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Operational assessment of solar-wind-biomass-hydro-electrolyser hybrid microgrid for load variations using model predictive deterministic algorithm and droop controllers

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ABSTRACT

This study presents the operation and assessment of a solar-wind-biomass-hydro-electrolyser hybrid microgrid for different types of load variations by using a proprietary derivative-free algorithm (Model Predictive Deterministic Algorithm) and voltage IQ droop controller. The proposed hybrid microgrid integrates various renewable energy sources and an electrolyser to generate hydrogen and produce electricity. The objective is to optimize the microgrid's performance and provide reliable power supply to meet varying load demands. The proprietary derivative-free algorithm is used to determine the optimal dispatch of power from each energy source to meet the load demand while minimizing the overall cost of energy. Additionally, a voltage IQ droop and voltage Q droop controller are employed to regulate the voltage, frequency and active power of the microgrid and maintain its stability during load variations. The proposed hybrid microgrid is assessed under different load scenarios for both grid tied and isolated modes. The results demonstrate that the proposed hybrid microgrid with the derivative-free algorithm and voltage droop controllers can effectively operate and provide reliable power supply under different load variations while maintaining the power system stability of the microgrid. Further, the mutual performances of the controller are compared to find the best controller for the specific microgrid. The findings of this study can contribute to the development of efficient and reliable hybrid microgrid systems for sustainable energy production and distribution.

1. Introduction

A hybrid microgrid is an energy system that combines multiple sources of electrical power generation specially the renewable ones and storage devices to provide electricity to a local community or facility [1]. Among the various types of hybrid microgrid configurations, the solar-wind-biomass-hydro-electrolyser hybrid microgrid is gaining popularity due to its ability to harness electrical energy different renewable energy sources. However, the operation and assessment of such a complex system require a sophisticated control mechanism [2,3] and special attention. The intermittent nature of the renewables and varying nature of the connected load demand often introduce challenge in regulating the best performance of the microgrid [4]. The voltage instability issues due to load variation and source intermittency is common among the renewable hybrid microgrids. The intermittency and voltage instability issues can be solved incorporating different storage units and controllers within the operation of the microgrid. Another challenge of these renewable hybrid microgrids is to ensure the optimum operation of the microgrid. To ensure the optimum operation, different optimization algorithms have been adopted by different researchers [5].

In recent years, there has been a growing interest in developing

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hybrid microgrid systems that integrate multiple renewable energy sources for sustainable energy production and distribution due to it's efficient performance. Various studies have been conducted to optimize the operation of hybrid microgrids under different load scenarios. One such study was conducted by M Thirunavukkarasu et al. (2023), who proposed a multi-objective optimization approach for the operation of a solar-wind-battery hybrid microgrid under different load variations. The results showed that the proposed approach can effectively optimize the microgrid's performance and improve its reliability under varying load conditions [6,7]. Another recent study by Z Ullah et al. (2022) focused on the operation and assessment of a solar-wind-hydro-battery hybrid microgrid for different types of load variations using a hierarchical control strategy. The study used simulation models to evaluate the microgrid's performance under different load scenarios, including constant, step, and random load variations. The results demonstrated that the hierarchical control strategy can effectively regulate the power flow in the microgrid and ensure reliable power supply under varying load conditions [8,9]. In a recent study by HA Raeisi et al. (2022), a hybrid microgrid was designed and operated using a derivative-free algorithm to optimize the microgrid's performance under different load scenarios. The proposed hybrid microgrid integrated solar, wind, and biomass energy sources along with an electrolyser to produce hydrogen. The results showed that the derivative-free algorithm can effectively optimize the microgrid's performance and ensure reliable power supply under varying load conditions [10,11].

After optimizing the design of the hybrid microgrid system it is necessary to attain the stability of the outputs of the network. Implementing various control algorithms in purpose of controlling the power system responses like voltage, frequency, active-reactive powers, current etc. have been common among various studies. Among the implemented controllers, droop controllers are very well known due to their effectiveness and ease of use. A study by S Arfa et al. (2023) proposed a novel voltage IQ droop control strategy for the operation of a solar-wind-battery hybrid microgrid under different load variations. The study demonstrated that the proposed control strategy can effectively regulate the microgrid's voltage and maintain its stability under varying load conditions. The results showed that the voltage IQ droop control strategy can improve the microgrid's performance and reliability under different load scenarios [12–14]. The study though, did not address any comparison between various controllers through which, the relative performance of the specific controller on stabilizing the power system responses can be determined. However, the benefit of current based controllers is that, they offer faster responses than other controllers and thus the transient response of the system gets better. The power sharing ability and P-Q decoupling is improved in case of V-I based droop controllers.

On the other hand, the integration of biomass, hydrogen production systems and other comparatively complex components in a hybrid microgrid requires advanced control algorithms such as MPC, RL, GA, and ANN to optimize the system's performance. However, the practical implementation of these algorithms requires careful consideration of the system's hardware and software requirements, as well as the availability and reliability of the data sources [15–18]. Overall, these recent studies demonstrate the potential of hybrid microgrid systems for sustainable energy production and distribution. The use of advanced optimization and control strategies can improve the microgrid's performance and reliability under varying load conditions, making them a promising solution for future energy systems [19–21]. An optimization strategy using Grey Wolf Optimization (GWO), a meta-heuristic technique, has been proposed by researchers in [22]. Utilizing MATLAB software, the suggested work is applied to a standard IEEE 30 bus test system, utilizing the GWO and the line stability voltage index to solve the issue of optimal power flow. Reducing the generating cost, carbon emissions, voltage variation, and line losses have been prioritized as goals to enhance the transmission system's line loadability. The results of the simulation demonstrate how well the suggested strategy works to increase line loadability while lowering fuel costs and line congestion. In terms of control of the outputs, no specific control has been adopted in the work. In order to demonstrate the relative importance of each cost component for the best possible Microgrid functioning, a priority-based cost optimization function is constructed in [23]. The suggested scheduling methodology now includes the uncertainty related to different intermittent characteristics in the microgrid. The cost function additionally includes a penalty function for any constraints that are broken. GWO is employed in this work to minimize the developed cost optimization function of microgrid. To verify the effectiveness of the GWO method for the suggested optimization problem, the acquired results are compared with the outcomes of the Jaya and PSO (particle swarm optimization) methods. Here as well no specific control algorithm is adopted to govern the outputs.

The research gaps within the available research works in this domain can be highlighted as following:

- The evaluation of an optimized design of a Solar-Wind-Biomass-Hydro-Electrolyser Hybrid Microgrid with a continuous load demand variation in both grid connected and isolated modes.
- The testing of the optimized microgrid further for both modes with various controller implemented to offer stable voltage, power and frequency responses against the changes in load.
- A comparative study between the performances the controllers in terms of power system responses.

