[1]Sushil Kumar Bhoi
[2], *Niranjan Behara
[3]Bikash Meher
[4]Nabin Kumar Naik
[5]Pradeep Kumar Shill

A Hybrid System Combining Photovoltaic, Wind Turbine, Diesel Generator, and Battery Storage Technologies

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Abstract: - The high cost of delivering power to rural areas is a major concern, leading to many areas lacking electricity. To address this, some countries use diesel generators or small-scale renewable energy sources like photovoltaics and wind. However, these generators have drawbacks such as high fuel requirements and non-linear load demand profiles. To address these issues, hybrid power generation systems can be formed, combining photovoltaic and wind turbines with diesel generators. This system reduces fuel consumption, minimizes fuel costs, and reduces environmental pollution. The research aims to develop two control strategies to minimize daily operational costs of hybrid systems involving PV/WT/DG and batteries, using MATLAB functions to simulate the control strategies. The models will help optimize power flow and minimize operational costs.

Keywords: *Optimal operation control, hybrid power generation system, cost minimization, optimization system and optimization algorithm.*

1 INTRODUCTION

Rural electrification in developing countries faces challenges such as lack of reliable electrical power supply, high costs of AC grid extension, and rough topography [4]. Diesel Generators (DGs) are used for power generation due to their low initial capital costs, ability to generate electricity on demand, and modularity. However, DGs are often inefficient and expensive due to long running times and non-linear load demand profiles [27]. Renewable energy sources like solar photovoltaic (PV) and wind turbines are being considered due to their low operation and maintenance costs. Hybrid solar PV-WT-diesel-battery hybrid systems can address these issues by balancing power supply from renewable sources and battery systems, enhancing system efficiency and output capability [1]. Hybrid Renewable Energy Systems are being considered for rural areas where grid supply is expensive. However, these systems are inherently intermittent due to climatic conditions and fluctuating loads [22]. To ensure reliability and cost-effectiveness, they must be strategically controlled. This research focuses on developing models to optimize the use of a diesel generator in hybrid systems, minimizing fuel consumption. By strategically controlling these systems, they can offer greater reliability and reduce fuel costs.

This study focuses on optimizing daily operational costs of hybrid Photovoltaic-Wind-Diesel-battery systems from an energy efficiency perspective. It aims to enhance operational efficiency by sizing and matching system components, time control, and human coordination. The study develops two models: "continuous" control strategy and "ON/OFF" control strategy, considering only the fuel cost of the DG for a 24-hour period

This research will be limited to:

- Computer simulation of the models through case studies.
- Development of mathematical models to minimize the operational cost of the proposed system.

2 PROPOSED HYBRID SYSTEM

The proposed hybrid system model consists of a combination of photovoltaic, wind turbine, diesel generator and battery system. Fig. 1.

[1,2,3,4] Department of Electrical Engineering, Government College of Engineering Kalahandi, Bhawanipatna, Kalahandi, Odisha, India, PIN-766003([1]sushilkumarbhoi@gmail.com, [2*]Corresponding author: niranjan.265@gmail.com, [3]bikashmeher1981@gmail.com and [5]pkshill92@gmail.com,

[4]Department of Electronics and Communication Engineering, Silicon Institute of Technology, Sambalpur, PIN-768200, (nabin.naik@silicon.ac.in)

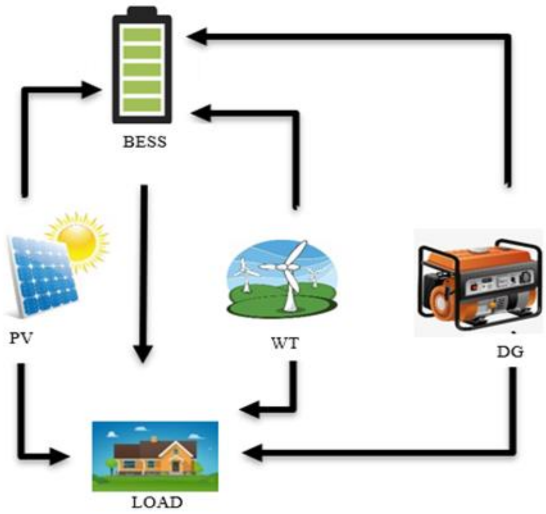

Figure. 1. Proposed Hybrid System

2.1 PV System

A solar panel consists of photovoltaic (PV) solar cells connected in series and parallel. These cells, typically made of semiconductor material, absorb sunlight, releasing electrons. These electrons, flowing from the negative layer to the positive, generate an electrical current, generating DC electricity.

In the outdoor environment the magnitude of the current output from a PV module directly depends on the solar irradiance and can be increased by connecting solar cells in parallel. The voltage of a solar cell does not depend largely on solar irradiance, but depends primarily on the cell temperature [7]. PV modules can be designed to operate at different voltages by connecting solar cells in series. Electrical parameters of a PV system are determined at standard test conditions, i.e. 1000 W/m2 solar irradiance, 25°C cell temperature and AM1.5 solar radiation.

The power output (P_{PV}) of the PV module can be expressed as follows[9]:

$$P_{PV} = A_{PV} \times \eta_{PV} \times I_{PV} \quad (1)$$

Where, A_{PV} is the total area of the photovoltaic generator (m^2);

η_{PV} is the module efficiency;

I_{PV} is the hourly irradiance(kWh/m^2).

2.2 Wind energy System

A wind turbine converts wind kinetic energy into mechanical energy, which is then converted into electric energy by a generator. They are divided into horizontal and vertical-axis types and can be onshore, offshore, or aerial. Power produced by wind generators has AC voltage but variable amplitude and frequencyTo maintain the frequency, the AC is converted to DC, stored in battery and then converted back to AC [8].

The extractable power from the wind is given by:

$$P_{WT} = \frac{1}{2} \times \rho_a \times A_{WT} \times C_{pWT} \times V^3 \quad (2)$$

Where, P_{WT} is the output power of the wind turbine;

ρ_a is the density of air (kg/m3);

C_{pWT} is the coefficient of the wind turbine performance;

A_{WT} is the wind turbine area (m2);

V is the wind velocity (m/s).

Power transferred to a wind turbine is directly proportional to the area swept by the rotor, air density, and wind speed cube. Limitations include wind machine size, density, friction losses, and energy conversion efficiency. Albert Betz's law states no wind turbine can convert more than 59.3% of wind kinetic energy into mechanical energy.

Standalone wind energy systems generate unstable, unreliable energy due to fluctuating wind speed. Hybrid systems, using wind turbines in combination with other sources, increase performance, reduce size, and cost.

2.3 Diesel Generator

A DG is a normal diesel engine coupled to an electrical generator. DGs are usually designed in such a way that they always operate close to their power rating to achieve high efficiency; 35 this condition can be used later as an operational constraint.

With this operation strategy as well as operational constraint, the DG is expected to run at high load factors, which will result a decrease of the fuel consumption, a small carbon footprint and an increase in the DG lifespan.
The fuel cost (FC) calculated for a day is given by the quadratic non-linear function below

$$C_f \sum_{j=1}^{N}(aP_{DG(j)}^2 + bP_{DG(j)} + C) \quad (3)$$

Where, a,b and c are the parameters related to any DG's fuel consumption curve (available from the manufacturer) C_f is the price of one liter of diesel fuel; $P_{DG(j)}$ is the output power or control variable from the DG in any sampling interval. It has to be highlighted that different DGs of different sizes as well as from different manufacturers present different fuel consumption curves and parameters.

