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Hybrid Microgrid Optimisation: Power Management, Economic Dispatch and Emission Reduction for Renewable-Diesel Systems

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This paper explores the modelling and simulation of a hybrid power grid that integrates conventional and renewable energy sources such as diesel generators, wind turbines, and solar panels. The system is structured to meet the energy demands of residential and industrial sectors using a step-down transformer to regulate voltage levels and ensure effective operation across different components. The research employs Simulink to simulate and evaluate key operational factors, such as energy distribution, voltage stability, load-sharing strategies, emission reductions, and cost efficiency. An important feature of the system is its automatic diesel generator control, which restricts generator use to periods when renewable energy is insufficient. This, in turn, achieves a substantial reduction in fuel consumption, exceeding 20%, while maintaining system reliability. The findings confirm the viability of hybrid microgrids in delivering stable energy supplies, improving efficiency, and reducing environmental and economic costs.
Keywords: Automatic Generator Control, Economic dispatch, Emission reduction, Fuel consumption reduction, Hybrid power grid.

1. Introduction

As the global demand for energy continues to rise, integrating renewable energy sources with conventional systems has emerged as a practical approach to reducing dependence on fossil fuels while promoting sustainability within power grids [1]. This research examines the modelling and simulation of a hybrid power grid that utilises diesel generators, wind farms, and solar panels to fulfil the energy needs of residential and industrial sectors. The hybrid system is configured to optimise energy distribution [2], minimise emissions [3], and reduce operational costs through efficient control strategies [4]. Simulink is used to model the grid, simulate its performance, and analyse the dynamic interactions between the various power sources [5]. The grid includes three main power generation sources: a diesel station equipped with three diesel generators, a wind farm, and solar panels. These sources work in tandem to supply electricity, with diesel generators primarily compensating for fluctuations in renewable energy generation [6]. The control system ensures that the diesel generators are activated only when renewable sources cannot meet demand, thereby reducing fuel consumption, emissions, and maintenance costs. The voltage regulation system maintains the stability of power supplied to residential and industrial consumers by keeping voltage within prescribed limits, despite variations in generation and load. The load model includes both residential and industrial loads, with the industrial sector imposing higher and more constant demand. The residential load fluctuates, and renewable sources like wind and solar are prioritised to meet these demands. When renewable generation is insufficient, the control system automatically dispatches diesel generators based on load demand and generation capacity [7]. Economic dispatch is implemented to balance the cost of power generation from each source, with specific cost functions defined for diesel fuel consumption [8], wind turbine maintenance, and photovoltaic (PV) panel upkeep. Automatic generator scheduling optimises the power output and significantly reduces operational costs and emissions. This study also highlights the environmental benefits, as the optimised generator dispatching strategy reduces greenhouse gas emissions, contributing to a cleaner and more sustainable power grid.

2. System Overview and Configuration

The microgrid integrates three distinct power generation sources: a diesel station housing three diesel generators, a wind farm, and a solar farm. These are connected to residential and industrial loads through a step-down transformer [9], to regulate voltage and ensure compatibility with consumption requirements. A centralised control unit would then supervise the total load demand alongside the power output from renewable sources. During periods when wind and solar generation fall short of meeting demand, the control unit deploys the diesel generators to bridge the energy gap, thus guaranteeing a stable and uninterrupted power supply. While prioritising renewable energy to maximise sustainability, the system concurrently employs diesel generators strategically to achieve balanced and efficient load distribution. The configuration is illustrated in Figure 1, presenting the structure of the microgrid under examination.

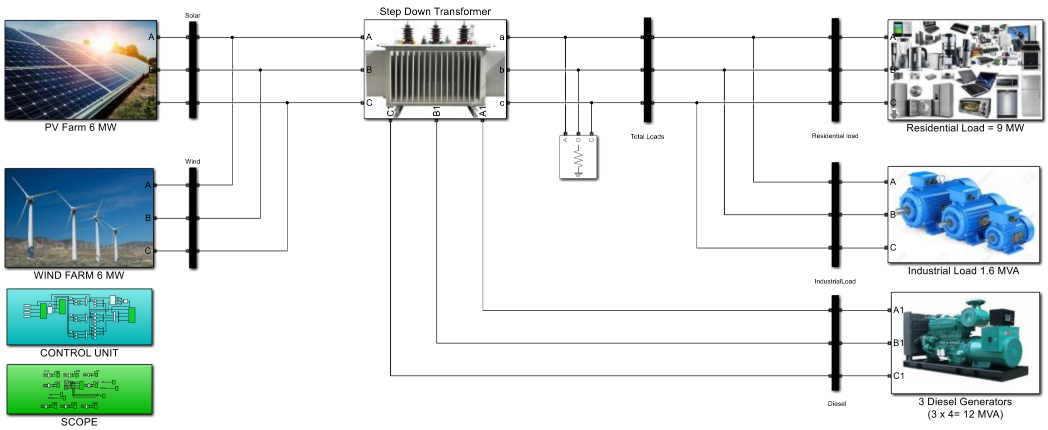

Fig. 1 Hybrid Microgrid

2.1. Power Generation Sources

The microgrid utilises three distinct power generation sources, each defined by specific operational characteristics and power capacities. Wind and solar energy are prioritised to maximise renewable utilisation, with diesel generators serving as a supplementary resource. These generators are activated exclusively when renewable production proves insufficient to meet the load, which, in turn, ensures reliability and efficiency.

2.1.1. Diesel Station (3 Diesel Generators)

The diesel generator offers a dependable and consistent power source that serves primarily as a backup during periods when renewable energy sources are insufficient to meet grid demand, such as during low wind speeds or limited solar activity. However, its operation at suboptimal efficiency can lead to increased fuel costs and emissions, as will be discussed later [10]. Each diesel generator, with a rated power of (4 MVA), is integrated into the microgrid via a three-phase breaker, allowing for an autonomous connection or disconnection based on the prevailing load demand. These breakers operate under signals from the control unit, which continuously monitors both load requirements and power generated from all sources. The layout of the diesel station is illustrated in Figure 2.

