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Optimal Control of PV/Wind/Hydro-Diesel Hybrid Power Generation System for Off-grid Macro Base Transmitter Station Site

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ABSTRACT An operational control system was proposed in order to control and supervise the operations of PV/Wind/Hydro-Diesel hybrid power generation systems at GSM base station sites. The control system was developed in such a way that it coordinates when power should be generated by renewable energy (PV panels, wind turbine and hydro turbine) and when it should be generated by diesel generators. This system is intended to maximize the use of the renewable-energy system while limiting the use of the diesel generator. The diesel generator is utilized only when the demand cannot be met by the renewable energy sources including battery bank. A developed control system was used to study the operations of the hybrid PV/Wind/Hydro-Diesel energy system. The control simulation shows that the developed control system reduces the operational hours of the diesel generator thereby reducing the running cost of the hybrid energy system and pollutant emissions. From the simulation result, the developed control system reduces the operational hours of the diesel generator from 7,106 h yr^{-1} to 1,786 h yr^{-1} saving 28,087 L of fuel annually, and thereby preventing about 73,961 kg of CO_2 from entering the environment of the studied area. This control system is suitable for use in a more complex hybrid system.

KEYWORDS Base station site, renewable energy, hybrid system, power supply, control strategy, optimization.

Introduction

In hybrid systems with batteries and without diesel generators, the dispatch strategy is simple: the battery charges if the renewable energy exceeds the demand, and the battery discharges if the load exceeds the renewable energy. However, the control strategies of a hybrid system can become very complex if the system includes a diesel generator and batteries [José et al. 2009]. Therefore, it is necessary to determine how the batteries are charged and what element (batteries or diesel generator) have priority to supply energy when the load exceeds the energy generated from renewable sources.

Barley et al. [1995] proposed various strategies for the operation of hybrid PV–Diesel–Battery systems.

One-hour intervals are considered, during which the system parameters remain constant. They also consider ideal batteries, without taking into account losses or the influence of the cycles in the lifespan of these. The three basic control strategies proposed are the following:

- Zero-charge strategy (Load Following Diesel): the batteries are never charged using the diesel generator. Therefore, the Setpoint of the State of Charge (SOC_Setpoint) is 0%.
- Full cycle-charge strategy: the batteries are charged to 100% of their capacity every time the diesel generator is on (SOC_Setpoint = 100%).
- Predictive control strategy: the charging of the batteries depends on the prediction of the demand and the energy expected to be generated by means of renewable sources, so there will be a certain degree of uncertainty. With this strategy, the energy loss from the renewable energies tends to decrease.

This study proposed an optimum point for the SOC_Setpoint between 0 and 100% in such a way that the total operation cost of the system is minimal. The strategy used is between the Zero-charge and Full cycle-charges. Barley and Winn [1996] improved the control strategies model of Barley et al. [1995], introducing new parameters that have become of great importance in the control strategies of the HOMER software tool. The Critical Discharge Power (Ld) is the value as from which the net energy (which is demanded by the charges minus that supplied by the renewable sources) is more profitable when supplied by means of the diesel generator, than when supplied by means of the batteries (after being charged by the diesel generator). The authors propose four control strategies:

- Frugal dispatch strategy: if the net demand is higher than Ld, the diesel generator is used. If it is lower, the batteries are used.
- Load following strategy: the diesel generator never charges the batteries.
- SOC_Setpoint strategy: the diesel generator is on at full power, attempting to charge the batteries until the SOC_Setpoint is reached.
- Operation strategy of diesel at maximum power for a minimum time (charging the batteries).

Muselli et al. [1999] and Muselli et al. [2000] simulate a hybrid PV–Diesel–Battery system with only DC load in such a way that all the energy from the diesel generator goes through the batteries. The diesel generator works at nominal power, providing that the State of Charge (SOC) of the batteries is within determined limits (SDM and SAR, in % of the battery capacity). Yang et al. [2008] suggested an optimal sizing method to optimize the configurations of a hybrid Solar/Wind system with battery banks. They used a genetic algorithm (GA) to calculate the optimum system configuration that could achieve the required loss of power supply probability (LPSP) with minimum annualized cost of system (ACS). Ekren et al. [2009] designed and developed an optimum sizing procedure of Wind-PV/diesel hybrid system for small applications in Turkey. Saheb-Koussa et al. [2010] proposed a hybrid power system to generate power for grid connected applications in the southern parts of Algeria. Results showed that it is possible for Algeria to use the solar and wind energy to generate enough power for villages in the desert and rural areas with slightly lower estimation of energy cost and significant decrease in pollutant emissions. Saheb-Koussa et al. [2009] designed a Wind/PV/Diesel hybrid energy system with battery backup and conducted a techno-economical feasibility of the system for remote applications in Algeria. Results indicated that the hybrid system is the best option for all the sites considered, provided higher system performance than photovoltaic or wind-only systems. The reliability of the system improved, and it was found that the energy cost depends largely on the renewable energy potential. Nfah et al. [2007] studied a Solar/Diesel/Battery hybrid power systems to meet the typical rural domestic energy demands in the range 70–300 kWh yr^{-1}, and found that a hybrid power system comprising a 1440 Wp solar PV array and a 5 kW single-phase generator operating at a load factor of 70%, could meet the required load. Rehman et al. [2007] in their paper titled

"Feasibility study of Hybrid Retrofits to an isolated off-grid diesel power plant" used HOMER software to perform a pre-feasibility of wind penetration into an existing diesel plant of a village in north eastern part of Saudi Arabia. Of all these reviewed literatures, none looked at the operational control, which can lower the use of diesel in a hybrid system, thereby significant decreasing emissions, as well as costs.

The main objective of this study was to develop an optimal operational system to control and supervise the operations of PV/Wind/Hydro-Diesel hybrid power generation system for GSM base station sites.

Power consumption of macro base transmitter station site

The electric power needed for the Base station equipment and the energy required to remove heat from the shelter (cabin) are given by [Ani and Emetu, 2013] and stated below:

- Base station site equipment power requirement = 8,060 W h^{-1}
- Climate equipment power requirement = 5,274 W h^{-1}

Total power requirement for the GSM base station site = 13,334 W h^{-1}

This implies that a site consumes 13.3 kW of electricity.

