Design and Dynamic Modeling of a Solar Electric Boat Power System

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Overview

1. Introduction & Literature Review
2. Sizing of Solar Power System for a Boat
3. *Dynamic Modeling of the Proposed System in Simulink*
4. *Proposed Instrumentation Design and Control Mechanism*
5. Sensitivity and Economic Analysis
6. Conclusion and Recommendation

1. Introduction & Literature Review

Research Objective

- ✓ **Design a solar power system for a river boat in Bangladesh**
- ✓ **Develop a dynamic model of boat power system in Simulink**
- ✓ **Propose a basic control system for a low-cost solar boat and**
- ✓ **Complete a sensitivity economic analysis of a solar electric boat**.

Currently Used Boats in Bangladesh

On the waterway more than 700,000 boats are available. Among those,

- ➢ 60% are diesel engine driven, and
- ➢ 150 types of flood-basin fishing boats, cargo boats, and passenger boats exist.

Challenges

- ➢ Harvesting power from Renewable Energy (Photovoltaic). It fluctuates depending on the season, weather conditions, and geographic location which is one of the prime limitations of alternative sources.
- ➢ The stability between the power generation and the consumption of real-time electricity by a boat motor.

Typical River Boats in Bangladesh

A typical Flood-basin passenger boat (FBPB) could:

- Carry 10-12passengers at a time
- Run at speed 4knots (7.5km/h) and
- Cross the Buriganga river within 12-15minutes.

Fig1.1: Conventional Catamarans type passenger boat (CPB) in Bangladesh

Prospectus of Solar Energy in Bangladesh

- 300 sunny days a year
- Average solar radiation of 4 – 6.5 kWh/m^2/d, peak in April and the lowest in December and
- Air temperature 23.4 °C - 26.5 °C and optimum tilt of PV modules 22° - 27°.

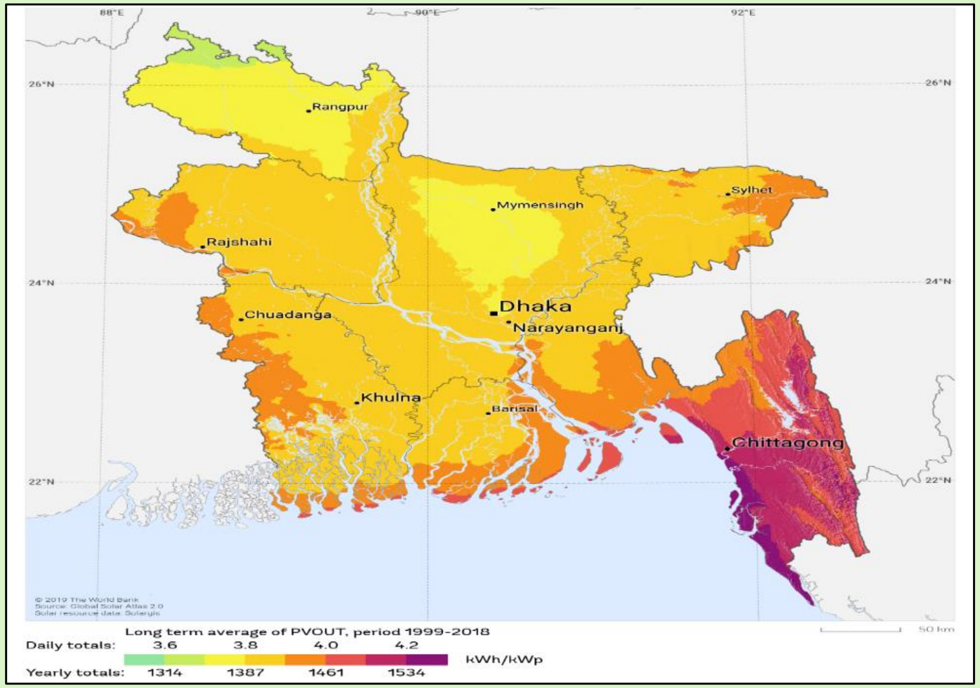


Fig1.2: Bangladesh photovoltaic power potential map in six metrological stations (Dhaka, Rajshahi Chittagong, Khulna, Rangpur and Sylhet

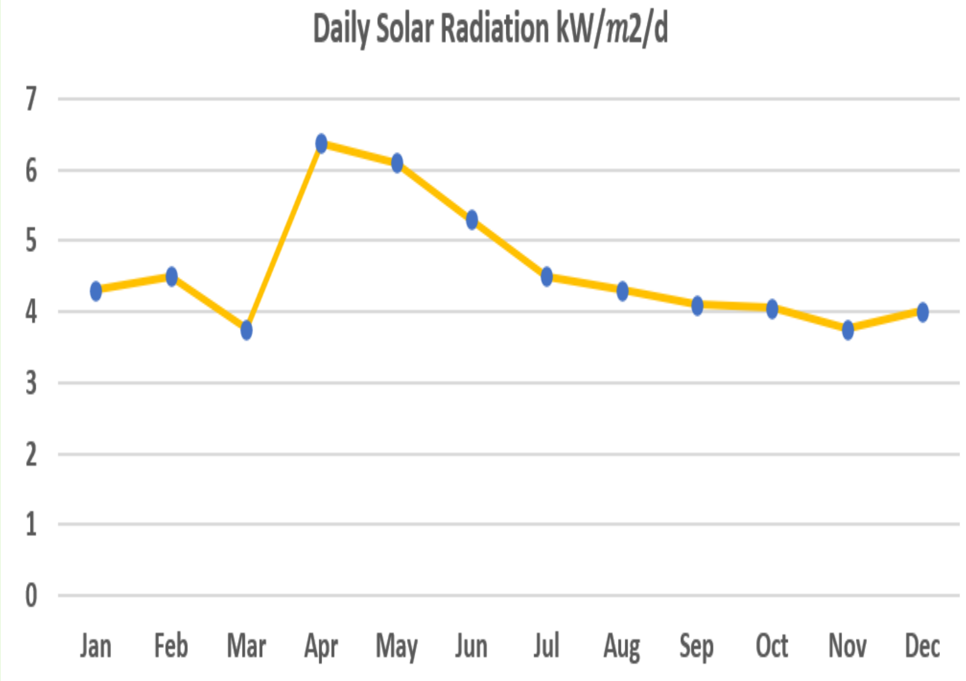


Fig1.3: Monthly average solar radiation profile in Bangladesh

Literature Review

- *PMSM motor driven zero emission electric propulsion boat which was designed for public transportation and water sports events. The designed boat was wave penetrating Catamaran characterised which is powered by lithium-ion batteries and option to charge battery at the harbor and, partly, with photovoltaic solar panels.*

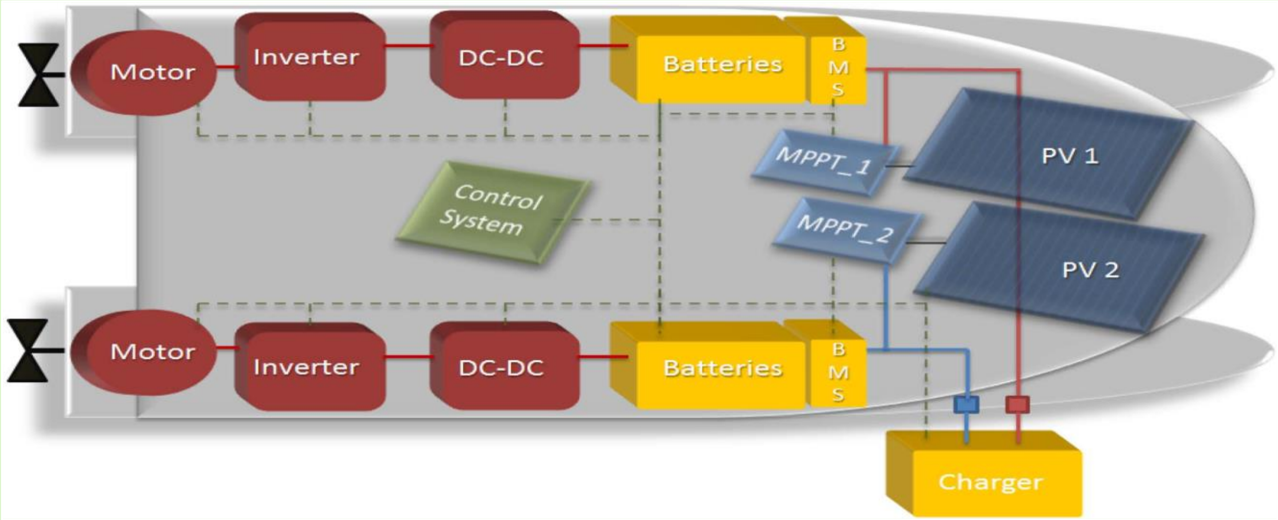


Fig1.4: Diagram of the electric catamaran

- *Optimistic control technique of a solar powered vessel which is driven by an indirect vector-controlled induction motor*

- Three-phase asynchronous machine driven boat which was powered by hybrid power system (solar and small range generator).

- *A country boat which is powered by stand-alone photovoltaic system. Buck-Boost converter has been used to simplify the power system and to make stable the economic factor*

Literature Review

- A mechatronic system was proposed for a solar power boat that incorporates distributed PV system, BMS, motor control and the boat operation control according to the Fig.1.5.

