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A solar-powered autonomous power system for aquaculture: optimizing dual-battery management for remote operation

Thomas Yuven Handaka Laksi, Levin Halim, Ali Sadiyoko
Department of Electrical Engineering, Parahyangan Catholic University, Bandung, Indonesia

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ABSTRACT

In Indonesia, growing fish consumption demands necessitate expanded, yet sustainable, fish production without sacrificing quality. The process of feeding and the quality of the surrounding water are important factors influencing fish quality. To address this, Parahyangan Catholic University's Fishery 4.0 project pioneers a unique technology that integrates water quality monitoring with a fish feeding feature. The design and implementation of an independent, reliable power module, which is fundamental to the functionality of this system, is at the focus of this research. This study shows that a designed power module adapted to the specific needs of Fishery 4.0 is feasible. The system powers all modules with a 12 V battery and is recharged with a solar panel. The battery can be charged to 95% capacity, yielding 8550 mAh from a 9000 mAh capacity. A UC-3906 charger IC controls the charging process, deliberately managing the parameters required for optimal battery charging. Particularly, when exposed to ideal solar radiation, the charger recharges a 9 Ah battery from 30% to full capacity in about 10 hours and 10 minutes. This study proposes a novel to battery management, which is critical for the operation of aquaculture equipment at isolated locations.

Corresponding Author:

Levin Halim
Department of Electrical Engineering, Faculty of Engineering Technology, Parahyangan Catholic University
Ciumbuleuit street No. 94, Hegarmanah, Bandung, West Java - 40141, Indonesia
Email: halimlevin@unpar.ac.id

1. INTRODUCTION

The increasing consumption of fish in Indonesia encourages the need for sustainable aquaculture that maintains quality while increasing production capacity. Implementing six interventions in Indonesian aquaculture can reduce environmental impacts by 28% to 49% per unit of fish, with more conservative production targets and sustainable farming practices recommended [1]. Floating net cages in Lake Maninjau, Indonesia, produce tilapia, carp, gourami, clarias catfish, and catfish, with gross yields of 12, 11, 5, 10, 4, and 8.89 kg/m^3/cycle, respectively [2]. Inland aquaculture, particularly in Asia, has contributed the most to global production volumes and food security, with improved feed efficiency and fish nutrition [3].

To meet the increasing consumption demand, sustainable aquaculture practices are essential, focusing on maintaining high fish quality. Intelligent and sustainable fish farming uses the intelligent technology and high biosecurity to maintain high fish quality [4]. Increasing surface water utilization and controlling pond fertilization can lead to increased efficiency and resilience in aquaculture systems [5]. Adequate environmental monitoring are essential to ensure the growth and sustainability of marine fish aquaculture production [6].

Important factors that affect fish quality include feeding methods and water conditions, which are crucial for the success of aquaculture operations. The quality of fish feed affects the aquatic environment of the aquaculture, affecting the utilization of nutrients [7]. The choice feeding methods determines the growth of fish and affects the quality of products in aquaculture [8]. Higher stocking densities in Atlantic salmon farming are associated with reduced water quality [9].

Technological advancements have led to the development of real-time water quality monitoring systems, utilizing wireless sensor networks and internet of things (IoT) technologies to increase productivity and maintain optimal conditions in aquaculture environments. Real-time sensor monitoring for water quality is increasingly being applied [10], [11]. IoT-based smart water quality monitoring systems offer real-time capabilities, making them more efficient, safer, and less expensive [12].

Implementing a reliable electric power system is essential for long-distance aquaculture, especially to support equipment such as water quality monitors and automatic feeders in remote areas. Research [13] is implementing solutions for energy independence and the use of energy storage. The proposed sustainable hybrid energy system in [14] uses renewable resources to produce pure oxygen and generate reserve power. Combining photovoltaics (PV) with desert aquaculture can provide additional benefits and offset the shortcomings of the aquaculture industry [15].

The specific energy management needs of isolated aquaculture systems, especially those that require sustainable, high-quality power for optimal performance, are still unclear. However, solar energy can reduce 40% of the total energy cost in aquaculture [16]. Solanki *et al.* [17] only presents a practical energy management system model for isolated microgrids. The proposed energy management approach in [18], using muddy soil fish optimization algorithms, minimizes production overhead costs and energy import costs.

