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Assortment of Dispatch Strategies with the Optimization of an Islanded Hybrid Microgrid

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ABSTRACT

In this work, the optimization of an off-grid micro-hybrid system is evaluated. This is conducted with the estimation of the proper sizing of each element and the steady-state voltage, frequency, and power responses of the microgrid. Kangaroo Island in South Australia is considered to be the test case location and the grid incorporates solar PV (photo-voltaic), diesel generator, battery storage, and wind turbine. Optimal sizing of the studied microgrid is carried out for four various power dispatch techniques: (i) cycle charging (CC), (ii) generator order (GO), (iii) load following (LF), and (iv) combined dispatch (CD). The proposed off-grid micro-hybrid is optimized for three performance indices; minimal Levelized Cost of Energy (LCOE), CO_2 emission, and Net Present Cost (NPC). Using iHOGA (improved hybrid optimization by genetic algorithm), microgrid optimization software, all the above-mentioned dispatch strategies have been implemented and following this, MATLAB/Simulink platform has been used for the steady-state studies. The results show that the LF strategy is the utmost optimum dispatch technique in terms of the studied performance indices i.e. considering the optimal size and voltage and frequency responses. The results obtained from these studies provide a pathway for the estimation of the resource-generation-load combination for the islanded off-grid microgrid for its optimal operation with the various dispatch strategies.

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1. INTRODUCTION

Power is the main strength behind urbanization and industrialization. The conventional electrical power plants mostly depend on fuels like coal or HFO (heavy fuel oil), which emits a large amount of polluting greenhouse gasses (GHG) like CO_2, creating a threat to the environment and mankind and is one of the reasons behind global warming (Ishraque et al., 2021). Moreover, day by day, the production cost of electrical power is getting higher and higher as the amount of fossil fuel reserve is decreasing. As an obvious result, research interest in renewable and non-conventional types of sources of energy like wind, solar, biomass, wave energy, hydro and geothermal energy is increasing day by day. Among the many other renewables and non-conventional energy resources, because of the ease of availability and accessibility of wind and sunlight, wind and solar energy systems are considered the most significant renewable energy resources (Ishraque, Shezan, et al., 2021). Over the last decades, the fields of both wind and solar power have availed their advancements independently of each other (Sinha & Chandel, 2015).

Solar and wind have intermittent nature and that's why they have some limitations (Ishraque & Ali, 2021; Shezan

& Ishraque, 2019). The variable nature of wind speed and solar radiation may cause some uncertainty issues in the off-grid microgrid. The quality of power in a hybrid microgrid is always a vital issue because of the fluctuation between the amount of generated power and load demand (Sarangi et al., 2020). Moreover, a sudden change in the load demand can lead to a sudden voltage and frequency fluctuation in the system (Al-Hinai et al., 2021; Ishraque et al., 2021). Besides all these facts, the integration of more than one renewable energy source can make the system unstable and infeasible (Ishraque et al., 2021; Shezan et al., 2022).

The world is looking for longer-lasting power sources emphasizing solar radiation and wind power-based renewable systems. Al Busaidi et al. in (Al Busaidi et al., 2016) suggested a probable solution to the uncertainty issues with solar and wind resources and load-related issues as well. Voltage deviation in an off-grid microgrid affects the stability of the system. STATCOM (Static Synchronous Compensator) can be a solution to this problem with the implementation of the genetic algorithm (GA) proposed by Hale Bakir (Bakir & Kulaksiz, 2020). The main concept of various optimization techniques and control strategies to minimize different parameters like frequency and voltage stabilization, Net Present Cost, and pollutions are shown by Tao ma et al. (2014). PI (proportional integral) based on a modified controller along with genetic algorithm (GA) integration-based control technique is studied by Obara et al. (2018) for the output voltage control.

In (Wang et al., 2016), Wang et al. assessed an optimal dispatch technique for an islanded micro-hybrid grid system by keeping in mind vehicle-to-grid (V2G) technology under TOU (time of use) tariffs. The use of optimal and coordinated dispatch strategy methodologies can ensure power production minimization as well as maximum renewable resource usage. A voltage-frequency stabilization methodology has been demonstrated by Zhao et al. (2015). They designed a second-storied optimized dispersed dispatch regulator technique applicable for an off-grid microgrid system for voltage-frequency stabilization.

Chowdhury et al. demonstrated the advancement in the field of economic dispatch for unorthodox power sources. The correlation between the optimal power flow and the economic dispatch has been reported and pointed out in (Chowdhury & Rahman, 1990). Many researchers have already expressed their views regarding the dispatch strategies with the techno-economic analysis and optimization of islanded microgrid (Liu et al., 2018). Liu et al. evaluated and proposed a method based on distributed economic alternative dispatch strategies for designing an islanded microgrid (Liu et al., 2019). An optimal dispatch technique for the islanded hybrid microgrid is assessed by Abdullah et al. by incorporating V2G operation under time-of-use tariffs (Abdullah et al., 2014). MAS (multi-agent system) based energy management system for the decentralized optimization approach facilitating power dispatch control techniques for an islanded microgrid that working at high elevation is proposed by B. Zhao et al. in (Zhao et al., 2015). Qadrdan et al. introduced an operative power dispatch strategy to enhance the generation schedulability of a wind-BESS (battery energy storage system) hybrid microgrid system (Qadrdan et al., 2013). An energy management platform based on a MAS considering real-time power dispatch strategies is proposed by Zhang et al. (Zhang et al., 2013). Researchers introduced a modified operating dispatch strategy for a compact electricity and gas network system considering the stochastic behavior of wind power predictions (Ye et al., 2019).