Load variation of the GSM base station site

The slight changes as well as the flat lines for extended periods of time in Fig. 1 are of daily electricity consumption of the GSM base station site. All the facilities (radio equipment, power conversion equipment, antenna equipment, transmission equipment, and climate equipment) at the base station site are ON for 24 h (00:00 h – 23:00 h), except the auxiliary equipment (security light) that comes on only for 13 h (18:00 h – 7:00 h). It is assumed that this load is identical for every day of the year. The annual peak load of 13 kW was observed between 18:00 h and 07:00 h, with 318 kWh d^{-1} energy consumption. The daily average load

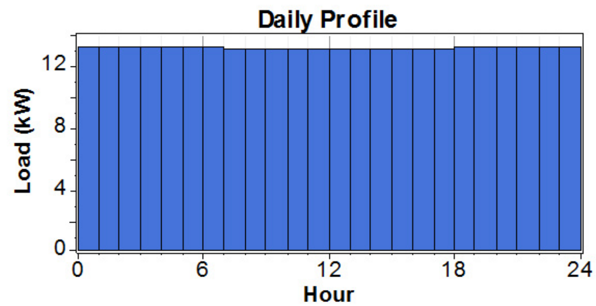

Figure 1 Daily profile of electricity consumption at the GSM base station site [Ani and Emetu, 2013]

variation for the Base station site is shown in Fig. 1 and Table 1.

Methodology

The study involves theoretical load demands as shown in Table 1 and Fig. 1. The load is assumed constant all year. The hybrid renewable consists of a hydro-turbine, a wind turbine and solar photovoltaic (PV) panels. A Generator (diesel or petrol-based) with battery and inverter are added as part of back-up and storage system. The renewable energy supplied is based on hourly basis as well as the fluctuation of parameters involved in wind turbine and solar PV.

Resources Assessment

In the system design, a resource Renewable energy sources (RES) is considered anything that can be used to generate electricity, and that comes from outside the system. RES available at a location can differ considerably from site to site and this is a vital aspect in developing the hybrid system. As RES like wind, solar and hydro are naturally available and intermittent, they are the best option to be combined into a hybridized diesel system. All of these resources depend on different factors – apart from seasonal or even hourly changes: whereas the amount of solar energy available is dependent on climate and latitude, the hydro resource depends from the location's topography and its rainfall patterns; the wind resource is influenced by atmospheric circulation patterns and geographic aspects [Ani, in press]. In turn, the dependence of the

Table 1 The electrical load (daily load demands) data for the base station site [Ani and Emetu, 2013]

DAILY LOAD DEMANDS									
Time	Radio Unit	Base Band	Power Supply & Rectifier	RF feeder	Remote Monitoring and Safety	Signal Transmitting	Security and Lighting	Climate Equipment	Total/h
00-01	4160	2190	1170	120	100	120	200	5274	13334
01-02	4160	2190	1170	120	100	120	200	5274	13334
02-03	4160	2190	1170	120	100	120	200	5274	13334
03-04	4160	2190	1170	120	100	120	200	5274	13334
04-05	4160	2190	1170	120	100	120	200	5274	13334
05-06	4160	2190	1170	120	100	120	200	5274	13334
06-07	4160	2190	1170	120	100	120	200	5274	13334
07-08	4160	2190	1170	120	100	120		5274	13134
08-09	4160	2190	1170	120	100	120		5274	13134
09-10	4160	2190	1170	120	100	120		5274	13134
10-11	4160	2190	1170	120	100	120		5274	13134
11-12	4160	2190	1170	120	100	120		5274	13134
12-13	4160	2190	1170	120	100	120		5274	13134
13-14	4160	2190	1170	120	100	120		5274	13134
14-15	4160	2190	1170	120	100	120		5274	13134
15-16	4160	2190	1170	120	100	120		5274	13134
16-17	4160	2190	1170	120	100	120		5274	13134
17-18	4160	2190	1170	120	100	120		5274	13134
18-19	4160	2190	1170	120	100	120	200	5274	13334
19-20	4160	2190	1170	120	100	120	200	5274	13334
20-21	4160	2190	1170	120	100	120	200	5274	13334
21-22	4160	2190	1170	120	100	120	200	5274	13334
22-23	4160	2190	1170	120	100	120	200	5274	13334
23-00	4160	2190	1170	120	100	120	200	5274	13334
Total	99840	52560	28080	2880	2400	2880	2600	126576	317816

Table 2 Wind, solar and hydro resource for Nkanu-West [Ani and Nzeako, 2012]

Month	Clearness Index	Average Radiation ($kWh/m^2/day$)	Wind Speed (m/s)	Stream Flow (L/s)
Jan	0.605	5.680	2.100	19.5
Feb	0.578	5.740	2.200	20.0
Mar	0.537	5.570	2.100	20.0
Apr	0.503	5.250	2.000	20.0
May	0.487	4.940	1.900	19.0
Jun	0.458	4.540	2.100	18.0
Jul	0.415	4.140	2.400	16.0
Aug	0.382	3.910	2.500	13.0
Sep	0.406	4.190	2.300	13.5
Oct	0.457	4.570	1.700	14.5
Nov	0.539	5.110	2.000	16.0
Dec	0.595	5.460	1.800	18.5
Scaled annual average		4.950	2.1	17.3

resource on various factors influences when, and how much power can be generated, which defines the behaviour and economics of the hybrid system. Table 2 shows the solar, wind and hydro resource for Nkanu-West (Enugu State), Nigeria, used for the simulation.

Model Development

The following equations, used in this study, are based on equations used by [HOMER, 2012; Kamaruzzaman et al. 2008; Lambert, 2009], to derive the power supplied by renewable, battery charging and discharging.

The PV Power:

$$P_{pv} = \eta_{pv} \cdot N_{pvp} \cdot N_{pvs} \cdot V_{pv} \cdot I_{pv} \quad \text{Eq. (1)}$$

The Wind Power:

$$P_w = \eta_w \cdot \eta_g \cdot 0.5 \cdot \rho_a \cdot C_P \cdot A \cdot V_r^3 \quad \text{Eq. (2)}$$

The Hydro Power:

$$P_h = \eta_h \cdot \rho_{water} \cdot g \cdot H_{net} \cdot Q \quad \text{Eq. (3)}$$

Total Renewable Power:

$$P(t) = \sum_{pv=1}^{n_{pv}} P_{pv} + \sum_{w=1}^{n_w} P_w + \sum_{h=1}^{n_h} P_h \quad \text{Eq. (4)}$$

Battery Discharging:

$$P_b(t) = P_b(t-1) \cdot (1-\sigma) - \left[\frac{P_{bt}(t)}{P_{bl}(t)}\right] \quad \text{Eq. (5)}$$

Battery Charging:

$$P_b(t) = P_b(t-1) \cdot (1-\sigma) + \left[P_{bt}(t) - P_{bl}(t)\right] \cdot \eta_{bb} \quad \text{Eq. (6)}$$

