Research Article

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Design of control system for solar power generation based on an improved bat algorithm for an island operation

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Abstract: Solar energy is sustained using the principle of photovoltaic effect through a solar photovoltaic (PV) system as the main receiver of sunlight for the island. The use of photovoltaic (PV) systems to generate power from solar energy has increased in recent years due to its availability and sustainability. The proposed bat algorithm provides a very quick confluence and high accuracy since it interactively merges with the exploration advancements with the substantial distinctive signal search during the maximum power point tracking process from the PV array. The improved bat algorithm proposes a signal search method to increase the speed and tracks more power at a longer distance by using the signal between the bat and its prey. An energy storage system (ESS) stores solar energy and releases it into the system for use when energy generation from the source is low. DC to DC converter controls and regulates the output generated voltage from the PV array. DC to AC converter converts DC power produced to AC power to be supplied to the island for use. The design and simulation were performed in MATLAB Simulink and the result shows the effectiveness of the proposed design.

Keywords: bat algorithm; control system design; power generation; power island operation; signal search; solar photovoltaic (PV) systems.

Introduction

Island operation is explained as a self-supporting operation of an entire or a part of the electricity network that is isolated after it has been disconnected from the interconnected system, having not less than one power-generating module supplying power to the network. The demand for power generation has become very high due to the high demand for power by a grid. The more power generated for the grid, the higher performance of the grid by being able to supply power to the various substations and vice versa. Energy generated on an island could be from the collection of solar energy, wind energy, geothermal energy, biomass, etc. This helps in the generation of power and sustains the island's power demand. Renewable energy has obtained great importance at a very speedily rate due to concerns about climate change and the high cost of fossil fuels. In the last decade, the increasing amount of renewable energy resources by solar energy per watt cost has improved. Solar energy has become economical, an unlimited source of energy available at no cost. Some of the benefits of solar energy are that it can be reached out to common people and is available in large amounts to be able to generate power and also requires considerably lower manpower expenses over conventional energy production technology compared to the price of various fossil fuels and oils (Shaikh et al. 2017). It is non-polluting, usage does not emit any greenhouse gases or harmful waste, it is versatile, it is perfect and saving for power generation in common areas or where the cost of expansion utility grid is high. Also due to simple construction and low maintenance, solar energy systems are mainly used for generation purposes (Vinaya 2013). With the isolationism of the electric power industry and the improvement of new technologies, the recognition of usefulness has been retracted towards adopting distributed generation (DG) into their remaining framework. DG was instituted and the expansion of DG brings abundant technological and environmental merit to power generation. Distributed generation (DG) has many sources which usually come from renewable energy. There is a contradictory formation of DG which comprises wind power, solar photovoltaics, fuel cells, micro-turbines, and small diesel generators but this paper focuses on solar photovoltaics

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which is one of the most popular sources of DG systems. DG is more feasible and accord when associated with energy storage systems to generate a greater portion of power.

In this paper, solar is the main source of energy used in power generation by the use of a solar panel (PV array). The establishment of photovoltaic (PV) generation has become a prospectively cost-effective alternative for utility planning in terms of intensified dependability, system expansion, and environmental relief. This has helped the sunlight produced on the island not to go to waste but will be used to generate power for an island system. The solar power generated by the photovoltaic (PV) array is found in the apathy of solar radiation which in round hinges on the extra-terrestrial radiation. The bigger the number of PV with inverters installed on an island, the more considerable the chances of islanding during which PV carries on to supply local loads after a utility fault. The solar panel is very important to be used to track the location of the sun as it shines during the day. The movement of solar panels will increase the maximum quantity of power of solar energy radiated by the sun. For the output power generated to increase in quantity by the use of the maximum power point tracker, different algorithms to extract MPP from PV systems have been introduced. Such MPP algorithms include a hill-climbing algorithm, fuzzy logic control algorithm, current sweep algorithm, perturb and observe algorithm, and incremental conductance algorithm (Ahmed and Salam 2018; Atallah, Abdelaziz, and Jumaah 2014; Farh and Ali Eltamaly 2020; Hong, Buay, and Beltran 2019; Ilyas et al. 2018; Morales 2010; Parlak and Can 2012; Ropp and Hohm 2003; Subudhi and Pradhan 2013; Tuffaha et al. 2016; Zhu et al. 2018). Most of these methods proposed performed well and produced good results especially the perturb and observe algorithm, and an incremental conductance algorithm has been used to track maximum power point from a solar panel with constant sunlight and temperature (Garg and Gupta 2014; Morales 2010). Nevertheless, when there is a fast change in sunlight and temperature, these algorithms are unable to quickly change along, and also the rate of extracting MPP is slow enough. The proposed bat algorithm is very fast to track maximum power point from a PV system and very reliable. It increases the amount of output power from the PV system which produces a large quantity of power for the island. The bat algorithm increases the efficiency by extracting 30% of the maximum power point from PV systems (Ali, Hassan, and Mamdooh 2019). The MPPT will force the maximum power available from the PV array to work by controlling the output voltage from the PV array (Darwish et al. 2019).

In the paper, the bat algorithm is improved whereby the speed of the bat determines the rate at which maximum power is extracted. When the number of bats and iterations increases, maximum power is tracked at a very high speed. The iteration interval and average are updated by the bat signals. The signals can track maximum power within the iteration range for the fitness of the bat to be able to actively refurbish. The best movement and position of bats are evaluated. When the best position and speed are updated, the fitness of the bat is achieved. The energy storage system will store DC energy generated from the PV system. The current generated by the PV system is a direct current and moves in only one direction. Solar inverter changes DC generated to AC. Alternating current (AC) can be operated both forward and backward by moving in more than one direction and can also transfer power across long distances. The AC generated will then be used to power the island system. The proposed design is easy to implement. When the system receives solar irradiation (sunlight) and temperature, then the operation of the system starts. The proposed control design with the bat algorithm was compared with the perturb and observe algorithm in this paper to overlook the results of the outcome of these two algorithms.

The organization of this paper is as follows: Section two describes related works, section three describes the proposed control system design explaining the steps and components, section four presents the experimental implementations of the control system design and simulation results in MATLAB Simulink and section five concludes the paper.

Related work

Different control strategies have been integrated with power operation and control for an island using different approaches and algorithms (Abd-Elazim and Ali 2016; Asim et al. 2022; Ishwarya et al. 2021; Oshaba, Ali, and Abd Elazim 2017a, 2017b; Priyadarshi et al. 2019), the results for various strategies declare that the proposed method fits and is suitable for delivering a good performance and successful operation. A robust fuzzy logic controller is designed for producing and controlling voltage, current, frequency, and power that is used for an islanded microgrid controlling under different uncertainties (Dola and Das 2020). This proposed method produced good results however, the implementation of the proliferation of islanded microgrid against two types of dynamic loads for single-phase operational mode causes harm when the microgrid is operated as a result it creates a serious hazard for the grid which will lead to the deterioration of the grid.

