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Techno-Economic and Power System Optimization of a Renewable Rich Islanded Microgrid Considering Different Dispatch Strategies

MD. FATIN ISHRAQUE[1,2], SK. A. SHEZAN[2], M. M. RASHID[3], ANANTA BIJOY BHADRA[3], (Associate Member, IEEE), MD. ALAMGIR HOSSAIN[4], RIPON K. CHAKRABORTTY[4], (Member, IEEE), MICHAEL J. RYAN[4], (Senior Member, IEEE), SHAHRIAR RAHMAN FAHIM[5], (Member, IEEE), SUBRATA K. SARKER[6], AND SAJAL K. DAS[7]

[1]Department of Electrical, Electronic and Communication Engineering, Pabna University of Science and Technology, Pabna 6600, Bangladesh
[2]School of Engineering, RMIT University, Melbourne, VIC 3001, Australia
[3]Department of Electrical and Electronic Engineering, Rajshahi University of Engineering & Technology, Rajshahi 6204, Bangladesh
[4]Capability Systems Centre, School of Engineering and Information Technology, UNSW Canberra at ADFA, Campbell, ACT 2612, Australia
[5]Department of Electrical and Electronic Engineering, American International University-Bangladesh, Dhaka 1229, Bangladesh
[6]Department of Electrical and Electronic Engineering, Varendra University, Rajshahi 6204, Bangladesh
[7]Department of Mechatronic Engineering, Rajshahi University of Engineering & Technology, Rajshahi 6204, Bangladesh

Corresponding author: Subrata K. Sarker (subrata@vu.edu.bd)

ABSTRACT In this work, the evaluation of the design and optimization of proposed offgrid hybrid microgrid systems for different load dispatch strategies is presented by assessing the component sizes, system responses and different cost analyses of the proposed system. This study optimizes the sizing of the Barishal and Chattogram (two popular divisions in Bangladesh) hybrid microgrid systems consisting of wind turbine, storage unit, solar PV, diesel generator and a load profile of 27.31 kW for five dispatch techniques: (i) generator order, (ii) cycle charging, (iii) load following, (iv) HOMER predictive dispatch and (v) combined dispatch strategy. The considered microgrids are optimized for the least CO_2 gas emission, Net Present Cost, and Levelized Cost of Energy. The two microgrids are analyzed for the five dispatch techniques using HOMER software, and subsequently, the power system performance and feasibility study of the microgrids are performed in MATLAB Simulink. The results in this research provide a guideline to estimate different component sizes and probable costing for the optimal operation of the proposed microgrids under various load dispatch conditions. The simulation results suggest that 'Load Following' is the best dispatch strategy for the proposed microgrids having a stable power system response with the lowest net present cost, levelized cost of energy, operating cost, and CO_2 emission rate. Additionally, the combined dispatch strategy is determined to be the worst dispatch technique for the proposed off-grid hybrid microgrid design having the maximum levelized cost of energy, net present cost, operating cost and CO_2 emission.

INDEX TERMS Microgrid, dispatch strategies, optimization, techno-economic analysis, power system performance.

I. INTRODUCTION

The demand for power is increasing rapidly due to globalization and industrialization. As a result, the dependency on various power sources is increasing which increases carbon emissions and associated costs, resulting in a focus by many countries on investment in alternative sources of energy. Renewable energy solutions, such as solar and wind, are particularly attractive as fossil fuels diminish and, in the meantime, their consumption results in the emission of

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poisonous gases. To introduce these distributed renewable resources into the power system network, microgrids (MG) are a feasible and highly effective solution [1]–[3], particularly since the extension of the conventional power grid often becomes more costly than setting up a MG for a remote offgrid location [4]. The effectiveness of MGs, have attracted several researchers to the topic [5]–[7], [9], [10], [14] recently. MGs mainly contain distributed renewable generation sources like wind turbines, fuel cells and photo voltaic (PV) cells that integrate different sources and loads like light emitting diodes (LED) in the system. Hybrid alternating current (AC)/ direct current (DC) MGs contain both DC and AC buses which can integrate both DC and AC sources and loads in the network [10]. To introduce these sources with conventional power sources, an appropriate energy management system (EMS) is needed [11]. An EMS-based multi-agent system (MAS) is conceptualized in [12] where a hybrid MG consisting of solar PV and hydro energy sources for high altitude using virtual bidding (VBD) and an optimal dispatch for the distributed generators is obtained. Although a control strategy is developed here for a MG, but no optimization or dispatch strategy was considered.

Solar and wind energy oriented standalone hybrid MGs can provide a better solution for the decentralized and remote distribution of electrical power. However, such operation is challenging due to the intermittent nature of the solar and wind energy resources [10] which can cause some uncertainty issues in a standalone MG. Because of the significant deviation in both power consumption and generation, the reliability of the power system has always been a vital issue for a standalone renewable MG [13]. Moreover, frequency and voltage fluctuation can occur because of the rapid and sudden changes of the power consumption in the distribution system that directs to system instability [14].

In MGs, electrical power is generated and distributed in a localized way. Distributed power stations produce power for a localized area. The insertion of different distributed power generators has an important contribution to the power system. Thus, the need for efficient methods to maintain the generators and loads has also increased [15]. It is therefore critical for a system designer to make sure that the loads are being reliably satisfied by the generators. A ''dispatch strategy'' is the part of the control algorithm of the system that deals with the flow of energy within the system [4]. The dispatch strategy has effect on the overall system cost and guides in designing a more economic and efficient system. In MGs, economic dispatch (ED) is used as a guideline to ensure economic and safe operation of the MG [16]. ED ensures the repletion of the demand at a reduced cost by scheduling the output of the predefined generation units and satisfying the system and all generation units' equality and inequality constraints [17]. An efficient ED technique can save an ample amount of renewable resource consumption and money and can reduce the emission of greenhouse gases significantly [18].

Assessment of the dispatch methodologies and optimization algorithms for offgrid MG draws more research interest for renewable energy management systems. In recent years, due to the high efficiency, MG along with ED has been an appealing topic among researchers [19], [20]. ED-related problems can be solved by either a centralized control technique or a distributed control technique. A bidirectional communication link is required for centralized control between the centralized controller and all the generator units which, in turn, increases communication complexity, cost and cyber-attack risk. On the other hand, distributed control uses distributed controllers which control only a specific area offering simpler control and communication network [21]. In [22], a novel distributed control theory was developed for the solution of ED problems based on a consensus algorithm. This algorithm allowed the generators to learn the mismatch between demand and generation. This assumed mismatch data was sent to each generator and thus the amount of power generation was adjusted to compensate the demand-generation mismatch.

At present, several theories have been introduced to solve ED related problems. Deterministic methods for ED problems are proposed in [23] but such approaches are not efficient for complex systems such as large-scale renewable-driven systems (e.g., battery charging and discharging scheduling, adjusting to uncertainty in solar and wind energy resources, generator back-up synchronization, considering dynamic loads), as they consider renewable sources as negative loads and they cannot take the uncertain character of the renewable energy sources into account [24]. In [16], a dynamic ED model was proposed for an AC/DC hybrid MG having a target of regular operating cost reduction.

Distributed economic alternative dispatch strategies for designing an offgrid MG was proposed in [26]. The multi-agent system (MAS) based energy management system considering real-time power dispatch techniques was reported in [27]. In [29], a robust energy distribution plan was implemented with the dispersed ED strategy for a MG to maintain the high renewable energy penetration. A dynamic active power dispatch strategy with a hierarchical model predictive controller for the wind-based hybrid energy system was proposed by Wen *et al.* [30] to improve the system stability of the network. The authors in [31] presented a technologically advanced dispatch model for the islanded MG to tune the system frequency within the acceptable range, but no voltage response analysis was considered in the work. Researchers demonstrated an advanced optimal dispatch strategy with the distributed technology for the unbalanced three-phase islanded MG in [32] with no comparative dispatch strategy analysis. In [40], a dispatch strategy based hybrid renewable MG design and optimization is done considering four different locations of Northern Bangladesh. In this study, both the power system response and techno economic analysis is considered and best and worst dispatch strategy for the proposed locations have been determined by analysis.

From the literature study, it is quite evident that none of the existing studies to the best knowledge of the authors, considered a techno-economic analysis (e.g., optimal sizing, costing and emission) considering both the power system response of different MG components and various dispatch strategies for the proposed locations of Barihal and Chattogram (two southern divisions of Bangladesh). In [40], the authors have taken four northern divisional areas of Bangladesh into consideration. The concerned areas have a lower renewable resource profile because of their geographical location and the frequency response of the MGs are not much smooth. So a research gap exists in this concerned area which is being filled up in this research work by considering a more renewable rich area of Barishal and Chattogram, which are also commercially very much important for the country. In this present work, the response of MG frequency is also found better than the mentioned work as better renewable resource is available in the present locations.