The use of advanced optimization and control strategies can improve the microgrid's performance and ensure reliable power supply under varying load conditions. Further research is needed to develop more advanced and efficient control strategies for the operation of hybrid microgrids [24,25] and to address the above mentioned research gaps. In this context, this research work presents:

- An operational performance assessment and optimized design of a Solar-Wind-Biomass-Hydro-Electrolyser Hybrid Microgrid using a derivative independent methodology (Model Predictive Deterministic Algorithm) with a continuous load demand variation.
- The testing of the optimized microgrid further against the variation of load demand for both grid tied and isolated modes. During the load demand variation, a voltage IQ droop controller and voltage Q droop controller is also implemented to offer stable voltage, power and frequency responses against the changes in load demand profile.
- A comparative study between the performances of both the controllers in terms of power system responses for both grid tied and isolated modes. This comparison enlightens the relative performances of the controllers for the specific modes and ensures that the one with the best performance be selected.

The novelty of this work lies into the consideration of Solar-Wind-Biomass-Hydro-Electrolyser based hybrid system for the microgrid and the implementation of droop controllers to stabilize the active power, frequency and voltage responses due to the variation in load demand and highlighting the differences in the mutual performances of both the controllers.

The remaining sections of the paper are organized as: Section 2 discusses the research methodological approach, Section 3 presents the results and discussion while key conclusions are drawn in Section 4.

2. Methodology

This section gives an idea about the methodological approach adopted for this research work. The optimization process contains the implementation of a proprietary derivative free algorithm (Model Predictive Deterministic Algorithm) which provides with an idea of the optimal sizes of the different components within the microgrid and the estimated costs as well as estimated toxic emissions under varying load

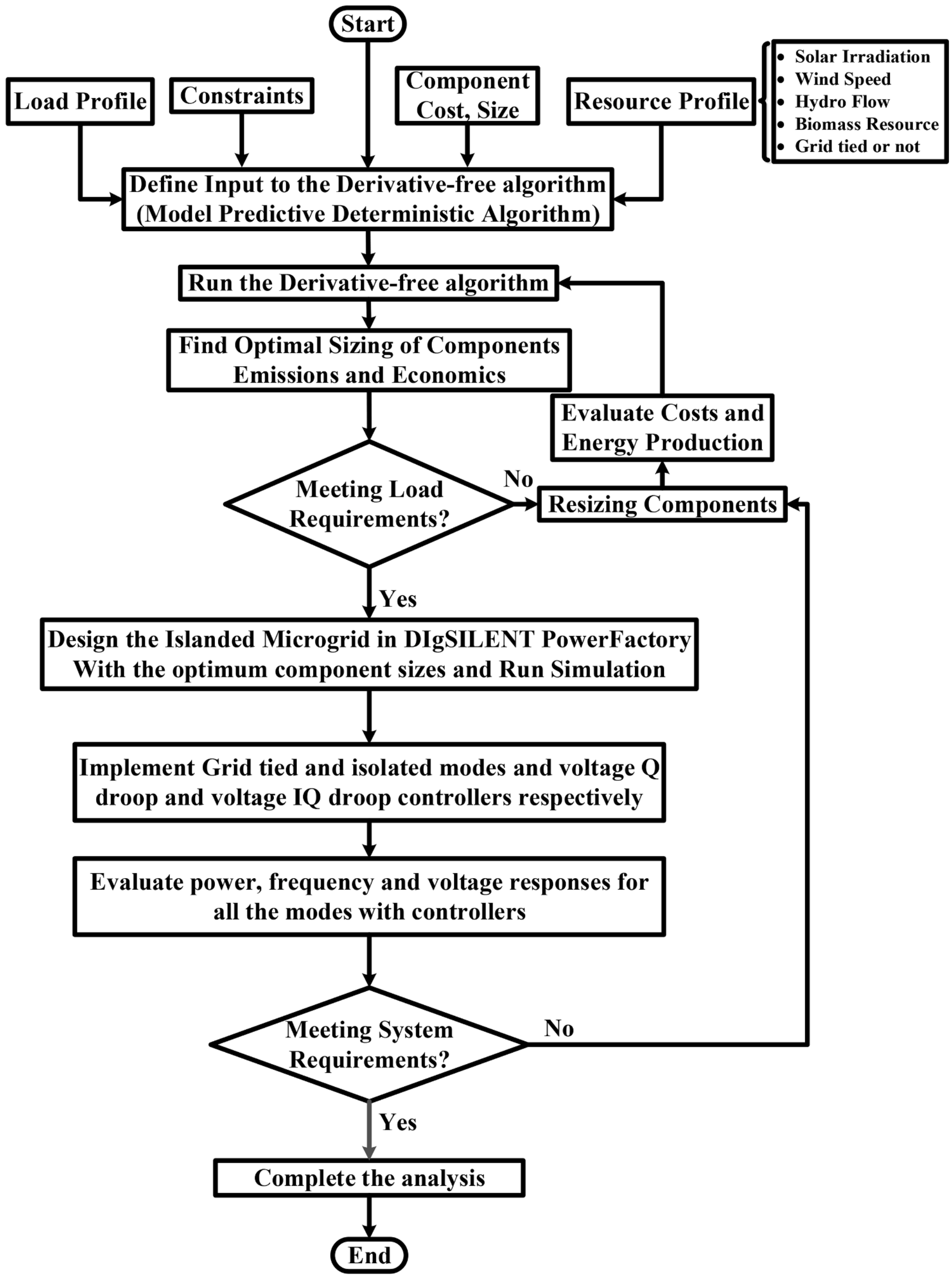

Fig. 1. Illustration of the methodology in a flow chart.

demand. The sizes of the different microgrid components are optimized by examining the meteorological condition of the proposed location of the microgrid e.g., solar irradiation, wind speed, biomass resource, hydro flow, etc. Further, the optimization of component size depends on the considered size of the microgrid that means on the different types of load demand connected to the microgrid and their respective priorities to be served according to various control techniques. Finally, the different components cost is taken into consideration for the optimization process. To optimize the sizes, numerous simulations are made and only the feasible solutions (which are really practically implementable) are kept for further consideration and the other solutions are discarded. Finally, they are categorized according to least costly and feasible combinations of different microgrid components with different optimized sizes within the program. The simulation of the hybrid system using derivative free algorithm has been conducted in MATLAB simulation platform using code. After the optimization, the power system response variation has been stabilized implementing Voltage Q droop and voltage IQ droop controllers. A comparative analysis in between them is also presented in subsequent sections. The stabilization utilizing different power system controllers have been conducted using DIgSILENT PowerFactory simulation platform. The following subsections contain the detail of the methodological approach. Fig. 1 demonstrates the methodological approach utilized in this research work.