2.1.2. Wind Farm

The wind farm, with a rated capacity of 6 MW, operates as a renewable energy source within the microgrid. Its turbines operate at variable speeds [11], determined by the prevailing wind conditions, with a cut-in wind speed of 3.5 m/s, a nominal wind speed of 13.5 m/s, and a cut-out wind speed of 14.9 m/s. The power output is modelled in relation to wind speed, which employs performance curves based on specifications from real-world turbine operations to ensure accurate representation of their behaviour under varying environmental conditions.

$$P_{mech} = C_p(\lambda, \beta) P_{wind} = \frac{\rho A}{2} C_p(\lambda, \beta) V_{wind}^3 \quad (1)$$

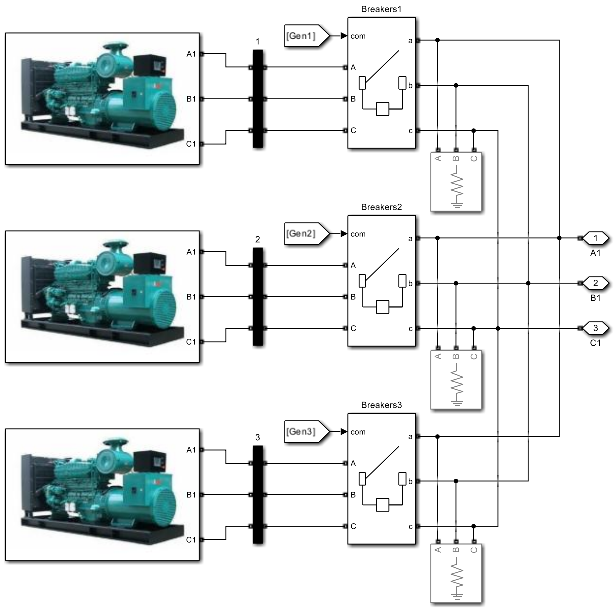

Fig. 2 Diesel Station (Three Diesel generators)

Where P_{mech} is mechanical output power of the turbine (W), P_{wind} is power extracted from the wind (W), C_p is performance coefficient of the turbine, λ is tip speed ratio, β is pitch angle (deg), ρ is air density (kg/m^3), A turbine swept area (m^2) and V_{wind} is Wind speed (m/s).

A time-varying wind profile, which reflects actual wind speed data over time, captures the natural fluctuations of wind conditions in real-world environments [12]. The wind profile, as shown in Figure 3, demonstrates fluctuations in wind generation within the microgrid over the course of a day, and exert a direct influence on the power output of the wind farm. Consequently, the availability of renewable energy alternates between periods of high production and intervals of reduced generation, which reflect the dynamic nature of wind resources.

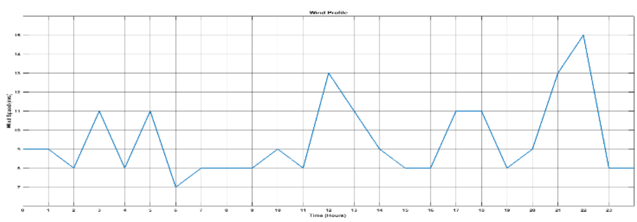

Fig. 3 Wind Profile over (24) hours

2.1.3. Solar Panels

The solar photovoltaic (PV) array, with a total capacity of 6 MW, an efficiency of 10%, and a covered area of 80,000 m^2, is designed to harness energy from sunlight. The power output fluctuates based on the irradiance profile, with peak generation during daylight hours. The power output varies in accordance with the irradiance profile, reaching its peak during daylight hours. The performance of the solar panels is modelled based on standard irradiance levels and temperature conditions [13]. The irradiation profile is shown in Figure 4.

$$P_{solar} = A\,\eta\,G \qquad (2)$$

A PV farm generates power (W) in proportion to three key factors: (A) the area covered by the PV panels (m^2), (η) the efficiency of the solar panels, and (G) the irradiance data (W/m^2), which represents the amount of solar energy available at a given location. The larger the area of the PV farm, the greater the potential energy output. Higher panel efficiency ensures more effective conversion of sunlight into electrical power. Lastly, irradiance data, which varies throughout the day, directly influences the amount of energy the PV farm can produce.

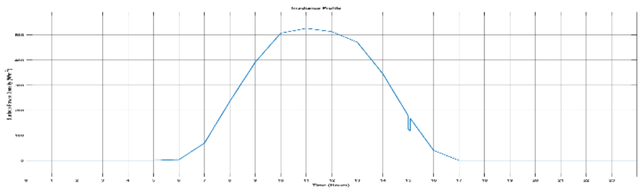

Fig. 4 Irradiation Profile of the solar panel

2.2. Voltage Regulation

The voltage output from the diesel generator, wind turbine, and solar panels is reduced using a step-down transformer to align with the voltage levels required for residential and industrial loads. The transformer operates with a primary voltage of 25 kV and a secondary voltage of 380 V. This configuration ensures that the voltage levels remain suitable for both types of loads. Voltage fluctuations are controlled and kept within acceptable ranges to maintain a stable power supply despite variations in load demand and renewable energy generation.

2.3. Load Modelling

2.3.1 Residential Load

The residential load model captures the typical energy consumption patterns of households which typically varies throughout the day with higher demand during morning and evening hours and diminishing consumption during nighttime [14]. The total residential load is modelled at 9 MW, with variations designed to replicate real-world usage patterns. The residential load in the microgrid follows a specific consumption profile, which varies over time based on typical household usage patterns. This pattern is characterised by a given power factor, which reflects the ratio of real power to apparent power. The power factor affects the efficiency of power delivery, as a lower power factor indicates higher reactive power and less efficient energy usage. The control unit takes the residential load's power factor into account when managing the overall energy supply to ensure that the generators and renewable sources meet the demand efficiently.