On the other hand, the effectiveness of integrated battery management in isolated and solar-powered aquaculture environments has not been extensively tested or optimized. A distributed adaptive model predictive control (MPC) scheme is proposed in [19] for robust power management in solar battery-based isolated microgrid systems. Hybrid maximum power point tracking (HMPPT) algorithms and integrated power flow approaches improve system performance and reduced stress on batteries in PV/wind turbine/battery hybrid systems was explored in [20]. The proposed real-time energy management system in [21] maximizes revenue from rooftop PV installations with battery storage.

The impact of varying levels of solar radiation on the efficiency of battery charge cycles in remote aquaculture environments is not yet fully understood. Also, how well the battery management system maintains the power supply at night or in conditions of limited sunlight exposure has not been well documented. Moreover, the potential of dual battery systems to extend operational time in isolated aquaculture environments lacks substantial empirical evidence. The rechargeable Na-ion battery system can store/release energy in seawater and desalinate seawater without a membrane, which allows for a versatile energy storage system [22]. The dual battery storage system increases the life cycle of the main storage system which is suitable for remote applications [23]. The research [24] develops a laboratory-scale isolated wind battery system which are robust and easy to operate, thereby reducing technical problems in off-grid electric power systems.

The Fishery 4.0 at Parahyangan Catholic University, Bandung, Indonesia consists of several main modules, including communication and data transmission module, fish feeder module, water quality module, and reliable power system module as shown in Figure 1. However, this research focuses exclusively on the development of reliable electric power systems for isolated aquaculture environments. Fishery 4.0 are designed to float on water and function independently of land, requiring a powerful and efficient power solution. The use of electricity from land is impractical because it is inefficient across large waters; Therefore, a standalone solar power source is an ideal choice.

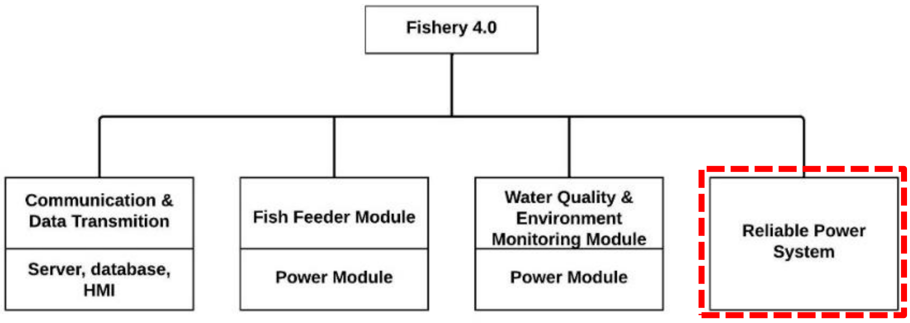


Figure 1. Fishery 4.0 overall system

To meet this need, the power module is designed with solar panels that charge the "priority" battery, which supplies power to the system, and a "backup" battery, which supports the priority battery during low sunlight conditions, such as at night. This setup requires an efficient battery management system to optimize charge cycles and ensure continuous operation. By focusing on the design and implementation of this system, this research aims to address the reliability and sustainability of power for long-distance aquaculture applications.

2. METHOD

The methodology used in this study involves a charger reference search to determine the current designs and technologies relevant to our objectives. Following the collection of charging references, a thorough study is conducted to establish the most effective design that meets the operating requirements of the Fishery 4.0 modules. After selecting an appropriate charger reference, we proceed with the design phase, which involves crafting a bespoke PCB layout, selecting the requisite battery charging management components, and integrating these with the chosen charger reference design. This phase is critical in ensuring that the charger corresponds to meet the system's specific requirements.

Once the design is finalized, the charger and incorporate it into the Fishery 4.0 system was constructed. This integration makes the next essential step easier: data retrieval. The system that has been deployed with our unique charger collects operational data. This information is critical for evaluating the design against actual performance measurements. The overall methodology flowchart is illustrated in Figure 2.

