Design Optimization and Energy Management of Photovoltaic powered Electric Boat

Wunna Swe*

*Department of Electrical Power Engineering
*Mandalay Technological University, Myanmar
Email:[1]wunnaswe@mtu.edu.mm

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Abstract - **Diesel only propulsion system for transportation system in navigation route caused the river pollution. The green house gas emission and pollution to environment will occur seriously. Beside, the fuel price is gradually increased from year by year; it is importance to replace the diesel only propulsion system for boat. Solar energy is one of the most importance energy resource which abundance in most parts of the world. Photovoltaic (PV) system with energy storage is one of the replacement propulsion systems for boat. The photovoltaic (PV) generation system, the diesel generator and the energy storage system in a hybrid power supply system for boat that minimizes the fuel cost and the CO_2 emissions. The aim of this paper is the optimal design of a Solar-Electric Boat for transportation along the Bago River. This paper shows the practical new technologies (mechanical and electrical design), rational design and engineering approach, safety and reliability methods used in solar boats. In this paper, the boat is powered by lithium-ion batteries that can be charged at any time by the photovoltaic generator placed on a flat top structure. It also uses the diesel generator as an emergency backup power supply system. The power generation from PV modules on a boat relies on the date, local time, time zone, longitude and latitude along a navigation route and is different from the conditions of power systems on land. It takes the seasonal and geographical variation of solar irradiations and temperatures along the route from Bago to Yangon in Myanmar into account. The proposed method considers three conditions along the navigation route to model the total ship load.**

***Keywords* –Photovoltaic generation, Energy storage system, Solar Electric boat, Electric Propulsion, CO2 emission**

I. Introduction

The amount of greenhouse gas produced by the transportation systems is increased year by year. Among them, CO_2 emission by boat is involved with a certain number and the International Convention for the Prevention of Pollution from Boat has made the claim that the boats must find a new way to reduce their collective emissions of greenhouse gas. Serious environmental pollution and the low energy efficiency of traditional boat systems whose power is supplied only by diesel generators can be mitigated by properly integrating renewable energy.

Almost all boats that now are travelling along the river are monohull boats powered by outboard or inboard engines using fossil fuels where the exhaust gasses causing measurable negative effects on the earth's atmosphere so called as the carbon emission. Besides that increasing of oil price will increase the operational cost of the boats/farries especially when there is small number of passengers using the ferries hence will not making profit but loss. Electric boat is not produced any pollution during its operation; no carbon emission, no waste engine cooling water and no noise.

Photovoltaic (PV) energy has been introduced into ship power systems to reduce their greenhouse gas emissions, improve energy efficiency and reinforce the boat power system stability. However, the use of too much solar energy may increase investment cost and make the power system unstable owing to the uncertainty associated with solar power. Additionally, a wide range of investigations have found that the use of an energy storage system (ESS) is one of the most effective solutions for ensuring the reliability and power quality of power systems and the increased penetration of distributed generation resources. The PV system applied for marine vessels has been discussed to reduce the fuel cost.

The integration of a significant amount of PV power into a boat power system to reduce CO2 emission is challenging. The PV power generation in a boat depends on its position of the river. Using the PV system consider the date, local time, time zone, longitude and latitude to formulate the power generated by PV on a moving boat. The optimal sizing of hybrid PV/battery/diesel power system was proposed, taking into account various tilt angles of PV panels. Owing to the strong dependency of the performance and rating of a solar-based system on climatic conditions, parameters such as date, local time, longitude and latitude were considered and corrections for the output of PV modules were made for different locations. The optimal design of hybrid power supply system for boat which considered various environmental conditions.

The boat is powered by direct solar energy. This boat uses solar cells that transform the solar energy into electrical energy, which is stored temporarily in lithium-ion batteries, and used to drive the boat through electric motors (permanent magnet synchronous motors) and drive systems electric propulsion offers effective system, precise and smooth speed control, reduced fuel using, low noise and low pollution rates. This paper represents the optimal electric supply for boat.