Where,

V_{pv} : Operating voltage of PV panels

N_{pvs} : Numbers of PV panels in series

η_g : Efficiency of the gravitational acceleration

P_w : Wind turbine power output

η_w	: Efficiency of wind turbine
ρ_a	: Density of air
C_p	: Power coefficient of wind turbine
A	: Wind turbine swept area
V_r^3	: Wind velocity
P_{pv}	: PV power output
η_{pv}	: Conversion efficiency of PV
N_{pvp}	: Number of PV panels in parallel
N_{pvs}	: Number of PV panels in series
I_{pv}	: Operating current of PV panels
P_b	: Battery energy at time interval
P_{bt}	: Total energy generated
σ	: Self discharge factor
P_{bl}	: Load demand at time interval
η_{bb}	: Battery charging efficiency
P_h	: Hydro turbine power output
η_h	: Efficiency of hydro turbine
ρ_{water}	: Density of water
g	: Gravitational acceleration
H_{net}	: Effective head
Q	: Flowrate

Based on a system energy balance, and on the storage continuity equation, the battery charger output power $P_{b\ charger}(t)$, the PV output power $P_{pv}(t)$, the wind output power $P_w(t)$, the hydro output power $P_h(t)$ and the load power $P_L(t)$ on the simulation step Δt (the consumption patterns previously described), the battery energy benefit during a charge time Δt_1 is given by ($\Delta t_1 < \Delta t$):

$$C_1(t) = \rho_{ch} \int_{\Delta t_1} \left[P_{pv}(t) + P_w(t) + P_h(t) + P_{b\,charger}(t) - P_l(t) \right] dt \quad \text{Eq. (7)}$$

The battery energy loss during a discharge time Δt_2 is given by ($\Delta t_2 < \Delta t$):

$$C_1(t) = \left(\frac{1}{\rho_{dch}} \right) \int_{\Delta t_2} \left[P_{pv}(t) + P_w(t) + P_h(t) + P_{b\,charger}(t) - P_l(t) \right] dt \quad \text{Eq. (8)}$$

The state of charge of the battery is defined during the simulation time-step Δt by:

$$C(t) = C(t - \Delta t) + C_1(t) + C_2(t) \quad \text{Eq. (9)}$$

If $C(t)$ reaches the Stopping threshold (SAR) by an energy benefit $C_1(t)$ during the charge period with the engine-generator working, the generator has to be stopped, and the charge time Δt_1 during Δt is calculated assuming a linear relation:

$$\frac{\Delta t_1}{\Delta t} = \left| \frac{SAR - C(t - \Delta t)}{C_1(t)} \right| \quad \text{Eq. (10)}$$

Moreover, if during the discharge period, the engine generator is stopped, $C(t)$ reaches Starting threshold (SDM), the motor is started and the discharge time Δt_2 during Δt is calculated by a linear relation as:

$$\frac{\Delta t_2}{\Delta t} = \left| \frac{C(t - \Delta t) - SDM}{C_2(t)} \right| \quad \text{Eq. (11)}$$

As an input of a simulation time-step Δt (taken as 1 h), several variables were determined: PV output power, wind output power, hydro output power, load power, battery state of charge, and back-up generator state (ON or OFF). A battery energy balance indicates the operating strategy of the PV/Wind/Hydro-Diesel hybrid system: charge (energy balance positive) or discharge (energy balance negative). If SOC(t) falls below SDM, the motor is started; and if SOC(t) exceeds SAR, it is stopped.

Control system for power management

Operating strategy for the hybrid PV/Wind/Hydro-Diesel system with battery

When the renewable sources produce less energy than what is demanded (the wind speed, the solar radiation and the stream flow are low), the deficit power should be supplied by the battery bank. When the state of charge of battery bank reaches its minimal level (40%), then the diesel generator functions.

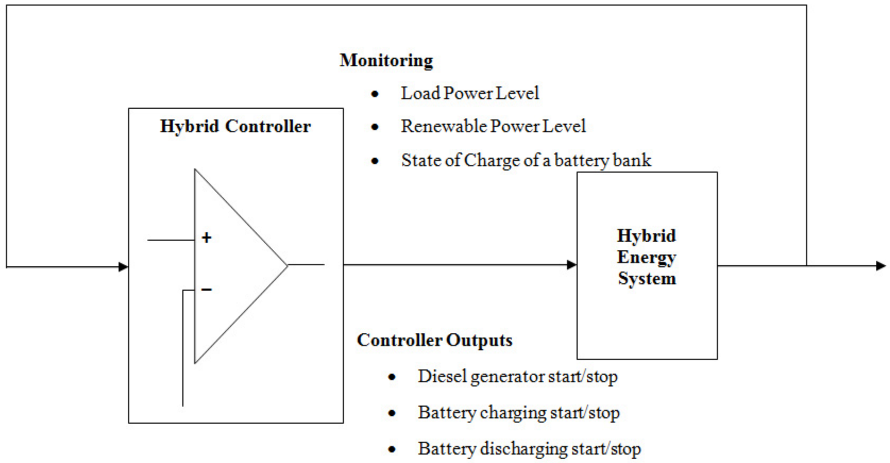

Figure 2 Hybrid system controller block diagram.

Optimization of operational strategy

Good operation of a hybrid system can be achieved only by a suitable control of the interaction in the operation of the different devices. An exhaustive knowledge of the management strategies to be chosen in the preliminary stage is therefore fundamental to optimize the use of the renewable sources, minimize the wear of batteries, consume the smaller possible quantity of fossil fuel [Seeling-Hochmuth, 1997; Seeling, 1995].

Hybrid system controller

An operational control strategy consists of certain predetermined control settings that are set when installing the system. Such settings concern the set-point of when to switch on the diesel or not, based on certain values representing the system state, such as the battery state of charge and the demand placed on the system. The time-independent controller setting in the developed design system is shown in Fig. 2. The hybrid system control consists of 4 modes. PV is chosen as the primary energy generation mechanism and therefore Mode 1 is used when solely the PV power generated is sufficient to power the system. This power is regulated using sliding mode control as shown in Fig. 3. In Mode 2, the PV power is generated at its maximum and wind energy generation then tracks the load power using sliding mode control. In Mode 3, the PV power and wind power is generated at its maximum and hydro energy generation then tracks the load power using sliding mode control. In Mode 1, 2 and 3, the battery is recharged and therefore adds to the load on the system. In Mode 4, the load is greater than what the PV, wind and hydro can supply and the hybrid system control connects to the program which determines what element (batteries or diesel generator) have priority to supply energy to enable the necessary load to be met. This is done by monitoring the power needed by the load and the power of the generating mechanism.