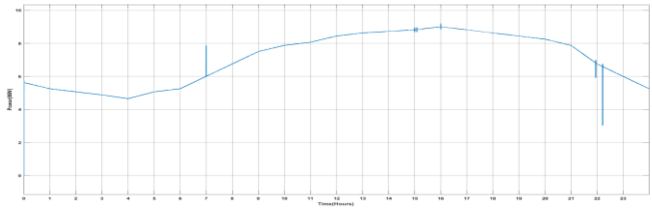

Fig. 5 Residential Load Power

2.3.2 Industrial Load

The industrial load represents a constant energy demand from manufacturing or heavy industry [15], with a base load of 1.6 MVA. Unlike the residential load, which fluctuates, the industrial load requires a continuous supply of electricity to maintain operations. The industrial loads are two plants used asynchronous machines with three-phase circuit breakers to turn them on by connecting them to the microgrid at specific times. The first plant starts working at 07:00 am and stops at 12:00 am, where the other starts at 06:00 pm and stops at 12:00 am. Figure 6 shows the power consumption pattern of the industrial loads over the 24-hours simulation period.

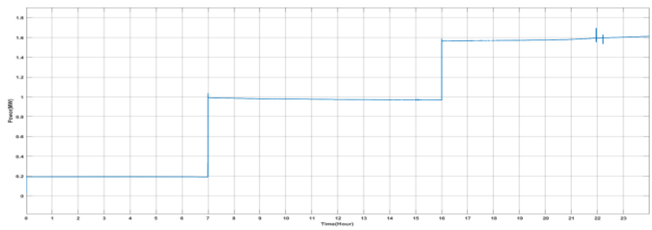

Fig. 6 Industrial Load Power.

3. Load Demand and Power Contribution

This system is designed to share the load among the different power sources as efficiently as possible. The solar panels and wind turbines are configured to provide maximum available power, with the diesel generator compensating for any shortfall in renewable energy. The total power supplied is split between the residential and industrial loads, with priority given to maintaining power stability.

4. Economic Dispatch Implementation

The economic dispatch problem is formulated to minimise the total operating cost of the microgrid, which includes the fuel costs of diesel generators while maximising renewable energy use [16]. The objective function is defined as:

$$\min\left(\sum_{i=1}^{3} C_{\text{diesel}_i}\left(P_{\text{diesel}_i}\right)\right) \qquad (3)$$

Where: C_{diesel_i} is the cost of operating diesel generator i, which is dependent on its power output (P_{diesel_i}).

Constraints:

- The power generated by each diesel generator must lie within its operational limits.

$$P_{diesel_i min} < P_{diesel_i} < P_{diesel_i max} \qquad (4)$$

- Power Balance which means that the total generated power must match the total load demand

$$P_{wind} + P_{solar} + \sum_{i=1}^{3} P_{diesel_i} = P_{load} \qquad (5)$$

During light load periods (low demand), one or two diesel generators can be disconnected, and renewable sources are prioritised. Diesel generator scheduling shows how economic dispatch schedules diesel generators based on load to ensure that the system only runs the necessary number of generators.

4.1. Cost Functions Defined for each Power Source

4.1.1 Fuel and Maintenance Costs for Diesel Generator

The cost of operating diesel generators is divided into two main parts: fuel cost and maintenance costs.

Fuel Cost Calculation

The fuel consumption of a diesel generator is determined by its operational efficiency and the load it handles during operation. Each generator has a specific fuel consumption rate, measured in litres per kilowatt-hour (litres/kWh), which is typically provided in its specification sheet. To calculate the total fuel consumption, the consumption rate is multiplied by the generator's operating hours and the percentage of its rated load during those hours.

$$\text{Total Fuel Consumption (L)} = \text{Fuel Consumption Rate (L/h)} \times \text{Operating Hours} \times \text{Load Percentage} \qquad (6)$$

There is a typical curve that describes the relationship between the fuel consumption rate and the percentage of the rated power for a diesel generator. This curve is generally non-linear and varies depending on the specific generator model, but the trend is usually the same for most diesel generators [17]. Table 1 illustrates this relationship.

Table 1. Fuel Consumption Rate (L/kWh) at % of Rated Power

Load (% of rated power)	Fuel Consumption Rate (L/kWh)
25%	0.30
50%	0.25
75%	0.22

100%	0.25

When operating at low loads, below 25% of the rated power, diesel generators exhibit poor fuel efficiency, consuming more fuel per kilowatt-hour and displaying a higher fuel consumption rate. As the load increases to medium levels, typically between 50% and 75% of the rated power, fuel efficiency improves significantly, with the generator functioning closer to its optimal performance. At high loads, ranging from 75% to 100% of the rated power, the fuel consumption rate increases marginally as the generator nears full capacity, but it generally remains within an efficient operating range. In overload conditions, where the load exceeds 100% of the rated power, fuel consumption rises sharply, and efficiency declines substantially, although most generators are not designed to operate under such conditions.

The fuel cost is calculated by multiplying the total fuel consumption by the price per litre of diesel fuel.

$$\text{Fuel Cost} = \text{Total Fuel Consumption (L)} \times \text{Diesel Price (per liter)} \quad (7)$$

To calculate the kilowatt-hour (kWh) energy consumed by the loads, the power curve (in kW) from Simulink scope is integrated over time (in hour). The area under the power curve gives the total energy in kilowatt-hours (kWh), which is the standard unit for electrical energy.

$$E = \int P(t)dt \quad (8)$$

Where $P(t)$ is the power at time t (kW), dt is the time differential (hour) and E is the energy (kWh).

