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Optimal assessment of smart grid based photovoltaic cell operational parameters using simulated annealing

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ABSTRACT

With the ever-increasing load demand throughout the globe, natural renewable resources integrated into the existing network architecture for sustainable energy production are gaining considerable significance. Photovoltaic (PV) generation systems is one such technique to deal with the worldwide challenge for achieving green energy and low carbon footprint while simultaneously providing emission free electrical power from solar radiations. In this paper, we consider smart grid architecture connecting the end-users and the utility power plant with solar energy sources through an effective power optimization system. Multiple performance criteria associated with solar cell operation are evaluated and analyzed using the simulated annealing algorithm. These objectives considered for optimization include the cell saturation current, photo-generated current, material band gap, cell temperature, annualized life cycle cost, fill factor and cell efficiency. The formulated optimization conditions are specified in terms of two independent variables of cell ambient temperature and cell illumination. Moreover, the adaption of distinct values of short circuit current coefficients on the light originated current is measured. Through extensive simulation experiments, two disparate annealing procedures of fast annealing and Boltzmann annealing are applied coupled with three categories of temperature update schemes, viz. exponential, logarithmic and linear.

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1. INTRODUCTION

The smart metering and grid concept has evolved immensely in the past two decades. Smart electric meter systems transmit all the real-time usage information stored in grid to the central server at the utility for the implementation of billing and troubleshooting analysis schemes for a particular interval of time. This leads to huge amount of data content resulting from metering and sensing procedures which is modelled and integrated through the smart grid techniques. Interpretation, management and processing of a large pool of crucial information is dynamically handled by utilizing modern intelligent technology in the existing automated power grid system. Moreover, the progression of greener utilization of energy sources around the world has attracted significant research interest in the recent few years. Particularly, the demand for energy in India is expected to increase considerably by about 45% of the global energy requirements by the year 2050. The extensively high aggregate losses encountered in the network applications is a challenging component that needs to be addressed. To alleviate these distribution losses and attain efficient utilization of scarce available energy, smart grid technology is emerging as a potential model. The contribution of renewable energy sources for energy production in India is approximately 17% of the net energy generated. This is highly beneficial to achieve low carbon footprints in future through the sustainable environment protection.

The smarter technology is required to accommodate the renewable and clean resources for stable operation of the electrical energy grid. The proprietary Zigbee (IEEE 802.15.4) communication devices are typically used for applications developed for home automation systems, smart grid, etc. This cost-effective wireless technology supports very low data rate of up to 250 kbps and requires diminished power consumption. Electrical energy flow and communication interfaces jointly conceptualize the design and operation of the smart grid. The smart grid technology with pervasive control system is mainly intended to establish a strong two-way communication between the power plant and the appliances. It is aimed at efficient transfer of electricity and information flow, together with the enhanced integration of substantial renewable energy systems.

The development of smart grid technology relies not only on the progressive improvement of technical power equipment, but also on the intricate design and optimization of centralized utility locations, distribution and transmission grids. The major challenge in smart grid technology against the conventional grid systems is the optimal operation at each level of generation, transmission and distribution for accomplishing reliable and economical transfer of produced energy to the customers. Smart information subsystem within a smart grid infrastructure is aimed at achieving the interoperability and modelling of data exchanges for specific experimental applications. The exemplary wireless communication techniques such as cognitive radio, satellite communications, cellular networks, optical systems, and microwave radio technology are critical and significant for ensuring the successful smart grid operation. In general, the electrical power generated in vast quantities at the generating stations is transferred to the customers' end through the transmission and distribution networks. The major 60% generation of power in conventional grids is from non-variable and non-renewable coal system. In smart grid implementation, these generation systems are basically the renewable sources of energy such as solar generation, wind generation systems, fuel cells, geothermal heat, hydro based generation from flowing water, etc. The current grid systems employ merely 7% of the renewable power consumption through the bulk generation domain. The smart grids' random-access memory (RAM) monitor the greenhouse gas emissions, increment in the utilization of renewable energy sources, whilst configuring the energy storage equipment's to supervise the inconsistency in renewable generation systems.

The current status of the installed photovoltaic (PV) capacity in India is nearly 35.1 GW. This is expected to increase to around 100 GW of solar capacity by 2022. This necessitates smarter technology to incorporate renewable energy sources to facilitate stable and economical operation of the conventional electrical grid. From the customer's perception, the smart grid system is designed based on the bidirectional communications infrastructure between the electrical utility power plant and its end-users. The digital data transmission is accomplished through secured and high bandwidth connections coupled with the sensing capabilities. This technology deploys intelligent design architecture and sophisticated services for proficient delivery and maintenance of security and reliability of electricity supply systems. The harmful effusion of greenhouse gases into the environment should be controlled by extensively relying on the renewable sources such as solar energy. The environmental impact is monitored and considerably improved through automated optimization procedure of the system operation in the smart grid network. In this work, we consider smart grid architecture connecting all residential and commercial customers with solar energy sources through an effective power optimization system. The electrical power produced by the solar radiation panels is converted into the direct current. Distributed generation plays a crucial role in these emission free smart technologies.