2.1. System configuration

The grid connected microgrid system considered for a location in Perth, Australia which consists of suitable amount of Solar PV units for the generation of clean energy using the radiated power from the sun. Also, Wind turbines are incorporated in the design for the production of energy from the wind. Hydro turbines are also added for the production of energy utilizing the kinetic energy of the water head. For the storage

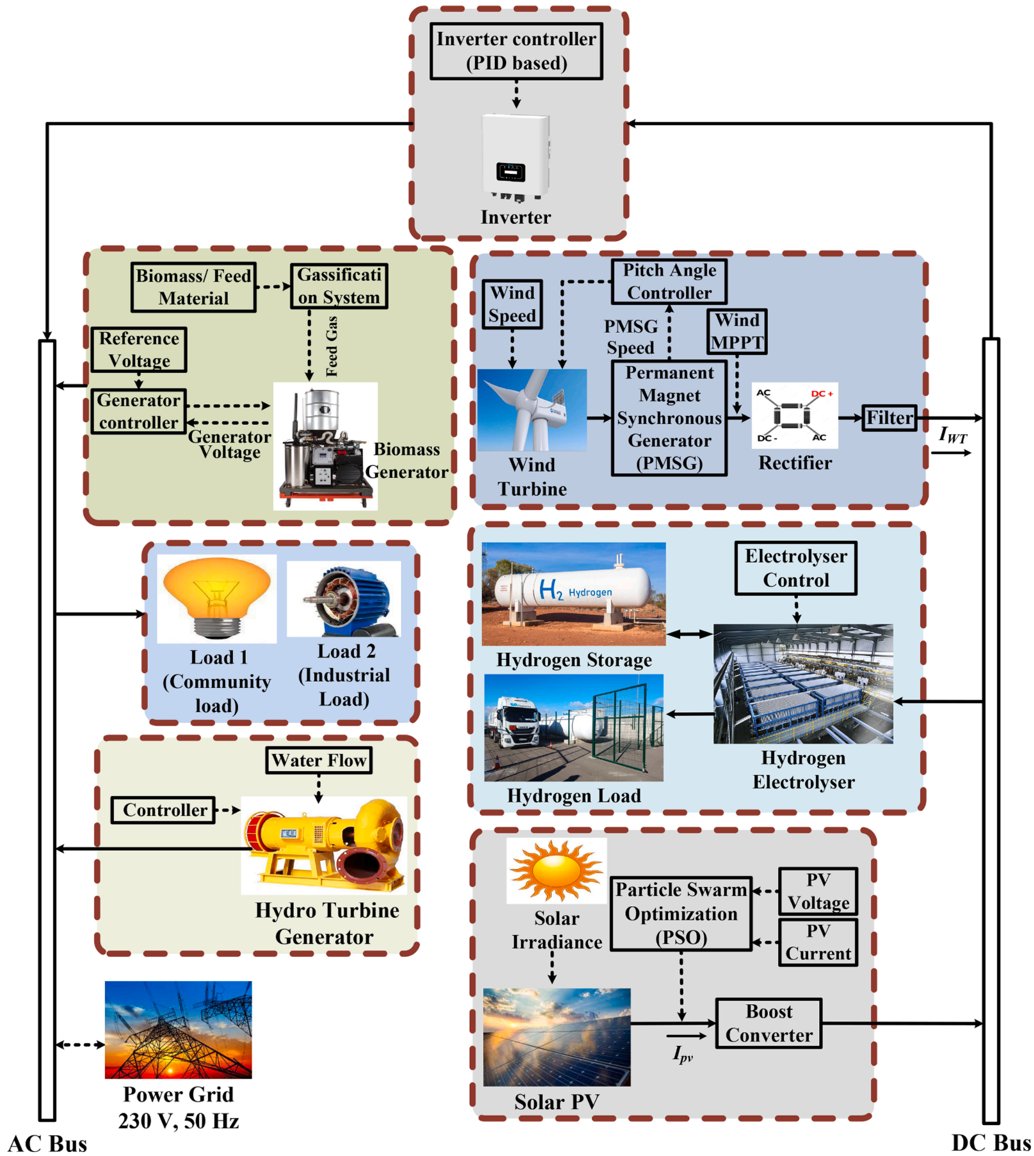

Fig. 2. Illustration of the system configuration.

of excess energy produced from the above mentioned sources in the off-peak hours, hydrogen based storage devices have been considered. The electrolysers do the necessary reactions to convert hydrogen to electrical energy and vice versa. The schematic diagram for the system configuration has been illustrated in Fig. 2.

2.2. Objective function

The main objective of microgrid optimization is to reduce each node's cost in the microgrid in a sustainable way [26]. A traditional objective function that employs a single quadratic equation can be used to approximate the objective function of the proposed research project [27,28].

$$Expense_{minimum} = \sum_{t=1}^{Num_g} F_t(P_t) \tag{1}$$

here, $F_t(P_t) = x_t + y_t P_t + z_t P_t^2$. Here, x_t, y_t, and z_t are the fuel cost coefficients of the tth generator. The term P_t is the power output of the tth generator in MW, Num_g indicates the total number of generators, and $F_t(P_t)$ is the fuel cost function of the tth generator in dollars/h.

Optimal Sizing and Cost Function Reduction: The optimization equations that must be solved in order to determine the ideal operating sizes and the required number of power generation units are listed below [28,29]. Here, v_1, v_2, and v_3 are weights to reveal the significance of the corresponding component, and t,u, w, x, y, and z are the corresponding sizes of different pieces of equipment in the system. The corresponding components' levelized cost of energy is denoted by *Energycost*, the corresponding components' net present cost is denoted by *Netcost* and Operating cost is denoted by *OperatingCost*, and C.CO_2 quantifies the gas emission from the diesel generator unit. Here, the subscript WT = wind turbine, SPVC = solar photovoltaic cell, BM = Biomass generator unit, HU = Hydrogen storage unit, HG = Hydro generator, G = conventional grid, and Net = summation of individual values.

$$\frac{min}{t, u, w, x, y, z, v_1 \epsilon N^0} (v_1 (t.Energycost_{HU} + u.Energycost_G + w.Energycost_{SPVC} + x.Energycost_{WT} + y.Energycost_{HG} + z.Energycost_{BM})) \tag{2}$$

$$\frac{min}{t, u, w, x, y, z, v_2 \epsilon N^0} (v_2 (t.Netcost_{HU} + u.Netcost_G + w.Netcost_{SPVC} + x.Netcost_{WT} + y.Netcost_{HG} + z.Netcost_{BM})) \tag{3}$$

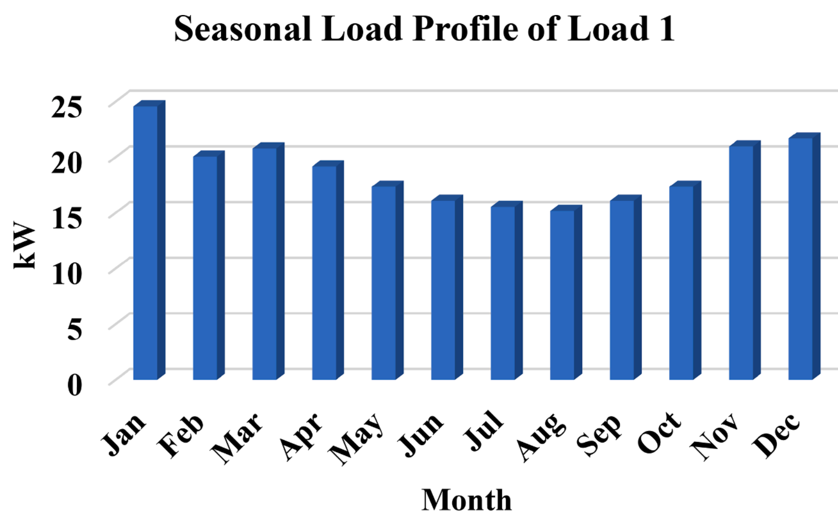

Fig. 3. Illustration of Load variation for Load 1.