Control strategies propose the operation of a microgrid under isolation mode. The inverter-fed microgrid dynamic behavior under an islanded operation for different load conditions was tested by the use of two different control strategies known as storage devices and load shedding strategies (Peças Lopes, Moreira, and Madureira 2006), photovoltaic power generation system has been designed. This power plant is composed of photovoltaic panels connected in series and parallel strings, a DC–DC boost converter, and a three-phase inverter is used. Here, the DC–DC boost converter uses an MPPT controller to extract maximum power and the inverter uses a control method based on a d-q theory with a PI current regulator. The solar irradiance and temperature change were addressed (Popa et al. 2016). An incremental conductance algorithm was proposed which was used as the MPPT for the PV system with battery storage using a bidirectional DC–DC converter to generate power. The voltage and current produced by the PV system are sent to the DC load and then connected to an inverter which changed the direct current to alternating current (Iqbal and Islam 2017). The author studied the impact of solar irradiance and temperature on an overall power generation by PV system to a grid-connected. Different methods such as the use of an LC filter were proposed to control and maintain the inverter's output voltage and decrease the inverter's output harmonic currents and synchronize output frequency with the electric utility grid, phase-locked loop, and regulators were designed. The proposed modeling method was easy and can be adopted simply to study system characteristics at different conditions of temperature and solar irradiation (Atiq and Soori 2017). Mathematical analysis and modeling of solar systems by the perturb and observe method for the interconnection of distributed generation such as PV were designed and implemented to be able to produce power (Dave and Kalpa 2017).

Metaheuristic techniques (Eltamaly, Farh, and Al-Saud 2019; Prasanth and Rajasekar 2017) have been introduced in the past recent years to be able to solve problems associated with the extraction of maximum power point. Metaheuristic techniques such as bat algorithm (BA) (Ali, Hassan, and Mamdooh 2019; Chakri et al. 2017; Kaced et al. 2017; Karagöz and Demirel 2017; Maslo and Hruska 2015; Umar and Rashid 2021; Yang 2010; Yilmaz and Kucuksille 2015), particle swarm optimization (PSO) (Darwish et al. 2019), cuckoo search (CS) (Bose and James 2014), ant colony optimization (ACO) algorithm (Heussen, Saleem, and Lind 2009), firefly algorithm (FA) (Tavakoli et al. 2014), artificial bee colony (ABC) (Hassan, Majid, and Mourad 2016; Liu et al. 2017), gray wolf optimization (GWO) (Ali and Hassan 2019; Seyed et al. 2018), flower pollination algorithm (FPA) (Mohamed et al. 2019), glowworm swarm optimization (GSO), bacteria foraging (BF), whale optimization algorithm (WOA), shuffled frog leaping algorithm (SFLA), generalized pattern search (GPS), and many other techniques have been used to track maximum power from a PV system.

Control strategies have been proposed for power systems in island operation, an island system is designed to operate under three modes which are maximum power point tracking mode, dispatchable mode, and isolated operation mode (Xin et al. 2012). A PI controller has been designed using Artificial Bee Colony (ABC) algorithm as the maximum power point tracker of the PV system which supplies DC motor–pump load (Oshaba, Ali, and Abd Elazim 2017a). The proposed method uses two ways to extract maximum power by monitoring the voltage and current of the PV array and also adjust the duty cycle of the DC/DC converter and controlling the speed of the DC series motor by fixing the voltage fed to the DC series motor by using another DC/DC converter. Here, since the ABC algorithm was used, the optimization process is slow since the new position is determined by the bees, therefore more time is needed for the bees to find their new position. A PI controller has been designed for MPPT by which switched reluctance motor (SRM) is supplied through a bat algorithm by the use of a photovoltaic system (Oshaba, Ali, and Abd Elazim 2017b). The proposed algorithm performed well by adjusting the duty cycle of the DC/DC converter which also monitors the voltage and current of the PV array however, during this process the DC/DC converter controls the whole process and as a result, when there is a slight fault on the DC/DC converter, it will affect the whole system from not being able to perform well. A control design for load frequency using the bat algorithm for a nonlinear interconnected power system has been proposed (Abd-Elazim and Ali 2016). The bat algorithm is used in tuning the PI controller to search for the optimistic result. The proposed method performed well but from the results, the tracking speed with changes in environmental conditions was slow in the beginning. A bat algorithm-based MPPT technique for bidirectional converter in a photovoltaic system under partial shading conditions has been proposed (Ishwarya et al. 2021). The bat algorithm increases the output power generated and the bidirectional converter allows the flow of power in both forward and backward directions. An MPPT-based on-bat algorithm for PV systems working under partial shading conditions has been proposed (Asim et al. 2022). Nevertheless, these design approaches proposed alternatives used to control and operate an island, and therefore the outlook of designing a control system that will be used to generate power using different methods and components based on the bat algorithm technique as the maximum power point tracker for an island has not been adopted yet. This paper proposes a control system design approach for power generation for the operation of an island by the use of different components and different strategies proposed using the bat algorithm as the MPPT.

Method proposed

With the actual aim of designing a control system that can be used to power and operate an island, this control system steps in Figure 1 were designed. It illustrates the outline of the control system design steps. This was the utmost duty since all the proposed steps are important to help in the power generation of an island system. These steps were explained further in this paper. When designing the control system, the following steps need to be taken into consideration.

Environmental analysis

Since the environment for an island differs in temperature and the rate of sunshine is based on climate change, therefore, before this control system design method is implemented, there is the need to make sure the island is located in an area where there is enough sunshine to be able to produce a high amount of sunlight generated to produce enough power for the island to operate properly. Since the amount of power that will be produced depend entirely on the amount of sunlight. For example, if the island is located at a place where sunshine is very low, the control system is not advisable to be integrated into such an environment otherwise the power generation will be very low which in the end will not be able to produce enough power for the island.

Photovoltaic (PV) systems

Photovoltaic (PV) systems employ photovoltaic cells to accumulate solar energy from the sunlight. They depend on sunlight and temperature to produce output results by converting sunlight into electricity. When the sun keeps on shining, solar panels will carry on to generate power for the island. To be able to increase the energy output from the solar panels installed on the island, the panels have been designed in a form that while the front faces the sun, the body will be able to rotate by rotating the front face as well to be able to turn to the directions where sunlight is being generated from. In this case, the solar panel will be able to trace and receive a higher quantity of sunlight on the island. Since there are solar panels used, the current produced by the sun is direct current (DC).

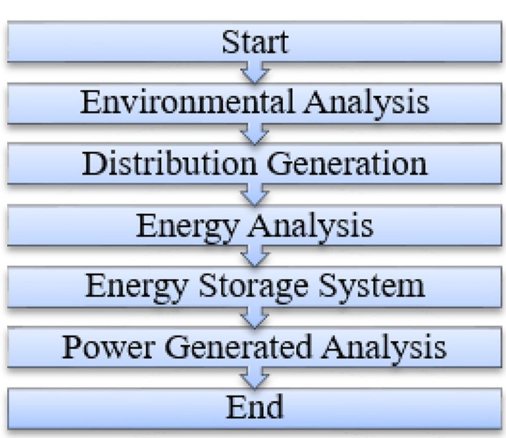

Figure 1: Outline of the control system design steps.

Modelling of PV system

A PV system consists of different cells and the solar cell is one of the basic units. When solar cells are connected in series, a PV panel is formed. These panels are then connected in series and parallel to form PV arrays. PV array has been modeled by using a single diode of a PV cell (Mingrui, Zheyang, and Li 2019). Figure 2 shows the modification of PV panels and equations have been derived based on the total number of solar cells and series and parallel connection of the PV panels.

$$I_{pv} = I_{ph} - I_d - I_{sh} \tag{1}$$

$$I_{pv} = N_p I_{ph} - N_s I_d \left[\exp\left\{ \frac{q(V_{pv} + I_{pv} R_s)}{N_s AKT} \right\} - 1 \right] - V_{pv} + \frac{(I_{pv} R_s)}{R_{sh}} \tag{2}$$

Where, I_{pv} is the photovoltaic cell output current, I_{ph} is the photon current, I_d is the diode saturation current, I_{sh} is the shunt-leakage current, V_{pv} is the photovoltaic cell output voltage, R_{sh} is the shunt resistance, R_s is the series resistance, A is the ideality diode factor, K is the Boltzmann constant $(1.38 * 10^{-23})$ JK^{-1}, q is the electronic charge $(1.602 * 10^{-19})$, T is the cell temperature, N_s is the number of series-connected cells, N_p is the number of parallel-connected cells.

