# Power Management, Control and Optimization of Photovoltaic/Battery/Fuel Cell/Stored Hydrogen-Based Microgrid for Critical Hospital Loads

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## Abstract

Renewable-energy-based DC microgrids are acting as a possible replacement for the diesel-generator-based stand-alone power systems for critical loads as they are environment friendly, efficient and reliable. Research attention is required on optimization and effective power management of DC microgrids to address power failures and affordability issues. This paper performs optimization and proposes a power management strategy for a DC microgrid consisting of Solar PV/battery/fuel cell and stored hydrogen. A suitable case study is implemented in HOMER (Hybrid Optimization of Multiple Energy Resources) to check the feasibility of the proposed system configuration for the remote location of North India (74.75° E and 34.05° N). The HOMER is used to evaluate the best system configuration in size and cost per unit of energy. A custom-based power management algorithm is suggested to enhance the proposed microgrid topology scope for any given site. The custom-based power management algorithm helps in effectively

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sharing the critical load demand among the various renewable power sources, considering the various parameters like battery state-of-charge (SOC) and availability of solar photovoltaic power. Time-domain simulations are performed to check the proposed custom-based power management algorithm's microgrid response and effectiveness considering random solar irradiance profile and various operating modes. It is assumed that hydrogen is available in the tank and supplied to the fuel cell at a constant flow rate for the time-domain simulations. The contribution of this work is to describe the application of renewable-energy-based DC microgrid in electrifying ventilator critical loads, where load shedding is not feasible and neither allowed. The optimization results indicate the economic feasibility with the best optimal system configuration providing electricity at $ 0.186 with a total NPC of $83103. Time-domain simulations are performed in MATLAB/Simscape software and the results indicate the technical feasibility of electrifying the ventilator loads through the proposed renewable-energy-based DC microgrids.

**Keywords:** Optimal sizing and costing, power management, solar photovoltaic, hydrogen fuel cell, battery, DC microgrid, critical loads.

## 1 Introduction

A microgrid is a combination of different power sources, energy storage systems and loads [1]. These power sources, loads, and energy storage systems can be AC and DC types that broadly classifies microgrids as AC, and DC microgrids [2]. Energy storage systems are integrated with microgrids to store energy during off-load periods and supply energy during peak or transient periods. In addition to their fundamental uses, they are also used to overcome the slow dynamic response of some power sources like fuel cells when responding to transient or load switching [3]. Due to the production of $CO_2$ and other emissions, diesel-generator-based hybrid systems are no longer encouraged to supply power in campuses, remote villages, and critical loads like hospitals or defence establishments. Unlike the conventional power plants, which are centralized and do not allow consumer participation in power generation, microgrids are decentralized, diverse, de-carbonized and democratic.

Although microgrids have many advantages associated with them, as discussed above, they have a limitation of the high initial cost. Research attention is needed on the optimization front that will help in optimal sizing and costing of microgrids. Apart from optimal sizing and costing, other objectives in microgrid optimization can be energy performance and environmental protection (minimum emission level). As per the recent literature, many optimization techniques and tools like Genetic Algorithm [4], particle swarm algorithm [5, 6], linear programming [7], stochastic optimization [8] ant colony optimization [9] etc., have been proposed for microgrid optimization. The disadvantage of these techniques is that they have a complex programming process. At present, the software tools used for the optimization process of microgrids are RETscreen, PVSyst, Hybrid 2, iHOGA, TRNSYS, HOMER etc. Among these software tools, HOMER (Hybrid Optimization of Multiple Energy Resources), designed by the US's National Renewable energy laboratory, has an easy process and is used for techno-economic analysis of microgrids [10, 11]. In HOMER, the simulation time step is an hour that suits the microgrid optimization, simulation and sensitive analysis for carrying the detailed yearly analysis of the hybrid power systems [12–14]. In [15], techno-economic analysis of the grid-connected photovoltaic system, fuel-cell and battery-based system was performed using HOMER optimizer for combined heat and power to hospitals located in Malaysia. Authors in [16] performed optimization for an islanded microgrid using HOMER for different load dispatch strategies. From these techno-economic analyses, the takeaway is that the results obtained through HOMER are helpful and acceptable for microgrid optimization. It is encouraged to use HOMER for microgrid optimization while designing microgrids for various applications like residential buildings, electric vehicles, electric ships, electric aeroplanes, defence establishments, data centres etc.

As per the available literature on microgrids, many hybrid systems have been proposed for islands, campuses, remote areas etc. Mahmoud Saleh et al. [17] have studied the implementation, design, control and power-management strategies of DC microgrids for campus electrification. Shigong Jiang et al. [18] developed the power-management plan for PV-based hybrid systems utilizing energy storage devices. Different power-management strategies have been proposed for the successful operation of hybrid systems [19–22]. Various control strategies have been developed to control the power-electronic converters during the closed-loop and dynamic operation of the hybrid systems [23–25]. The role of energy storage devices in hybrid systems for stability, control, load levelling, energy-saving and uncertainty mitigation has been discussed [26, 27]. Different energy storage systems have been used in hybrid systems, as each of these has certain advantages over the others in a particular application [28]. In [29], a new power management control and delivery architecture were developed for the parallel operation of fuel cells and batteries. This new power management algorithm helped in active and passive charging of the battery based on the power difference between fuel cell and motor power rating and ensured the safety of the hybrid system for electric aircraft. So based on the literature, it is concluded that different applications demand different microgrid topology and custom based power management algorithms. The electrification of critical loads like hospitals has, till now, received less attention. This paper proposes a hybrid system topology and custom based power management algorithm for electrifying critical hospital ventilator load.

In hybrid power plants, power generation is mainly made from renewable energy sources like fuel cells, solar power, wind power etc. These renewable-energy-based hybrid systems are challenging to control as they involve a lot of decision or control variables and, hence, require advanced controllers and modern tools for analysis purposes [30–32]. Apart from control, optimization of such hybrid systems also needs non-linear, mixed-integer programming techniques involving continuous, discrete, and binary decision variables. The main objectives like system reliability (by overcoming system uncertainties), increasing overall profit and reducing the levelized cost of electricity cannot be achieved simultaneously. There is a need to prioritize, e.g. for supplying electricity to hospitals and defence establishments; reliability is primarily essential.

Post COVID-19 pandemic, renewable-energy-based hybrid systems will receive long-term support from the public and private sectors to pace up the power generation from these power sources citing pollution and other environmental factors. Many people lost their lives during the pandemic because of viral infection. However, many cases were reported across the world where people lost their lives because of power failure [33–35]. The main reasons for the power failure were regular maintenance, faults, and in some cases discharging of the battery bank. This has been the motivation of the present work to develop a hybrid power system to supply uninterrupted power to hospitals so that life-saving gadgets like ventilators, oxygen supply systems etc., do not fail to operate. In this paper, the main contributions are as follows:

- From the point of view of critical Hospital loads, DC microgrid topology is proposed. The DC microgrid should address the issue of power failures and should be operated in such a way that it overcomes uncertainty associated with solar PV power and battery deep discharging.

- As a real case study, optimal sizing and costing followed by simulation of the proposed microgrid topology is performed for a remote north India (Srinagar, J&K) location.
- Custom based power management algorithm is proposed for power balance and coordination among the various power sources and battery storage.
- Time-domain simulations are performed to evaluate the effectiveness of the power management algorithm for the proposed DC microgrid topology. Closed-loop control with reference signals generated from power management algorithm is developed for DC-DC converter interfacing power sources with the DC bus.