Many research scholars have already implemented their ideas regarding the system stability and mitigation of voltage and frequency fluctuations for the islanded hybrid microgrid (Ishraque et al., 2021). Another decentralized optimization control methodology is suggested to keep the system frequency within the specified operating range and minimum operating cost (Chowdhury, 1992). In (Nasr et al., 2020), a first-level decentralized hang pay control method has been applied for load sharing and other force dispersion results keeping up as per the foreordained inventory request succession. Voltage fluctuation issues are very common for an off-grid microgrid. To solve this issue, a solution is suggested by Mahmud et al. by utilizing Static Synchronous Compensator (STATCOM) alongside the usage of the hereditary calculation improvement technique in (Kumar et al., 2019). In (Vergara et al., 2018), Vergara et al. introduced different optimization and control strategies to minimize NPC, COE, environmental pollution, frequency, voltage, and power fluctuations. A novel control technique is implemented by Chowdhury et al. to improve the power system performance of an islanded microgrid by considering the bidirectional interlinking converter (BIC) (Chowdhury & Taylor, 2000). Hale et al. demonstrated a multi-agent-based distributed control technique suitable for the islanded hybrid microgrid to mitigate the voltage and frequency stability (Bakir & Kulaksiz, 2020).

The main lacking in the existing literature is the lack of correlation between the techno-economic analysis and optimal sizing along with the system stability such as frequency and voltage stability according to the dispatch strategies. The proper operation of an off-grid microgrid can be ensured by fulfilling three criteria which are technical, system stability and economic feasibility. The possible solution might be ensured by a proper co-relation and combination of these criteria for an off-grid microgrid. The proposed Kangaroo Island is situated in the southwest of Adelaide, South Australia. Moreover, the proposed Kangaroo Island has enough renewable resources such as wind speed and solar irradiation to produce enough renewable power to fulfill the need. The main target of the conducted research is to build a strategy of an off-grid PV-wind-diesel generator-battery storage-based hybrid microgrid network that will be connected along with the already established power distribution system for the proposed Island. The wind turbine, solar PV, battery storage and diesel generator are the power sources for the proposed micro-hybrid grid. The principal contribution of this work is two-fold: the first contribution includes the optimal design of an off-grid microgrid based on minimum NPC, CO_2 emissions and COE according to various dispatch strategies and the second contribution incorporates the voltage, power, and frequency stabilization for the whole system according to the optimized size. The rest of this article has been systematized as tracks: The architecture of an off-grid Microgrid along with the system components and energy transformation method has been summarized in Section 2; System methodology and working principles of this research work are represented briefly in section 3; Section 4 compassions the research and simulation outcomes and a brief discussion with indispensable diagrams and tables to illustrate the proportional studies among the premeditated microgrid and the non-renewable power system networks; Then the later segments converse the conclusion along with the acknowledgment and references.

2. ARCHITECTURE OF AN ISLANDED MICROGRID

The power that comes from the solar cell and Battery both are Direct Currents (DC) and thus using DC/AC converters are converted to Alternating Current (AC) before going to the AC bus bar. The Diesel Generator and Wind Turbine both generate AC power and thus are directly connected to AC bus-bar after a simple voltage conversion. The loads are then fed from the AC bar. VSC (Voltage Source Controller) is introduced for the converter unit.

In Figure 1, a block representation of the proposed off-grid Microgrid along with the system components is depicted. The Microgrid consists of a wind turbine, solar PV, diesel generator, various loads, system converter module, and battery storage unit.

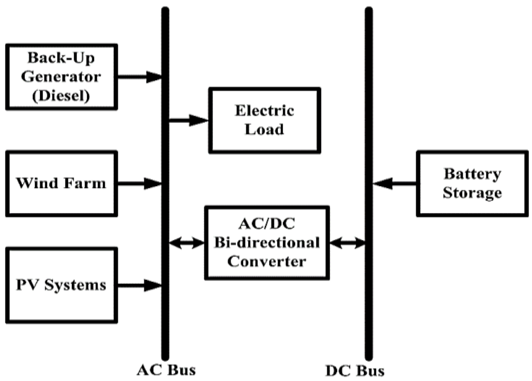


Figure 1: A Schematic diagram of the optimization strategy for the proposed hybrid Microgrid

3. METHODOLOGY

By considering the load profile, power sources, and meteorological conditions of Kangaroo Island, various optimization strategies adopt various dispatch techniques.

Load following (LF) strategy makes a generator deliver just enough power to fulfill the demand whenever it is required. This technique is ideal especially in systems having a large amount of renewable power that exceed the demand occasionally (Shezan, 2019).

In Cycle Charging (CC) strategy, the generator works at its full rating whenever it is required. The excess power produced by the generator charges the battery units. In general, the CC technique is an ideal choice for the frameworks having practically no renewable sources of power (Ishraque et al., 2021; Shezan, 2019).

In, Generator Order (GO) dispatch strategy, the operating capacity is fulfilled by the first combinations in the rundown process. GO strategy supports frameworks that have generators, wind turbines, converters, solar PVs, and extra battery units (Bukar & Tan, 2019).