Maintenance Cost Calculation

Maintenance costs for diesel generators typically include scheduled service, parts replacement, and unscheduled repairs [18]. Diesel generators have scheduled maintenance intervals after a certain number of running hours, typically every 250, 500, or 1000 hours. Each interval will have an associated cost. Maintenance costs can include Oil changes, Air and fuel filter replacements, Coolant replacement, Labor costs and Miscellaneous spare parts. The total maintenance cost is the sum of these costs per maintenance cycle [19]. The unscheduled maintenance, which can be estimated based on the generator's operating history or industry standards can be added to the maintenance costs. Once fuel and maintenance costs are determined, they can be combined to calculate the total operating cost of the generator:

$$\text{Total Operating Cost} = \text{Fuel Cost} + \text{Maintenance Cost} \quad (9)$$

4.1.2 Maintenance Costs for Wind Turbines

The maintenance cost of an operating wind turbine involves both preventive (scheduled) and corrective (unscheduled) maintenance. The cost is generally divided into labour, spare parts, and services like crane rentals [20].

Scheduled (Preventive) Maintenance Costs

This includes routine inspections and replacement of parts such as lubricants, filters, and sometimes major components depending on the age of the turbine. Wind turbines typically have scheduled maintenance every 6 months to a year, depending on the manufacturer's guidelines and operating conditions. Each scheduled maintenance cycle includes costs such as labour (number of hours for inspection and part replacement), lubricants and consumables (Oil, filters, etc.) [21], and Spare Parts (sensors, minor electronics, etc.). Figure 7 shows lubrication points of the wind turbine at start up according to Table 2.

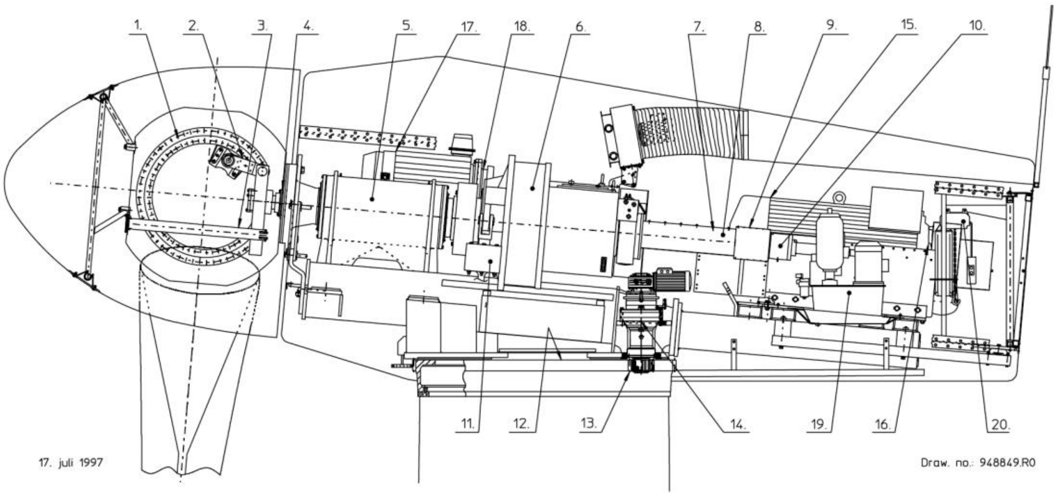

Fig. 7 Lubrication points of wind turbine.

Table 2. Lubrication points of wind turbine and their interval at start up

Pos	Lubrication point	Interval	Pos	Lubrication point	Interval
1	Blade bearings, each bearing	6 months	11	Torque arm system, disc springs	6 months
2	Connecting rod	6 months	12	Yaw system	6 months
3	Traverse anti rotation device	6 months	13	Yaw system toothing	6 months
4	Traverse holder, front bushing	6 months	14	Yaw gears	6 months
5	Main bearings	6 months	15	Primary generator, front bearing	6 months
6	Gearbox	According to oil analysis	16	Primary generator, rear bearing	6 months
7	Guide rings, pitch bearing housing	6 months	17	Secondary generator, front bearing	6 months
8	Pitch bearing	6 months	18	Secondary generator, rear bearing	6 months
9	Link bearings	6 months	19	Hydraulic system	5 years
10	Hydraulic cylinder mounting	6 months	20	Crane	Lubricated for life

Unscheduled (Corrective) Maintenance Costs

Corrective maintenance for wind turbines is inherently less predictable, as it is contingent upon the frequency and severity of unexpected failures, which may involve the replacement of critical components such as gearboxes, blades, or electrical systems [22]. Estimates for the failure rates of major components can be derived from industry data or the historical performance of the turbine. For instance, a gearbox may require replacement every 10 years, whereas electronic systems often necessitate more frequent repairs. The occurrence of such failures incurs additional expenses, including the cost of replacement parts (e.g., gearboxes, blades, or converters), labour for removing and installing components, and crane rentals for handling large-scale replacements. The total maintenance cost of a wind turbine is therefore a combination of preventive maintenance expenses, and the unpredictable costs associated with unscheduled corrective actions:

$$\begin{aligned}&\text{Total Annual Maintenance Cost}\\&=\text{Preventive Maintenance Cost}\\&+\text{Unscheduled Maintenance Cost}\end{aligned} \quad (10)$$

4.1.3 Maintenance Costs for PV Farm

Maintenance costs for solar panels are generally lower than those for other power generation systems, such as diesel generators or wind turbines, due to the relatively simple and static nature of solar photovoltaic (PV) systems. However, there are still important factors to consider, such as cleaning, inspections, and inverter or component replacements.

Scheduled (Preventive) Maintenance Costs

Preventive maintenance for solar panels primarily involves cleaning, inspections, and replacing components like inverters or wiring over time. Dust, debris, or snow can accumulate on the panels, reducing their efficiency [23]. The frequency of cleaning depends on the surrounding environment (dusty, rainy, or snowy conditions). Cleaning costs involve labour, water, and sometimes specialised equipment [24]. Routine inspections are performed to ensure all electrical components are working correctly and to identify any damage at an early stage. Inspections are typically done annually or semi-annually, depending on the system's size and location. Solar inverters, wiring, and mounting structures may need to be replaced over the lifespan of the solar system [25].