The organisation of the paper is as follows. Section 2 illustrates the proposed hybrid system topology with a description of the system components. The optimization process that gives the best optimal sizing and costing is explained in section 3. The power management and control algorithm are given in section 4. Section 5 presents the power electronic interfacing of the different power sources linked with the DC bus. The results of the time-domain simulation of the proposed hybrid energy system are present in section 6.

## 2 System Topology and Component Description

Figure 1 shows the topology of the proposed hybrid system for electrifying DC critical loads. The PV system and fuel cell are the primary energy sources, and the battery energy storage system is used to provide power balance between the energy sources and load. DC-DC converters are used to interface the various components of the hybrid system and control power flow between them. In addition to increased system reliability, the proposed hybrid system has zero carbon emissions and does not produce any noise.

For optimal sizing and least cost of electricity, benchmark optimization software HOMER (Hybrid Optimization of Multiple Energy Resources) was used [36–38]. HOMER uses non-derivative evolutionary optimization algorithms to find the best optimal sizing after doing the search through different sizes (search space) of system components [39]. The drawback of HOMER software is that it is not capable of performing system stability analysis, transient analysis, and voltage control [2].

Power management strategies, control algorithms, and optimisation are the heart of effective microgrid operation. A custom-based power dispatch

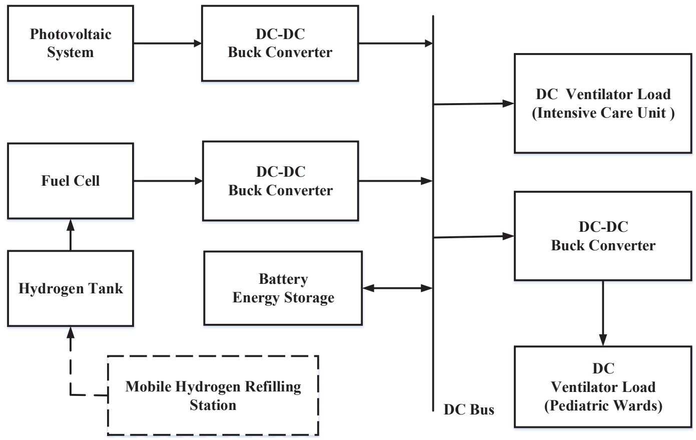



**Figure 1** Block diagram of the proposed hybrid system.

algorithm was implemented in MATLAB/Simscape environment for the proposed hybrid system to achieve load-following while maintaining the system parameters within specified limits.

## 2.1 Photovoltaic System

A solar PV system converts solar energy directly into electric energy. The disadvantages of solar photovoltaic are its low efficiency and high panel cost. However, due to mass-scale manufacturing, its price has been reduced considerably. The practically silicon-based solar cell is used, with an efficiency of 20–25%. However, due to the advancement of nanotechnology, the efficiency of a solar cell is expected to improve. For the simulation of the proposed hybrid system, the single-diode model of PV cell is used [23,40]. To operate the PV system at its maximum power point on the P-V characteristics, perturb and observe algorithm is employed due to its ease of implementation and quickly tracking the maximum power point [41]. Some other MPPT techniques can be found in [42]. The simulation parameters of the PV array and its associated DC-DC converter for the time-domain simulations are given in Table 1.

## 2.2 Fuel Cell

Fuel cells are excellent backup power sources compared to diesel generators as they have high efficiency, high reliability, and silent operation [43].

**Table 1** PV array and converter specifications

| | |
|---|---|
| Module type | 1soltech 1STH-215-P |
| Maximum power (W) | 213.15 |
| Voltage at MPP (V) | 29 |
| Current at MPP (A) | 7.35 |
| Cells per module | 60 |
| Series connected modules per string | 2 |
| Parallel strings | 20 |
| **PV DC-DC Converter** | |
| Input capacitor | 3000 $\mu F$ |
| Output capacitor | 4000 $\mu F$ |
| Inductor | 10 mH |

Different types of fuel cells are available in the market. However, due to excellent load-following capability, proton-exchange-membrane fuel cells (PEMFC) are preferred for standalone power systems [22]. For time-domain simulations, PEMFC is modelled as a controlled voltage source in series with internal resistance; the simulation parameters for the fuel cell stack and its associated DC-DC converter are given in Table 2.

## 2.3 Battery Energy Storage

Many different types of batteries are available in the market. Still, for microgrids, a Lithium-ion battery is recommended due to its advantages like high efficiency, low self-discharge, high energy density and lightweight compared to Nickel Cadmium batteries. The battery is modelled as a current-controlled voltage source in series with internal resistance to validate the power dispatch and control algorithm. The critical parameters that indicate the charge level of a battery are its voltage and state of charge [44]. Equation (1) gives the state of charge of the battery [45], where Q is the maximum battery capacity. The lifetime of a battery, i.e. the time in which a fully charged battery will be discharged altogether, is given by Equation (2). Table 3, provides the battery parameters for time-domain simulations.

$$SOC(t) = 100(1 - \frac{1}{Q}\int_0^t i(t)dt) \tag{1}$$

$$\textit{Life time} = \frac{\text{Battery Capacity}}{\text{Battery Current}} \tag{2}$$

**Table 2** Fuel cell stack and converter specifications

| | |
|---|---|
| Model type | PEMFC-6kW-45 Vdc |
| Maximum operating current | 225 A |
| Maximum voltage | 65 V |
| Number of cells | 65 |
| Nominal stack efficiency | 55 % |
| **Fuel Cell Nominal Parameters** | |
| Nerst voltage of one cell | 1.1288 V |
| Nominal hydrogen utilization | 99.56% |
| Nominal oxidant utilization | 59.3% |
| Fuel cell resistance | 0.07833 ohms |
| Nominal fuel consumption | 60.38 slpm |
| Nominal air consumption | 143.7 slpm |
| Fuel composition | 99.95% |
| Oxidant composition | 21% |
| System temperature (T) | 338 K |
| Exchange current | 0.29197 A |
| Fuel supply pressure | 1.5 bar |
| Air supply pressure | 1 bar |
| **Fuel Cell Stack DC-DC Converter** | |
| Input capacitor | 4000 $\mu$ F |
| Output capacitor | 5000 $\mu$ F |
| Inductor | 10 mH |
| Fuel cell response time | 1.1 s |

**Table 3** Battery simulation parameters

| | |
|---|---|
| Battery type | Lithium-Ion |
| Nominal voltage | 46 |
| Initial state of charge | 89 % |
| Rated capacity | 40 Ah |
| Battery response time | 0.002 s |

## 2.4 Stored Hydrogen

Hydrogen stored in hydrogen tanks helps overcome the intermittent nature of non-dispatchable power sources like solar photovoltaic or wind power. In fuel-cell-based hybrid systems, in case solar photovoltaic power is absent, a fuel cell can be operated for hours, days or even for the seasons, depending on the hydrogen stored in the tank [46]. Hydrogen can be generated on-site or off-site through water electrolysis or steam reforming. If generated through water electrolysis and by utilising renewable power, it is considered a green fuel; otherwise, it is blue or brown. Hydrogen production through water electrolysis has many components like an electrolyser and compressor that adds cost to the standalone system.

