Energy management system for a small-scale microgrid

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Abstract

In recent years, the power system has been evolved into microgrids, which are little pockets of self-contained entities. Different distributed, interconnected generation units, loads, and energy storage units make up a typical microgrid system. The increased energy efficiency of these units on microgrids is gaining popularity day by day. Because of their stochastic behavior, renewable generation causes an imbalance in the power system, which needs microgrid energy management. To solve these issues, a variety of novel approaches have been explored in the literature. For the stand-alone microgrid in this research, efficient energy management and control mechanism is adopted. A photovoltaic system, a wind turbine, and a battery energy storage device make up this stand-alone microgrid. The power stability of the hybrid system is ensured by a sophisticated controller. The main purpose of this study is to regulate the DC/DC bidirectional converter (DBC), which connects the Li-ion battery to the DC bus of the stand-alone microgrid. This paper describes the development of a wind/photovoltaic power generation system to the load, as well as MPPT techniques like perturb and observe (P&O). The system is simulated and the results are presented using MPPT techniques. There is no requirement for a specific power model in the suggested method. Only power and voltage system data are used by DBC. A stand-alone microgrid system was simulated using MATLAB.

Keywords: Microgrid, Maximum power point tracking, Photovoltaic, Wind energy, Battery energy storage

Introduction

Renewable energies are the new trend in power production with their clean and environmentally friendly power. Because of the high dependence on weather and climate conditions, in numerous cases, the best possible system is the renewable energy hybrid system (based on renewable sources) with energy storage systems [1]. The hybrid microgrids are generally used to provide electricity for multiple consumers like homes or farming areas that are out of grid extension based on smart control. A microgrid consists of loads, energy storage systems, small-scale production systems, and a control center [2]. Microgrids are used in communication systems for real-time management [3]. Microgrid (MG) when joined to a network can also operate in isolation. Depending on the sort of energy source, the microgrid can be categorized as alternating current (AC), direct

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current (DC), or hybrid AC/DC. Microgrid energy management systems face difficulties in managing renewable energy sources like solar power and wind.

Hybrid energy systems are among the most promising systems for using renewable energy. The phrase hybrid energy system points out electric power generation systems that use multiple sources. The combination of renewable energy sources like solar, wind, biomass, wind power, solar photovoltaic, or small hydroelectric power plants can be a compliment or an alternative to the diesel generator sets generally used to produce electricity in remote areas. In general, hybrid energy systems are created to fulfill energy needs ranging from simple lighting to total electrification of villages or small islands, and hybrid systems are established by the selected criteria [4].

Different research work has discussed multiple aspects of microgrid, such as a study of experimental systems installed in several countries [5] and microgrid protection and energy management systems [6]. The energy management system is referred to as an information system that supported by a platform, in which the required functions to verify that production and distribution give energy at the lowest possible price. When the main grid goes down, keeping a dependable power supply to customers takes precedence over economic benefits. As a result, the operation goal of microgrids is to maximize load satisfaction while minimizing operating costs. It means that wind and solar power should be used to compensate for the lack of electricity, and a portion of the load could be turned off to balance power when required [7]. If the consumer to be electrified is a group of isolated buildings, such as a village in an area with a very low population density, or difficult to access, an alternative solution is to reproduce the pattern of distributed generation, but on the scale of a small independent network, called a microgrid. Faced with the difficulties of connecting to the main grid, this solution then becomes economically feasible [8]. Generation sources must then be small in size, which makes renewable energy sources very interesting. They must be chosen and placed according to the availability of the driving source: wind, sunshine, a river. They can be centralized where the energy is available, or placed next to the buildings to be powered; in all cases, this distance must remain limited to minimize line losses. Energy efficiency is indeed vital in this type of system to ensure economic profitability [9]. According to the most recent research, the goal of microgrid energy management is to reduce operating costs while maintaining a balance between the energy produced and the load demanded and the cost of electricity purchased and operating maintenance costs from the main grid. The energy management approach proposed in [10] is based on two market policies that only consider power balance. Security is not considered in the microgrid operation. Other papers [11] have discussed various approaches for microgrid control and renewable energy resources integration. The authors in [12] presented energy management approaches for micro-grids. Various stand-alone microgrid and grid-connected hybrid network designs are discussed. The control goals of microgrid energy management systems and supervisory controllers have been shown in another review report [13]. The proper energy management, operation, and control of the microgrid are significant for an energy-saving smart electrical grid [14]. The performance and quantity level of DSTATCOM's power circuit and control parameters are assessed during the design and selection process [15]. The control of power factor in a radial distribution system has been assessed by comparing two algorithms backpropagation control algorithm (BPCA)

with synchronous reference frame theory (SRFT) techniques. These control methods are used to create switching pulses for IGBTs in DSTATCOM's voltage source converters [16]. The author presented a self-excited induction generator (SEIG) with DSTATCOM that mitigates voltage sag, compensates for reactive power, and improves power factor [17].

Microgrid energy sources combine renewable modules like wind turbines (WTs) and photovoltaic (PV) panels with non-renewable ones like diesel generators, etc. The PV panels and wind turbines are used to collect the highest power, which is governed by MPPT (Maximum Power Point Tracking) blocks. It is a goal of the energy management system of microgrids [18]. The asynchronous machine was the first type of generator used for bigger wind turbines [19]. Robust and inexpensive, it has no wearing parts (no collector brush system), thus reducing maintenance costs. In addition, the need for electronic equipment is reduced by joining the stator directly to the grid. Recently, the article reviews modeling powerful (WTs) systems to optimize and efficiently make use of the output power of the turbine via the MPPT method. The use of changeable speed (WTs), which quickly adjusts the rotation speed of the (WTs) in response to changeable wind speed, can produce higher efficiency in providing a wind source. With these techniques acquired by the MPPT controller which collects the highest power, we can find fuzzy inference system (FIS), nonlinear control, perturb and observe, and power signal feedback (PSF) control [20]. Photovoltaic (PV) energy is sustainable energy that can be an alternative to fossil fuels. To this end, researchers are considering its future energy needs. Currently, the technology for manufacturing PV modules is greatly improved in terms of quality and manufacturing cost. The temperature and irradiation have a direct effect on the performance of a photovoltaic cell resulting in the degraded performance of the solar panel. The current–voltage features of a photovoltaic cell changed linearly with all changes in the solar irradiation. Because of the cloudy season (PV), module production has consistent fluctuations in insolation. The MPPT controller is used to magnify (PV) cell power by accordingly modifying the duty cycle of the (DC–DC) converter. In multiple works of literature, various MPPT techniques for PV solar have been suggested. Incremental conductance (INC) compares the slope of the power curve to determine whether the duty ratio should be increased or decreased [21]. Perturb and observe (P&O) observes the voltage level and perturbs the voltage until it holds the highest power point and the P&O technique that uses the power variation as an error signal and calculates the required perturbation step using a traditional PI controller is proposed in [22]. In [23], a progressive approximation register type MPPT algorithm is presented; this method follows the MPPT by increasing the perturbation step in a binary manner starting from the least important bit. After spending the MPPT, a monotonically decreased step system is then utilized to find the exact MPPT. Furthermore, modified variants of the (P&O) algorithm with minor changes in the results have been suggested by [24] to reduce steady-state oscillations.