In Combined Dispatch (CD) strategy, future net loading assumption is avoided by the utilization of the current net load for deciding on the battery if the battery module is to be charged using the generator unit or not. The CD strategy abstains from using the generator unit when the amount of load is low. The CD chooses the cheapest option to make CC or LF in each time step (Shezan et al., 2019).

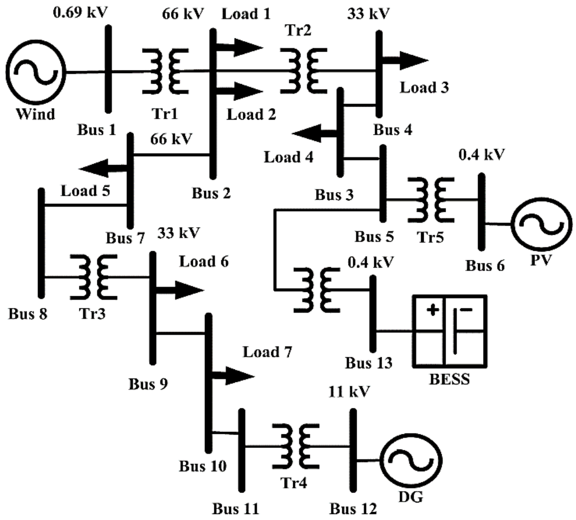


Figure 2: A single line diagram of proposed Kangaroo Island Microgrid with the power distribution network

Figure 2 depicts a simplified single line diagram for the distribution system for the proposed off-grid Kangaroo Island microgrid system is shown. The distribution network consists of a total of twelve busses, five transformers, a Solar PV module, a wind turbine module, a diesel generator, and seven loads. The 7 loads are connected at various nodes of the distribution network having voltages of 11 kV, 33 kV, and 66 kV. The sun-based PV, Wind Turbine unit, and Diesel Generator modules in the dissemination network are associated with three unique focuses having a voltage level of 11 kV. Utilizing venture up transformers this 11 kV is then ventured up to 33 kV. An underlying voltage of 575 V is set for the Wind Turbine, Solar PV and Diesel generator. A recurrence of 50 Hz is considered for the entire framework (Shezan et al., 2019).

Figure 3 shows the flowchart for the proposed work showing the research methodology at a glance. Firstly, the required inputs are needed to be put in the simulation software. According to the load profile, meteorological condition, and dispatch algorithm the simulation should suggest some optimum solutions. Upon the satisfaction of the load demand the optimum solution is chosen and simulated in Simulink microgrid model in order to assess the proposed microgrid on the basis of power system responses. Upon the satisfaction of the requirements, the optimum solution is finalized.

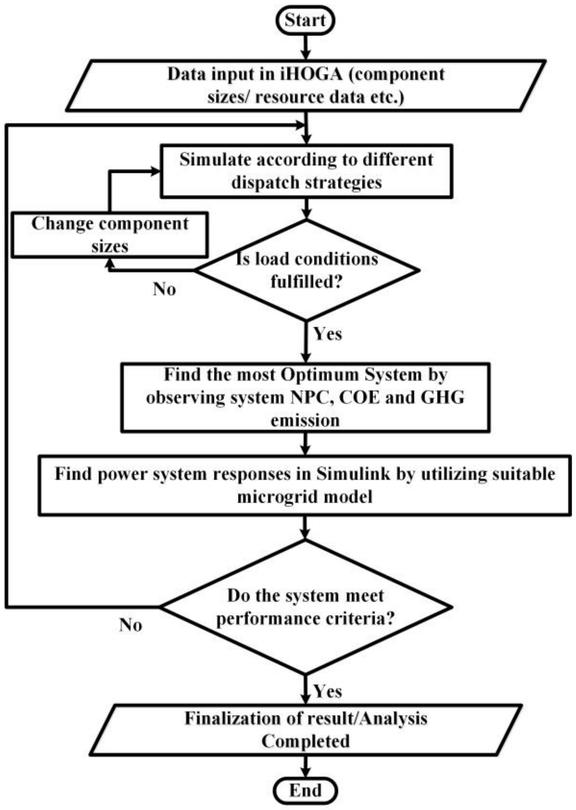


Figure 3: Flow chart for the proposed research work

Figure 4 shows the cost curve for solar PV used in the proposed Kangaroo Island Microgrid system is shown. From the cost curve, the optimal sizes of the solar PV setup and the replacement and capital costs have a proportional relationship. The maintenance and operation cost ratios are approximately the same because of the fixed cost for maintenance and operation. In this work, the PV module has a size of a maximum of 15 MW that is considered in this cost curve.

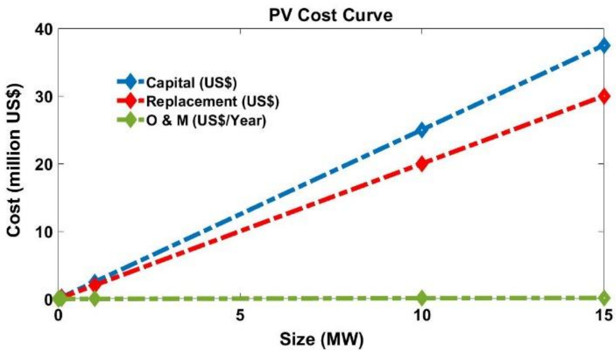


Figure 4: Cost curve for Solar PV

Figure 5 depicts the Wind Turbine cost curve used in the proposed Kangaroo Island Microgrid system is shown. From the cost curve, along with the optimal size of the turbine setup, the replacement and capital costs also increase. The maintenance and operation cost ratios are approximately the same because of the fixed cost for maintenance and operation. In this work, the Turbine module has a size of a maximum of 1.5 MW that is considered in this cost curve. In this analysis, a total of 10 turbines are considered having a 1.5 MW size each.