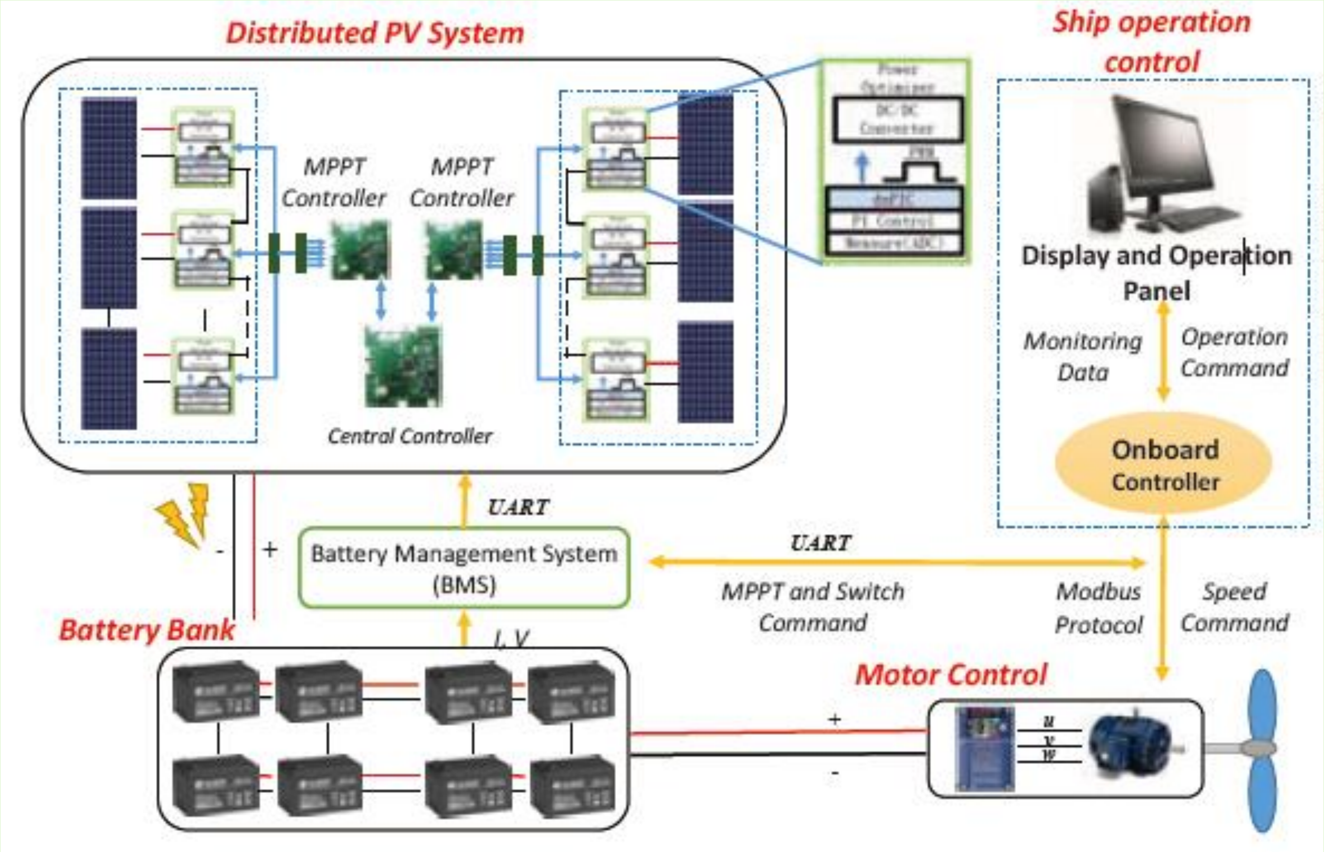


Fig1.5: Schematic diagram for the solar boat mechatronic system

Literature Review

- A conventional ferry boat was converted into solar powered boat in Bangladesg that is shown in Fig 1.6 and the way it was designed is shown in Fig.1.7.

Fig1.6: A complete solar boat

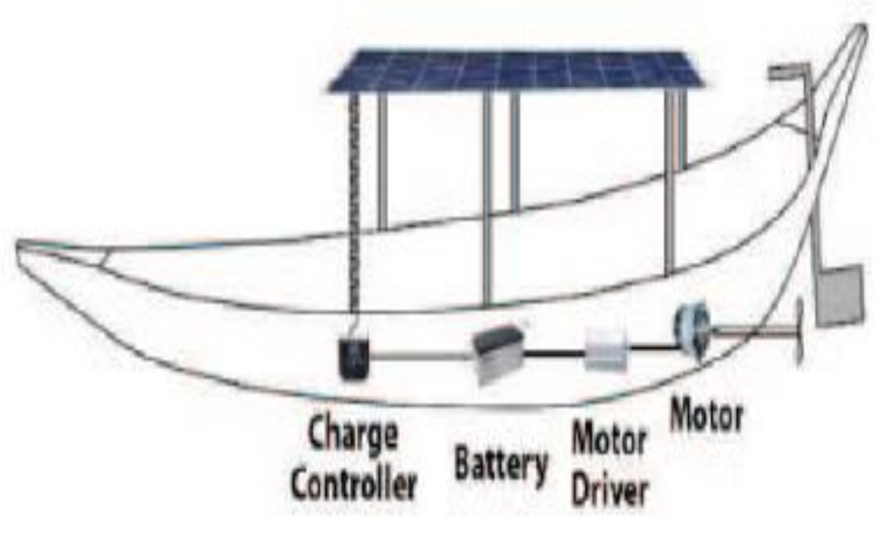


Fig 1.7: Schematic diagram of a solar power driven ferry boat

- A hybrid power system was designed for an electric boat to operate the AC motor , which includes wind turbine, solar PV panel, and polymer electrolyte membrane (PEM) fuel cell as the first, second and third renewable energy source.

Sizing of Solar Power System for a Boat

Design overview

The proposed electric motor-driven boat is powered by a hybrid power system which includes solar PV, generator, and battery bank (BB).

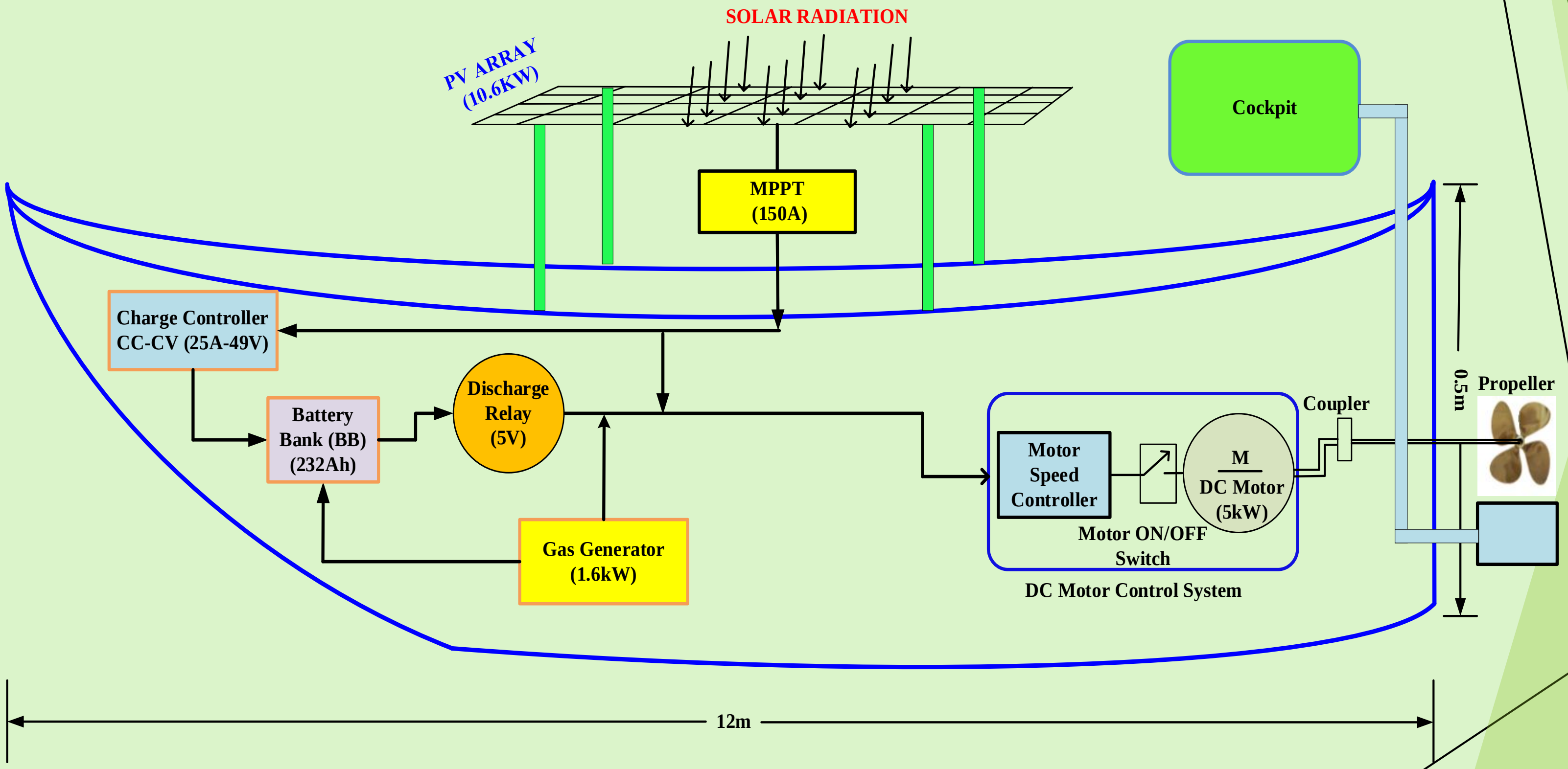


Fig.2.1: The schematic diagram of a hybrid-powered Catamarans type passenger boat (CPB)

Boat Components Sizing Calculation

Boat Speed Selection

- ✓ The designed hull speed of the proposed boat is 15.58km/hr, calculated by using equation,

  Hull Speed = 1.34* $\sqrt{(\mathrm{LWL})}$ and
- ✓ The chosen boat speed is 10km/hr (5.4 knots)

Power Demand Calculation for Boat

The necessary horsepower to achieve hull speed, defines according to the below equation:

$$\text{Motor power (Horsepower)} = (\text{Displacement})/((150)^2/(\text{Hull Speed})^2)$$

$$\text{Motor power} = 6.86\text{hp} \cong 5.0\text{kW}$$

Boat Motor selection

There are various types of DC motors are available in the market, like:

- ➢ Induction motor (need an inverter (DC to AC) and driver to control speed, also high maintenance cost),
- ➢ DC shunt motor (the existence of brushes while utilize frequently the magnetic field could be badly-behaved), and
- ➢ Brushless DC motor

We have chosen A 5.0kW 48V 3000rpm rated brushed permanent magnet motor

Boat Components Sizing Calculation

Energy Demand Calculation

The daily required power and energy are approximately 5.34kW and 42.10 kWh, respectively which has been calculated by equation,

$$\text{Energy demand} = \text{Load(kW)} \times \text{Time(hr)}$$

Boat Specifications

Boat Hull Type	Catamarans type of passenger boat (CPB)
Boat materials	Fiber Glass Polyester materials
The gross weight of the boat (full load capacity)	2400kg (5291lb)
Passenger on board	20 people
Boat length	12m (39.37ft)
Boat beam (the transverse distance between the outer sides of the boat)	4.8m (15.75ft)
Displacement of water by fully loaded boat	2400kg (5291lb)
Maximum and the safest Hull speed	15.58km/hr (8.41knots)
Considered Hull speed	10km/hr (5.4knots)

HOMER Input Parameter

Daily Load Profile

The solar boat will be in operation 220days in a year. Annual average energy demand is scaled 25.38kWh/d which is obtained by using following equation:

Scaled value = ((operating days/ year)/(365days))*energy demand

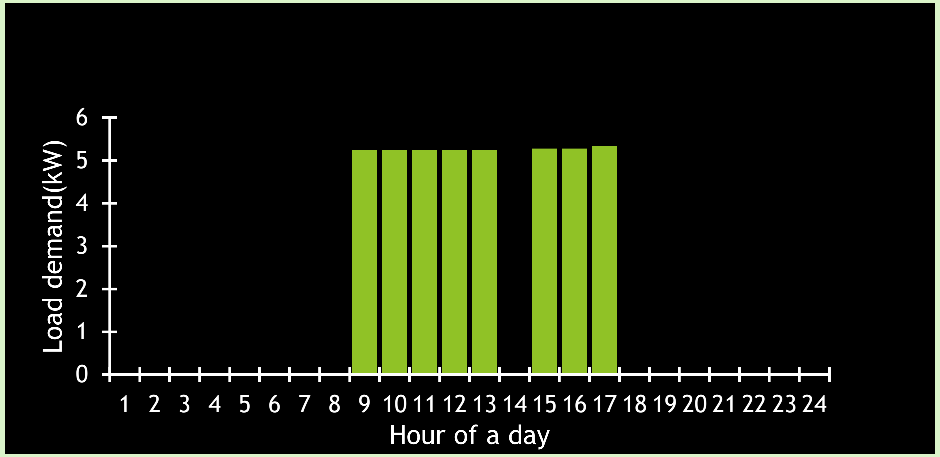


Fig.2.2: Daily load profile for solar boat

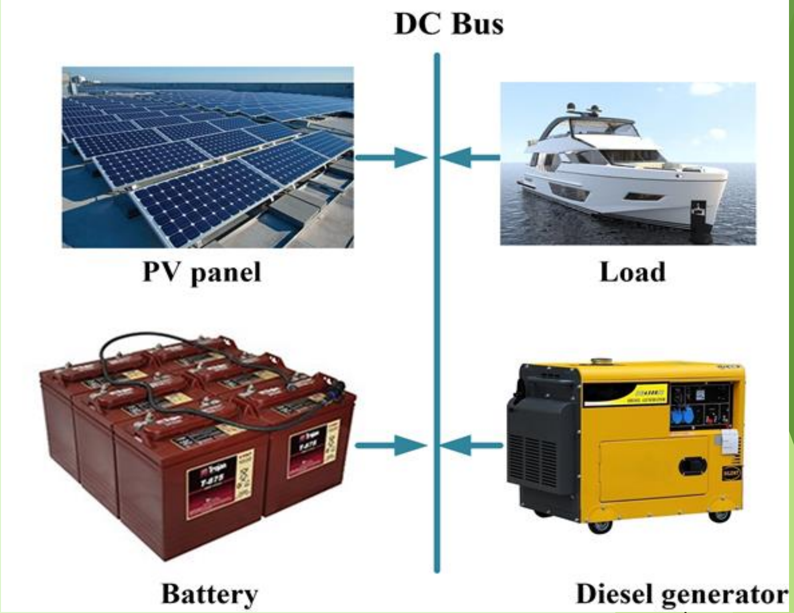


Fig.2.3: Schematic layout in HOMER of the proposed hybrid energy system for solar boat

Solar PV panel

We have chosen 330 Watts, 24 Volts, and 1.96m x 0.992m polycrystalline 72-cell solar panel.

Capacity (kW)	Capital/kW ($)	Replacement cost ($)	O & M cost ($/year)	longevity (year)	Derating Factor (%)
1	650.00	0.00	10.00	25.00	88.00

HOMER Input Parameter

Battery Parameter

We have considered a battery with a nominal voltage of 6.0V, nominal capacity 240Ah (1.45kWh).

Nominal voltage (V)	String Size (V)	Capital ($/Battery)	Replacement ($)	O & M ($/year)	Throughput (kWh)
6	48	362.00	330.00	15.00	1257.40

Gas Generator

For the emergency, we have considered a small-sized gas generator and the details are given below table:

Capacity (kW)	Capital/kW ($)	Replacement cost ($)	O & M cost ($/year)	Life time (hours)	Diesel fuel price ($/L)
1.6	600.00	400.00	0.05	12000.00	0.76

Solar Charge Controller

The solar charge controller (MPPT) rating is 140A which is designed based on the following equation and costing has been given in the below table:

$$\text{MPPT current rating} = (\text{total required power})/(\text{BUS voltage})$$

Capital ($)	Replacement ($)	O & M ($/year)	Lifetime (years)	O & M ($/year)	Throughput (kWh)
100.00	100.00	10.00	4	15.00	1257.40

Homer Simulation Result

The proposed model was run in Homer software. It is found that the battery bank (BB) consists of 02 string battery and contains 08batteries/string, each battery rated 6V, 240Ah whereas the system bus voltage is 48V DC.

Table: Summary of hybrid PV-DG-Battery system

System Sizing	
PV Module	10.6 kW
Generator	1.6 kW
BB	18.5 kWh
Electrical Energy	
PV energy	15990 kWh/yr
Generator	779 kWh/yr
Total	16769 kWh/yr

Cost Summary	
COE	0.228$/kWh
NPC	$ 15625.00
Annualized cost	$ 2115.00
Fuel Consumption	
fuel consumed/yr	223 L
Avg. fuel consumed/d	0.611 L
Avg. fuel consumed/hr	0.0255 L

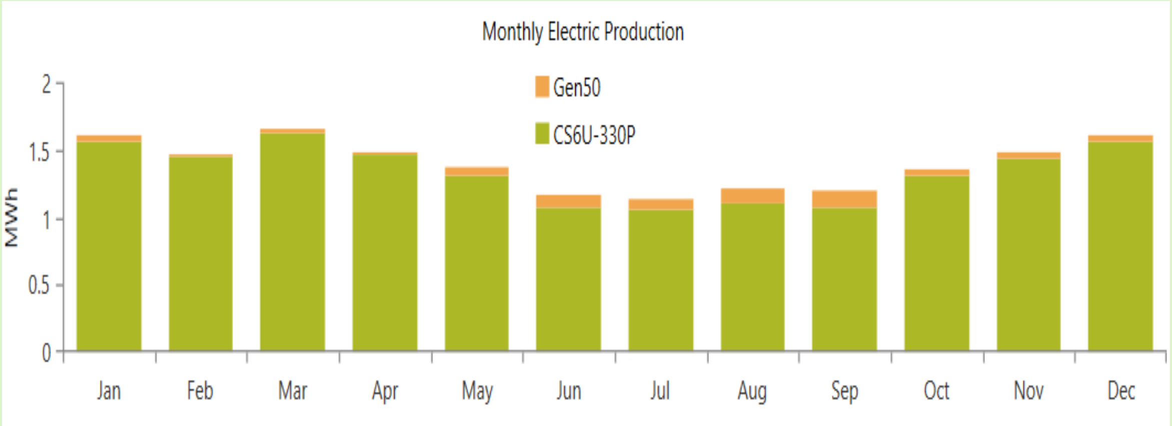


Fig.2.4: Monthly electricity production by PV and Generator

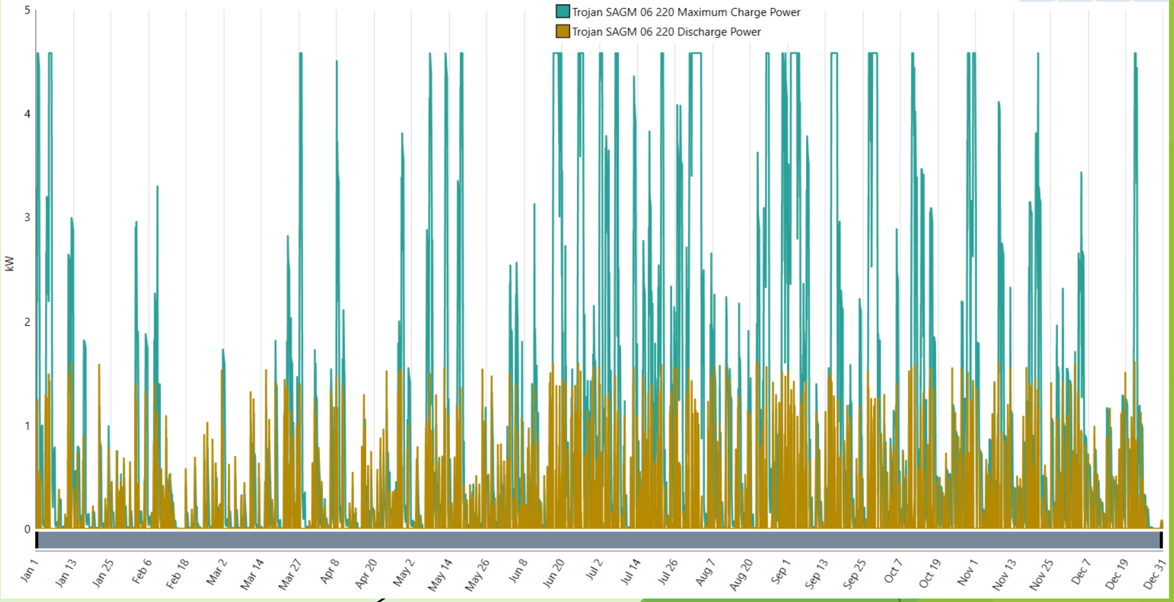


Fig.2.5: Charging and discharging time-series graph of Battery over a year

Homer Simulation Result

The harvested energy from solar PV and generator, as well as the stored energy in BB is always been utilized by the proposed system to drive the boat, Fig.2.6 and Fig. 2.7.