Previously that was to maximize the production of sources and thus validate the objectives of energy autonomy and material profitability. The principle is to define a sequence recursive function of the power to be optimized, which always converges toward the maximum point, and this despite climatic variations. At each calculation step, one element of the sequence is evaluated and must be applied as a command instruction. We

will see how to exploit the power characteristics of the wind turbine and PV panels, to design adapted MPPT algorithms; the battery energy storage system (BESS) is composed of static components and has a very fast dynamic reaction compared to typical generators. It can support a variety of different applications ranging from short-term power quality control to long-term power management [25]. The incorporation of BESS into smart grids and microgrids systems considerably moves forward the computational complexity of the optimal power flow (OPF) difficulty, as it addresses the issue of dynamic OPF promptly [26]. The optimal use of BESS is determined by network topology, meteorological conditions, and the state of charge (SoC) of the BESS. The battery systems suffer significant lifetime declines when undercharged or overcharged so the SoC limits are especially important [27]. Furthermore, due to their low output voltage, very low SoC batteries are unable to supply power to the network. The SoC of the BESS systems will also have an impact on the optimization actual function after battery efficiency is dependent on the SoC [28]. For distributed systems, in the microgrid, or isolated sites, a good solution can be mixed-coupling, associating an AC and DC bus. Among the sources and storage units, we have presented are photovoltaic panels and batteries that operate at DC power. Instead, wind turbines operate on alternating power. Finally, the loads can be either continuous or alternating, depending on the case. This solution makes it possible to connect each one to its corresponding bus, then to exchange the load or loads power between buses employing reversible DC/AC converters.
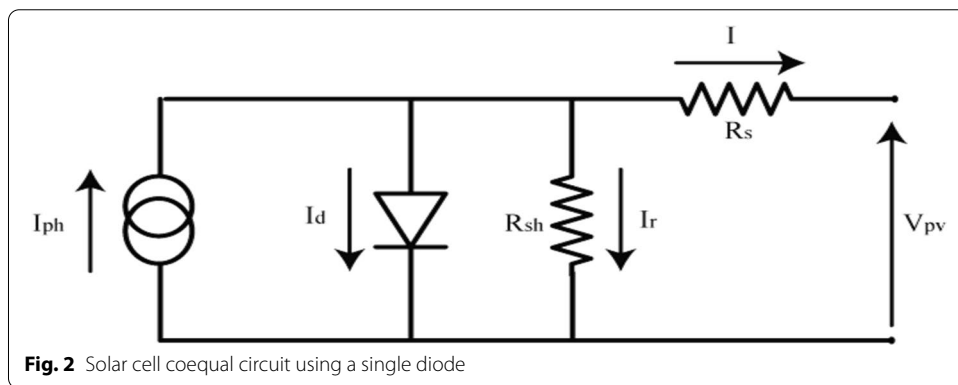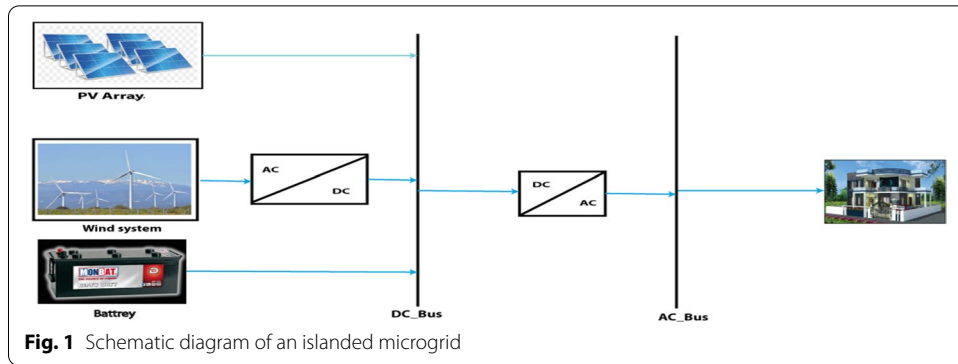
We pursue to define the possible structures for a power system in an isolated site, thus generating little but having to ensure the management of its energy produced in total autonomy. Two components are then essential to its architecture: an energy source, if possible renewable, available close to the structure to be fed, and a storage unit capable of both storing excess production and returning it to complete it. MATLAB software is used to design an optimal structure and sizing scheme for the hybrid microgrid to supply load in this analysis. A hierarchical energy management system is suggested to increase the economy and robustness of the overall system by increasing the robustness and versatility of the island PV/wind/battery hybrid AC MG.

This article uses MPPT control methods to control the converters of distributed generation for energy management in the microgrid.

The rest of the paper is presented as follows: In stand-alone mode, Sect. 2 explains the device modeling of each part of the microgrid. The proposed method is discussed in Sect. 3. The simulation results for stand-alone mode are given in Sect. 4. Section 5 concludes this paper.

Microgrid system

Microgrids are small power grids built to provide a limited number of customers with a more efficient and higher-quality energy supply. It combines numerous energy sources such as (PV panels, micro-turbines, small hydropower, fuel cells, small diesel generators, and mini-wind turbines), storages systems as a backup energy system, and AC/DC load for the energy consumption as illustrated in Fig. 1 [29]. The microgrid can run in two modes: grid-connected and islanded. Research on microgrids in the literature mainly focuses on DC (constant voltage)- and AC (variable voltage)-type microgrids, which are defined by the nature of the voltage at the bus used. The DC bus connects all of the

Fig. 1 Schematic diagram of an islanded microgrid

Fig. 2 Solar cell coequal circuit using a single diode

microgrid's components in a DC-type microgrid. In an AC microgrid, all system components (sources and load) are joined to an AC bus using power converters. In this work, we will use a hybrid microgrid, which is an incorporation of the DC and AC bus. The system has some advantages over both AC and DC systems. AC or DC loads can be supplied without the need for an additional converter interface, increasing the efficiency and reliability of the system.

