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Hybrid Solar/Diesel Power System Design for Electric Boat with MPPT System

Waleed Obaid*[1], Abdul-Kadir Hamid*, and Chaouki Ghenai[+]

Abstract – *This proposed design is a hybrid power system for electric boats using solar power from PV array combined with Maximum Power Point Tracking (MPPT) system and energy from a diesel generator. The main objective is obtaining continuous operation and stable speed for the electric boat regardless the time of the day and weather conditions changes that affect solar irradiance which is directly related to solar PV panel that charge the battery bank. The hybrid power system output is used to drive a three-phase asynchronous machine for the propulsion system of the electric boat. Switching between diesel and solar power depends on battery operation and measurements. The simulation results of the hybrid power system are presented using SIMULINK. The results will demonstrate the stable operational speed of the electric boat due to the continuous operation. The novelty of the proposed design over other hybrid solar/diesel electric boat system designs from the previous work is maintaining continuous operation and stable speed despite the variations in battery state of charge and solar irradiance level. Another advantage is maintaining stable operation without resulting in problems associated with power stability.*

Keywords – *electric boat, hybrid system, maximum power point tracking, simulink, solar power.*

1. INTRODUCTION

Renewable energy is a significant source of energy as it is sustainable and clean source compared to other conventional sources of energy such as fuel [1]. The reduction of cost for PV panels encouraged more research and development to be done to increase their efficiency such as in Maximization Maximum Power Point Tracking (MPPT) system which is achieved by a DC-DC converter, software block, and sensors for voltage and current measurements. MPPT algorithm is used to achieve operation with very high efficiency [2] – [4]. Marine solar boats are vehicles which use solar cells for transforming solar energy into electrical energy that can be stored in batteries. The stored electrical energy in batteries is used for moving the boat by electrical motor combined with drive system. The power usage can range from few hundred watts to few thousand watts [5].

The use of solar energy for ships has advantages over using wind turbines as a source of renewable energy because PV panels do not produce sound and they do not have moving parts that may affect the ship stability. Moreover, using solar energy for boats is recommended over using regular types of boats because solar energy does not cause water pollution or harmful emissions in air and solar energy has low operating costs.

There are challenges that face solar powered boat applications. The size of the boat has to be taken into consideration in order for the PV panels to fit on the boat. Continuity has to be considered as solar panel operation is affected during cloudy conditions and depending on the time of the day. Other important aspects that should be considered are battery management [6]–[7] and having real-time information about the boat performance [8]. Another factor that affects the amount of obtained energy from solar panels is the location from the equator as the closer the location is, the more solar energy is gained [9].

One of the important features about electric boats is that an electric motor is used in replacement of diesel generator and that enables the use of solar power [10]–[11]. PV-diesel hybrid boats reduce the generated power from the diesel generator and that reduces fuel consumption, operation cost, and exhausted gas.

One design for PV-diesel hybrid boat was proposed in [12] for a car carrier ship with a 60213-ton weight. There was a difficulty in the design related to power stability as the weather condition changed in the sea and that affected the sun irradiation. Other designs were proposed for stabilizing the power of the PV-diesel hybrid system in [13]–[15]. A design in [16] was proposed for a recreational boat with only one load which was the electric motor with 800 watts rated power. Another design in [17] relied on the concept of Artificial Neural Network (ANN) for controlling the power. Another design for PV-diesel hybrid system had reduced fuel consumption in [18] but it had problems related to high current harmonics which was dealt with by using a filter. An optimal hybrid design was proposed in [19] for a cruise ship renewable power system with solar PV panels, fuel cell, and diesel generator. The aim for that design was reducing fossil fuels energy consumption and increasing the renewable energy systems penetration for marine applications.

These previous designs for hybrid electric boat system had difficulties related to power stability and continuity due to different factors such as the changes in solar irradiance values for solar PV panels. The

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proposed design deals with the power continuity problem, aiming to maintain continuous power supply for the electric boat regardless the changes that affect the hybrid system power components. The proposed hybrid system uses two main components: solar PV panels and diesel engine. The following sections will demonstrate the overall components of the proposed hybrid electric boat system in addition to the simulation results of the components which will emphasize the continuity of operation and stability of speed.

2. PV-DIESEL HYBRID SYSTEM COMPONENTS

Figure 1 shows a common PV-diesel hybrid system that consists generally of a number of PV panels as a power source, boost converter circuit to raise the source DC voltage, power inverter to convert the DC voltage to AC, MPPT system to obtain maximum power from solar energy, diesel generator to provide an extra power source, and a switching circuit for switching between solar and diesel power operation depending on battery measurements. The obtained AC power supplies the electric motor as well as other connected loads inside the boat such as lighting. Figure 2 demonstrates PV only power system for a solar boat application. This system is similar to the PV-diesel hybrid system but without having a diesel generator and its corresponding components.