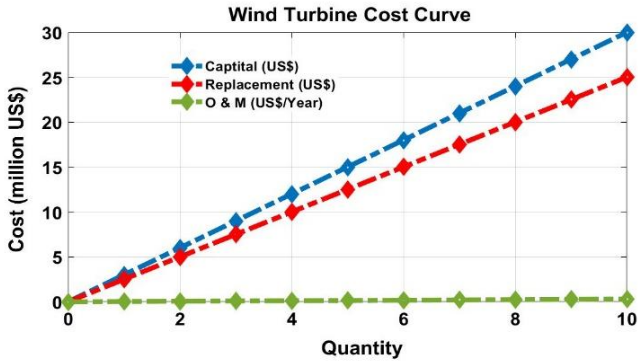


Figure 5: System cost curve for Wind Turbine system

In Figure 6, the diesel generator cost curve used in the proposed Microgrid system is shown. From the cost curve, along with the optimal size of the generator setup, the replacement and capital costs also increase. The maintenance and operation cost ratios are approximately the same because of the fixed cost for maintenance and operation. In this work, the generator module has a size of a maximum of 8 MW that is considered in this work.

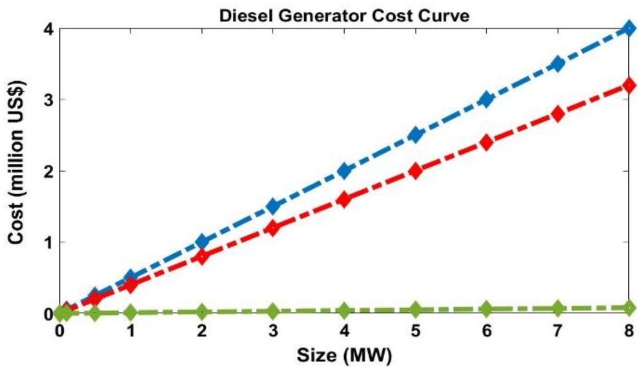


Figure 6: Cost curve for Diesel Generator unit used in the system

Figure 7 shows the battery storage cost curve used in the proposed Microgrid system is shown. From the cost curve, along with the optimal size of the battery module, the replacement and capital costs also increase. The maintenance and operation cost ratios are approximately the same because of the fixed cost for maintenance and operation. In this work, the battery storage module has a total size of a maximum of 10 MW that is considered in this cost curve for both analyses.

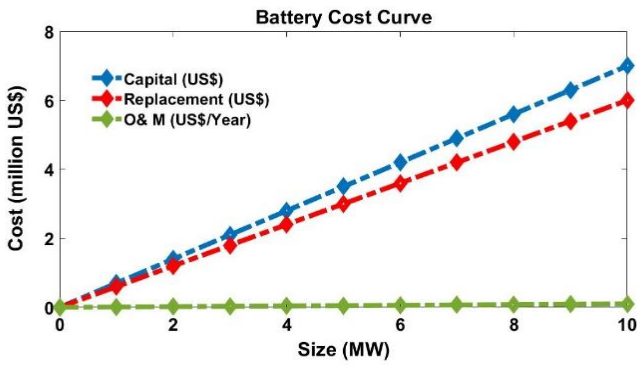


Figure 7: System cost curve for Battery

4. RESULTS AND DISCUSSION

A. Optimal Sizing of the Network

Table 1 shows, a brief comparison between the required sizes of various components for the proposed Microgrid under different dispatch strategies have been highlighted. From the comparison of the results, a clear difference can be observed in the sizes of different components for different dispatch techniques with the same load profile. Various dispatch strategy causes different optimal sizes of the Wind turbine module, battery storage unit, Solar PV, and converter. The table further illustrates that a wind turbine needs the highest size among the others under the LF technique. On the other hand, Solar PV has the highest size among others under the CD technique. The Diesel Generator (DG) occupies the same 1 MW size for CC and LF as well as for GO strategies. For CD strategy, the size of DG increases to 5 MW. This is because of the combination variation offered by the CD Strategy. The highest 10 MW battery size is required for LF strategy because the total power generation from the Wind turbine module and PV solar cell is higher than the load size. Thus, surplus power is needed to be stored for future usage. From Table 1, it is further observable that for GO dispatch technique, the optimum sizes of the Solar PV, converter, and the battery module are lowest than any other dispatch techniques. This is attributable to the Generator Order technique in which the segment sizes are picked by absolute burden and force generator succession. Along these lines, as the interest is fulfilled by the most minimal sizes of the various parts as indicated by the meteoroidal condition, the cycle of ideal estimating of finding further least sizes will be ended.