Unscheduled (Corrective) Maintenance Costs

Solar panels themselves rarely fail, but unscheduled maintenance could involve fixing damaged wiring, replacing faulty inverters earlier than expected, or addressing issues like panel cracking due to environmental damage [26].

4.1.4 Automatic Dispatching of Diesel Generators Control

Automatic Dispatching of Diesel Generators Control refers to the system that intelligently manages the startup, operation, and shutdown of diesel generators based on real-time load demands and grid conditions. In microgrids or hybrid power systems that integrate renewable energy sources, automatic dispatching ensures efficient use of diesel generators to minimise fuel consumption, reduce emissions, and improve system reliability [27]. The control system continuously tracks power demand from loads and renewable energy contributions. When renewable generation, such as wind or solar, falls short due to environmental factors like insufficient sunlight or low wind speeds, the system promptly dispatches diesel generators to fill the energy deficit. Renewable sources are prioritised wherever possible, and diesel generators are only activated when renewable contributions are inadequate or fluctuate. Diesel generators operate most efficiently at 70%–80% of their rated capacity, and automatic dispatching ensures that generators are deployed only when required to maintain their operation within this optimal efficiency range. This, in turn, minimises fuel consumption, reduces wear on the generators, and prolongs their operational lifespan. The system also automates the sequencing of generator start-up and shutdown by employing a control strategy that activates smaller or more fuel-efficient units during periods of low demand and incrementally brings additional generators online as demand increases.

5. Impact of Generator Scheduling on Emission Reduction

Reducing the emissions produced by diesel generators is directly linked to decreasing their fuel consumption, as the combustion of diesel releases pollutants such as carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM). Reducing fuel consumption leads to a corresponding reduction in emissions [28]. CO_2 emissions are proportional to fuel consumption as CO_2 is a byproduct of burning carbon-based fuels like diesel. A reduction in fuel consumption proportionally lowers CO_2 emissions, given that each litre of diesel burned generates approximately 2.68 kg of CO_2 [29]. For instance, a 10% reduction in fuel usage results in a corresponding 10% decrease in CO_2 emissions. NO_x emissions, which contribute to smog and acid rain, are influenced by both fuel consumption and combustion temperature, with reductions in fuel use directly lowering overall NO_x output. Diesel engines are a significant source of Particulate Matter (PM), which consists of tiny particles that can harm respiratory health, with higher PM levels associated with increased fuel consumption, particularly under heavy load conditions [30]. Additionally, SO_x emissions are determined by the sulfur content of the diesel fuel, and reducing fuel consumption directly curtails SO_x output. Reducing the fuel consumption of a diesel generator leads to lower emissions of CO_2, NO_x, SO_x, and PM, which, in turn, benefits both the environment and operational costs. Techniques such as optimising load, improving engine efficiency, and hybridising the system can contribute to both fuel savings and emission reductions.

6. Results and Discussion

6.1. Load Demand and Power Contribution

The simulation results illustrate the allocation of power among the diesel generator, wind turbine, and solar panels over a 24-hour period. During times of adequate wind and solar energy availability, the diesel generator either operates at a reduced capacity or remains entirely offline. On the hand, during periods of limited renewable generation, such as nighttime for solar energy or low wind speeds, the diesel generator increases its output to meet the prevailing demand. The flow of power between the sources and the loads is dynamically managed through a Simulink-based control system, which continuously adjusts the contributions of each source in response to real-time variations in load demand and renewable generation levels.

6.1.1. Wind Power vs Wind Profile

When wind speeds are below the cut-in threshold of 3.5 m/s, the turbine blades remain stationary, resulting in no power generation. As wind speeds surpass the cut-in value but stay below the rated speed of 13.5 m/s, the power output increases proportionally to the cube of the wind speed. Between the rated speed and the cut-out limit of 14.9 m/s, the turbine operates at its maximum capacity, generating 6 MW. If wind speeds exceed the cut-out threshold, the turbine is halted to prevent potential damage, resulting in zero power output. Figure 8 provides a detailed representation of the correlation between wind speed and power generation across these operational ranges.

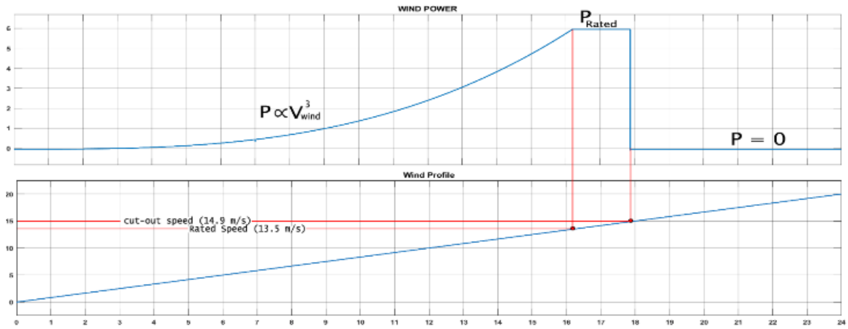

Fig 8. Power curve of wind turbine according to wind speed.

In the wind profile used for the simulation, as shown in Figure 9, the wind speed does not surpass the cut-out speed until 9:57 p.m. As a result, the output power drops to zero and remains at that level until the wind speed decreases back to the rated value at 10:13 pm.

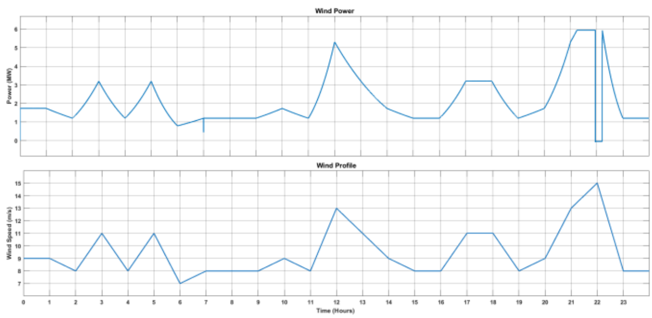

Fig 9. Wind Power Vs Wind Profile for the wind Farm.