Bangladesh has enough wind and solar energy resources [25]. The main purpose of this research work is to design and evaluate solar PV-wind turbine-diesel generator-battery based standalone hybrid MG along with the already available distribution network for the Barishal and Chattogram divisions of Bangladesh. The preliminary design of the MGs were optimized using HOMER pro. Then, for the proposed MGs, the system responses were analyzed using the Matlab/Simulink platform for five selected dispatch strategies. The core contributions of this work are three-fold:(to the best of the authors' knowledge, such a study does not exist in the literature)

- first, utilizing HOMER MG software platform, to determine the most suitable MG component combination for the optimal operation of the MG which will ensure the lowest Net Present Cost (NPC), Levelized Cost of Energy (LCOE) and CO_2 emissions for the proposed MGs for five dispatch techniques;
- second, ensuring stable and feasible operation of the designed and optimized MG by conducting a power system performances (frequency and voltage responses of the optimized MG) analysis using Simulink; and
- third, finding the most suitable dispatch strategy for the proposed MGs on the basis of minimum harmful gas emissions, different costs and best power system responses.

The remainder of the research paper is organized as follows. The modelling of a standalone MG along with the system equipment and power conversion process is presented in section II. The next section presents methodology for this research work with necessary formulation. The result of this research work along with relevant discussion and findings is presented in Section IV. Section V finally concludes the research work with a summary of the core contribution of this work with the findings of this research.

II. MODELLING OF AN ISLANDED MICROGRID

In this study, for two divisional area in Bangladesh, Barishal and Chattogram have been considered and two hybrid MG systems for the two locations have been designed and optimized. Barishal is located in the south-central part of Bangladesh and Chattogram division is located in the south-eastern part of the country. Both of the locations are gifted with sufficient renewable sources such as solar irradiation and wind speed, so off-grid hybrid MGs in these areas can help reduce the energy problems of the country. As the divisions are being situated in the same territory of the country, having similar meteorological conditions, the study can provide a complete idea of hybrid MG implementation in that part of the country. A simple block representation of proposed MG along with the MG equipment and their mutual relations is presented in Fig. 1. The MG comprises converter module, wind turbine (WT), diesel generator (DG) solar panels, storage units, and different loads. Direct current DC power is provided in the MG by battery storage units and solar PV modules. Before being connected to the AC bus bar, the DC supply is converted to alternating current (AC) using inverter (DC/AC converters). In the MG system, AC power is directly being generated by DG and WT. Thus it is directly connected to the AC bus bar only after a simple voltage level conversion. The AC loads are fed from the AC bus bar and DC loads are directly fed from the DC bus. Voltage source controller (VSC) has been inaugurated for the bidirectional AC/DC converter [31].

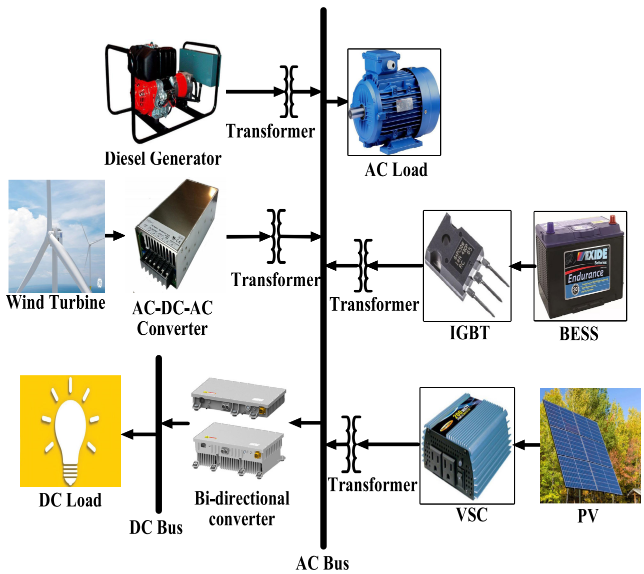


FIGURE 1. A schematic diagram of the proposed hybrid microgrid.

III. METHODOLOGY

In this section the methodology of this research work is demonstrated in two subsections comprising several sub subsections. In the first subsection, dispatch strategy and the various types are discussed and the next subsection formulates the problem.

A. DISPATCH STRATEGIES

A dispatch strategy is a bunch of rules used for the control of the generator and the storage bank operation whenever there is insufficient renewable energy to supply the load [31]. In this research, five different dispatch techniques: (i) combined dispatch (CD), (ii) load following (LF), (iii) generator order (GO), (iv) HOMER Predictive Dispatch (PS) strategy, and v) cycle charging (CC) are implemented for optimization. In LF strategy, as a generator is needed, enough capacity is delivered to satisfy the primary load such that the load demand should have been fulfilled by renewable resources to keep the system stable and feasible [32]. The CC dispatch technique operates the generator to the full limit at whatever point it is required and any surplus power is utilized to charge the storage device. CC strategy is mostly ideal in systems having practically zero renewable energy resources [32]. In GO strategy, a predefined order of generator combinations fulfils the demand by accepting the generator combination that first meets the operating capacity. In GO, the usage of battery unit is only permissible in special circumstances. The CD dispatch strategy abstains from the future net-load assumption using the present net load evaluation to determine whether to charge the storage devices using the generator. When the load demand is low, the CD dispatch technique abstains from using of the generator and chooses the least costly optimal combination of the components to decide whether to choose the LF or CC strategy in every time step [33]. In the HOMER PS dispatch strategy, the upcoming probable electric and thermal load demand and the availability of the upcoming resource (solar irradiation and wind speed) is already known by prediction. With the use of this technique, system's overall operating cost can be reduced [41].

The influence of back-up generator and renewable resources on generation of electrical power according to the five different dispatch techniques for the proposed hybrid MG is shown in Fig. 2. That analysis shows that the GO has the best impact on the back-up generator and LF strategy has the highest influence on renewable resources. Dispatch strategies guide optimal sizing and power management criteria in a standalone MG. In all five dispatch strategies, the utilization strategy of the diesel generator back-up is very much significant when the availability of renewable resources and load demand are subject to sudden changes.

B. PROBLEM FORMULATION

1) OBJECTIVE FUNCTION

The main objective of economic dispatch strategies implementation in case of MG optimization is to minimize the MGs cost for all nodes in a sustainable way [26]. Traditional objective function in a single quadratic function can be used to approximately represent the objective function of the traditional ED problems mentioned below [18], [34]–[36].

$$\text{min cost} = \sum_{j=1}^{N_{gen}} F_j(P_j) \tag{1}$$

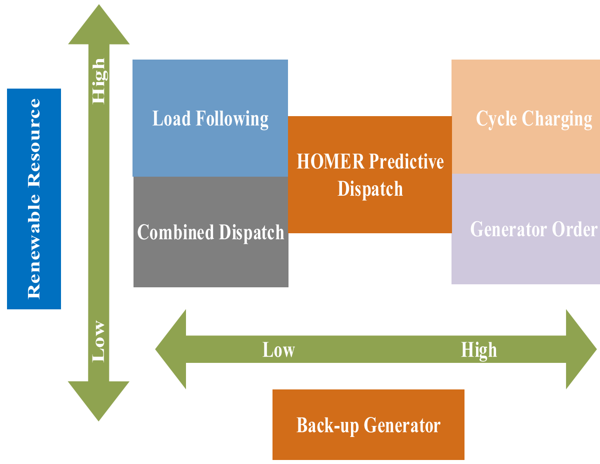


FIGURE 2. Impact of diesel generator and renewable resources according to the five dispatch techniques for hybrid microgrid.

where, $F_j(P_j) = a_j + b_jP_j + c_jP_j^2$. Here, a_j, b_j, and c_j are the j^{th} generator's fuel cost coefficients. The term N_{gen} indicates the total number of generators, P_j is the power output of the j^{th} generator unit measured in MW and $F_j(P_j)$ is the fuel cost function of the j^{th} generator in dollars per hour.

