception entities. Thus, our focus is on the building block in this case, that is the solar insolation interception entities.

In the existing case, the scenario is one in which the solar panels in the conventional solar farm use trackers. The use of trackers in this case enables each of the concerned solar panel to achieve the maximum power output. The associated data shown in Table 1 concerns the maximum solar power output. In addition, the use of tracker is deemed to be sub-optimal with varying deviations from the achievable maximum solar power output. Furthermore, the simulation parameters for the proposed case are presented in Table 2. In this case, the use of trackers is connected at a significantly small level. The relations in Figure 1 shows that the tracker deployment ratio is higher in the existing case than in the proposed case. The tracker deployment ratio is a simulation parameter introduced to determine the level of tracker incorporation in the solar farm.

The simulation results obtained for the output power, and tracker costs are presented in Figure 2, and Figure 3, respectively. The simulation parameters in Table 2 have been selected for the scenario of a solar farm having 25 deployed solar panels. The maximum output of the deployed solar panel is 120 W. This is feasible as seen in [30]. The simulation also considers varying deviation from the maximum solar power output.

This is necessary to consider varying influence of the weather on the solar panel power output. A maximum deviation from the highest solar panel output with a value of 94.2% corresponds to a scenario with bad weather. A case of a minimum deviation of the highest solar panel output with a value of 0.73% implies an output that is close to the maximum of 120W. In addition, the tracker being considered in the simulation has varying level of sophistication.

A sophisticated tracker has a maximum acquisition cost of US$99. This is feasible as seen in [31] for a single axis solar tracker. An inexpensive, used, and refurbished tracker is also utilized having an acquisition cost of US$2.50. The simulation parameter specifications also consider a tracker deployment ratio to indicate the composition of solar tracker related entities. These entities consider that each solar panel incorporates different capabilities and sophistication as it related to tracking.

The proposed case considers more sophisticated trackers to enable movement along all directions in the solar tree. In addition, the solar panel in this case have a reduced output in comparison to those utilized in the existing case. However, the tracker deployment ratio is reduced since it is deployed per tree (comprising of a group of solar panels).

The results in Fig. 5 and Fig. 6 shows that the use of the proposed approach enhances the power output and reduces the Tracker costs. Additional analysis shows that the output is improved, and the cost is reduced by an average of 35.6 %, and 65.9%, respectively.

Table 2. Simulation Parameters

S/N	Parameter	Value
Existing Case		
1	Number of Solar Panels	25
2	Maximum Output of Solar Panel Unit	118.1 W
3	Mean Output of Solar Panel Unit	60.4 W
4	Minimum Output of Solar Panel Unit	3.2 W
5	Maximum Deviation from the Highest Solar Panel Output	90.5 %
6	Mean Deviation from the Highest Solar Panel Output	45.5 %
7	Minimum Deviation from the Highest Solar Panel Output	1.03 %
8	Maximum Tracker Costs ($)	94.3
9	Mean Tracker Costs ($)	46.3
10	Minimum Tracker Costs ($)	5.13
11	Maximum Tracker Deployment Ratio	96.4 %
12	Mean Tracker Deployment Ratio	44.8 %
13	Minimum Tracker Deployment Ratio	9.15 %

Table 3. Simulation Parameters

Proposed Case		
14	Number of Solar Trees	2
15	Number of Mini Solar Panels per Tree	25
16	Maximum Output of Mini Solar Panel	14.9 W
17	Mean Output of Mini Solar Panel	5.93 W
18	Minimum Output of Mini Solar Panel	0.1992 W
19	Maximum Tracker Costs ($)	106.8
20	Mean Tracker Costs ($)	56.5
21	Minimum Tracker Costs ($)	9.48
22	Maximum Tracker Deployment Ratio	7.34 %
23	Mean Tracker Deployment Ratio	3.67 %
24	Minimum Tracker Deployment Ratio	0.07 %

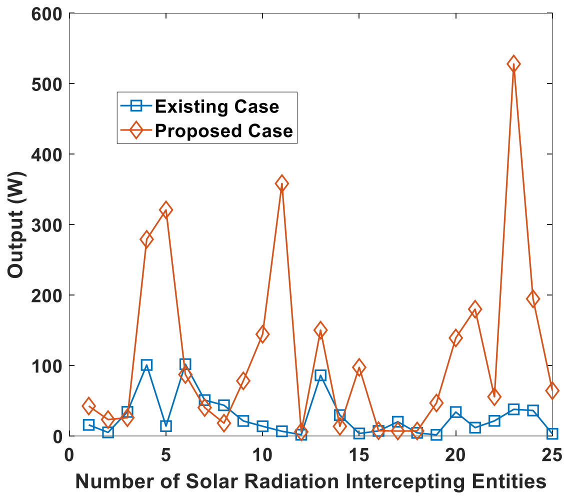

Fig. 5. Power Output (Watts) obtained through Simulation.

