Design of a PV system for a small boat for use in Bangladesh

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***Abstract*— Bangladesh is a land of rivers, cannel, and lakes where water transportation is an important means of communication. The country use boats as one of the main resources of transportation in its widespread inland waterways. Most of the currently used boats use diesel for fuel. Appropriate use of renewable energy sources particularly solar energy could reduce diesel consumption. In this research, a typical boat energy requirement was calculated to be 13.6kWh/day. A boat could be driven by a DC motor using electrical power which is generated using an onboard PV system. The size of the boat is, length 5.5m, width 2m, and depth 1m with a carrying capacity of 900kg load for 10hours a day. The designed system consists of an 8.53kW, PV, onboard battery storage and a 48V DC motor with a speed controller. The paper also includes a dynamic model and Simulink simulation results.**

Keywords— Photovoltaic (PV), Battery, Permanent Magnet Synchronization Motor (PMSM), simulation, load analysis.

I. INTRODUCTION

In Bangladesh, during the rainy season, many low land area's roads are obstructed, basically from July to October, when rivers rise in average 4 meters (12 feet). There are around 800 rivers including tributaries flow through the country covered total water distance around 24140 km, among them Padma, Megha, Jamuna, Brahmaputra, and Buriganga are the prime drivers. Also, more than 700,000 boats are running on waterway, approximately 60% are diesel engine driven and 150 types of flood-basin fishing boats, cargo boats, and passenger boats exist which are varied in design, size and construction materials [1]. Recently, many country boats are driven by only solar power, whereas Photo Voltaic Cells convert solar energy into dc and feeding to dc load [2] [3].

The average solar radiation is around 4 – 6.5 kWh/m^2/d with peak amount in April and the lowest amount in December [4]. After analysis weather data in polysun software, it has been found that in the proposed area buriganaga river (longitude 90.4, latitude 22.7) solar radiation of 4 – 5.7 kWh/m^2/d with peak amount in April and lowest amount in November.

In this paper, the flood-basin passenger boat (FBPB) which is 7m long and 2.5m wide as a model for economic feasibility study, load analysis and designing solar PV system to drive FBPB on Buriganga river for the transportation around 10 to 12 passengers at a time from one riverbank to opposite riverside. An existing same sized diesel engine has driven passenger boat running 4 knots (7.5km/h) taken 12-15minutes to cross the buriganga river. This said water transport system has been used for shuttling offices, marketing, and merchandising business, nevertheless, the frequency of travel decreases considerably in the evening. Henceforth, in this project, FBPB is considered not to be operated after dawn.

II. LITERATURE REVIEW

In the literature, there are a few studies related to the solar power-driven boat has found. Revolution of Electric motorboat did not move further in last century due to lack of technology, energy source and energy-storing facility in the electrical system. In addition, electric motor efficiency was not up to the mark [5].

Sayidul Mursalin et al.,[6] defined their designed solar boat but complete design technique is absent. The boat momentum was achieved by using motor-driven engine. Also, the boat was made of light mass composite materials and it was not established by changing an existing boat. A motor-driven engine is used for the propulsion of the boat.

D. S. L. Simonetti [7] proposed an optimistic control technique of a solar-powered vessel which is driven by an indirect vector-controlled induction motor. To make sure the anticipated method, a trial drive load was coupled and experimented in the laboratory. This paper does not explain properly because of insufficient field data regarding the performance and impact of solar power and induction motor.

Anton Wachter [8] developed solar boats for drifting long distances. He proposed the design and progress of a solar boat for a precise race. Also, a history of the solar boat for notable rivalry and recommendation has been made for forthcoming boat design. This paper did not explain design methodology, only a set of project information had been provided in this paper.
In this paper, the solar PV based passenger boat has been designed with proper component sizing and necessary control system as well.

III. DESIGN OVERVIEW

An electric motor driven boat powered by solar energy is the perfect replacement of conventional water boat. The schematic diagram of a PV powered flood-basin passenger boat (FBPB) is shown in Fig.1. Solar Photo Voltaic (PV) panel will be installed in such a way so that it could work as an energy source and roof of this proposed system boat simultaneously. PV panel is controlled by MPPT controller and its output is connected to the energy storage battery (ESB). ESB is connected to the Motor Speed Controller

(MSC) through the overcurrent protection device (DC relay). Motor ON/OFF manual switch is proposed between Motor speed controller and Motor. Finally, the DC motor transmit mechanical rotative power to the boat propeller via coupler and shaft mechanism, while Switch is ON state.