No on-site hydrogen generation has been considered; the hydrogen tank is refilled at regular intervals via a mobile hydrogen production system. Hydrogen generation should not be part of the standalone hybrid system installation to encourage fuel-cell-based hybrid systems. Instead, the refilling agency should own the tank. It is recommended that the refilling agencies should merge all the other costs like delivery charges, generation cost, and tank rent to fix the price per kg of $H_2$. As per the current literature, the price per kg of $H_2$ is $ 0.96, and the hydrogen tanks are kept at different pressure levels like 300 bar, 137 bar, 700 bar [47].

### 2.5 Critical DC Load Profile

Critical services like hospitals, communication, and defence establishments have a fairly constant-load profile compared to domestic load profiles. The ventilator load of hospitals is a critical DC load. Ventilators used in pediatric wards typically have a power rating of 40 W with a voltage rating of 16–24 V. However, ventilators used in intensive care units have a power rating of 80 W with a voltage rating of 24-50 V [48]. The ventilators power consumption in intensive care units is considered for designing the proposed hybrid system. The number of such ventilators in most existing healthcare facilities is around 10. However, considering the COVID-19-like global emergency, there is a need to upgrade the number of ventilators in hospitals to about 50. Power requirement for such 50 ventilators would be equal to 4000 W. This load is present on the proposed hybrid power system continuously with $\pm 5\%$ variation due to switching on and off of ventilators. Hence, the proposed hybrid power system is designed and controlled to supply a constant load of 4000 W.

## 3 Microgrid Optimization: A Real Case Study of Remote North India

Optimization is the key to the effective utilization of available resources. In this paper, the main objective of the optimization process would be to obtain the system configuration that yields a minimum per unit cost of energy subject to user-defined constraints like system-component sizes and quantities, cost of system components and dispatch strategies. The other system constraints taken into consideration are; maximum annual capacity shortage is taken as

(0%), and operating reserve as a percentage of renewable output (solar power) is taken as (15%). The best optimal system configuration is the one whose net present cost (NPC) & cost of electricity (COE) are minimum [2,49,50]. NPC and COE are calculated in HOMER using the following equations:

$$NPC = \frac{C_{annual,t}}{CRF_{i,R_p}} \tag{3}$$

$$CRF(i,N) = \frac{i(1+i)^N}{i(1+i)^N - 1} \tag{4}$$

$$COE = \frac{C_{annual,t}}{E_p + E_d + E_{g,sales}} \tag{5}$$

where CRF is the capital recovery factor, $C_{annual,t}$ is the annual total cost, $i$ is the annual interest rate, $R_p$ is the project lifetime, $N$ is the number of years, $E_p$ is the primary load served, $E_d$ is the deferred load and $E_{g,sales}$ is the energy exchange with grid. $E_{g,sales}$ is considered to be zero for systems that work in standalone mode.

### 3.1 Input Data for Optimal Sizing and Costing

Optimal sizing and costing depend on parameters like geographical location, solar irradiance, wind speed, sunshine hours, availability of fuel, load demand etc. In order to check the economic and technical feasibility of the proposed hybrid system for hospital electrification, a case study was performed for a geographical location with longitude and latitude equal to $74.75°$ E and $34.05°$ N (Srinagar, J&K, India) respectively. The monthly average solar irradiance profile for this location is given in Figure 2 [51].

HOMER performs hourly-based, time-series simulations over a year, considering different system configurations, operating strategies and constraints. The operating method used in the simulation was load-following. Among the simulated designs, technically feasible are those that match the load demand as per the operating strategy over a given lifetime and economically viable are those that are primarily technically feasible and at the same time incur a minimum cost of electricity. The size and cost details of the system components of the proposed hybrid topology used for the optimization process are given in Table 4. In choosing the cost of the system components for the microgrids, care needs to be taken as the prices vary from company to company due to the rapid research and development activities. The price also varies due to the competition in renewable energy sales markets. In addition to the cost of

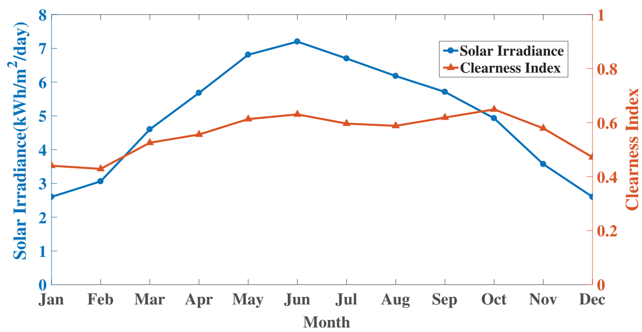



**Figure 2** Monthly average solar irradiance.

**Table 4** Data of system components for optimization

| Solar Photovoltaic | | | |
|---|---|---|---|
| Cost/kW | Capital ($) | Replacement ($) | O&M ($) |
| | 800 | 800 | 2 |
| Sizes to consider | 15 kW, 20kW, 35kW, 45 kW, 50 kW | | |
| Lifetime | 25 years | | |
| **Fuel Cell** | | | |
| Cost/kW | Capital ($) | Replacement ($) | O&M ($/hr) |
| | 2500 | 2300 | 0.067 |
| Sizes to consider | 3 kW, 4kW, 5kW | | |
| Hydrogen tank sizes | 500 kg, 1000 kg, 2000 kg, 3000 kg, 5000 kg | | |
| **Battery** | | | |
| Cost/battery | Capital ($) | Replacement ($) | O&M ($/yr) |
| | 85 | 85 | 0.85 |
| Number of batteries to consider | 20, 32, 40, 48 | | |
| Number of batteries per string | 4 | | |
| Voltage rating/battery | 12 V | | |
| Nominal capacity | 55 Ah | | |
| Battery Type | Vision 6FM55D | | |

system components, the size and cost of the hydrogen tank vary with specific parameters like days of autonomy, refilling time, tank storage pressure, etc.

## 3.2 HOMER-based Optimization and Simulation Results

A large population of the candidates given in Table 4 was simulated in HOMER using load-following (LF) dispatch strategy. There are many other dispatch strategies like cycle charging and combined dispatch also available. However, for the critical loads load following strategy is used. Some of the optimal design configurations obtained are shown in Table 5, with OD1 as the

**Table 5** Optimal designs

| Optimal Design | PV (kW) | Fuel Cell (kW) | Battery Vision 6FM55D Quantity | Hydrogen Tank (kg) | Dispatch Strategy | NPC ($) | LCOE ($) |
|---|---|---|---|---|---|---|---|
| OD1 | 45 | 4 | 40 | 3000 | L.F | 83103 | 0.186 |
| OD2 | 45 | 4 | 40 | 2000 | L.F | 83103 | 0.186 |
| OD3 | 45 | 4 | 48 | 3000 | L.F | 84372 | 0.189 |
| OD4 | 45 | 4 | 48 | 2000 | L.F | 84372 | 0.189 |
| OD5 | 35 | 5 | 20 | 3000 | L.F | 84943 | 0.190 |
| OD6 | 35 | 5 | 20 | 2000 | L.F | 84943 | 0.190 |
| OD7 | 35 | 5 | 32 | 3000 | L.F | 85061 | 0.190 |
| OD8 | 35 | 5 | 32 | 2000 | L.F | 85061 | 0.190 |
| OD9 | 35 | 5 | 40 | 3000 | L.F | 86275 | 0.193 |
| OD10 | 35 | 5 | 40 | 2000 | L.F | 86275 | 0.193 |
| OD11 | 50 | 4 | 40 | 3000 | L.F | 86386 | 0.193 |
| OD12 | 50 | 4 | 40 | 2000 | L.F | 86386 | 0.193 |
| 0D13 | 35 | 5 | 48 | 3000 | L.F | 87535 | 0.196 |
| 0D14 | 35 | 5 | 48 | 2000 | L.F | 87535 | 0.196 |

