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ORIGINAL RESEARCH ARTICLE

Design and implementation of an off-grid hybrid microgrid for Chittagong and Faridpur

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ABSTRACT

The challenge of rural electrification has become more challenging today than ever before. Grid-connected and off-grid microgrid systems are playing a very important role in this problem. Examining each component's ideal size, facility system reactions, and other microgrid analyses, this paper proposes the design and implementation of an off-grid hybrid microgrid in Chittagong and Faridpur with various load dispatch strategies. The hybrid microgrids with a load of 23.31 kW and the following five dispatch algorithms have been optimized: (i) load following, (ii) HOMER predictive, (iii) combined dispatch, (iv) generator order, and (v) cycle charging dispatch approach. The proposed microgrids have been optimized to reduce the net present cost, CO_2 emissions, and levelized cost of energy. All five dispatch strategies for the two microgrids have been analyzed in HOMER Pro. Power system reactions and feasibility analyses of microgrids have been performed using ETAP simulation software. For both the considered locations, the results propound that load-following is the outperforming approach, which has the lowest energy cost of $0.1728/kWh, operational cost of $2944.13, present cost of $127,528.10, and CO_2 emission of 2746 kg/year for the Chittagong microgrid and the lowest energy cost of $0.2030/kWh, operating cost of $3530.34, present cost of 149,287.30, and CO_2 emission of 3256 kg/year for the Faridpur microgrid with a steady reaction of the power system.

Keywords: renewable energy technology; optimization; power system stability; control technique; coastal area

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1. Introduction

Bangladesh, a relatively small country with a population of 160 million and an area of 147,570 square kilometers, is one of the world's most densely populated countries. Electricity demand exceeds generation capacity and distribution capabilities every year, so the scarcity of energy will persist for the next 50 years. New power stations cannot be built hastily enough. Additionally, power stations require large amounts of fuel every hour due to Bangladesh's lack of fuel. A major role is being played in this problem by both grid-connected and off-grid microgrids, as their lower costs and ease of installation make them a very good option[1]. When the neighbors have advanced much, Bangladesh is still at the elementary level of developing renewable energy. In Bangladesh, the renewable energy policy journey began in 2008. Since then, Bangladesh has made small but steady progress in this field. Renewable energy sources in Bangladesh, like wind and solar, now take up a larger share of the energy mix. For this, Bangladesh has 579 megawatts of installed renewable energy capacity[2]. This concludes both on-grid and off-grid installations. Renewable energy sources and conventional power plants are currently used in Bangladesh to produce electricity. However, the net quantity of energy production from renewable sources is insufficient[3]. But recently, Bangladesh has made significant strides in the renewable energy sector. Bangladesh wants to produce around 4100 megawatts of power from renewable sources by the year 2030. Solar energy will contribute the most energy (2277 MW), followed by hydropower (1000 MW) and wind energy (597 MW). **Table 1** shows the renewable energy installed capacity in Bangladesh, and **Figure 1** shows the renewable energy share in Bangladesh. Numerous renewable energy projects are being carried out in Bangladesh by renewable energy groups. Sustainable Renewable Energy Development Authority (SREDA) data show that solar energy constitutes 75.3% of renewable energy in Bangladesh, hydropower makes up 24.3%, and wind power makes up 1%. Additionally, SREDA reports a total installed renewable energy capacity of 948.03 MW[4].

Table 1. Bangladesh's installed renewable energy capacity[4].

Technology	On-grid (MW)	Off-grid (MW)	Total (MW)
Hydro	230	0	230
Wind	0.9	2	2.9
Solar	357.89	356.15	714.04
Biomass to electricity	0	0.4	0.4
Biogas to electricity	0	0.69	0.69
Total	588.79	359.24	948.03

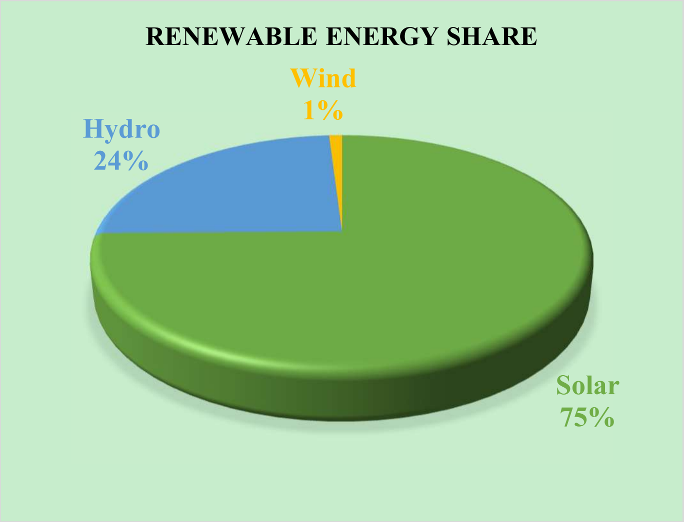
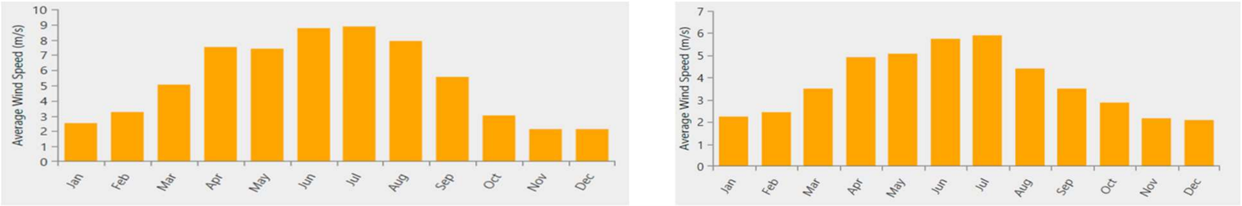


Figure 1. Renewable energy share in Bangladesh (SREDA)[4].