The concept of annealing is derived from metallurgy corresponding to slow and controlled cooling for manufacturing strong metallic objects. This minimizes the overall system energy, resulting in the mitigation of defects through gradual lowering of temperature. Simulated annealing is a metaheuristic algorithm for acquiring the global optimal solution to a given function. It is a physical procedure of minimization based on the exploration of discrete search space. This iterative technique probabilistically selects a point in the feasible objective space with random distribution determined by the temperature parameter.

The remainder of this work is organized as follows. The preliminaries of the smart grid architecture and solar energy systems are discussed in sections 2 and 3, respectively. Section 4 presents the related work in literature regarding the efficient utilization of solar energy resources through smart grid techniques. Section 5 provides the system model together with the mathematical description of various disparate objective functions connected with solar PV cells. Section 6 analyses the simulation results obtained via the application of simulated annealing algorithm on the presented optimization design. Finally, the whole work presented in this paper is concluded in section 7.

2. GENERAL SMART GRID ARCHITECTURE

The major constituent of the smart grid system is the dedicated communication network for the flow of information from one customer end to other customer boundary, primarily achieved through the energy services interface (ESI). Each category of customer domain including commercial, industrial automation, residential home type systems consist of electrical equipment's, metering infrastructure and gateways. All the components of the smart grid system viz., the bulk electricity generation, transmission, distribution, customer, market, service provider and operations systems are essentially interconnected with each other for the precise and reliable operation of these systems. This paper is aimed at optimizing the operation of the smart PV grid by measuring and controlling the stored information access in the transmission domain. In these systems, energy storage units are required when the power consumption rate is less than the power generated.

Smart metering infrastructure should be installed within the premises of each consumer sector such that each meter is assigned a unique IP address. These metres are connected to the meter data management system (MDMS) on the utility side through the meter concentrator and the data and control center (DCC) routers. This communication architecture setup is facilitated through the neighbourhood area network (NAN). The information transmission between the smart meters and the MDMS systems employs a two-way communication infrastructure through the NAN and the meter concentrator, which is responsible for collecting the periodic measurements of the smart meters.

With the availability of advanced infrastructure of communication network and effective signal processing computational technologies in the smart grid systems, pragmatic economical techniques for data acquisition and processing with automated operation can be developed. The distribution transformer in the feeder component steps down the voltage levels of the substation in the distributed automation system of the smart grid. Renewable energy resources combined with the battery storage devices constitute the distributed energy resources (DER), which are connected to the distribution system. These DERs include the solar PV resources, wind turbines, fuel cells, hydropower, and biomass combustion installed within the residential, commercial and industrial sectors. Solar PV energy has high installation cost and lower efficiency in the range of 10-17%. Any surplus energy can be stored in the storage system for future use.

3. PRELIMINARIES OF SOLAR ENERGY SYSTEM

The solar PV cell basically consists of a photo current source, diode, shunt resistance and series resistance in the associated equivalence circuit. When photons of light or other radiant energy from the sun is incident on the solar cell, they are absorbed by the semiconductor materials and the electrical energy is generated according to the PV effect. This effect based on the physical and chemical phenomena transfers considerable energy to the negatively charged electrons in the cell to produce voltage that permits the current flow across the terminals. The electric current through a particular load in the external circuit generates the desired power for utilization at the customer sites. A single solar cell is expected to deliver around 0.5-0.6 volt of direct current (DC) power. It is conventionally characterized by the solar irradiance and the atmospheric temperature conditions. The environment compatible solar energy systems have long service lifetime and minimal maintenance. However, they have huge installation cost and the operational efficiency directly depends upon the uncertain sunlight accessibility. Besides, the solar panels mounted at the rooftop necessitate greater surface area.

The solar cells are usually connected in series or parallel to form solar modules and panels for power amplification. Solar PV systems are broadly classified into two types, namely grid-connected and off-grid solar PV systems. The cost-effective grid-connected technology inherently exports the surplus energy to the grid whilst mitigating the carbon dioxide emissions. This power source grid supplies electricity to the distribution stations and customer locations. On the contrary, the off-grid structure is a stand-alone system that employs batteries and charge controller to store, manage and extricate electricity. This electrical energy is intended for powering machines in the remote and inaccessible buildings.

Typically, there are three generations of solar cells. The first traditional generation comprises of wafer-based crystalline silicon cells, which are further categorized into poly-crystalline and mono-crystalline types of solar cells. The second generation thin-film solar cell technology is aimed at providing lower production cost associated with the design of solar panels. It consists of amorphous silicon, and non-silicon materials such as cadmium telluride (CdTe), and copper indium gallium diselenide (CIGS). The advanced thin-film solar cell system constitutes the third generation focusing on the enhanced efficiency and reduced manufacturing cost of solar energy cells. This novel generation of solar cells is fabricated from variety of materials including silicon, nanotubes, silicon wires, organic dyes, and conductive plastics.