**Table 6** Important features of OD1

| | |
|---|---|
| PV array production | 40% |
| Fuel cell production | 60% |
| Excess electricity | 8.05% |
| Unmet electric load | 0 |
| Hydrogen consumption | 1139 kg/yr |
| Initial capital cost | $ 49400 |
| Operating cost | $2637/yr |
| Pollutant emission | 0 |

most optimal design configuration. OD1 is the most optimal system configuration as it yields the minimum NPC and LCOE values. Table 6 gives some essential features of the optimal design OD1. If we discuss some of the vital elements of OD1, this system configuration meets the load demand accurately with surplus power, indicating the high reliability of the system configuration. Since the system is associated with a hybrid combination of battery and fuel cell, this helps overcome the intermittency associated with solar power. At the same time, it also helps the system to take care of the load switching. The presence of a fuel-cell stack guarantees a long time autonomous operation in the absence of solar PV power for a long time. In addition to increased system reliability, this system configuration has a minimum levelized cost of energy and pollutant emission level is zero. Thus OD1 can be declared as economically viable and environmentally friendly. Figures 3 and 4 depict the average monthly electricity production and the monthly average of minimum hydrogen stored in the tank from the most optimal design (OD1). Analysing the Figure 3, the average power curves show that both solar PV and fuel-cell

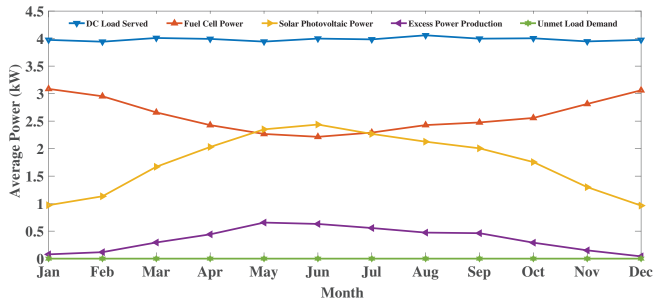



**Figure 3** Monthly average power generation and load demand served.

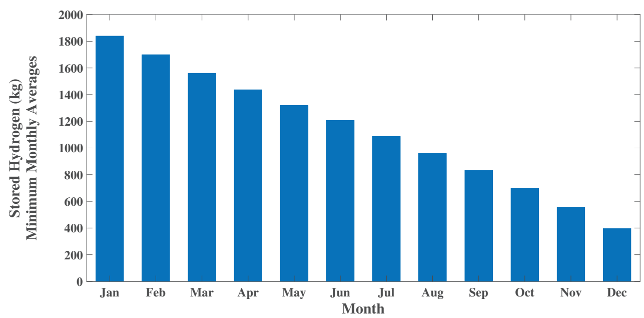



**Figure 4** Stored hydrogen monthly average (minimum levels).

power are aiding one another to meet the power load demand. If solar PV power is not available, the battery immediately takes care of the load demand. The fuel cell is turned on when its SOC falls below the minimum allowed limit. Thus, the role of the battery is to overcome the intermittency associated with the PV power and aid the fuel cell operation. Based on the HOMER simulation results, many benefits are associated with the method adopted for electrifying the critical hospital loads; these benefits are given as under:

- Uninterrupted power is supplied to the critical loads with maximum utilisation of solar PV power.
- The hybrid energy storage consisting of battery and fuel cell helps overcome the intermittency associated with solar PV power.
- The proposed system configuration does not produce sound as it has all static components.
- The proposed system configuration does not produce any carbon emissions.
- Hospitals and health centres can locally utilise fuel cell operation by-products (hot water and heat).

- The system is not grid dependent hence can be deployed to any geographical location.

## 4 Custom Power Management and Control Algorithm

Before discussing the proposed power management algorithm, it is crucial to understand what custom design means and why is it important? Custom design means to develop some algorithm, strategy, control etc., where design depends on the pre-defined specifications or objectives that one wants to achieve. Through these custom designs, human intelligence can be added to the machines to be operated and controlled well to overcome system uncertainties. One such custom power management and control algorithm is proposed for the microgrid topology already discussed. Time-domain simulations are carried for the proposed microgrid topology with the simulation parameter of each system component given in the section 2. The readers should not get confused why the optimal system configuration obtained in section 3 was not used to carry out the time-domain simulations. The reason is straightforward that HOMER obtained the optimal system configuration through yearly simulations with a time step of 1 hour. It is time-consuming to perform time-domain simulations of microgrids with switched circuits of power electronic converters in sim power systems. In order to perform simulations quickly scaled-down battery size, low range between minimum and maximum SOC limits and other components are chosen because our primary importance is to verify and demonstrate the system response for different operating modes and to check the effectiveness of the proposed power management and control strategy.

The goal of the power management algorithm in the hybrid energy systems is to serve uninterrupted power supply to load and generate the reference power commands for the respective power sources [21]. There are various uncertain parameters in renewable-based hybrid energy systems like solar irradiance, wind speed, and load changes. When these uncertain parameters change with time, there is an imbalance in the power generation and load demand in the system, which demands the development of efficient power management algorithms [24, 52, 53]. Power management algorithm helps to run the system in different operating modes by turning on and off various power sources and energy storage devices within their power limits in the system [20, 54]. The proposed power management algorithm for operating the hybrid energy system is given in Algorithm 1.

**Algorithm 1** Power Management and Control Algorithm

1: The overall power-balance equation for the proposed hybrid system is given by

$$P_{PV} + P_{FC} \pm P_B = P_L \tag{6}$$

2: If photovoltaic power is absent i.e $P_{PV} = 0$, there are two choices to meet the load demand.
C1: Battery is passively connected to DC bus and is assumed to be fully charged at its maximum SOC. Therefore, the battery becomes the natural choice to supply load demand.

$$P_B = P_L \tag{7}$$

C2: When battery SOC reaches to its lower SOC limit, fuel cell is controlled to turn on and take up the load demand.

$$P_{FC} = P_L \tag{8}$$

3: If photovoltaic power is less than the load demand ($P_{PV} < P_L$), there are two choices to meet the load demand.
C1: The load demand will be shared between the solar photovoltaic power and battery power, subject to a condition that battery SOC is above the minimum allowed SOC Level. Here the battery is in discharging mode of operation.

$$\text{If} \qquad Bat_{SOC} \geq SOC_{min} \,,$$

$$P_{PV} + P_B = P_L \tag{9}$$

C2: The load demand will be shared between solar photovoltaic power and fuel cell when battery SOC is below the minimum allowed SOC level.

$$\text{If} \qquad Bat_{SOC} \leq SOC_{min} \,,$$

$$P_{PV} + P_{FC} = P_L \tag{10}$$

$$P_{FC,ref} = P_L - P_{PV} \tag{11}$$

$$I_{FC,ref} = \frac{P_{FC,ref}}{V_{FC}} \tag{12}$$

4: If photovoltaic power is more than load demand ($P_{PV} > P_L$). This is possible only when there is high solar irradiance or low load demand. In this case, keep fuel cell in off mode and battery in charging mode.