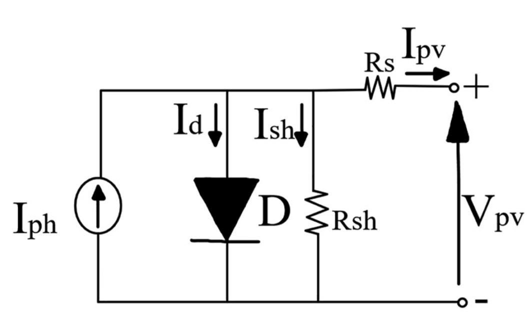

Figure 2: Modelled photovoltaic panel.

The photovoltaic system has been carried out in MATLAB Simulink. Figure 3(a) and (b) show the *I*–*V* and *P*–*V* curves of the photovoltaic cell with varying solar irradiation ranging from 450 to 1000 W/m^2 at a constant temperature of 25 °C. Figure 4(a) and (b) shows the *I*–*V* and *P*–*V* curves of the photovoltaic cell with varying temperature ranging from 25 to 60 °C at constant solar irradiation of 1000 W/m^2. PV system performs well when the temperature is normal. Higher temperature affects the performance of the PV system by decreasing output voltage.

Maximum power point tracker

Maximum power point tracker (MPPT) extracts maximum power from the solar panel by increasing voltage. MPPT is used to trace more light intensity from solar panels to help maximize the power generated. The higher the light intensity emitted by MPPT, the more power will be

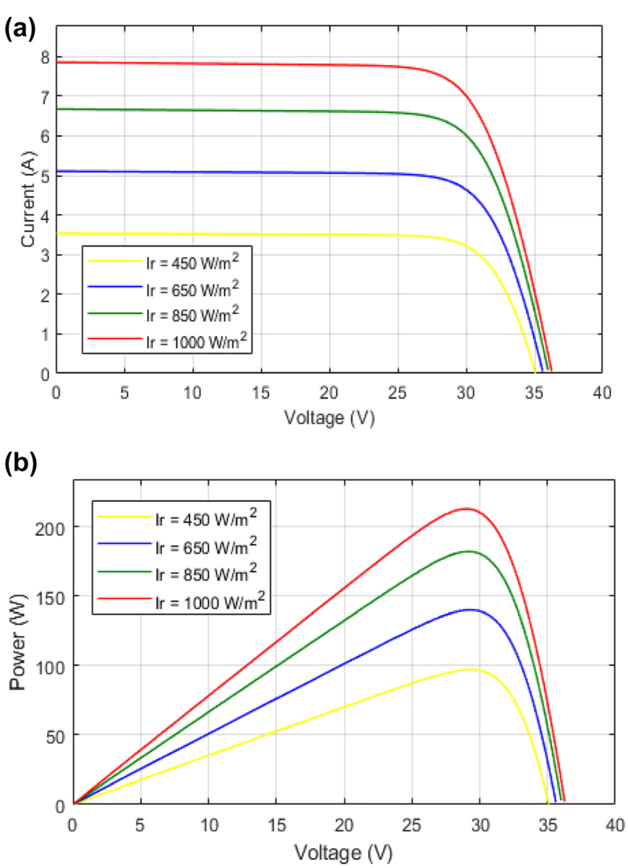

Figure 3: *I-V* and *P-V* MATLAB simulation characteristics of a photovoltaic cell with constant temperature and different solar irradiations. (a) *I*–*V* characteristics of a photovoltaic cell with constant temperature and different solar irradiations. (b) *P*–*V* characteristics of a photovoltaic cell with constant temperature and different solar irradiations.

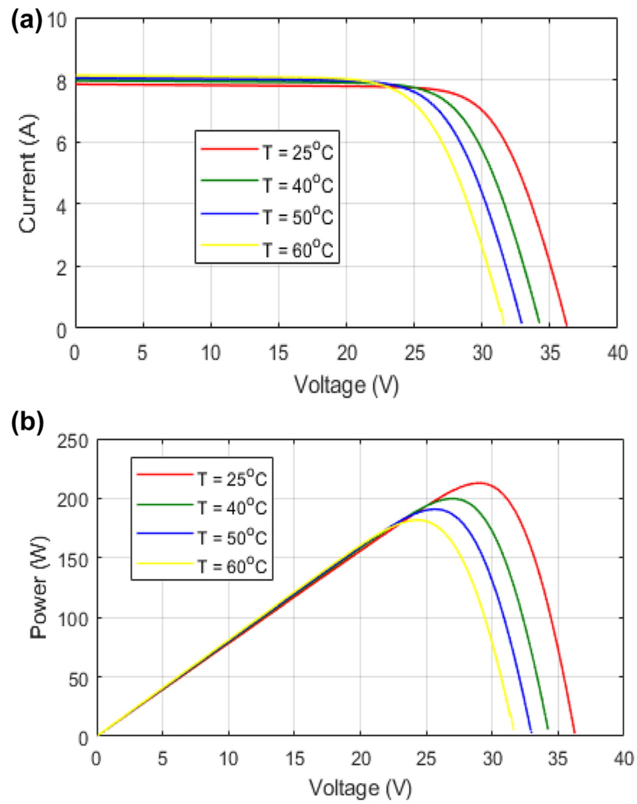

Figure 4: *I-V* and *P-V* MATLAB simulation characteristics of a photovoltaic cell with different temperatures and constant solar irradiation. (a) *I*–*V* characteristics of a photovoltaic cell with constant solar irradiation and different temperatures. (b) *P*–*V* characteristics of a photovoltaic cell with constant solar irradiation and different temperatures.

produced therefore enhancing the control system and generating more power for the island operation. Output power generated by the solar panel will be highly decreased if the maximum power point tracker is not used. Bat algorithm is proposed in this paper to enhance power generated by a solar panel by enhancing voltage and tracking more power under varying and constant sunlight and temperature with a fast speed at shorter or longer distances. Figure 5 shows the MPPT diagram for the system.

Proposed signal search bat algorithm

The optimal management of the available energy received from the output of the solar panel is highlighted by the accuracy of the proposed bat algorithm. The bat algorithm is said to be one of the speedy convergences of meta-heuristic techniques and looking at the performance it shows a good performance than the swarm optimization (PSO) technique. Bat algorithm was first proposed by Yang in 2010 (Titri, Larbes, and Benatchba 2017). The voltage