2.3.1 ***Standalone operation of diesel generation system***

Electric power generators can be classified into three modes: continuous, prime, and standby. Continuous generators operate continuously with a consistent load, while prime generators operate for extended periods at variable load. Standby generators are used in remote locations with limited grid access. Diesel generators are simple and cost-effective, but have disadvantages like high operational and maintenance costs, environmental pollution, noise pollution, and fuel availability issues. They are primarily used in remote locations with limited grid access.

2.3.2 ***Operation of diesel generator in a hybrid system***

A diesel generator is utilized in hybrid system as a backup to meet energy deficits from other sources, increasing system reliability and minimizing fuel consumption, thus reducing the running cost of the diesel generation power system.

2.4 Battery Storage System

Battery energy storage systems (BESS) are crucial for micro grids, efficiently utilizing intermittent energy sources like PV. Deep-cycle lead-acid batteries are the most common due to their low cost and high efficiency. A bidirectional DC-DC charge controller controls power flow, ensuring maximum discharge doesn't exceed 75%[13].
The number of batteries in series is dictated by the nominal voltage of the DC bus, which is a constant. The instantaneous output power from the whole battery bank depends on variables such as the type and the size of the battery used, and the number of battery strings in parallel [26] . B The dynamics of the battery state of charge SOC can be expressed in discrete-time domain by a first order difference equation as follows).
The battery dynamic equation can be expressed as:

$$SOC_{(J)} = SOC_{(0)} - t_s \frac{\eta_{Bat}}{E_{(nom)}} \sum_{j=1}^{j} P_{Bat}(i) \quad (4)$$

Where, SOC is the state of charge of the battery;
η_{Bat} is the battery charging or discharging efficiency;
t_s is the sampling time (interval);
$E_{(nom)}$ is the battery system nominal energy;
P_{Bat} is the power flowing from the battery system.
Battery lifespan depends on operating conditions and ambient temperature, with lead-acid batteries losing 15%-20% for 5°C above 25°C. Deeper discharge depths also shorten battery lifespan. To achieve optimal lifespan, a large 40-enough battery is needed for suitable discharge depth.

2.4.1 ***Operation of battery storage system in hybrid systems***

Battery storage systems store excess energy from renewable sources during low peak periods and use it during peak demand periods. When combined with renewable energy sources, these systems ensure reliability and continuity of power supply. Battery storage systems extend battery life as they are not used permanently to supply loads, operating only when other sources are not generating enough energy.

2.5 Inverters and Rectifiers

Renewable energy sources often require transformation before use by loads. Inverters and rectifiers convert DC to AC current, while rectifiers convert AC to DC for load use or battery charging.
Stand-alone inverters operate isolated from electrical distribution networks, requiring batteries for constant voltage. Grid-tied inverters are coupled to the network and produce sinusoidal voltages and currents. Hybrid inverters combine a power inverter with a battery, allowing homeowners to use their solar power more effectively. These systems allow for day-to-day use of solar power, reducing the need for day-to-day work.

2.6 Loads

Household power demand depends on appliances and utilization factors, with rural households primarily using fluorescent and incandescent light, television sets, refrigerators, irons, and stoves, requiring designed power sources.

2.7 Standalone Hybrid power system

The combination of diesel generators with renewable energy and a battery storage system offers reliability and reduced fuel consumption compared to stand-alone generators. Renewable energy sources like solar and wind provide sustainable alternatives but face technical and economic challenges [1]. They are intermittent, unpredictable, and uncontrollable, making them unsafe for reliable power supply. Additionally, renewable energy is generally more expensive than conventional generators and can't be competitively priced.

3 PROPOSED OPTIMIZATION USING CONTINOUS OPERATION MODE

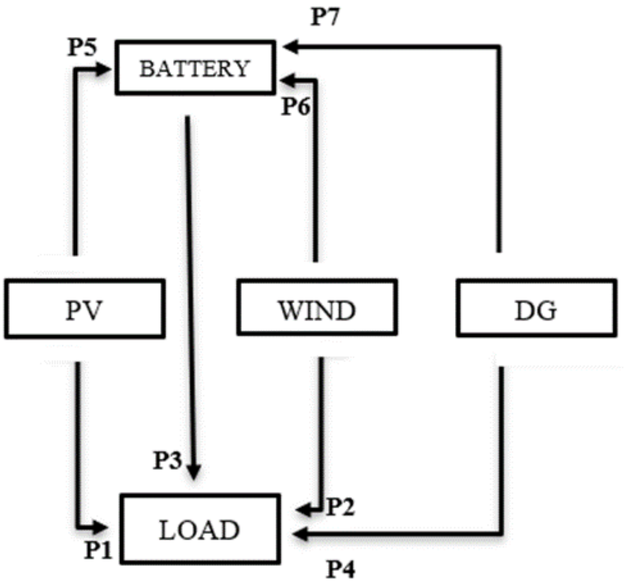

Figure. 2. Continuous model power flow layout

3.1 Model Development

3.1.1 ***Continuous model power flow layout***

From figure 4.1 the following variable can be defined: P1 is the control variable representing power flow from the PV to the load at any sampling interval (j) (kW); P2 is the control variable representing power flow from the WT to the load at any sampling interval (j) (kW); P4 is the control variable representing power flow from the DG to the load at any sampling interval (j) (kW); P3 is the control variable representing power flow from the battery to the load at any sampling interval (j) (kW), and P5 is the control variable representing power flow from the PV to the Battery at any sampling interval (j) (kW); P6 is the control variable representing power flow from the WT to the Battery at any sampling interval (j) (kW); P7 is the control variable representing power flow from the DG to the Battery at any sampling interval (j) (kW); PL is the load demand at any sampling interval (j) (kW).

The model proposed consists of the integration of different power sources. The model includes: photovoltaic, wind turbine, diesel generator and battery storage system as shown in figure 4.1. The load demand in the model is primarily met by the sum of the power from photovoltaic (P1) and wind turbine (P2) and the battery (P3) starts discharging within its operating limits as soon as the (P1) and (P2) do not meet the demand. If the sum of the power from the PV and WT is above the load demand, the excess power is used to recharge the battery (P5 & P6) (a dump load can be used to dissipate this power in a case in which the RE generation is more than the load and the required power to recharge the battery). Power from the DG (P4) is used when the sum of P1, P2 and P3 cannot respond to the load requirements. The deficit of power from the DG (P7) can be used to recharge the battery.