3. THE PROPOSED SYSTEM DESIGN AND OUTPUTS

The proposed PV-diesel hybrid system uses 9 main components: PV panel array, MPPT system consisting of boost converter combined with voltage and current sensors, battery bank, boost converter, DC-AC power inverter, diesel engine, synchronous machine with transformer, switching circuit, and three phase asynchronous motor. Figure 3 shows the block diagram of the PV panel array with the MPPT system and the battery bank. The MPPT system has boost conversion process as well as measurements for voltage and current. The measurements are utilized to control the duty cycle based on the obtained values over time. Figures 4 and 5 demonstrate the characteristics of the PV panel array (the change in the power and current with respect to voltage) and the characteristics of the battery bank (the change in voltage over time for different current values) respectively for one PV array module from the PV panel array. The irradiance was chosen as a random function that has values between 0 and 1000 W/m^2. The values of the irradiance over time are shown in Figure 6. The time interval for all the output results was chosen between 0 and 5 seconds. It can be seen that the irradiance has two minimum values that are 250, these cases are the cases of changing weather conditions such as in cloudy weather.

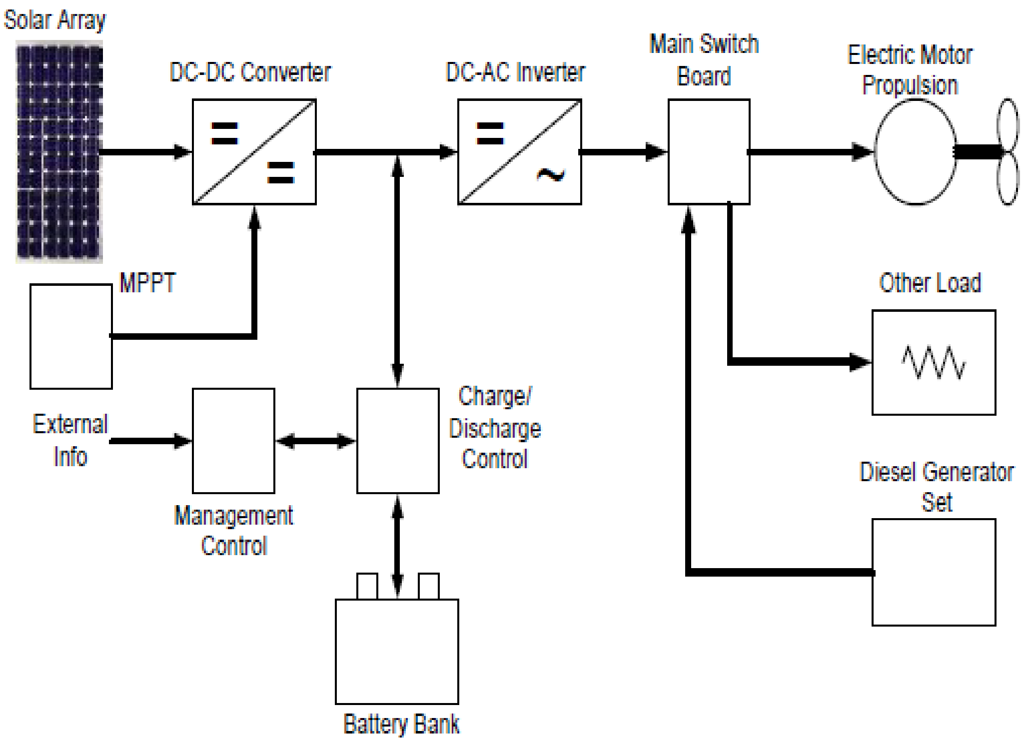

Fig. 1. General PV-diesel hybrid system for boats [6].

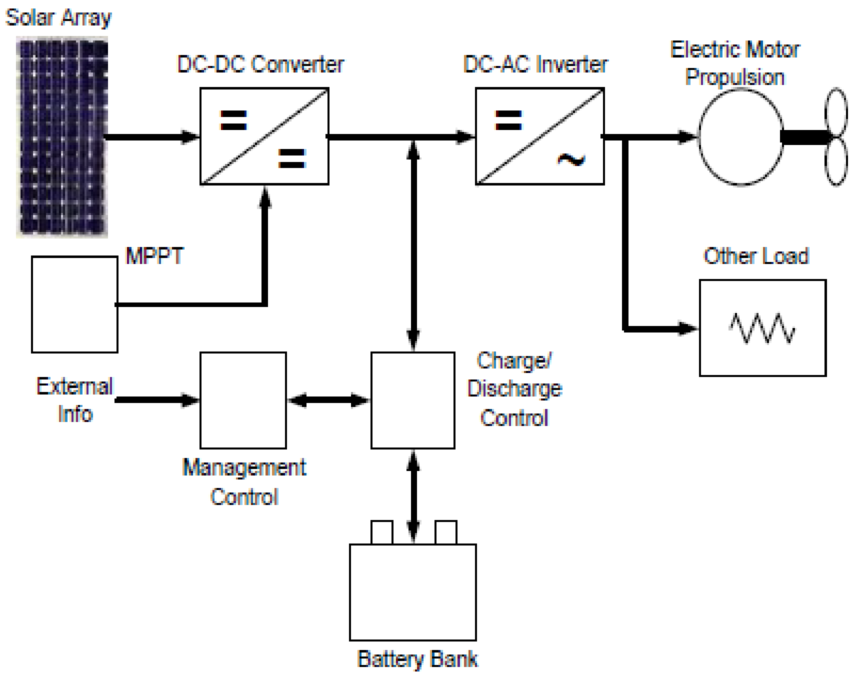

Fig. 2. General PV system for boats [6].