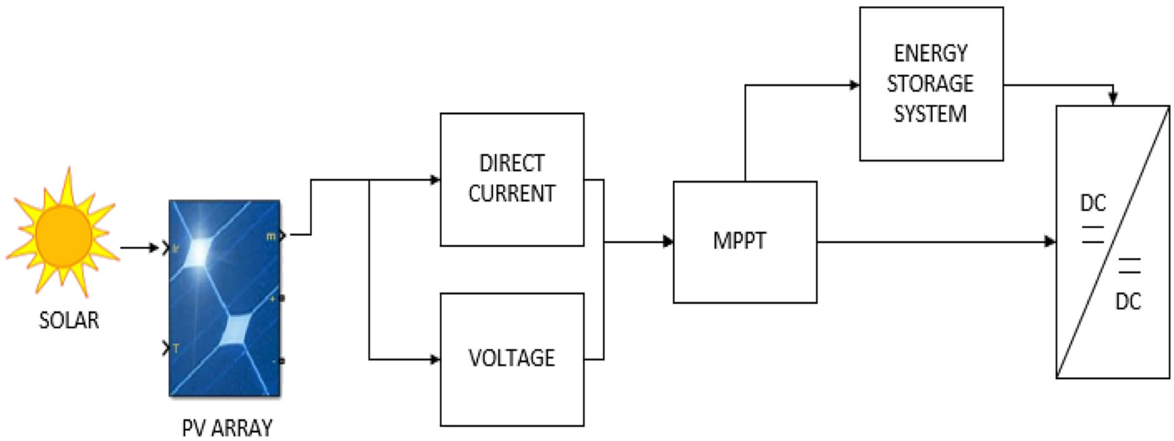

Figure 5: Diagram of maximum power point tracker.

and current of the PV array were monitored and extracted at its maximum power point when the MPPT established is extended to the PI controller. The design of the MPPT is devised as an optimization problem which is determined by the bat algorithm to look for the optimal parameters of the PI controller. The speed of the bat determines the rate at which maximum power is extracted. When the number of bats and iterations increases, maximum power is tracked at a very high speed. The iteration interval and average are updated by the bat signals. The signals can track maximum power within the iteration range for the fitness of the bat to be able to actively refurbish. The best movement and position of bats are evaluated. When the best position and speed are updated, the fitness of the bat is achieved. In the case of MPPT, the best position is voltage and the fitness of the bat's best position is the power extracted from the PV array at its maximum power point.

This proposed algorithm is stimulated by the bat echolocation mechanism. The subsequent precept is explained for the idealized bat algorithm and employs its biological characteristics (Titri, Larbes, and Benatchba 2017):

- Each bat can distinguish between hurdles and prey, by the mechanism of echolocation.
- The rate at which bats fly with a speed V_i at position S_i and these bats modify the pulse emissivity P_i at the interval of [0,1] according to the degree at which the prey is close to the bat and the frequency of the pulse is immediately regulated.
- When the number of iterations continues to increase, the loudness emitted by the bat will slowly decrease from the initial loudness D_0 to the minimum $D_{\min}$.

From the above statements, the pulse frequency of ith bat, f_i is defined as

$$f_i = f_{\min} + (f_{\max} - f_{\min})r \tag{3}$$

$$f_i = f_{\max} - (f_{\max} - f_{\min})\cos\left(2\pi\left(\frac{k}{k_{\max}} - \frac{k}{k_{\min}} + 1\right)\right) \tag{4}$$

where $f_{\min}$ is the minimum frequency, $f_{\max}$ is the maximum frequency and r is a random number that is between the interval of [0,1]. $k_{\min}$ and $k_{\max}$ are the minimum and maximum iteration numbers respectively.

For the convergence accuracy of the frequency and iteration to be obtained, a mechanism was added (4). When the iteration number increases (4), the pulse frequency of ith bat f_i decreases non-linearly which increases the speed of bats' ability to trace their prey.

The speed V_i for the ith bat is derived as (5).

$$V_i^{k-1} = V_i^k + \left(S_i^k - S_{\text{best}}\right)f_i \tag{5}$$

$$S_i^{k-1} = S_i^k + V_i^k \quad i = 1, 2, 3, \ldots N \tag{6}$$

$$i = i + N \quad k = 1, 2, 3, \ldots N \tag{7}$$

$$k = k + N \tag{8}$$

Where k is the number of iterations, N is any integer, S_{best} is the best position, and S_i^k is the position of the ith bat in the kth iteration and it is refurbished based on (9) and (10).

$$S_i^k = S_i^{k-1} + V_i^k \quad \text{if } P_i^k \le r \tag{9}$$

$$S_i^k = S_{\text{best}} + \alpha D_i^{k-1} \quad \text{if } P_i^k \ge r \tag{10}$$

Where P_i^k is the pulse emissivity of ith bat in the kth iteration, r is a random number that is between the interval of [0,1], α is a random number between −1 and 1, D_i^k is the average loudness of ith bat in the kth iteration.

From (10),

$$S_{\text{best}} = S_{\text{new}} - S_{\text{old}} \tag{11}$$

Where S_{new} and S_{old} are the new and old positions respectively.

The old position S_{old} is when the bat is at the initial position. When the bat starts to move, a new position S_{new} is obtained. As the bat moves in search of its prey, the signal search method connects the signal between the bat and its prey at different positions. The bat then traces its prey at a very high-speed rate. When there is any hurdle ahead of the bat, the signal will not be operated in that position. The signal only connects when the prey is in the danger zone. When the signal is updated, the best position is obtained as the bat approaches its prey at any distance. The best position can be obtained with the iteration interval value $k_1 \le k \le k_2$,

$$\int_{K_1}^{K_2} S_{\text{best}}(k)\mathrm{d}k = \int_{K_1}^{K_2} (S_{\text{new}}(k) - S_{\text{old}}(k))\mathrm{d}k \tag{12}$$

From (12), the average best position is obtained as

$$\frac{1}{K_2 - K_1}\int_{K_1}^{K_2} S_{\text{best}}(k)\mathrm{d}k = \frac{1}{K_2 - K_1}\int_{K_1}^{K_2} (S_{\text{new}}(k) - S_{\text{old}}(\mathrm{k}))\mathrm{d}k \tag{13}$$

The best position is accepted when the random number r is less than the loudness of the bat D_i and pulse emissivity P_i. The iteration number increases when the loudness and pulse emissivity is refurbished.

$$D_i^{k-1} = \beta D_i^k \tag{14}$$

$$P_i^k = P_i^0\left[1 - e^{-\gamma k}\right] \tag{15}$$

$P_i^k \to P_i^0$, when γ is 0, $D_i^{k-1} \to 0$ when β is 0, $k \to \infty$ β and γ are random numbers between –1 and 1.

When the best position is updated with the iteration interval value $k_1 \le k \le k_2$,

$$\int_{K_1}^{K_2} |S_{\text{best}}(k)|^2\mathrm{d}k \tag{16}$$

When $k \to \infty$, the iteration interval is $-\infty < k < \infty$

$$S_{\text{best}\infty} = \lim_{K\to\infty}\int_{-K}^{K} |S_{best}(k)|^2\mathrm{d}k = \int_{-\infty}^{+\infty} |S_{\text{best}}(k)|^2\mathrm{d}k \tag{17}$$

The average iteration interval is

$$S_{\text{best}\infty} = \lim_{K\to\infty}\frac{1}{2K}\int_{-K}^{K} |S_{\text{best}}(k)|^2\mathrm{d}k \tag{18}$$

When the best position is updated, the speed increases. At $k \to \infty$, the iteration tracking signal refurbishes twice which enhances the best position obtained. When S_{best} is furbished, the fitness of the bat is achieved faster due to an improvement in the movement of bats which tracks the maximum power point at a very fast rate. Here, S_{best} is the maximum voltage and $f(S_{\text{best}})$ which is the fitness of S_{best} is the maximum power.

Figure 6 shows the steps that were implemented on how the bat algorithm works and Figure 7 shows the MATLAB Simulink diagram of the signal search bat algorithm implementation. Figure 8 shows the flow chart of energy storage system.

The signal search bat algorithm tracks the maximum power by extracting maximum voltage and current from the PV system which is sent to the input of the bat algorithm. The output of the bat algorithm is sent to the PI controller.