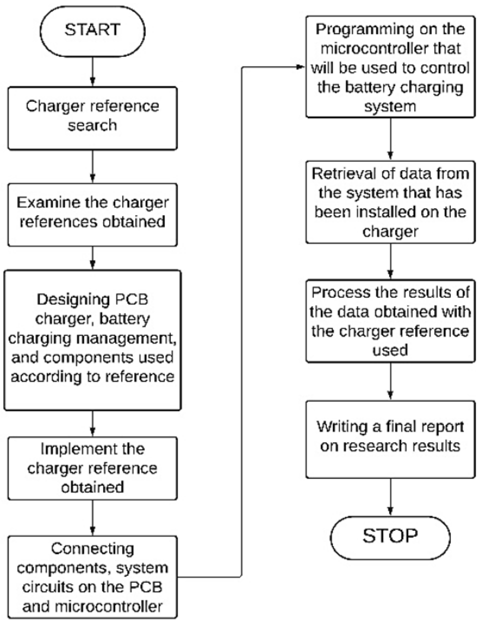


Figure 2. Research methods

2.1. Charger design

The conditions of voltage and current in battery charging process [25], [26], can be done by the UC-3906 IC. This IC can carry out the battery charging process using certain electrical circuits. This circuit will be designed for the charger used in this research. This electrical circuit must be able to create identical battery charge charts for each scenario that will be tested in this research. This will be a reliability point which is the excess of the charger designed in this research. Power from solar panels cannot be used directly to charge the battery. Battery charging requires certain conditions and rules. This paper will design a charger that can provide these conditions and rules. Each battery charging condition can be resolved using a charger IC.

The UC-3906 charger IC is a specialized integrated circuit designed exclusively for charging lead-acid batteries. Its architecture fulfills the stringent requirements for battery charging, as evidenced by the data presented in Figure 3. To harness the full capabilities of the UC-3906, it necessitates the integration of supplementary electrical circuits. These additional circuits are crucial as they define the final specifications and functionality of the charger system.

The electric circuit has variables that need to be determined through mathematical calculations. These calculations include:

– Pick divider current, I_D. Recommended value is 50 µA to 100 µA.
– R_C = 2.3 V/I_D
– $R_{SUM} = R_A + R_B = (V_F$ - 2.3 V)/I_D
– R_D = 2.3 V * R_{SUM} * (V_{OC} - V_F)
– R_A = (R_{SUM} + R_X) (1 -2.3 V * V_T)

where: $R_X = R_C * R_D * (R_C + R_D)$

– $R_B = R_{SUM} - R_A$
– R_S = 0.25 V * I_{MAX}
– R_T = (V_{IN} - V_T - 2.5 V) * I_T

From the mathematical calculations above, there are several variables that are determined, that is I_D, V_F, V_{OC}, I_{MAX}, V_{IN}, V_T, and I_T. This specified variable is obtained from the battery datasheet to be used. In Fishery 4.0, the battery that will be used is a valve regulated lead acid (VRLA) type lead acid battery with a capacity of 9 Ah. Then it can be determined that the value of the specified variable includes:

– I_D = 100 µA
– V_F = 13.8 V
– V_{OC} = 14.8 V
– I_{MAX} = 0.47 A
– V_{IN} = 24 V
– V_T = 10 V
– I_T = 25 mA

From the determination of variables and knowledge of component calculations, a charger can be designed according to the needs of the fulfillment of the power module in Fishery 4.0.

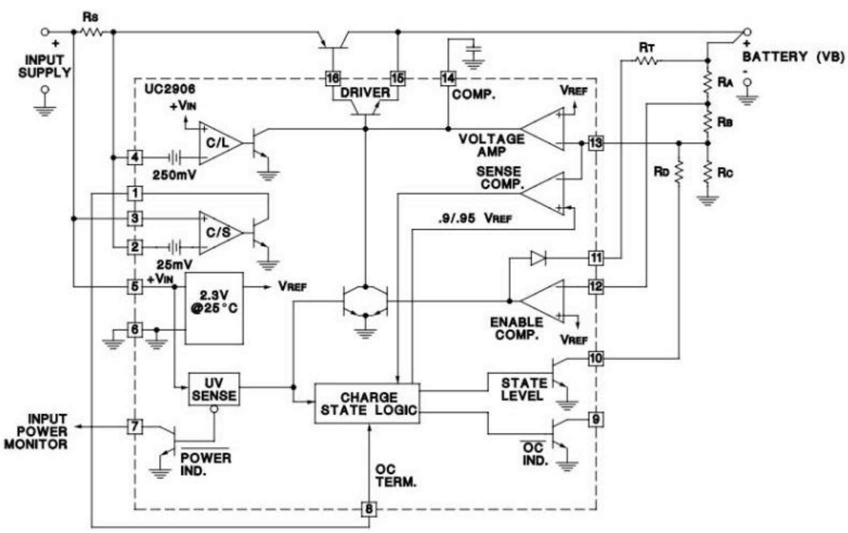


Figure 3. Circuit that supports the UC-3906 IC [26]