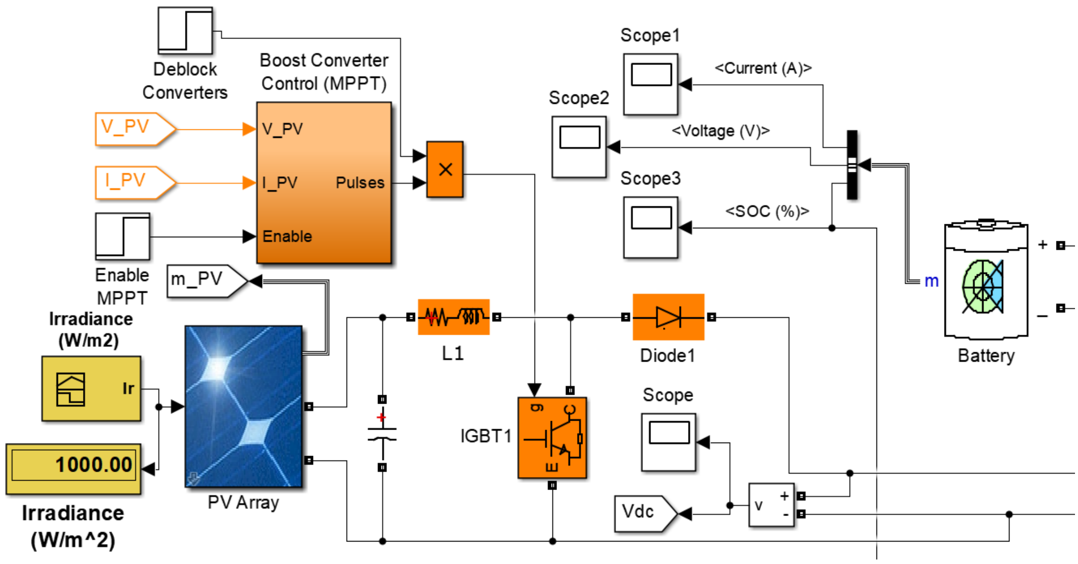

Fig. 3. PV panel array with the MPPT system and battery bank.

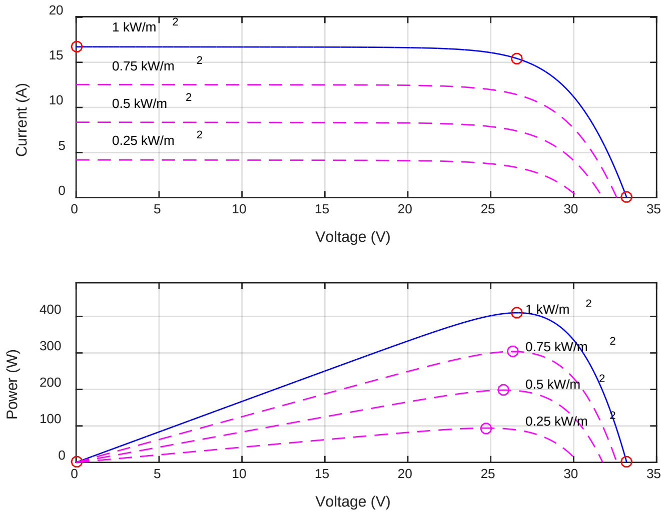

Fig. 4. PV panel array characteristics.

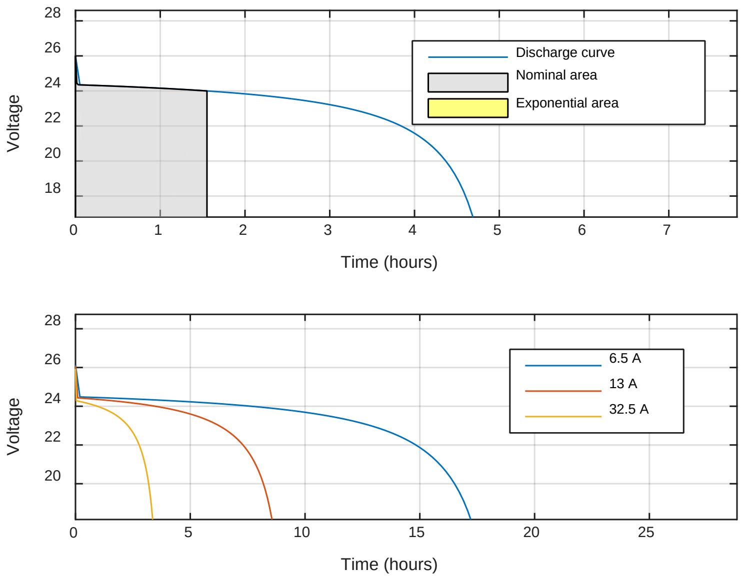

Fig. 5. Battery bank characteristics.