Energy storage system

Since the sun shines most during the day and it goes off at night or when it rains, a battery energy storage system will help to store the energy generated during the day and will be used to power the island during the nighttime or anytime there is not enough sunshine. Battery stores energy produced by PV arrays. When the battery is low, it automatically charges itself by using the current generated which is sent from the PV system. The charge controller guides the battery to stop charging when it is fully charged by controlling DC from the solar panel.

Proposed control system design

The diagram in Figure 9 shows the complete proposed control system design diagram for the island operation. It shows how each task is carried out from energy receiving to power generation. This control system initiated instructs and regulates the performance of an island system to generate power. It will start to work when it receives sunlight. The process will continue to generate power as much as it continuously receives energy from the source or energy storage system.

Experimental design and simulation results

The proposed control system was designed and implemented in MATLAB Simulink to produce output power generated for an island. Figure 10 shows the complete MATLAB Simulink design of the control system. Output current, voltage, and power generated to the island were achieved. The output power generated by the battery will be used to supply power to the island when there is not

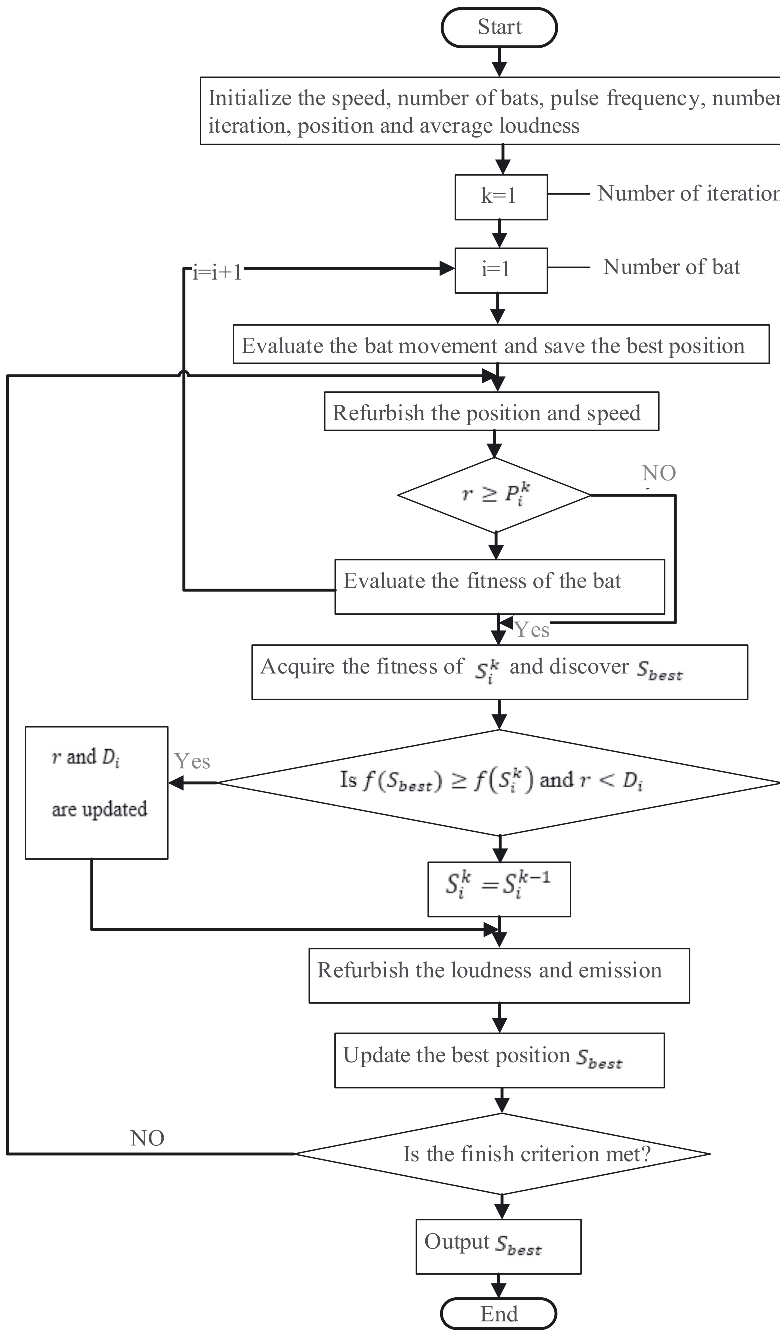

Figure 6: Flow chart of signal search bat algorithm.

enough sunlight produced on the island at night or on rainy days was also achieved. This power produced by the battery will be supplied to the grid when there is no solar irradiation produced. The simulation results were tested at different solar irradiation and different temperatures to generate power at different conditions. The results obtained were then compared with the perturb and observe algorithm.

Figure 11(a)–(c) shows output current, voltage, and power generated when sunlight is produced to the island at solar irradiation of 800 W/m^2 with a constant temperature of 25 °C and with the time of 10 s, and Figure 12(a)–(c) show output current, voltage, and power generated using perturb and observe algorithm at solar irradiation of 800 W/m^2 with a constant temperature of 25 °C and with the time of 10 s. Comparing the results of current, voltage, and power produced by the bat algorithm and perturb and observe algorithm, the bat algorithm produced an accurate result at a high speed with more power generated than perturb and observe algorithm. Figure 11(d) shows the output power generated by the battery when energy stored during sunshine time is used.

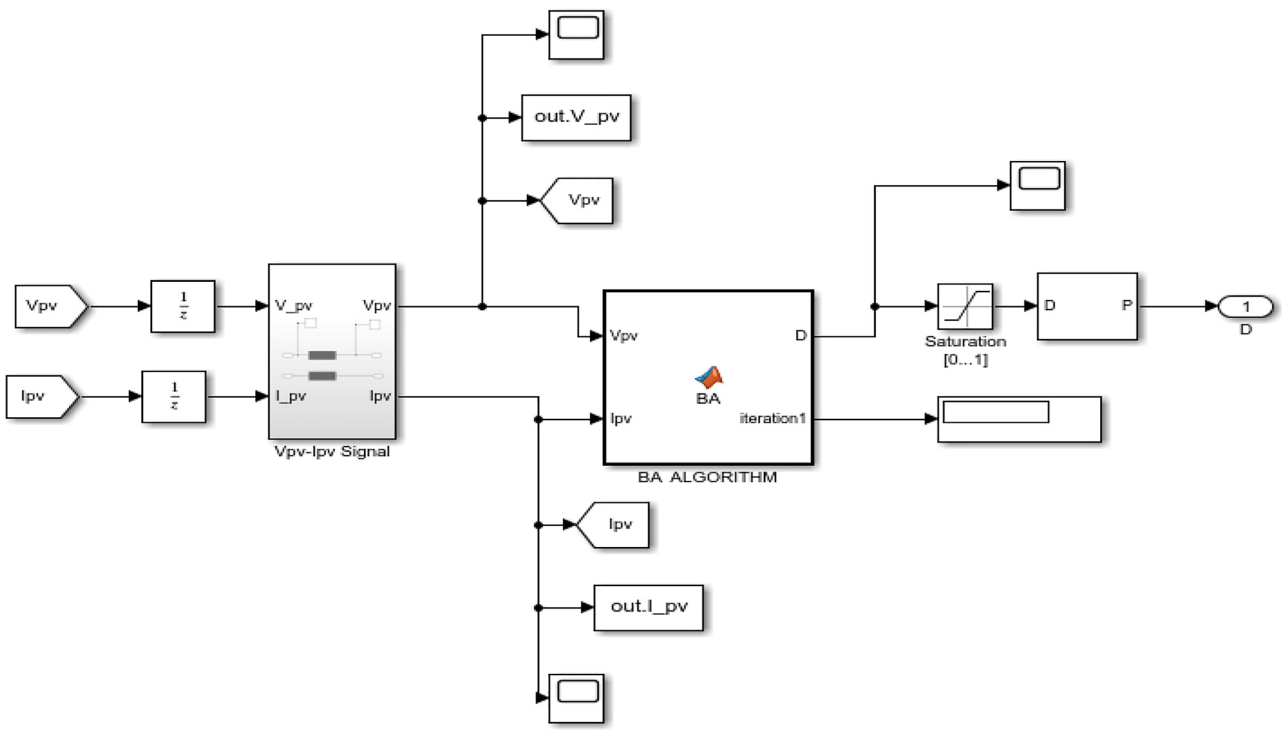

Figure 7: Diagram of signal search bat algorithm in MATLAB Simulink.