2. Renewable energy prospects of Bangladesh

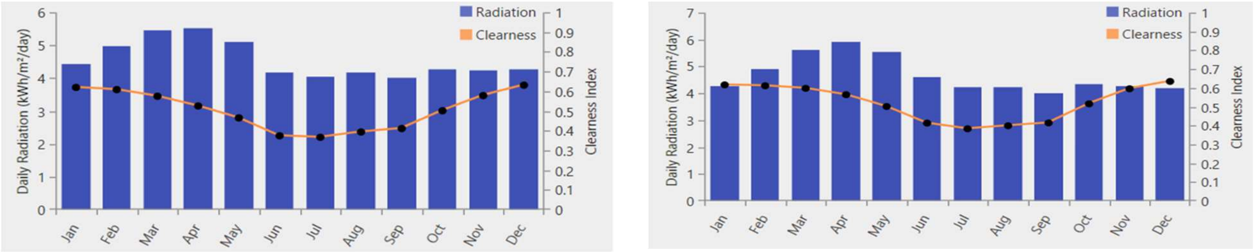
Considering Bangladesh's geographic location, solar energy has the highest share of renewable energy. Over 300 days per year, Bangladesh receives 5 kWh/m^2 of solar radiation due to its location. Considering Bangladesh's abundance of solar energy, various sectors are expected to benefit greatly from it. A wide variety of large and small solar projects are currently being implemented in Bangladesh by DESCO, DPDC, WZPDCL, and BPDB[5]. Wind is another popular mode of renewable and sustainable source of energy[6]. On-shore and offshore wind farms may have a significant impact on producing electrical energy in a sustainable way[7]. A low proportion of Bangladesh's renewable energy comes from wind energy. There is potential for wind turbines in the coastal area. The Bay of Bengal has many islands and a coastline that stretches 700 km[8]. It is possible to generate electricity from wind farms using the south/southwesterly monsoon winds from the Indian Ocean. Numerous programs are currently being conducted in the country to assess wind resources. **Figure 2** shows wind speed at Chittagong and Faridpur. Both wind profiles have a minimum required wind speed of 2 ms^{-1} to rotate a wind turbine and start generating electricity. The statistics for the Chittagong and Faridpur regions' monthly average solar global horizontal irradiance (GHI) are shown in **Figure 3**.



(a) Chittagong wind speed.

(b) Faridpur wind speed.

Figure 2. Annual wind speed profile (average Chittagong 5.35 m/s, Faridpur 4.14 m/s).



(a) Chittagong GHI.

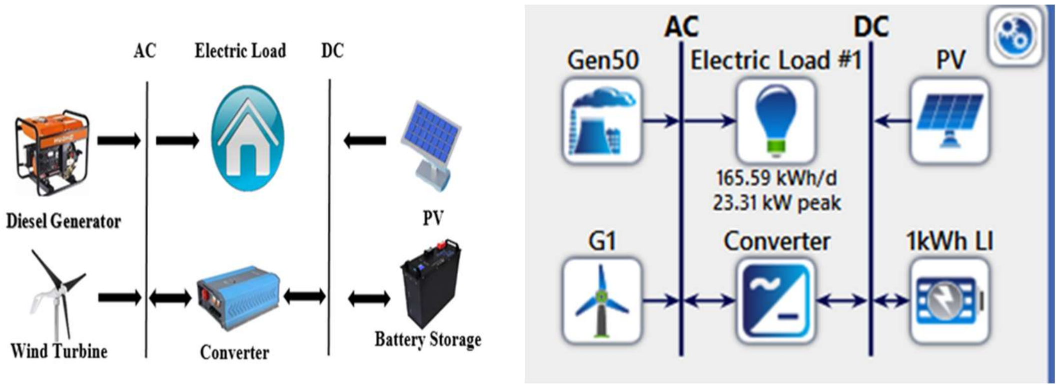
(b) Faridpur GHI.

Figure 3. Monthly average GHI (Chittagong average 4.56 kWh/m^2/day, Faridpur average 4.68 kWh/m^2/day).

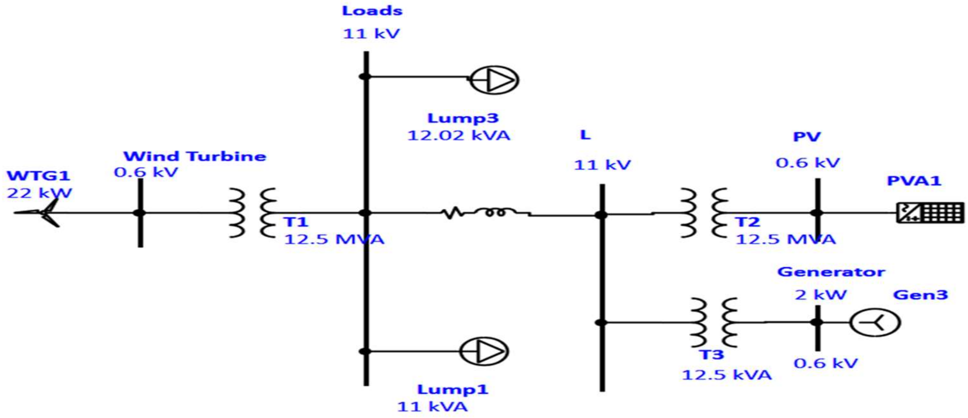
Hybrid electric systems are an association of solar and wind electric types of machinery. As we can see, most countries' wind speed is high during the winter, but the availability of sunlight is less. And during summer, the sun shines brightest and the wind speed remains lower. So, the peak operational times for hybrid electric systems vary depending on the time of day and year. Hybrid electric systems have the advantage of producing power according to load demand. Most hybrid systems operate off-grid[9]. Most hybrid systems deliver power through batteries and diesel generators if both the solar and wind systems are not able to produce power[10]. As a part of this research, diesel generators, batteries, and solar PV-based hybrid off-grid microgrids will be designed and assessed for rural communities in Chittagong and Faridpur, implementing dispatch strategies. In addition to evaluating the performance of the microgrid for five distinct dispatch strategies, various costs, optimal component sizes, harmful gas emissions, and power system (frequency, angle, and voltage) stability have been analyzed[11].

3. Methodology

An off-grid hybrid microgrid system is illustrated in **Figure 4** as a block schematic. It includes a solar system, diesel generator, battery storage system, load profile, and conversion module. Before being connected to the AC bar, DC power from solar panels and battery packs is transformed to alternating current (AC) using AC/DC converters. Afterward, AC bars will distribute combined energy to electric utilities and individuals[12]. The hourly load demand profile considered in this research work is shown in **Figure 5**.



(a) Schematic diagram. **(b)** HOMER model.



(c) ETAP model.

Figure 4. Schematic diagram, HOMER model, and ETAP model of proposed off-grid hybrid micro-grid.