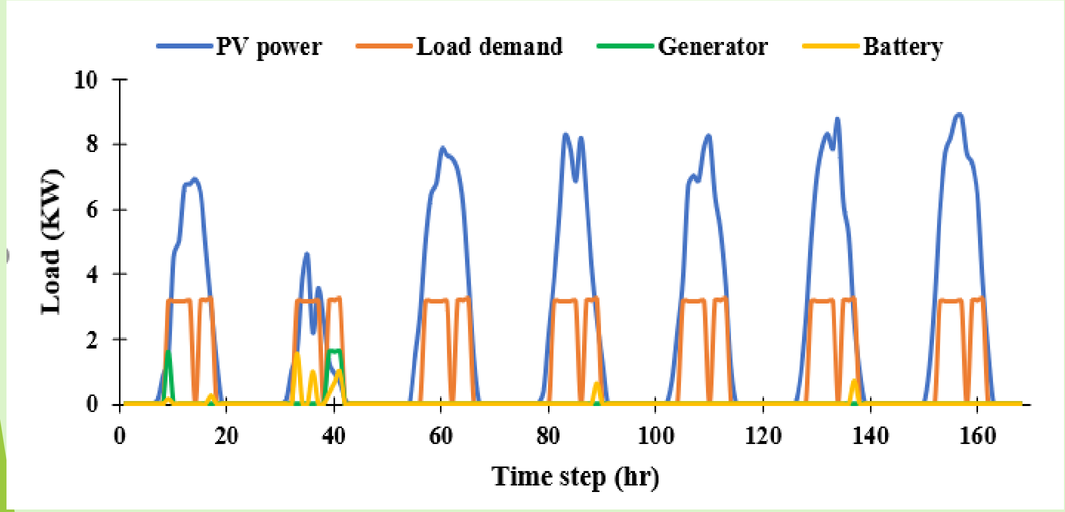


Fig.2.6: Energy share for hybrid PV-Generator-Battery system over a week in March

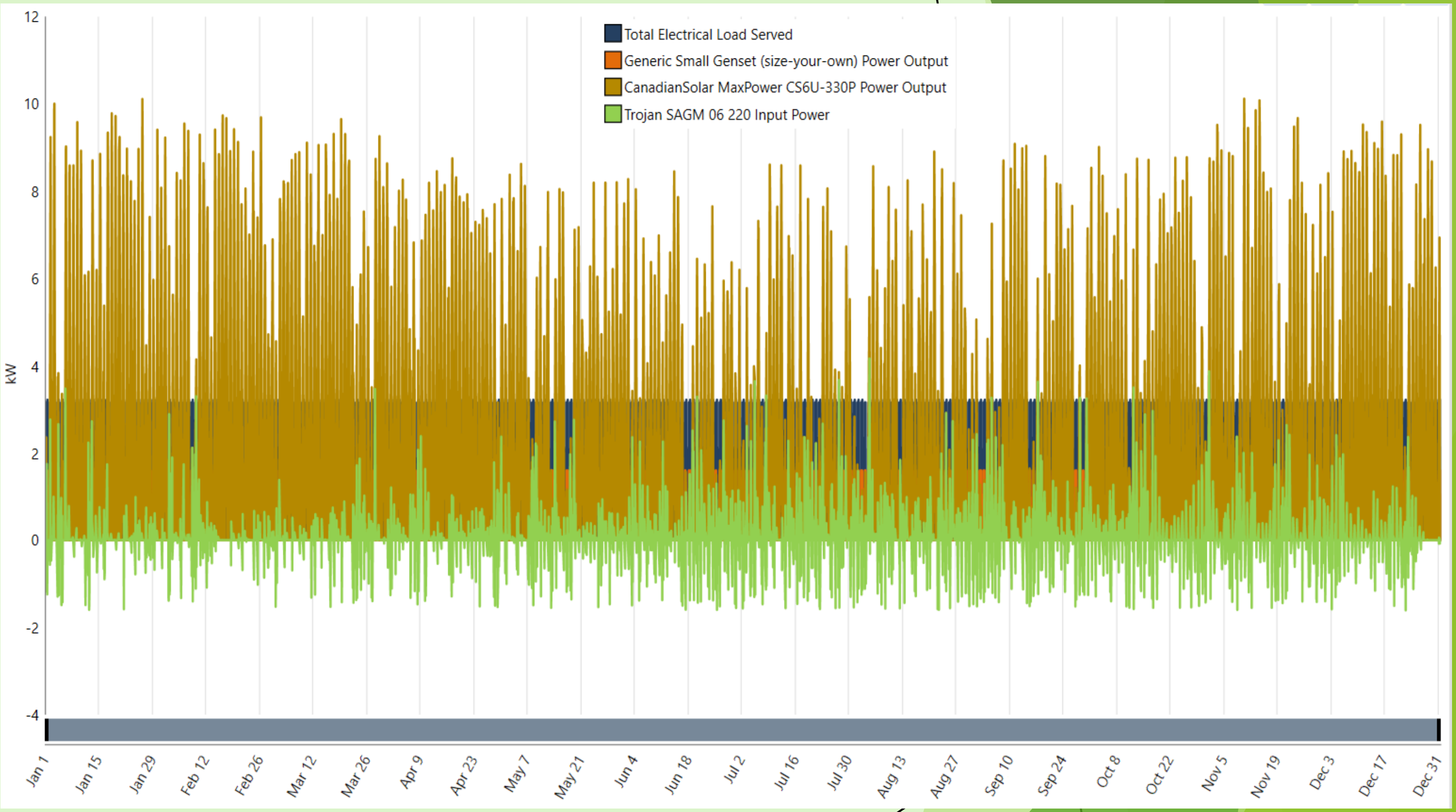


Fig.2.7: Time-series graph of energy share by PV-Generator-Battery over a year

Proposed Design to Fix PV Array on Boat's Roof

The area of the boat is 57.6m^2 ,the total area of the PV module is 62.3 m^2. The boat's roof area becomes 63.6 m^2 by extend the roof by 0.25 m with help of cantilever support from both sides. 10.6kW PV array (16nos of parallel string and 2nos series/string, each PV module 330W), Battery Bank(440Ah) consists of 2nos of parallel string and 8nos/string, each battery rated 6V, 220Ah.

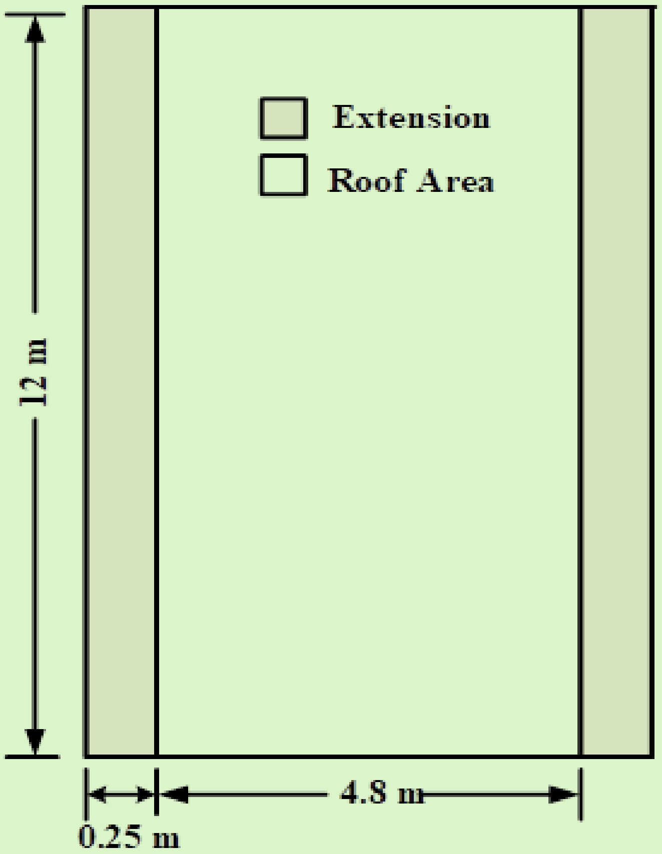


Fig. 2.4: Design to fix PV array on the proposed solar boat.

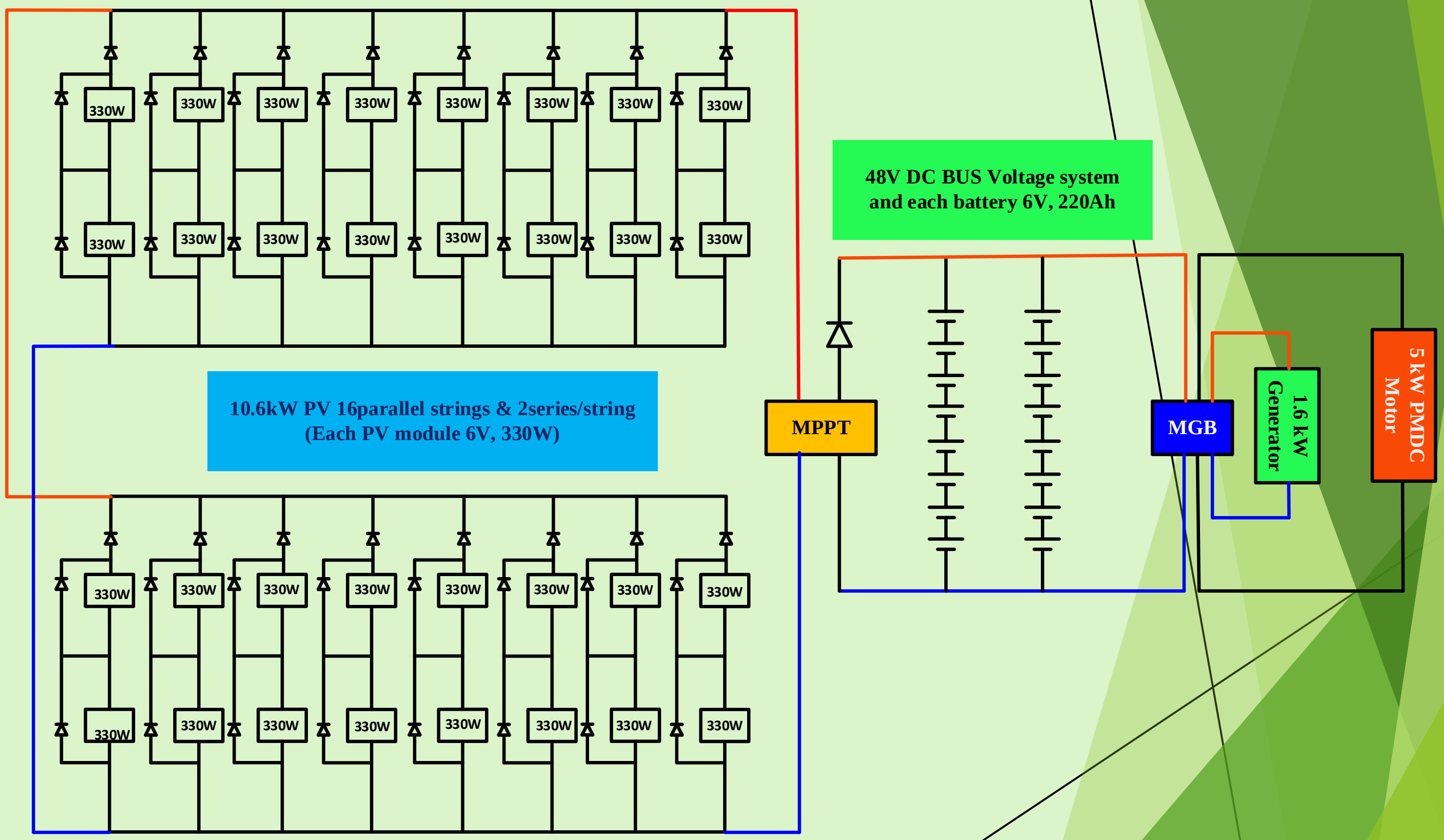


Fig. 2.5: Designed components PV module, Battery Bank, Generator and PMDC motor of the proposed solar boat