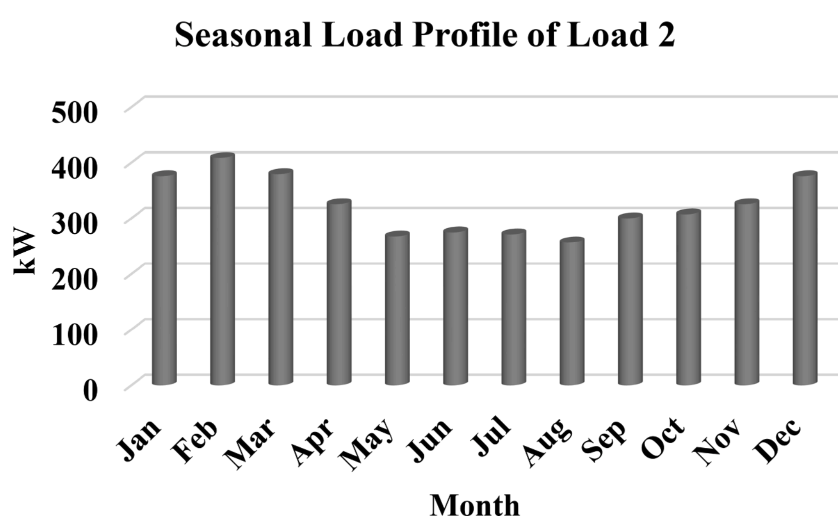

Fig. 4. Illustration of Load variation for Load 2.

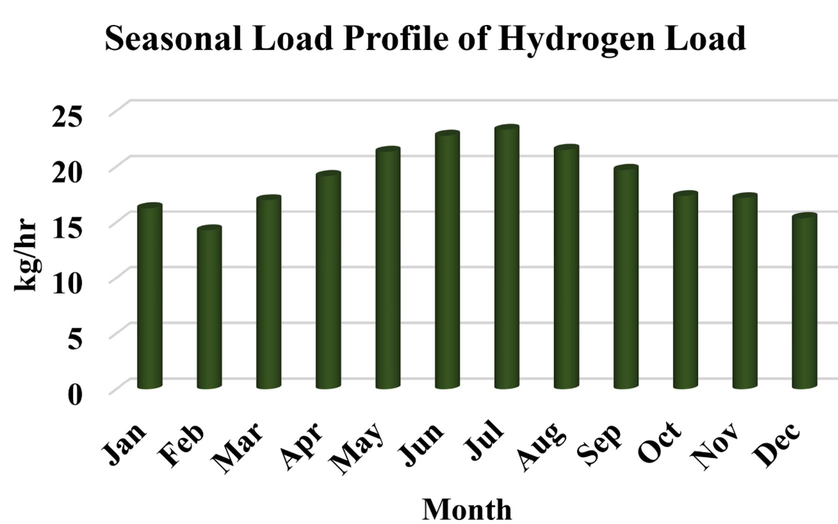

Fig. 5. Illustration of Load variation for Hydrogen Load.

Table 1
Optimization result of the research work.

PV (kW)	Wind (kW)	Bio. Gen. (kW)	Grid (kW)	Hydro (kWh)	Elec. (kW)	H.Gen Tank (kg)	Conv. (kW)	NPC ($)	COE ($)	Op. Cost ($/yr)	Energy Pur.(kWh)	Energy Sold (kWh)
Grid connected mode												
5,640	90	480	999,999	526	1000	100	1,836	-83.8M	-0.00974	-27.6M	32,242	664,717,440
Grid isolated mode												
PV (kW)	Wind (kW)	Bio. Gen. (kW)	Grid (kW)	Hydro (kWh)	Elec. (kW)	H.Gen Tank (kg)	Conv. (kW)	NPC ($)	COE ($)	Op. Cost ($/yr)	Energy Pur.(kWh)	Energy Sold (kWh)
1,621	1	480	-	526	1000	100	417	6.61M	0.542	202,712	-	-

*Bio.Gen=Biomass Generator, Elec=Electrolyser, H.Gen=Hydrogen Generator, Conv. Converter, Op. Cost=Operating Cost, Energy Pur. =Energy Purchased

Table 2
Estimation of probable emission from the microgrid.

Grid connected mode			Grid isolated mode		
Quantity	Value	Units	Quantity	Value	Units
Carbon Dioxide	20,377	kg/yr	Carbon Dioxide	73.6	kg/yr
Carbon Monoxide	0	kg/yr	Carbon Monoxide	7.73	kg/yr
Unburned Hydrocarbon	0	kg/yr	Unburned Hydrocarbon	0.337	kg/yr
Particulate Matter	0	kg/yr	Particulate Matter	0.0468	kg/yr
Sulfur Dioxide	88.3	kg/yr	Sulfur Dioxide	0	kg/yr
Nitrogen Oxides	43.2	kg/yr	Nitrogen Oxides	7.26	kg/yr

$$\frac{min}{C, v_3 \epsilon N^0}\left(v_3\left(C.CO_{2_{DG}}\right)\right) \tag{4}$$

$$\frac{min}{v_1, v_2, v_3 \epsilon N^0}\left(v_1 Energycost_{Net} + v_2 Netcost_{Net} + v_3 OperatingCost_{Net}\right) \tag{5}$$

2.3. Optimization

This research implements a derivative free algorithm (Model Predictive Deterministic Algorithm) for the optimization purpose. The optimization has been conducted to find out the least Operating costs, Net cost (NPC), energy cost (COE), and harmful gas emissions in both grid tied and isolated modes of operation of the hybrid microgrid. The following derivative free formulations have been utilized to calculate the costs and harmful emissions from the microgrid.

Operating Cost: The operational cost of the proposed microgrid has been determined using the formula [30]:

$$\begin{aligned} OperatingCost &= (C_{invest}(PV) + C_{O\&M}(PV))S_{PV} \\ &+(C_{invest}(wind) + C_{O\&M}(wind))S_{wind} \\ &+(C_{invest}(Bio) + C_{O\&M}(Bio))S_{Bio} \\ &+(C_{invest}(hydro) + C_{O\&M}(hydro))S_{hydro} \\ &+C_{Loss} \end{aligned} \tag{6}$$

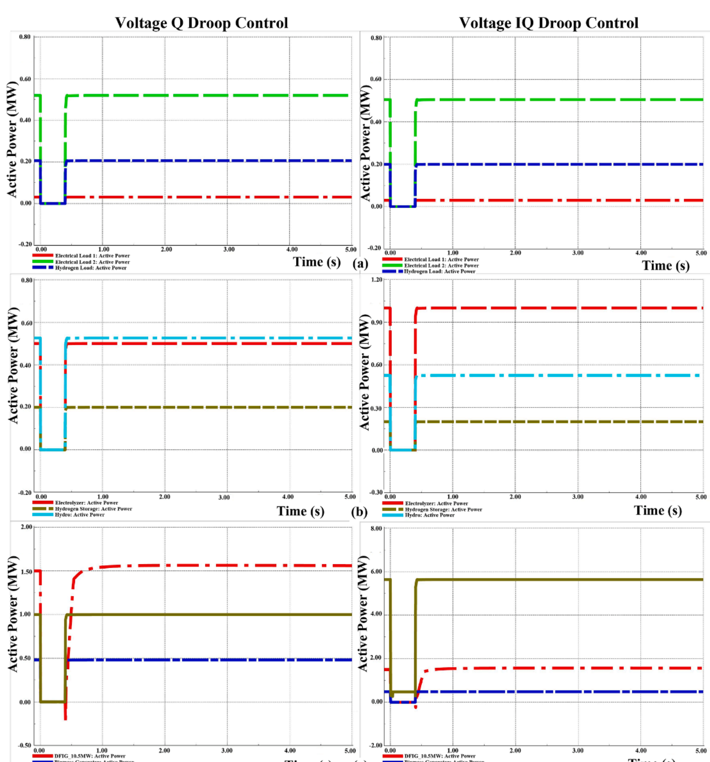

Fig. 6. Comparison between active power responses for both controllers in Grid tied mode: (a) Loads, (b) Electrolyser, Hydro Generator and Hydrogen Storage, (c) Wind turbine, biomass generator and PV.