Table 1
Comparison of sizes of every component for Proposed Microgrid for Various dispatch strategies

Dispatch Strategies	PV (kW)	Wind (kW)	Diesel Generator kW)	Battery (kWh)	Converter Size (kW)	Load Profile
Load Following (LF)	2,700	8,000	1,000	5,000	1,200	82,656.32 kWh/d 7345.00 kW
Cycle Charging (CC)	2,900	8,500	1,200	2,000	1,400	
Generator Order (GO)	600	7,000	1,400	500	600	
Combined Dispatch (CD)	3,200	6,500	4,500	4,000	2700	

For various dispatch techniques, the differences in COE, NPC, operating costs, and CO_2 emissions are shown in Table 2 applicable for Kangaroo Island. The table shows that a significant difference lies between the four dispatch strategies on behalf of the CO_2 emissions, COE and NPC. The CO_2 emissions, COE and NPC are highest in the Combined Distance strategy and lowest in the Load Following strategy. In Figure 8, the total amount of electrical power production a year is depicted according to various dispatch strategies and meteorological conditions. The NPC can be varied by equipment cost, fuel cost, maintenance and operation cost, and lifetime. The analysis shows that NPC for the designed off-grid microgrid has been successfully lessened than the conventional power plant.

Table 2
Comparison of NPC, COE, CO_2 emissions and operating cost of proposed design for various controller

IHOGA Controller	NPC (million US$)	COE (US$/kWh)	CO_2 Emissions (kt/yr.)	Operating Cost (million US$)
Load Following (LF)	28.03	0.08	2.7	0.97
Cycle Charging (CC)	37.24	0.10	3.7	2.17
Generator Order (GO)	39.98	0.12	4.7	3.01
Combined Dispatch (CD)	69.97	0.18	6.9	4.11

Table 3
Comparison between the proposed hybrid microgrid and the non-renewable power stations

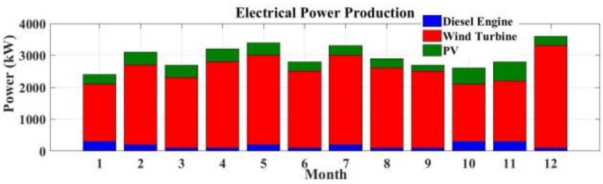
Criteria	Dispatch Strategies				Non-Renewable Power Station
	(LF)	(CC)	(GO)	(CD)	
CO_2 Emission/ Year (Kt)	2.7	3.7	4.7	6.9	12.45
NPC/Year (million US$)	28.03	37.24	39.98	69.97	245
COE (US$/kWh)	0.08	0.10	0.12	0.18	1.48
Operating Cost/Year (million US$)	0.97	2.17	3.01	4.11	11.13

The results obtained from the analysis and simulation, the COE, NPC, CO_2 emissions/year, and operating cost have been reported and compared with the conventional power station. The comparison in Table 3 highlights the noteworthy differences in between the designed off-grid Microgrid and a similar conventional generation plant on the reference of COE, NPC, operating cost, and total CO_2 emission.

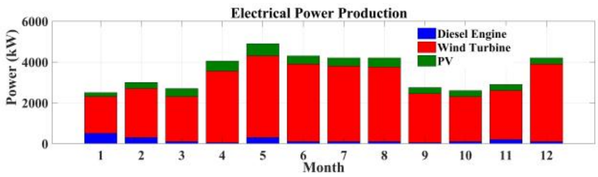
B. Steady-state Frequency and Voltage Response

Analyzing the optimal output results from iHOGA, the optimal sizing of each component in the proposed microgrid has been evaluated. In MATLAB/Simulink platform, the optimal sizes of the components have been set. The power responses for diesel generator, PV, wind, load profile, and battery module are captured and the simulation results have been plotted.

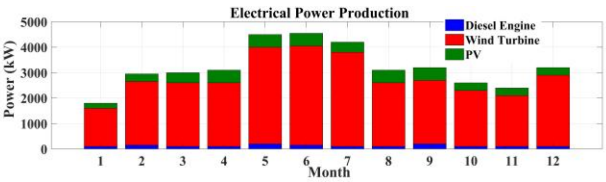
In Figures 9-12, the frequency responses for the time of 3 - 4 seconds as a steady-state response for all the generation strategies are depicted. From the result in Figures 9-10, it can be observed that the frequency is slightly higher than the nominal value for CD and GO strategies.



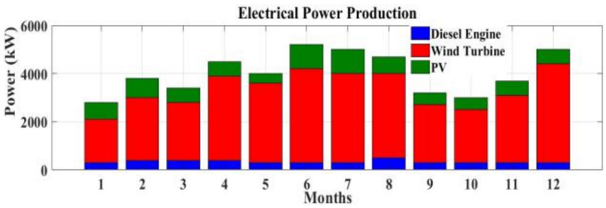
(a) LF



(b) CC



(c) GO



(d) CD

Figure 8: Electrical Power Production according to the four dispatch strategies for Kangaroo Island

Figure 11 shows that the frequency lies within the acceptable range of 50+/-2% Hz for the power distribution system of Australia. However, the LF strategy shows the best response in consideration of the minimum and the maximum frequency values. This range of frequency can clearly depict the efficacy of the optimized size of the network which maintains the steady-state operation limit. The Islanded microgrid system may suffer from an unexpected fluctuation in frequency due to a huge deviation between the load demand and the supplied power which on the other hand results in due to an unexpected deviation in the wind and solar power output.

In Figures 13-17, the voltage response of the off-grid microgrid under the base case and with the proposed four dispatch strategies are shown. The figures depict that a stable voltage response can be obtained for all four dispatch strategies. The comparative results of voltage illustrate that the LF strategy results in the best response among all other dispatch strategies. For all the dispatch strategies, wind turbine voltage is similar. The voltage output from the PV unit also stays within the considerable limit and within the rated capacity. The voltage of the battery module fluctuates in between 300V to 350V. The voltage across load seems more stable for LF and CC strategies. For CD and GO, the voltage is distorted. The voltage across the DG output is better in LF than observed in CC. The outputs discussed are so obtained because of the different operating principles of the dispatch control algorithms. The outputs obtained are satisfactory as they are stable within the considerable limit and hence, the proposed microgrid can be determined feasible with respect to voltage outputs performances.