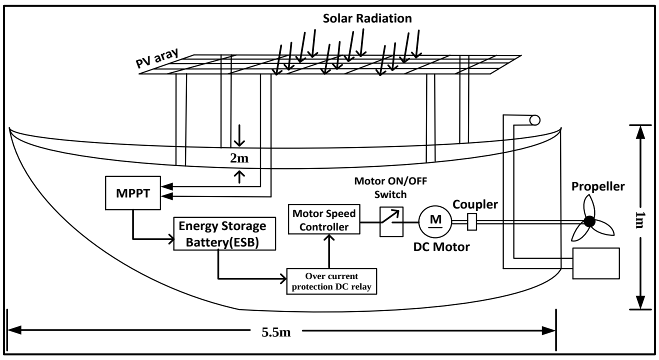

Fig. 1. The schematic diagram of a PV powered flood-basin passenger boat (FBPB)

IV. BOAT COMPONENTS SIZING CALCULATION

The selected main components are the dimension, speed, power demand, motor sizing, battery sizing, solar panel sizing, solar charge controller. The complete design and proper sizing calculation are given step by step below:

A. Boat Specifications

The wooded FBPB has considered which is described in Table 1. For safely boat journey in good weather and boats which are less than 6.0 meter in length without capacity plate, the thumb rule to calculate the number of persons (assume each, on average weighing 68kg) [9].

The number of people = (L × W)/15 = 8 person.

Where, L= Boat length in meter

W=Boat width in a meter.

TABLE I. SPECIFICATIONS OF BOAT

Parameters	Specifications
Boat length × beam × depth	5.5 × 2 × 1 (m)
Passenger carrying capacity	8 to 10 people
Total weight in full capacity (including passenger, PV-Battery back up system, motor, and others)	900kg
Boat speed	4.0knots (7.5km/hr)
Required power to drive the boat	1.7kW
Boat operating duration/day	8h
The required energy to drive boat	13.6kWh

B. Boat Speed Selection

The boat speed normally scaled from 6.5km/hr. to 8.5km/hr. to cross the buriganga river. As it is well known that for designing higher speed, PV panel size needs to be increased to supply required power which could affect the stability of the said sized boat while sailing. Therefore, in this project, the boat speed 4.0 knots (7.5km/hr.) have been chosen which is more than the necessary speed to accomplish its journey across the river.

C. Power Demand Calculation for Boat

The total weight of a boat is essential to analyses power requirement of it [10]. The designed boat is belonging to weight in 900 kg and operational 8 hours a day. To move it at 4 knots (7.5 km/hr.) speed, need to overcome resistive forces which calculation is given below.

Drag force (F_D) value in Newton (N) can be calculated by using equation (1) [11].

$$F_D = \left(\frac{1}{2}\right)\rho V^2 C_D A = 11900\ N$$

Where

ρ=Density of the water fluid=997kg/m^3.

V=Boat speed=7.5km/hr.

A=Cross sectional area=11m^2.

C_D= Drag coefficient =0.5.

Also, the required power to overcome the aerodynamic drag is [3].

$$P_d = F_D \times V = 1.65\ \text{kW} \quad (1)$$

For the safety operation, adding 5% more of P_d, resultant required power to drive the boat,

$$R_{equired} = 1.7\ \text{kW}$$

Daily Energy required, $R_{equired}$ = 13.6 kWh

D. Boat Motor selection

There are various types of DC motors are available in the market, like DC shunt motor, Brushless DC and Induction motor. To run induction motor need inverter (DC to AC) and driver to control speed, also high maintenance cost, which opposed to using it. DC shunt motor could serve the purpose, but the risk is existence of brushes which could be badly-behaved in the field when it will be depreciated because of frequent utilization. In this project, a 1.5 kW, 48 V, 1500 RPM brushless permanent magnet synchronization motor (PMSM) has been considering with 12% margin [12].