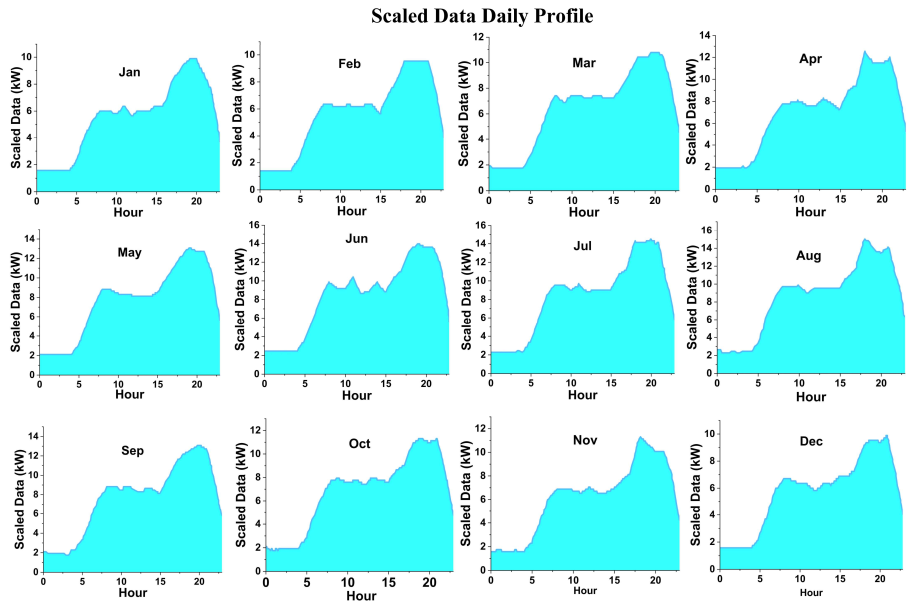


Figure 5. Daily load profile considered for the two microgrids.

3.1. Dispatch strategies

A variety of dispatch mechanisms are used by optimization algorithms based on power sources, load demand, and weather conditions[13]. In an insufficient renewable energy scenario, dispatch strategies are used to govern the operation of the storage and the generator. A total of five dispatching strategies were studied and tested in this study, including (i) load following, (ii) HOMER predictive, (iii) combined dispatch, (iv) generator order, and (v) cycle charging approach.

Load following: every time a generator is required, load following ensures that it only generates the necessary amount of electricity. Since the supply of renewable energy frequently outpaces the need for electricity, the method works best in systems that generate a lot of it.

Cycle charging: in a cycle charging system, the generator runs at full capacity whenever it is needed, and any extra power is used to charge the battery bank. Typically, systems with little to no renewable energy are best suited for this kind of system.

Generator order: in the generator order approach, HOMER employs a set sequence of generator combinations, starting with the combination that corresponds to the operating capacity. Only systems with generators, storage devices, wind turbines, PVs, and/or converters are capable of using generator orders.

Combined dispatch: the combined dispatch approach may achieve greater outcomes than cycle charging and load-following dispatch systems by making better use of the generator.

Predictive dispatch: when the HOMER predictive dispatch method is employed, the dispatch algorithm is aware of when there will be an increase in electric and thermal demand as well as an increase in the availability of solar and wind resources. In HOMER Pro, it will often result in cheaper system running costs compared to alternative dispatch options.

3.2. HOMER optimization

The HOMER algorithm simulates all of the plausible configurations of the search space for the original search algorithm. A patented derivative-free technique is employed in this new HOMER optimizer to identify the system with the lowest cost. The net present cost, also known as the life-cycle cost, of various configurations allows us to evaluate system design possibilities[14].

3.3. ETAP microgrid controller

The ETAP microgrid controller offers a high level of flexibility through its configurable, model-driven design. This allows for a variety of control options to be implemented[15]. The controller logic can be tested using hardware-in-the-loop (HIL) or software-in-the-loop (SIL) simulations, where the physical controller interacts with a model of the microgrid and its connected devices[16].

3.4. Mathematical formulation

COE formulation: the HOMER program can compute the cost of energy (COE) for an HRES[14]:

$$COE = \frac{C_{ann}}{L_{pri} + L_{deff} + E_{grs}} \tag{1}$$

where, L_{deff} = cumulative deferrable load demand, C_{ann} = net annual expense, L_{pri} = cumulative primary load demand, E_{grs} = quantity of sold energy to grid.

NPC formulation: Equation (2) may be used to determine NPC for the suggested system[14]:

$$C_{NPC} = \frac{C_{ann}}{CF(int, T_L)} \tag{2}$$

where, T_L = project lifespan, int = yearly rate of interest, $CF(.)$ = capital recovery factor.

Operating cost formulation: the operational cost of the proposed microgrid has been determined using th formula[17]:

$$
\begin{aligned}
&Operating\ Cost\\
&= \big(C_{invest}\ (PV) + C_{OM}\ (PV)\big)S_{PV} + \big(C_{invest}\ (wind) + C_{OM}\ (wind)\big)S_{wind}\\
&+ (C_{invest}\ (Diesel) + C_{OM}\ (Diesel))S_{Diesel} + (C_{invest}\ (battery)\\
&+ C_{OM}\ (battery))S_{battery} + (C_{invest}\ (converter) + C_{OM}\ (converter))S_{converter}\\
&+ C_{Loss}
\end{aligned} \tag{3}
$$

where, S_{PV}, S_{wind}, S_{Diesel}, $S_{Battery}$ and $S_{converter}$ are the respected optimum sizes of the components, C_{invest} = investment cost, C_{OM} = operation and maintenance cost, C_{Loss} = power loss cost. The whole methodological approach has been illustrated within a flow chart in **Figure 6**.

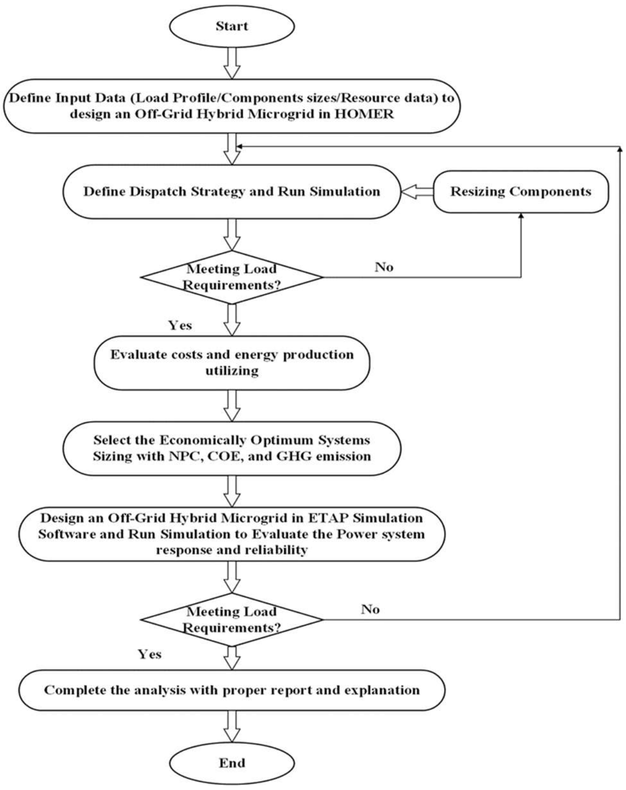


Figure 6. Flowchart illustration of the proposed work's entire workflow.