4. LITERATURE REVIEW

To date, numerous research studies have been conducted on the implementation of smart grid architecture techniques in solar energy systems. Khare and Rangnekar [1] evaluated the sizing optimization of grid-connected solar PV modules by computing the system output power based on particle swarm optimization technique. This model aimed at alleviating the annualized operational lifetime cost associated with the integrated technology. Han *et al.* [2] proposed distribution network model for energy generation in grid-integrated PV access station to assess the power loss rate analysis. The maximum power point of a PV array is estimated using the Levenberg–Marquardt method [3]. It contemplated the relative humidity and ambient temperature data to experimentally compute the global solar irradiance power. Work in [4] explored the efficiency performance of smart grid-connected PV array system by determining the impact of irradiance and temperature on the current-voltage and power-voltage simulation curves. A comprehensive review of the effects, challenges and advantages of integrating the solar energy systems into the electrical grid technology is presented in [5], coupled with its environmental impact. The temperature variability conditions are investigated in [6] for designing a PV system in the real application of the sports stadium in Oman. This cost-effective framework aimed at achieving sustainable development and improved PV output, while storing the residual power to the utility grid. In [7], the time-domain model for power quality analysis with increase in PV array size is developed for grid-integrated solar plants. Shahjehan *et al.* [8] developed hybrid system composed of solar PV array connected to the electrical grid for continuous power supply to the load and attaining minimal power consumption from the main grid.

Bernal *et al.* [9] employed fuzzy control strategy for modelling uncertain information obtained from the smart metering infrastructure associated with real-time distribution power grid. This work achieved reactive power optimization whilst minimizing the power loss and voltage upgrade level of the solar inverters. The body of work in [10] investigated the voltage stability and energy storage issues in transmission and distribution networks of power utility companies incorporating solar PV systems. This framework assessed the optimal location and sizing of generation units executing the DER allocation. Wan *et al.* [11] presented forecasting models for solar energy resources and PV irradiance to implement energy management and secured cost-efficient operation of the smart grid. In [12], the solar energy supply is embedded in the smart home micro grid to reliably meet the residential electricity demands without causing adverse effects to the environment. Rauf *et al.* [13] proposed PV distributed generation for smart DC grid with controlled accessible load, negligible electric corrosion, and accurate sizing of solar array and battery storage systems. In addition, Markov process and fault tree analysis techniques are employed to implement the smart operational framework with enhanced reliability for PV systems [14]. Smart networking paradigm is designed to provide economical electrical power to the residential customers through the hybrid logical energy efficient system [15]. This excess power is stored at the distribution station of the intelligent grid and efficiently assigned to the domestic buildings via energy scheduling mechanism. Patel *et al.* [16] presented the application of multifunctional inverter based solar DERs and micro grids in the customer utility services. Their approach accomplished minimal transmission and distribution losses and improved power quality while delivering the required load to the consumers in a controlled way. Farhad *et al.* [17]demonstrated that grid-connected solar system can be designed and operated effectively without necessitating the massive battery bank, such that the solar energy can be fed to the national as well as the local grids. This scheme alleviated the system maintenance cost and the inherent losses incurred during battery charge and discharge processes. Through experimental validation, work in [18] explored the active and reactive power management of a three phase grid-tied PV strategy using the maximum power point tracking scheme. Bajracharya and Rawat [19] examined smart grid architecture in radio frequency spectrum accessible domestic networks. The simulation analysis results achieved reinforced reliability and enhanced dynamic spectrum allocation to smart grids integrated with cognitive communications technology. The impact of fault level and short circuit operation of solar power system is contemplated in the distribution network of smart grid technology [20]. Furthermore, work in [21] analyzed the application of smart grid comprising of the main grid and several micro grids in solar power generation units and battery storage structures. The deployed storage scheme ensures the system reliability and stability despite the irregular supply of solar irradiance.

Despite these previous works, we consider the optimization of grid-connected solar energy systems through the implementation of simulated annealing algorithm. For this, two distinct annealing processes of fast annealing and Boltzmann annealing are implemented in conjunction with three types of temperature update schemes, viz. exponential, logarithmic and linear. To the best of our knowledge, the work presented in this paper is the first attempt to optimize the PV cell parameters by employing the simulated annealing technique. The schematic representation of this optimization model is illustrated in Figure 1. The varying effects of these joint methodologies on various operational characteristics of the smart grid based solar PV modelling is evaluated. The contemplated performance objectives for optimization include cell saturation current, photo-generated current, material band gap, cell temperature, annualized life cycle cost, fill factor and PV cell efficiency. The formulated optimization criteria are defined in terms of two independent variables of cell ambient temperature and cell illumination. Additionally, the influence of different values of short circuit current coefficients on the light induced current is measured.