II. Solar Powered Electric Boat

Solar power is started to be used in boats is around 1985, and the first commercial solar boats are introduced in 1995. Solar powered electric boats are reduced greenhouse gas emission, operating cost and improve energy efficiency and stability than diesel boat. The boat is powered by direct solar energy. It used solar cells that is converted the solar energy into electrical energy, which are stored temporarily in lithium-ion batteries. The boat is powered by lithium-ion batteries that can be charged at any time by the photovoltaic generator placed on a flat top structure. Then it is also used electric motors for rotating the boat propeller. Electric propulsion offers effective maneuverability, precise and smooth speed control, reduced engine room, reliability, low noise and low pollution rates. Solar-electric boats are recommended solution for navigation in areas where combustion engines are prohibited (lake, protected areas) [12Giu].

Figure1. Solar Powered Electric Boat [10]

There are many electrical and mechanical components for solar powered electric boat are Photovoltaic array, Battery bank, Charge Controller and Inverter, Buck/Boost Converters, Loads (Induction motor, lumps, pump, TV, etc), Diesel Generator and GPS System, Rudder and Propeller.

The electrical components for solar powered electric boat are described in the followings:

- Photovoltaic array
- Battery bank
- Charge Controller
- Inverter
- Buck/Boost Converters

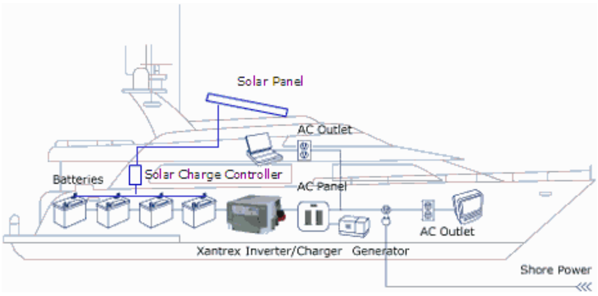

Figure2. Electric Supply System for Solar Powered Electric Boat

III.NAVIGATION ROUTE

In this research, the proposed river is Bago River. It is located in lower Myanmar. The river is flowing from north to south. So, it comes from Bago Division to Yangon Division. East Longitude and North Latitude for Bago Division are 96.48° and 17.34°. Yangon Division for East Longitude and North Latitude are 96.16° and 16.81° [2].

Bago River is start from Bagoyoma, which is connected Yangon River near the Thanlyin Bridge. The distance between the Yangon and Bago Bridge is about 40miles. BagoRiver flows from North to South. The river is gradually wider in Yangon Division. It passes through Tabu, Tawa, Ywathikon and Thonegyi village.

It is carry about 30 passengers on the boat. It is started from Botataung harbor (Yangon) at 7:00am. During this time it cannot get solar power from the sun. It is 30minutes docking at Tabu harbor. Tabu is located at Bago Region. Itwill reache that harbor in lunch. Then, it is continued to Bago region. It will reach the Bago bridge harbor at 5:00pm. So, the time duration for navigation route is about 10 hours. The river for the Bago River is $0.3ms^{-1}$. Itis sailing the upstream speed is 2.3ms-1 and downstream speed is $1.7ms^{-1}$.Figure 3 is shown the proposed river for solar powered electric catamaran by using the Google map searching [2].

Figure3. The Proposed River Location and Map

The total radiation is the sum of the direct radiation, diffuse radiation and reflected radiation. Latitude for the proposed river is 16.8° and 17.3°[1]. In this research, December 21 is used as the typical day for solar radiation along the navigation route and tilt angle for the collector is assumed to zero. The region is received enough solar power for proposed system. The solar radiation for the navigation route is shown in figure 4.