2) EQUALITY AND INEQUALITY CONSTRAINTS

The problems relating economic dispatch should satisfy the constraints below.

a: ACTIVE POWER BALANCE CONSTRAINT

The total power generation should be equal to the total loss in transmission network (P_{loss}) plus the total demand of the system (P_{demand}) [18]. Then,

$$\sum_{j=1}^{N_{gen}} F_j(P_j) = P_{demand} + P_{loss}. \tag{2}$$

where, P_{loss} can be evaluated by using B coefficients as,

$$P_{loss} = \sum_{i=1}^{N_{gen}} \sum_{j=1}^{N_{gen}} P_iB_{ij}P_j + \sum_{i=1}^{N_{gen}} P_iB_{oi} + B_{oo} \tag{3}$$

In eq. (3), B_{ij}, B_{oi} and B_{oo} are the loss coefficients.

b: GENERATION CAPACITY CONSTRAINTS

The power $P_{gen(i)}$ generated from the i^{th} source have to be greater than or equal to the minimum limit of generation $P_{gen.min(i)}$ and must be less than or equal to the maximum capacity of the source $P_{gen.max(i)}$ [18], [34], [36]. Now,

$$P_{gen.min(i)} \leq P_{gen(i)} \leq P_{gen.max(i)} \tag{4}$$

The combined total power losses (P_{losses}), total load demand (P_{demand}) and storage power ($P_{storage}$) should be equal to the total power generation [18].

$$\Sigma_i P_{gen(i)} = P_{demand} + P_{losses} + P_{storage} \tag{5}$$

c: OPTIMAL SIZING AND COST FUNCTION REDUCTION

The optimization problems (equations) required to be solved to get the optimal sizes and the required number of power generation units [37] are mentioned below. Here, f_1, f_2, f_3 are weights to reveal the significance of the corresponding component and a, b, c, d are corresponding sizes of different equipment in the system. Corresponding component's levelized cost of energy is denoted by LCOE, corresponding component's net present cost is denoted by NPC and GHG, and e.CO_2 quantifies the gas emission from the Diesel Generator unit. Here, subscript PV = solar photo voltaic cell, WT = wind turbine, DG = diesel generator, BT = battery unit and Total = summation of individual values.

$$\frac{min}{a,b,c,d,f_1\epsilon N^0}(f_1(a.LCOE_{PV}+b.LCOE_{WT}+c.LCOE_{DG}+d.LCOE_{BT})) \quad (6)$$

$$\frac{min}{a,b,c,d,f_2\epsilon N^0}(f_2(a.NPC_{PV}+b.NPC_{WT}+c.NPC_{DG}+d.NPC_{BT})) \quad (7)$$

$$\frac{min}{e,f_3\epsilon N^0}(f_3(e.CO2_{DG})) \quad (8)$$

$$\frac{min}{f_1,f_2,f_3\epsilon N^0}(f_1LCOE_{Total}+f_2NPC_{Total}+f_3GHG_{Total}) \quad (9)$$

d: CALCULATION OF LCOE

The levelized cost of energy (LCOE) for the proposed hybrid system can be evaluated in HOMER using the formula below [38].

$$LCOE=\frac{C_{annual}}{L_{Primary}+L_d+E_{gs}}. \quad (10)$$

Here, C_{annual} = annualized total cost, E_{gs} = total energy sold to the conventional grid per year, $L_{Primary}$ = total primary load, and L_d = total deferrable load.

e: CALCULATION OF NPC

The Net Present Cost (NPC), C_{NPC} of the proposed hybrid microgrid can be evaluated using the following formula [38].

$$C_{NPC}=\frac{C_{annual}}{CRF(i,T_{project})}. \quad (11)$$

In (11), i = interest rate, $T_{project}$ = lifetime of the project, $CRF(.)$ = capital recovery factor, and C_{annual} = annualized total cost.

f: CO_2 EMISSION CALCULATION

CO_2 emissions from the microgrid can be quantified as follows [38],

$$e.CO_2=3.667\times m_{fuel}\times FHV\times CEF_{fuel}\times X_c. \quad (12)$$

Here, FHV = fuel heating value in MJ/L, e.CO_2 = CO_2 emissions, m_{fuel} = amount of fuel in liters, CEF_{fuel} = carbon emission factor measured in ton carbon/TJ, and X_c = oxidized carbon fraction. Another part should be considered is that 3.667g of CO_2 contains 1g of carbon.

g: ECONOMIC DISPATCH

The optimization problem can be stated by formulating the economic dispatch problem through the use of following equations [39].

$$E_{P_{G_i}}^{min\Sigma_i C_{G_i}P_{G_i}} \quad (13)$$

Subject to:

$$P_{G_i}^{minG_{iG_i}^{max}} \quad (14)$$

$$\Sigma_i P_{G_i}=P_D \quad (15)$$

The power generation cost is decreased by utilizing the objective function in (13), where C_{G_i} is the cost (marginal) of each generator unit and P_{G_i} is the quantity of it's power generation. The term in eq. (14) requires that all the generators' maximum or minimum limits must not be violated, while eq. (15) stipulates that total generation of power must be equal to the demand of electricity P_D.

h: FREQUENCY STABILIZATION

A stable MG frequency can be ensured by keeping frequency nadir (fnadir) and the post–fault rate of change of frequency (RoCoF) within their precarious inceptions as below [30]:

$$|RoCoF|\leq RoCoF^{max}, f^{min}\leq f^{nadir}\leq f^{max} \quad (16)$$

The frequency response of the hybrid microgrid can be administered by the swing equation below,

$$2H\frac{d\Delta f(t)}{dt}=\sum_i \Delta P_{Gi}(t)+\sum_j \Delta P_{Sj}(t)-D\Delta f(t)-P_M. \quad (17)$$

Here H = inertia of the MG, D = damping factor of load demand and $\Delta f(t)$ = deviation in frequency. $\Delta P_{Gi}(t)$ and $\Delta P_{Sj}(t)$ are respectively the power variations of synchronous unit i and battery storage j and P_M denotes the power imbalance in MG.

i: VOLTAGE STABILIZATION

An appropriate optimal function can be utilized to keep the voltage profile constant. The following equation can be utilized in this case [39].

$$min\sum_i(V_i-V_{setpoint,i})^2 \quad (18)$$

here, particular node voltage V_i and reference node voltage is $V_{setpoint,i}$. For this case, the objective function minimizes both the negative and positive fluctuations of the voltage output from the intended set-point or reference value.

Fig. 3 demonstrates a simplified line diagram of the proposed integrated hybrid MG system (IHMS) for four divisional area of Southern Bangladesh considered in the Matlab/ Simulink analysis. The model considered in Simulink consists of diesel generator, solar PV module, battery storage

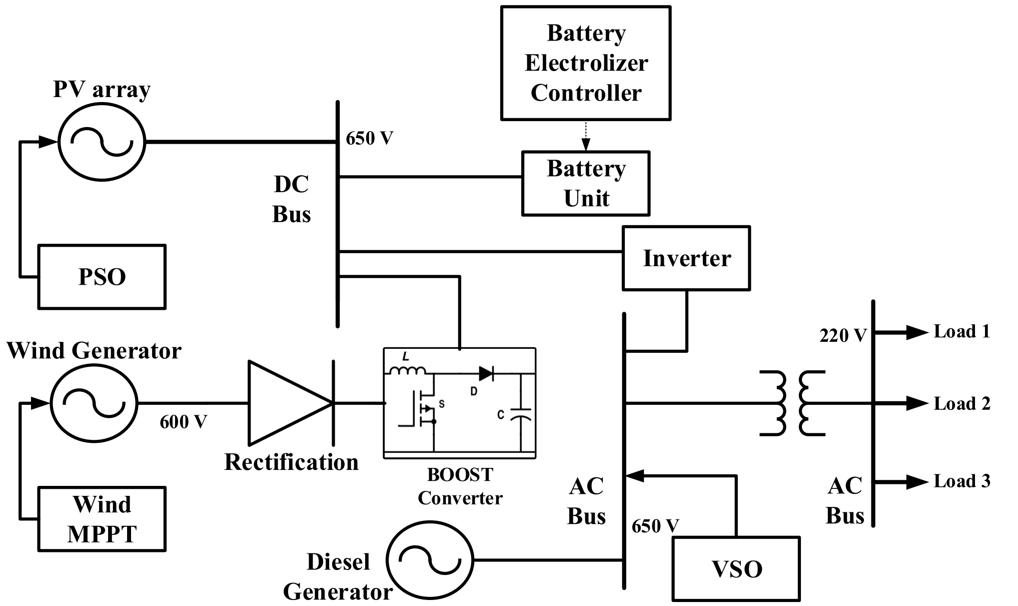


FIGURE 3. Simulink oriented single line diagram of proposed microgrid system.

TABLE 1. NPC, CO_2 emission and COE variation from HOMER study for different dispatch strategies for Barishal and Chattogram.

Barishal				
Dispatch Strategies	NPC (USD)	COE (USD/kWh)	Operating Cost (USD/year)	CO_2 Emission (kg/year)
Cycle Charging (CC)	303,723	0.389	19,024	38,716
Combined Dispatch (CD)	410,877	0.526	15,490	18,310
Generator Order (GO)	193,616	0.267	3,377	0
Load Following (LF)	163,316	0.223	3,854	3,416
Predictive Strategy (PS)	207,831	0.266	10,598	19,662
Chattogram				
Dispatch Strategies	NPC (USD)	COE (USD/kWh)	Operating Cost (USD/year)	CO_2 Emission (kg/year)
Cycle Charging (CC)	312,144	0.400	19,454	39,431
Combined Dispatch (CD)	363,015	0.465	15,893	23,651
Generator Order (GO)	186,209	0.256	3,182	0
Load Following (LF)	160,360	0.219	3,752	3,297
Predictive Strategy (PS)	206,301	0.264	10,627	19,723

system, wind turbine, different controllers, loads and converters, as shown in Fig. 3. In Fig. 4 the complete flow chart of the design, optimization and evaluation process is shown for the proposed IHMS. The process of optimization begins with module selection and input of various parameters like load profile, component sizes and resource data followed by the economic and technical constraints, load profile evaluation and then defining the dispatch strategies in HOMER platform. If the required load demand is fulfilled, then the costing of the system is evaluated. If the load demand is not fulfilled, then the components are resized and the simulation is repeated until the load requirements are fulfilled. According to the various costs and emission from the MG, the optimum MG design is chosen and then the optimal sizes obtained from the simulation are categorized and implemented for the power system performance analysis to check for the technical validity of the designed model using Matlab/Simulink. According to the performance in both techno-economic and power system aspect, the best and worst MG design with respect to dispatch strategy is chosen.