Control simulation for hybrid a PV/Wind/Hydro-Diesel system

Control strategies have been recognized as an efficient way to improve process profitability. In fact, the major benefit of integrating control modeling and simulation into the energy development process is a significant reduction in total cost of ownership. A sliding control has been used for this, using PV energy generation as the primary source of energy; wind and hydro energy generation are the secondary source, the battery is the supplement, and the generator iss the back-up source of energy. The system moves between different modes depending on the power needed by the load and the power able to be supplied by each of the sources. Fig. 3 outlines the flow between the different modes.

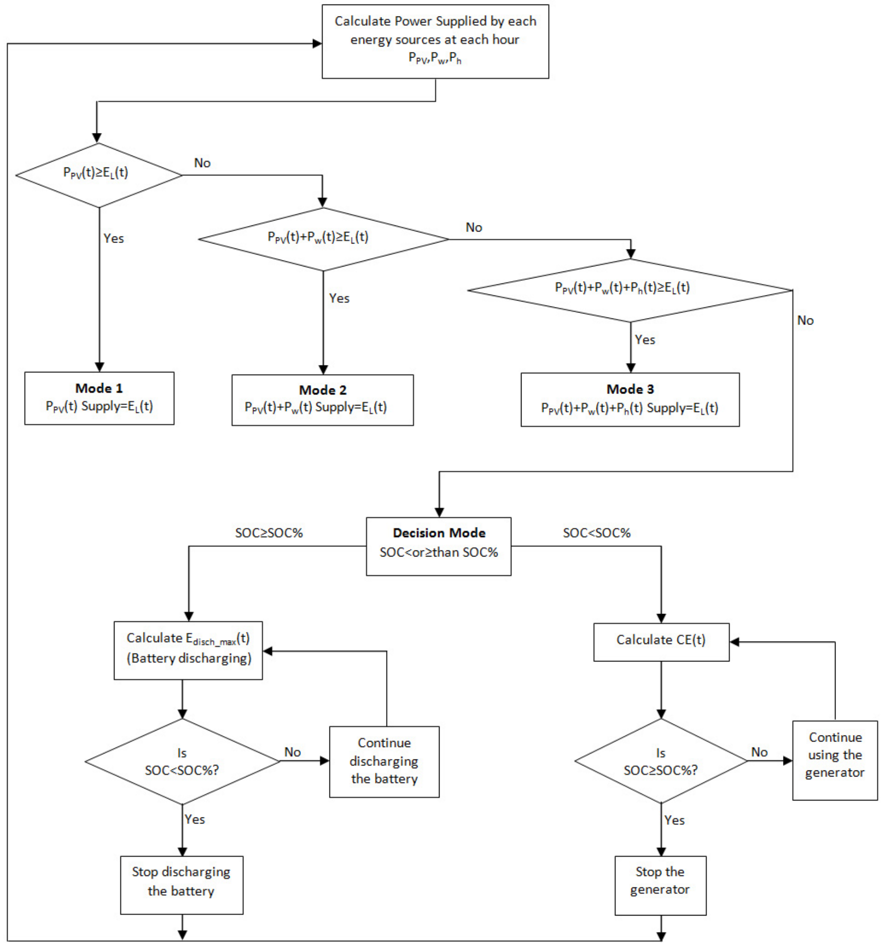

Figure 3 Overview of the Decision Strategy and Modes of Control for the System Operation.

Initially, the power supplied by the PV panels, the wind turbine and the hydro turbine is calculated for each hour over the year and stored in matrices, so that power availability in each hour can be accessed easily. The control process then begins at hour 1. The first decision loop looks at the power that can be supplied by the PV panel in this hour and the power required by the load. If the power generated by the PV panel is sufficient to match the load, the system enters Mode 1. If the PV panel cannot provide sufficient energy for the load, the control looks at the total amount of energy that can be provided by the PV panel and the wind turbine together. If these together are sufficient to provide power for the load, the system enters Mode 2. If the combined energy supplied by the PV panels and the wind turbine is not sufficient to supply the load, the control looks at the total amount of energy that can be provided by the PV panel, the wind turbine and hydro turbine together. If these together are sufficient to provide power for the load, the system enters Mode 3. If the combined energy supplied by the PV panels, the wind turbine and the hydro turbine is not sufficient to supply the load, then the system goes to the decision mode where the program determines what element (batteries or diesel generator) have priority to supply energy using decision rules based on constraints.

Mode 1

Mode 1 uses solely the energy generated by the PV panels to supply the load. When the system is in Mode 1, sometimes the energy available from the wind turbine and hydro turbine might be in excess of what is needed by the load and therefore the amount of energy supplied to the load must be matched to the load demand. This is called sliding control. As the wind turbine and hydro turbine are connected to the system, but not used to supply the load in this mode, the energy generated by the wind turbine and hydro turbine as well as any excess energy from the PV panels can be used to charge the battery.

Mode 2

Mode 2 uses the power of the PV panels plus the power of the wind turbine to supply the load. In Mode 2, if the energy available from the PV panels and the wind turbine combined is in excess of what is needed by the load, then the full power available from the PV panel is used to supply the load and the power from the wind turbine is supplied using sliding control to match the power required by the load. As the hydro turbines are connected to the system, but not used to supply the load in this mode, the energy generated by the hydro turbine as well as any excess energy from the PV panels and wind turbine can be used to charge the battery as in Mode 1.

Mode 3

The system enters Mode 3 when the power generated by the PV panel and wind turbine is not sufficient to supply the load. In this mode, if the energy available from the PV panels, the wind turbine and hydro turbine combined is in excess of what is needed by the load, then the full power available from the PV panel and wind turbine is used to supply the load, and the power from the hydro turbine is supplied using sliding control to match the power required by the load. The excess energy from the PV panels, the wind turbine and hydro turbine can be used to charge the battery, as in Mode 1 and 2.

Decision mode

Decision mode uses a program to determine what element (batteries or diesel generator) have priority to supply energy based on the following decisions:

- If the SOC of the battery is greater than the minimum amount and therefore the battery is able to supply power to the load. The battery will be used.
- If the battery is at its minimum SOC and therefore cannot be used to supply the deficit of power required. Then the diesel generator will be used.

Results and discussion

Tables (3, 4, 5, 6, 7, 8 and 9) show how the demand is met by the hybrid energy system (PV, wind, hydro and diesel generator) for the first seven days of February. It shows how the sources were allocated according to the load demand and availability. It was observed that the variation is not only in the demand but also the availability of sources. The battery or the diesel generator compensates the shortage depending on the decision mode. The entire operations of the hybrid controller can be seen from Fig. 3.