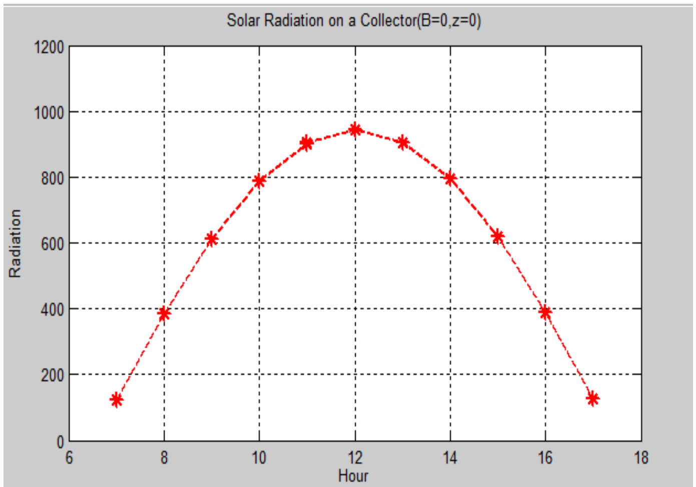

Figure4. Solar Radiation on a Collector Surface

IV.ENERGY CONSUMPTION

A. Characteristics of Solar Electric Boat

For this research, it is consider for a boat in the following characteristics:

- From Bago to Yangon
- Cruising speed: 2.3ms-1(up), 1.7ms-1 (down)
- Cruising range: 10hours
- Length over all: 10.8 m
- Width over all: 6.49 m
- High over all: 3 m
- The boat is equipped with one 4.7kW permanent magnet synchronous motors;
- Boat travels for about 28miles per day;

Not all boats are suitable targets for the integration with photovoltaic generating system. A solar-electric boat must have sufficient deck space. In boat a flat top structure is used for putting up a photovoltaic array.

B. Load Profiles

The time duration for boat sailing in Bago river is about 10hours (7:00am – 5:00pm). The followings are details calculation for propulsion components at upstream speed and downstream speed.

Table 1. Load profile

S / N	Appliances	Qty	Power Rating (Watt)	Hours of use per Day	Energy per Day (Wh)
1	19″ Plasma TV	1	80	3	240
2	Lighting	5	20	1	100
3	Water Pump	1	350	1	350
4	GSM (System)	1	25	10	250
5	Cell Phone	4	2.5	10	100
6	Motor (up) Motor (down)	1 1	4.7×10^3 2.6×10^3	10 10	47×10^3 26×10^3

Thus, the load profile of the residence is 48040watt-hours per day and will be used to determine the PV and battery power system. The speed for the Bago River is 0.3ms-1and the boat speed is 2ms-1. So, the above table is considered the upstream speed 2.3ms-1.

Thus, the load profile of the residence is 27040watt-hours per day and will be used to determine the PV and battery power system. The above table is considered the downstream speed at 1.7ms-1.

V. Sizing of Power Supply System

A PV Array Sizing

The photovoltaic array is the important component of any PV system. It is responsible for the conversion of sunlight into electricity. The fundamental power conversion units are the solar cells, which typically produce less than 2 Watts of power. In order to produce increased power output, the solar cells are normally connected in series and parallel to form modules. Modules are then also connected in series and parallel architecture to form an array so as to meet the desired power output.

The modules in a PV array are usually first connected in series to obtain the desired voltage; the individual strings are then connected in parallel to allow the system to produce more current as desired. The following information should be determined before the actual sizing of the PV array begins:

- ❖ The dc voltage of the system (V_{dc})
- ❖ The average sun hours of the installation site per day (T_{sh})
- ❖ The daily average energy demand in watt-hours (E_d)

Required Information:

Solar Module: SunPower 345 Solar Panel,

Vrm = Vmp = 57.3V, Irm = Imp = 6.02A, Isc = 6.39A
System Voltage (Vdc) = 48 V
Average Sun-hours for Bauchi (Tsh) =4.8 Daily
Average Demand (Ed) = 48kWh Battery Efficiency
(ηb) = 0.98 Converter Efficiency (η_c) = 0.985
Charge Controller Efficiency (η_{cc}) = 0.98

Table 2.PV Array Sizing

Parameter	Equation	Value	Unit
Required Daily Energy Demand (Erd)	Erd = Ed / ηbηcηcc	51.78	kW
Average Peak Power(Pave,peak)	Pave,peak = Erd / Tsh	10.79	kW
Total dc Current (Idc)	Idc= Pave,peak / Vdc	225	A
Number of Series Modules(Nsm)	Nsm= Vdc / Vrm	1	No
Number of Parallel Modules(Npm)	Npm= Idc / Irm	37	Nos
Total Number of Modules(Ntm)	Ntm= NsmxNpm	37	Nos

In this boat the area available for laying a photovoltaic array is about 70.09m^2. The Total area of PV modules is 68.79 m^2. So the area is enough for placing of PV array.