IV. RESULTS AND DISCUSSION

This section analyzes the performance of the proposed MG systems in Barishal and Chattogram division. First, a study to explore the design of an optimal size MG system for two-division is exposed and then the voltage and frequency responses of that MG are described through the use of various dispatch strategies. Accordingly, a dedicated comparison is also provided in this section to explore the best performance of MG system. The details study of these experiment is done in the following section.

A. OPTIMAL SIZING OF THE PROPOSED MICROGRID

Table 1 reports a comparative study on basis of proposed MG's CO_2 emissions, COE and NPC among the five different dispatch techniques for the two divisions according to HOMER simulation. This comparison is demonstrated in Fig. 5 in a normalized fashion for both the divisions. From which, an idea of comparative analysis of the emissions and different costs for different dispatch strategies can be obtained. The LF dispatch technique has the lowest LCOE,

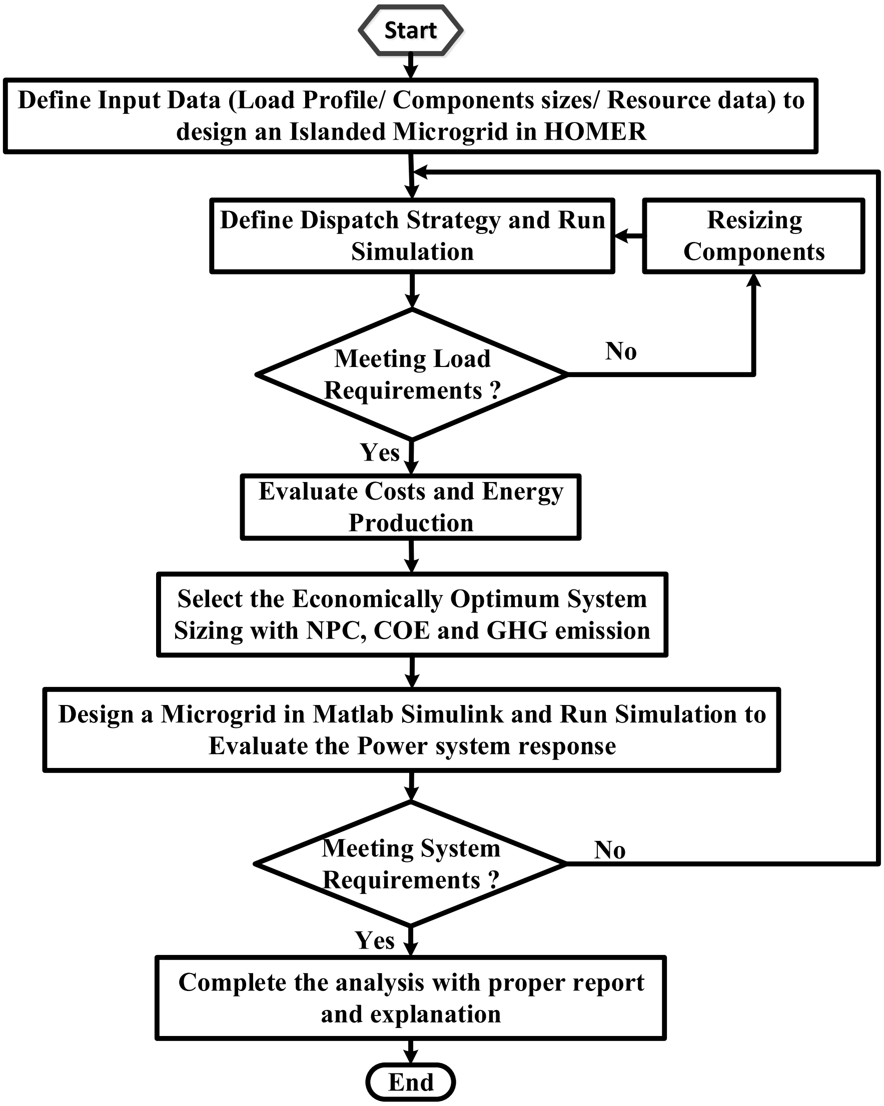


FIGURE 4. Complete system flow diagram for the design, optimization and evaluation process of the proposed microgrids.

NPC and CO_2 emission of 0.219 \$/kWh, 160,360\$ and 3,297 kg/year, respectively and the CD dispatch strategy has the highest of 0.526 \$/kWh, 410,877\$ and 18,310 kg/year, respectively for Chattogram and Barishal. The reason behind the lower costing of the LF strategy is that, as discussed above, LF satisfies the primary load first and lower priority is given to storage devices and deferrable loads and only feeds them if the renewable energy generation is considerably in excess to the need. The CD strategy on the other hand chooses between CC and LF and most often selects CC which gives priority on charging the battery unit first and then feds the dedicated primary load demand. Thus the costing becomes higher.

Accordingly, for the optimum operation of the MG, the optimized sizing of different MG components (i.e. diesel generator, solar PV, battery, converter and wind turbine) found from HOMER simulation result analysis, are shown in Table 2. On the contrary, for Simulink study, all the HOMER provided component sizes in Table 2, didn't always give stable and feasible power system performance. For this reason, Table 2 results have been re calibrated on a 'trial and error' basis to get stable and feasible voltage and frequency response in Simulink MG model analysis and the modified sizes of different MG components are shown in Table 3. Here, 'stable' refers to a response within allowable limit and 'feasible' refers to practically implementable. Thus, the HOMER simulation predicted optimized components sizes in Table 2 have been modified wherever necessary in Table 3 for real-time power system performance analysis in Simulink. Fig. 6 and Fig. 7 respectively show the optimum sizes of different MG components used in designing Barishal and Chattogram MG found from HOMER and Simulink in a

TABLE 2. Optimum sizes of different components of proposed microgrid from HOMER study.

Dispatch Strategies	PV (kW)	Wind (kW)	DG (kW)	Battery (kWh)	Converter (kW)
Barishal					
CC	10	1	8	132	14.9
CD	30	10	12	538	27.1
GO	75	1	1	207	39.4
LF	65	1	3	142	14.2
PS	30	1	7	112	14.6
Chattogram					
CC	10	1	8	139	17.5
CD	25	8	12	388	21.9
GO	75	1	1	194	36.1
LF	65	1	3	135	15.7
PS	30	1	7	106	14.2

TABLE 3. Optimum sizes of different components of proposed microgrid from simulink study.

Dispatch Strategies	PV (kW)	Wind (kW)	DG (kW)	Battery (kWh)	Converter (kW)
Barishal					
CC	10	1	8	132	14.9
CD	30	10	9	210	27.1
GO	75	1	1	194	39.4
LF	65	5	8	638.7	14.2
PS	30	1	7	112	14.6
Chattogram					
CC	10	1	8	132	17.5
CD	25	8	12	120	21.9
GO	75	1	1	194	36.1
LF	65	5	8	638.7	15.7
PS	30	1	7	110.799	14.2

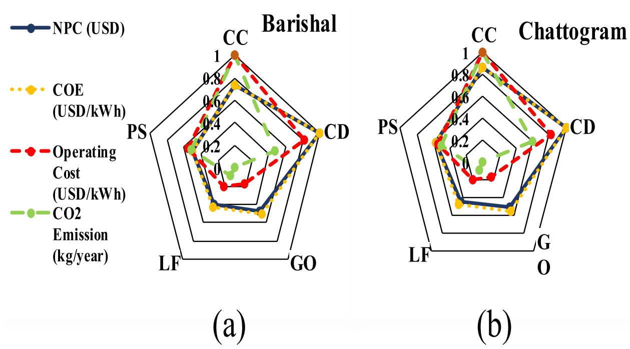


FIGURE 5. Various costs using different dispatch strategies (normalized) for (a) Barishal division and (b) Chattogram division.