From the simulation results, the wind power is poor and variable. The hydro system has a steady power supply. The PV power supply is between 8:00 h to 19:00 h while the radiation peak is between 12:00 h to 14:00 h as can be seen in Tables (3, 4, 5, 6, 7, 8 and 9). Between 12:00 h and 14:00 h there is no deficit in the system and the renewable energy supplies the load and charges the battery. There is likely to be deficit in other remaining hours due to poor radiation, and the deficit is being completed by either the battery or the diesel generator.

Hybrid controller switches the batteries into charging mode whenever excess power is available from the renewable sources, and switch to discharging mode whenever there was a shortage of power from sources. Battery power indicates the operating strategy of the hybrid system: charging (power positive) or discharging (power negative). It shows that the hybrid controller utilizes the battery bank effectively.

It was mentioned in the Fig. 2, that the hybrid controller turns off the diesel generator when the load demand can be met together by the PV, wind, hydro and battery bank. For example on the typical day (day six), at 10:00 hours when the battery state of charge

Table 3 Power demand met by the hybrid energy system (PV, wind, hydro and diesel generator) in day one.

Time (h)	Global solar (kW/m^2)	Incident solar (kW/m^2)	Wind Speed (m/s)	Stream Flow (L/s)	Dc Load (kW)	PV power (kW)	Wind Output (kW)	Hydro Output (kW)	Diesel generator (kW)	Rectifier input (kW)	Rectifier output (kW)	Battery power (kWh)	Battery State of Charge (%)
0:00	0.000	0.000	2.505	19.481	10.667	0.000	0.000	7.184	0.000	0.000	0.000	-3.483	47.021
1:00	0.000	0.000	2.440	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	46.774
2:00	0.000	0.000	1.332	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	46.527
3:00	0.000	0.000	2.540	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	46.281
4:00	0.000	0.000	2.430	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	46.034
5:00	0.000	0.000	2.190	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	45.788
6:00	0.000	0.000	2.385	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	45.541
7:00	0.001	0.000	1.072	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	45.295
8:00	0.126	0.223	1.431	19.981	10.467	2.146	0.000	7.368	0.000	0.000	0.000	-0.953	45.224
9:00	0.329	0.411	0.876	19.981	10.467	3.957	0.000	7.368	0.000	0.000	0.000	0.858	45.275
10:00	0.570	0.660	1.907	19.981	10.467	6.356	0.000	7.368	0.000	0.000	0.000	3.257	45.470
11:00	0.834	0.925	1.894	19.981	10.467	8.906	0.000	7.368	0.000	0.000	0.000	5.807	45.817
12:00	1.022	1.102	2.096	19.981	10.467	10.615	0.000	7.368	0.000	0.000	0.000	7.516	46.266
13:00	1.064	1.134	2.123	19.981	10.467	10.925	0.000	7.368	0.000	0.000	0.000	7.826	46.734
14:00	1.082	1.159	2.133	19.981	10.467	11.157	0.000	7.368	0.000	0.000	0.000	8.058	47.216
15:00	0.888	0.967	3.038	19.981	10.467	9.315	0.084	7.368	0.000	0.000	0.000	6.300	47.592
16:00	0.652	0.730	2.521	19.981	10.467	7.028	0.000	7.368	0.000	0.000	0.000	3.929	47.827
17:00	0.493	0.604	2.227	19.981	10.467	5.812	0.000	7.368	0.000	0.000	0.000	2.713	47.989
18:00	0.258	0.384	1.819	19.981	10.667	3.700	0.000	7.368	0.000	0.000	0.000	0.401	48.013
19:00	0.041	0.161	2.825	19.981	10.667	1.546	0.038	7.368	0.000	0.000	0.000	-1.715	47.885
20:00	0.000	0.000	3.571	19.981	10.667	0.000	0.198	7.368	0.000	0.000	0.000	-3.101	47.653
21:00	0.000	0.000	2.070	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	47.407
22:00	0.000	0.000	2.537	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	47.160
23:00	0.000	0.000	1.523	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	46.914

Table 4 Power demand met by the hybrid energy system (PV, wind, hydro and diesel generator) in day two.

Time (h)	Global solar (kW/m^2)	Incident solar (kW/m^2)	Wind Speed (m/s)	Stream Flow (L/s)	Dc Load (kW)	PV power (kW)	Wind Output (kW)	Hydro Output (kW)	Diesel generator (kW)	Rectifier input (kW)	Rectifier output (kW)	Battery power (kWh)	Battery State of Charge (%)
0:00	0.000	0.000	0.871	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	46.667
1:00	0.000	0.000	0.381	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	46.421
2:00	0.000	0.000	0.947	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	46.174
3:00	0.000	0.000	1.425	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	45.928
4:00	0.000	0.000	1.575	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	45.681
5:00	0.000	0.000	1.463	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	45.435
6:00	0.000	0.000	0.932	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	45.188
7:00	0.000	0.000	1.560	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	44.942
8:00	0.054	0.052	1.337	19.981	10.467	0.498	0.000	7.368	0.000	0.000	0.000	-2.601	44.747
9:00	0.178	0.171	1.761	19.981	10.467	1.648	0.000	7.368	0.000	0.000	0.000	-1.451	44.639
10:00	0.184	0.169	2.611	19.981	10.467	1.628	0.000	7.368	0.000	0.000	0.000	-1.471	44.529
11:00	0.212	0.194	3.542	19.981	10.467	1.872	0.192	7.368	0.000	0.000	0.000	-1.035	44.452
12:00	0.364	0.337	3.946	19.981	10.467	3.243	0.274	7.368	0.000	0.000	0.000	0.418	44.477
13:00	0.742	0.759	4.698	19.981	10.467	7.313	0.550	7.368	0.000	0.000	0.000	4.764	44.761
14:00	0.460	0.433	4.898	19.981	10.467	4.171	0.677	7.368	0.000	0.000	0.000	1.749	44.866
15:00	0.253	0.232	4.089	19.981	10.467	2.235	0.304	7.368	0.000	0.000	0.000	-0.561	44.824
16:00	0.349	0.332	5.444	19.981	10.467	3.196	1.083	7.368	0.000	0.000	0.000	1.180	44.895
17:00	0.315	0.326	5.207	19.981	10.467	3.139	0.872	7.368	0.000	0.000	0.000	0.912	44.949
18:00	0.192	0.235	4.404	19.981	10.667	2.260	0.368	7.368	0.000	0.000	0.000	-0.671	44.899
19:00	0.039	0.141	4.547	19.981	10.667	1.354	0.454	7.368	0.000	0.000	0.000	-1.490	44.788
20:00	0.000	0.000	4.711	19.981	10.667	0.000	0.558	7.368	0.000	0.000	0.000	-2.741	44.583
21:00	0.000	0.000	3.881	19.981	10.667	0.000	0.261	7.368	0.000	0.000	0.000	-3.038	44.356
22:00	0.000	0.000	4.610	19.981	10.667	0.000	0.494	7.368	0.000	0.000	0.000	-2.805	44.146
23:00	0.000	0.000	2.370	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	43.900

Table 5 Power demand met by the hybrid energy system (PV, Wind, Hydro and diesel generator) in day three.