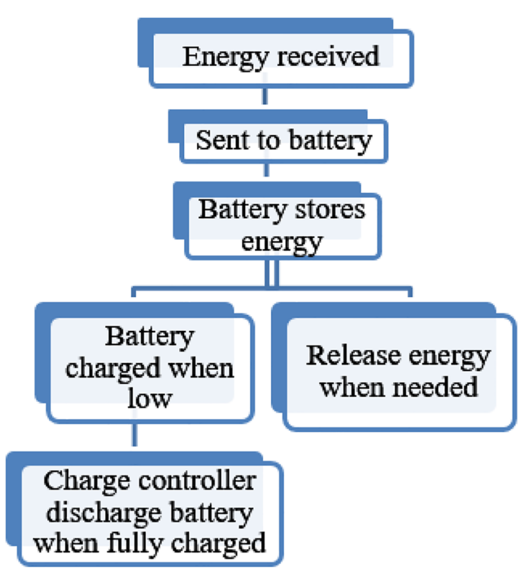

Figure 8: Flow chart for energy storage system.

From Figure 11(c) and (d), the power generated in (c) was higher and the power generated in (d) reduces. This is because when the battery is low, it charges itself by using the direct current produced by the PV array which decreases the PV array's output current and voltage, therefore output power produced decreases.

Figure 13(a) shows the output power produced at solar irradiation of 1200 W/m^2 with a constant temperature of 25 °C and with the time of 10 s, and (b) shows the output power produced by the battery at solar irradiation of 1200 W/m^2 with a constant temperature of 25 °C and with the time of 10 s. From the results obtained, the proposed bat algorithm tracking speed is faster which enhances and extracts more output current, voltage, and power to be generated than the perturb and observe method.

Figure 14 shows the output power produced at solar irradiation of 800 W/m^2 with a temperature of 40 °C and with a time of 10 s.

As shown in the simulation results, comparing Figures 12(c) and 13(a), change in solar irradiation affects output power. When solar irradiation is 1200 W/m^2, more power is produced than when solar irradiation is 800 W/m^2 which shows that the higher the solar irradiation, the more power will be produced. From Figure 13(a), when solar irradiation is 1200 W/m^2, at a time of 4.9 s, the output power increases and became stable while in Figure 12(c), when solar irradiation is 800 W/m^2, the output power became stable at a time of 8.4 s. Change in solar irradiation also affects the tracking speed. So, at higher solar irradiation, the tracking speed becomes faster.

Comparing Figures 12(c) and 14, temperature change slightly affects the output power, when the temperature is

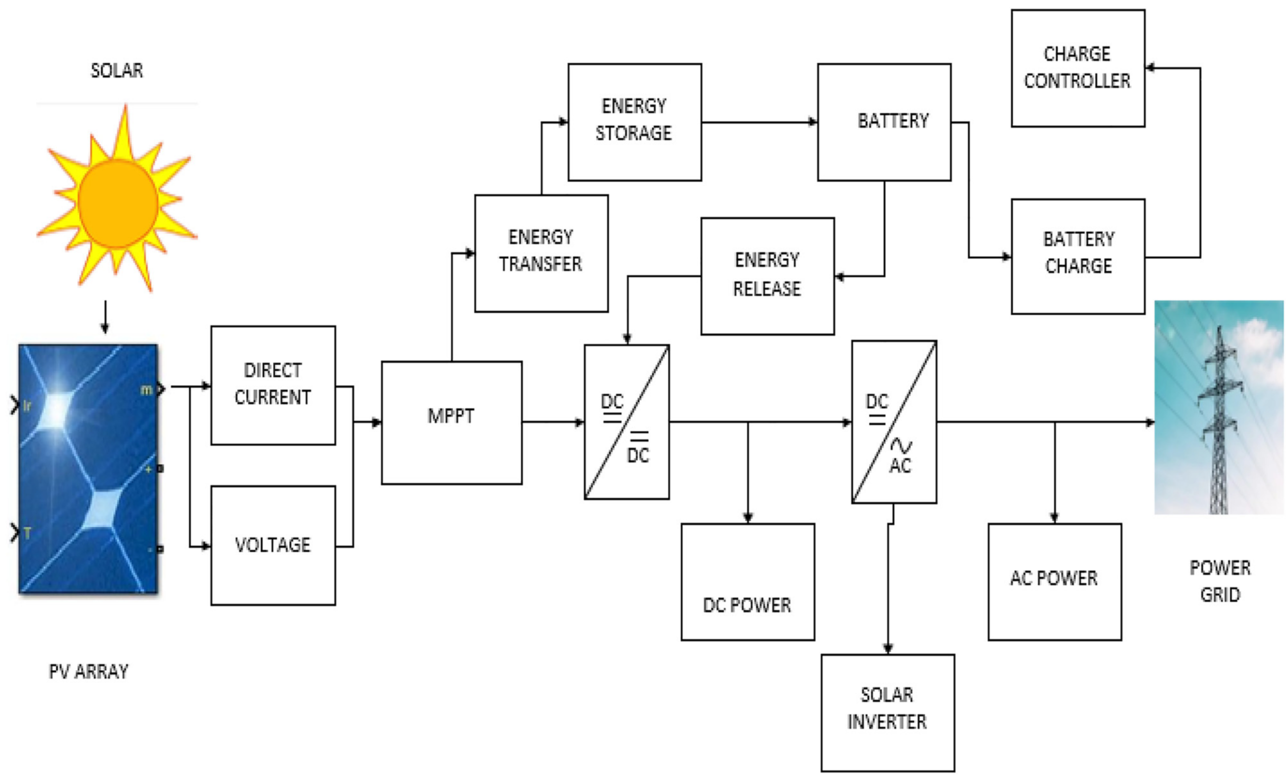

Figure 9: Control system design diagram for an island operation.