3.1.2 ***System Modelling***

The proposed optimization problem is to be simulated in a 24-hour period divided into equal intervals "N" with sampling interval "Δt". The number of sampling intervals are to be limited to "N=2" for modelling purposes, then the expression of the objective function and of the different constraints of the system can be summarized into canonical forms required by the solver. The variable "x" will be the only variable in the MATLAB code to be developed. Therefore, the output powers from different sources of the system have to be expressed in functions of the variable "x". The following allocations on variable "x" have been made:

$$P_1 = X(1:N) = [x_1, x_2] \quad (5)$$

$$P_2 = X(N+1:2N) = [x_3, x_4] \quad (6)$$

$$P_3 = X(2N+1:3N) = [x_5, x_6] \quad (7)$$

$$P_4 = X(3N+1:4N) = [x_7, x_8] \quad (8)$$

$$P_5 = X(4N+1:5N) = [x_9, x_{10}] \quad (9)$$

$P_6 = X(5N + 1{:}6N) = [x_{11}, x_{12}]$ (10)
$P_7 = X(6N + 1{:}7N) = [x_{13}, x_{14}]$ (11)

3.1.3 ***Objective function of the system***

The continuous operational mode of a diesel generator aims to reduce fuel consumption costs while responding to load power requirements. The generator is constantly on, controlling output power based on demand, and serves as a backup power source [8].

The objective function is expressed as:

$\min C_f \sum_{j=1}^{N}\{(aP_{4(j)}^2 + bP_{4(j)} + C) + (aP_{7(j)}^2 + bP_{7(j)} + C)\}$ (12)

Where: a, b, c are the parameters related to any DG's fuel consumption curve (available from the manufacturer); C_f is the price of one litre of diesel fuel; $P_{4(j)}$&$P_{7(j)}$ are the output power from the DG in any sampling interval (j) . The parameters of the DG differ as per the size and manufacturers.

3.1.4 ***Constraints***

The different constraints on the operation are as follows:

- Power balance

At any sampling interval j, the sum of the supplied powers (control variables) P_1, P_2, P_3, and P_4 from different power sources must be equal to the power required by the load. This can be expressed as:

$P_{1(j)+}P_{2(j)+}P_{3(j)+}P_{4(j)} = P_{L(j)}$ (13)

- Control Variable limits

The P_1 &P_5 from Photovoltaic and P_2 &P_6 from Wind Turbine are modelled as control variable power sources controllable in the range of zero to their maximum available power in the specific sampling interval power, and P_4 &P_7 from DG and P_3 from the Battery are modelled as a control variable controllable in the range of Type equation here.zero or minimum to their rated power for the 24-hour period. Therefore, the variable limits are the output limits of these different 50 power sources as well as of the battery storage system at any sampling interval (j) . These constraints depend on the characteristics of each power source and can be expressed as:

$0 \le P_{1(j)} \le P_1^{max} (1 \le j \le N)$ (14)
$0 \le P_{2(j)} \le P_5^{max} (1 \le j \le N)$ (15)
$0 \le P_{3(j)} \le P_2^{rated} (1 \le j \le N)$ (16)
$0 \le P_{5(j)} \le P_5^{max} (1 \le j \le N)$ (17)
$0 \le P_{6(j)} \le P_6^{max} (1 \le j \le N)$ (18)
$0 \le P_{7(j)} \le P_7^{rated} (1 \le j \le N)$ (19)

Where: $P_1^{max}, P_2^{max}, P_5^{max}$&$P_6^{max}$ is the maximum value of a given renewable power source at any sampling interval (j) and P_4^{rated} , P_7^{rated}, P_3^{rated} are the rated power of the DG and the battery system respectively.

- Battery state-of-charge

The available battery state-of-charge in any sampling internal (j) must not be less than the minimum allowable state-of-charge and must not be higher than the maximum allowable state of-charge. This can be expressed as:

$SOC^{min} \le SOC_{(j)} \le SOC^{max}$ (20)

$$SOC_{(j)} = SOC_{(0)} + \frac{\eta_c \times \Delta_1}{E_{nom}} \sum_{j=1}^{N} \left(P_{5(j)} + P_{6(j)} + P_{7(j)}\right)$$
$$- \sum_{j=1}^{N} P_{3(j)} \times \frac{\Delta_t}{\eta_D \times E_{nom}} \quad (21)$$

Where, SOC^{min} & SOC^{max} are respectively, the minimum and maximum of the battery state of charge; η_C is the battery charging efficiency; η_D is the battery discharging efficiency; E_{nom} is the battery system nominal energy, and Δ_t is the sampling time interval.

3.1.5 ***Proposed optimization solver and algorithm***

The developed problem has a non-linear objective function and linear constraints and can be solved using "fmincon" . Fmincon solves problems in the form[25]:

$$x^{min} f(x) \text{Subject to:} \begin{cases} C(X) \le 0 \\ C_{eq}(X) \le 0 \\ A.X \le b \\ A_{eq.}X \le b_{eq} \\ I_b \le X \le u_b \end{cases} \quad (22)$$

Where, X, b, b_{eq}, I_b and u_b are vectors; A & $A_{eq.}$ are matrices; $C(X)$&$C_{eq}(X)$ are functions that return vectors; and $f(x)$ is a function that returns a scalar; $f(x), C(X), C_{eq}(X)$ are non-linear functions.

3.1.6 ***Objective function definition in fmincon syntax***

The objective function is to minimize the fuel consumption costs of the DG during operational time, and this can be expressed as follows:

$\min FC = \Delta_t \sum_{j=1}^{N} (aP_{4(j)}^2 + bP_{4(j)} + c) + (aP_{7(j)}^2 bP_{7(j)} + c)$ (23)

*3.1.7 **Constraints definition in fmincon syntax***

• Power balance

The power balance at any j^{th} sampling interval can be expressed as:

$P_{1(j)+}P_{2(j)+}P_{3(j)+}P_{4(j)} = P_{L(j)}$ (24)

As N = 2, the power balance can be developed for these two sampling intervals as:

$j = 1 \rightarrow x_1 + x_3 + x_5 + x_7 = P_{L1}$ (25)

$j = 2 \rightarrow x_2 + x_4 + x_6 + x_8 = P_{L2}$ (26)

Taking the coefficient of the equations, the system can be rewritten in a matrix form as:

$$\begin{pmatrix} 10101010000000 \\ 01010101000000 \end{pmatrix} \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_{14} \end{pmatrix} = \begin{pmatrix} P_{L1} \\ P_{L2} \end{pmatrix} \quad (27)$$

Using the canonical formulation of the linear equality constraints in fmincon, the power balance can be finally expressed as:

$Aeq = [eye(N,N), eye(N,N), eye(N,N), eye(N,N),$
$zeros(N,N), zeros(N,N), zeros(N,N)]$ (28)

$b_{eq} = P_L(1:N)$ (29)

• Linear inequality

⅄ Linear inequality for battery bank

The available battery bank state-of-charge in any sampling internal must not be less than the minimum allowable state-of-charge and must not be higher than the maximum allowable state-of-charge. This can be expressed as:

$SOC^{\min} \le SOC_{(j)} \le SOC^{\max}$ (30)

⅄ Dealing with maximum inequality(SOC^{max})

$For\ j = 1$

$SOC_{(0)} + d(X_9 + X_{11} + X_{13}) - eX_5 \le SOC^{max}$ (31)

$For\ j = 2$

$SOC_{(0)} + d(X_9 + X_{10} + X_{11} + X_{12} + X_{13} + X_{14}) - eX_5 - eX_6 \le SOC^{max}$ (32)