B Battery Sizing

The storage batteries are used to supply the load during non-sunshine hours whilst being charged by the PV array during periods of high solar radiation. The recommended batteries that should be used in hybrid power system for solar boat are lithium-ion batteries because of their high performance.

Lithium iron phosphate batteries have higher energy densities. Lithium iron phosphate batteries are lighter and smaller per amp hour capacity so more energy can be stored in the same amount of space as lead acid.

To get a system that can ensure a reliable transport, it must assume that the energy, used during the cruise (5 h), must be entirely taken from the batteries; for designing in safety, it have to hypothesize that the photovoltaic system doesn't supply energy. Therefore, the daily energy consumption that the batteries have to provide is equal to the average energy (38.25kW) for half cruise time (5hours). With all these hypotheses, the total storage battery capacity has to be >90 kWh. It proposed the electrical load during a typical day without return in emergency.

The battery type recommended for use in solar PV power system is lithium-ion battery, specifically designed such that even when it is discharged to low energy level it can still be rapidly recharged over and over again for years. The battery should be large enough to store sufficient energy to operate all loads at cloudy, rainy and dusty days.

The daily average energy demand per day is 19.2kWh. The nominal system voltage is 48V. The day of autonomy is 2days, allowable depth of discharge is 0.8 (80%) and the derate factor is 1. The rated battery voltage is 12V. The sizing of the battery bank proposed the following:

Required Information:

Lithium-Ion Battery

Number of Days of Autonomy (Daut) = 2 Days
Battery: LIT / D12-200
Cb=200Ah, Vb=12.8V, Ddisch=80%

Table 3.Battery Bank Sizing

Parameter	**Equation**	**Value**	**Unit**
Total Capacity of Battery Bank (Ctb)	Ctb= Esafe / Vb	1	kAh
Total Number of Batteries in Bank (Ntb)	Ntb= Ctb / Cb	20	Nos
Number of Batteries in Series (Nsb)	Nsb= Vdc / Vb	4	Nos
Number of Batteries in Parallel (Npb)	Npb= Nb / Nsb	5	Nos

Total weight: 20 × 25.69 kg ≈ 513.8 kg
Volume: 485 × 170 × 245 × 20 ≈ 404 x 10^6 mm3 ≈ 0.4m^3

C. *Sizing of Charge Controller*

A charge controller must be able to withstand the array current as well as the total load current and must be designed to match the voltage of the PV array as well as that of the battery bank. Table 3 shows the parameters of the selected solar charge controller.The rating of charge controller should be 25% greater than short circuit current of PV array. Required charge controller current is 295.54A. The total number of charge controller is divided the required charge controller current by the selected charge controller current. The selected charge controller current is 60A. The total number of charge controller is five.

Table 4. Parametersof Charge Controller

Model Number	FSR 60/12
Rated Charge/Discharge Current	60A
Nominal System Voltage	12V
Dimension	91 x 103 x 228 mm
Weight	1.73kg

D. *Sizing of Inverter*

The selected inverter for the proposed system is three phase inverter. The data specification for the three phase inverter is described in Table 4.

Table 5.Parameters of Inverter

Model Number	Delta M15A
Nominal Voltage	635V_{dc}
Rated Power	15kW
AC output	230/400V_{ac}
Efficiency	98.3%
Maximum AC Current	24A
Start up Voltage	>250V

The frequency for the selected inverter is 50Hz.The weight for the inverter is 43kg and dimension is 612mm × 625mm × 278mm.

E. *Selected Buck/Boost Converters*

In this thesis, it selected boost converter between the PV modules, batteries and motor. It is connected buck converter between the PV modules and batteries. It is selected the 20kHz switching frequency, output voltage ripple is 5% and inductor current ripple 10%. The specification for the buck/boost converters is shown in Table 5.