E. Battery Capacity Sizing

For sizing Battery i.e. to calculate energy demand, it is required to assume hours to utilize battery power without solar power by boat and in this case, it is considered that a 12V, 80Ah Li-ion battery with 2 hours backup time, 80% DOD and 95% of efficiency [13]. So, by considering the 48V DC BUS voltage, Energy demand is calculated by the following equations [14].

$$\text{Peak Load} = \text{V} \times \text{I} = 1.8\ \text{kW}$$

$$\text{Maximum Load Current} = \text{Pl} / V_{bb} = 37.5\text{A} \quad (2)$$

Where, Pl= peak load in kW

V_{bb}= Battery bus voltage in V

$$\text{No. of string} = (\text{E} \times \text{B}) / (V_{bb} \times \eta_B \times \text{DoD} \times \text{Ah})) = 0.37\ \text{string} \cong 1 \quad (3)$$

Where,

E= Daily Energy demand for boat in kWh

B= Required Battery Back Upper day

V_{bb}= Battery bus voltage in V

η_B= Battery efficiency (%)

DoD= Battery depth of discharge (%)

Ah=Selected each battery Ah

$$\text{No of Batteries} = \frac{\text{capacity}}{\text{String}} = \frac{V_{bb}}{V} = 4 \text{ No's} \quad (4)$$

F. Solar Array Sizing

In Dhaka, Bangladesh, the average irradiation (G_{avg}) is 4.52 kWh/m^2/day as shown in Fig. 2.

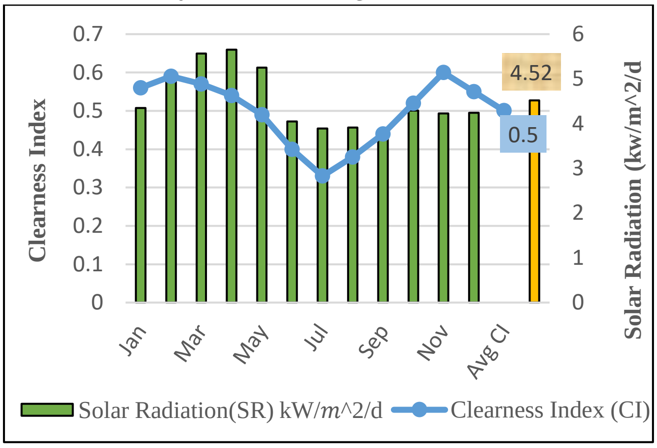

Fig. 2. Monthly solar radiation and clearness index

The PV panel will generate average energy for 8 hours/day which will be feed directly to the DC motor and rest will be stored in the storage battery which will secure back up power for 02 hours/day. Henceforth, the proposed boat will run 10 hours/day from 8.0 AM to 6.0 PM.

The solar array has been sizing properly based on the following consideration:

MPPT Charge controller efficiency, $\eta_{cc=}$ 95%

PV panel efficiency, η_{PV} = 18%

Battery efficiency, η_b = 95%

Maximum Depth of Discharge, DOD = 80%.

PV module specification = 200 Watt, 12V, 0.6 m^2

$$\text{Energy demand from PV} = \frac{(E)}{(\eta cc * \eta_B)} = 15 \text{ kWh}$$

$$\text{PV array area, } A_T = \frac{(E)}{(\eta_{PV} \times \text{Gavg})} = 18.43m^2$$

$$\text{No. of PV module} = \frac{(A_T)}{(A_{PV})} = 28$$

No of string = 7 No's

No modules per string= 4 No.

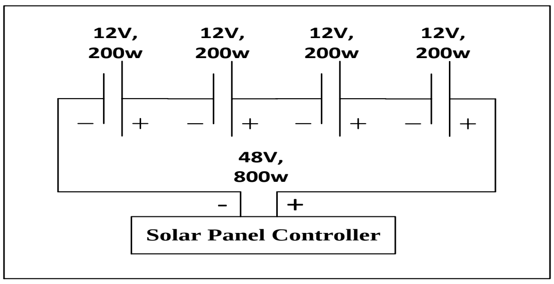

Fig. 3. Solar PV array connection diagram.

G. Solar Charge Controller

Maximum power point tracking (MPPT) is system that included in charge controllers used for extracting maximum available power from the PV module under certain conditions. The voltage at which PV module can produce maximum power is called 'maximum power point' (or peak power voltage). Maximum power varies with solar radiation, ambient temperature, and solar cell temperature.

MPPT charge controller sizing has been calculated by using the following calculation [15].

MPPT Current rating = 1.7 kW/48 V = 35 A

To overcome unexpected light reflection factors, need to add an extra 25%,

So, designed MPPT current rating = 35+35×25% =44 A

As 44 A MPPT is not available in the market so a 48V, 60 A-rated MPPT charge controller has been considered in this project.