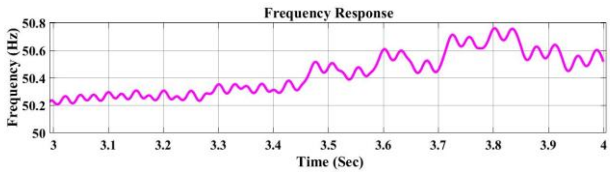


Figure 9: Frequency response of Islanded wind-PV Microgrid for CD dispatch Strategy

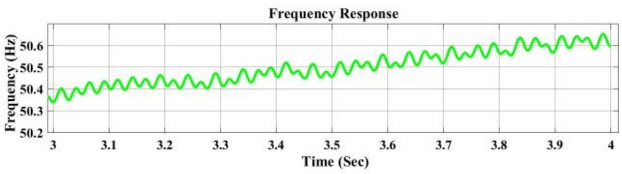


Figure 10: Frequency responses of off-grid PV-wind Microgrid for GO dispatch Strategy

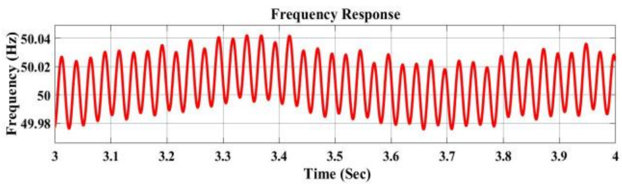


Figure 11: Frequency response of off-grid wind-PV Microgrid for LF dispatch Strategy

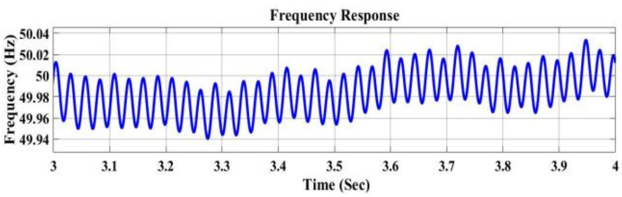


Figure 12: Frequency response of off grid PV-wind Microgrid for CC dispatch strategy

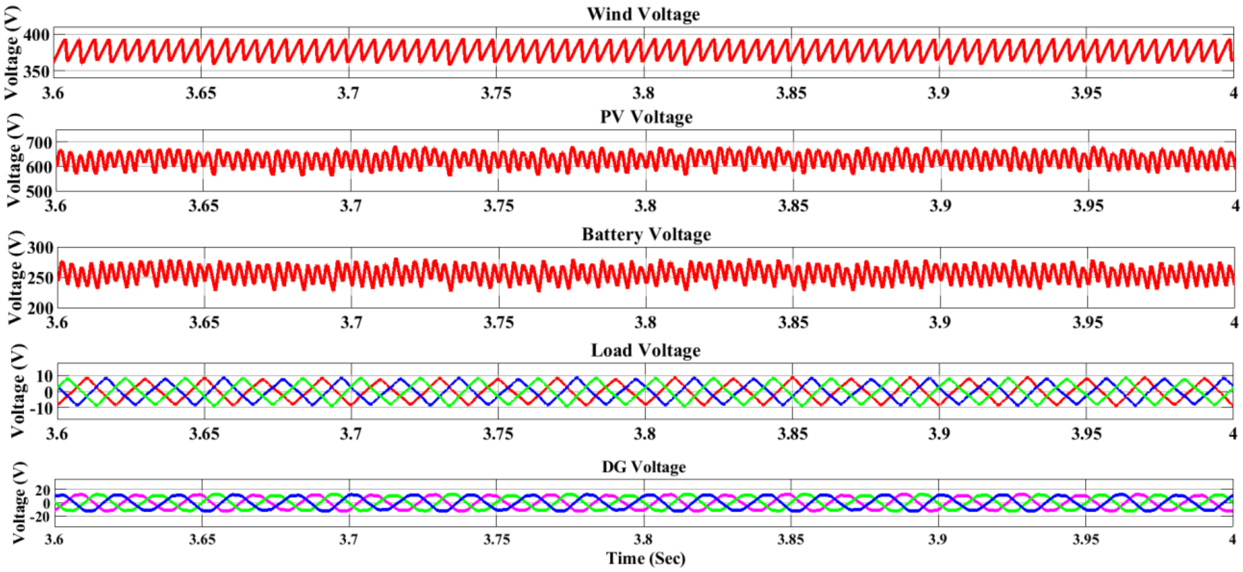


Figure 13: Voltage responses from wind, PV, Battery, Load, and DG module of IHMS for LF dispatch Strategy