As we can see from Fig. 1, the microgrid system is composed of a battery, PV array, and wind turbine for the storage system. The modeling of each source has been performed by MATLAB. A power converter was used to link each system's output to the DC bus; furthermore, control algorithms have been used to produce the switching signal of each converter device to provide the system [30].

Photovoltaic system

The PV cell model focuses on the dynamic PV model built and tested [31], and Simulink subsystems were used (Fig. 2, Table 1).

The current of the PV cell is represented as:

$$I_{pv} = I_{ph} - I_0 \left[\exp\left(\frac{qV_d}{K_b F T_c} \right) - 1 \right] - \frac{V_d}{R_p} \tag{1}$$

In this work, we used an implemented PV model at MATLAB (Sun Power SPR-250NX-BLK-D) as a reference module. The choice of a 250 W module is useful to facilitate the calculation. Table 2 shows the characteristics of this PV model.

Table 1 Description of the parameters used in Eq. (1)

Parameters	Description
I_{ph}	Light current
I_o	Cell saturation current
Q	Charge of electron (1.6×10^{-19} C)
K_b	Boltzmann's constant
F	Ideality factor
T_c	Cell's absolute temperature
V_d	Voltage of diode
R_p	Parallel resistance

Table 2 Characteristics of (Sun Power SPR-250NX-BLK-D) PV model

Parameters	Values
Highest power	250 W
Highest power voltage	42.8 V
Highest power current	5.84 A
Open-circuit voltage	50.93 V
Current court circuit	6.2 A
Cellule numbers	72
Temperature coefficient of open-circuit voltage	−0.29103%/°C
Temperature coefficient of current court circuit	0.013306%/°C
Shunt resistance	448.6949 Ω
Series resistance	0.37759

Fig. 3 Solar conversion system with controller
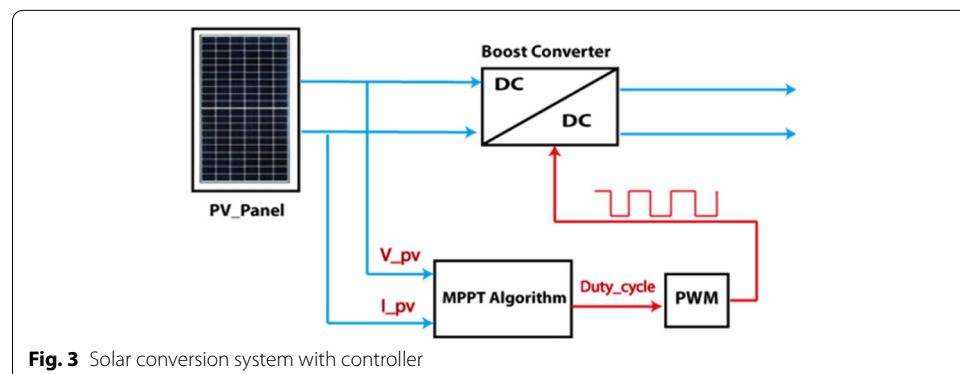
Photovoltaic arrays have limited conversion efficiency, for this reason, an MPPT technique is suggested. The P&O is the algorithm used for the MPPT in this work as shown in Fig. 3.

The P&O algorithm is traditional and straightforward; it is extremely dependent on the initial conditions and exhibits oscillations around the optimal value. As shown in the flowchart of Fig. 4, this algorithm works by disrupting the PV panel voltage when working on the cyclic ratio. Evidently, after this disturbance, the power supplied by the panel is calculated PV at an instant (k) and compared to the previous one at an instant ($k-1$) [12].

Fig. 4 Flowchart of MPPT algorithm
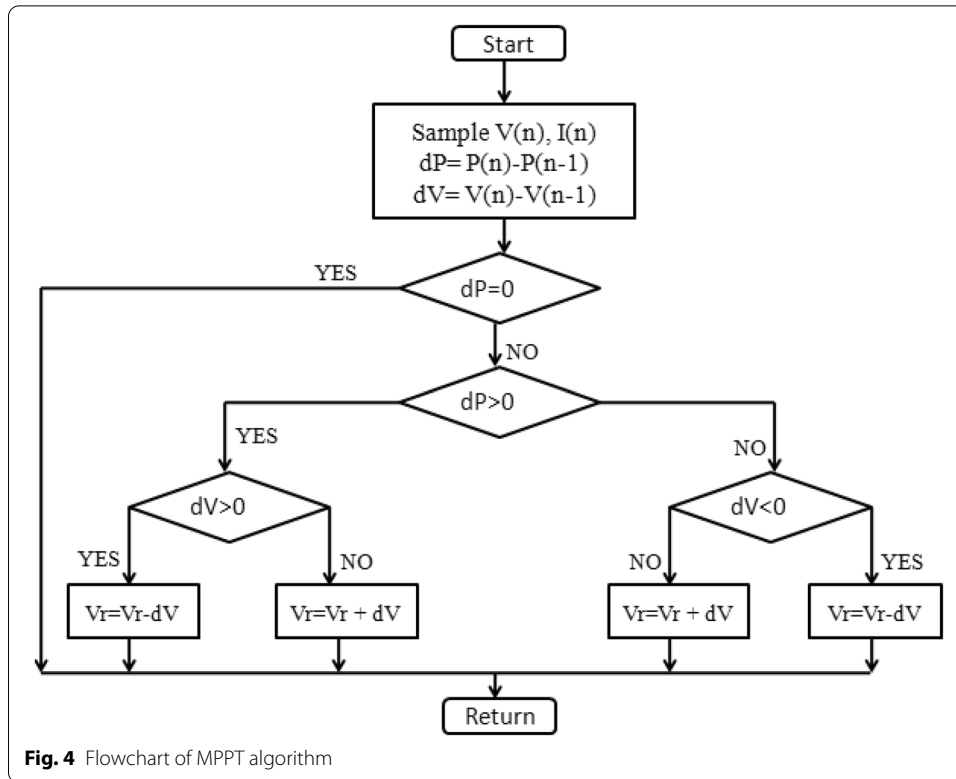
If the power is increased, the maximum power point (MPP) is reached, implying that the service cycle variance will remain constant. If the power decreases, we shift away from the MPP, so we must reverse the direction of the duty cycle transition.