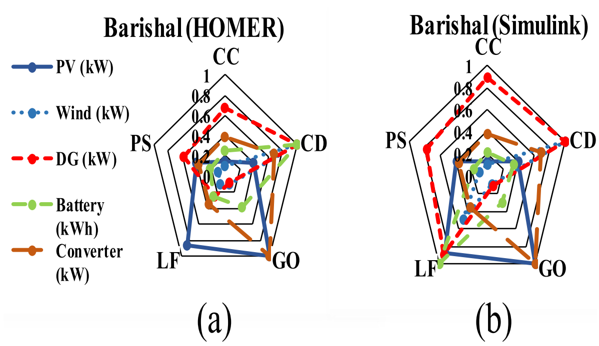


FIGURE 6. Optimum Sizes for Barishal division using (a) HOMER (normalized) (b) MATLAB simulink (normalized).

normalized (per unit) way. From the figures it can be seen that, for the optimized operation of the MGs, the required component sizes vary along with the various dispatch strategies. The size of PV is largest for GO strategy for both the MGs and lowest for CC strategy. It is also evident from the figures that the component sizes obtained in the HOMER analysis is not always suitable for the MGs stable operation and thus can be observed in the Fig. (b) of Fig. 6 and Fig. 7.

B. POWER SYSTEM RESPONSES FOR VARIOUS DISPATCH TECHNIQUES

In this work, power system performance refers to "within considerable limit" and stable frequency and voltage responses found from Simulink study. Various components sizes shown in Table 3 have been utilized to form the Simulink MG model presented in Fig. 3 and accordingly by simulation, the responses of the system have been observed and their voltage and frequency responses are demonstrated in the following section.

1) VOLTAGE RESPONSE FOR VARIOUS DISPATCH STRATEGIES

The responses for voltage for different system components (i.e., battery voltage, solar PV voltage, load voltage, wind turbine output voltage and diesel-generator output voltage)

TABLE 4. Range of stable voltage for various sources using different dispatch strategies.

Barishal					
Dispatch Strategies	PV Voltage (V)	Wind Voltage (V)	Peak to Peak DG Voltage (V)	Battery Voltage (V)	Peak to Peak Load Voltage (V)
Cycle Charging	600-650 V	440-500 V	1000 V	323-323.5 V	400 V
Combined Dispatch	600-650 V	440-500 V	1000 V	323.5-323.8 V	400 V
Generator Order	630-660 V	440-500 V	1000 V	324.3-324.5 V	400 V
Load Following	620-660 V	440-500 V	1000 V	324 V	400 V
Predictive Strategy	600-660 V	440-500 V	1000 V	323.3-323.7 V	400 V
Chattogram					
Dispatch Strategies	PV Voltage (V)	Wind Voltage (V)	DG Voltage (V)	Battery Voltage (V)	Load Voltage (V)
Cycle Charging	600-650 V	440-500 V	1000 V	322.8-323.2 V	400 V
Combined Dispatch	600-650 V	440-500 V	1000 V	323.3-323.7 V	400 V
Generator Order	620-670 V	440-500 V	1000 V	324.35-324.5 V	400 V
Load Following	610-660 V	440-500 V	1000 V	324 V	400 V
Predictive Strategy	600-660 V	440-500 V	1000 V	323.2-323.7 V	400 V

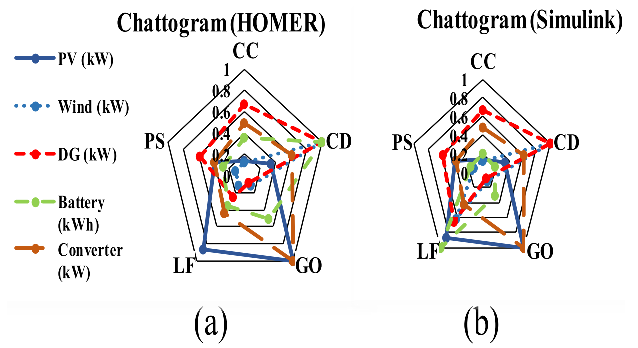


FIGURE 7. Optimum Sizes for Chattogram division using (a) HOMER (normalized) (b) MATLAB simulink (normalized).

found for Barishal and Chattogram division are illustrated in Fig. 8 and Fig. 9, respectively for various dispatch strategies. From the analysis, it is seen that all the voltage responses mentioned above are stable within 2 to 3 seconds time frame. The quantitative measurements from the mentioned voltage responses are reported in Table 4. It is observed that all the PV voltage responses are stable within 600 V to 670 V, wind voltage is stable within 500 V to 440 V, battery voltage is stable within 322.8 V to 324.5 V, the three-phase DG voltage is stable within 1000 V (peak to peak) voltage and the three phase load voltage is stable within 400 V (peak to peak) voltage. From Fig. 8 and Fig. 9, it is evident that all the responses are within limit and are stable and thus can be declared as 'technically feasible' responses. All these responses has been obtained from simulink analysis where the different components had the optimal sizes as shown in table 3. The component sizes used are also available in the market and hence according to the voltage responses, the MGs can be declared as 'feasible' ones.

2) FREQUENCY RESPONSES/FEASIBILITY ANALYSIS

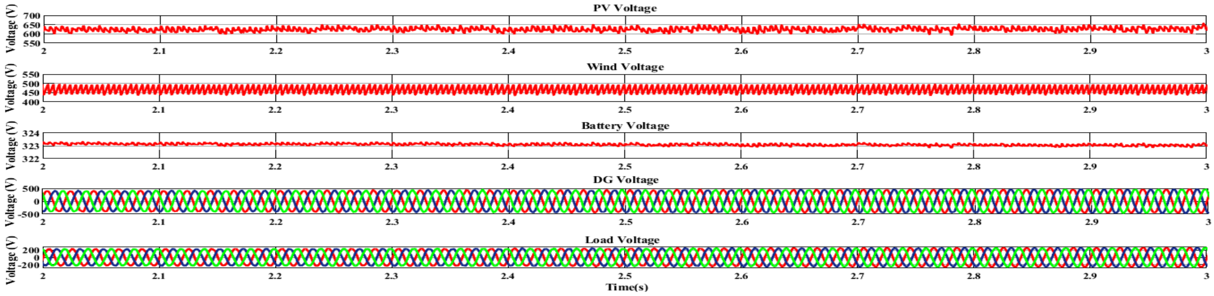
Fig. 10 shows the frequency response for Barishal division for various dispatch strategies. In spite of having some variations in the frequency amplitudes, the responses of frequency have been stable for the considered time limit of 2 to 3 seconds and is within the endurable limit of 50 +/−2 Hz. In Fig. 10 (a) for the CC strategy, from starting at 2 seconds, the frequency is about 49.817 Hz and, after having a downward slope up to 2.3 seconds, a rise in frequency can be observed up to 2.45 seconds. From 2.45 seconds to 2.6 seconds, there is a downward slope and from 2.6 to 2.7 seconds the frequency is approximately constant. In 2.7 to 3 seconds, the frequency response has some ups and downs and finally settles down to 49.825 Hz. Similar results can also be found for other dispatch strategies for Barishal division and for the five dispatch strategies for Chattogram division as exposed in Fig. 11. From Fig.10 and Fig.11, it can be observed that all the frequency responses are within tolerable limit and are 'stable' in nature. So, on the context of the frequency responses, the MGs can be declared as feasible. From the figures it is also evident that LF dispatch strategy, for the both MGs offer a better frequency response than the other dispatch strategies although all the responses are stable. LF strategy fulfills the primary load first and lower priority is given to storage devices and deferrable loads and only feeds them if the renewable energy generation is considerably in excess to the need and thus offers a better system frequency.

TABLE 5. Comparison of different performance parameters in between the designed IHMS, other HRES and conventional power plant (CPP).

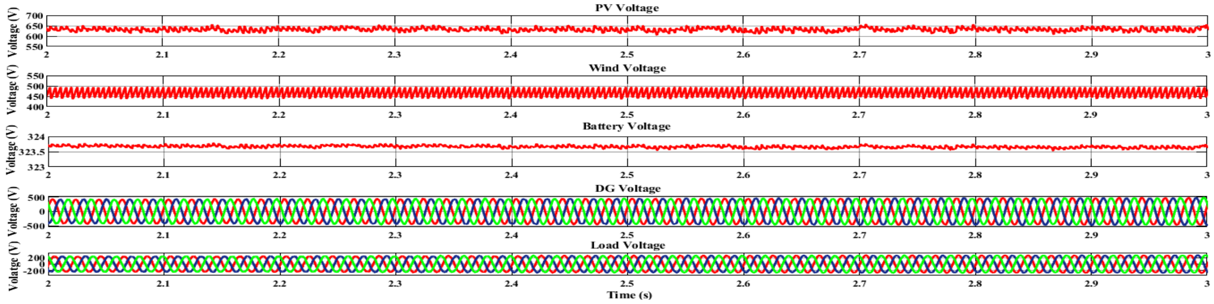
Parameters	Proposed	HRES [38]	CPP [38]
CO_2 /Year (Kt)	0.003182	198347.984	198,348.00
NPC/Year (USD)	160,360	288,194	297,000.00
COE (USD/kWh)	0.219	1.877	0.380
Operating Cost (USD)	3,182	19,516	—

C. COMPARISON OF THE DESIGNED MG WITH OTHER WORKS

From the simulation result analysis, it can be determined that, in comparison with the NPC for other HRES designs and the other conventional power plants, the NPC found for the proposed islanded hybrid MG systems (IHMS) has been reduced significantly as reported in Table 5. Table 5 shows a brief comparison between the designed IHMS, conventional power plants and other HRES design on the basis of NPC, CO_2 gas emission, operating cost and COE.