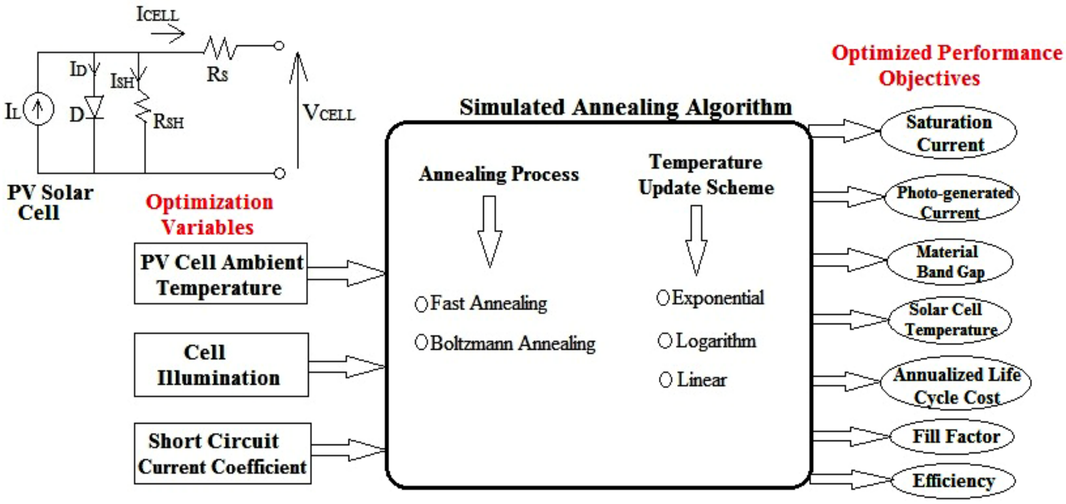

Figure 1. Schematic illustrating the proposed smart grid based PV cell optimization model

5. PERFORMANCE MODELING OF SOLAR CELL PARAMETERS

In this section, we describe the mathematical modeling of the deployed solar cell characteristics. In particular, we explore the generation component of smart electrical grid system, where energy is produced at the generating station. Multiple performance objectives are optimized using the simulated annealing algorithm implemented in the optimization toolbox of the MATLAB simulator [22]. These operational goals are specified in terms of two optimization variables λ_1 and λ_2. Among these basic parameters, λ_1 corresponds to the ambient temperature (in degrees Celsius) at a particular location. Besides, λ_2 denotes the percentage of cell illumination, such that 100% PV cell illumination is congruent to 1000 W/m^2. The first objective considered for optimization is the PV cell temperature, which is the key performance attribute influencing other operational criteria. This objective T_{Cell} is specified in terms of the optimization variables as follows:

$$T_{Cell} = \lambda_1 + 0.3 * \lambda_2 \quad (1)$$

The other significant performance objectives are the maximization of the saturation and photo-generated currents flowing through the PV cell circuits. This is required to augment the power generation in these cells acquired by the solar energy systems. These quantities I_{Sat} andI_L are respectively expressed in (2) and (3).

$$I_{Sat} = I_{Sat\rho}\left(\frac{T_{Cell}}{T_\rho}\right) exp\left\{\frac{e\mathfrak{B}_G}{\gamma_i K}\left(\frac{1}{T_\rho} - \frac{1}{T_{Cell}}\right)\right\} \quad (2)$$

$$I_L = \left[I_{SC} + \eta_{I_{SC}}(T_{Cell} - 28)\right] * 10\lambda_2 \quad (3)$$

Here, T_ρ is the reference temperature, $I_{Sat\rho}$ is the reverse saturation current at T_ρ, e is the electronic charge, $\mathfrak{B}_G$ is the band gap for the employed silicon material, γ_i is the ideality factor, K is the Boltzmann constant, I_{SC} is the cell short circuit current at 28 °C and 100% illumination, $\eta_{I_{SC}}$ is the short circuit current temperature coefficient. This coefficient is varied to obtain its effect on the photo-generated current in the subsequent section. In equation (3), λ_2 is scaled by 10 to convert its unit from % illumination to W/m^2. Moreover, the generalized equation for the material band gap is formulated as:

$$\mathfrak{B}_G = 1.121\ eV\ \left(1 - 0.0002677\ (T_{Cell} - 28)\right) \quad (4)$$

The annualized life cycle cost $(ALCC)$ is given by:

$$ALCC = \frac{r\ (1+r)^{\Omega}}{(1+r)^{\Omega} - 1}\ n_{Cell}\ C_{Cell} \quad (5)$$

where r is the annualized interest rate expressed in decimal form, Ω is the system lifespan which is the number of interest periods in years, n_{Cell} is the number of solar PV cells, and C_{Cell} is the uniform annual capacity of cells. In (5), $\frac{1}{(1+r)^{\Omega}}$ yields the present worth factor. Further, the fill factor and efficiency metrics of the solar based smart grid system are defined in (6) and (7) respectively.

$$Fill\ Factor = \frac{V_{mp}*I_{mp}}{V_{OC}*I_{SC}} \tag{6}$$

$$Efficiency = \frac{V_{mp}*I_{mp}}{A*P_{in}} \tag{7}$$

V_{mp} and I_{mp} are the voltage and current associated with the maximal power supplied by the PV cell when the output electrical load connectors are shorted together. V_{OC} is the open circuit voltage, P_{in} is the input system power, and A is the area of PV cell. Affected by the resistance connected in series across the load, the fill factor is increased significantly by reducing the short circuit current. The solar panel can be utilized to harness more power if the fill factor is close to unity. The values of the V_{OC} and I_{SC} quantities are specified by the manufacturer of the solar panel. The efficiency of the solar panel system is measured by the ratio of the maximal electrical power generated by the solar array to the amount of solar irradiance intensity striking through the installed panel.