3. Dynamic Modeling of the Proposed System in Simulink

Purpose of Dynamic Modeling

- ✓ To analyze the system components' dynamic performance
- ✓ To predict how the scheme will function, if implemented in real life and
- ✓ For instrumentation layout

Setup for Dynamic Modeling in Simulink

- Solar Irradiance and Temperature Signal
- PV Array (32nos of module, series 02/string and parallel strings 16nos)
- Perturbation and Observation (P & O) Method for the maximum power point tracking (MPPT)
- BUS BAR
- Boost Converter
- Constant voltage (48V to 50V) dropper (CVD) to load
- Battery Bank (48V, 440Ah)
- Battery Charge Controller (BCC); [48V to 50V and 25A]
- Battery Discharge Controller (BDC)
- DC Generator (48V, 1.6kW)
- Permanent Magnet DC Motor (PMDC);[48V, 5kW, 3000rpm and gain K=0.0001612]
- PMDC Motor Driver (consists of PI controller for rpm, DC current controller and PWM generator)and
- Switching Controller for DC Generator and PMDC Motor

Architecture of the Proposed System

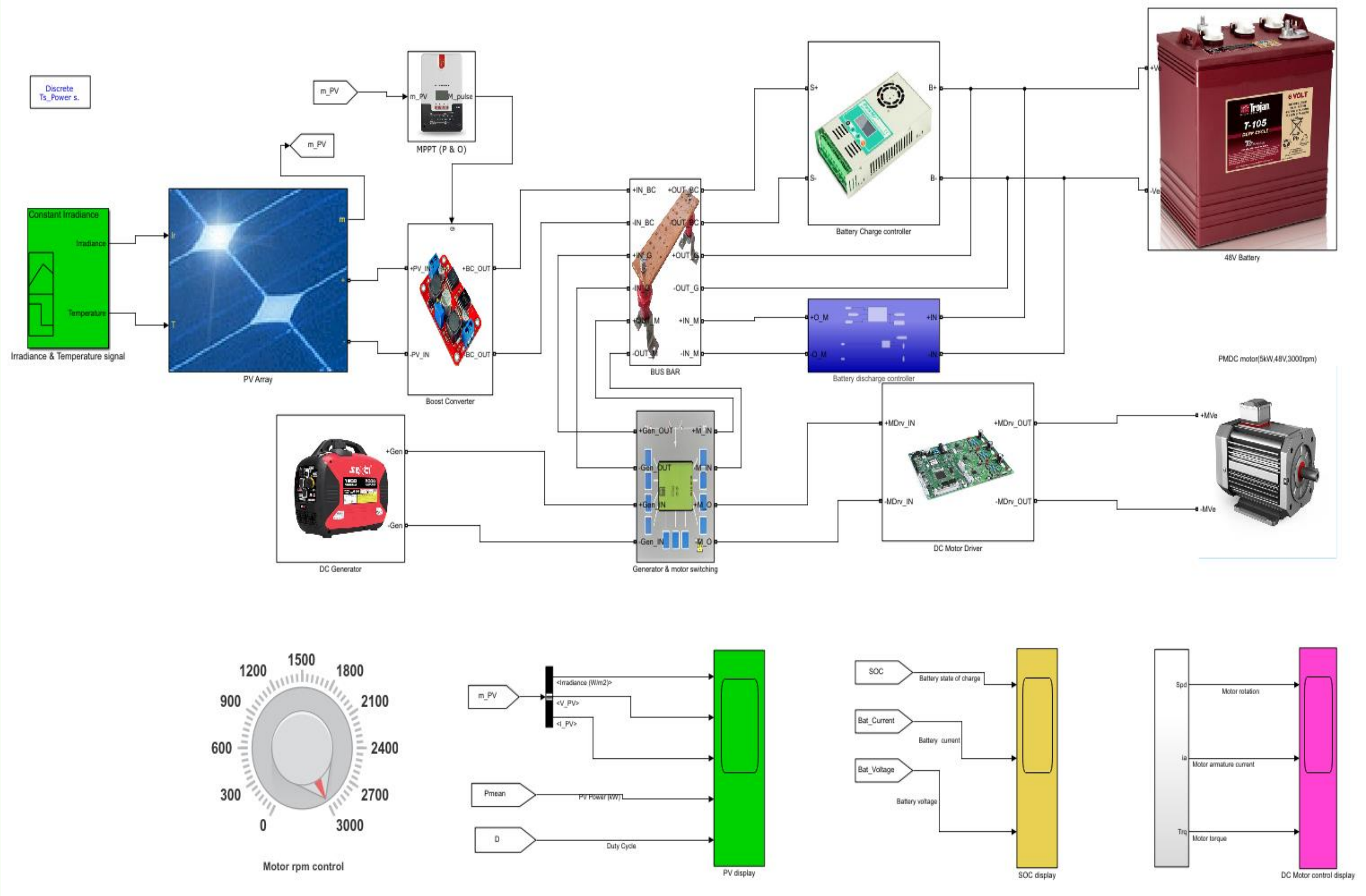


Fig. 3.1: Simulink model of the proposed system in MATLAB

Control Mechanism of the Proposed System

Ensures 48V to 50V constantly, while:

PMDC motor speed increasing i.e. more electrical power require (V-constant, I-increasing) and

PMDC motor speed decreasing i.e. less electrical power require (V-constant, I-decreasing).

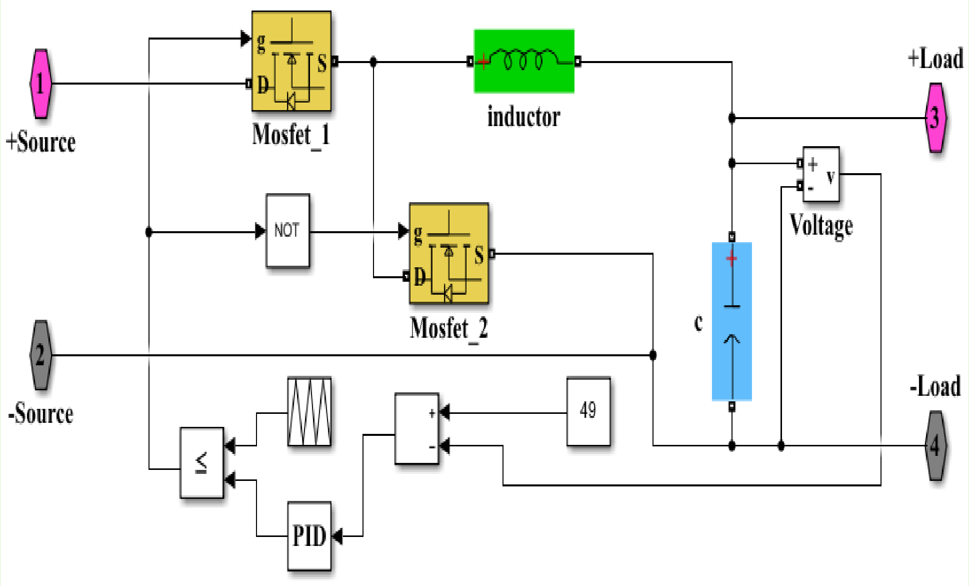


Fig. 3.2: Constant voltage (48V to 50V) dropper (CVD)

Battery discharge switch ON state, while:

DC gas generator is either in ON or OFF mode

Solar irradiance is less than 700w/m^2 and

Solar irradiance is greater than 700w/m2 and motor speed more than 2500rpm.

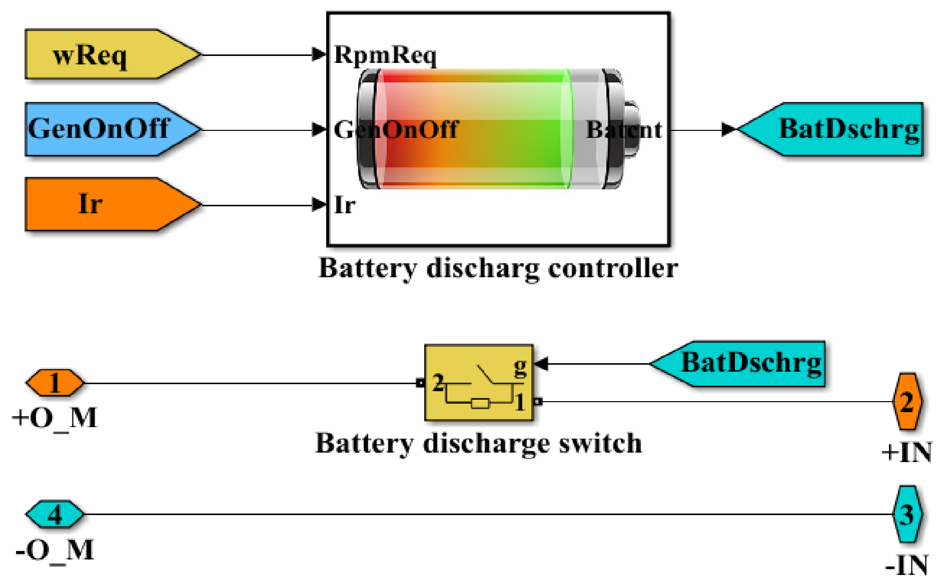
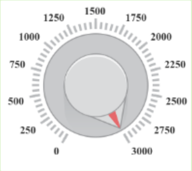


Fig. 3.3: Battery discharge controller Simulink model)

Control Mechanism of the Proposed System

PMDC Motor's Speed Control

- Requested speed (0 to 3000rpm) launched by knob
- Actual revolution (ω) is tuned by PI controller
- Motor's I_a is controlled by DC current controller
- PWM generator produce final pulse for the rectifier
- Finally, rectifier delivers the controlled current to the PMDC motor to response accordingly.