$$P_{FC} = 0 \tag{13}$$

$$P_{PV} - P_L = P_{Bat} \tag{14}$$

5: If PV power is more than load demand and battery has reached to its maximum SOC level. PV DC-DC converter is controlled in off-MPPT mode with reference voltage given by Equation (16).
If still excess power is present, dump load is activated that prevents over-voltage across the DC bus. Dump load in the proposed hybrid system can be considered to be a boiler for water heating.

$$P_{PV} > P_L \tag{15}$$

$$\text{If} \qquad Bat_{SOC} >= SOC_{max} \,,$$

$$Vref = \frac{P_L}{I_{PV}} \tag{16}$$

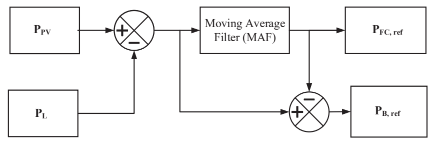



**Figure 5** Frequency separation using moving-average filter (MAF).

### 4.1 Moving-Average Filter

In the literature, low-pass filters have been frequently used to separate the high-frequency components [28]. Separating high-frequency components prevents frequent on and off of the fuel cell system, thus improving its lifetime. However, the disadvantage of a low-pass filter is that it brings lag in the system and, hence, creates stability issues [22]. Therefore, a moving-average filter is used in the proposed method to generate the power command for the fuel cell [54]. As the battery is passively connected to the DC bus, the battery supplies sharp high-frequency power components. If the battery is actively connected to the DC bus through a DC-DC bidirectional power converter, then the reference power for the battery is generated as per Figure 5.

## 5 Power-Electronic Interface and Its Control

PV array is connected to DC link via DC-DC buck converter with the primary objective of operating the PV array at the maximum power point (MPP). The solar PV system is operated at MPP till battery SOC is below the maximum limit. When the battery attains its maximum allowable SOC level, solar PV is operated at off-MPPT. During off-MPPT mode, the reference voltage is given by Equation (16). The overall control circuit for photovoltaic system is shown in Figure 6 [21].

Fuel-cell stack is interfaced to DC link via buck converter. Buck converter is designed to work in continuous-conduction mode (CCM). As shown in Figure 7, the reference current for the fuel-cell control is generated through the proposed power-management algorithm. This reference current is compared with the fuel-cell current, and the error is passed through the hysteresis-current controller, which produces the correct switching sequence for the DC-DC buck converter [55]. Hysteresis current controller (HCC) is a non-linear controller, which is fast and robust. The only disadvantage of HCC is that it has a fluctuating switching frequency and non-zero steady-state error. Linear controllers like PI, PD, and PID cannot effectively control non-linear systems like DC microgrids. DC microgrids involve multiple converters

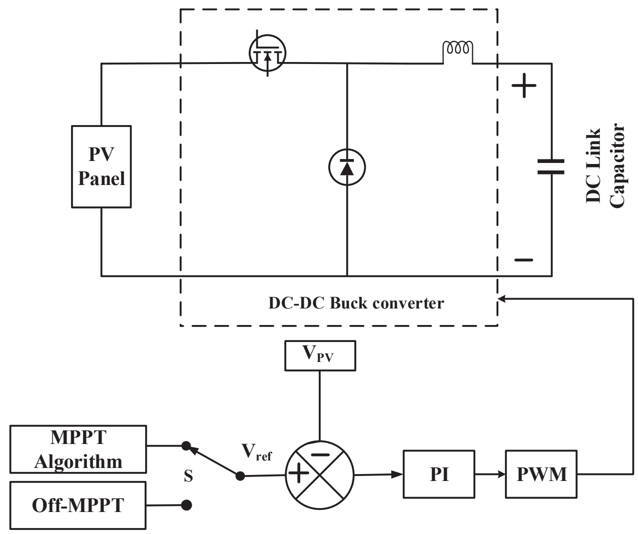



**Figure 6** Control for photovoltaic system.

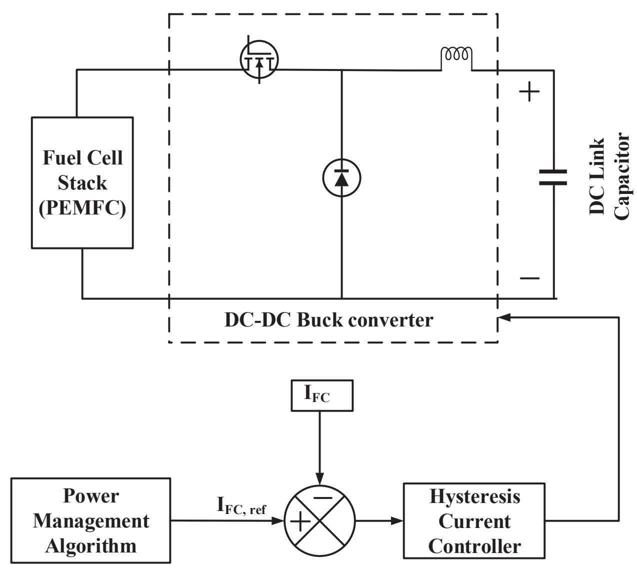



**Figure 7** Control for fuel-cell system.

(buck-boost) that bring some instability in the system in the form of chaos and bifurcation phenomena [56].

## 6 Time-Domain Simulation Results

To verify the performance of the proposed power management and control strategy, the proposed microgrid for ventilator electrification was simulated in MATLAB/Simscape environment. The simulation was run for a period of 350 s; various operating scenarios with random solar irradiance profiles, as shown in Figure 8 were simulated. The solar irradiance profile is hypothetical to verify the control action for sudden disturbances in the solar irradiance. The practical solar irradiance has a gradual rise and fall, as given in Figure 2.

The load is represented by a fixed resistor, across which voltage is maintained by a battery within a margin of 48±3 V so that it partially behaves as a constant-power load. Figures 9(a) and 9(b) depict the battery voltage and state of charge, respectively. The load is met through three different power sources under different operating scenarios as shown in Figure 10. It is initially assumed that the battery is charged at 89%, the solar power is zero, and the fuel cell is turned off. Therefore, the load is met by the battery alone. As the battery discharges and its SOC falls below $SOC_{min}$ (t = 63.5 s), the fuel cell is turned on as shown in Figure 10 (d). The fuel cell continues to supply load demand with a power output of 3945 W. At t = 100 s, the solar irradiance increases from 0 to 50 W/$m^2$ which increases the solar power and decreases the fuel-cell power by a slight margin. At t = 150 s, the solar irradiance increases to 300 W/$m^2$ which increases the solar power to 2347 W and decreases the fuel cell power to 3392 W; the battery now starts charging up to 162.7 s as shown in Figure 10(b). As the battery SOC crosses the 85% mark, pushing the fuel cell to turn off. At