2.2. Battery management system

There are two batteries used in the Fishery 4.0 system, namely priority batteries and backup batteries. These two batteries will experience a decrease in power, so a system is needed that controls the flow of power from the charger to the that two batteries. Based on the designed battery management system, Figures 4(a), 4(b), and 4(c) shows that the charger will automatically charge to the priority battery. The relay that is connected to the priority battery is in a normally closed condition and the relay that is connected to the backup battery is in a normally open condition. Then the voltage sensor will read the voltage from both batteries. Since the backup battery is also being used up by the load, the power of the backup battery will also be reduced. If the charger is connected to the priority battery, and the backup battery voltage is less than 12.3 V (55% capacity), the charger must charge the backup battery. Relay 2 will close and relay 1 will be open, and this condition will cause the power only flows to the backup battery. Then the backup battery current sensor will read again, whether the backup battery has reached a constant voltage charging process with a lowered current. In this charger, the specified current for the full indicator on the backup battery is 0.18 A or 180 mA (95% capacity). If the current sensor read this current value, relay 1 will close and relay 2 will open. This causes the charger to charge back to the priority battery.

If the voltage sensor from the solar panel detects a voltage is less than 14.5 V, the priority battery voltage is less than 12.3 V (55% capacity), and the backup battery voltage is higher than 12.6 V (80% capacity). From these three conditions, relay 3 which is in the normally open condition will close and the backup battery will charge the priority battery until it is almost full, that is, it reaches 85% capacity. The process of charging the backup battery to the priority battery continues until the solar panel has regained enough power to charge the battery.