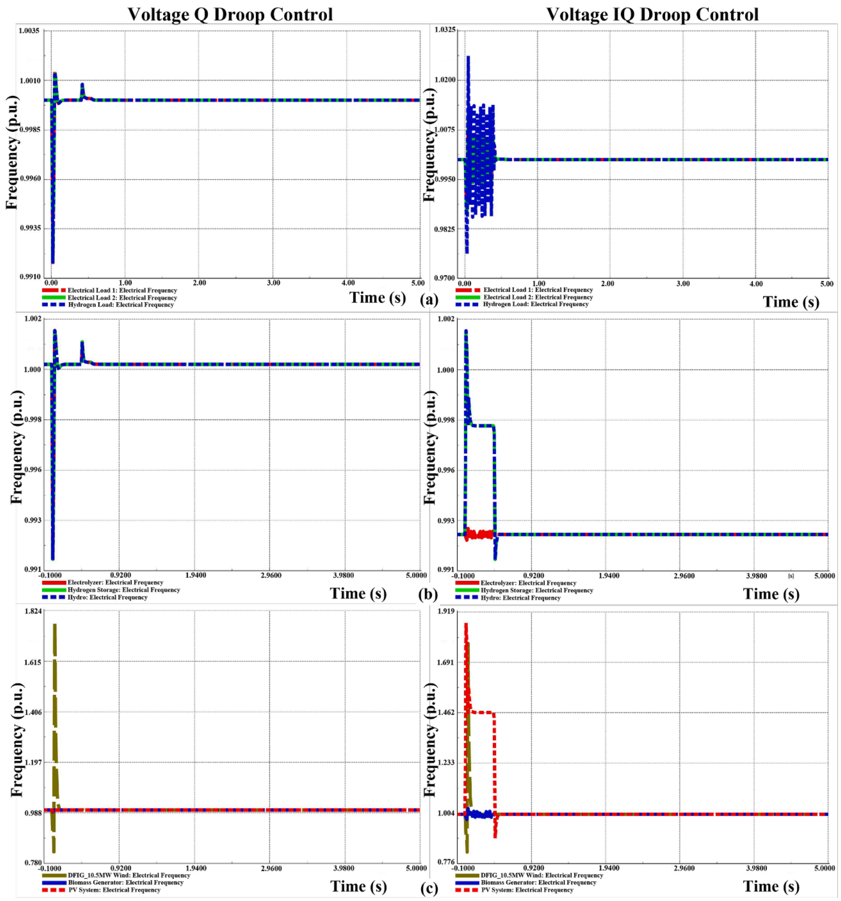

Fig. 7. Comparison between frequency responses for both controllers in Grid tied mode: (a) Loads, (b) Electrolyser, Hydro Generator and Hydrogen Storage, (c) Wind turbine, biomass generator and PV.

where, S_{PV}, S_{wind}, S_{Bio}, and S_{hydro} are the respected optimum sizes of the components, C_{invest} = investment cost, $C_{O\&M}$= Operation and Maintenance cost, C_{Loss}= Power loss cost.

NPC: The NPC of the hybrid system has been estimated with the following derivative free formula [31]:

$$Netcost = \frac{AnnualCost}{CaritalRecoveryFactor(i_r, T_l)} \tag{7}$$

where, i_r = annual interest rate, T_l= project's lifespan.

COE: The energy cost has been calculated using the formula [31]:

$$Energycost = \frac{AnnualCost}{L_p + L_{df} + S_s} \tag{8}$$

Here, C_{ac} = annual cost, L_p = total primary load, S_s = Energy sold to grid/annum, and L_{df} = deferrable load.

Harmful Emission Harmful CO_2 emission from microgrid is evaluated as [31]:

$$HE = 3.667 \times M_{fuel} \times H \times CF \times OCF \tag{9}$$

where, HE = harmful CO_2 emissions, OCF = Fractional value of oxidized carbon, CF = Carbon emission factor in ton carbon/TJ, H = Fuel heating value, MJ/L, M_{fuel} = Fuel measurement in Liter.

2.4. Load variation

The load on the microgrid has been varied on a continuous basis to analyse the impact of load demand variation on the performance of the microgrid system on top of the controller in both islanded and grid connected modes. Total three types of loads have been considered in this work as referred to Fig. 2. Load 1 is considered as normal community load having 165.29 kWh/day and 24.57 kW as peak load size. The deviation of load 1 on a yearly basis have been illustrated in Fig. 3.

As industrial load connected to the considered microgrid, Load 2 has been considered. Load 2 has a peak demand of 407.71 kW and a demand of 2422.06 kWh/day. The demand variation has been illustrated in Fig. 4 on a yearly basis to demonstrate the load demand fluctuation.

A hydrogen load is also considered within the microgrid connected with the electrolyser. The varying characteristics of this load has been illustrated in Fig. 5.

2.5. Voltage IQ droop controller

Droop controllers are used to regulate a system's drooping features. In a microgrid with parallel-connected distributed generating units, droop controls can be employed to prevent circulating current [32]. In practice, droop control strategies are frequently utilized to maintain load/generation balance while controlling voltage and frequency [33].

In order to maintain voltage stability in power systems, a technique known as voltage IQ droop control modifies the reactive power output of generators in response to variations in system voltage. The droop feature of the control scheme generally entails altering the generator's output voltage in response to variations in the system voltage.