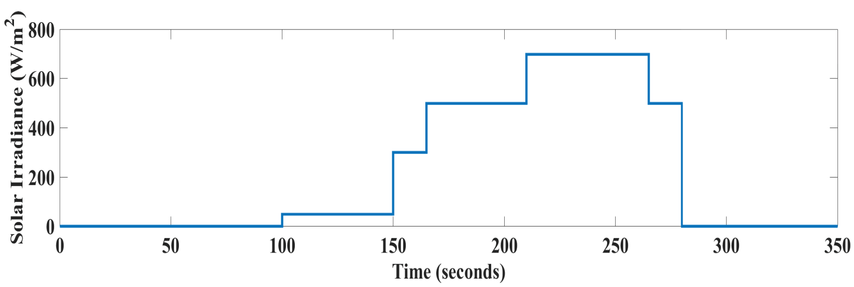
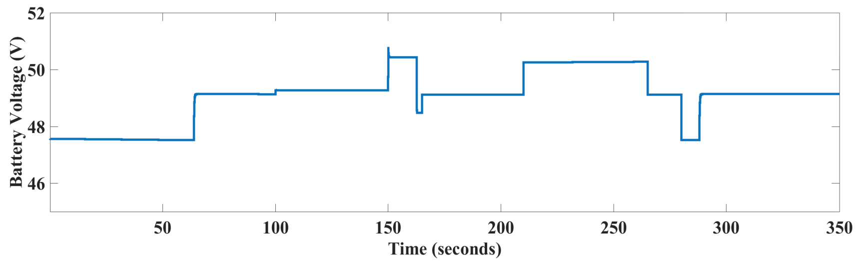
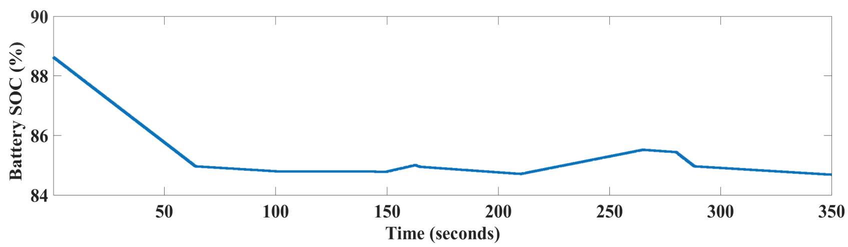



**Figure 8** Solar irradiance profile.



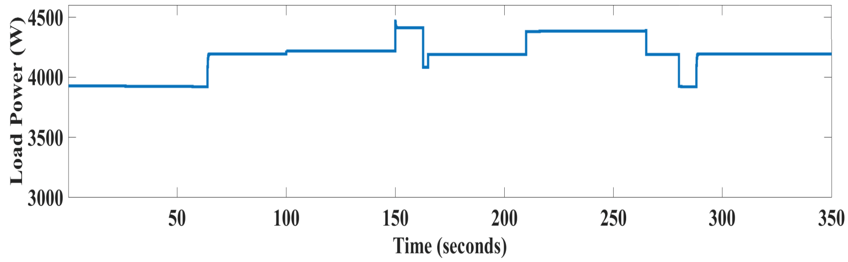

(a) *Battery Voltage* $(V_L = V_B)$



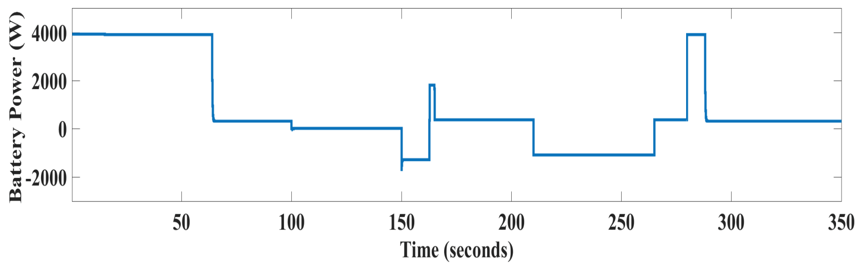

(b) *Battery State of Charge*

**Figure 9** Battery Voltage and SOC Waveforms.

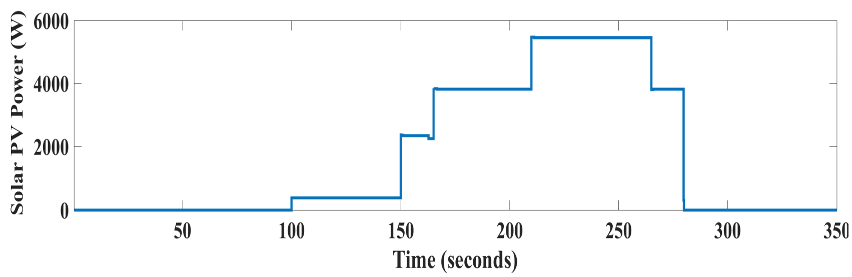
t = 165 s, solar irradiance increases further to 500 W/$m^2$ which increases the photovoltaic power to 3818 W; as the fuel cell is already in off mode, now the load demand is met by battery and solar power. At t = 210 s, the solar irradiance increases from 500 to 700 W/$m^2$, which increases the solar power to 5463 W as shown in Figure 10(c), supplying the load demand with extra power being supplied for charging the battery. At t = 265 s, the solar irradiance again decreases to 500 W/$m^2$ thereby decreasing the solar power to 3818 W. As the battery SOC is above the minimum allowed limits, the solar PV and battery continue to supply the load demand till t = 280 s. At t = 280 s, solar power decreases to zero, which pushes the battery to supply the load demand. The battery continues to meet the load demand until its SOC falls below 85% at t = 288 s. When the battery SOC falls below the minimum allowed limit, the fuel cell is again turned on to take up the load demand as the solar PV power is not available. This cycle of turning on and off different power sources continues depending on the operating scenario. In this time-domain simulation, the battery SOC limits were maintained with a small band of 85% and 89%. This is done so that the battery does not act as the main power source but provides space for switching the other power sources



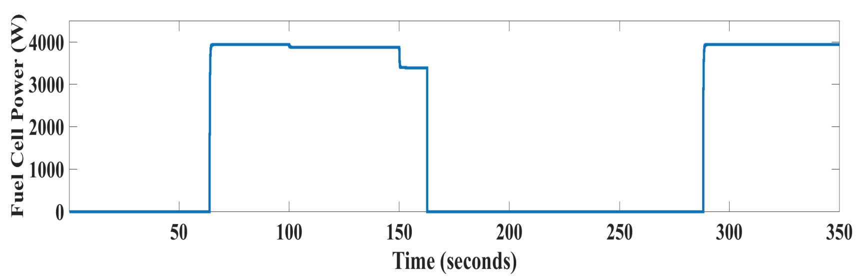

(a) *Load Power*




(b) Battery Power




(c) *Solar Photovoltaic Power*




(d) *Fuel Cell Power*

**Figure 10** Power flow waveforms.

and loads. The time-domain simulation results demonstrate that the critical ventilator load can be supplied uninterruptedly by the proposed renewable-based microgrid in a handshake with energy-storage devices like a battery and stored hydrogen.

## Conclusion

In this paper, a DC microgrid consisting of solar PV, battery and fuel cell and their associate power converters was proposed for the electrification of hospital critical loads. The critical hospital loads remain continuously on round the clock, hence requiring a continuous power supply. A suitable case study was simulated and analysed for the feasibility of the proposed microgrid topology for the remote location of North India. The best system configuration produced electricity at a minimum cost of ($0.186). The proposed power management algorithm integrated the power sources and battery storage in proper coordination for power-sharing, as revealed from the time domain simulation results. These time-domain simulations were performed under different operating scenarios and considered uncertainty associated with solar power. PV extracted maximum power from the solar energy, and the PEMFC fuel cell was properly controlled through Hysteresis current controller after receiving reference signals from the power management algorithms; the same can be confirmed from the time-domain simulation results. The overall conclusion is that the optimal system designed and managed through the proposed power management algorithm ensured uninterrupted and affordable power to critical hospitals loads during low PV and low energy reserves.