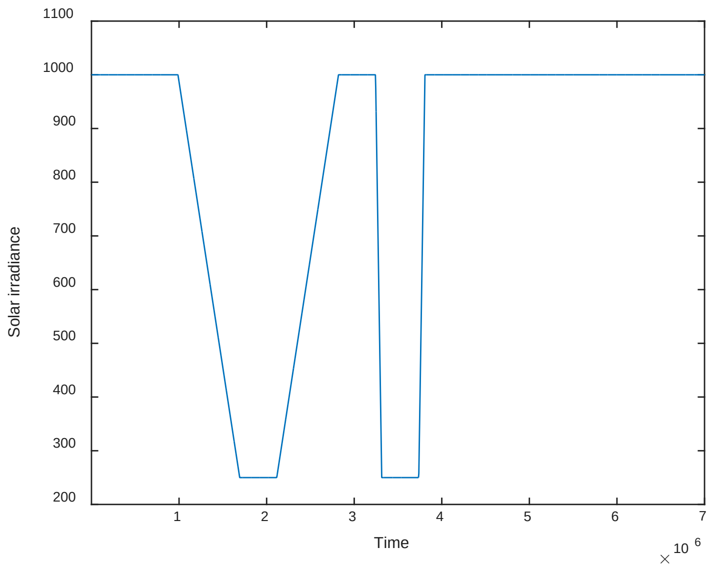

Fig. 6. The irradiance change over time.

The overall solar energy system was designed to provide continuous 24 v output voltage to charge the battery bank by the help of the MPPT algorithm blocks regardless the change in the random values of the irradiance. The output power from the solar panels in kw, the output voltage, and the current were measured by the scope blocks. Figures 7 and 8 display the measurements of the PV panel array outputs: power in kw and the voltage. The power was affected by the change in solar irradiance values over time. It can be seen that the voltage was maintained at 24 v by the MPPT algorithm using the measurements and duty cycle control regardless solar irradiance variations. The stable 24 v was suitable for the proposed design in order to charge the battery bank continuously.

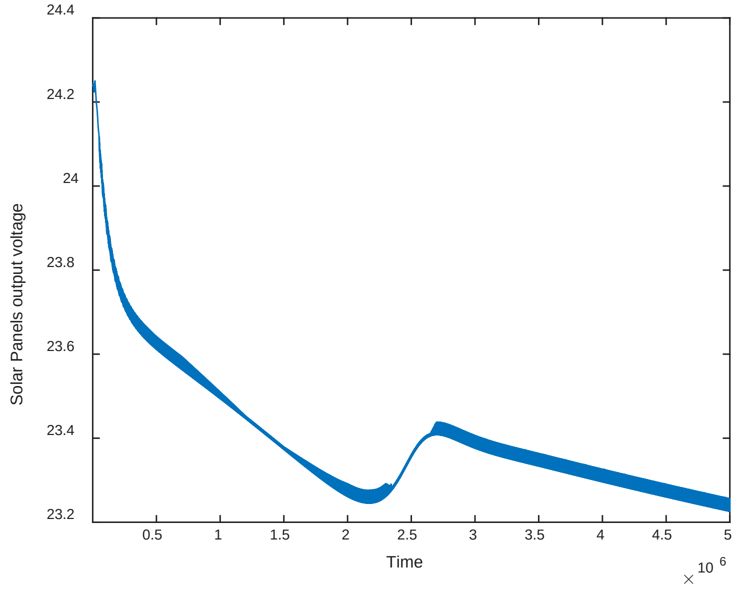

Fig. 7. The output voltage from the PV panel array.

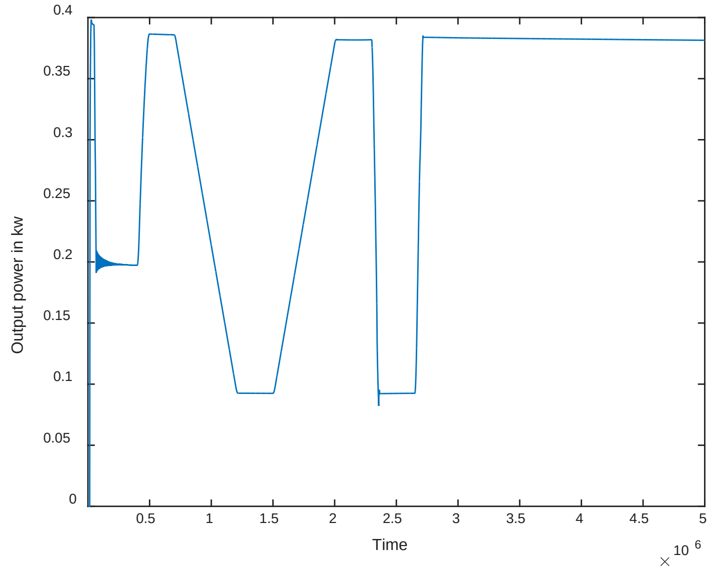

Fig. 8. The output power in kw from the PV panel array.