There are two scenarios where the wind power remains constant. The first occurs when the wind speed stays steady at a value below the rated speed, resulting in constant power output, which is lower than the wind farm's rated power. This scenario repeats four times throughout the simulation. The second situation happens when the wind speed is between the rated and cut-out speeds, during which the turbine generates constant power at its rated output 6 MW, as seen between 9:15 pm and 9:57 pm.

6.1.2 Solar Power vs Irradiance Profile

The power generation of a PV farm is influenced by three primary factors: the area of the solar panels, their efficiency, and the irradiance data, which represents the solar energy available at a particular location. As irradiance fluctuates throughout the day, it directly impacts the amount of energy the PV farm can produce. As outlined in equation (2), the solar power generated is directly proportional to the irradiance. Figure 10 illustrates the irradiance pattern, beginning at 6:00 am as sunlight appears and progressively intensifying as the sun ascends, peaking at 11:00 am when the sun is at its highest point. Thereafter, the irradiance gradually diminishes until sunset at 5:00 pm. A brief interruption caused by partial shading is observed between 3:00 pm and 3:05 pm, momentarily reducing power generation. The daily cycle of irradiance governs the PV farm's output, with maximum energy generation occurring around midday and lower production in the early morning and late afternoon.

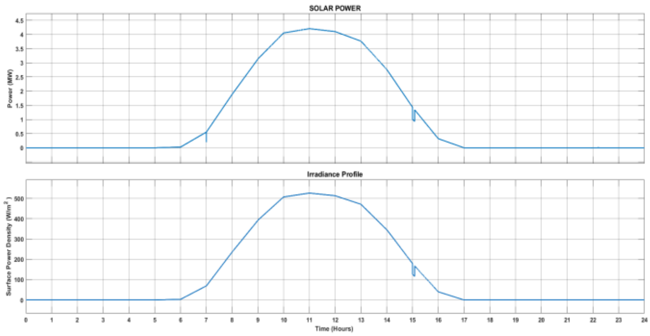

Fig 10. Solar Power Vs Irradiance Profile for the PV Farm.

6.1.3 Diesel Power Vs Load Demand

The total load demand determines the power drawn from the diesel station. Renewable energy sources are utilised as the primary contributors, while the diesel generators are employed to compensate for any shortfall. The interaction between load demand and diesel power generation is explored through five distinct scenarios, as shown in Figure 11. These scenarios capture the variations in power consumption and the role of diesel generators in meeting demand when renewable energy generation is insufficient.

Scenario 1: 12:00 am to 7:00 am

At midnight, renewable energy is supplied exclusively by the wind farm, as solar power is unavailable. During this period, diesel generators supplement the wind farm's output to meet the load demand. As wind power generation gradually increases, the reliance on diesel generators diminishes. Solar power begins contributing at 6:00 am, further reducing the load on diesel generators. However, at 7:00 am, the first industrial plant commences operations and increases the total load demand to 7.1 MW. To meet this heightened demand, diesel generators compensate for any shortfall to ensure a stable and uninterrupted energy supply.

Scenario 2: from 7:00 am to 3:00 pm

The irradiance gradually increases to reach its peak at 11:00 am. With rising wind power, the diesel power output drops to nearly zero around noon. As irradiance and wind speed decrease later, renewable power diminishes, and the diesel station generates more to meet the load.

Scenario 3: from 3:00 pm to 3:05 pm

During this period, partial shading temporarily reduces solar power generation. To compensate for the decrease in solar output, the diesel generators increase their power contribution to meet the load demand. As solar power falls, the diesel station adjusts its output to ensure a stable energy supply and maintain system reliability despite the fluctuations in renewable energy availability.

Scenario 4: from 3:05 pm to 4:00 pm

The wind power stabilises at 1.2 MW due to a consistent wind speed of 8 m/s, while solar power continues to decline as sunset approaches. To offset the reduction in renewable energy output, the diesel station increases its generation to meet the ongoing load demand. At 4:00 pm, the second industrial plant begins operation, further increasing the total load demand. In response, the diesel generators ramp up their output to compensate for this additional requirement.

Scenario 5: from 04:00 pm to 10:13 pm

Wind power drops to zero as wind speeds exceed the turbines' cut-out speed, causing the diesel generators to take on more load to meet demand during this period.

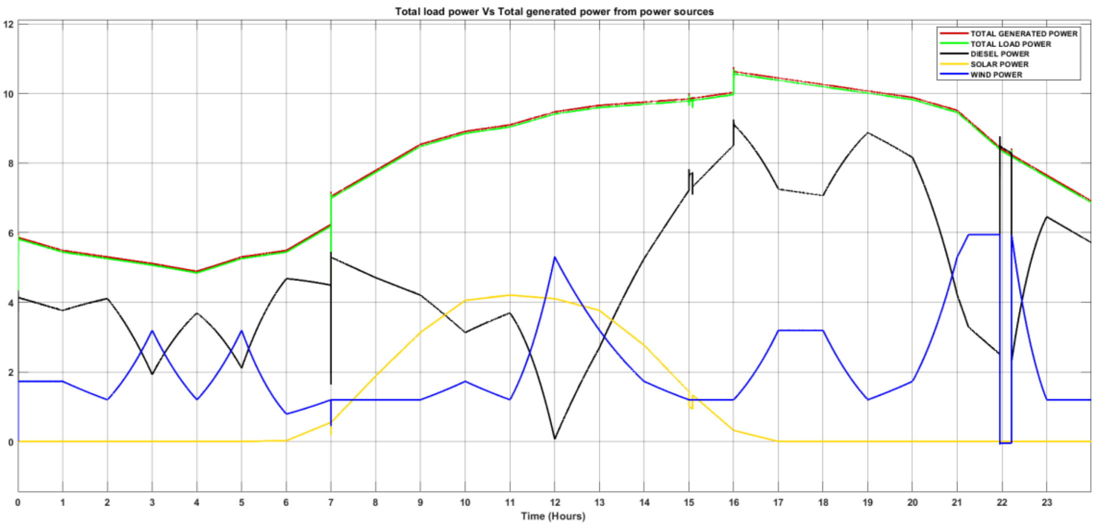

Fig 11. Total Load Demand Vs Total Power Generated from Power Sources in the Microgrid.