4. Results and discussions, optimal sizing, and techno-economic analysis

4.1. Expenses of the microgrids

Tables 2 and **3** provide information about the Chittagong and Faridpur microgrid expenses (e.g., NPC, COE operating costs, capital expenditures, and operational and maintenance costs), as well as some other aspects of the design for the microgrid. In designing the microgrid, 23.31 kW of maximum peak power and 165.59 kWh of daily power consumption were considered.

Table 2. Expenses of the Chittagong microgrid.

Dispatch tech	NPC (US$)	COE (US$/kWh)	Operation cost (US$)
Load following (LF)	$127,528.10	$0.1728	$2944.13
Cycle charging (CC)	$183,881.20	$0.2354	$4956.11
Combined dispatch (CD)	$158,518.90	$0.2030	$4291.95
Generator order (GO)	Insufficient	Insufficient	Insufficient
Predictive (PS)	$149,639.20	$0.1915	$4288.57

Table 3. Expenses of the Faridpur microgrid.

Dispatch tech.	Total NPC (US$)	Levelized COE (US$/kWh)	Operation cost (US$)
Load following (LF)	$149,287.30	$0.2030	$3530.34
Cycle charging (CC)	$205,919.10	$0.2637	$7009.38
Combined dispatch (CD)	$182,704.40	$0.2340	$4875.85
Generator order (GO)	Insufficient	Insufficient	Insufficient
Predictive (PS)	$170,216.30	$0.2180	$4,809.86

4.2. Emissions from the microgrids

In **Tables 4** and **5**, we can see various harmful gas emissions produced by the proposed microgrids, such as carbon dioxide and carbon monoxide.

Table 4. Emissions from the Chittagong microgrid.

Controller	CO_2 (kg/yr)	CO (kg/year)	Hydrocarbons (unburned) (kg/year)	Particulate matter (kg/year)	SO_2 (kg/year)	Oxides of nitrogen (kg/year)
Load following (LF)	2,746	17.1	0.755	0.103	6.72	16.1
Cycle charging (CC)	5,806	36.2	1.60	0.217	14.2	34.1
Combined dispatch (CD)	5,315	33.2	1.46	0.199	13.0	31.2
Generator order (GO)	Insufficient	Insufficient	Insufficient	Insufficient	Insufficient	Insufficient
Predictive (PS)	5,528	34.5	1.52	0.207	13.5	32.4

Table 5. Emissions from the Faridpur microgrid.

Controller	CO_2 (kg/year)	CO (kg/year)	Hydrocarbons (unburned) (kg/year)	Particulate matter (kg/year)	SO_2 (kg/year)	Oxides of nitrogen (kg/year)
Load following (LF)	3,256	20.3	0.895	0.122	7.97	19.1
Cycle charging (CC)	10,326	64.4	2.84	0.387	25.3	60.6
Combined dispatch (CD)	6,189	38.6	1.70	0.232	15.2	36.3
Generator order (GO)	Insufficient	Insufficient	Insufficient	Insufficient	Insufficient	Insufficient
Predictive (PS)	5,961	37.2	1.64	0.223	14.6	35.0

4.3. Optimum sizing of the microgrids

HOMER analysis results in **Tables 6** and **7** show the optimal microgrid components for the proposed microgrids.

Table 6. Optimum sizing of the Chittagong microgrid.

Dispatch strategies	Converter size (kW)	Wind (kW)	Battery (kWh)	PV (kW)	Diesel generator (kW)
Load following (LF)	12.7	23	100	37.8	2.00
Cycle charging (CC)	21.4	17	156	48.2	10.0
Combined dispatch (CD)	16.2	19	124	43.7	10.0
Generator order (GO)	Insufficient	Insufficient	Insufficient	Insufficient	Insufficient
Predictive (PS)	15.6	24	110	37.0	5.00

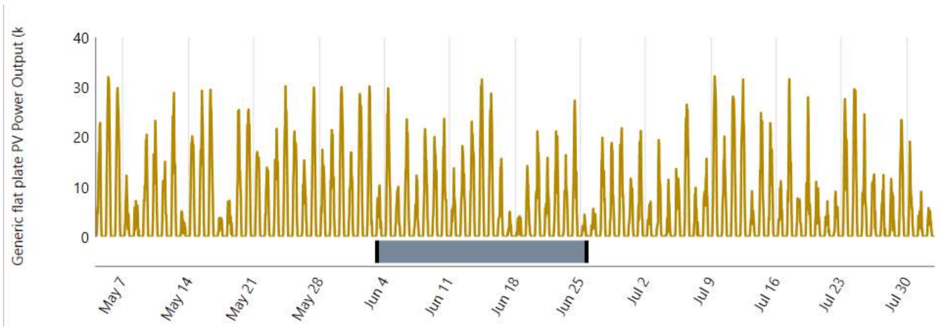
Table 7. Optimum sizing of the Faridpur microgrid.