(a)



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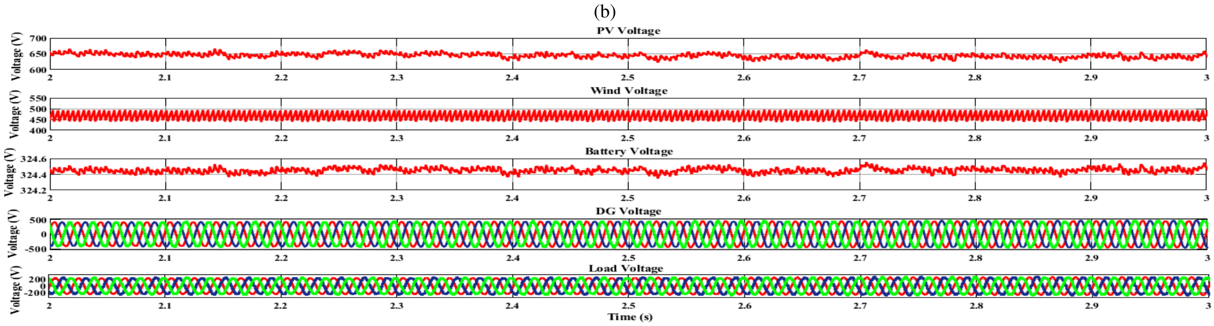

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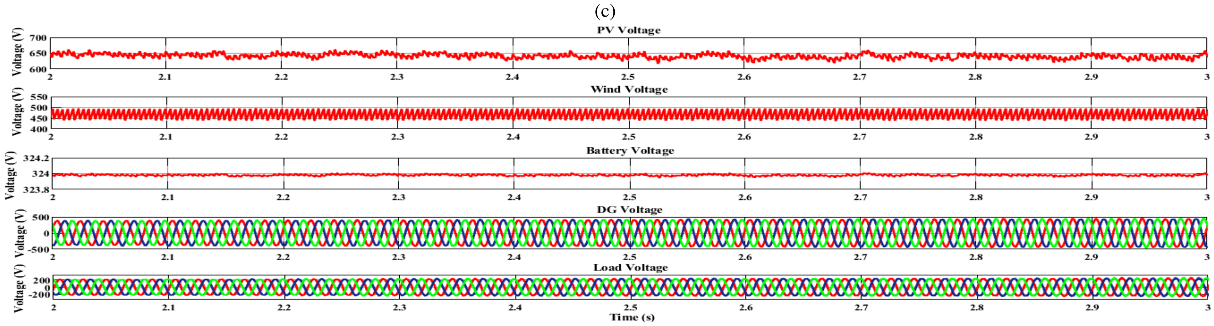

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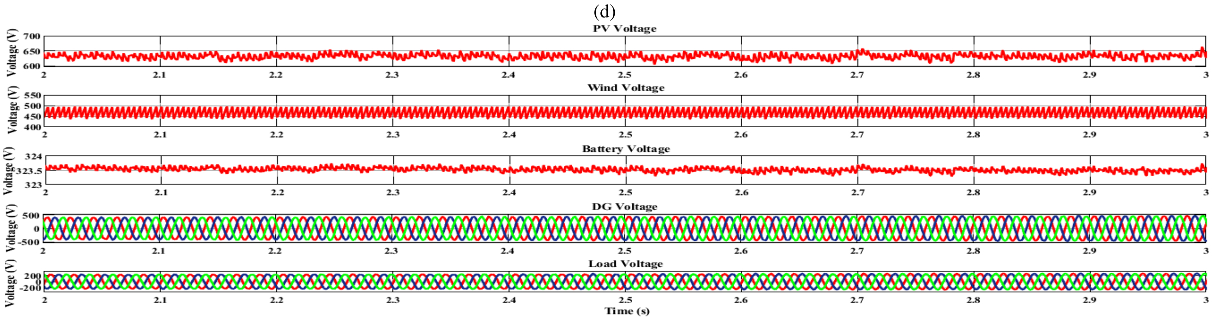

(e)

FIGURE 8. Voltage responses of microgrid for Barishal division using various dispatch strategies (a) CC (b) CD (c) GO (d) LF, and (e) PS.

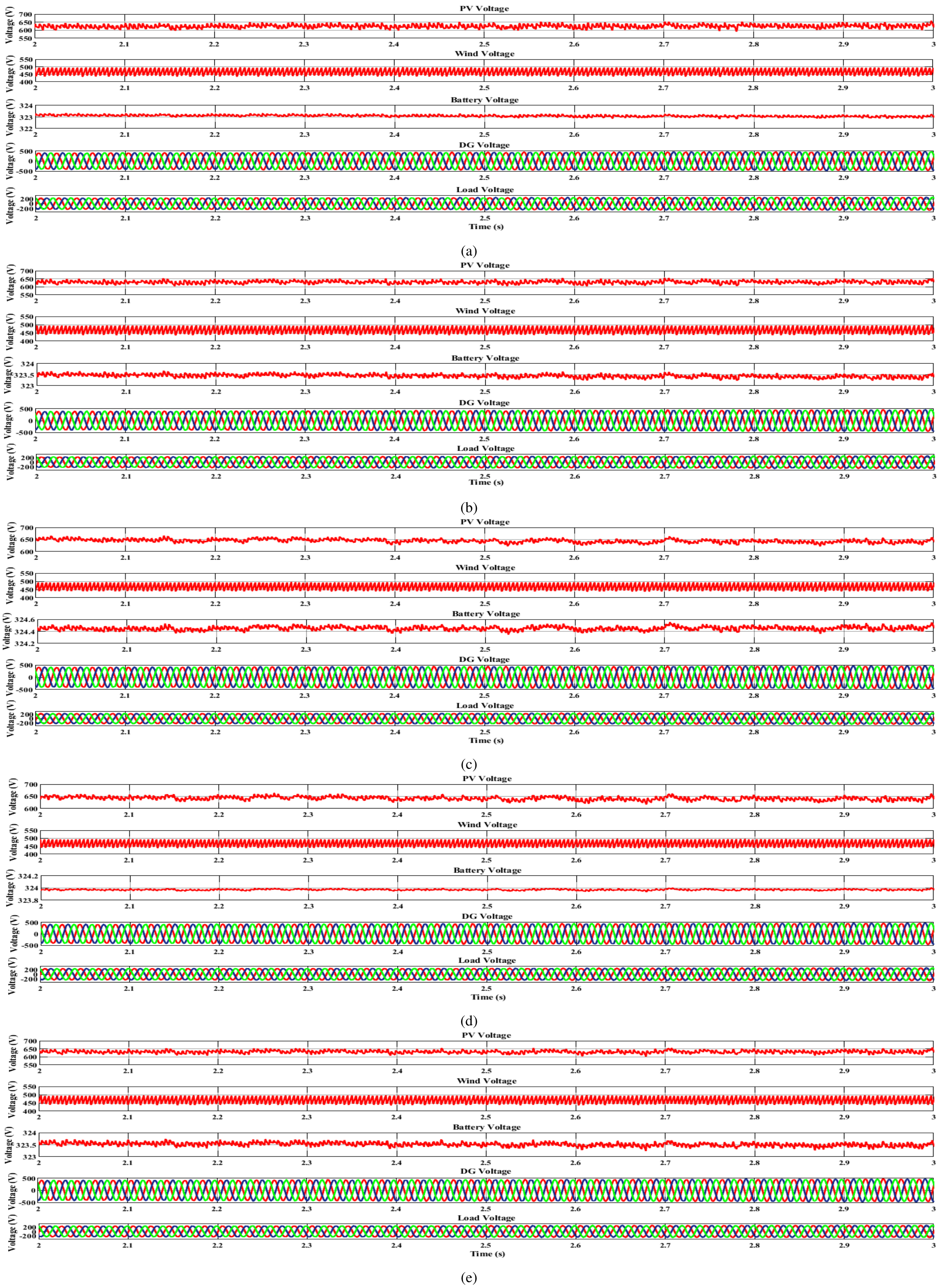

FIGURE 9. **Voltage responses of microgrid for Chattogram division using various dispatch strategies (a) CC (b) CD (c) GO (d) LF, and (e) PS.**