The system's efficiency was evaluated by comparing the energy produced by each source to the total energy consumed by the loads. The diesel generator’s efficiency varied depending on the load, with higher efficiency observed during periods of higher demand. The overall system efficiency improved as renewable energy sources reduced reliance on the diesel generator.

6.2. Automatic Dispatching of Diesel Generators Control

Automatic dispatching is used to control generator operation when renewable energy alone cannot meet load demand. If all three generators are running continuously, even during periods of light demand, they operate below their rated power, which leads to higher fuel consumption compared to using just one generator that matches the load. Figure 12 illustrates the power output of each generator when running constantly. The total diesel power in the microgrid is determined by the load demand, plus transmission line losses, minus renewable power. By summing the power curves of the three generators, the total power output of the diesel station can be obtained. From 12:00 am to 2:20 am, the power curve remains below 50% of the rated capacity of the three generators, resulting in increased fuel consumption and extended operating hours, which in turn leads to higher maintenance and monitoring costs.

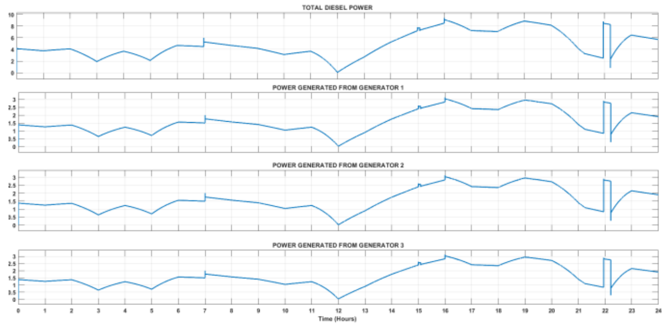

Fig 12. Power generated from diesel generators without control.

Once the grid is controlled, the generators will only run, when necessary, specifically when the load demand exceeds what renewable sources can supply. The control system constantly monitors the load demand and compares it with the available renewable power. If the load surpasses renewable generation, the first generator is activated. If the demand remains higher than the combined renewable power and 75% of the first generator's rated power, the control system will signal the circuit breaker to start the second generator. If the load continues to increase, the control system will activate the third generator to help share the load. Figure 13 displays the control signals used to turn the generators on and off based on load demand throughout the simulation.

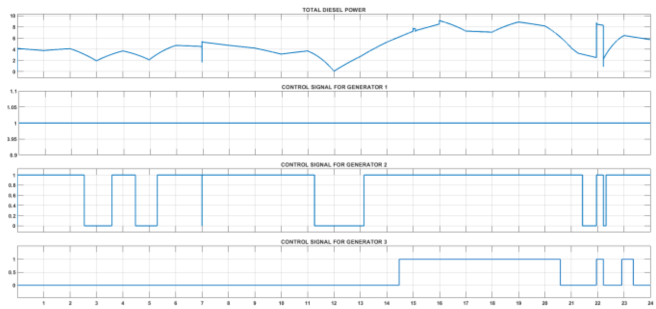

Fig 13. Control signal to switch Generators on & off.

With the controlled system, generators operate only when needed. As shown in Figure 14, from midnight to 2:32 am, the load demand exceeds the available renewable power, so the diesel station compensates with around 4 MW. Since this exceeds 75% of the first generator's rated power, the control system activates a second generator, and both share the load. From 2:32 am to 3:35 am, the load drops below 75% of generator 1's capacity, causing generator 2 to shut down, while generator 1 continues to meet the demand. When a generator shuts down, the load is redistributed among the remaining generators and increases their power output. As the load rises again, additional generators are switched on to share the load, lowering the power curve across all active generators. Generator 3 remains off until the peak demand period from 2:28 pm to 8:35 pm, during which all generators are operational, but none exceed 75% of their rated power. With the microgrid under control, the sum of the individual generator power curves at any given time matches the total power output of the diesel station.

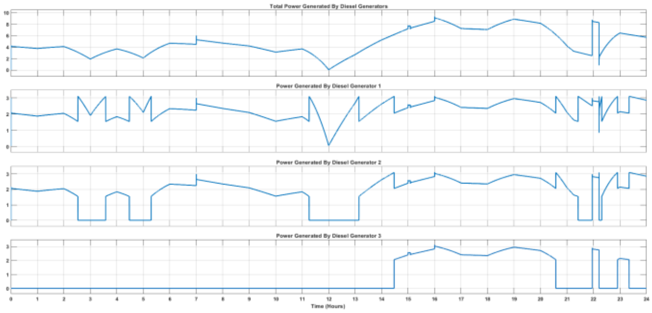

Fig 14. Power Generated from (3) Generators with Control.

Automatic dispatching effectively lowers fuel consumption by running generators only when needed and optimising their efficiency. Operating generators within their optimal efficiency range reduces wear and tear. By minimising the use of diesel generators and optimising their performance, the system also reduces greenhouse gas emissions and pollutants. The control system ensures smooth transitions between generators and renewable power sources to prevent blackouts and maintain power quality. Ultimately, reduced fuel consumption and lower maintenance requirements lead to significant operational cost savings.

6.3. Cost Optimisation through Load-Responsive Diesel Generator Control

The power output of each diesel generator is monitored using a scope, with the data logged to MATLAB's workspace. Figure 15 provides a comparison of power distribution between generators operating with a load-responsive control system (blue solid line) and without control (red dashed line). Each generator has a rated capacity of 4 MVA and achieves optimal fuel efficiency when operating at 70%–80% of its rated power.