## Future Work

- In the future new optimisation algorithms should be developed, and a comparative analysis should be carried out with HOMER based results.
- Develop new protection circuits for batteries and accordingly improve power management algorithms.
- These DC microgrids have a stability problem when supplying constant power loads. Mainly when the voltage across the load is tightly regulated, it develops negative incremental impedance that becomes a reason for system instability. Future work should be carried out to design

and develop non-linear control strategies for multi converter based DC microgrids.
- To perform experimental verification and check the practical feasibility of the proposed microgrid topology.

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## References

[1] M. Farrokhabadi, C. A. Cañizares, J. W. Simpson-Porco, E. Nasr, L. Fan, P. A. Mendoza-Araya, R. Tonkoski, U. Tamrakar, N. Hatziargyriou, D. Lagos, R. W. Wies, M. Paolone, M. Liserre, L. Meegahapola, M. Kabalan, A. H. Hajimiragha, D. Peralta, M. A. Elizondo, K. P. Schneider, F. K. Tuffner, and J. Reilly. Microgrid stability definitions, analysis, and examples. *IEEE Transactions on Power Systems*, 35(1):13–29, 2020.

[2] Anastasios Oulis Rousis, Dimitrios Tzelepis, Ioannis Konstantelos, Campbell Booth, and Goran Strbac. Design of a hybrid ac/dc microgrid using homer pro: case study on an islanded residential application. *Inventions*, 3(3), 8 2018.

[3] C. Wang and H. Nehrir. Load transient mitigation for stand-alone fuel cell power generation systems. In *2007 IEEE Power Engineering Society General Meeting*, pages 1–1, 2007.

[4] Stefano Leonori, Maurizio Paschero, Fabio Massimo Frattale Mascioli, and Antonello Rizzi. Optimization strategies for microgrid energy management systems by genetic algorithms. *Applied Soft Computing*, 86:105903, 2020.

[5] Zhao Xin-gang, Zhang Ze-qi, Xie Yi-min, and Meng Jin. Economic-environmental dispatch of microgrid based on improved quantum particle swarm optimization. *Energy*, 195:117014, 2020.

[6] Mehrun Nisa, Marya Andleeb, and Bakhsh Farhad Ilahi. Effect of partial shading on a pv array and its maximum power point tracking using particle swarm optimization. In *Journal of Physics: Conference Series*, volume 1817, page 012025. IOP Publishing, 2021.

[7] Sergio Balderrama, Francesco Lombardi, Fabio Riva, Walter Canedo, Emanuela Colombo, and Sylvain Quoilin. A two-stage linear programming optimization framework for isolated hybrid microgrids in a rural context: The case study of the "el espino" community. *Energy*, 188:116073, 2019.

[8] Jamal Faraji, Hamed Hashemi-Dezaki, and Abbas Ketabi. Stochastic operation and scheduling of energy hub considering renewable energy sources' uncertainty and n-1 contingency. *Sustainable Cities and Society*, 65:102578, 2021.

[9] Farag K. Abo-Elyousr, Josep M. Guerrero, and Haitham S. Ramadan. Prospective hydrogen-based microgrid systems for optimal leverage via metaheuristic approaches. *Applied Energy*, 300:117384, 2021.

[10] Bing Han, Mingxuan Li, Jingjing Song, Junjie Li, and Jamal Faraji. Optimal design of an on-grid microgrid considering long-term load demand forecasting: A case study. *Distributed Generation and Alternative Energy Journal*, 35:345–362, 2021.

[11] Seyyed Ali Sadat, Jamal Faraji, Masoud Babaei, and Abbas Ketabi. Techno-economic comparative study of hybrid microgrids in eight climate zones of iran. *Energy Science & Engineering*, 8(9):3004–3026, 2020.

[12] Hassan Z. Al Garni, Anjali Awasthi, and Makbul A.M. Ramli. Optimal design and analysis of grid-connected photovoltaic under different tracking systems using homer. *Energy Conversion and Management*, 155:42–57, 2018.

[13] Venkatesh Boddapati and S. Arul Daniel. Design and feasibility analysis of hybrid energy-based electric vehicle charging station. *Distributed Generation and Alternative Energy Journal*, 37:41–72, 2022.

[14] Haipeng Guan, Yan Ren, Qiuxia Zhao, and Hesam Parvaneh. Techno-economic analysis of renewable-based stand-alone hybrid energy systems considering load growth and photovoltaic depreciation rates. *Distributed Generation and Alternative Energy Journal*, 35:209–236, 2020.

[15] Normazlina Mat Isa, Himadry Shekhar Das, Chee Wei Tan, A.H.M. Yatim, and Kwan Yiew Lau. A techno-economic assessment of a

combined heat and power photovoltaic/fuel cell/battery energy system in malaysia hospital. *Energy*, 112:75–90, 2016.

[16] Md. Fatin Ishraque, Sk. A. Shezan, M.M. Ali, and M.M. Rashid. Optimization of load dispatch strategies for an islanded microgrid connected with renewable energy sources. *Applied Energy*, 292:116879, 2021.

[17] M. Saleh, Y. Esa, Y. Mhandi, W. Brandauer, and A. Mohamed. Design and implementation of ccny dc microgrid testbed. In *2016 IEEE Industry Applications Society Annual Meeting*, pages 1–7, 2016.

[18] Shigong Jiang, Wei Wang, Heng Jin, and Dianguo Xu. Power management strategy for microgrid with energy storage system. In *IECON 2011 - 37th Annual Conference of the IEEE Industrial Electronics Society*, pages 1524–1529, 2011.

[19] Dimitris Ipsakis, Spyros Voutetakis, Panos Seferlis, Fotis Stergiopoulos, and Costas Elmasides. Power management strategies for a stand-alone power system using renewable energy sources and hydrogen storage. *International Journal of Hydrogen Energy*, 34(16):7081 – 7095, 2009. 4th Dubrovnik Conference.

[20] F. Nejabatkhah and Y. W. Li. Overview of power management strategies of hybrid ac/dc microgrid. *IEEE Transactions on Power Electronics*, 30(12):7072–7089, 2015.

[21] A. Merabet, K. Tawfique Ahmed, H. Ibrahim, R. Beguenane, and A. M. Y. M. Ghias. Energy management and control system for laboratory scale microgrid based wind-pv-battery. *IEEE Transactions on Sustainable Energy*, 8(1):145–154, 2017.

[22] R. K. Sharma and S. Mishra. Dynamic power management and control of a pv pem fuel-cell-based standalone ac/dc microgrid using hybrid energy storage. *IEEE Transactions on Industry Applications*, 54(1):526–538, 2018.

[23] Naziha Harrabi, Mansour Souissi, Abdel Aitouche, and Mohamed Chaabane. Modeling and control of photovoltaic and fuel cell based alternative power systems. *International Journal of Hydrogen Energy*, 43(25):11442 – 11451, 2018. Alternative Energies for Sustainability.

[24] Vaishalee Dash and Prabodh Bajpai. Power management control strategy for a stand-alone solar photovoltaic-fuel cell–battery hybrid system. *Sustainable Energy Technologies and Assessments*, 9:68 – 80, 2015.

[25] A. M. O. Haruni, M. Negnevitsky, M. E. Haque, and A. Gargoom. A novel operation and control strategy for a standalone hybrid renewable power system. *IEEE Transactions on Sustainable Energy*, 4(2):402–413, 2013.

[26] H. S. V. S. K. Nunna, A. Sesetti, A. K. Rathore, and S. Doolla. Multiagent-based energy trading platform for energy storage systems in distribution systems with interconnected microgrids. *IEEE Transactions on Industry Applications*, 56(3):3207–3217, 2020.