H. Over current protection.

For boat motor safety, it is mandatory to protect motor by shut off power while unwanted over current flow exists. A single-pole DC contactor with normal open contact (SPST-NO) 35 A-rated 48V DC overcurrent relay, as the normal operating current of the selected PMSM motor is 35A and its rated current is 37.5A.

V. COMPONENTS OPTIMIZATION IN HOMER

The motor will operate for 10 hours and the load profile is almost same for the whole period and it is 13.6 kWh/day. The other components are in optimization mode and home will optimize the proper size.

TABLE II. INPUT DATA OF HOMER SIMULATION

Name	Rated Capacity	Capital ($)	Replacement cost ($)
PV	0.23 kW	0.3/watt	0.2/watt
Battery	4.31kWh	400/pc	200/pc

The system schematic diagram is given below:

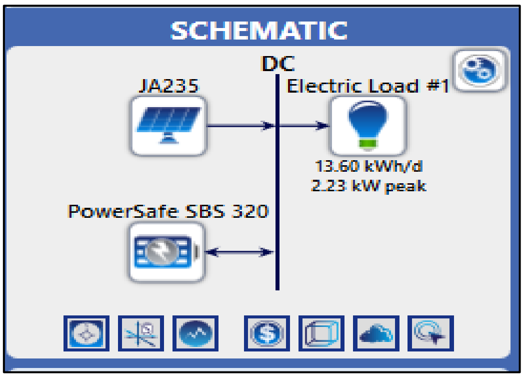

Fig.4. Homer schematic diagram

The homer system has been simulated for components optimization. After running the simulation, the components proper sizing was found which is given in Table 3.

TABLE III. HOMER OPTIMIZATION RESULT

PV	5.6 kW
Battery	12V*4 Nos), 80Ah

VI. SYSTEM MODELING IN SIMULINK

The overall systems have been designed in the Matlab Simulink environment and the size of every component has been selected based on the homer optimization as mentioned in Table 3.

A. System design

The complete system diagram of PV control, motor speed control, battery charging, and motor overcurrent protection system has been described in Fig. 5.

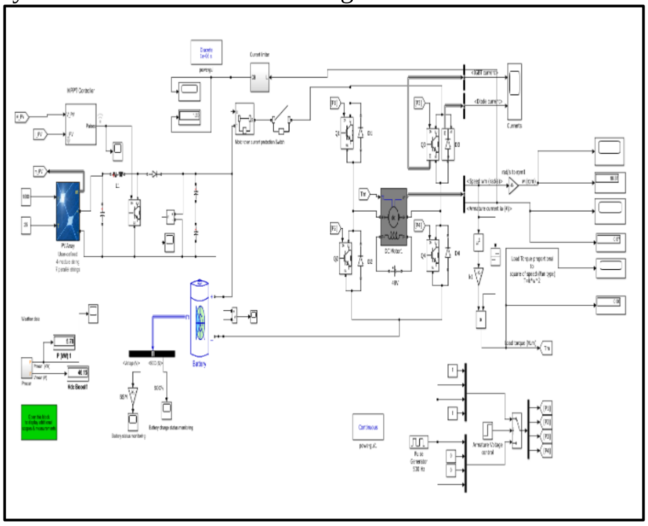

Fig. 5. Complete Simulink model of PV-Battery driven Motor system

TABLE IV. THE SYSTEM MODEL OVERVIEW

Description	Rating
The solar radiation in Dhaka, Bangladesh	4.6 kWh/m^2(avg. daily), 1712 W/m² (global irradiation) 1387 W/m² (direct normal irradiation)
The temperature in Dhaka	25^{0}C (avg), 11.4^{o}C (min), 36.3^{o}C (max)
Average Boatload demand	1.7 kW
PV module and bus voltage	28 No's (12V, 200 W each) (calculated) 48 V DC bus voltage
Total area required for PV panel	**18.43** m^2
Maximum Load	1.8kW
Battery storage	1string (12V*4nos), 80Ah

There are three control and protection system has been implemented in this project, which is given below.
(i) Maximum power point tracking (MPPT) system for PV
(ii) Boost Converter for Battery charging and
(iii) Motor speed control by PID controller
(iv) Motor over current protection by the current limiter

B. Simulation Result.

After the simulation, it is found that the switching time for motor overcurrent protection switch is 0.3seconds and maximum current limit is 37.5A which is motor rated current and set it as a reference. Fig. 6 shows the PV power generation and battery voltage status.