6. SIMULATION ANALYSIS AND RESULTS

Various simulation setup parameters comprising of the basic PV cell attributes and the deployed simulated annealing algorithm variables, together with their values are illustrated in Table 1. Figure 2 depicts the evolution of cell saturation current as the atmospheric temperature rises from 30 to 100 °C. The mean value of saturation current is estimated as 141.2 mA. The variation of photo-generated current for the same range of temperature is demonstrated in Figure 3, with different values of short circuit current coefficients. It can be computed that as the coefficient $\eta_{I_{SC}}$ increases from 0.0017 to 0.11, the light generated current amplifies by 73.36%, improving the overall operating power performance of the proposed solar system design architecture.

Table 1. Simulation setup parameters

Parameter name	Description/Value
Simulation software	MATLAB
Channel type	AWGN Wireless channel
Radio propagation model	Two-ray ground
Antenna model	Omni-directional
Short circuit current (I_{SC})	2.52 A
Open circuit voltage (V_{OC})	45.4 V
Reference temperature (T_{ρ})	301 K
Reverse saturation current ($I_{sat\rho}$)	19.96 μA
Electronic charge (e)	1.6$\times 10^{-19}$ C
Band gap ($\mathfrak{B}_G$)	1.11 eV
Ideality factor (γ_i)	1.92
Boltzmann constant (K)	1.38$\times 10^{-23}$ J/K
Short circuit current coefficient ($\eta_{I_{SC}}$)	0.0017, 0.015, 0.08, 0.11 A/°C
Annualized interest rate (r)	8%
System lifespan (Ω)	25 years
Number of solar PV cells (n_{Cell})	72
Annual cell capacity (C_{Cell})	550 MW
Input system power (P_{in})	500 kWh
Area of PV cell (A)	100*100 mm^2
Maximum function evaluations	6000
Function tolerance	10^{-6}
Stall iterations	1000
Reannealing interval	100
Initial temperature	100 K
Acceptance probability function	Simulated Annealing Acceptance
Maximum number of iterations	8000

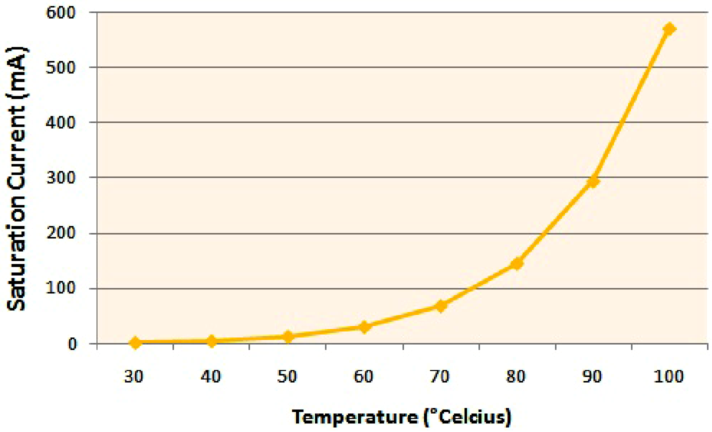

Figure 2. Evolution of saturation current for varying temperature

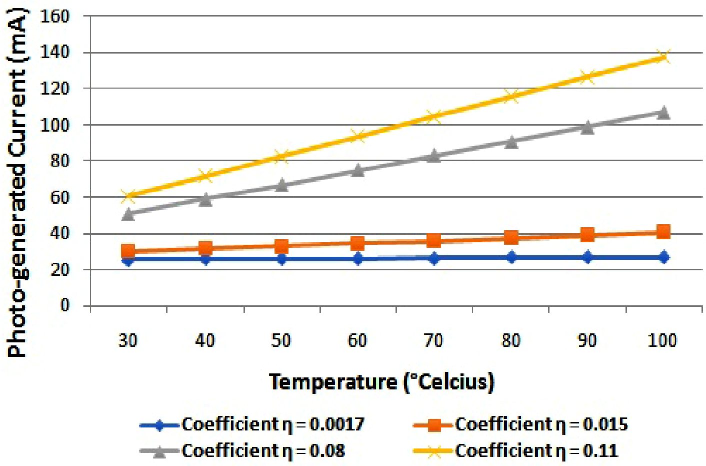

Figure 3. Evolution of photo-generated current for varying temperature with different short circuit current coefficients