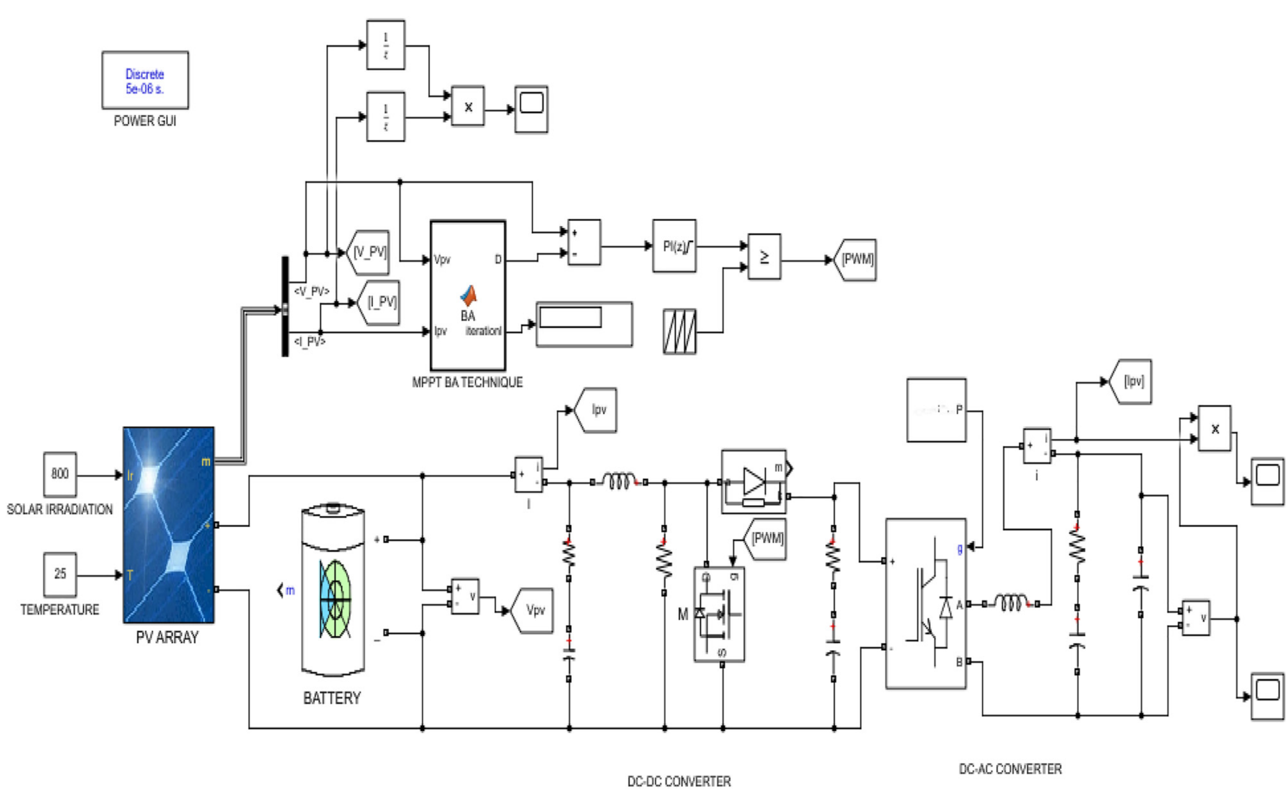

Figure 10: MATLAB Simulink diagram of the designed control system.

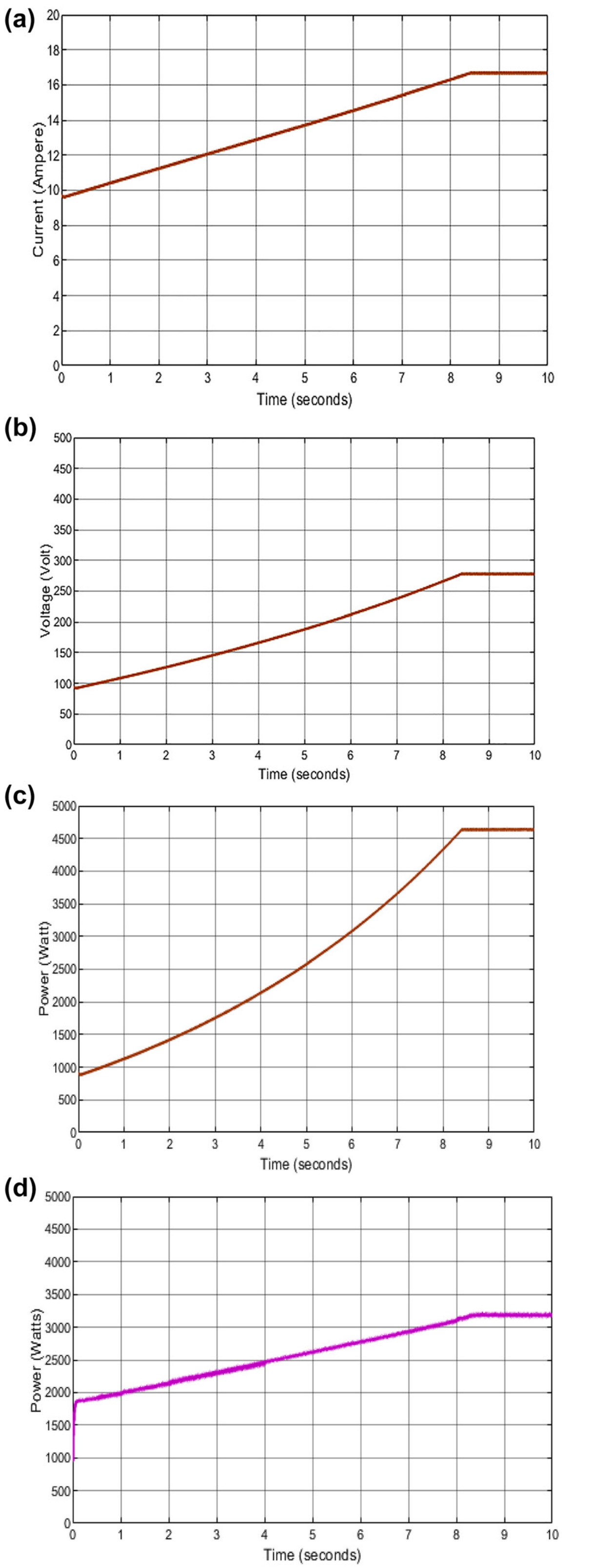

Figure 11: Simulation results of output current, voltage, and power generated using the bat algorithm at solar irradiation of 800 W/m^2 with a constant temperature of 25 °C with time of 10 s. (a) Output current at solar irradiation of 800 W/m^2 with a constant temperature of 25 °C. (b) Output voltage at solar irradiation of 800 W/m^2 with a constant temperature of 25 °C. (c) Output power at solar irradiation of 800 W/m^2 with a constant temperature of 25 °C. (d) Output power is produced by the battery at solar irradiation of 800 W/m^2 with a constant temperature of 25 °C.