Time (h)	Global solar (kW/m^2)	Incident solar (kW/m^2)	Wind Speed (m/s)	Stream Flow (L/s)	Dc Load (kW)	PV power (kW)	Wind Output (kW)	Hydro Output (kW)	Diesel generator (kW)	Rectifier input (kW)	Rectifier output (kW)	Battery power (kWh)	Battery State of Charge (%)
0:00	0.000	0.000	2.125	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	43.653
1:00	0.000	0.000	1.086	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	43.407
2:00	0.000	0.000	0.666	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	43.160
3:00	0.000	0.000	1.265	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	42.914
4:00	0.000	0.000	1.483	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	42.667
5:00	0.000	0.000	1.008	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	42.421
6:00	0.000	0.000	0.724	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	42.174
7:00	0.001	0.000	0.486	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	41.928
8:00	0.145	0.282	1.100	19.981	10.467	2.719	0.000	7.368	0.000	0.000	0.000	-0.380	41.899
9:00	0.244	0.260	1.374	19.981	10.467	2.499	0.000	7.368	0.000	0.000	0.000	-0.600	41.854
10:00	0.306	0.294	1.616	19.981	10.467	2.827	0.000	7.368	0.000	0.000	0.000	-0.272	41.834
11:00	0.512	0.513	2.558	19.981	10.467	4.936	0.000	7.368	0.000	0.000	0.000	1.837	41.944
12:00	0.611	0.610	1.931	19.981	10.467	5.871	0.000	7.368	0.000	0.000	0.000	2.772	42.110
13:00	0.614	0.603	1.603	19.981	10.467	5.805	0.000	7.368	0.000	0.000	0.000	2.705	42.271
14:00	0.568	0.553	1.544	19.981	10.467	5.321	0.000	7.368	0.000	0.000	0.000	2.222	42.404
15:00	0.428	0.405	1.351	19.981	10.467	3.899	0.000	7.368	0.000	0.000	0.000	0.800	42.452
16:00	0.460	0.466	2.025	19.981	10.467	4.485	0.000	7.368	0.000	0.000	0.000	1.386	42.535
17:00	0.266	0.260	2.642	19.981	10.467	2.504	0.000	7.368	0.000	0.000	0.000	-0.595	42.490
18:00	0.127	0.125	1.907	19.981	10.667	1.202	0.000	7.368	0.000	0.000	0.000	-2.097	42.334
19:00	0.029	0.056	2.072	19.981	10.667	0.536	0.000	7.368	0.000	0.000	0.000	-2.764	42.127
20:00	0.000	0.000	2.537	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	41.881
21:00	0.000	0.000	2.548	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	41.634
22:00	0.000	0.000	2.066	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	41.388
23:00	0.000	0.000	1.953	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	41.141

Table 6 Power demand met by the hybrid energy system (PV, wind, hydro and diesel generator) in day four.

Time (h)	Global solar (kW/m^2)	Incident solar (kW/m^2)	Wind Speed (m/s)	Stream Flow (L/s)	Dc Load (kW)	PV power (kW)	Wind Output (kW)	Hydro Output (kW)	Diesel generator (kW)	Rectifier input (kW)	Rectifier output (kW)	Battery power (kWh)	Battery State of Charge (%)
0:00	0.000	0.000	2.068	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	40.895
1:00	0.000	0.000	1.935	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	40.648
2:00	0.000	0.000	2.606	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	40.402
3:00	0.000	0.000	2.211	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	40.155
4:00	0.000	0.000	2.790	19.981	10.667	0.000	0.030	7.368	16.000	16.000	13.600	10.331	40.773
5:00	0.000	0.000	3.049	19.981	10.667	0.000	0.086	7.368	16.000	16.000	13.600	10.387	41.393
6:00	0.000	0.000	1.710	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	42.009
7:00	0.001	0.000	1.590	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	42.625
8:00	0.100	0.136	2.188	19.981	10.467	1.307	0.000	7.368	16.000	16.000	13.600	11.808	43.331
9:00	0.299	0.350	2.159	19.981	10.467	3.369	0.000	7.368	16.000	16.000	13.600	13.870	44.160
10:00	0.443	0.470	3.337	19.981	10.467	4.522	0.148	7.368	16.000	16.000	13.600	15.171	45.067
11:00	0.492	0.486	2.767	19.981	10.467	4.685	0.025	7.368	16.000	16.000	13.600	15.211	45.976
12:00	0.900	0.957	2.651	19.981	10.467	9.215	0.001	7.368	16.000	16.000	13.600	19.716	47.154
13:00	0.963	1.014	3.038	19.981	10.467	9.769	0.084	7.368	16.000	16.000	13.600	20.353	48.371
14:00	0.505	0.481	2.639	19.981	10.467	4.630	0.000	7.368	16.000	16.000	13.600	15.131	49.275
15:00	0.575	0.575	3.239	19.981	10.467	5.533	0.127	7.368	16.000	16.000	13.600	16.161	50.241
16:00	0.606	0.659	3.243	19.981	10.467	6.345	0.128	7.368	16.000	16.000	13.600	16.974	51.256
17:00	0.453	0.533	2.206	19.981	10.467	5.137	0.000	7.368	16.000	16.000	13.600	15.638	52.190
18:00	0.246	0.346	1.767	19.981	10.667	3.328	0.000	7.368	16.000	16.000	13.600	13.629	53.005
19:00	0.026	0.041	1.599	19.981	10.667	0.398	0.000	7.368	16.000	16.000	13.600	10.698	53.645
20:00	0.000	0.000	2.197	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	54.260
21:00	0.000	0.000	2.756	19.981	10.667	0.000	0.023	7.368	16.000	16.000	13.600	10.324	54.877
22:00	0.000	0.000	3.184	19.981	10.667	0.000	0.115	7.368	16.000	16.000	13.600	10.416	55.500
23:00	0.000	0.000	2.945	19.981	10.667	0.000	0.064	7.368	16.000	16.000	13.600	10.365	56.119

Table 7 Power demand met by the hybrid energy system (PV, wind, hydro and diesel generator) in day five.