Table 6.Parameters for Buck/Boost Converters

Types	Buck Mode	Boost Mode
Input Voltage	57.30V	57.3/12V
Output Voltage	12V	400V
Maximum Power	4.7kW	4.7kW
Duty Cycle	0.21	0.86
Selected Inductor	299µH	12µH
Selected Capacitor	100µF	100µF

VI.Energy Management System

The PMS is used for the right managing of the energy aboard. It is to provide the master with the real autonomy of navigation and the real power from the battery. In our system, a storage device (battery bank) is used for balancing the mismatch between the available energy by the photovoltaic array and power required by motors and ship instruments. Both the powers that flow in and out of the storage device have to be designed accurately and controlled for a global energy management strategy.

In particular, since the lithium-ion batteries decrease the storage capacity with aging, is not possible to know the instant energy available for the navigation, by measuring the output voltage of the battery. For a safety and reliable navigation, it is necessary to know the real autonomy of navigation, which means to know the real energy storage within the battery banks.

The boat is start sailing from Botataung harbor, Yangon Division. Firstly, it cannot get sufficient power from the sun. The sufficient solar power for the electric boat is from 9:00am to 3:00pm. It will get efficient solar radiation at 12:00pm. The sunrise, sunset and night cannot get sufficient solar power for the electric boat. The total load consumption for solar powered electric boat for 6hours (9:00am – 3:00pm) is 28685 watt-hours per day.

The time duration for supplying the battery power to the load is 7:00am – 9:00am and 3:00pm – 5:00pm. It is the 4hours for supplying the load. Then, it is recharged the battery for reusing the evening. The total load consumption for 2 hours is 9.75kWh. So, the total load consumption using the battery per day is 19.49kWh.

Manage the energy from PV and battery bank for sailing time of the boat is shown in figure 5. The boat is consumed 4.7kW and 4.8kW during sailing time. At 11:00am to 11:30am is dock time at harbor and no consumed energy.

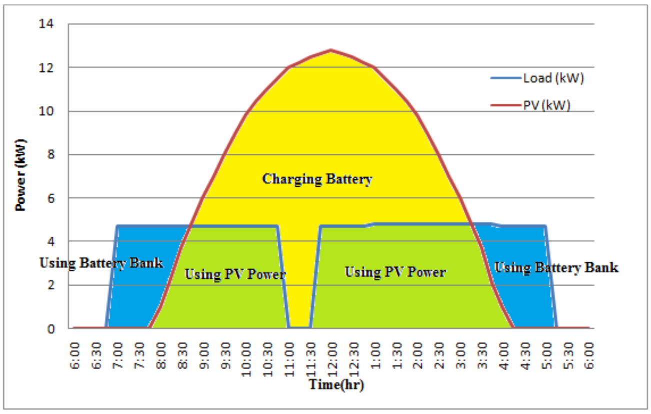

Figure 5.Energy supply from various sources

VII. Diesel Generator

It is used diesel generator as a backup emergency power supply system when the solar power and batteries power are insufficient. It is used 5kW diesel generator, which calculation is shown Table 4.20. The daily fuel consumption per day is about 18 gallons. The One nautical mile (nm) is 1knots and it equal to 1852m, the fuel consumption for liters per nm is 0.87.

Table 6. Data Sheet of Diesel Generator

Power	5kW, 41.7 amps, 240Volts AC
Dimensions	57″ x 33″ x 40″
Weight	950lbs
Liter/nm	0.87

IV. Conclusion

The optimal sizing of electric supply for solar Boat using in transportation along the coast, in the rivers, in the Lakes have been presented. It is possible to replace the standard fuel engine with an electric one, by accepting a loss in power, and without changing the weight and the dimension of the boat

In this paper is proposed to find the optimal size of hybrid PV/diesel/ESS generators in a boat's power system. Hourly loads are model with various conditions of power supply options, which are regular cruising, starting and docking. A navigation route from Bago to Yangon in Myanmar serves a route for decision makers considering three different seasons to allocate the sizes of PV and ESS herein.

The optimal sizes of the PV system, ESS and diesel generator for boat is reducing the fuel consumption and emission. It will get simulation results of optimal hybrid PV/diesel/ESS power supply for boat. The proposed method can be enhanced to study other mobile micro grid such as container ship and high-speed train.

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Authors

First Author – Dr. Wunna Swe, Professor and Head, Department of Electrical Power Engineering, wunnaswe@mtu.edu.mm