Dispatch strategies	Converter size (kW)	Wind (kW)	Battery (kWh)	PV (kW)	Diesel generator (kW)
Load following (LF)	18.8	22.0	122	44.0	3.0
Cycle charging (CC)	21.6	Insufficient	155	59.5	14.0
Combined dispatch (CD)	16.2	26.0	130	52.7	12.0
Generator order (GO)	Insufficient	Insufficient	Insufficient	Insufficient	Insufficient
Predictive (PS)	16.7	24.0	129	44.8	5.00

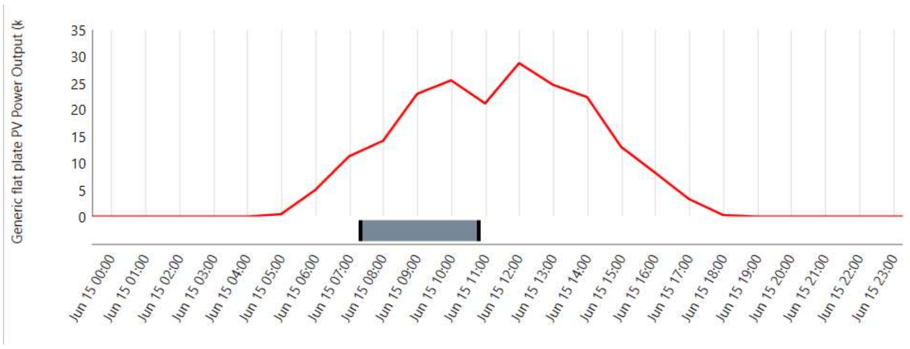
4.4. HOMER power output plots

4.4.1. Chittagong microgrid

In **Figure 7**, we can see the PV power output of peak months from May to July and the PV power output for a single day depending on the temperature and irradiation for the Chittagong microgrid. **Figure 8** displays the wind turbine power output of peak months from May to July.



(a) PV output (peak months).



(b) PV Output (single day).

Figure 7. PV power output for Chittagong microgrid for **(a)** peak months; **(b)** a single day in kW.

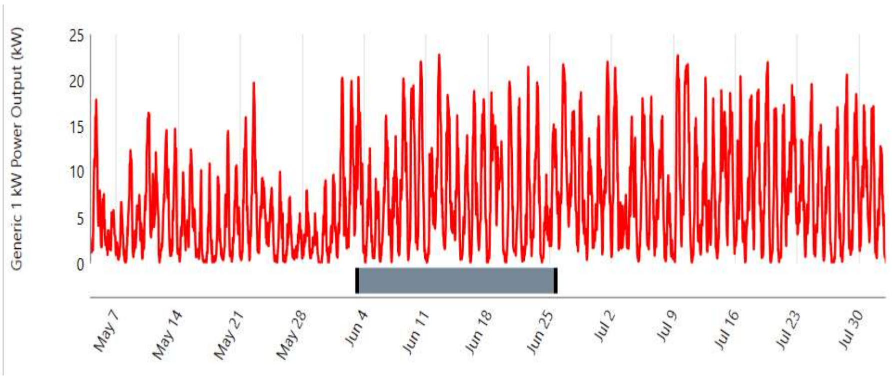
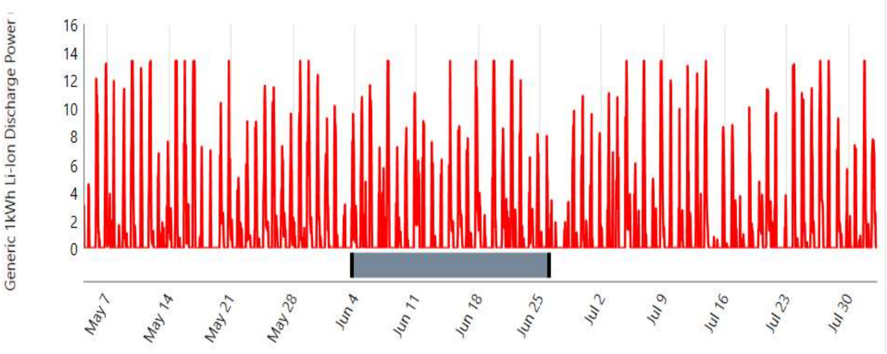
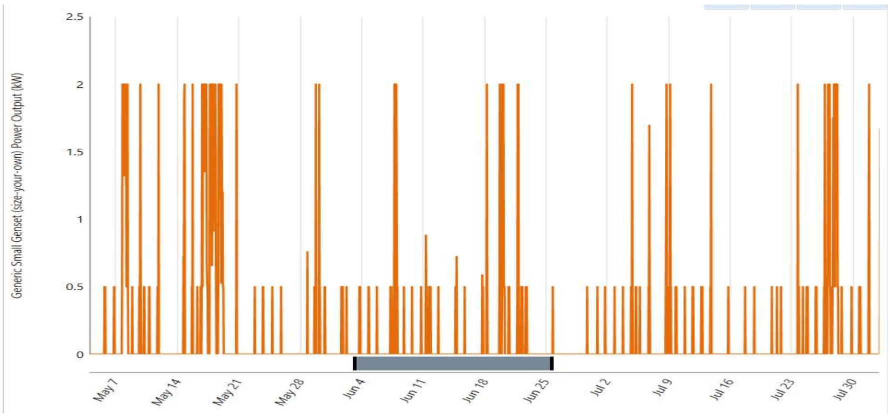


Figure 8. Wind turbine power output of peak months in kW.

Figure 9 shows the battery and diesel generator power output of peak months from May to July.



(a) Battery.

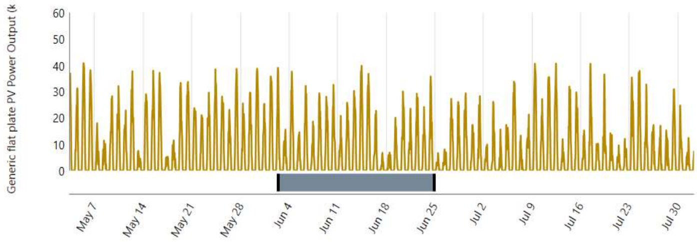


(b) Diesel generator.

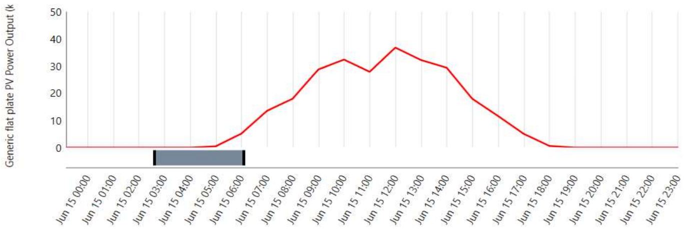
Figure 9. Power output of peak months in kW.

4.4.2. Faridpur microgrid

In **Figure 10**, we can see the PV power output of peak months from May to July and the PV power output for a single day depending on the temperature and irradiation for the Faridpur microgrid.



(a) Peak months.



(b) For a single day in kW.

Figure 10. PV power output.

Figure 11 shows the wind turbine power output of peak months from May to July.