Figure 4 represents the implementation of simulated annealing algorithm with disparate annealing process and temperature update schemes for optimal assessment of photo-generated current. This technique takes 5940 iterations to achieve the optimal photo-generated current using the proposed system model. It can be evaluated that fast annealing process execution with logarithmic temperature update exhibits 49.94% and 92.25% higher photo-generated current than the exponential and linear temperature update schemes, respectively. Likewise, Boltzmann annealing process implemented with logarithmic temperature update demonstrates 85.42% and 89.78% elevated current in compliance with the exponential and linear temperature update design. Figure 5 indicates the plots of the best point, the transient temperature and the retrieved function value of the light originated current using two optimization variables λ_1 and λ_2. The negative value of the light current (in μA) is attributed to the fact that this current is maximized for the optimal operation of solar based smart grid technology. Therefore, we minimize the negative of the formulated objective function for the current to obtain its maximal value.

In Figure 6, we plot the optimized saturation current metric for the deployed annealing systems and temperature update strategies. This parameter evaluation required 5970 iterations to assess the optimal objective function value. It can be observed that the highest saturation current of 523.75 mA is achieved through the fast-annealing process and logarithmic temperature update scheme. Figure 7 shows the optimal material band gap for the presented system design. In this case, the most significant performance is accomplished with the fast annealing and linear temperature system. However, the worst-case scenario in which band gap is increased by a proportion of 23.7 is shown by fast annealing and logarithmic temperature setting. Therefore, there exists a trade-off between the current flowing through the solar cells and the corresponding minimal required band gap. Figure 8 depicts the plots of the best point, the instantaneous temperature and the computed function value of the silicon material band gap in terms of the two optimization variables λ_1 and λ_2. The optimal band gap is estimated to be 0.596 eV, specified within 5912 iterations.

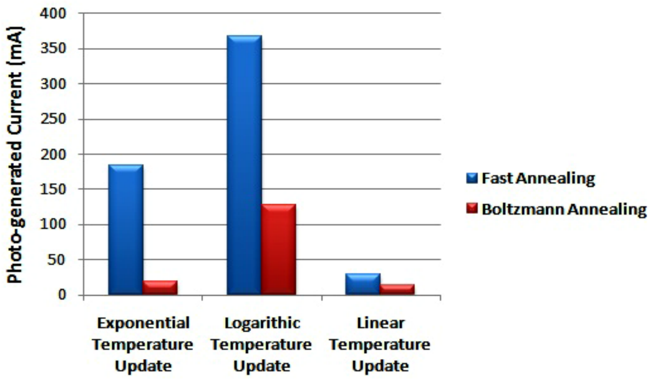

Figure 4. Photo-generated current for various types of temperature update schemes and annealing process

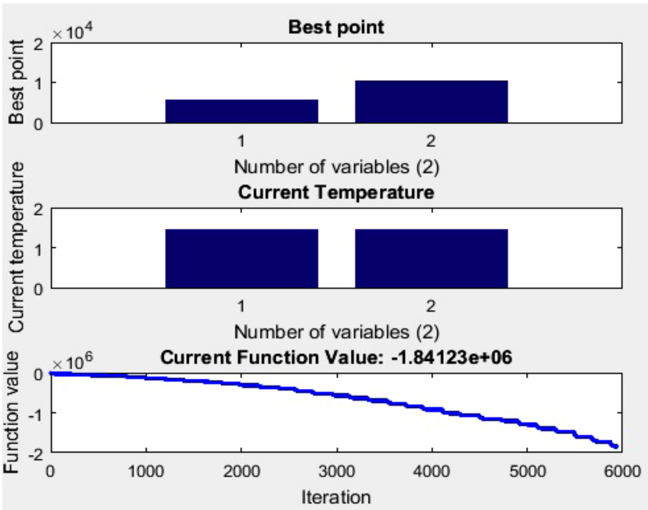

Figure 5. Plot illustrating the best point, the current temperature, and the current function value for photo-generated current

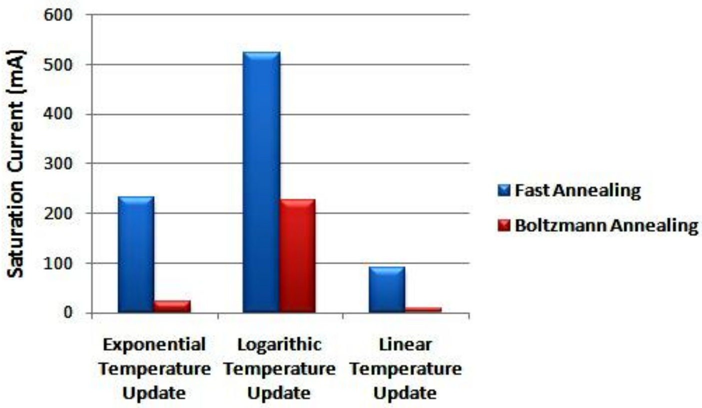

Figure 6. Saturation current for various types of temperature update schemes and annealing process