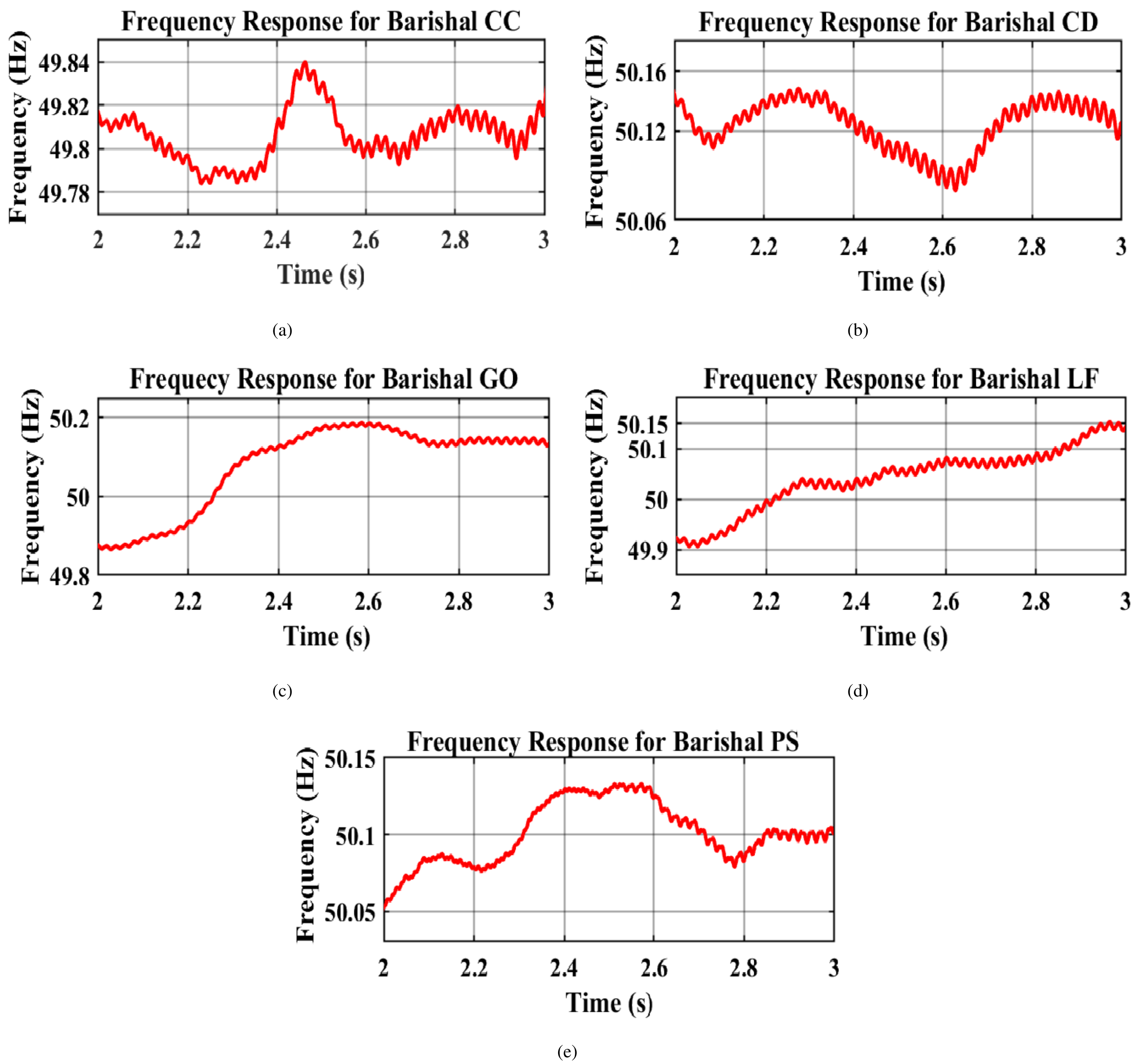

FIGURE 10. Frequency responses of microgrid for Barishal division using various dispatch strategies (a) CC (b) CD (c) GO (d) LF, and (e) PS.

From the comparative study, the COE of the proposed IHMS is 88.33%, the operating cost is 83.70%, and the NPC is 44.36%, the CO_2 gas emissions of the proposed IHMS are 99.99% less than other HRES respectively and the COE of the proposed IHMS is 42.37%, the NPC is 46%, and the CO_2 emissions of the designed IHMS are 99.99% less than conventional fossil fuel based power stations. The optimization results are better than the conventional power stations as the conventional plants are mainly dependent on fossil fuel for power generation and the proposed hybrid MGs rely on mainly renewable energy based generation techniques. The results are also more feasible than other HRES because the other researcher's did not consider dispatch strategy based analysis. As previously stated, dispatch strategy optimally manages the energy flow in the system with lower cost and component sizes. Accordingly, the optimal sizes required for this work is much less than the compared HRES and conventional power plants.

D. DETERMINATION OF BEST AND WORST DISPATCH TECHNIQUE

From the critical analysis in power system response aspects, techno-economic analysis and environmental pollution aspects it can be determined that the LF strategy has the best overall performance for all the criteria for the proposed MGs. On the other hand, for environmental

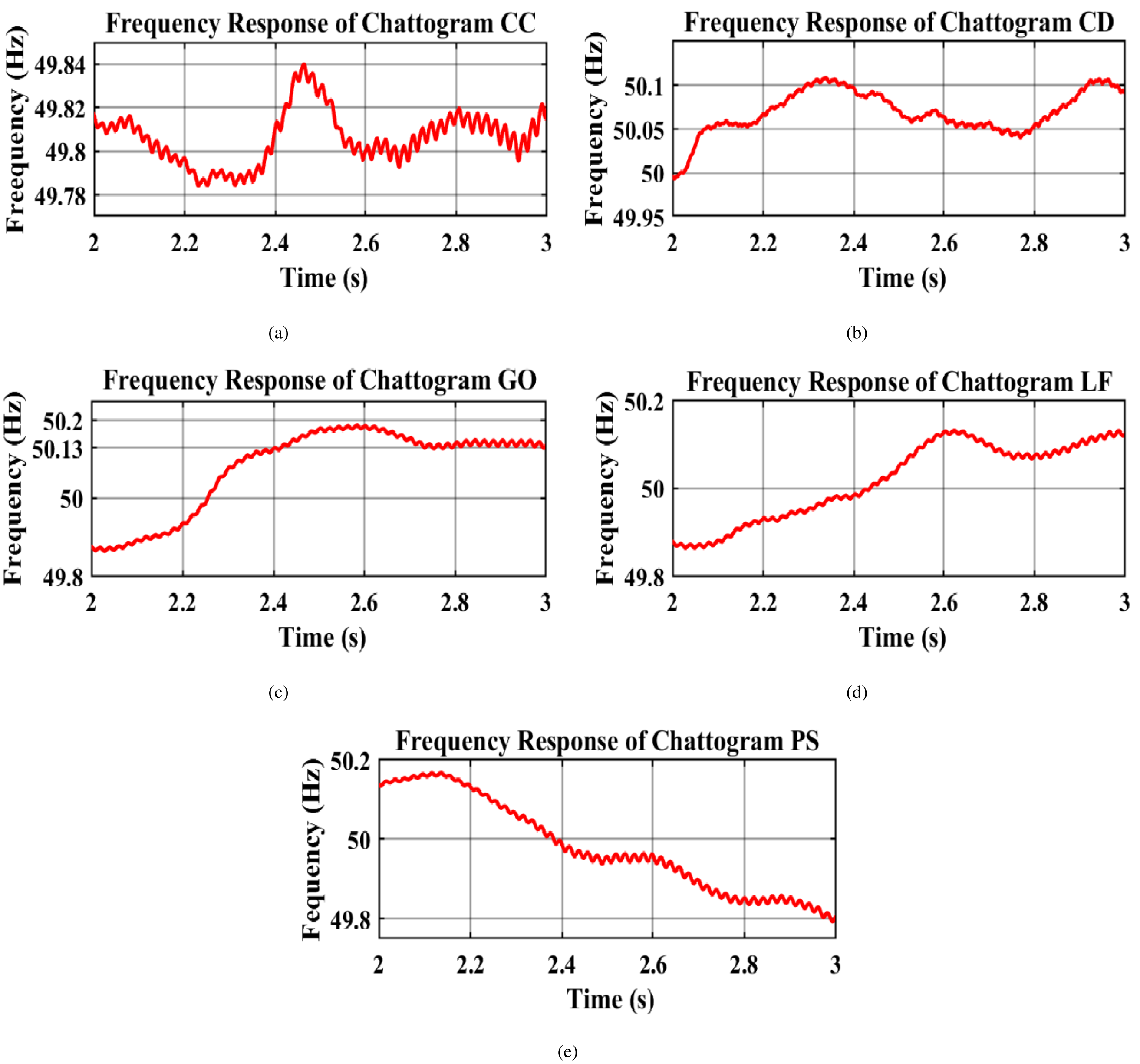

FIGURE 11. Frequency responses of microgrid for Chattogram division using various dispatch strategies (a) CC (b) CD (c) GO (d) LF and (e) PS.

and techno-economic aspects, the CD strategy has the worst response for the MG's sustainable optimization and operation. The LF strategy works by a principle that meets the primary load demand at first given that there is a sufficient generation by renewable sources. The primary load includes dedicated or predefined loads such as the household loads. The storage devices and deferrable loads are given low priority in this strategy. On the other hand, the combined dispatch (CD) strategy works by an arrangement that decides the cheapest route to select either the load following or cycle charging strategy. This requires additional system cost and component sizing which may worsen the outcome. The considered sites in this work consist of adequate renewable sources in the form of solar and wind that aid the LF strategy to perform superior for these specific locations. Alternatively, the CD strategy chooses the CC strategy for the studied systems and degrades the system response and optimal sizing.