Then

$dX_9 + dX_{11} + dX_{13} - eX_5 \le SOC^{max} + SOC_{(0)}$

$dX_9 + dX_{10} + dX_{11} + dX_{12} + dX_{13} + dX_{14} - eX_5 - eX_6 \le SOC^{max} + SOC_{(0)}$ (33)

⅄ Dealing with minimum inequality (SOC^{min})

$For\ j = 1$

$SOC^{min} \le SOC_{(0)} + d(X_9 + X_{11} + X_{13}) - eX_5$ (34)

$For\ j = 2$

$-dX_9 - dX_{10} - dX_{11} - dX_{12} - dX_{13} - dX_{14} + eX_5 - eX_6 \le SOC_{(0)} - SOC^{min}$ (35)

⅄ Linear inequality for PV

$P_{1(j)} + P_{5(j)} \le P_{PV}^{max}$ (36)

$For\ j = 1$

$X_1 + X_9 \le P_{PV1}^{max}$ (37)

$For\ j = 2$

$X_2 + X_{10} \le P_{PV2}^{max}$ (38)

⅄ Linear inequality for WT

$P_{2(j)} + P_{6(j)} \le P_{WT}^{max}$ (39)

$For\ j = 1$

$X_3 + X_{11} \le P_{WT1}^{max}$ (40)

$For\ j = 2$

$X_4 + X_{12} \le P_{WT2}^{max}$ (41)

⅄ Linear inequality for DG

$P_{4(j)} + P_{7(j)} \le P_{DG}^{rated}$ (42)

$For\ j = 1$

$X_7 + X_{13} \le P_{DG}^{rated}$ (43)

$For\ j = 2$

$X_8 + X_{14} \le P_{DG}^{rated}$ (44)

Taking the coefficient of the equations (33), (34) , (35), (36), (37), (38), (39), (40), (41), (42), (43) and (44) the system can be rewritten in a matrix form as:

$$\begin{pmatrix} 0&0&0&0&-e&0&0&0&d&0&d&0&d&0 \\ 0&0&0&0&-e&-e&0&0&d&d&d&d&d&d \\ 0&0&0&0&e&0&0&0&-d&0&-d&0&-d&0 \\ 0&0&0&0&e&e&0&0&-d&-d&d&d&d&d \\ 1&0&0&0&0&0&0&0&1&1&0&0&0&0 \\ 0&1&0&0&0&0&0&0&0&0&0&0&0&0 \\ 0&0&1&0&0&0&0&0&0&0&1&0&0&0 \\ 0&0&0&1&0&0&0&0&0&0&0&1&0&0 \\ 0&0&0&0&0&0&1&0&0&0&0&0&1&0 \\ 0&0&0&0&0&0&0&1&0&0&0&0&0&0 \end{pmatrix} \begin{pmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \\ X_7 \\ X_8 \\ X_9 \\ X_{10} \\ X_{11} \\ X_{12} \\ X_{13} \\ X_{14} \end{pmatrix} \leq \begin{pmatrix} SOC^{max} - SOC_{(0)} \\ SOC^{max} - SOC_{(0)} \\ SOC^{min} - SOC_{(0)} \\ SOC^{min} - SOC_{(0)} \\ P_{PV1}^{max} \\ \\ P_{WT1}^{max} \\ P_{WT2}^{max} \\ P_{DG}^{rated} \\ P_{DG}^{rated} \end{pmatrix} \quad (45)$$

Using the canonical formulation of the linear inequality constraints in fmincon, this can be finally expressed as:

$$A_1 = [zeros(N,N), zeros(N,N), -e * tril(ones(N,N), zeros(N,N), d * tril(\ zeros(N,N), d * tril(\ zeros(N,N), d * tril(\ zeros(N,N))] \quad (46)$$

$$A_2 = -A_1 \quad (47)$$

$$A_3 = [eye(N,N), zeros(N,N), zeros(N,N), zeros(N,N), eye(N,N),, zeros(N,N), zeros(N,N)] \quad (48)$$

$$A_4 = [eye(N,N), zeros(N,N), zeros(N,N), zeros(N,N), zeros(N,N), eye(N,N), zeros(N,N), zeros(N,N)] \quad (49)$$

$$A_5 = [\ zeros(N,N), zeros(N,N), zeros(N,N), eye(N,N), zeros(N,N), zeros(N,N), eye(N,N)] \quad (50)$$

$$A = [A_1; A_2; A_3; A_4; A_5] \quad (51)$$

$$b_1 = \left(SOC^{max} - SOC_{(0)}\right) * ones(N,1) \quad (52)$$

$$b_2 = \left(SOC_{(0)} - SOC^{mIN}\right) * ones(N,1) \quad (53)$$

$$b_3 = P_{PV}^{max}(1{:}N) \quad (54)$$

$$b_4 = P_{WT}^{max}(1{:}N) \quad (55)$$

$$b_5 = P_{DG}^{rated} * ones(N{:}1) \quad (56)$$

$$b = [b_1; b_2; b_3; b_4; b_5] \quad (57)$$

- Variable boundaries

These boundaries represent the upper and lower limits of outputs from each power source as well as of the battery storage system for each j^{th}sampling time.

$$Ib \leq x \leq ub \quad (58)$$

With, Ib: lower boundaries and ub: upper boundaries

These can be expressed for eachj^{th} sampling interval as:

$$0 \leq P_{1(J)} \leq P_1^{max} \quad (59)$$

$$0 \leq P_{2(J)} \leq P_2^{rated} \quad (60)$$

$$-P_3^{min} \leq P_{3(J)} \leq P_3^{max} \quad (61)$$

$$0 \leq P_{4(J)} \leq P_4^{rated} \quad (62)$$

$$0 \leq P_{5(J)} \leq P_5^{max} \quad (63)$$

$$0 \leq P_{6(J)} \leq P_6^{max} \quad (64)$$

$$0 \leq P_{7(J)} \leq P_7^{rated} \quad (65)$$

➤ Lower boundaries

The change of minimum values that each power source can produce in different time intervals is “zero”; however, for the specific case of the battery system, this value “P_3^{rated}” is the maximum power entering the battery while charging. The system's lower boundaries change can be expressed in vector forms as follows:

$$I_{b1} = P_1^{min} * ones(N,1) \quad (66)$$
$$I_{b2} = P_2^{min} * ones(N,1) \quad (67)$$
$$I_{b3} = -P_3^{min} * ones(N,1) \quad (68)$$
$$I_{b4} = P_4^{min} * ones(N,1) \quad (69)$$
$$I_{b5} = P_5^{min} * ones(N,1) \quad (70)$$
$$I_{b6} = P_6^{min} * ones(N,1) \quad (71)$$
$$I_{b7} = P_7^{min} * ones(N,1) \quad (72)$$
$$Ib = [I_{b1}; I_{b2}; I_{b3}; I_{b4}; I_{b5}; I_{b6}; I_{b7}] \quad (73)$$