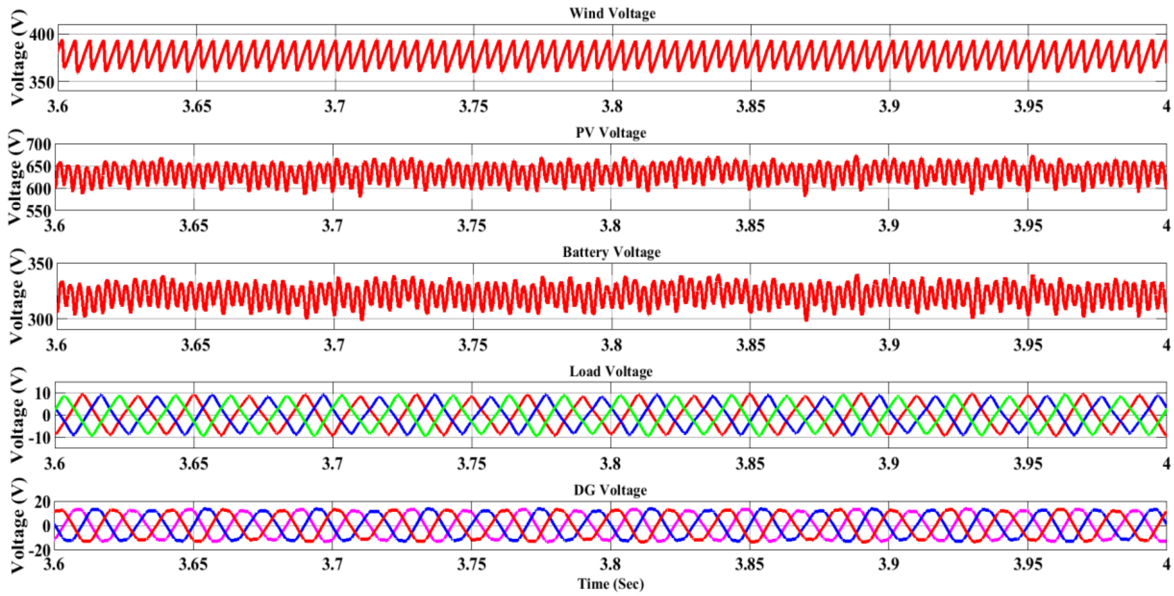


Figure 14: Voltage responses from wind, PV, Battery, Load, and DG module of IHMS for CC dispatch Strategy

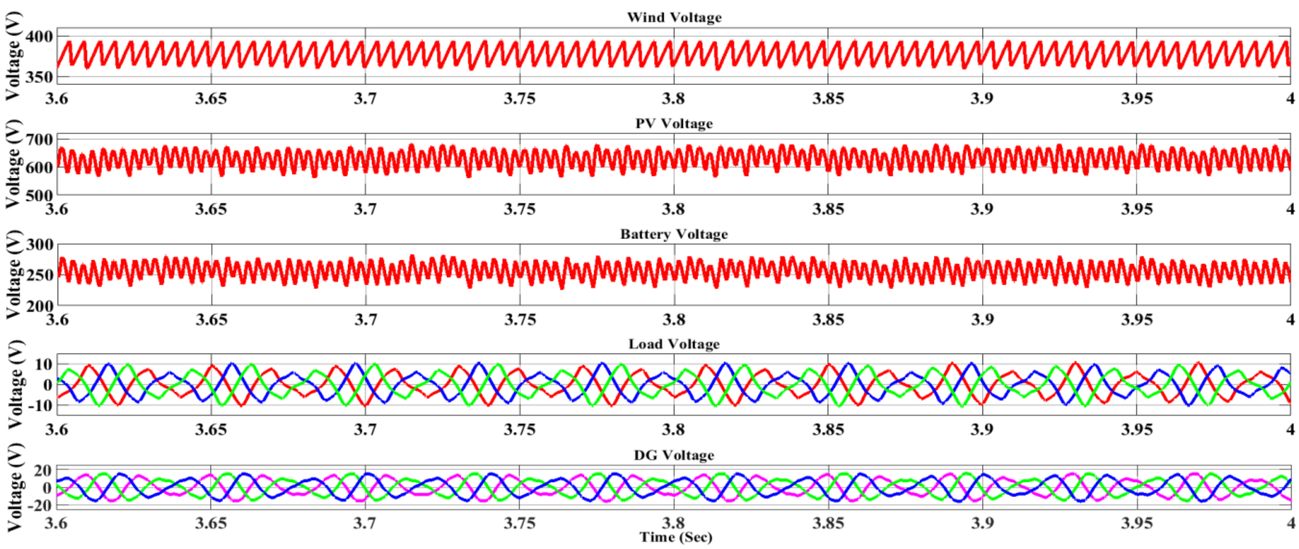


Figure 15: Voltage responses from wind, PV, Battery, Load, and DG module of IHMS for CD dispatch Strategy