Wind system

After solar energy, the wind energy system (WES) is the most readily available source and a promising electrical energy source. The wind's kinetic energy produces mechanical energy with the help of rotating turbines. The wind energy is generated in a linear relationship with the wind speed. When the wind speed is at a nominal level, the wind turbine will produce nominal power [11]. The wind turbine model is described as:

$$P_{\text{wind}}(v) = \begin{cases} \frac{P_{\text{nom}}(v - v_{\text{ci}})}{(v_{\text{r}} - v_{\text{ci}})} & (V_{\text{ic}} \leq v \leq v_{\text{r}}) \\ P_{\text{nom}} & (V_{\text{r}} \leq v \leq v_{\text{co}}) \\ 0 & (v \leq v_{\text{ci}} \text{ or } V_{\text{co}} \leq v) \end{cases}, \tag{2}$$

Final output $P_{\text{out}} \leq P_{\text{wind}}$ (ϑ) is due to losses. A wind turbine's output power can always be balanced to meet the load demand. The WES consists of wind turbines, a boost converter, a diode rectifier, permanent magnet synchronous generator (PMSG), and an MPPT controller as shown in Fig. 5 (Table 3).

Table 4 shows the characteristic of the used wind turbine. Following the direct connections of the PMSG to the wind turbine, the induced output voltage is rectified using a three-phase diode bridge. To monitor the maximum power point of the wind turbine, a DC–DC boost is used to apply to perturb and observe (P&O) algorithm shown in Fig. 4.

Fig. 5 Wind system with controller
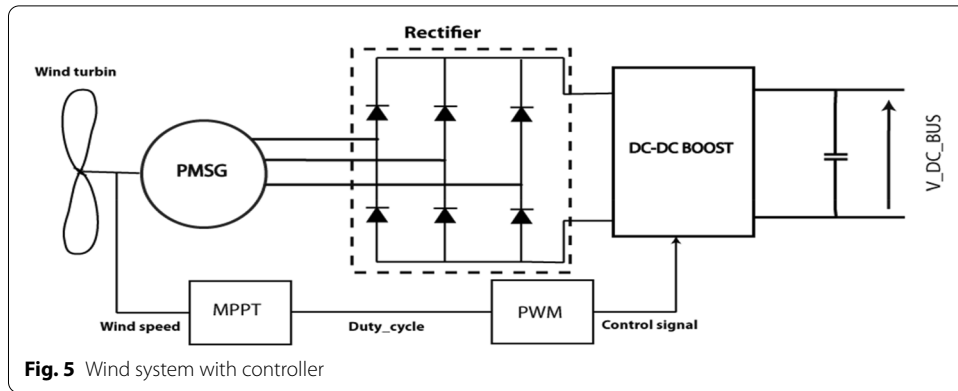
Table 3 Description of the parameters used in Eq. (2)

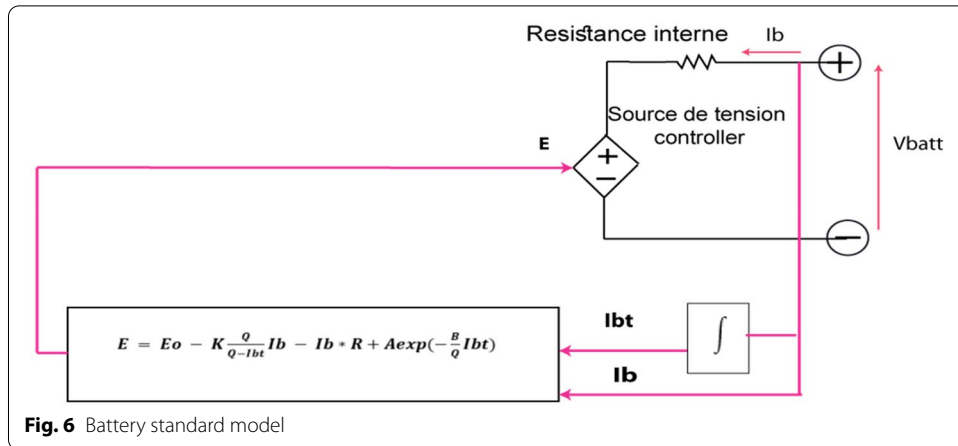| Parameters	Description
P_{wind}	Wind power (kW)
P_{nom}	Nominal power (kW)
v_{ci}	Cut-in wind speed
v_{co}	Cut-off wind speed
v_r	Rated wind speed
V	Wind speed (m/s)

Table 4 Characteristic of wind turbine

Parameters	Values
Stator resistance	0.048 Ω
Armature inductance	0.00016 H
Link flow	0.048 V s
Inertia	0.000002
Number of pair poles	3

Li-ion battery

Li-ion batteries are the chosen power source for many storage device applications. Despite all advantages of Li-ion batteries, these kinds of batteries need special care because Li-ion battery electrolyte, unlike other battery types, is a volatile, highly flammable solvent that burns quickly and easily. Previously, lithium-ion batteries were chosen because of their strengths (no memory effect, long life cycle, and high energy density) over other types of battery storage systems. In this work, the battery storage system will be used as a power source, when the renewable sources are not enough to satisfy the load demand and as a load when they have enough power and store the excess power to keep the system balanced.

Because of the nonlinearity of the voltage response, lithium-ion batteries are a difficult system to model. The dynamic battery model from Simulink's Sim power systems library is used in this article, as illustrated in Fig. 6.