- Upper boundaries

The change of maximum values that each renewable source can produce in different time intervals is " $P_{i(j)}^{max}$", which depends on the availability of the renewable resources. However, for the specific case of the DG and the battery system, these values are their maximum rated values "P_4^{rated}", "P_7^{rated}",and "P_3^{rated}", respectively. The system's lower bounds change can be expressed in vector forms as follows:

$$ub_1 = P_1^{max}(1{:}N) \quad (74)$$
$$ub_2 = P_2^{max}(1{:}N) \quad (75)$$
$$ub_3 = P_3^{max} * ones(N{:}1) \quad (76)$$
$$ub_4 = P_4^{max} * (N{:}1) \quad (77)$$
$$ub_5 = P_5^{max}(1{:}N) \quad (78)$$
$$ub_6 = P_6^{max}(1{:}N) \quad (79)$$
$$ub_7 = P_7^{max} * ones(N{:}1) \quad (80)$$
$$ub = [u_{b1}; u_{b2}; u_{b3}; u_{b4}; u_{b5}; u_{b6}; u_{b7}] \quad (81)$$

3.1.8 ***Final model of continuous operation mode***

The final model of the continuous operation of the system will be a MatLab code that any user can use by changing the technical input data. The user will be able to introduce his own load profiles, the capacity of the diesel generator, the battery state of charge, and the profile of photovoltaic and wind turbine. The final model developed will be able to optimize the operation of the system by minimizing the consumption of the diesel generator, therefore minimizing the cost.

3.2 Simulation results and discussions

Here the continuous operation is simulated using MATLAB function and the simulation results are discussed. As indicated under the objective function, the aim of the simulation is to show how the diesel's generator fuel consumption can be minimized using the continuous control strategy developed. In this case the diesel generator is on most of the time and its output is continuously controlled to minimize fuel consumption, while in the meantime responding to requirement of the load. The simulation of the household is carried out during summer and winter to indicate how climate change can influence the load demand, RE primary resources, and as result influence the operation and cost of the hybrid systems.

3.2.1 ***Data Presentation***

The solar radiation data used in this study are calculated from stochastically generated values of hourly global and diffuse irradiation using the simplified tilted-plane mode. This is calculated for a South African rural area close to Bloemfontein. Wind speed data measured at 10m height at the site over a period of two years is used in this work. Two typical summer and winter load demand profiles for institutional applications based on an energy demand survey carried out in rural communities in South Africa, are used. The load and RE data for the selected summer and winter days are as shown in Table. 1. The two daily load profiles are used to analyze the benefit of the hybrid system operating under the two control strategies compared with the DG used as stand-alone.

3.2.2 ***Resources and load data of the household***

The Table. 1. below indicates the detailed load profile taken from typical household for a 24-hour simulation period during summer and winter. The household has low consumption appliances, such as TV, lights, kettle, iron, toaster, laptop, etc. The Table also indicates the hourly profiles of solar irradiation and wind speed during summer and winter.

Table. 1. household resources & load data

Time	Summer			Winter		
(h)	Global solar ($kW/^2$)	Wind speed at rotor hub (m/s)	Load (kW)	Global solar (kW/m^2)	Wind speed at rotor hub (m/s)	Load (kW)
00:00	0.000	0.821	0.3	0.000	0.871	0.3
01:00	0.000	1.665	0.2	0.000	0.381	0.2
02:00	0.000	0.998	0.1	0.000	0.947	0.1

03:00	0.000	0.956	0.0	0.000	1.425	0.0
04:00	0.000	2.549	0.3	0.000	1.575	0.3
05:00	0.000	2.558	0.0	0.000	1.463	0.0
06:00	0.000	2.775	2.4	0.000	0.932	3.0
07:00	0.002	3.754	0.6	0.000	1.560	0.7
08:00	0.141	2.948	4.3	0.145	1.337	8.0
09:00	0.417	2.828	5.6	0.244	1.761	5.6
10:00	0.687	2.870	3.2	0.306	2.611	2.6
11:00	0.940	2.522	1.6	0.512	3.542	3.0
12:00	1.062	1.766	0.3	0.611	3.956	0.5
13:00	1.061	2.576	2.0	0.614	4.698	3.4
14:00	0.978	2.017	0.4	0.568	4.898	0.7
15:00	0.846	2.282	0.8	0.428	4.089	1.3
16:00	0.679	3.116	3.9	0.460	5.544	1.4
17:00	0.464	2.626	1.8	0.266	4.404	1.5
18:00	0.208	3.427	1.7	0.000	4.547	3.8
19:00	0.043	2.972	1.9	0.000	4.711	4.6
20:00	0.000	2.543	2.2	0.000	3.881	5.9
21:00	0.000	2.336	0.9	0.000	4.610	2.1
22:00	0.000	1.863	0.7	0.000	2.537	0.8
23:00	0.000	1.231	0.3	0.000	2.370	0.3

3.2.3 ***Components sizes & model parameters***

The hybrid system is designed so that the load power demand is met at any given time. The sizes of different components of the system have already been discussed in chapter 3. This chapter focuses more on the simulation and discussion of the results. This study also emphasizes mainly the optimal energy management of the given hybrid system. The different parameters used in the simulations are given in Table.2. [26]

Table. 2. Simulation Parameters

Item	Figure
Sampling time	30 min
Battery maximum SOC	95%
Battery minimum SOC	40%
Battery charging efficiency	85%
Battery discharging efficiency	100%

3.2.4 ***Simulation and discussion results during winter***

a) 24-Hour load Supplied by the hybrid system during winter

• Load profile

Figure. 2. indicates the load profile of the household during winter. From the figure it can be seen that from 22:00 to 6:00 in the morning, the load demand is very minimum. The load starts picking up after 6h in the morning and reaches its maximum demand between 8:00 and 9h, after 9h it starts decreasing up to 17:00 in the evening. The load is high again around 22:00.

• Power from different sources to the load

Figures. 3. to 5. show power flow from various sources to loads. At midnight and early morning, the household's power demand is low,

With Only the battery used. The diesel generator is off, and renewable energy output powers are zero. After 6:00, renewable energy sources generate, meeting the household's power needs. From 8:00 to 9:00, the load reaches peak demand, and renewable energy sources generate more.

The household load demand decreases from 9:00 to 10:00, with PV power generation increasing. The load requirement is met by the sum of output power from PV, WT, and battery, without running the DG. Between 17:00 and 20:00, load demand picks up, and WT generates again. The system is backed up by a diesel generator. Between and 20:00 and 21:00, renewable energy sources cease, and the battery cannot meet the load requirement. The PV is the main component of the system, influencing the running cost and recharging the battery. It contributes more to the system's running cost when renewable energy sources cease, reducing load demand and accumulating excess power

• Power from different sources to the battery system

Figures.7. To 9. indicate the power from PV, DG and WT used to recharge the battery system. From Figures 4.6 and 4.7, it can be seen that when power produced by the renewable energy sources is more than the power required by the load, the excess is used to recharge the battery. From Figure 4.6, it can be noticed that the PV is the source that contributes more to recharging the battery than WT. As indicated in the figure 4.7, the WT contributes very little to the recharging of the battery. Figure 4.8 below indicates that for a continuous operation mode, the diesel generator output power is not used to recharge the battery as its output is controlled to supply only the deficit of power from other power sources required by the load.