[27] U. Manandhar, B. Wang, X. Zhang, G. H. Beng, Y. Liu, and A. Ukil. Joint control of three-level dc–dc converter interfaced hybrid energy storage system in dc microgrids. *IEEE Transactions on Energy Conversion*, 34(4):2248–2257, 2019.

[28] Safa Slouma, Sondes Skander-Mustapha, Ilhem Slama-Belkhodja, and Mohamed Machmoum. Frequency seperation model based on infinite impulse response filter applied to hybrid power generation intended for residential sector. *International Journal of Renewable Energy Research*, 9(1), 2019.

[29] Pia Hoenicke, Debjani Ghosh, Adel Muhandes, Sumantra Bhattacharya, Christiane Bauer, Josef Kallo, and Caroline Willich. Power management control and delivery module for a hybrid electric aircraft using fuel cell and battery. *Energy Conversion and Management*, 244:114445, 2021.

[30] J. A. P. Lopes, C. L. Moreira, and A. G. Madureira. Defining control strategies for microgrids islanded operation. *IEEE Transactions on Power Systems*, 21(2):916–924, 2006.

[31] A. Bidram and A. Davoudi. Hierarchical structure of microgrids control system. *IEEE Transactions on Smart Grid*, 3(4):1963–1976, 2012.

[32] F. Gao, R. Kang, J. Cao, and T. Yang. Primary and secondary control in dc microgrids: a review. *Journal of Modern Power Systems and Clean Energy*, 7(2):227–242, 2019.

[33] Peerzada Ashiq. *Coronavirus Power cuts leave Kashmir's COVID-19 patients gasping*, 2020 (accessed November 28, 2020).

[34] Jem Porcaro Rob Fetter, Anthony Fuller and Cyrus Sinai. *You can't fight pandemics without power—electric power*, 2020 (accessed December 22, 2020).

[35] Yana Mokhonchuk. *2 COVID-19 patients die in hospital as power outage stops ventilators*, 2020 (accessed December 21, 2020).

[36] Ting Qiu and Jamal Faraji. Techno-economic optimization of a grid-connected hybrid energy system considering electric and thermal load prediction. *Energy Science & Engineering*, 2021.

[37] R. Singh and R. C. Bansal. Optimization of an autonomous hybrid renewable energy system using reformed electric system cascade analysis. *IEEE Transactions on Industrial Informatics*, 15(1):399–409, 2019.

[38] Jamal Faraji, Hamed Hashemi-Dezaki, and Abbas Ketabi. Multi-year load growth-based optimal planning of grid-connected microgrid considering long-term load demand forecasting: A case study of tehran, iran. *Sustainable Energy Technologies and Assessments*, 42:100827, 2020.

[39] Muhammad Shahzad Javed, Aotian Song, and Tao Ma. Techno-economic assessment of a stand-alone hybrid solar-wind-battery system for a remote island using genetic algorithm. *Energy*, 176:704 – 717, 2019.

[40] Shirazul Islam, Farhad Bakhsh, and Qamar Islam. *Modeling and Analysis of the Photovoltaic Array Feeding a SPWM Inverter: SIGMA 2018, Volume 1*, pages 449–457. 01 2019.

[41] A. Ali, K. Almutairi, S. Padmanaban, V. Tirth, S. Algarni, K. Irshad, S. Islam, M. H. Zahir, M. Shafiullah, and M. Z. Malik. Investigation of mppt techniques under uniform and non-uniform solar irradiation condition–a retrospection. *IEEE Access*, 8:127368–127392, 2020.

[42] Neetan Sharma, Farhad Ilahi Bakhsh, and Shivinder Mehta. Efficiency enhancement of a solar power plant using maximum power point tracking techniques. In *2018 International Conference on Computational and Characterization Techniques in Engineering Sciences (CCTES)*, pages 106–111, 2018.

[43] Zhongliang Li, Zhixue Zheng, Liangfei Xu, and Xiaonan Lu. A review of the applications of fuel cells in microgrids: opportunities and challenges. *BMC Energy*, 1:1–8, 2019.

[44] A. Tani, M. B. Camara, and B. Dakyo. Energy management in the decentralized generation systems based on renewable energy—ultracapacitors and battery to compensate the wind/load power fluctuations. *IEEE Transactions on Industry Applications*, 51(2):1817–1827, 2015.

[45] J. Timmermans, A. Nikolian, J. De Hoog, R. Gopalakrishnan, S. Goutam, N. Omar, T. Coosemans, J. Van Mierlo, A. Warnecke, D. U. Sauer, M. Swierczynski, D. I. Stroe, E. Martinez-Laserna, E. Sarasketa-Zabala, J. Gastelurrutia, and N. Nerea. Batteries 2020 — lithium-ion battery first and second life ageing, validated battery models, lifetime modelling and ageing assessment of thermal parameters. In *2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe)*, pages 1–23, 2016.

[46] K. Agbossou, M. Kolhe, J. Hamelin, and T. K. Bose. Performance of a stand-alone renewable energy system based on energy storage as

hydrogen. *IEEE Transactions on Energy Conversion*, 19(3):633–640, 2004.

[47] T. Nguyen, Z. Abdin, T. Holm, and W. Mérida. Grid-connected hydrogen production via large-scale water electrolysis. *Energy Conversion and Management*, 200:112108, 2019.

[48] Stuart Fludger and Andrew Klein. Portable ventilators. *Continuing Education in Anaesthesia Critical Care and Pain*, 8:199–203, 2008.

[49] Ali Saleh Aziz, Mohammad Faridun Naim Tajuddin, Mohd Rafi Adzman, Azralmukmin Azmi, and Makbul A.M. Ramli. Optimization and sensitivity analysis of standalone hybrid energy systems for rural electrification: A case study of iraq. *Renewable Energy*, 138:775 – 792, 2019.

[50] Prachuab Peerapong and Bundit Limmeechokchai. Optimal electricity development by increasing solar resources in diesel-based micro grid of island society in thailand. *Energy Reports*, 3:1–13, 2017.

[51] NASA. *Power data access viewer*, 2021 (accessed July 21, 2021).

[52] Adel Choudar, Djamel Boukhetala, Said Barkat, and Jean-Michel Brucker. A local energy management of a hybrid pv-storage based distributed generation for microgrids. *Energy Conversion and Management*, 90:21 – 33, 2015.

[53] Sheikh Javed Iqbal Sheikh Suhail Mohammad. Improved dispatchability of solar photovoltaic system with battery energy storage. In *Proceedings of the 7th International Conference on Advances in Energy Research*, pages 1003–1013, 2020.

[54] Amin Hajizadeh, Samson G. Tesfahunegn, and Tore M. Undeland. Intelligent control of hybrid photo voltaic/fuel cell/energy storage power generation system. *Journal of Renewable and Sustainable Energy*, 3, 2011.

[55] Kanhu Charan Bhuyan, Subhransu Padhee, Rajesh Kumar Patjoshi, and Kamalakanta Mahapatra. Hysteresis control of power conditioning unit for fuel cell distributed generation system. *International Journal of Energy and Power Engineering*, 8(7):1175 – 1180, 2014.

[56] S. Banerjee, P. Ranjan, and C. Grebogi. Bifurcations in two-dimensional piecewise smooth maps-theory and applications in switching circuits. *IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications*, 47(5):633–643, 2000.

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