Time (h)	Global solar (kW/m^2)	Incident solar (kW/m^2)	Wind Speed (m/s)	Stream Flow (L/s)	Dc Load (kW)	PV power (kW)	Wind Output (kW)	Hydro Output (kW)	Diesel generator (kW)	Rectifier input (kW)	Rectifier output (kW)	Battery power (kWh)	Battery State of Charge (%)
0:00	0.000	0.000	1.844	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	56.735
1:00	0.000	0.000	3.040	19.981	10.667	0.000	0.084	7.368	16.000	16.000	13.600	10.385	57.356
2:00	0.000	0.000	3.459	19.981	10.667	0.000	0.174	7.368	16.000	16.000	13.600	10.475	57.982
3:00	0.000	0.000	2.988	19.981	10.667	0.000	0.073	7.368	16.000	16.000	13.600	10.374	58.602
4:00	0.000	0.000	2.342	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	59.218
5:00	0.000	0.000	1.146	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	59.833
6:00	0.000	0.000	0.840	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	60.449
7:00	0.001	0.000	1.118	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	61.065
8:00	0.059	0.057	1.719	19.981	10.467	0.554	0.000	7.368	16.000	16.000	13.600	11.055	61.726
9:00	0.256	0.277	2.918	19.981	10.467	2.664	0.058	7.368	16.000	16.000	13.600	13.223	62.516
10:00	0.276	0.260	3.242	19.981	10.467	2.503	0.128	7.368	16.000	16.000	13.600	13.132	63.301
11:00	0.399	0.379	2.492	19.981	10.467	3.648	0.000	7.368	16.000	16.000	13.600	14.149	64.147
12:00	0.779	0.811	3.585	19.981	10.467	7.813	0.201	7.368	16.000	16.000	13.600	18.514	65.253
13:00	0.905	0.946	3.327	19.981	10.467	9.109	0.146	7.368	16.000	16.000	13.600	19.756	66.434
14:00	0.709	0.717	4.743	19.981	10.467	6.903	0.578	7.368	16.000	16.000	13.600	17.982	67.509
15:00	0.327	0.302	4.263	19.981	10.467	2.906	0.339	7.368	16.000	16.000	13.600	13.746	68.331
16:00	0.267	0.246	4.253	19.981	10.467	2.372	0.337	7.368	16.000	16.000	13.600	13.210	69.120
17:00	0.201	0.187	3.865	19.981	10.467	1.803	0.258	7.368	16.000	16.000	13.600	12.562	69.871
18:00	0.038	0.034	3.766	19.981	10.667	0.332	0.238	7.368	16.000	16.000	13.600	10.871	70.521
19:00	0.022	0.026	3.267	19.981	10.667	0.252	0.133	7.368	16.000	16.000	13.600	10.686	71.160
20:00	0.000	0.000	3.418	19.981	10.667	0.000	0.166	7.368	16.000	16.000	13.600	10.466	71.785
21:00	0.000	0.000	2.576	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	72.401
22:00	0.000	0.000	1.894	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	73.017
23:00	0.000	0.000	0.732	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	73.632

Table 8 Power demand met by the hybrid energy system (PV, wind, hydro and diesel generator) in day six.

Time (h)	Global solar (kW/m^2)	Incident solar (kW/m^2)	Wind Speed (m/s)	Stream Flow (L/s)	Dc Load (kW)	PV power (kW)	Wind Output (kW)	Hydro Output (kW)	Diesel generator (kW)	Rectifier input (kW)	Rectifier output (kW)	Battery power (kWh)	Battery State of Charge (%)
0:00	0.000	0.000	0.821	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	74.248
1:00	0.000	0.000	1.665	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	74.864
2:00	0.000	0.000	0.998	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	75.479
3:00	0.000	0.000	0.956	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	76.095
4:00	0.000	0.000	2.549	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	76.711
5:00	0.000	0.000	2.558	19.981	10.667	0.000	0.000	7.368	16.000	16.000	13.600	10.301	77.326
6:00	0.000	0.000	2.775	19.981	10.667	0.000	0.027	7.368	16.000	16.000	13.600	10.328	77.944
7:00	0.002	0.000	3.754	19.981	10.667	0.000	0.235	7.368	16.000	16.000	13.600	10.536	78.574
8:00	0.141	0.260	2.948	19.981	10.467	2.506	0.064	7.368	16.000	16.000	13.600	13.071	79.355
9:00	0.417	0.543	2.828	19.981	10.467	5.227	0.038	7.368	16.000	16.000	13.600	15.766	80.297
10:00	0.687	0.791	2.870	19.981	10.467	7.616	0.048	7.368	0.000	0.000	0.000	4.564	80.570
11:00	0.940	1.025	2.522	19.981	10.467	9.866	0.000	7.368	0.000	0.000	0.000	6.767	80.975
12:00	1.062	1.126	1.766	19.981	10.467	10.843	0.000	7.368	0.000	0.000	0.000	7.744	81.437
13:00	1.061	1.113	2.576	19.981	10.467	10.714	0.000	7.368	0.000	0.000	0.000	7.615	81.893
14:00	0.978	1.028	2.017	19.981	10.467	9.895	0.000	7.368	0.000	0.000	0.000	6.796	82.299
15:00	0.846	0.901	2.282	19.981	10.467	8.679	0.000	7.368	0.000	0.000	0.000	5.580	82.632
16:00	0.679	0.748	3.116	19.981	10.467	7.204	0.101	7.368	0.000	0.000	0.000	4.206	82.884
17:00	0.464	0.544	2.626	19.981	10.467	5.234	0.000	7.368	0.000	0.000	0.000	2.135	83.011
18:00	0.208	0.257	3.427	19.981	10.667	2.479	0.168	7.368	0.000	0.000	0.000	-0.653	82.963
19:00	0.043	0.165	2.972	19.981	10.667	1.591	0.070	7.368	0.000	0.000	0.000	-1.638	82.840
20:00	0.000	0.000	2.543	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	82.594
21:00	0.000	0.000	2.336	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	82.347
22:00	0.000	0.000	1.863	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	82.101
23:00	0.000	0.000	1.231	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	81.854

Table 9 Power demand met by the hybrid energy system (PV, wind, hydro and diesel generator) in day seven.