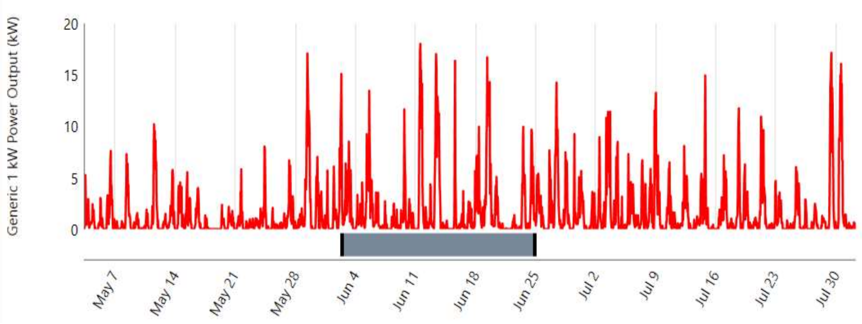


Figure 11. Wind turbine power output of peak months in kW.

Figures 12 and **13** show the storage and generator power output of peak months from May to July.

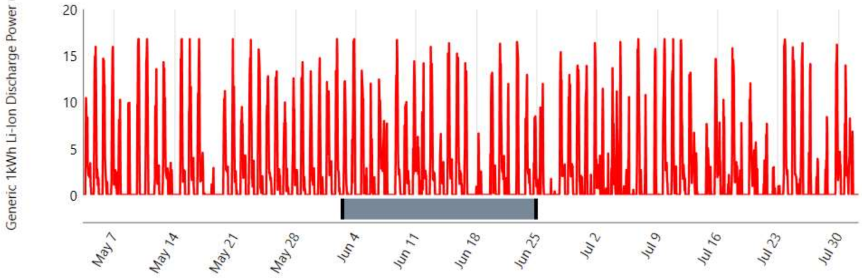


Figure 12. Battery power output of peak months in kW.

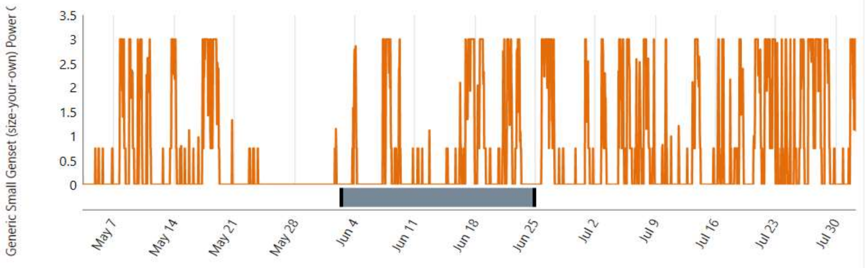


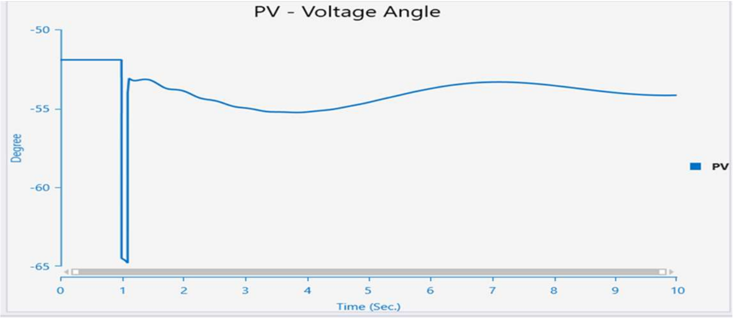
Figure 13. Diesel generator power output of peak months in kW.

4.5. Power system stability analysis

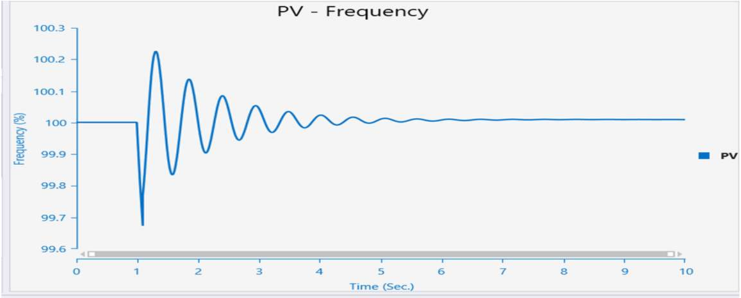
The ETAP software was utilized to assess the stability of the proposed microgrid systems. The HOMER-optimized microgrid was implemented in the ETAP microgrid models, and stability was analyzed by simulating a 3-phase short circuit fault at a bus and examining the system's recovery to a stable state after the fault was cleared. Further analysis of the results is discussed in subsequent sections. The output plot below illustrates the frequency, angle, and voltage response of the microgrid systems.

4.5.1. Chittagong microgrid

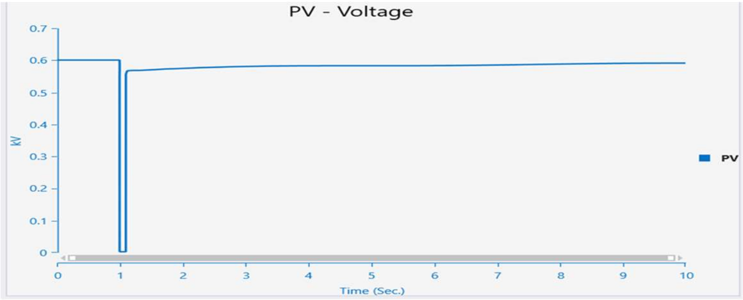
Figure 14 depicts the PV angle, frequency, and voltage stability, respectively. In these plots, we can observe that a fault was initiated at 1 s and withdrawn at 1.1 s. Upon clearing the fault, the system experiences some fluctuations before returning to a stable state.



(a) Voltage angle plot.



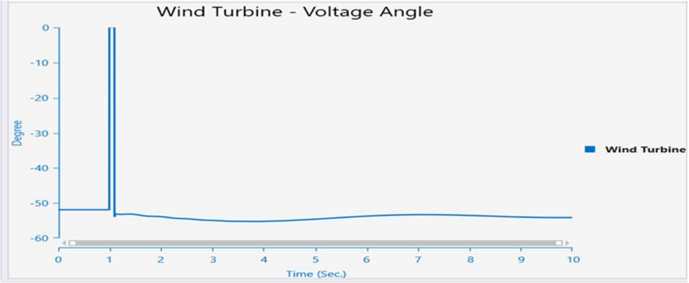
(b) Frequency plot.