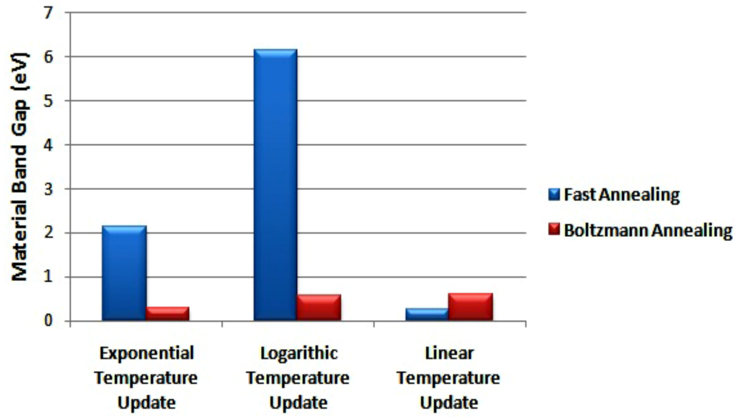

Figure 7. Material band gap for various types of temperature update schemes and annealing process

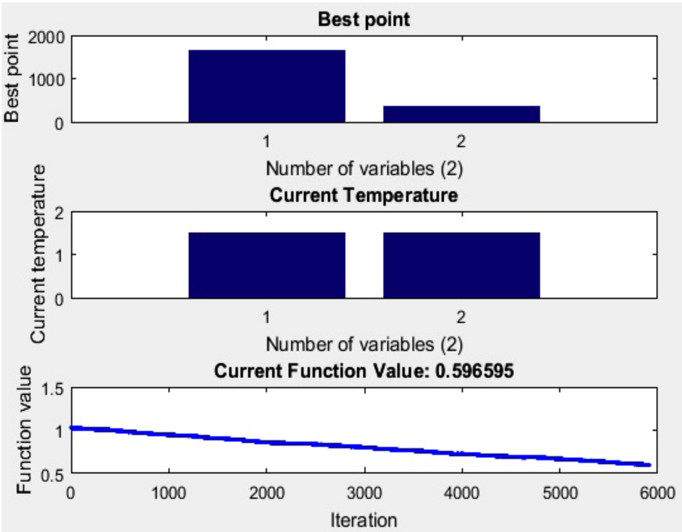

Figure 8. Plot illustrating the best point, the current temperature, and the current function value for energy band gap parameter

In Figure 9, the goal of achieving higher solar cell temperature is illustrated utilizing the contemplated annealing algorithms and temperature update procedures. Boltzmann annealing and logarithmic temperature update phenomenon exhibit the maximum cell temperature with 5920 iterative complexity for operating the developed smart grid based solar system design. This is 63.95% higher than the lowest solar PV cell temperature acquired using Boltzmann annealing and linear temperature update techniques. Figure 10 illustrates the $ALCC$ (in \$/kW) performance objective optimized in 5842 iterations by implementing the proposed framework. This parameter is augmented to the greatest extent possible with the application of fast annealing process and logarithmic temperature update. Finally, the fill factor and efficiency criteria are graphically represented in Figures 11 and 12, respectively. These objectives converge to their optimal solutions within 5936 iterations. Specifically, the fill factor is maximized with the optimal value of 0.95 through the joint implementation of fast annealing and logarithmic temperature update. Besides, fill factor of fast annealing with logarithmic temperature update is higher by 12.52% and 32.73% as compared with exponential and linear temperature update mechanisms, respectively. Similarly, the fill factor of Boltzmann annealing with logarithmic temperature update is increased by 55.46% and 66.32% contrary to the exponential and linear counterparts, respectively. In addition, maximal efficiency of 63.5% is accomplished with fast annealing and logarithmic temperature update schemes.

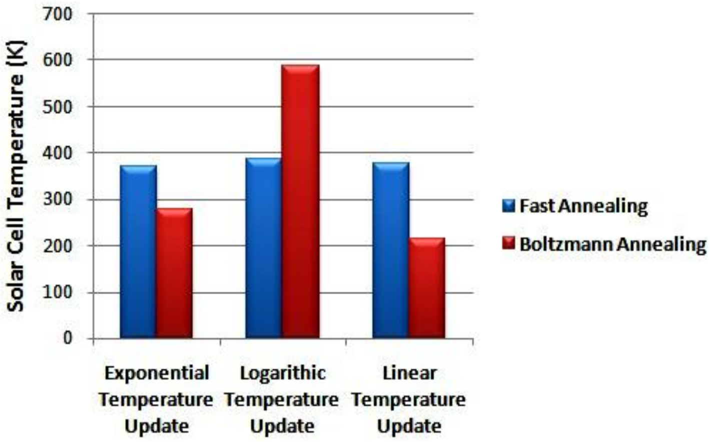

Figure 9. Solar cell temperature for various types of temperature update schemes and annealing process