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Fig. 6 Battery standard model

Table 5 Description of the parameters used in Eq. (4)

Parameters	Description
E	Battery open-circuit voltage
E_0	A constant voltage of the battery
K	Polarization constant or polarization resistance
Q	The capacity of the battery
$q = it$	Actual charge of the battery
A	Exponential zone amplitude
B	Exponential zone time constant inverse
R	Internal resistance

This model has been proposed by Shepherd [31] which is focused on an equation that accurately describes a wide range of cell and battery discharges. The parameters of this equation are calculated from many discretized points of a manufacturer's curve. The internal resistance and the fixed voltage V_{oc} make up the battery's equivalent circuit. Two different equations can be used to compute the open-circuit voltage E. In discharge mode, $E = V_{Dish}$, as denoted in Eq. (3) (Table 5).

$$V_{Dish} = E_0 - \frac{KQ}{Q-q} * i - \frac{KQ}{Q-q} * q + A \exp(-Bq). \tag{3}$$

In the charge mode, $E = V_{Ch}$, as calculated in Eq. (4).

$$V_{ch} = E_0 - \frac{KQ}{0.1Q-q} * i - \frac{KQ}{Q-q} * q + A \exp(-Bq). \tag{4}$$

DC/DC Bidirectional converter (DBC)

A DBC allows power to be transmitted in either path between two DC supplies. Because of their ability to reverse the direction of current flow, and thus power, while keeping the voltage polarity at either end unaltered, it is increasingly used as a linkage between the battery and the microgrid system to maintain battery charging/discharging [32]. The battery storage system consists of a Li-ion battery and a DBC. This converter is
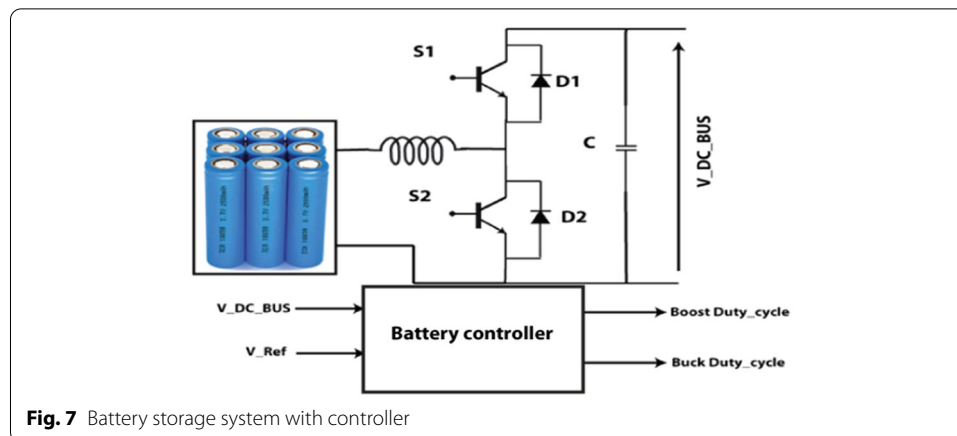
Fig. 7 Battery storage system with controller

Table 6 Parameters of the bidirectional converter

Parameter	Value
Converter inductance	2.4 Mh
Converter capacitance	0.8 Uf
Semiconductor type	IGBT

responsible for maintaining and stabilizing the DC bus voltage through the controller as demonstrated in Fig. 7.

The converter parameters used in this simulation are shown in Table 6. The converter shown in this study is a half-bridge IGBT topology that operates in continuous conduction mode (CCM). When discharging the battery, the converter operates in boost mode, and when storing excess energy on the DC bus, it operates in buck mode. S2 and D1 are active in boost mode, and current flows to the DC bus. S1 and D2 are active in buck mode, and power flows to the battery [29].

Bidirectional DC/DC controller

The bidirectional DC–DC convert shown in Fig. 7 represents the principal element for energy management. The bidirectional converter is used to keep the voltage fixed at 400 V at the DC_BUS of the microgrid system by charging or discharging the battery and works as a boost converter when the voltage of DC_BUS is less than 400 V, and energy flow is from the battery to bus. In the other direction, the converter works as a buck and charges the battery when The Voltage of the BUS is more than 400 V.

The control strategy used in this system is illustrated in Fig. 8. Because the bidirectional converter works with voltage-controlled, the DC_BUS voltage was measured and compared with the reference voltage. The difference between these voltage values is processed in PI blocks and generates the duty cycle of each direction.

The bidirectional converter's control is the most important aspect of the energy management system. Three operating modes are used to manage energy exchanges between the DC bus, renewable sources, and the storage device: charging, discharging, and stop mode. The proposed battery charger algorithm Fig. 11 uses the measured data of voltage and battery state of charge measured at the DC bus for the

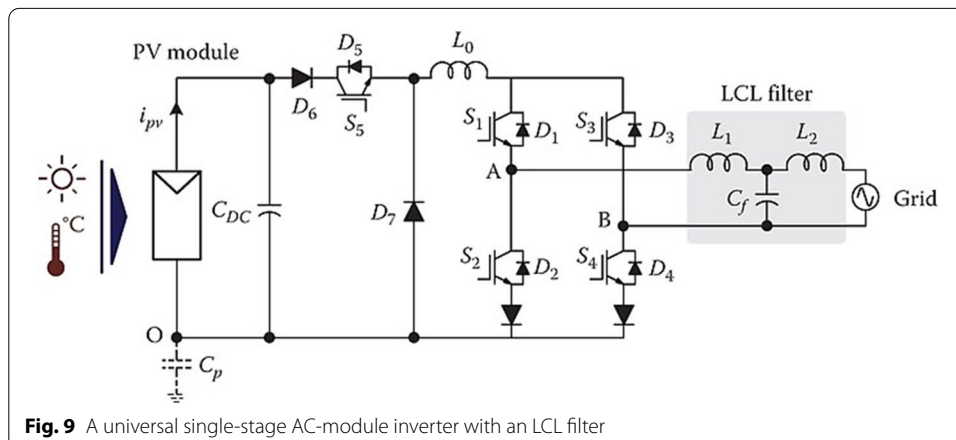**Fig. 8** Bidirectional DC–DC converter control technique
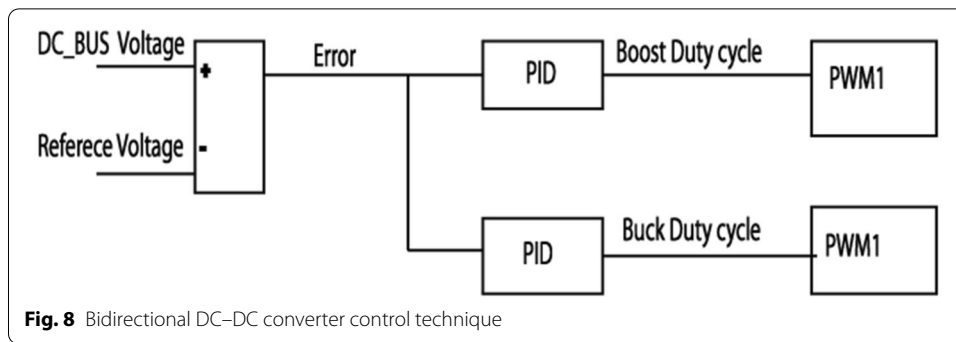
generation of the duty cycle value, to control the system converter using PWM signal. PID controller parameters given in the following table have been successfully yielded the stable output voltage of 400 V with 10% overshoot, 3.0 s of settling time, and 1.5% of steady-state error (Table 7).