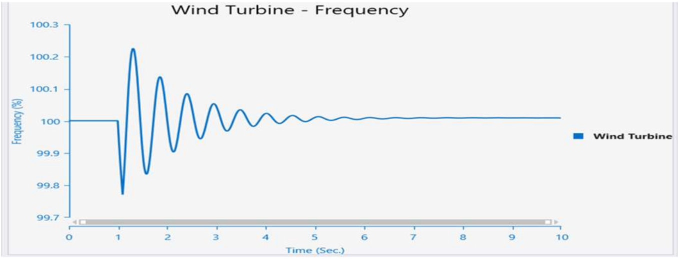
(c) Voltage plot.

Figure 14. PV performance for Chittagong microgrid.

Figure 15 shows the wind turbine angle, frequency, and voltage stability, respectively.

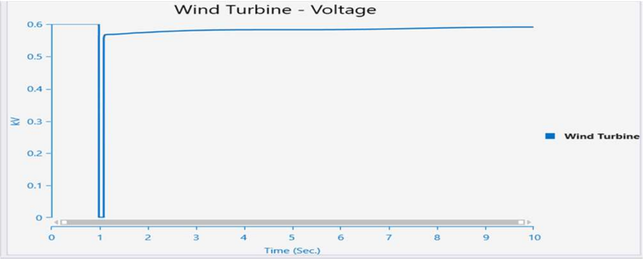


(a) Voltage angle plot.



(b) Frequency plot.

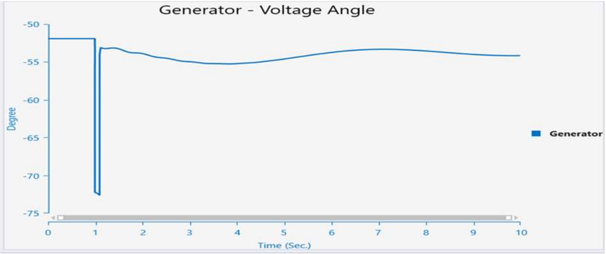
Figure 15. (*Continued*).



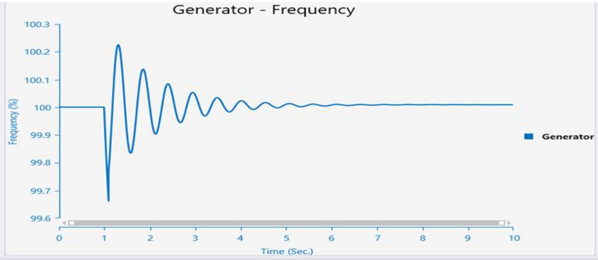
(c) Voltage plot.

Figure 15. Wind performance for Chittagong microgrid.

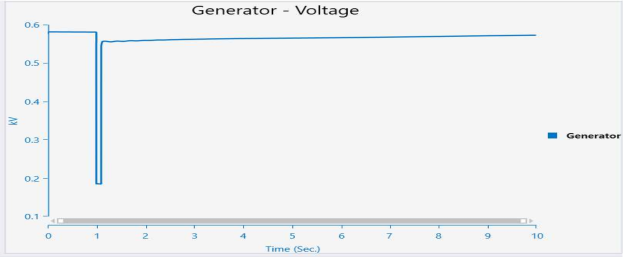
Figure 16 shows the diesel generator angle, frequency, and voltage stability, respectively.



(a) Voltage angle plot.



(b) Frequency plot.

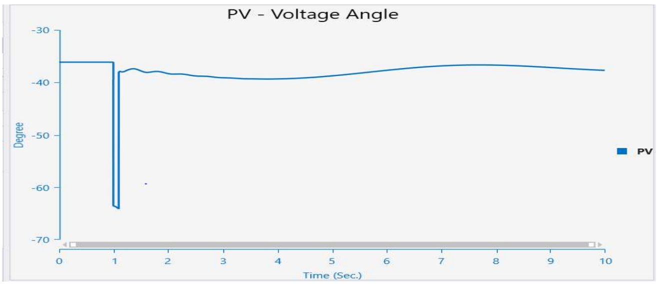


(c) Voltage plot.

Figure 16. Diesel generator performance for Chittagong microgrid.

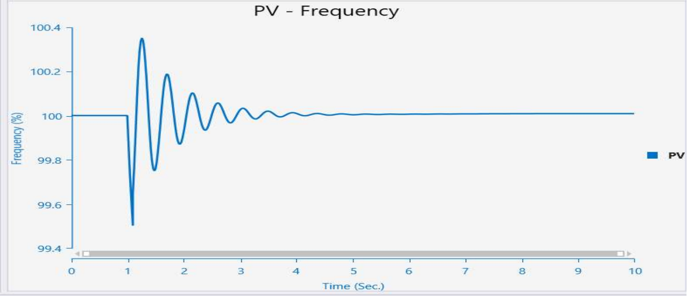
4.5.2. Faridpur microgrid

Figure 17 shows the PV angle, frequency, and voltage stability, respectively for the Faridpur microgrid.

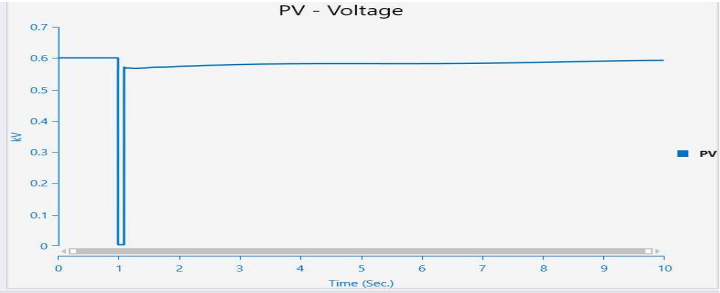


(a) Voltage angle plot.

Figure 17. (*Continued*).



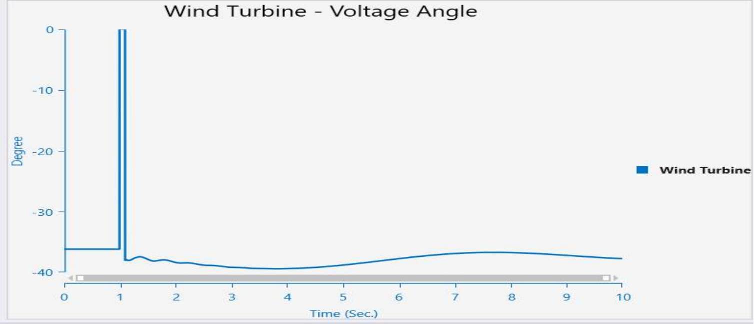
(b) Frequency plot.