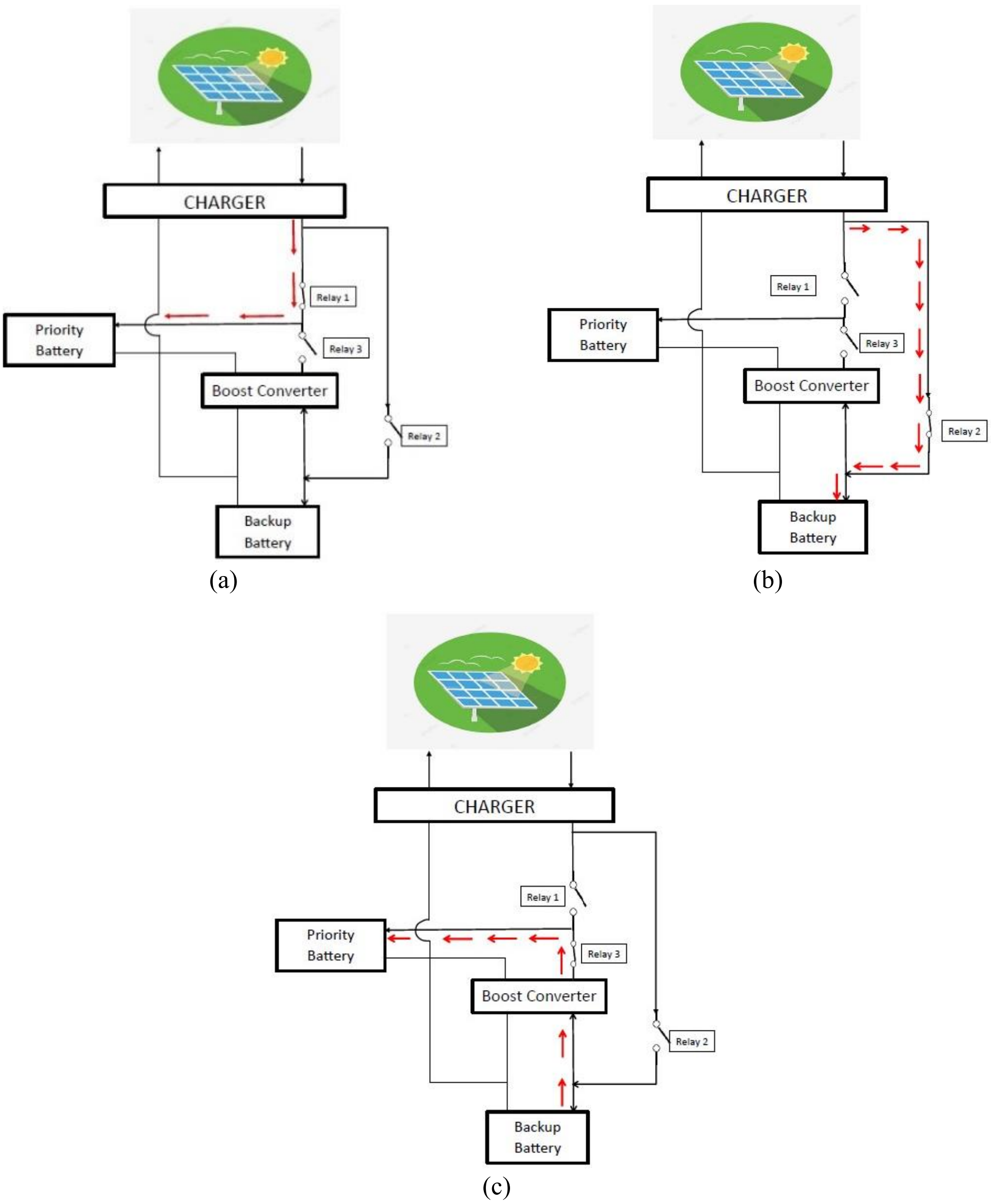


Figure 4. Battery management system workflow when priority battery (a) connected, (b) not connected, and (c) no power from solar panel

2.3. Evaluation and performance testing of the system

The charger designed on Fishery 4.0 will use a test module to simulate the sun shining on a solar panel. The test module will be made using 16 halogen lamps with 100 watts power per lamp. The brightness level of this test module is regulated using a dimmer. On the other hand, there are 3 levels of radiation considered in this research. This test was carried out to see the characteristics of the charger when given different solar radiation. Figure 5 shows solar radiation data located at Parahyangan Catholic University, Indonesia from 10 am to 2 pm which was chosen because it was assumed that during this time, the sun is at its maximum brightness level. This data is obtained from the NREL website [27] as shown in Table 1. The radiation level of 1063 W/m^2, 870 W/m^2, and 502 W/m^2 were chosen to be considered as shown in Table 1 which is the minimum, average, and maximum solar radiation at Parahyangan Catholic University, Indonesia. On the other hand, for experiment, there will be 7 scenarios that will be considered which is shown in Table 2.

The data collection in this research is stopped when the current decreasing process reaches a certain value. For the priority battery condition connected, when the current reaches 180 mA, the data retrieval process is also stopped. For priority batteries not connected, data capture is stopped when the current drop reaches 120 mA. This number was chosen because at these numbers, the condition of the battery is sufficiently fully charged, namely 95%, and is sufficient to power the load until the next charge.

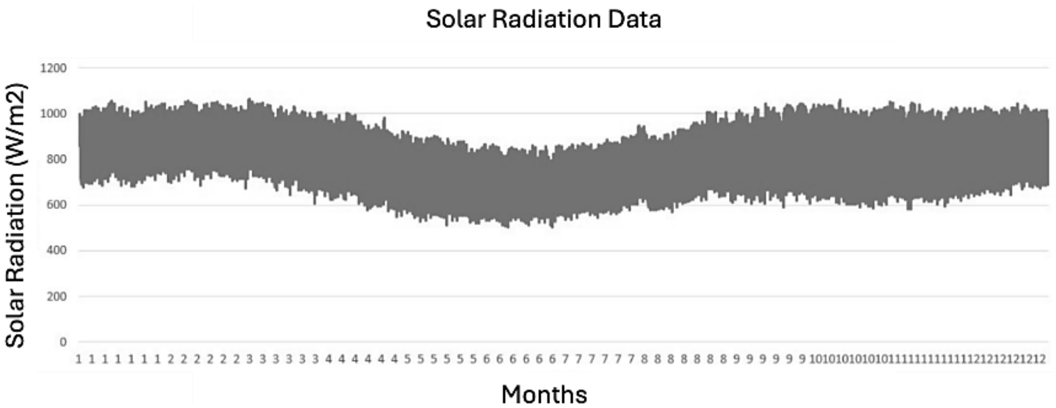


Figure 5. Radiation data from NREL

Table 1. Radiation level

Radiation level	Value (W/m^2)
Minimum	502
Average	870
Maximum	1063

Table 2. Experiment scenario

Scenario	Radiation (W/m^2)	Priority battery connection
1	502	Connect
2	502	Disconnect
3	870	Connect
4	870	Disconnect
5	1063	Connect
6	1063	Disconnect
7	0	Connect

3. RESULTS AND DISCUSSION

The data obtained is charging data for a 9 Ah lead acid battery with a halogen lamp testing module. Testing will be carried out by connecting the priority battery with the charger and disconnecting it. When the priority battery is not connected, the charger should charge the backup battery. When the priority battery is connected, the charger must charge the priority battery first, and if in the middle of charging the backup battery must be filled immediately, the charger must first charge the backup battery and after the backup battery reaches a certain full point, then the charger will cut off power to the backup battery and re-charge the priority battery.