The voltage IQ droop control formulae rely on the particular system architecture and control method used. However, the generic equation that depicts the voltage droop characteristic is shown below:

$$V_{droop} = V_{nominal} - (k \times (P_{gen} - P_{load})) \tag{10}$$

Where, V_{droop} is the adjusted generator voltage based on the droop control, $V_{nominal}$ is the nominal voltage setpoint, k is the droop coefficient,

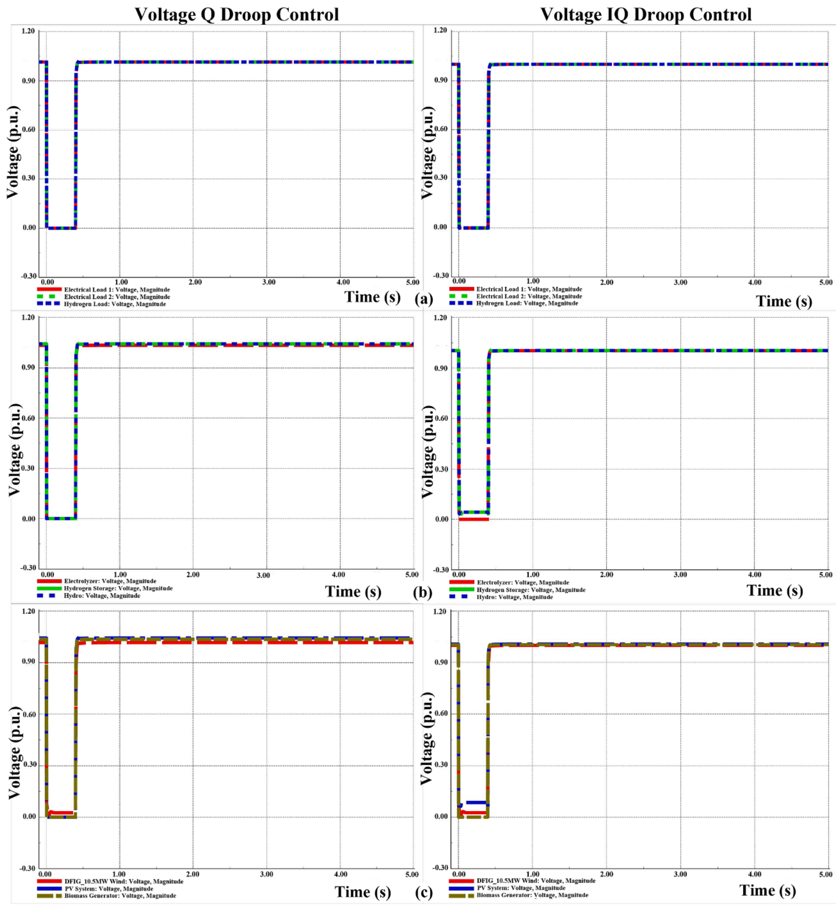

Fig. 8. Comparison between voltage responses for both controllers in Grid tied mode: (a) Loads, (b) Electrolyser, Hydro Generator and Hydrogen Storage, (c) Wind turbine, biomass generator and PV.

which determines the sensitivity of the voltage adjustment. It is typically expressed in per unit (pu) per megawatt (pu/MW) or per unit (pu) per kilovar (pu/kVAR), P_{gen} is the generator's active power output and P_{load} is the total active power demand in the system.

Frequency stability can be impacted by the entire management and synchronization of reactive and active power in the power system, even when voltage IQ droop control has no direct effect on frequency. For the power system to operate steadily and dependably, proper voltage and frequency management must be implemented.

However, there is a connection between the frequency control and the voltage IQ drop when the microgrid begins to energize. The particular control method and system configuration affect the frequency control of a power system. However, the simplified equation that follows illustrates the fundamental connection between frequency and power imbalance:

$$\delta f = \left(\frac{1}{M}\right) \times \left(\delta P - \delta P_{droop}\right) \tag{11}$$

Where, δf is the change in frequency (in Hz), M is the system inertia constant (in seconds per megawatt), δP is the power imbalance between generation and load (in megawatts), δP_{droop} is the droop component of power control (in megawatts). In this equation, δP represents the difference between the total power generated by the generators and the total power consumed by the loads. It indicates the power imbalance in the system. δP_{droop} represents the droop component, which is usually proportional to the frequency deviation.

The system's capacity to sustain frequency stability is indicated by the system's inertia constant, M. It is based on the system's linked generators' combined inertia. Since the system can sustain greater power imbalances without experiencing substantial frequency variations, a higher inertia constant suggests better frequency stability.

2.6. Modified voltage q droop (Q-V droop)

Voltage q droop control has been applied in this research work to compare the mutual performances of both IQ droop and Q-V droop controllers on basis of power, voltage and frequency responses for the optimized microgrid. The study in [34] offers a reliable and user-friendly droop control system that is suitable for high-voltage microgrids. Q-V droop management is typically used when an internal microgrid's equivalent impedance, which links dispersed generators to the utility grid, is inductive [35]. Referencing [34], reference Eqs. (12) and (13) illustrate the fundamental theoretical ideas for Q-V droop control [36]:

$$Reactive_Q = \frac{V}{X_I}(E_G - V_B) \tag{12}$$

$$Real_P = \frac{E_G \times V_B}{X_I}\delta \tag{13}$$

where, $Reactive_Q$ and $Real_P$ respectively refer to reactive and active power of the microgrid, E_G refers the generator's output voltage, δ refers the rotor angle, V_B defines the voltage for AC bus, and X_I refers the reactance which is inductive in nature.

Therefore, it is possible to modify the output voltage of distributed generators using the equation below (Eq. (14)) [34]:

$$E_M = E_M^{'} - G \times Reactive_Q \tag{14}$$

where, G refers to the voltage droop gain, and $E_M^{'}$ refers the microgrid's

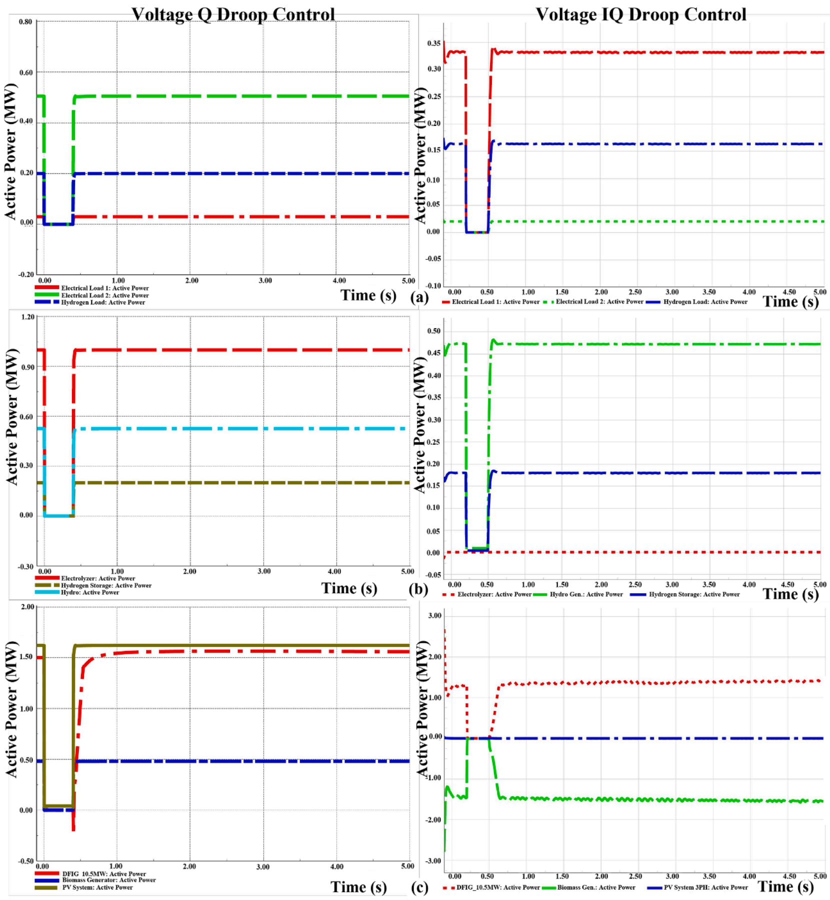

Fig. 9. Comparison between active power responses for both controllers in Grid isolated mode: (a) Loads, (b) Electrolyser, Hydro Generator and Hydrogen Storage, (c) Wind turbine, biomass generator and PV.

rated voltage.