Inverter DC/AC

Figure 9 shows the electrical circuit diagram of the considered AC inverter. It is made up of a four-quadrant inverter in the shape of an H-bridge chopper, the output voltage of which is controlled in an open loopy of a PWM signal. The LCL filter is applied at the output of a DC/AC inverter to repress higher-order current harmonics caused by the inverter's PWM switching action, resulting in low inverter output current harmonic distortion.

Table 7 Parameters of PID controller

Parameters	Values
K_p	0.04
K_i	0.005
K_d	0
Settling time (s)	3.0
Sample time (s)	$1e^{-5}$
Steady-state error	1.5%

Fig. 9 A universal single-stage AC-module inverter with an LCL filter

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Energy management system

The system case study in this work is composed of two renewable energy sources (photovoltaic solar system, and wind turbine) fueling a DC bus to supply loads connected to a DC bus. And a backup system consists of a Li-ion battery for energy storage, and a DC/AC converter to connect the AC charger with the DC bus as shown in Fig. 10.

The primary controller in stand-alone systems is the energy management system, which coordinates and controls all converters. The DC bus, which collects all energy sources, includes the entire energy management system. Overcharging/discharging was the primary cause of the majority of Li-ion battery explosion accidents. As a result, controlling the battery SoC is important for safe battery operation. As a result, we used the SoC value in energy management in this study. The following flowchart depicts the energy management strategy employed.

As we can see from the flowchart, the concept of energy transfer is achieved using an effective control algorithm. The main object of the control method used here is to regulate the voltage of the DC bus equal to 400 V. The bidirectional DC–DC convert shown in Fig. 7 represents the principal element for energy management. The bidirectional converter is used to keep the energy balance of the microgrid system by charging or discharging the battery and works as a boost converter when the voltage of the DC bus is less than 400 V, and energy flow is from the battery to the bus. In the other direction, the converter works as a buck and charges the battery when the voltage of the bus is more than 400 V to store the surplus energy, consequently, regulating the voltage at the bus (Fig. 11).

Results and discussion

The studied small hybrid wind–solar battery technical details are described in Table 8.

The electricity produced with renewable sources is not stable with time due to the intermittent of renewable energies. Therefore, it results in two different modes of processing which are the surplus or absence of energy at the DC bus. The proposed
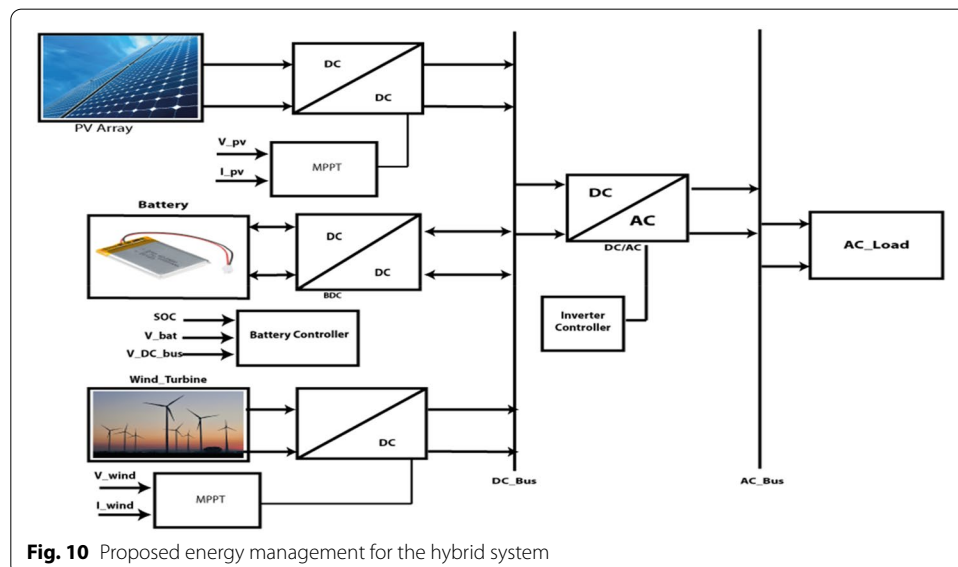
**Fig. 10** Proposed energy management for the hybrid system

Fig. 11 Flowchart of energy management strategy
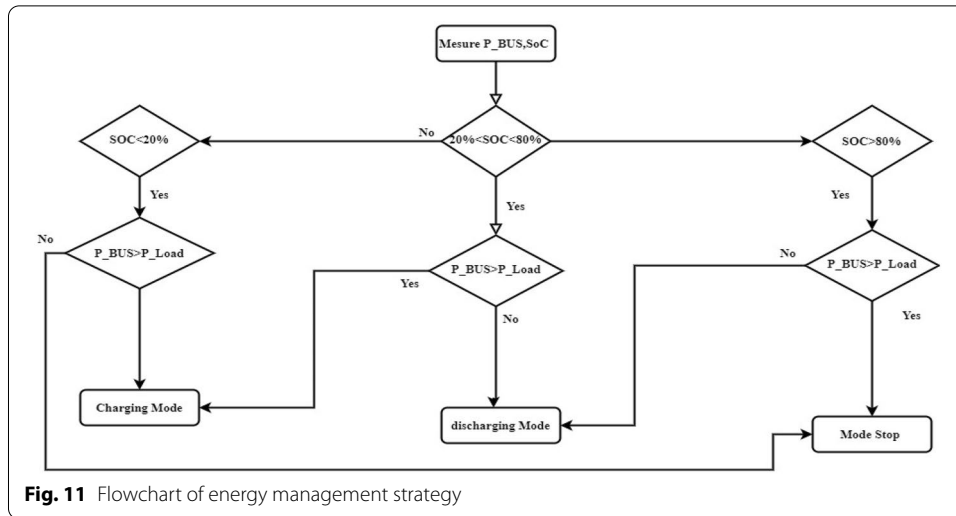
Table 8 Small hybrid wind–solar battery technical details