- Battery SOC dynamic

Figure. 10. below shows that the battery state-of-charge operates within acceptable boundaries with the minimum being 40% and the maximum being 95%.The simulation results show that during the winter the diesel generator runs for 7 hours and the highest output power that it supplies to the load does not exceed 30% of its rated capacity, therefore its fuel consumption is minimized.

The simulation results show that during the winter the diesel generator runs for 7 hours and the highest output power that it supplies to the load does not exceed 30% of its rated capacity, therefore its fuel consumption is minimized.

b) 24 Hourly load supplied by a stand-alone diesel generator only (Winter)

The Figure. 11. above illustrates the output power supplied by the DG when used as a standalone to supply the full load of the household during a 24-hour period. It can be seen that the DG works almost 24 hours and during peak times, it has to generate the highest power load required. This illustration of running the DG alone to supply the full load required by a household will help in determining the cost required for such a household and this can be compared with a case which the DG is used in combination with renewable

c) Daily operational cost summary of the continuous operation mode

The table. 1. compares the costs of running a household with a stand-alone diesel generator and a hybrid power system, with a 75-diesel generator as a backup. Fuel consumption is directly proportional to the generator's power and running time. A hybrid system can save more fuel. Winter consumption is higher than summer.

Table. 3. continuous mode fuel saving

	Winter		Summer	
	Consumption (L)	Cost ($)	Consumption (L)	Cost ($)
DG only	28.26 L	22.6 $	19.23 L	15.39 $
Hybrid system	3.55 L	2.84 $	0.36 L	0.29 $
Savings	24.71 L	19.78 $	18.87 L	15 $
Savings	87.5 %	87.5 %	98 %	98 %

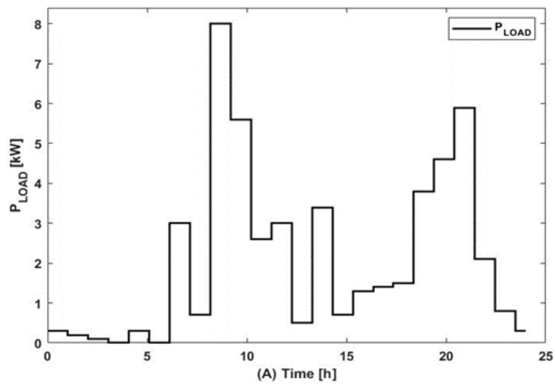

Figure. 3. Household 24-hr load profile during winter

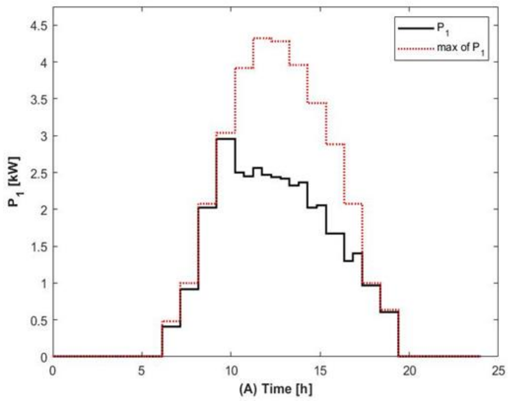

Figure. 4. Photovoltaic output power & power supplied to the load during winter

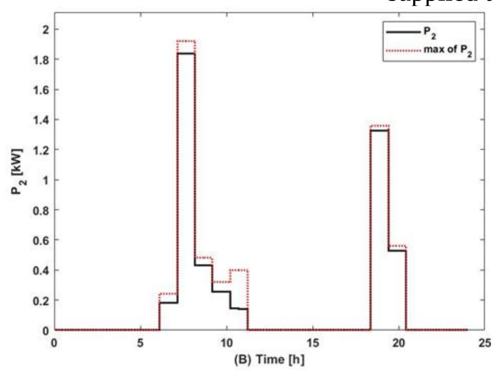

Figure. 5. Wind turbine output power & power supplied to the load during winter

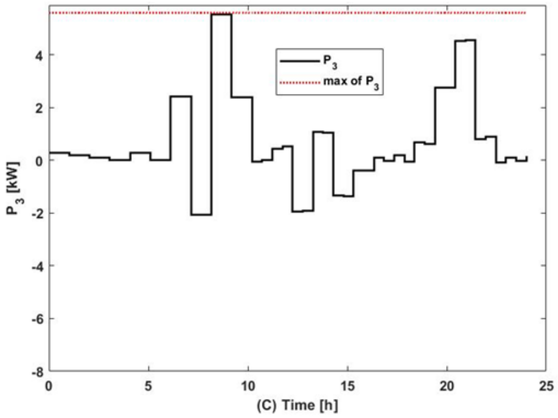

Figure. 6. Battery output power & power supplied to the load during winter

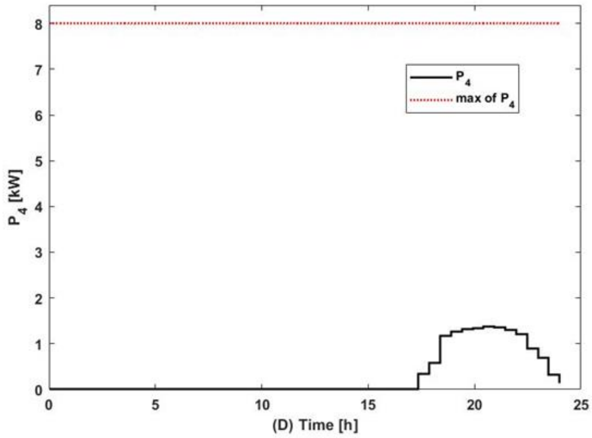

Figure. 7. Diesel generator output power & power supplied to the load during winter

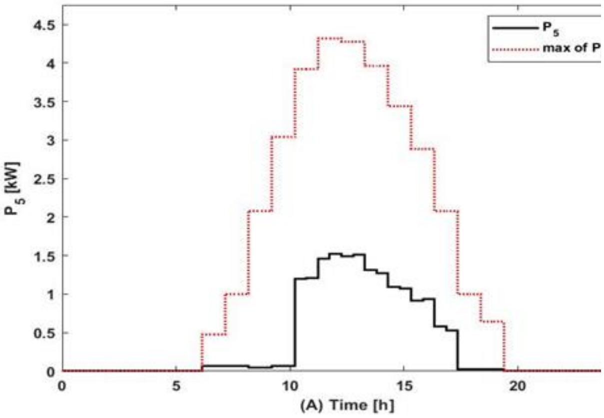

Figure. 8. Photovoltaic output power & power supplied to the battery during winter

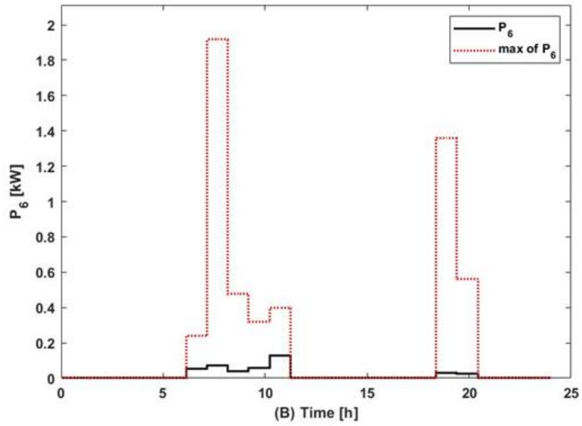

Figure. 9. Wind turbine output power & power supplied to the battery during winter