Time (h)	Global solar (kW/m^2)	Incident solar (kW/m^2)	Wind Speed (m/s)	Stream Flow (L/s)	Dc Load (kW)	PV power (kW)	Wind Output (kW)	Hydro Output (kW)	Diesel generator (kW)	Rectifier input (kW)	Rectifier output (kW)	Battery power (kWh)	Battery State of Charge (%)
0:00	0.000	0.000	0.662	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	81.608
1:00	0.000	0.000	1.001	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	81.361
2:00	0.000	0.000	1.087	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	81.115
3:00	0.000	0.000	1.245	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	80.868
4:00	0.000	0.000	1.376	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	80.622
5:00	0.000	0.000	1.610	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	80.375
6:00	0.000	0.000	1.410	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	80.129
7:00	0.001	0.000	1.556	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	79.882
8:00	0.110	0.162	3.552	19.981	10.467	1.557	0.194	7.368	0.000	0.000	0.000	-1.348	79.782
9:00	0.291	0.332	3.950	19.981	10.467	3.198	0.275	7.368	0.000	0.000	0.000	0.374	79.804
10:00	0.694	0.795	3.981	19.981	10.467	7.659	0.282	7.368	0.000	0.000	0.000	4.842	80.093
11:00	0.882	0.956	4.516	19.981	10.467	9.207	0.434	7.368	0.000	0.000	0.000	6.542	80.484
12:00	1.013	1.070	5.015	19.981	10.467	10.303	0.751	7.368	0.000	0.000	0.000	7.955	80.960
13:00	1.086	1.135	4.786	19.981	10.467	10.931	0.606	7.368	0.000	0.000	0.000	8.438	81.464
14:00	0.963	1.008	3.934	19.981	10.467	9.704	0.272	7.368	0.000	0.000	0.000	6.877	81.875
15:00	0.709	0.735	2.874	19.981	10.467	7.080	0.048	7.368	0.000	0.000	0.000	4.030	82.116
16:00	0.654	0.713	3.349	19.981	10.467	6.868	0.151	7.368	0.000	0.000	0.000	3.919	82.350
17:00	0.440	0.504	3.467	19.981	10.467	4.855	0.176	7.368	0.000	0.000	0.000	1.932	82.466
18:00	0.261	0.367	3.692	19.981	10.667	3.531	0.223	7.368	0.000	0.000	0.000	0.454	82.493
19:00	0.027	0.041	3.068	19.981	10.667	0.397	0.090	7.368	0.000	0.000	0.000	-2.812	82.283
20:00	0.000	0.000	2.623	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	82.036
21:00	0.000	0.000	2.285	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	81.790
22:00	0.000	0.000	1.692	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	81.543
23:00	0.000	0.000	1.261	19.981	10.667	0.000	0.000	7.368	0.000	0.000	0.000	-3.299	81.297

Table 10 Simulation results of Electricity Production (kWh/yr).

Quantity	Diesel only		Diesel in Hybrid System (Diesel-Solar PV/Wind/Hydro)	
	kWh/yr	%	kWh/yr	%
Load				
DC primary load	92,715	100	92,715	100
Production				
PV array	None	None	16,024	16
Wind	None	None	539	1
Hydro	None	None	55,885	55
Diesel Generator	113,687	100	28,576	28
Total energy	113,687	100	101,024	100

Table 11 Hours of Operation and Fuel consumption of diesel only and diesel in hybrid system.

Quantity	Diesel only		Diesel in Hybrid System (Diesel-Solar PV/Wind/Hydro)	
	Value	Units	Value	Units
Hours of operation	7,106	hr/yr	1,786	hr/yr
Fuel consumption	37,517	L/yr	9,430	L/yr

Table 12 Simulation results of Emissions from diesel only and diesel in hybrid system.

Pollutant	Emissions (kg/yr)	
	Diesel only	Diesel-solar PV/Wind/Hydro system
Carbon dioxide (kg/yr)	98,793	24,832
Carbon monoxide (kg/yr)	244	61.3
Unburned hydrocarbons (kg/yr)	27	6.79
Particulate matter (kg/yr)	18.4	4.62
Sulfur dioxide (kg/yr)	198	49.9
Nitrogen oxides (kg/yr)	2,176	547

is 80.57%, the hybrid controller turns off the diesel generator and allocates PV, wind, and hydro to supply the load demand as well as charging the battery.

From the fourth day (4:00 h) till the sixth day (10:00 h), the hybrid controller allocated the diesel generator as shown in Tables (6, 7 and 8). The demand of the other remaining hours and days was met by the renewable energy sources (PV + wind + hydro) along with the battery bank. This reduced the operational hours of the diesel generator, reducing the running cost of the hybrid energy system as well as the pollutant emissions. It is observed that the hybrid controller allocates the sources optimally according to the demand and availability.

The Diesel-only system produces 113,687 kWh yr^{-1} (100%), whereas the Hybrid system (Diesel-Solar PV/Wind/Hydro) produces 16,024 kWh yr^{-1} (16%) from solar PV array, 539 kWh yr^{-1} (1%) from wind, 55,885 kWh yr^{-1} (55%) from hydro and 28,576 kWh yr^{-1} (28%) from Diesel Generator making a total of 101,024 kWh yr^{-1} (100%) as shown in Table 10. The load demand is 92,715 kWh yr^{-1}, and the Solar PV/Wind/Hydro-Diesel system gives an opportunity for renewable energy to supply 72% of the energy demand as shown in Table 10.

Reducing diesel hour of operation reduces fuel consumption; also means less emission from the energy system as shown by the solar PV/Wind/Hydro-diesel system which has the lowest emission of CO_2, PM and NO_x as shown in table 11 and 12, respectively.

Conclusion

An operational control system was developed to satisfy the load demand by optimally allocating the renewable energy sources to the maximum extent while limiting the use of diesel generator. From the control simulation, the hybrid controller reduces the operational hours of the diesel generator thereby reducing the running cost of the hybrid energy system as well as the pollutant emissions. It was observed that the hybrid controller allocates the sources optimally according to the demand and availability. From the simulation result, the developed control system reduces the operational hours of the diesel generator from 7,106 h yr^{-1} to 1,786 h yr^{-1} and this saves 28,087 L of fuel per annum, thereby preventing about 73,961 kg of CO_2 from entering into the environment of the studied area. From this control simulation we were able to see the performance of the system over the course of the year to see which mode(s) the system spends most time in, the power supplied by each of the energy sources over the year, and the power required by the load over the year. This is a very useful manner to check how the system is being supplied and which source of energy is the most proficient in supplying the load.

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