Without control, all generators run continuously, even during periods of low demand when a single generator could suffice. In this uncontrolled scenario, generators frequently operate below 50% of their rated capacity, and in turn result in higher fuel consumption and increased emissions. By contrast, the implementation of grid control ensures that generators only operate when needed. For instance, generator 3 is inactive for nearly 17 hours, conserving fuel and reducing wear.

Under controlled conditions, generator 1 operates most of the time at approximately 75% of its rated power, which achieves significant fuel savings. When generators are activated to share the load, they are utilised closer to their rated capacity. When deactivated, they avoid unnecessary fuel consumption, which clearly illustrate the effectiveness of the control system in reducing operational costs and emissions while maintaining reliability.

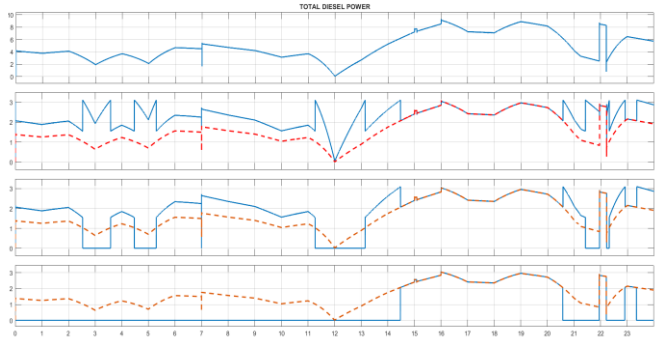

Fig 15. Power Generated from (3) Generators with and without Control.

The following code calculates the total fuel consumption (in Liters) for one generator over the 24-hour simulation period.

```
% Simulink data (power output in MW, time in seconds)

% Power output of one generator in MW
P = ScopeData1.signals(2).values;

% Time in seconds
time = ScopeData1.time;

% Rated power of the generator in MW
rated_power = 4;

% Power percentage vs fuel consumption rate (liters/MWh)
fuel_consumption_rate = @(P_percent) interp1([0, 25, 50, 75, 100], [0, 300, 250, 220, 
250], P_percent);

% Convert seconds to hours
delta_t = diff(time) / 3600;

% Initialize fuel consumption array
fuel_consumption = zeros(1, length(P)-1);

% Loop over time steps to calculate fuel consumption at each time 
step
for i = 1:length(P)-1
    % Calculate the percentage of rated power
    P_percent = (P(i) / rated_power) * 100;
    % Get fuel consumption rate for the power percentage
    fc_rate = fuel_consumption_rate(P_percent);
    % Fuel consumption (liters)
    fuel_consumption(i) = P(i) * fc_rate * delta_t(i);
end

% Calculate total fuel consumption for one generator
total_fuel_consumption = sum(fuel_consumption);

% Display the result
```

```
disp(['Total fuel consumption: ', num2str(total_fuel_consumption), ' liters']);
```

After running the code for all three generators without control, the total fuel consumption amounted to 3,378.9 Liters. When the code was applied to the controlled system, the total fuel consumption decreased to 2,704 Liters. This means that the diesel station's total fuel consumption is reduced by about 20% with the control strategy, resulting in a considerable fuel savings over the course of a single day.

6.4. Impact of Generator Scheduling on Emission Reduction

As mentioned previously, burning one Liter of diesel produces approximately 2.68 kg of CO_2. In the uncontrolled grid scenario, the total fuel consumption of 3,378.9 Liters results in 9,055.5 kg of CO_2 emissions. However, when the grid is controlled, fuel consumption drops to 2,704 Liters, which reduces emissions by 20% to 7,246.7 kg. Operating diesel generators closer to their optimal efficiency, around 75% of their rated capacity, minimises both fuel usage and emissions. Integrating renewable energy reduces the runtime

of diesel generators. Technologies such as automatic dispatching optimise generator operation by activating them only when needed. Additionally, upgrading to more fuel-efficient engines or implementing after-treatment systems can further decrease fuel consumption and emissions.

7. Conclusion

This paper demonstrates the viability of a hybrid power grid incorporating diesel, wind, and solar energy sources. The Simulink model effectively balanced the fluctuating power generation from renewable sources with the constant industrial loads and variable residential demand. The inclusion of renewable energy significantly reduced diesel fuel consumption and improved the system's sustainability and cost-effectiveness. Moreover, the study highlights the effectiveness of implementing a control strategy to optimiae diesel generator operation in the microgrid. By automatically dispatching generators only when necessary and maintaining their operation near optimal efficiency, the control system successfully reduces fuel consumption, harmful emissions, and operational costs. A comparison between controlled and uncontrolled scenarios reveals 20% fuel savings, which confirms the advantages of dynamic generator management. The control system further enhances overall efficiency by prioritizing renewable energy, extending the lifespan of generators through reduced operational hours, and ensuring smooth transitions between power sources to maintain power quality. The integration of a dynamic control system delivers both economic advantages and environmental gains, and establishes it as a technically viable framework for harmonising renewable and conventional power systems within microgrids. Further advancements could concentrate on enhancing control algorithms and incorporating energy storage solutions to improve system reliability and further reduce reliance on diesel generators.

Conflicts of Interest

The authors hereby declare, to the best of their knowledge, that no actual, potential, or perceived conflicts of interest exist in connection with the research, authorship, or publication of this paper.

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Nomenclature

ρ	Air density (kg/m^3)
β	Blade pitch angle (deg)
P_{mech}	Mechanical output power of the turbine (W)
C_p	Performance coefficient of the turbine
P_{wind}	Power extracted from the wind (W)
λ	Tip speed ratio
A	Turbine swept area (m^2), Area covered by PV panels (m^2)
V_{wind}	Wind speed at the height of the blade hub (m/s)
P_{solar}	PV power (W)
η	Efficiency of solar panels
G	Irradiance data

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