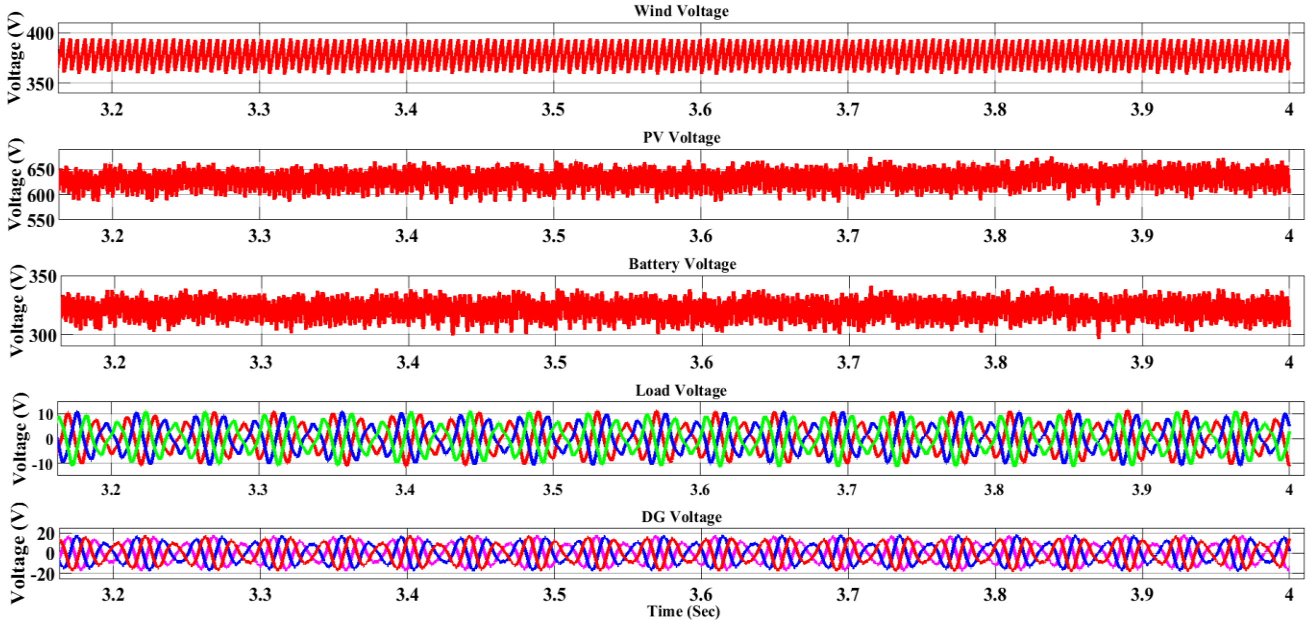


Figure 16: Voltage responses from wind, PV, Battery, Load, and DG module of IHMS for GO dispatch Strategy

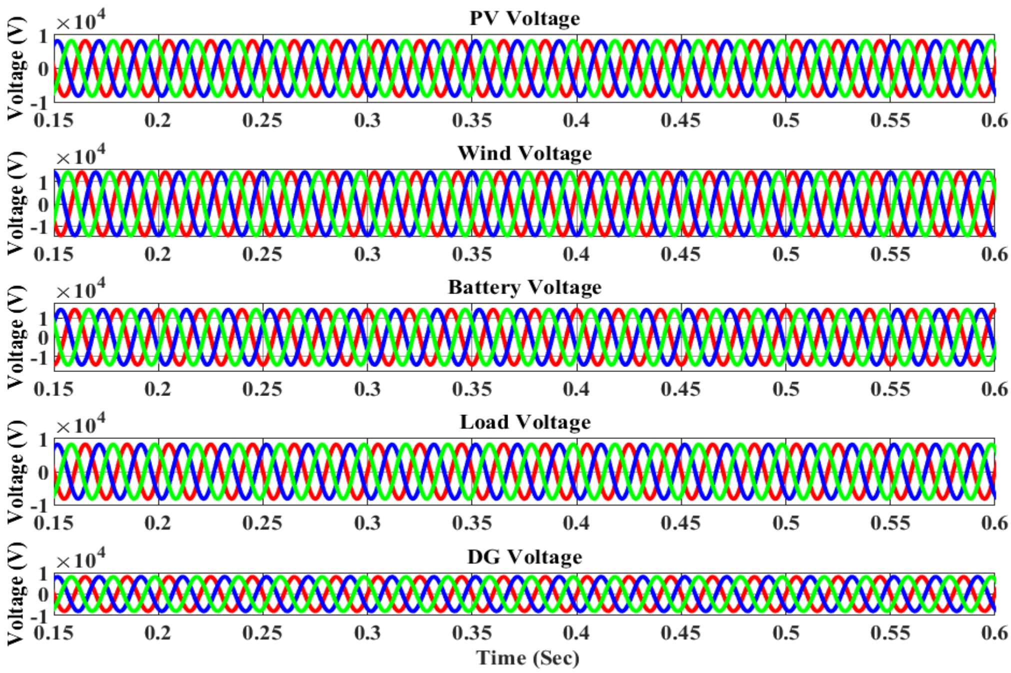


Figure 17: Voltage response from all modules with programmable three-phase voltage as a base case

5. CONCLUSIONS

To cope up with the increasing demand for electrical power, a renewable energy-based solar PV-wind turbine-diesel-battery islanded system has been designed. Analyzing the simulation results obtained under various dispatch strategies, the LF strategy can be stated as the most optimum dispatch technique based on the minimum CO_2 emission, NPC and LCOE. Because of having the maximum CO_2 emission, NPC and LCOE, the CD strategy can be concluded as the worst one. For dedicated loading, each component has been checked for frequency and voltage stability. The most optimal combinations of the components have been simulated and the combination having the highest efficiency has been selected. Matlab/Simulink analysis, according to the most optimal sizes, the frequency, and voltage responses, it can be said that the LF dispatch strategy performed as the best among others for the designed islanded hybrid microgrid. So, finally, it can be concluded that according to the brief studies of dispatch strategies in terms of optimal sizing, techno-economic analysis, and system stability of the designed IHMS, LF dispatch strategy has been proved as the most efficient dispatch technique in terms of economic, environmental and technical aspects. The proposed hybrid renewable off-grid energy model is especially applicable to isolated and islanded areas. The optimal sizing of the generation sources while maximizing the renewables and their transient behaviour would be taken into consideration in future work.

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