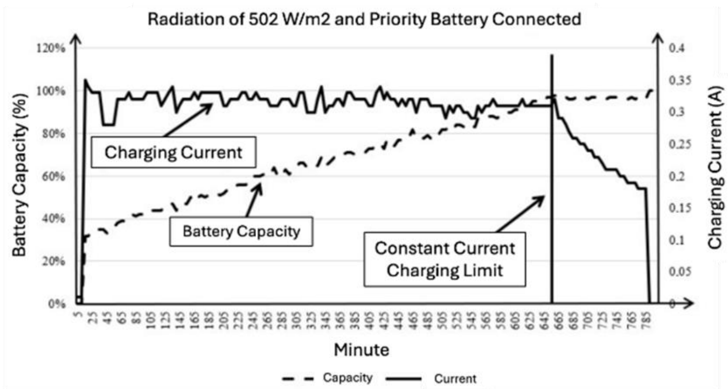
3.1. Experimental validation and results

This subsection is the result of the experiments that have been carried out. As explained, the charger test will be carried out with 3 radiation levels, that is 502 W/m^2, 870 W/m^2, and 1063 W/m^2. Figure 6 is a charger test with the condition that the solar panel receives 502 W/m2 radiation, with Figure 6(a) is a graph of battery charging when the priority battery is connected and Figure 6(b) with the priority battery not connected. The left image is charging the backup battery by the charger on the grounds that when the priority battery is connected, the charger has automatically filled the priority battery. However, there are also conditions when the backup battery also requires charging after passing the battery charging threshold. So that you can see the characteristics of the battery charging by the charger when the priority battery is connected.

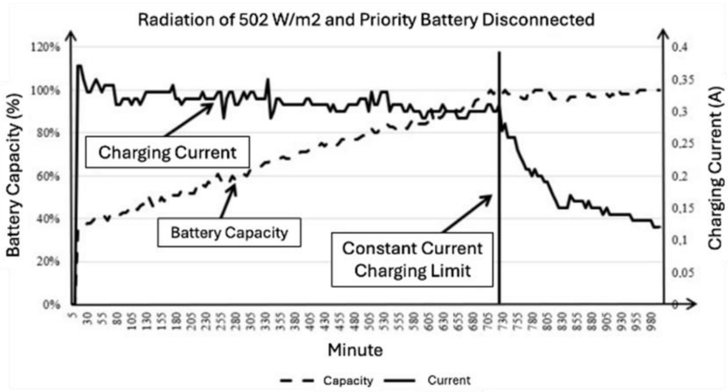
In the initial conditions, the charger automatically fills the priority battery, then the backup battery passes the lower threshold. Under these conditions, charging the backup battery will begin. The backup battery will go through the same battery charging stage as the priority battery. The difference is the backup battery will not experience a maximum current reduction process but will be stopped when the charging current reaches 180 mA. When the current sensor has read this number, the charger will return power to the priority battery. For a radiation of 502 W/m2, with the priority battery connected, it takes 13 hours and 20 minutes to reach a current of 180 mA. Meanwhile, the priority battery is not connected, it takes 16 hours and 30 minutes to reach a current of 120 mA.

Figure 7 is a charger test with the condition that the solar panel receives 870 W/m2 radiation, with Figure 7(a) a graph of battery charging when the priority battery is connected and Figure 7(b) with the priority battery not connected. The same as in the radiation condition of 502 W/m2, the test condition is carried out until the current reaches 180 mA in the connected priority battery condition and 120 mA in the disconnected priority battery condition. For 870 W/m2 radiation, with the priority battery connected, it will take 10 hours and 30 minutes to reach a current of 180 mA. Meanwhile, the priority battery is not connected, it takes 10 hours and 10 minutes to reach 120 mA current.

Figure 8 is a charger test with the condition that the solar panel receives 1063 W/m2 radiation, with Figure 8(a) a graph of battery charging when the priority battery is connected and Figure 8(b) with the priority battery not connected. For 1063 W/m2 radiation, with the priority battery connected, it will take 10 hours and 10 minutes to reach a current of 180 mA. Meanwhile, the priority battery is not connected, it takes 12 hours and 20 minutes to reach a current of 120 mA.