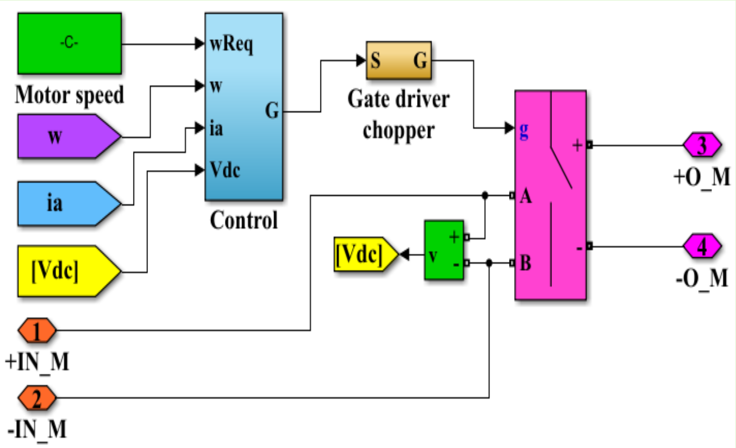


Fig. 3.4: Proposed PMDC motor control system in the Simulink

Switching Control Between Generator and Motor

- While, SOC < 54% ,Motor becomes disconnected
- While 74% ≤ SOC ≥ 55% , Generator and Motor both are connected and
- While SOC ≥ 74%, only Generator becomes disconnected.

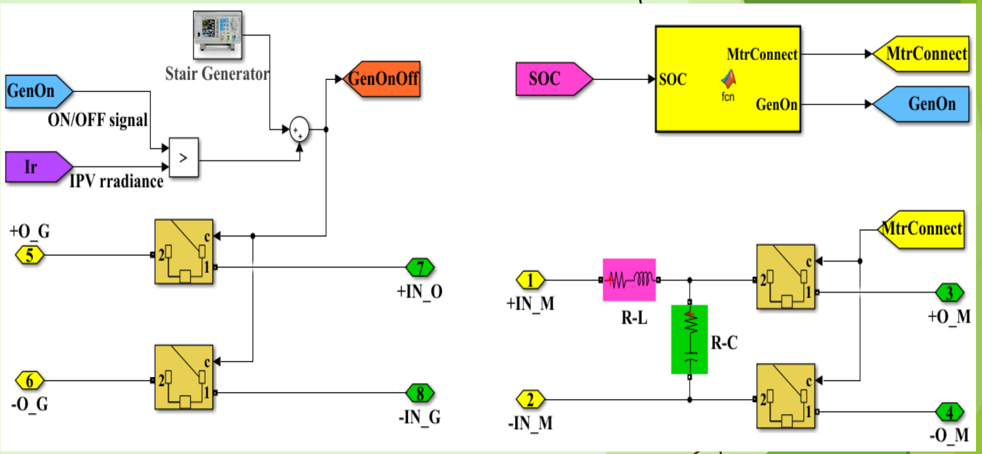
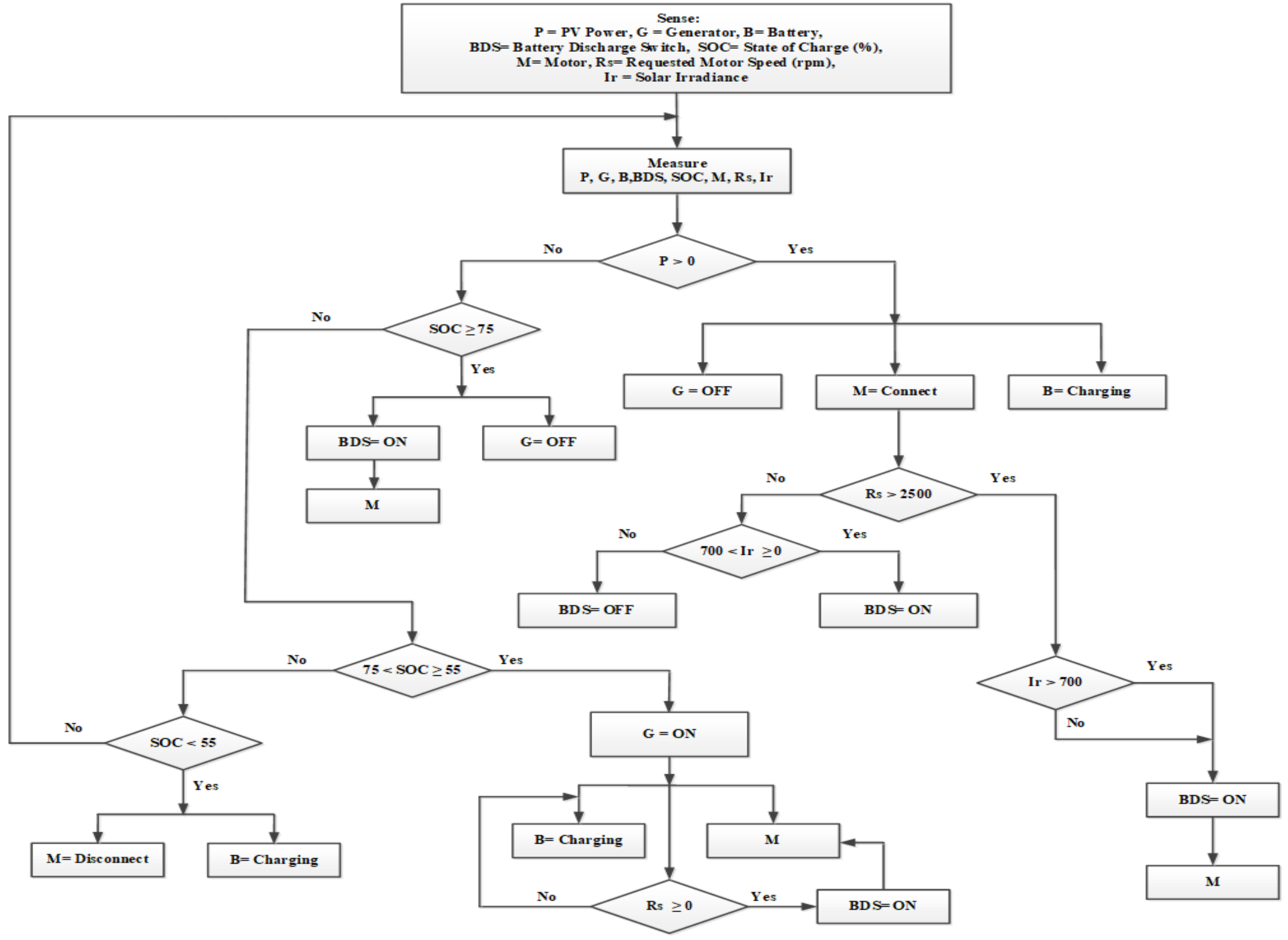


Fig. 3.5: Switching controller Simulink model for DC Generator and Motor

Functional flow chart of the proposed of the Dynamic System



MATLAB Simulation Result Analysis

The MATLAB simulation total time has been considered for 40seconds, and,

1. Partial cloudy sky T= 0sec to T= 10sec Clear sky T= 10sec to T= 20sec
2. Completely cloudy sky and only battery back up T= 20sec to T= 30sec and
3. Completely cloudy sky with Generator T= 30sec to T= 40sec

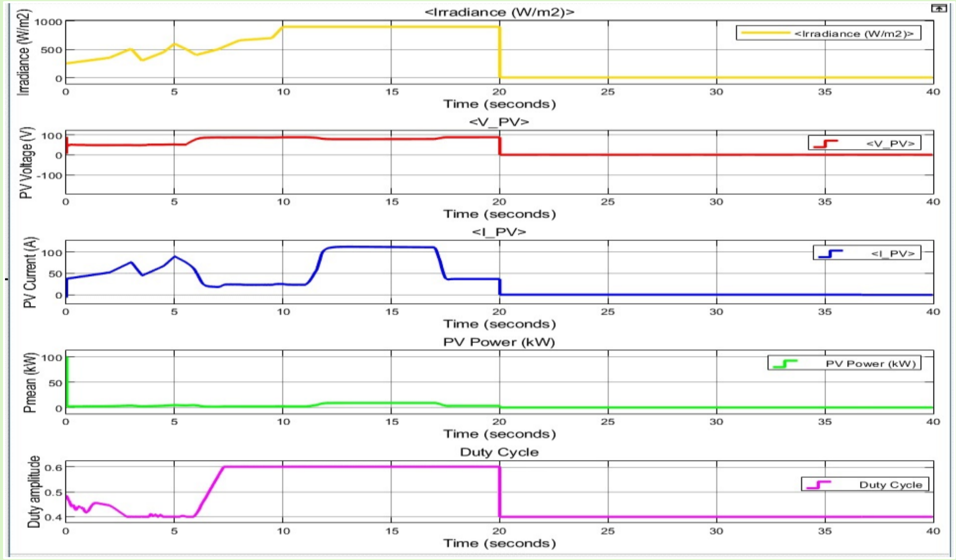


Fig. 3.6: Graph of PV irradiance (W/m2), PV Voltage (V), PV Current (A), PV mean power (kW), and PV Duty cycle amplitude versus time in second

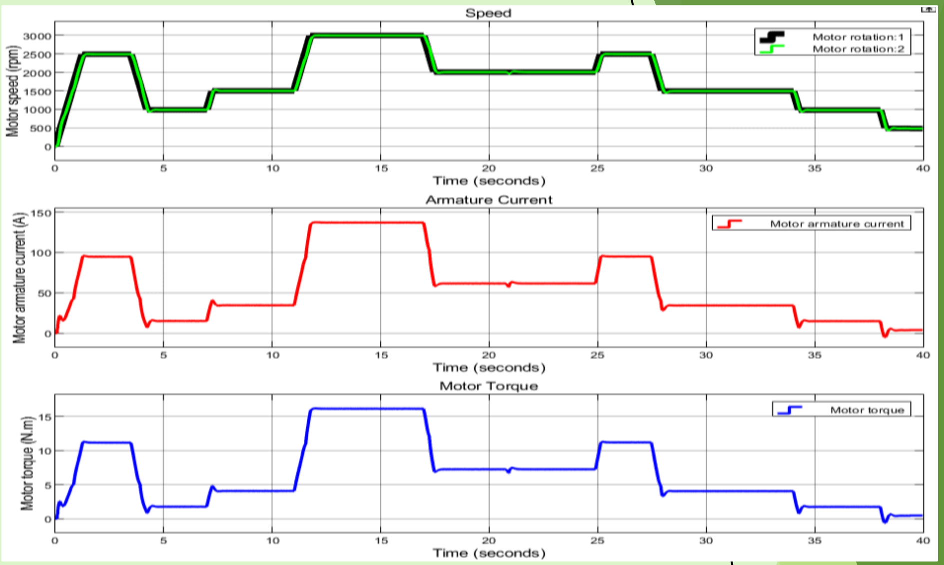


Fig. 3.7: Graph of Motor speed (rpm), motor armature current (A), and motor torque (N.m) versus time in seconds

The system voltage range has considered 48V-50V, and concluded from the MATLAB simulation, that:

- ✓ 10.6kW PV generates 8.82kW power, 12% variation noted.
- ✓ MPPT trigger pulse according to the required load and
- ✓ The motor driver is able to catch the requested speed within a sharp time.