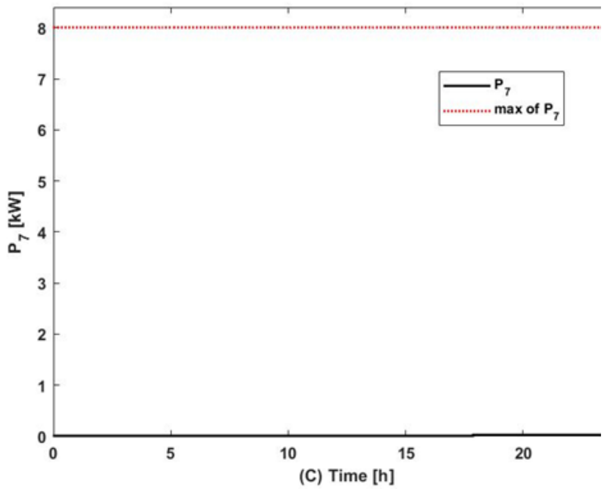

Figure. 10. Diesel generator output power & power supplied to the battery during winter

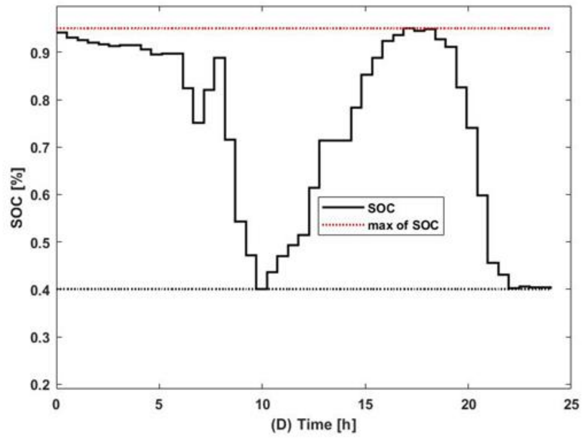

Figure. 11. Battery SOC dynamic

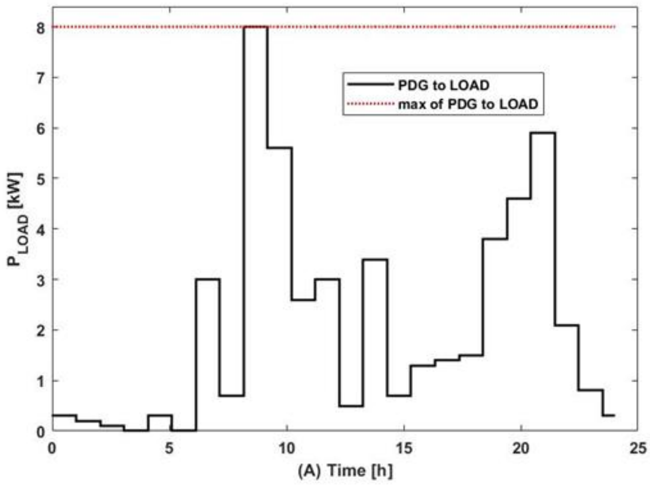

Figure. 12. Standalone diesel generator output power supplied to load during winter

4 PROPOSED OPTIMIZATION USING ON/OFF OPERATION MODE

4.1 Model development

The proposed model Figure. 13. integrates various power sources, including photovoltaic, wind turbine, diesel generator, and battery storage systems. The load demand is met by the sum of power from these sources, and excess power is used to recharge the battery. If the power is above the load demand, the generator is switched on, and when it is above the load demand, the generator is switched off. The DG's power can only take zero or rated power values, with a switch dictating its state.

P1 is the control variable representing power flow from the PV to the load at any sampling interval (j) (kW); P2 is the control variable representing power flow from the WT to the load at any sampling interval (j) (kW); P3 is the control variable representing power flow from the battery to the load at any sampling interval (j) (kW); P4 is The control variable representing power flow from the PV to the Bat at any sampling interval (j) (kW); 77 P5 is the control variable representing power flow from the WT to the Bat at any sampling interval (j) (kW); S is the control variable representing the switch that controls the state of the diesel generator; S can take two values either “0” or “1”; PDGmax is the rated power from the DG to the load or battery that depends on the state of the switch; PL is the load demand at any sampling interval (j) (kW).

*4.1.1 **System Modelling***

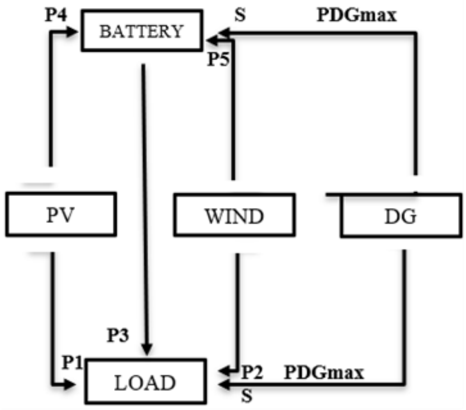

Figure. 13. System model power flow

The proposed optimization problem will be simulated in a 24-hour period divided into equal intervals “N” with sampling interval “Δt”. The number of sampling interval will be limited to “N=2” for modelling purposes, then the expression of the objective function and of the different constraints of the system can be summarized into canonical forms required by the solver. The variable “x” will be the only variable in the MatLab code to be developed. Therefore, the output power from different sources of the system have to be expressed in functions of the variable “x”.

The following allocations have been made:

$S = X(1{:}N) = [x_1, x_2]$ (82)
$P_1 = X(N+1{:}2N) = [x_3, x_4]$ (83)
$P_2 = X(2N+1{:}3N) = [x_5, x_6]$ (84)
$P_3 = X(3N+1{:}4N) = [x_7, x_8]$ (85)
$P_4 = X(4N+1{:}5N) = [x_9, x_{10}]$ (86)
$P_5 = X(5N+1{:}6N) = [x_{11}, x_{12}]$ (87)

4.1.2 ***Objective function of the system***

The ON/OFF operation mode aims to minimize fuel consumption costs of the diesel generator while responding to load power requirements. The DG is used as a backup to the system, running at its rated capacity to recharge the battery. The main goal is to switch the DG on or off without compromising load requirements.

The objective function is expressed as:

$$\min C_f \sum_{j=1}^{N} (aP_{DGmax}^2 + bP_{DGmax} + C) \times S_{(j)} \quad (88)$$

Where, a, b, c are the parameters related to any DG's fuel consumption curve (available from the manufacturer); C_f is the price of one litre of diesel fuel; P_{DGmax} is the rated power from the DG, and $S_{(j)}$ is a discrete-switching function that takes the value of either 0 or 1. $S_{(j)} = 0$ means that the DG is switched off during the j^{th} sampling interval, while $S_{(j)} = 1$ means that the DG is switched on. The output power of the DG is therefore constant.