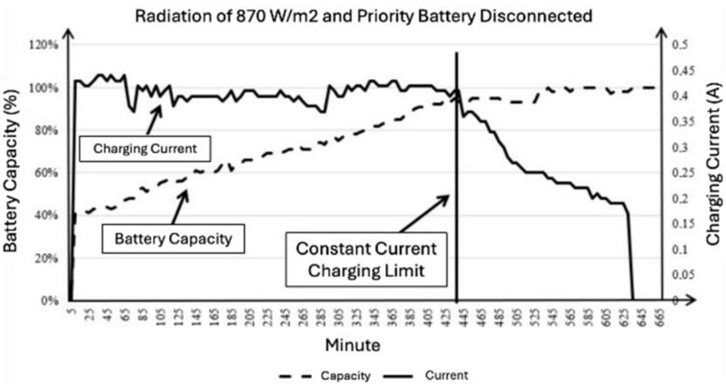


(a)

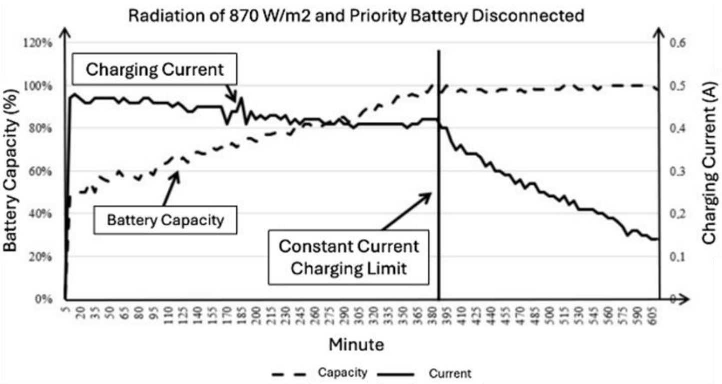


(b)

Figure 6. Experiment results: (a) scenario 1 and (b) scenario 2

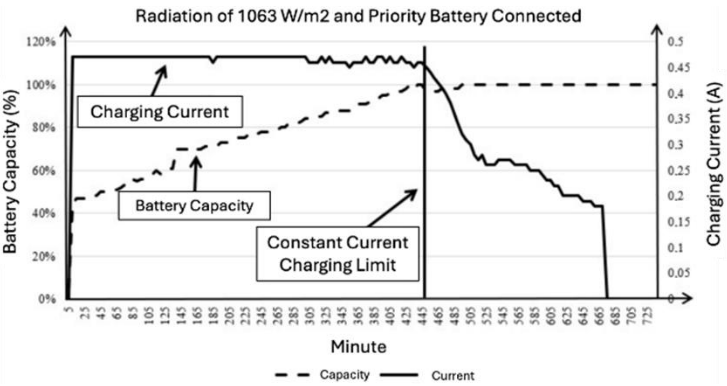


(a)

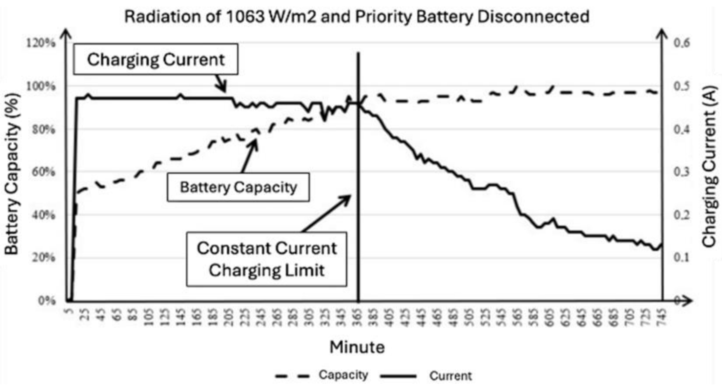


(b)

Figure 7. Experiment results (a) scenario 3 and (b) scenario 4



(a)



(b)

Figure 8. Experiment results (a) scenario 7 and (b) scenario 8

Battery-to-battery charging is carried out when the solar panel is not powered, by not connecting the solar panel to the charger as shown in Figure 9. Termination of this connection as an illustration that the solar panel does not get enough radiation to charge the battery, but the battery is in a condition to be charged. The condition is that the charge from the priority battery has been reduced to 35%-40%. Then the charging process is carried out using a constant current of 240 mA until the priority battery voltage reaches 13.45 V. The time needed to reach 13.45 V and the priority battery condition is 85% full is 1 hour and 35 minutes.