MATLAB Simulation Result Analysis

- ✓ The 48V, (220Ah + 220Ah) rated battery could serve the desired current to run the motor (0 rpm to 3000 rpm),
- ✓ PV could charge the battery @ constant 25A and 49V through the battery charge controller,
- ✓ 1.6kW rated DC gas generator able to run the motor at a maximum 2500 rpm and charge the battery @ constant 25A and 49V while motor revolution lies in 500rpm, otherwise slow charging.
- ✓ After 3hours, the battery will be 80% charged, and 5hours after, the battery will be fully charged (100%)
- ✓ Fixed voltage controller capable to ensure constant 49V to the motor and
- ✓ The battery's discharge controller discharges power according to the system requirement

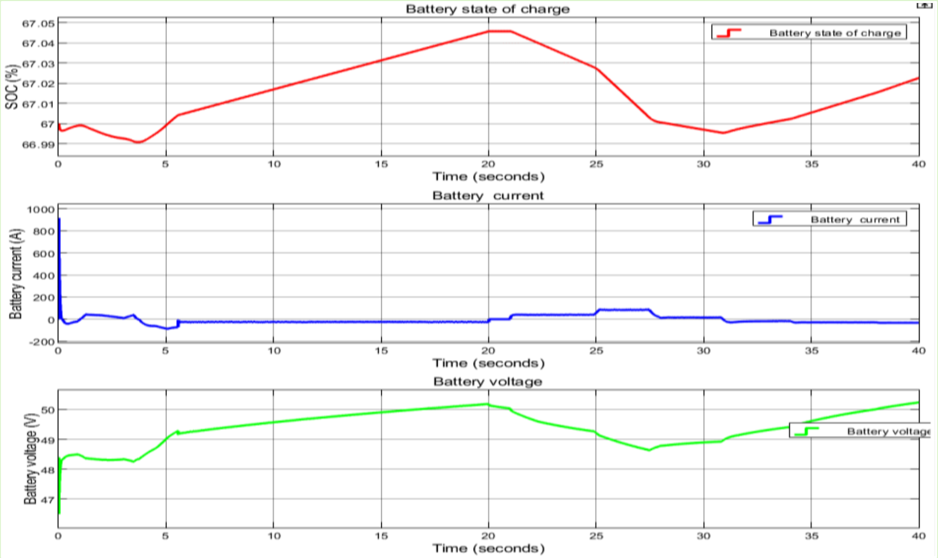


Fig. 3.8: Graph of SOC (%), Battery current (A), and Battery voltage (V) versus time in seconds.

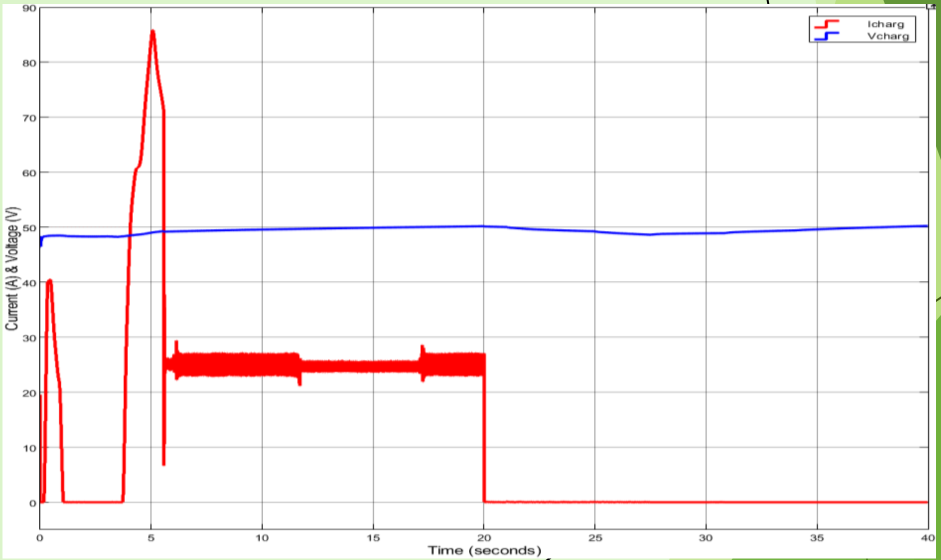


Fig. 3.9: Battery Charger Charging Current (A) and Voltage (V) versus time in second

4. Proposed Instrumentation Design and Control Mechanism

Proposed Instruments for Measuring, Collecting and Displaying Data of the Proposed System

- The system instruments are proposed to instal in the cockpit of the boat
- Airmar DST810 multi-sensor (Fig4.1) is recommended to measure water depth, boat speed, and water temperature
- Airmar "CAST App" (Fig4.3) and Raymarine i70 multifunction display instrument (Fig4.2) is recommended to display measured data from DST810 transducer.
- XCSOURCE branded digital instrument is proposed to measure and display battery capacity and voltage (Fig4.4).

Fig4.1: DST810 sensor

Fig4.2: Raymarine i70

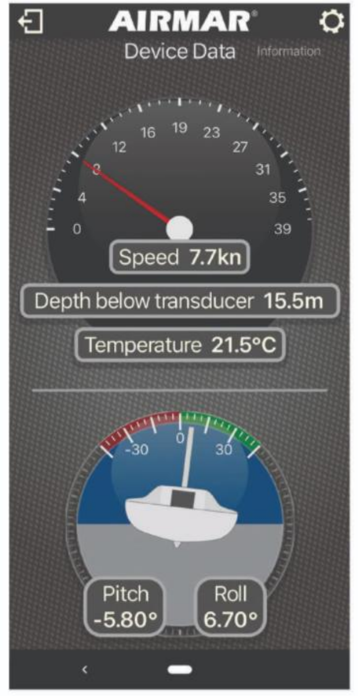


Fig 4.3: Airmar "CAST App"

Fig4.4: XCSOURCE for Battery SOC & Voltage measuring and display instrument.

Proposed Equipment of the Proposed System

- PV Module: 330W rated Canadian solar panel brand and CS6U-330P model PV module.
- MPPT Charge Controller: 48V DC, 150A rated Queenswing branded QW-JND-X Series MPPT
- Brushed PMDC Motor: 5.0kw 48V 2800RPM rated Super Motor brand motor.
- Motor Driver: 5kW rated Entweg branded programmable PWM PMDC motor driver.
- Lead-Acid Battery: 6V, 220Ah rated Trojan branded battery

Fig4.5: A super brand brushed PMDC motor

Fig4.6: Entweg brand motor driver

Proposed Switching Control Mechanism among BB, PV module and Generator

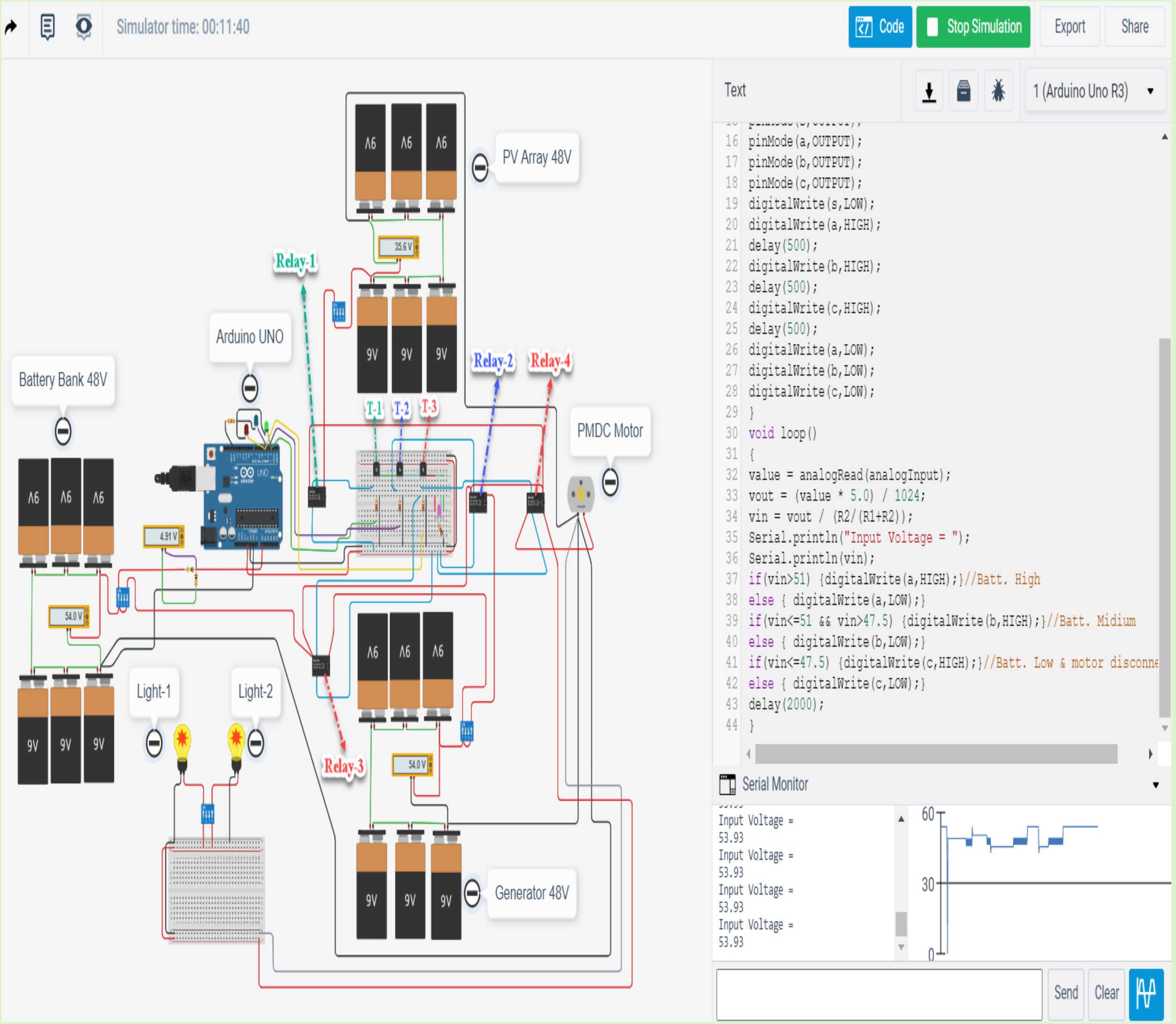


Fig.4.1: Proposed PV array, battery bank, generator and motor switching control with code.