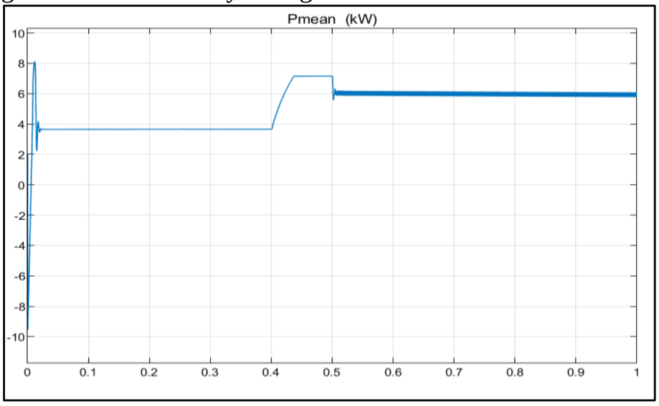

Fig. 6. Power generation by PV array

IGBT block is chosen to build a model with Bipolar Junction Transistor (BJT) device because of its operating properties in the saturated region, a forward voltage V_f (within the range of 1V) is created between collector and emitter. Henceforth, BJT functions as an IGBT when it is used for power switching applications.
The motor starts in a positive direction with a duty cycle of 75% (mean DC voltage of 48V*75/100 = 36 V). At t= 0.5 sec., the armature current is suddenly tending to reduce, and the motor starts to run slower as shown in Fig. 7 and the corresponding load torque is shown in Fig. 8.

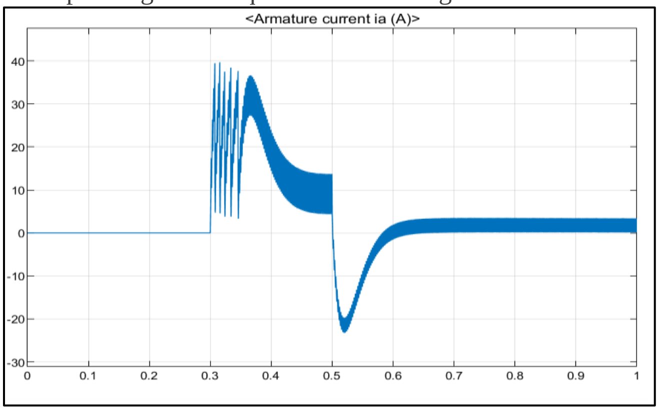

Fig. 7. Armature current control

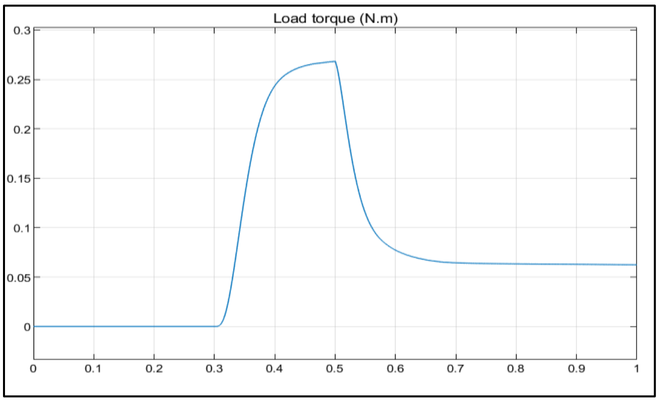

Fig. 8. Load torque control

VII. Economic Analysis

It has been seen from homer analysis that the initial cost is $5759.00 to implement which could be overcome within a year. If round trip from one riverbank to another bank takes time 01.00h, 08 nos of passengers and fare $0.2/person, then daily on an average could cross the river 16 times through the year. The total income year will be $9344.00. Excess $3585.00 could meet the boat man's daily expenses. Henceforth, the proposed solar boat system could implement.

VIII. Conclusion

System design component sizing and implemented MPPT charge controller, DC motor IGBT controller and motor armature over current protection switch are presented. Designed system has been verified by building the model in MATLAB Simulink and observed that the designed system is working properly. The PV protection system is introduced with diode but surge protection device (SPD) and PV Grounding does not use, as PV installed in the boat and which will be on water. Cost analysis has been done by homer software and found the designed system is cost-effective to implement. PV, Battery string and Motor on-off switch are also be used. In future, hybrid power (PV + diesel engine) driven boat could be developed and system size could improve to drive boat at night.

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