Battery bank output results are shown in Figure 9 and Figure 10. The results demonstrate the battery bank current and voltage over time. The voltage of the battery bank was maintained at 24 v by the continuous charge from the MPPT controlled PV panel array over the time interval. The current value was stable because of setting the electric motor propulsion system to operate at constant speed.

Since 24 v is small value for the operation of the three-phase asynchronous motor, a voltage boost converter circuit was needed to raise the DC voltage value. The used booster circuit block diagram is shown in Figure 11. The selected PWM duty cycle was chosen in the booster circuit to be 0.9 and the PWM frequency was 100 kHz in order to increase the resultant DC voltage to be more than 220 v for the operation of the boat electric motor. Figure 12 shows the output DC raised voltage that resulted from the booster circuit. It can be noted that the value was raised and maintained for all the time interval.

Figure 13 demonstrates the block diagram of the AC power inverter circuit which was used to convert the DC voltage from the booster circuit to AC for operating the three-phase asynchronous motor of the boat propulsion system. The output AC converted voltage from the power inverter is shown in Figure 14. The obtained AC voltage was maintained as the case of the DC boosted voltage from the battery bank. It can be noted that the obtained 220 v AC voltage is suitable for operating the boat electric motor which required 220 v AC three-phase voltage for operating at stable speed.

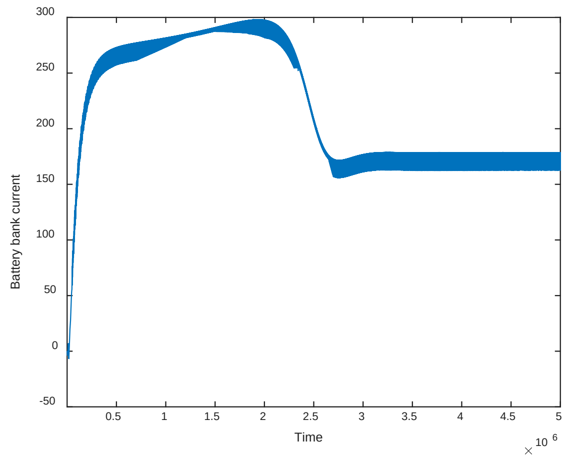

Fig. 9. The battery bank current.

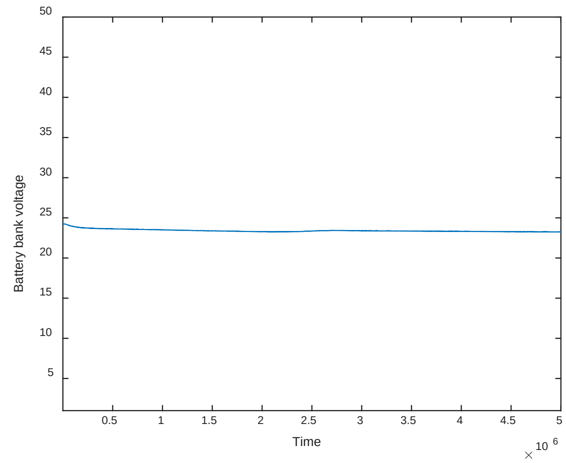

Fig. 10. The battery bank voltage.

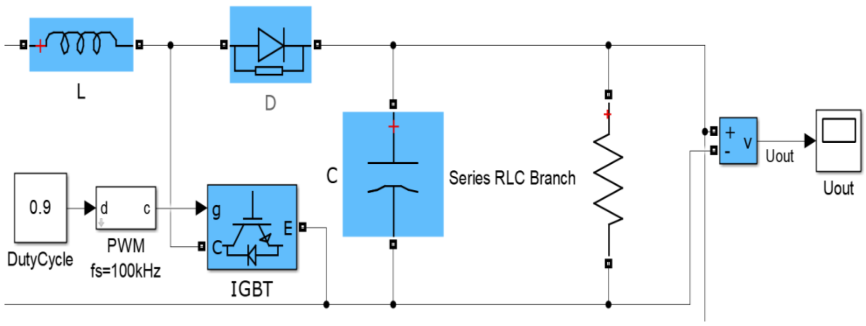

Fig. 11. Boost converter block diagram.