Symbol	Specification
DC_BUS	$V = 400\,V$
Battery	Type: Li-ION $V = 48\,V$; $Q\_batt = 30AH$
PV PANEL	TYPE: Sunpower SPR-250 NX-BLK-D Ns: 8, Np = 7
Wind turbine	$P\_W = 2\,KW$
Load	$P\_LOAD = 5\,KW$

single-phase hybrid energy system is simulated using MATLAB. The hybrid system has isolated DC sources. In this simulation, each energy source is connected with a boost converter to extract the maximum puissance from each source. So, the P&O MPPT technique is used for tracking the maximum voltage and current for the PV panel and wind turbine. The simulation runs for 3 s with 1e-5 sampling time, to present the voltage at the DC bus for different values of solar irradiation and wind speed. To show the robustness of our management strategy against the cruel variations of the meteorological condition, we have selected different scenarios containing multiple irradiation changes to represent all possible scenarios as we can see in Figs. 12 and 13.
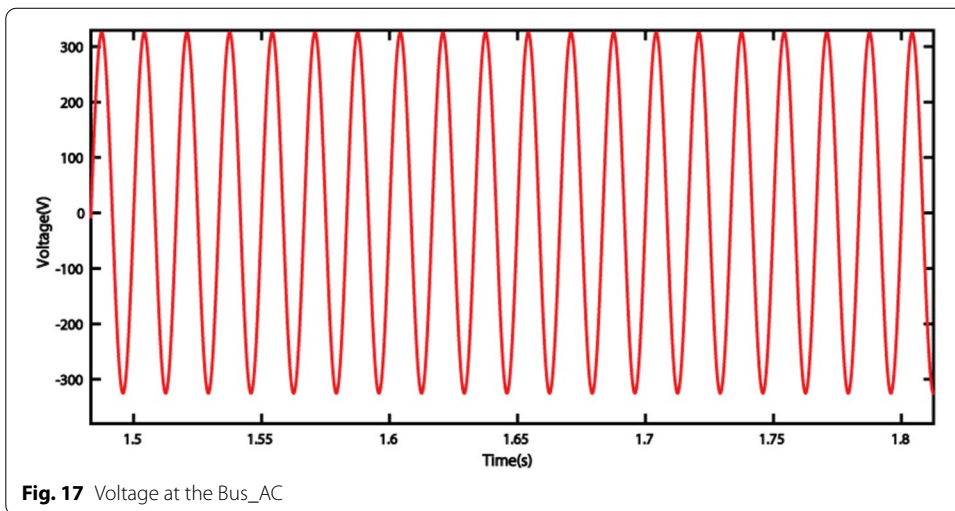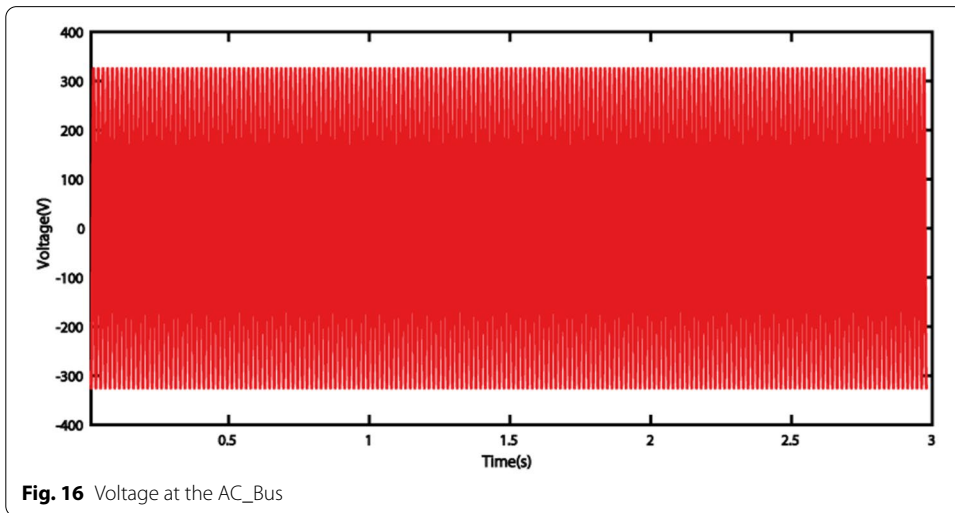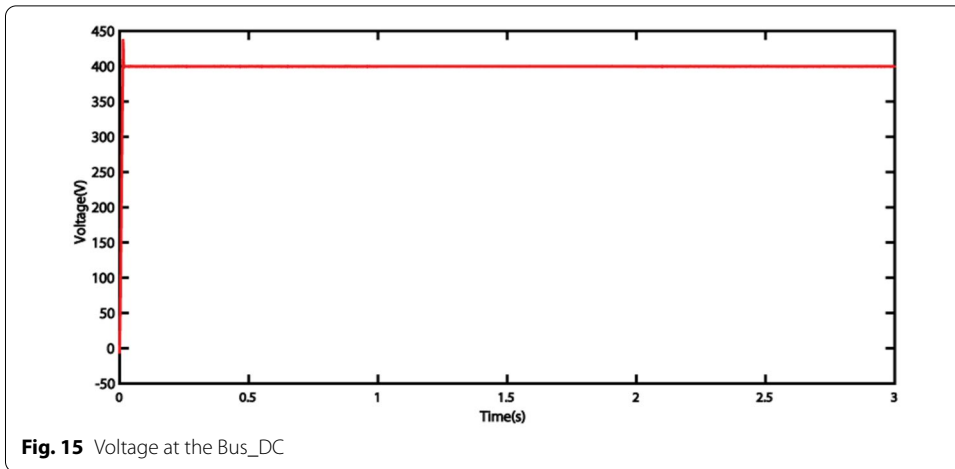
As we can see from Figs. 12 and 13 two proposed scenarios for the irradiation and the wind speed for three seconds. Figure 14 shows the variation of battery SoC during the proposed scenario.