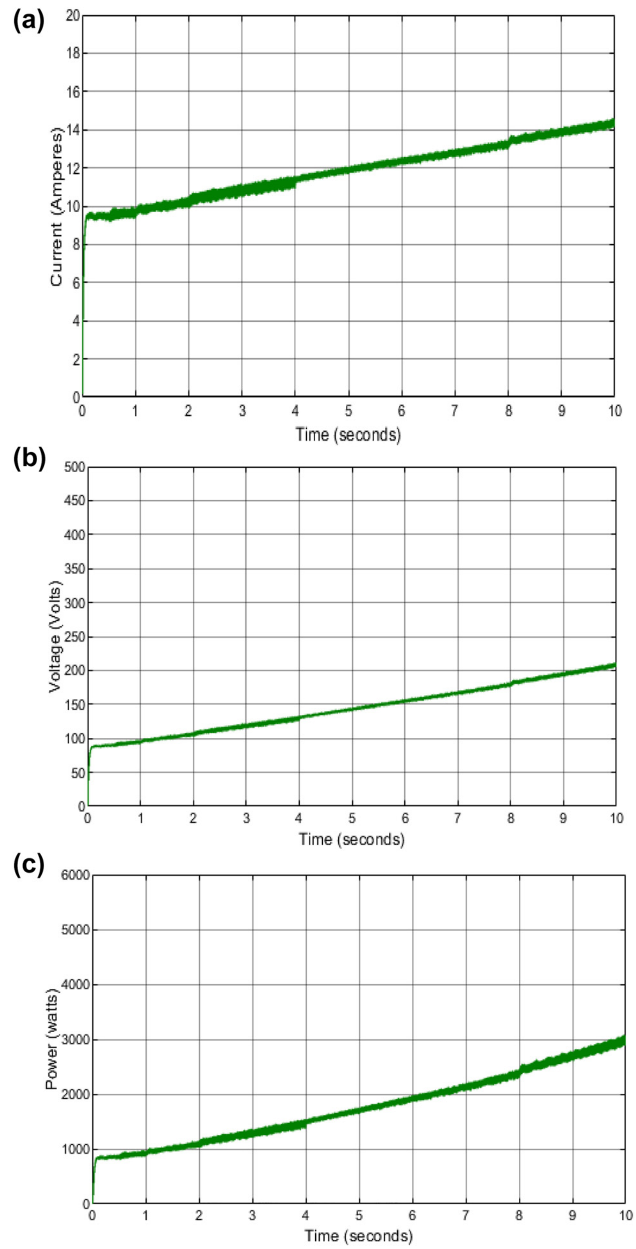

Figure 12: Simulation results of output current, voltage, and power generated using the perturb and observe algorithm at solar irradiation of 800 W/m^2 with a constant temperature of 25 °C with time of 10 s. (a) Perturb and observe output current at solar irradiation of 800 W/m^2 with a constant temperature of 25 °C. (b) Perturb and observe output voltage at solar irradiation of 800 W/m^2 with a constant temperature of 25 °C. (c) Perturb and observe output power at solar irradiation of 800 W/m^2 with a constant temperature of 25 °C.

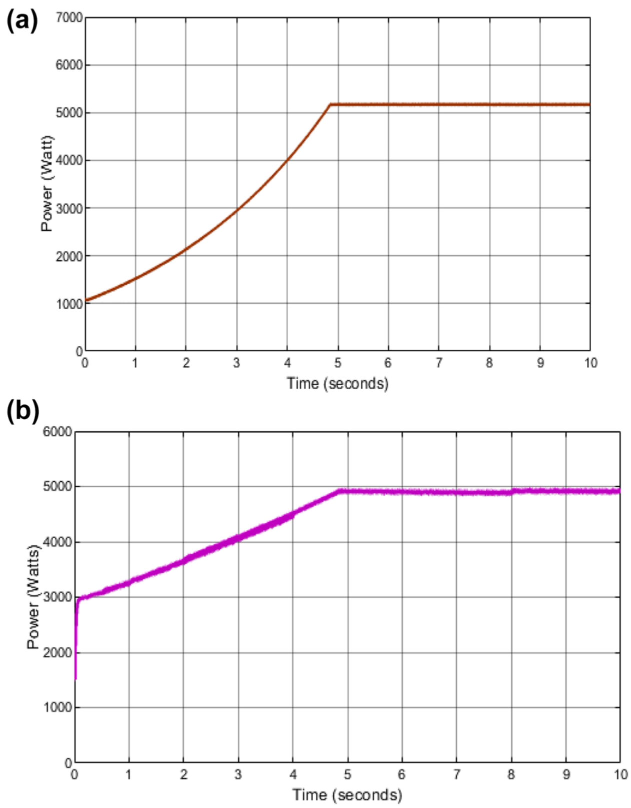

Figure 13: Output power produced at solar irradiation of 1200 W/m^2 with a constant temperature of 25 °C by the control system and by the battery. (a) Output power produced at solar irradiation of 1200 W/m^2 with a constant temperature of 25 °C. (b) Output power is produced by the battery at solar irradiation of 1200 W/m^2 with a constant temperature of 25 °C.

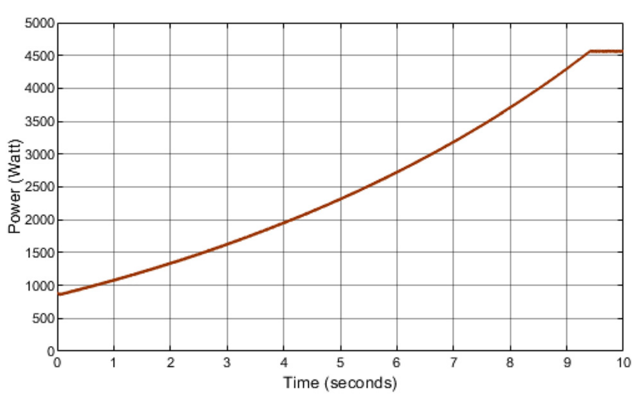

Figure 14: Output power at solar irradiation of 800 W/m^2 with a constant temperature of 40 °C.

25 °C, the power produced is quite higher than when the temperature is 40 °C. Also, at a temperature of 25 °C, the output power became stable at time 8.4 s while, at a temperature of 40 °C, the output power became stable at time 9.4 s. This shows that if the temperature is high, it affects the performance of the PV system by reducing the tracking speed and the output power generated to the grid.

Conclusions

This paper explains the detailed control system design that can be used to generate power for an island when there is no external grid available to generate power for the island. The detailed modeling of the control system was explained in detail using the design steps proposed. For the output power to be maximized, the bat algorithm using signal search was implemented to extract more power for the island by increasing the output voltage at a fast rate. Maximum power is tracked at a high speed for longer distances. The proposed bat algorithm was compared with the perturb and observe algorithm. The bat algorithm performed well than perturb and observe algorithm from the comparison of the simulation results. Energy storage system stores energy to be used when sunlight is low. DC to DC converter regulates the output voltage of the PV array. DC to AC converter was used to convert the output DC power produced to AC power to be supplied to the island for use. The proposed control system design was implemented and simulated in MATLAB Simulink. The tests for solar irradiation and temperature at different conditions were carried out. From the simulation results, it is seen that the output power generated to the island is determined based on the solar irradiation and temperature produced. However, change in solar irradiation affects the output power more than temperature change. This proposed control system method was successful and produced an accurate result by generating power. The results acquired stipulate that for the control system be able to continue to generate power for the island system, there must be high radiation of sunlight received thereby causing the island not to lack power and will help in the precise performance of the island operation.

In the future, the bat algorithm can further be improved, and also a higher number of bats and iterations can be tested with the proposed method to check the output simulation results since the higher the number of bats and iterations, the more complex the tracking becomes so the bat algorithm needs to be improved so that when the bats and iterations are a lot, the tracking speed can be faster through a high accuracy of the bat signal between the bat and its prey.

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Appendix A

Table A1: Abbreviations.

Abbreviation	Meaning
MPPT	Maximum power point tracking
BA	Bat algorithm
ESS	Energy storage system
AC	Alternating current
DC	Direct current
PV	Photovoltaic
PSO	Particle swarm optimization
DG	Distributed generation
MPP	Maximum power point
PI	Proportional integral

Table A2: Nomenclatures.

Symbols	Quantity	Units
I_{pv}	Photovoltaic cell output current	A
I_{ph}	Photon current	A
I_d	Diode saturation current	A
I_{sh}	Shunt-leakage current	A
V_{pv}	Photovoltaic cell output voltage	V
R_{sh}	Shunt resistance	Ω
R_s	Series resistance	Ω
A	Ideality diode factor	–
K	Boltzmann constant	–
q	Electronic charge	Ω
T	Cell temperature	Deg
N_s	Series-connected cells	Ω
N_p	Parallel-connected cells	Ω
I	Current	A
V	Voltage	V
P	Power	W
I_r	Solar irradiance	W/m^2

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