Once more, by using Eq. (15), the frequency output may be controlled [34]:

$$\omega = \omega' - x \times Real_P \tag{15}$$

where, x, and ω respectively defines the droop gain of frequency and output frequency, and ω' defines the microgrid's rated frequency.

Now, from various distributed generation units, Eq. (16) illustrates the active power, j (here j=1,2,...number of generators) [34]:

$$x_1 Real_{P1} = x_2 Real_{P2} = \ldots. = x_j Real_{Pj} \tag{16}$$

3. Results and discussion

This section discusses in detail, the findings of this research work. The following section has been further divided into subsections to better enlighten the findings.

3.1. Optimization result

The optimization part of this research work includes the optimal sizing of the different microgrid components used and the determination of the NPC, operating cost, COE and estimated harmful gas emission using a proprietary derivative free algorithm previously discussed. The optimization result of this research work has been summarized in the Table 1. The table contains the optimal sizes of the microgrid components and their least present and operational costings and amount of energy purchase and sold in case of grid tied mode. The off grid mode, as disconnected from the conventional grid, there is no option for selling excess energy to the grid or buying any energy from the grid in case of shortage. The grid tied mode requires larger component sizes as there is provision of selling energy and thus requires more NPC and operating cost than the off grid one. The negative sign before the costs indicate a grid tied version. The energy cost is about 98.2% less in grid tied mode than the off grid version due to the grid connectivity. The grid tied mode sells about 99.99% more energy than it requires purchase from the grid which indicates the commercial significance of the design.

Table 2 on the other hand predicts the harmful greenhouse gas emission from the design in both the grid tied and isolated modes of operation. Due to the usage of fossil fuel based electricity generation of the conventional electricity grid system, the grid tied mode emits 99.6% more Carbon Dioxide than the grid isolated mode. As the grid isolated mode does not contain any diesel or fossil fuel based generation within it's scope, the overall emission of this mode is less than the other mode of operation.

3.2. Results on the implementation of Voltage IQ droop and Voltage Q Droop controller

The optimized solution of the proposed microgrid is further evaluated on basis of their power, frequency and voltage performances when applied voltage IQ droop and voltage Q droop controllers for both the connection modes of the microgrid. The results are satisfactory in terms of their stability and bounded response within the range. The following subsections will discuss about the findings of the simulation with the droop controllers implemented for both the connection modes of the microgrid.

3.2.1. Grid tied mode

In grid tied mode, the microgrid is connected with the conventional

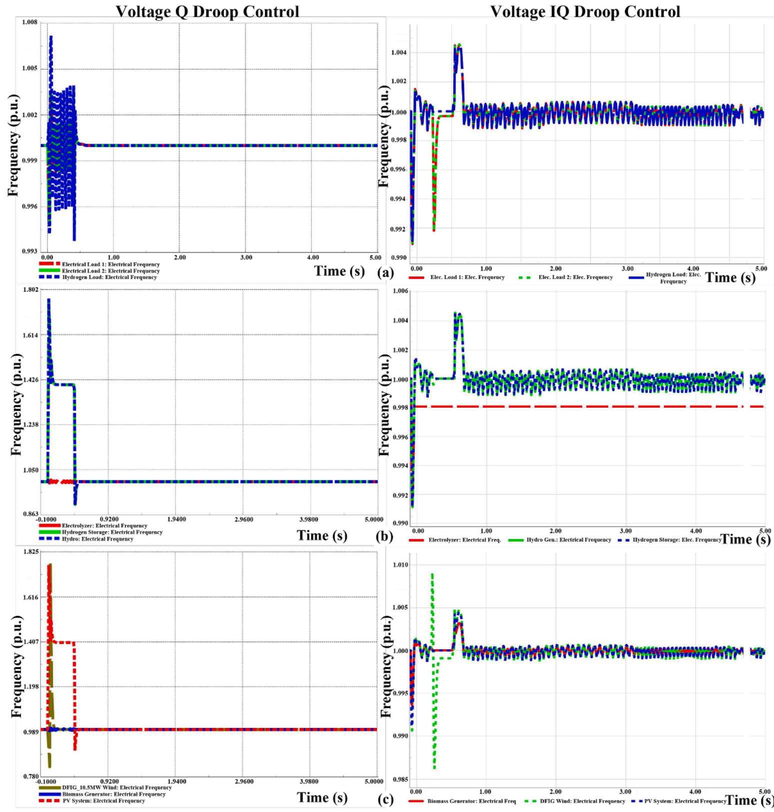

Fig. 10. Comparison between frequency responses for both controllers in Grid isolated mode: (a) Loads, (b) Electrolyser, Hydro Generator and Hydrogen Storage, (c) Wind turbine, biomass generator and PV.

grid and there is a flow of electrical power in both ways. When the microgrid has excess energy than it's need it can provide the excess energy to the conventional grid system and on the time of shortage can take power from the grid. Thus, the power, voltage and frequency responses in this mode of operation is quite dependent on the parameters of the grid, The active power responses of the three loads (load 1, load 2 and hydrogen load), Electrolyser, Hydro generator, hydrogen storage and sources (wind turbine, biomass generator and solar PV) in grid connected mode for both voltage Q and IQ droop controllers are illustrated in Fig. 6. The illustration demonstrates the stable nature in all the responses in terms of active power flow. The power responses have been evaluated for 5 seconds where upto 0.4 seconds, oscillations are observed in the responses which get stabled after 0.4 seconds and stays stable till the operation. For both the controllers. the power responses of the loads have similar responses as seen from 6 (a). From Fig. 6 (b) and (c) it can be observed that the IQ droop control offers better power responses for the sources and storage units within the microgrid than the Q droop control strategy. Hence, in this scenario, the IQ control offers better performance with regard to power responses in the grid connected version of the microgrid.

In grid tied mode, the frequency responses of three loads, Electrolyser, Hydro generator, hydrogen storage, and sources on the application of voltage IQ droop and voltage Q droop control strategies have been illustrated in Fig. 7. The frequency responses have been evaluated for 5 seconds. Upto 0.5 seconds there are some oscillations in the frequency after which the frequency signals get a stable output. The fluctuations is the frequency are due to the connectivity to grid where the microgrid and conventional grid get synchronized within the 0.5 seconds. After that, the microgrid is properly synchronized with the grid and the response is stable. The controllers here help reducing the overshoot and minimizing the time of oscillation. Observing the frequency responses it can be seen that, the Q droop control here offers better performance and stable responses than the IQ droop controlled responses.

The responses in terms of voltage for the same components within the microgrid in grid connected mode have been shown in Fig. 8 for both the controllers. For the same reason discussed previously, here, in the voltage responses as well oscillations are observed within 0.5 seconds of the time frame. After this transient state the voltage responses are stable and found steady throughout rest of the time. Here in this case, the voltage responses for both the controllers have approximately similar responses and oscillations. But a critical observation might show that, the Q droop has slightly better stable responses and performance than the IQ droop control. Hence, investigating the three power system responses (active power, frequency and voltage) for both the controllers in grid connected mode it can be concluded that, both the controllers are capable of providing acceptable range of stable operation which is good enough for the reliable operation of the microgrid in grid tied mode. But between the two, the Q droop control has better performance with the frequency and voltage responses. The different control dynamics of the controllers are liable for the difference in the performances of the controllers.