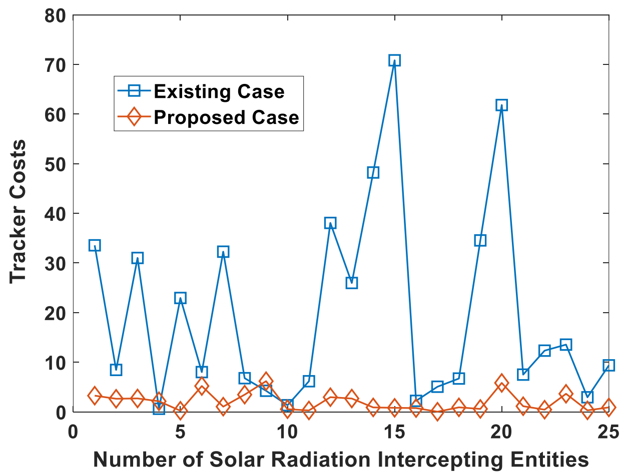

Fig. 6. Simulation Results for the Tracker Costs.

7. Conclusion

The study shows that the use of trackers in large scale solar panel farms faces scalability challenges due to high costs. Traditional solar tracking approaches have shown 30-

40% improvements compared to static panels [32]. However, loT (Internet of Things) technology advancements have opened doors for intelligent solar tracking systems with increased functionality compared to sun-sensing systems [32]. For network coupled PV system, the capacity of the Adaptive Neuro Fuzzy Inference System ANFIS based MPPT technique to increase not only the performance but also the tracking accuracy, speed and system stability under varying climatic conditions [33].

Generally, the economic cost of materials and the ease of moving of the control unit are very important for proposing a good solution such isolated sites systems [34]. Kolluru [35] suggests the best alternative among the available techniques of selection of PV system systems and techniques is based on the particular application, from standalone to grid connected mode and type of converter used, with or without MPPT. With respect to fixed tilted panels, energy gains between 22.9% and 31.9% were obtained, which correspond to 71% and 97% respectively to the gain obtained with a continuos tracking [35].

In this decade, the solar tracking method is facing a great challenge, namely: the minimization of the electrical energy consumption of electromechanical systems used to track the sun's position; ability to predict net electrical power output obtained from a tracking PV panel to save energy and time; hence an evaluation of the performance of a smart solar tracker and assess the accuracy of predictions [37].

For out study, the observation of the case of biological systems that benefit from solar radiation interception without trackers is recognized to present a potential solution model. In this regard, the research presents a model of the solar renewable energy system. The model incorporates solar trees and multiple small sized solar panels with varying mounting altitude and orientation. Further analysis shows that the use of the proposed solar renewable energy system enhances the power output by an average of 35.6 %.

In addition, the use of the proposed solar renewable energy reduces the cost by an average of 65.9%. The performance simulation results have been conducted using operational parameters that are feasible for the operation of similar systems. The system model considered in the simulation is stochastic and describes the performance results that are obtainable under different conditions. Furthermore, the adoption of biological design principles of heterogeneity as found in trees (which execute solar radiation interception) is shown to reduce the role of trackers. In this case, the incorporation of a bio-inspired design (through reduced role of high-cost trackers) is observed to reduce system acquisition costs by up to 65%.

The incorporation is considered to be beneficial as its adoption enhances the power output by 35.6%. Future work will focus on examining the scalability, i.e., number of mini solar panel units that can be accommodated by a solar tree. This requires the implementation and testing of the structural limits for the proposed solar trees. In addition, research will focus on incorporating the effect of shadowing on the deployment of multiple solar trees in a large solar farm array configuration. This has significant implications in the design of micro-grids, smart grids, and grid-integration or renewable energy solar-photovoltaics into national grids. In addition, the design of scalable computing approach to monitor and execute reconfiguration of the presented solar tree will also be considered in future research. This explores the data usage, monitoring, management, and reconfiguration aspects of the proposed solar tree when deployed in an intelligent fashion.

The conduct of research in this aspect addresses the drawback that is present as regards executing data driven reconfiguration for a solar farm system comprising the proposed solar tree. Additional research will also focus on designing an adoption strategy enabling the deployment of the proposed solar tree in existing solar farms. In this case, the adoption strategy should consider the consideration of backward compatibility with existing solar panels and their reconfiguration system. Furthermore, research will also address how to integrate the power output from the solar tree related energy farm to the grid.

Acknowledgements

The authors wish to acknowledge the support of Eskom TESP Grant for Smart Micro-Grids Optimization; F'SATI-ASIC, and the Department of Electrical, Electronic and Computer Engineering, Cape Peninsula University of Technology.

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