As previously stated, the battery will be used in the event of an unbalanced system. As a result, as demonstrated in Fig. 14, the curve of the battery SoC decreases at this time, indicating that the battery provides power to the system to maintain the power balance between production and load demanded. The SoC curve declined more than the beginning because of the decrease in irradiation and wind speed values. Figure 15 shows the variation of the bus DC voltage during the simulation, we can see the effectiveness of the energy management strategy in the stabilization of the DC bus voltage.

Fig. 12 Solar irradiation scenario with (W/m²)

Fig. 13 Wind speed scenario with (m/s)

Fig. 14 Battery SoC
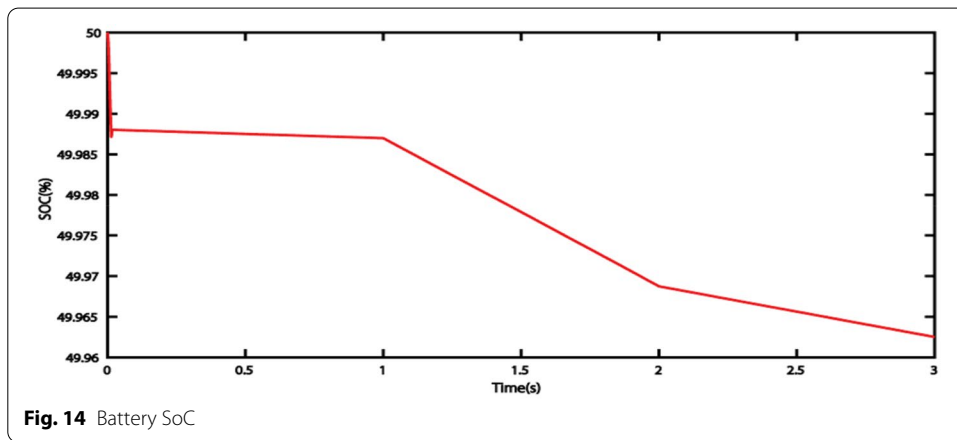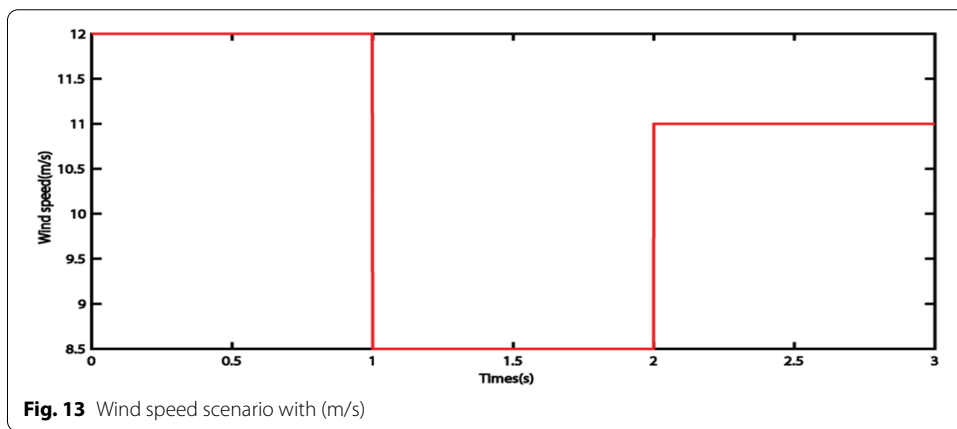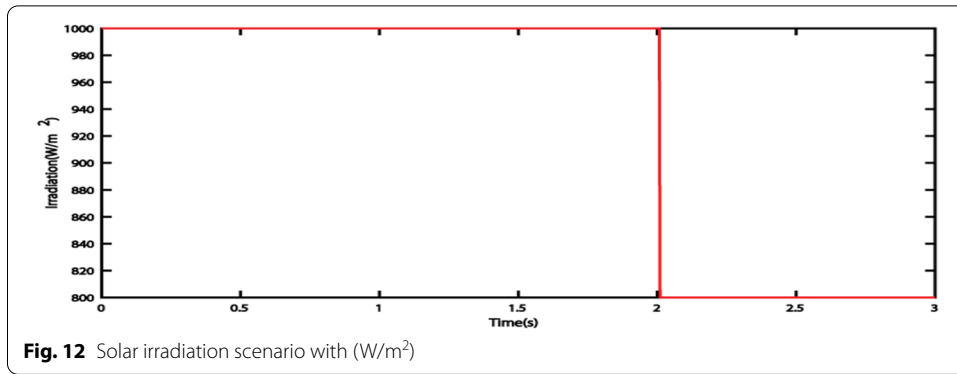
The load AC is coupled to the bus AC using DC/AC converter; Fig. 16 shows the voltage at the load AC during simulation.

Figure 17 shows a small interval between 1.5 and 1.8 to show the signal sinusoidal 230 V of the voltage at the AC_Bus.

Fig. 15 Voltage at the Bus_DC

Fig. 16 Voltage at the AC_Bus

Fig. 17 Voltage at the Bus_AC

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Conclusion

This paper has reviewed an understanding of the issues and possibilities associated with integrating solar PV and wind energy sources for energy production. The key obstacle for the stand-alone system is the intermittent existence of solar PV and wind sources. By integrating the two resources into an optimum microgrid, the DC bus or AC bus with an energy storage system as a backup system, the impact of the variable nature of solar and wind resources can be partially resolved and the overall system becomes more reliable and economical to run. This report presents the hybrid microgrid system, composed of multiple renewable energy resources. These renewable energy resources include a 2-kW solar plant, 2 kW for the wind turbine, and 2 kW provided using the battery system. The output voltage of each system has been connected to the DC bus to provide 400 V at the DC bus. Inverter input is powered by DC bus bar voltage. The full-bridge inverter converts direct current (DC) to alternating current (AC) and is controlled in an open loop. The system has been tested with a variety of wind speeds and PV panel irradiance values. The results show the robustness of the proposed system in synchronizing the AC output voltage, frequency, and amplitude of the load AC. The system has produced the desired outcomes. The voltages at the converters' outputs, despite variable variations (solar irradiation and wind speed), were observed as a result of the analysis to quickly reach the reference voltage of 400 V and remain stable at this value, thanks to the proposed control algorithms (MPPT-PID) proposed on the DC bus bar side.

Declarations

Competing interests

The authors declare that they have no competing interests.

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