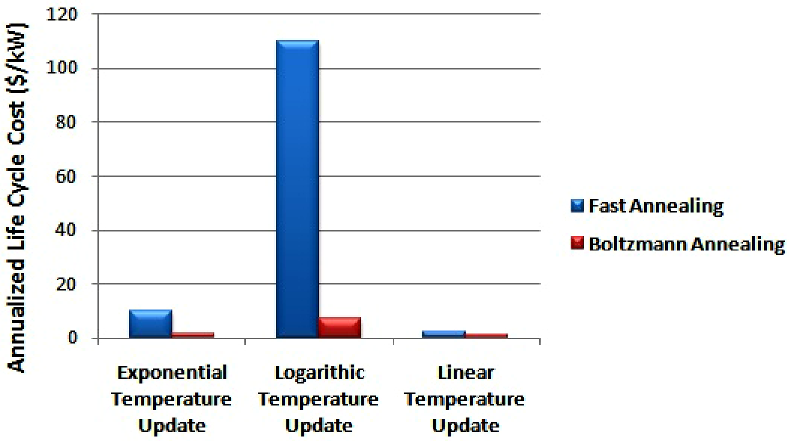

Figure 10. Annualized life cycle cost for various types of temperature update schemes and annealing process

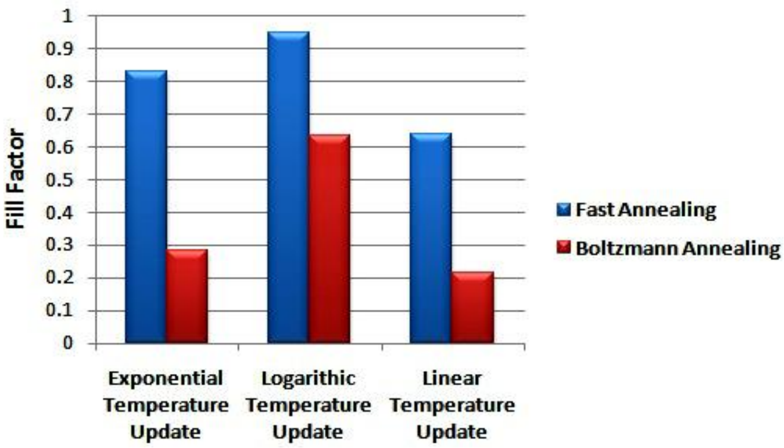

Figure 11. Fill factor for various types of temperature update schemes and annealing process

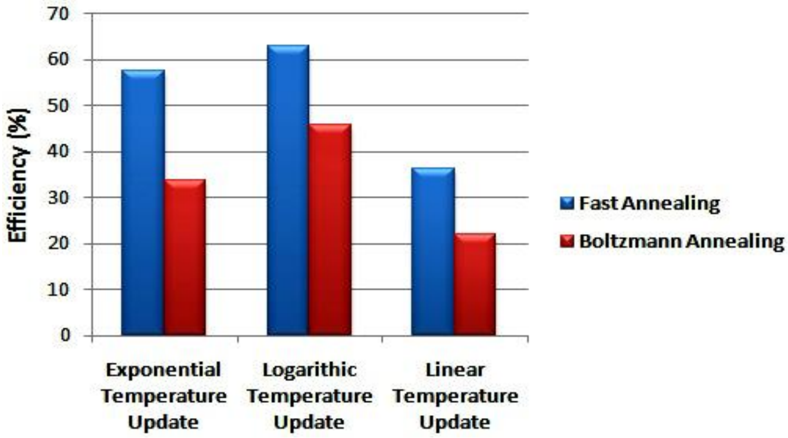

Figure 12. Solar cell efficiency for various types of temperature update schemes and annealing process

7. CONCLUSION

This paper addresses the problem of optimization of solar energy systems through the implementation of simulated annealing algorithm. For this, two distinct annealing processes of fast annealing and Boltzmann annealing are implemented in conjunction with three types of temperature update schemes, viz. exponential, logarithmic and linear. The varying effects of these joint methodologies on several performance characteristics of smart grid based solar PV modeling is evaluated. Various performance objectives considered for optimization include cell saturation current, photo-generated current, material band gap, cell temperature, annualized life cycle cost, fill factor and PV cell efficiency. These optimization criteria are defined in terms of cell ambient temperature and cell illumination parameters. Additionally, the influence of different values of short circuit current coefficients on the light induced current is measured. It is observed through simulation analysis that fast annealing and logarithmic temperature update techniques exhibit the most optimal values of photo-generated current, saturation current, annualized life cycle cost, fill factor and efficiency. The maximal cell temperature is achieved through the implementation of Boltzmann annealing and logarithmic temperature advancement scheme. Besides, fast annealing and logarithmic temperature update demonstrates the maximal band gap. However, fast annealing and linear temperature upgrade system improves the material band gap by approximately 96.7%.

In future, the presented model can be extended to grid network architecture with multiple energy storage devices to accumulate the large-scale and time-fluctuating renewable generation. Furthermore, the impact of cyber security and data privacy can be explored on the proposed real-time model implementing the bi-directional communication of digital information signals between the solar power utility systems and the end-customers in smart grid-based PV structure.

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