3.2.2. Grid isolated mode

In grid isolated mode the proposed microgrid design is fully isolated from the conventional grid and run only on their own generation and distribution. Here, as the microgrid is fully separated from the grid, the power, frequency and voltage responses do not depend on the grid and are controlled by the droop controllers implemented. The active power responses of the loads and other components of the microgrid in offgrid mode have been illustrated in Fig. 9. Compared to the grid tied mode, grid isolated mode has comparatively poor power responses having larger transient overshoots and longer transient periods. Here, the biomass generator has negative active power in IQ control meaning it is acting as a load to the microgrid. Here in the active power responses, the Q droop controller has better responses and stability than the IQ droop

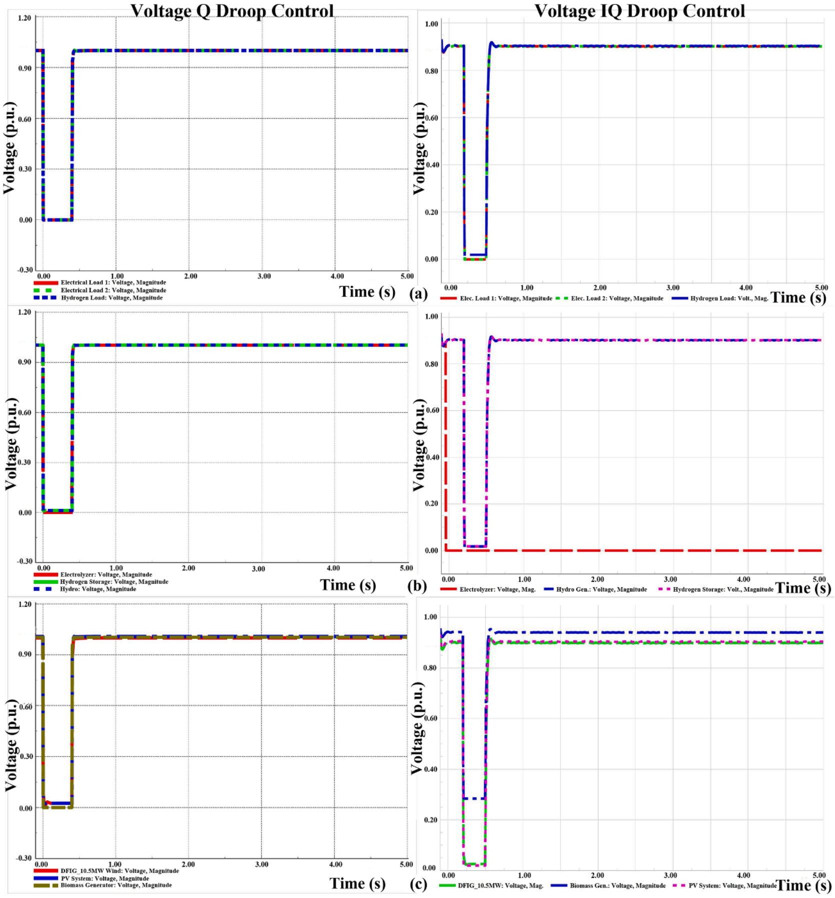

Fig. 11. Comparison between voltage responses for both controllers in Grid isolated mode: (a) Loads, (b) Electrolyser, Hydro Generator and Hydrogen Storage, (c) Wind turbine, biomass generator and PV.

control. As discussed earlier in the methodology section, the real power depends on the generator and bus voltage and the rotor angle (according to the Eq. (13)).

The frequency responses of the microgrid components with the droop controllers in grid isolated mode are shown in Fig. 10. Compared to the grid tied mode of operation, isolated mode has poorer frequency response having more oscillation throughout the time frame of operation. It is observed that except the electrolyser, the frequency responses keep oscillating around the unity value throughout the time span for IQ control strategy. With respect to frequency response, voltage Q droop control offers less oscillation and better stable frequency responses for the microgrid components.

Fig. 11 shows the voltage responses of the microgrid components in offgrid mode on the implementation of voltage IQ and voltage Q droop controllers. In the voltage response section as well for offgrid mode, the response takes longer time to get stabled. The responses have larger overshoot in comparison to the grid tied one. The Q droop controller has better responses in terms of voltage responses. The responses in Q control are closer to unity and have less unstability and oscillations in the transient level.

In conclusion, the responses found for both the modes implementing the voltage IQ droop and Q droop controllers, it is found that, the grid connected mode has better active power, voltage and frequency responses in terms of shorter transient times, lower overshoots and oscillations and higher stable responses. The droop control performs by injecting necessary reactive power to the system to balance the voltage, power and frequency responses. In this case, for the proposed microgrid, the controllers have better impact in the grid tied mode than the isolated one. In terms of the mutual performances of the controllers, the Q droop control has better performances in most of the cases of improving power, frequency and voltage responses. The IQ control dynamics has better performance only in the case of active power in the grid tied mode. So, it can be concluded that, the Q droop offered better performance and the grid tied mode has improved responses in terms of system's active power, voltage and frequency responses.

4. Conclusion

In conclusion, the study demonstrates the potential of hybrid solar-wind-biomass-hydro-electrolyser microgrids for reliable and sustainable energy production and distribution. With continued advancements in technology and research, hybrid microgrids have the potential to revolutionize the way we produce and distribute energy, enabling a more sustainable and resilient energy future. The integration of multiple renewable energy sources, energy storage systems, and electrolysers can enhance the microgrid's performance and ensure reliable power supply under varying load conditions. The use of advanced optimization and control strategies, such as proprietary derivative-free algorithms and voltage droop controllers, can further improve the microgrid's performance and stability. Within the scope of this research work, the optimized design of a hybrid solar-wind-biomass-hydro-electrolyser microgrid has been done along with the evaluation of the microgrid for both grid tied and isolated modes. The optimal sizes, estimated costs and predicted toxic gas emission are determined for both the operating modes and further, the voltage, frequency and active power performances have been evaluated implementing a voltage IQ droop and voltage Q droop control algorithms for both the operating modes. The performances found stable and the grid tied mode has been found more cost effective in terms of cost per unit energy and provision to selling the excess energy to the grid. On basis of minimum present and operation cost cost and required component size and emission, the grid isolated mode performed better than the grid tied one. However, the power system responses have been found better in the grid tied version rather than the offgrid one with the Q droop control performing better than the IQ droop control strategy.

CRediT authorship contribution statement

Md. Fatin Ishraque: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sk. A. Shezan:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **G.M. Shafiullah:** Writing – review & editing, Supervision, Methodology, Investigation. **SM Muyeen:** Writing – review & editing, Project administration, Funding acquisition. **Talal Alharbi:** Resources, Project administration, Methodology, Investigation. **Ali H Alenezi:** Supervision, Resources, Project administration, Methodology, Investigation. **Md. Delwar Hossen:** Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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