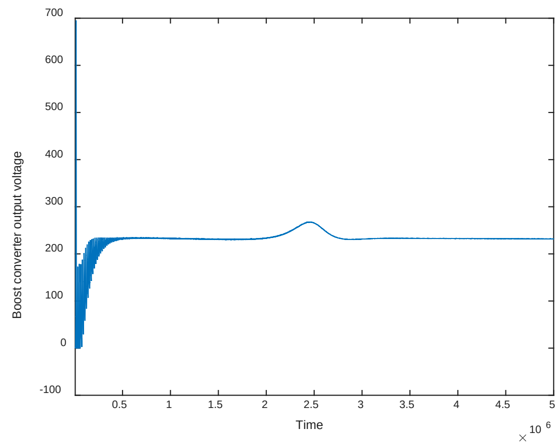

Fig. 12. Boost converter circuit output voltage.

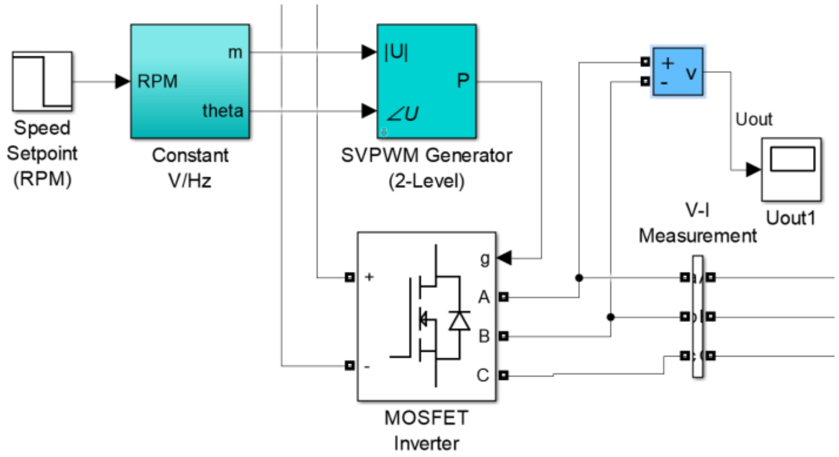

Fig. 13. Power inverter block diagram.

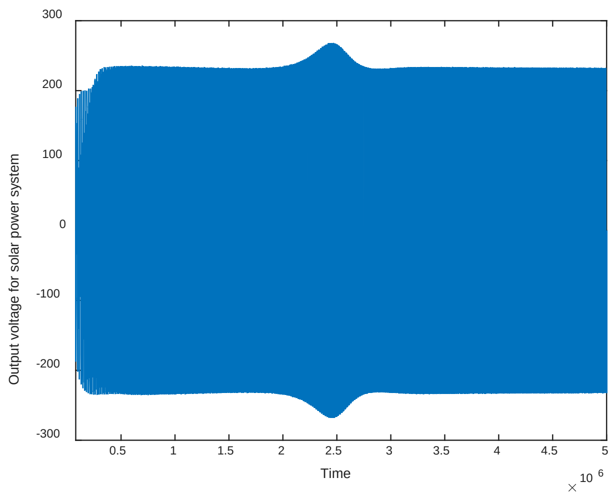

Fig. 14. Power inverter output voltage.