Table: Proposed Control Functions by Arduino

Case No.	Arduino Port No.	LED	LED status	SOC	Remarks (Measured voltage = Vin)
Case-A: PV ON, Generator OFF & Motor ON	2	LED-G (Green)	HIGH	High	Vin > 51V, else LED status LOW
Case-B: PV OFF, Generator ON & Motor ON	3	LED-B (Blue)	HIGH	Medium	51V ≤ Vin > 47.5V, else LED status LOW
Case-C: PV OFF, Generator ON & Motor disconnected	4	LED-R (Red)	HIGH	Low	Vin ≤ 47.5V, else LED status LOW

5. Sensitivity and Economic Analysis

Table: Sensitivity variables

Sensitivity variables	Values
Solar-scaled average (kWh/m²/day)	4.50, 4.65*, 4.70
Diesel fuel price ($/L)	0.70, 0.76*, 0.80

Summary of Analysis:

- ✓ The solar radiation and diesel price's baseline value is 4.65 kWh/m²/day and 0.76$/L, respectively.
- ✓ The optimized COE for the system is 0.228$/kWh
- ✓ Increase in solar radiation reduces the COE (Fig5.1)
- ✓ COE reached its maximum value of 0.289$/kWh & NPC comparatively higher $19,000, while 0.80$/L diesel price and 4.5 kWh/m²/day solar irradiation (Fig5.2) and
- ✓ At the diesel price of 0.70$/L, NPC is comparatively lower at $14,000 (Fig5.2).

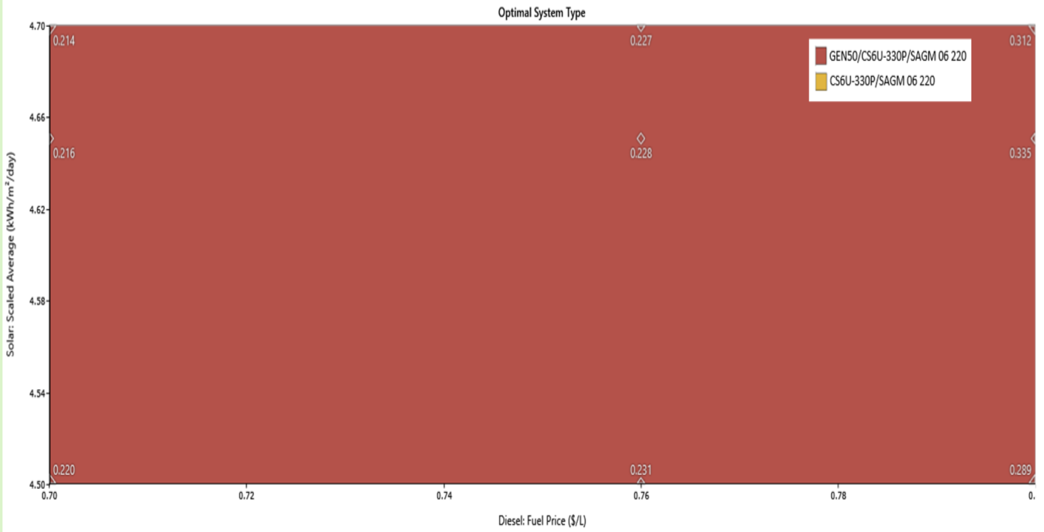


Fig.5.1: The sensitivity of solar radiation and diesel fuel price for PV/Diesel/batt system on COE.

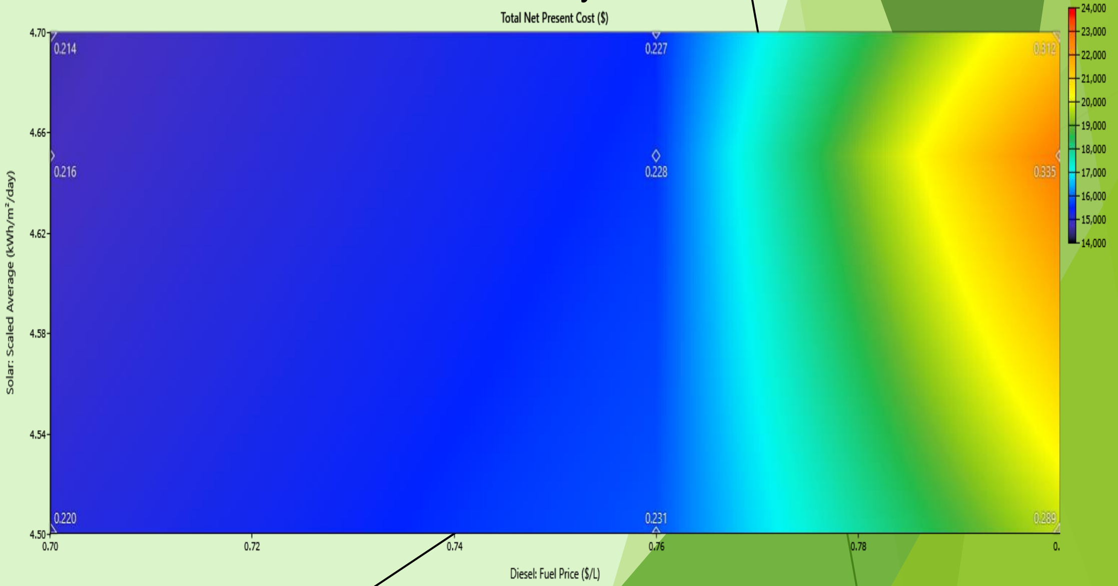


Fig.5.2: The sensitivity of solar radiation and diesel fuel price for PV/Diesel/batt system on NPC.

Payback Period

The payback period defines the total time that it requires to recover the expenditure of financing. The proposed boat could travel 8trip (80 km) in a day and convey 20nos of passengers per trip. If the ticket price 0.01 $/km/person and the proposed boat operates 220days in a year, then the total annual income will be $ 3520.00.

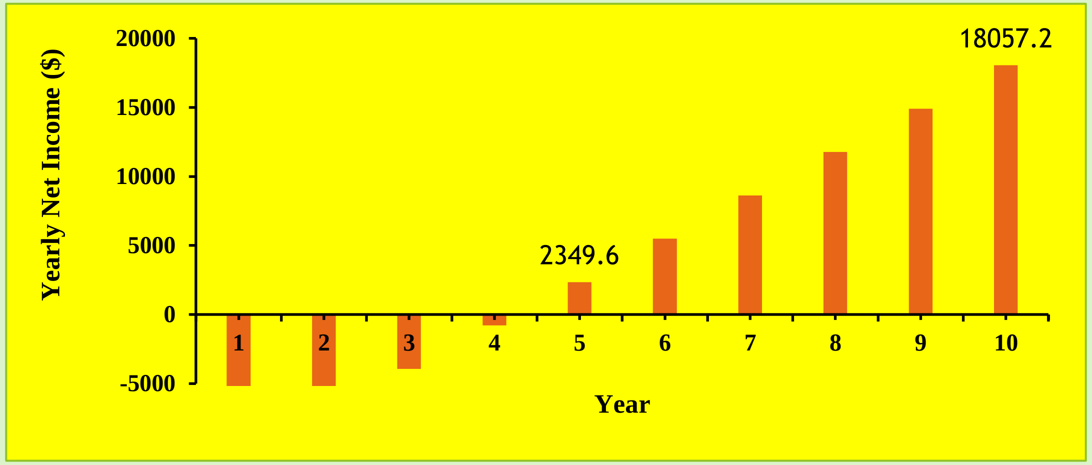


Fig. 7 Payback period graph of the proposed system

Environmental Benefits

- ✓ Decreased atmosphere pollution.
- ✓ Decreased dependency on fossil fuel.
- ✓ Decreased power costs.
- ✓ Decreased water consumption and
- ✓ Slow down weather changes over.

6. Conclusion and and Recommendation

Conclusion

- ✓ Firstly, manual calculation has performed to obtain the boat's dimension, carrying capacity, displacement of water and hull speed. Finally, calculated the required power to propel the boat.
- ✓ Proposed hybrid power system comprises of PV module, gas generator, and battery bank.
- ✓ HOMER optimized the proposed system for the solar boat that consists of 10.6 kW PV, 1.6 kW diesel generator and 18.5 kWh (440Ah) storage batteries.
- ✓ Sensitivity analysis was performed to observe the effect of different variables such as solar irradiance and diesel fuel price on the COE and NPC of the proposed hybrid system.
- ✓ The proposed project will be beneficial economically at end of the fifth year of operation.
- ✓ Dynamic modeling was performed in MATLAB Simulink to examine the dynamic behavior of the designed system and found that:
    i. The PV could produce power 8.82kW, charge the BB at a constant current of 25A and 49V and takes 5hours to full charge (100%) the battery and
    ii. The DC Generator (1.6kW) is capable to charge the battery and run the PMDC motor
- ✓ The proposed instrumentation and Arduino Uno R3 microcontroller-based switching control system were designed and verified through virtual simulation (tinkercad.com).

6. CONCLUSION AND and Recommendation

Recommendation

- ✓ The implementation of the proposed system into a physical system is still needed to confirm the practical feasibility and use in transportation.
- ✓ For more complicated system, a faster processing capable microcontroller is recommended.
- ✓ Wireless communication system might introduce to develop a solar boat network and
- ✓ A faster processing capable computer recommended to run the simulation for 08hours duration.

List of Publications

Refereed Journal Article and Conference Publications:

M. A. A. A. Mehedi and M. T. Iqbal, **"Optimal Design, Dynamic Modeling and Analysis of a Hybrid Power System for a Catamarans Boat in Bangladesh,"** Eur. J. Electr. Eng. Comput. Sci., vol. 5, no. 1, Art. no. 1, Feb. 2021, doi: 10.24018/ejece.2021.5.1.294.

M. A. A. A. Mehedi and M. T. Iqbal, **"Optimal Sizing of a Hybrid Power System for Driving a Passenger Boat in Bangladesh,"** in 2020 IEEE Electric Power and Energy Conference (EPEC), Nov. 2020, pp. 1–6, doi: 10.1109/EPEC48502.2020.9319920.

A. Sharan, M. Zamanlou, M. Rahman, and M. Al-Mehdi, **"Centralized Power Generation of Solar Parks using Wireless Controlling,"** Int. J. Curr. Eng. Technol., vol. 9, Aug. 2019, doi: 10.14741/ijcet/v.9.3.9.

Mohammad Abu Abdullah Al Mehedi, M. Tariq Iqbal, **"Design of a PV system for a small boat for use in Bangladesh,"** presented at the 28th Annual IEEE NECEC conference, St. John's, NL, Canada, November 19th, 2019.

Thanks for your patience