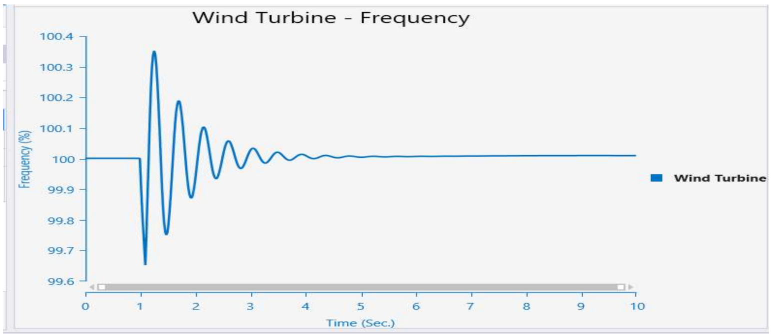
(c) Voltage plot.

Figure 17. PV performance for Faridpur microgrid.

Figure 18 demonstrates the wind turbine angle, frequency, and voltage stability, respectively, of the Faridpur microgrid.

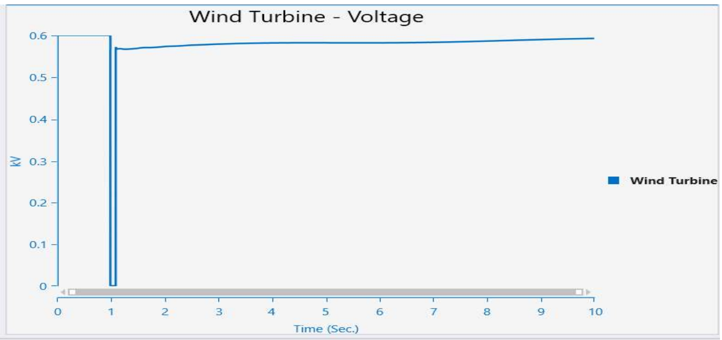


(a) Voltage angle plot.



(b) Frequency plot.

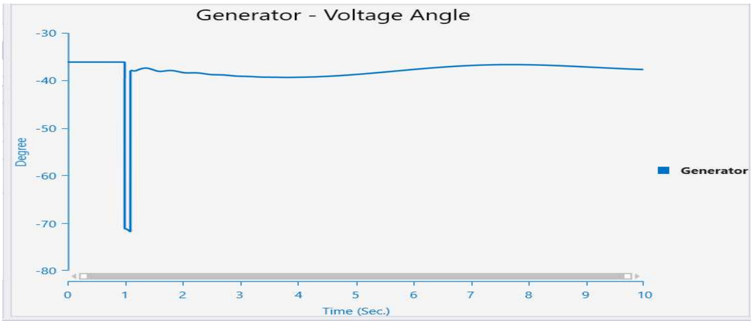
Figure 18. (*Continued*).



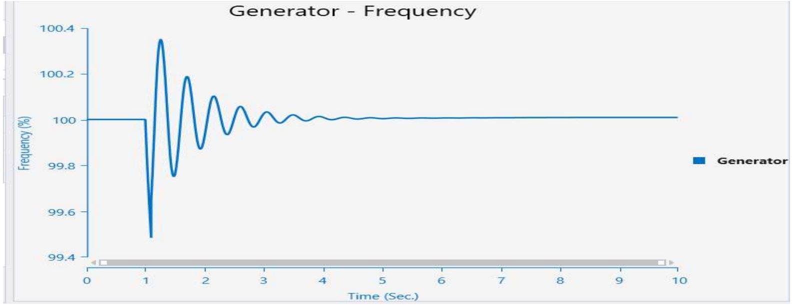
(c) Voltage plot.

Figure 18. Wind performance for Faridpur microgrid.

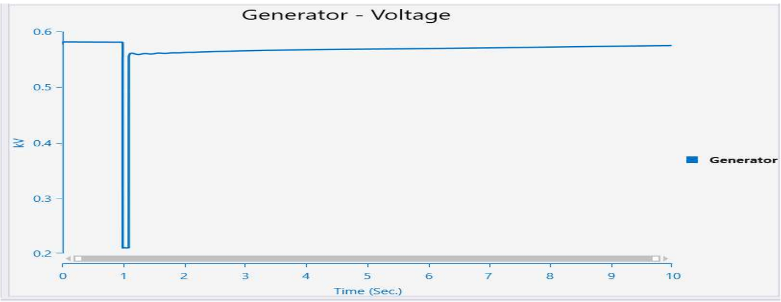
Figure 19 demonstrates the diesel generator angle, frequency, and voltage stability, respectively, of the Faridpur microgrid.



(a) Voltage angle plot.



(b) Frequency plot.



(c) Voltage plot.

Figure 19. Diesel generator performance for Chittagong microgrid.

Based on the results of this research, it has been demonstrated that the proposed microgrid has the feasibility and stability that are expected. Throughout the process, all of the possible responses have been found to be feasible, stable, and within an acceptable range.

5. Conclusions

This study examined various dispatch algorithms for an off-grid microgrid comprising a wind turbine, batteries, solar panels, and a diesel generator. Simulation results indicate that a load-following dispatch technique is the most suitable method for the proposed microgrid, based on the energy cost, CO_2 emissions, present costs, and microgrid frequency and voltage stability. In this scenario, the best net present cost, energy cost, and CO_2 formation were found to be $127,528 ($0.173 per kWh) and 2746 kg annually for Chittagong and $149,287.30 ($0.2030 per kWh) and 3256 kg annually for Faridpur. The proposed microgrid ensures an uninterrupted electricity supply for Chittagong and Faridpur. Its economic viability (optimal size and cost) and system stability (frequency, angle, and voltage stability) have been validated.

Author contributions

Conceptualization, AR, MHB and SAS; methodology, AR and SAS; software, AR, MHB and FI; validation, FI and AH; formal analysis, SI, MH, and SAA; investigation, AR, MHB and SAS; resources, SAS, FI and AH; data curation, AR and MHB; writing—original draft preparation, AR, MHB, SI, MH and SAA; writing—review and editing, AR, SAS and FI; visualization, AH and SAS; supervision, AH and SAS; project administration, AH, FI and SAS. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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