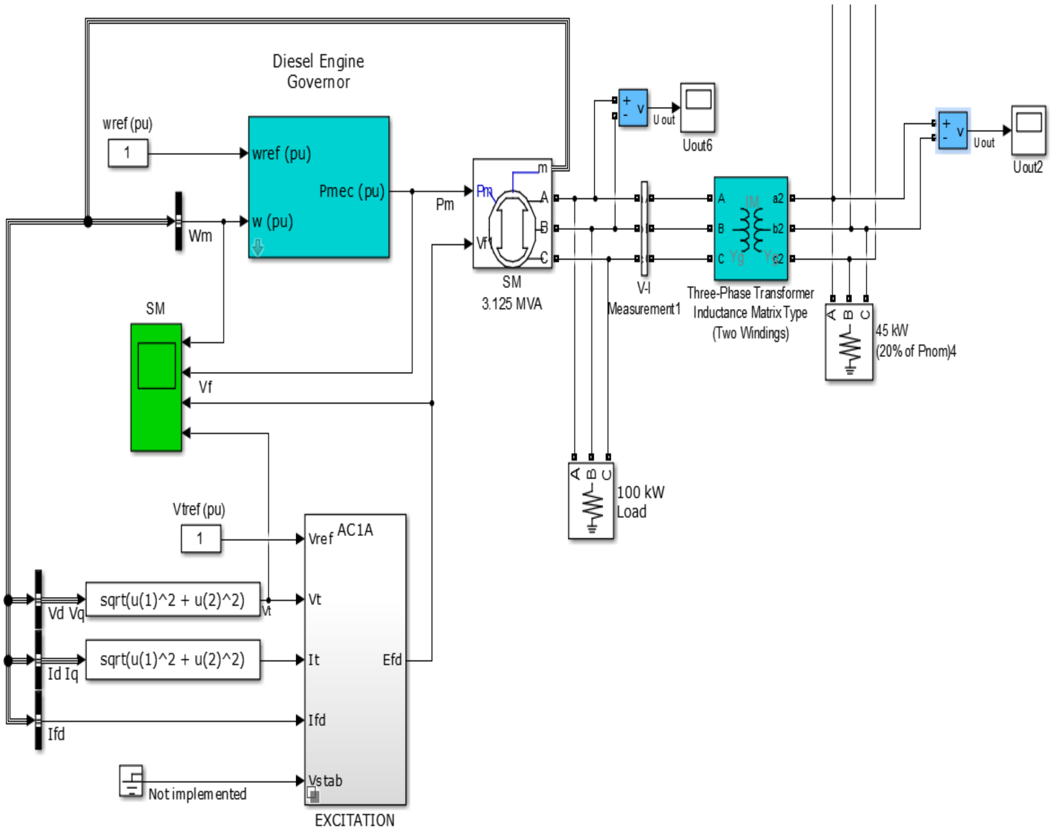

Fig. 15. Diesel system block diagram.

The diesel engine governor block combined with the synchronous machine block are shown in Figure 15. The engine governor supplies mechanical power input to the synchronous machine in order to obtain the necessary three-phase voltage for the boat motor. The diesel engine governor has two inputs: the desired speed and actual speed which is obtained from the synchronous machine operation. The output voltage from the synchronous machine was reduced by using a step-down three-phase transformer to obtain the desired output AC voltage in Figure 16. The resultant output AC voltage from the diesel system has a value that is close to 220 v which is suitable to operate the electric propulsion system of the boat.

The switching circuit block diagram is shown in Figure 17. It consists of 2 three-phase circuit breakers. The initial state of the breakers was set to open circuit. The state changes by external SIMULINK logical signal that was obtained by comparing the value of the state of charge for the battery bank to a constant value. The breaker that is connected to the PV system is closed (logical one) when the battery bank state of charge is above 60%, otherwise it gets opened (logical zero) and vice versa for the circuit breaker that is connected to the diesel power system.

The boat motor is a 3 hp, 220 v, and 60 Hz three-phase asynchronous machine operating in motor mode due to the positive value of the input shaft mechanical torque Tm which was set to 11.9. The output angular speed w_m and electromagnetic torque T_e of the three-phase asynchronous motor of the boat are shown in Figures 18 and 19 respectively. The motor angular speed starts from zero and reaches a constant value of 170 while the torque reaches 11.9 N.M. The input mechanical torque was set to a constant value to ensure a constant stable operating speed for the boat. It can be noted that the rotor speed as well as the electromagnetic torque were maintained stable at all the operation time interval regardless the changes in solar irradiance.

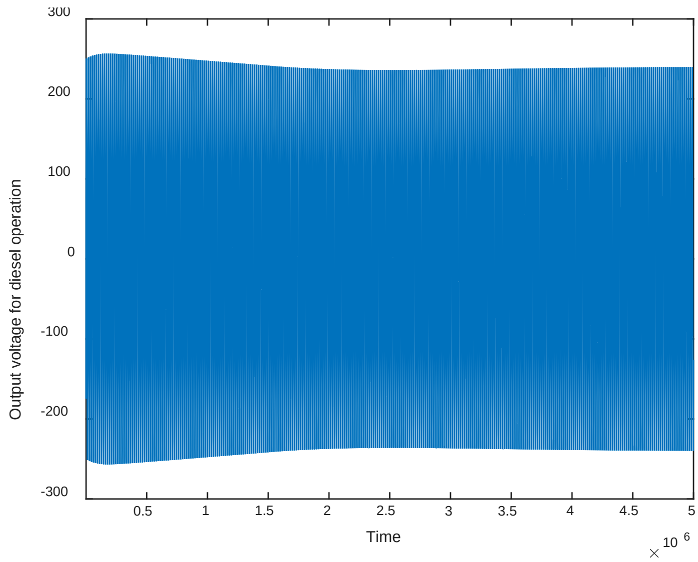

Fig. 16. Diesel system output AC voltage.