4.1.3 ***Constraints***

The different constraints on the operation are as follows:

• Power balance

At any sampling interval "j", the sum of the supplied power (control variables) P_1, P_2, P_3 and $P_{DGmax} \times S_{(j)}$ from different power sources must be equal to the power required by the load. This can be expressed as:

$$P_{DGmax S_{(j)}} + P_{1(j)} + P_{2(j)} + P_{3(j)} = P_{L(j)} \quad (89)$$

• Control Variable limits

The $P_{1(j)}$&$P_{4(j)}$from Photovoltaic and $P_{2(j)}P_{5(j)}$ from Wind Turbine are modelled as control variable power sources controllable in the range of zero to their maximum power, and $S_{(j)}$ is a discrete-switching function that takes the value of either 0 or 1 and $P_{3(j)}$ from the battery is modelled as control variable controllable in the range of zero or minimum to its rated power for the 24-hour period. Therefore, the variable limits are the output limits of these different power sources as well as of the battery storage system at any sampling interval (j) . These constraints depend on the characteristics of each power source and can be expressed as:

$0 \le P_{1(j)} \le P_1^{max} (1 \le j \le N)$ (90)
$0 \le P_{2(j)} \le P_2^{max} (1 \le j \le N)$ (91)
$0 \le P_{3(j)} \le P_3^{rated} (1 \le j \le N)$ (92)
$0 \le P_{5(j)} \le P_4^{max} (1 \le j \le N)$ (93)
$0 \le P_{6(j)} \le P_4^{max} (1 \le j \le N)$ (94)

4.1.4 ***Proposed optimization solver and algorithm***

The objective function has to be modelled as a function of the switch controlling the DG and the variable battery output power. This mixed-integer optimization problem can be solved using the "Intlinprog" function from MatLab Optimization toolbox.

$$x^{min} f(x) \text{Subject to:} \begin{cases} X(intcon) \\ A.X \le b \\ A_{eq}.X \le b_{eq} \\ I_b \le X \le u_b \end{cases} \quad (95)$$

Where , $X(intcon), b_{eq}, I_b, u_b$are vectors; $A_{eq.}, A$ are matrices.

4.1.5 ***Objective function definition in Intlinprog syntax***

The objective function is to minimize the fuel consumption cost of the DG during operational time, and this can be expressed as follows:

$$\min FC = \Delta_t \sum_{j=1}^{N} (aP_{DGmax}^2 + bP_{DGmax} + C) \times S_{(j)}$$

$$\min \Delta_t \sum_{j=1}^{N} [k * X(1{:}N)]$$

Where, $k = aP_{DGmax}^2 + bP_{DGmax} + C$

4.2 Simulation results and discussions

4.2.1 ***Simulation and discussion results during winter***

• Load profile

The load profile of a household during winter, with minimum demand from 22:00 to 6:00, peak demand between 8:00 and 9:00, decreasing to 17:00, and high again at 22h.

• Power from different sources to the load

The household's power demand fluctuates throughout the day, with renewable energy sources generating more power than the battery. The load demand starts at midnight and early in the morning, and the diesel generator is off. The load then picks up, and renewable energy sources generate output power from PV, WT, and battery, while the DG is off. The load demand reaches its peak demand from 8:00 to 9:00, and the DG is off. The PV power generation increases from 9:00 to 10:00, and the load demand drops from 10:00 to 18:00. The WT generates again, and the PV generates more power, which is used to supply the load and recharge the battery. The DG is switched on to back up the system, and the load demand is met by the battery only. PV is the main component of the system, influencing the system's running costs.

• DG ON/OFF state

The DG's ON/OFF state over 24 hours, with the generator being off most of the time and running for one hour between 20:00 and 21:00, responding to high load requirements.

• Power from different sources to the battery system

When renewable energy sources produce more power than the load, the excess is used to recharge the battery. PV contributes more than WT, while WT contributes little.

• Battery SOC dynamic

The battery state-of-charge (SOC) is within acceptable limits, with a high SOC between 20:00 and 21:00, indicating that excess power from the DG is used to recharge the battery, not generating [21].

b) Daily operation cost summary of ON/OFF operation mode

The table. 4. compares the cost of running a household with a standalone diesel generator and a hybrid power system, highlighting that fuel consumption is directly proportional to generator power and running time. The hybrid system can save more fuel. Winter consumption is higher than summer due to less power requirement.

Table. 4. ON/OFF mode daily fuel cost savings

	Winter		Summer	
	Consumption (L)	Cost($)	Consumption (L)	Cost($)
DG only	28.26 L	22.6 $	19.23 L	15.39 $
Hybrid system	5.01 L	4 $	2.5 L	2 $
Savings	23.25 L	18.6 $	16.73 L	13.35 $
Savings %	82.2 %	82.2 %	87 %	87 %

c) Daily operational cost summary of continuous and ON/OFF operation modes

The table. 5. compare continuous operation mode and ON/OFF operation mode for diesel generator use in hybrid systems. Continuous operation saves more fuel due to limited output, while ON/OFF operation mode reduces fuel consumption. Summer offers more cost savings, with continuous operation saving 11% more and 5.3% more than ON/OFF operation mode. On/Off operation mode uses more fuel but runs for fewer hours.

Table. 5. Daily fuel cost savings in winter using different control strategies

	Continuous		ON/OFF	
	Consumption(L)	Cost($)	Consumption(L)	Cost($)
DG only	28.26 L	22.6 L	28.26 L	22.6 $
Hybrid system	3.55 L	2.84 $	5.01 L	4 $
Savings	24.71 L	19.78 $	23.25 L	18.6 $
Savings %	87.5 %	87.5 %	82.2 %	82.2 %

Table. 6. Daily fuel cost savings in summer using different control strategies

	Continuous		ON/OFF	
	Consumption(L)	Cost($)	Consumption(L)	Cost($)
DG only	19.23 L	15.4 $	19.23 L	15.4 $
Hybrid system	0.36 L	0.29 $	2.5 L	2 $
Savings	18.87 L	15.1 $	16.73 L	13.4$
Savings %	98 %	98 %	87 %	87 %

• CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This paper concluded the optimal control of hybrid power systems using photovoltaic, wind turbine, diesel generator, and battery storage systems. High operational costs and fuel consumption issues can be addressed by introducing renewable energy to a standalone diesel generator. However, careful control is needed to minimize

diesel generator usage and operational costs. The research focuses on developing control strategies to minimize diesel generator use in hybrid systems, minimizing fuel consumption and operational costs.
A continuous operation mode is developed, aiming to minimize fuel consumption and operational costs for affordable rural applications.
An ON/OFF operation mode is developed, aiming to minimize fuel consumption and operational costs. Comparative tables show that introducing a hybrid system to a standalone diesel generator can save up to 98% on operational costs. Continuous strategies yield more cost savings. Winter results are included , while summer results are included in appendices and tables.

5.2 Recommendation

This research focused on developing control strategies for diesel generators in hybrid systems, focusing on optimal control rather than detailed designs. The model includes photovoltaic and wind turbines as renewable sources. Further studies should include additional sources for cost savings and minimize diesel generator use. Investigating running the generator at less than 50% of its capacity and considering long running times and multiple starts and stops will help determine the best control strategies for hybrid systems.

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