Additionally, on basis of the power system response, both PS and CC strategies have the worst performance because of the delay and long term instability in the mitigation of voltage and frequency stability.

V. CONCLUSION

This work designed islanded hybrid microgrids using wind turbine, backup diesel generator, solar PV, and battery storage device for two different locations for the optimal operation and resource planning on the basis of various dispatch strategies. Further, the frequency and voltage responses of the simulated microgrid have been analyzed in Simulink platform from which it can be observed that 'load following' is the best strategy and 'combined dispatch' is the worst dispatch strategy in terms of minimum and maximum LCOE, CO_2 emissions, NPC, and best and worst power system (frequency and voltage) responses respectively. The load following dispatch strategy have lowest LCOE, NPC and CO_2 emission of 0.219 $/kWh, 160,360$ and 3,297 kg/year and combined dispatch strategy has highest of 0.526 $/kWh, 410, 877$ and 18,310 kg/year respectively. From the comparative analysis, the COE of the designed and optimized microgird is 88.33%, the NPC is 44.36%, the operating cost is 83.70%, and the CO_2 gas emissions of the proposed IHMS are 99.99% less than other HRES designs respectively and the COE of the proposed IHMS is 42.37%, the NPC is 46%, and the CO_2 gas emissions of the proposed IHMS are 99.99% less than conventional fossil fuel based power stations. The designed microgrids are optimized to ensure system stability (stable frequency and voltage responses) and techno-economic feasibility for ensuring uninterrupted supply of electrical power for the proposed areas of the Barishal and Chattogram microgrids. This optimized standalone hybrid microgrid is feasible for application especially for the isolated and islanded region and the analysis is suitable for locations having similar load profiles and meteorological conditions anywhere in the world. The limitation of this work is that the distribution line considered in the Simulink study does not actually replicate the real-life Barishal and Chattogram distribution network. The analysis can be improved by considering the actual distribution network data as well as the stochastic behaviour of the wind and solar resources while optimizing the microgrid design.

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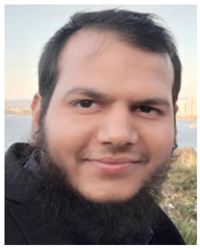
MD. FATIN ISHRAQUE was born in Rangpur, Bangladesh. He received the B.Sc. degree in electrical and electronic engineering (EEE) from the Rajshahi University of Engineering & Technology, in 2018, where he is currently pursuing the M.Sc. degree in electrical and electronic engineering (EEE). He is working as a Lecturer with the Department of Electrical, Electronic and Communication Engineering (EECE), Pabna University of Science and Technology, Pabna, Bangladesh. His research interests include renewable energy, dispatch strategy, and the IoT-based system designing.

SK. A. SHEZAN received the Bachelor of Engineering degree in electrical engineering and automation from the Shenyang University of Chemical Technology, China, in 2013, and the Master of Engineering degree from the University of Malaya, in 2016. He is currently pursuing the Ph.D. degree in electrical and electronic engineering with RMIT University, Melbourne, Australia. He was a Lecturer with the Electrical and Electronics Engineering Department, Uttara University, Dhaka, Bangladesh. His research interests include microgrid, HRES, solar energy, wind energy, optimization, power system analysis, and energy economics.

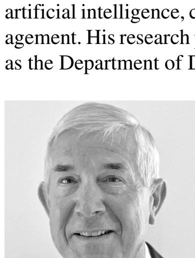
M. M. RASHID received the B.Sc. and M.Sc. degrees in electrical and electronic engineering (EEE) from the Rajshahi University of Engineering & Technology, Rajshahi, Bangladesh, in 2011 and 2017, respectively. He is currently working as an Assistant Professor with the Department of Electrical and Electronic Engineering (EEE), Rajshahi University of Engineering & Technology. His research interests include embedded systems, robust broadband beamforming, and signal processing.

ANANTA BIJOY BHADRA (Associate Member, IEEE) was born in Habiganj Sadar, Habiganj, Bangladesh, in August 1996. He received the Bachelor of Science (B.Sc.) degree in electrical and electronic engineering from the Rajshahi University of Engineering & Technology, in 2019. His research interests include power electronics, robotics, and IC design.



MD. ALAMGIR HOSSAIN received the B.Sc. degree (Hons.) in EEE from the Dhaka University of Engineering and Technology (DUET), Bangladesh, in 2012, and the Master of Engineering and Ph.D. degrees from the University of New South Wales (UNSW), Australia, in 2016 and 2020, respectively. He has published more than 20 high-impact journal articles and 15 international conferences in his specialist field, including modeling, analysis, control, optimization, and forecasting of renewable energy sources. He has received a number of awards, including the High Impact Publication Awards, the Overall and Second Winners at UNSW Research Day Competitions, the Top Peer Reviewer 2019, the Outstanding Reviewer from Elsevier, and the Prime Minister and President Gold Medals.

RIPON K. CHAKRABORTTY (Member, IEEE) received the B.Sc. and M.Sc. degrees in industrial and production engineering and the Ph.D. degree from the Bangladesh University of Engineering and Technology, in 2009, 2013, and 2017, respectively. He is currently the Deputy Director of the Capability Systems Centre, School of Engineering and Information Technology, UNW Canberra, Australia. He is a Lecturer on system engineering and project management and the program coordinators for Master of Decision Analytics and Master of Engineering. He is also the Group Leader of the Cross-Disciplinary Optimisation Under Capability Context Research Team. He has written two book chapters and over 120 technical journal articles and conference papers. His research interests include operations research, project management, supply chain management, artificial intelligence, cyber-physical systems, and information systems management. His research program has been funded by many organizations, such as the Department of Defence, Commonwealth Government, Australia.



MICHAEL J. RYAN (Senior Member, IEEE) is currently the Director of Capability Associates Pty Ltd. He lectures and regularly consults in a range of subjects, including communications systems, systems engineering, requirements engineering, capability management, and project management. He is the author or coauthor of thirteen books, three book chapters, and over 350 technical articles and reports. He is a Fellow of Engineers Australia, the International Council on Systems Engineering, the Institute of Managers and Leaders, and the Royal Society of New South Wales. He is the Co-Chair of the Requirements Working Group in the International Council on Systems Engineering (INCOSE).

SHAHRIAR RAHMAN FAHIM (Member, IEEE) received the B.Sc. degree in electrical and electronic engineering from the Rajshahi University of Engineering & Technology. His specialties in power transmission systems are fault detection, fault classification, fault location, power-quality event analysis, computer relaying, solar generation systems, and smart-grid systems. His areas of interests include diverse and cover human–machine interaction (HMI) and artificial intelligence. His current research interests include data-driven predictive maintenance, detection, diagnostics and prognostics, and application of machine-learning techniques in signal processing.

SUBRATA K. SARKER was born in Bangladesh, in 1996. He received the Bachelor of Science degree in mechatronics engineering from the Rajshahi University of Engineering & Technology (RUET), Rajshahi, Bangladesh. He is currently working as a Lecturer with the Electrical and Electronic Engineering Department, Varendra University, Rajshahi. He has been working as an active reviewer for many prestigious journals and conferences. He has published more than 25 high-impact journal articles and 30 international conferences in his specialist field. His research interests include control theory and applications, robust control of electro-mechanical systems, robotics, mechatronics systems, artificial intelligence, and power systems.

SAJAL K. DAS received the Doctor of Philosophy (Ph.D.) degree in electrical engineering from the University of New South Wales, Australia, in 2014. In May 2014, he was appointed as a Research Engineer at the National University of Singapore (NUS), Singapore. In January 2015, he joined the Department of Electrical and Electronic Engineering, AIUB, as an Assistant Professor. He continued his work at AIUB untill he joined the Department of Mechatronics Engineering, Rajshahi University of Engineering & Technology (RUET), as a Lecturer, in September 2015. He is currently working as an Assistant Professor with RUET. His research interests include control theory and applications, mechatronics system control, robotics, and power system control.