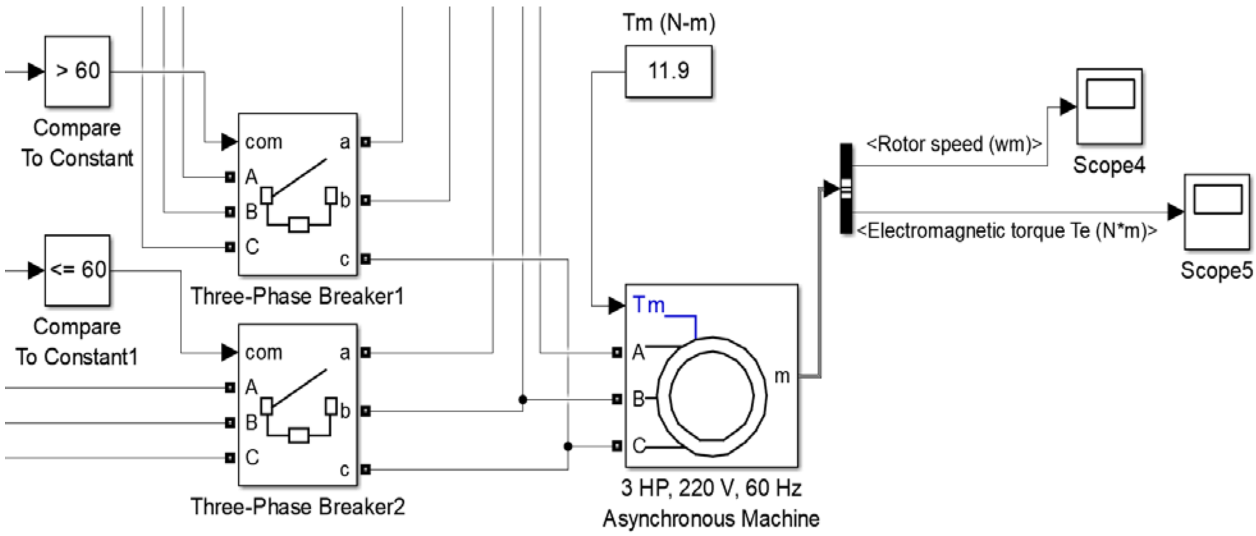

Fig. 17. Switching circuit block diagram based on battery bank state of charge.

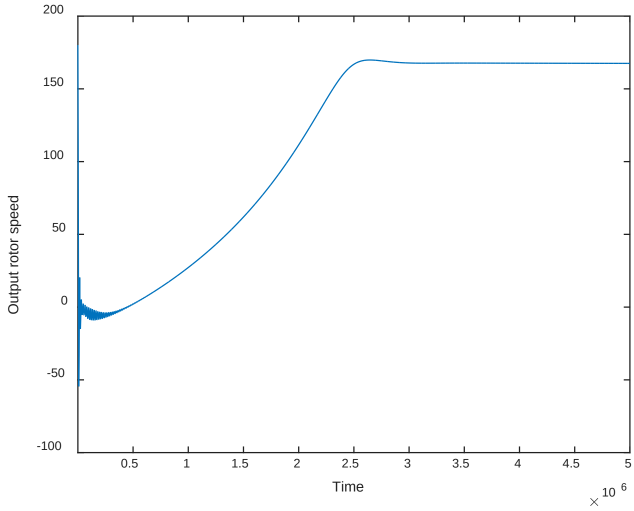

Fig. 18. The boat rotor speed in w_m **.**

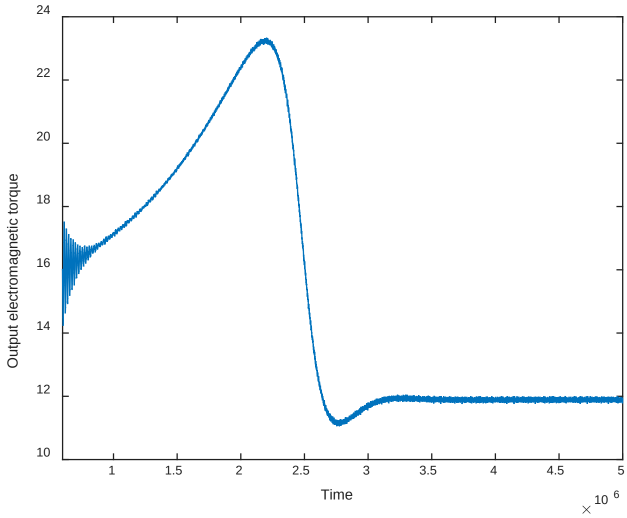

Fig. 19. The boat electromagnetic torque.

4. CONCLUSION

The proposed PV-diesel hybrid power system design for operating an electric boat was simulated by SIMULINK and the design was evaluated. The proposed solar PV panel array system was designed to provide a continuous 24 v to the battery bank by using the MPPT system block. The continuous charging voltage was maintained regardless the change in the value of the irradiance. The voltage from the battery was raised by the use of the PWM signal with 0.9 duty cycle that controlled the boost converter circuit. The raised DC voltage of the batter bank was converted to AC by using AC power inverter block in order to be able to operate the three-phase asynchronous motor of the boat. The diesel power system consisted of engine with governor and synchronous machine. The synchronous machine provided AC voltage which was reduced by using a step-down three phase transformer to 220 v to operate the three-phase asynchronous motor. The overall system was controlled by circuit breakers. The breakers switched the operation mode of the proposed power system depending on the state of charge for the battery bank. The boat motor was operated by solar energy if the state of charge for the battery bank was above 60%, otherwise it was operated by the diesel power system. The resultant output speed of the boat motor was maintained constant due to the use of switching circuit blocks and the MPPT system of the solar PV panels regardless the changes in solar irradiance values over time. The proposed design results demonstrated that it maintained stable operation and speed as compared with other designs from the previous work that had difficulties related to power stability and continuity due to weather conditions changes like solar irradiance.

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