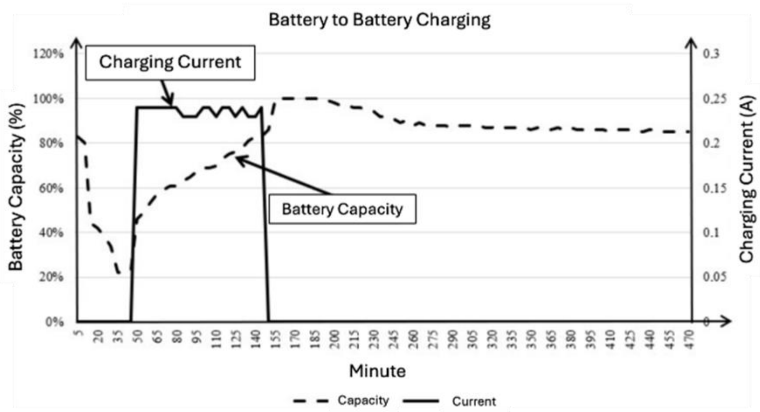


Figure 9. Scenario 7 experiment results

3.2. Charge duration for battery management

The charger test that has been carried out has results that can be analyzed, that is the battery charging time by the charger when the solar panels are given different radiation. The time in Table 3 is the time obtained in the experiments that have been carried out. The test is carried out using a test module with variable radiation. It can be seen that the radiation received by solar panels will affect the battery charging time. The greater the radiation received by the solar panel, the faster the battery will be charged by the charger.

Table 3. Battery charge duration for each scenario

Scenario	Time (hours minute)
1	13 hours 20 minutes
2	16 hours 30 minutes
3	10 hours 30 minutes
4	10 hours 10 minutes
5	10 hours 10 minutes
6	12 hours 20 minutes
7	1 hours 35 minutes

3.3. Reliability of power module

One of the goals of the Fishery 4.0 power module is to offer a reliable power module. According to [28], reliability is the ability of an item to perform the required function under the stated conditions for a certain period. It can also be defined as the characteristic of an item expressed by the probability that the item will perform the required function under certain conditions for a certain period of time.

The Fishery 4.0 power module ensures reliable power by keeping priority batteries charged, utilizing solar energy when available, and switching to backup batteries when sunlight is insufficient. The system incorporates a battery maintenance feature that follows a specific charging protocol, gradually reducing the current as the battery reaches 85% capacity to extend the life of the battery. This controlled charging process is designed to be consistent in every charge cycle, following an ideal charge curve to ensure optimal battery performance and life. As shown in the previous section, it can be seen that each process of charging the battery with various radiations applied produces a battery charge graph that tends to be identical to the reference [25], [26]. The reliability of the power system designed in this research can provide the appropriate battery charging results with ideal battery charging.

4. CONCLUSION

The Fishery 4.0 at Parahyangan Catholic University introduces a reliable solar-powered energy system that marks a significant advance in autonomous aquaculture technology. This innovative setup uses a 12V battery, charged by solar panels via the UC-3906 charger IC, ensuring efficient and stable power management that aligns with the ideal charging curve. The system's ability to recharge the battery to 95% capacity (reaching 8550 mAh from a capacity of 9000 mAh) highlights its effectiveness, especially considering the specific charging needs of a 12V lead-acid battery. With the ability to fully recharge a 9 Ah battery in about 10 hours and 10 minutes under optimal sunlight conditions, the study features a solution that supports sustainable operation in remote aquaculture environments. These findings have broader implications for the application of reliable solar-powered energy systems in other isolated and sustainability-focused applications.

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BIOGRAPHIES OF AUTHORS

Thomas Yuven Handaka Laksi is a committed student specializing in electrical power systems and engineering drawings at Parahyangan Catholic University in Bandung, Indonesia. His research focuses on renewable energy and maintenance of electric power systems. He can be contacted at email: thomasyuven83@gmail.com.

Levin Halim received a bachelor's degree in electrical power engineering and a master's degree in electrical engineering from the Bandung Institute of Technology in Indonesia in 2014 and 2015, respectively. Currently, they hold the position of assistant professor at the Department of Electrical Engineering at Parahyangan Catholic University. His research interests include renewable energy, power quality, power electronics, power generation, power grids, power supply quality, power transmission reliability, power transmission lines, power transmission planning, power transmission protection, battery chargers, circuit breakers, harmonic distortion, smart grid, power distribution protection, and the application of artificial intelligence in power systems. He can be contacted at email: halimlevin@unpar.ac.id.

Ali Sadiyoko was graduated from Electrical Engineering Department in 1995 and master's degree from Development Studies in 1999, and doctor degree in 2016, all from Institut Teknologi Bandung (ITB), Indonesia. He is currently Associate Professor of Mechatronics Engineering Department at Parahyangan Catholic University. He experienced for over than 10 years as information systems consultant for some organizations. His research interests include system modelling and simulation, mechatronics, system dynamics multi-agent systems, robotics and control systems. He can be contacted at email: alfa51@unpar.ac.id.