Design and Analysis of a Hybrid Power System for an Offshore Aquaculture Site in Newfoundland, Canada

Written by

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Abstract

The offshore aquaculture industry in Canada is bound to rely on non-renewable energy sources i.e. Diesel Generators (DGs) to meet its intensive energy needs due to absence of utility's electrical infrastructure. The said energy source is expensive, detrimental for the marine ecosystem, difficult to manage its transport and storage at site. This thesis presents a comprehensive solution to replace the high-cost energy source with a cost-effective and environmentally friendly energy source for an offshore aquaculture site located near Red Island, Newfoundland, Canada. The first step involves inputting the actual energy requirements of the site into Homer Pro software to design a hybrid power system, primarily featuring a floating solar power system (FSPV) to replace DGs. The techno-commercial viability of the designed system is assessed in three scenarios (Base, Ideal, and Worst), all of which show convincing and encouraging levels of renewable energy penetration. By comparing the cost of electrcity calculated by the software with the existing setup's energy cost, it is evident that the FSPV system is economically advantageous in all computed scenerios, base case of the designed FSPV system is 42% cost-effective. To validate the design, the system is modeled in MATLAB, and its dynamic performance is analyzed under varying conditions such as irradiance, temperature, and load side variations. The simulation results demonstrate the system's satisfactory and reliable response in all scenarios. For remote monitoring, a low-cost and open-source LoRA-based SCADA system is implemented. Additionally, an interactive Graphical User Interface (GUI) is developed to visualize historical and real-time data, showcasing the system's performance. The assembled hardware and results affirm that the proposed design is capable of providing a remote monitoring solution for offshore aquaculture sites. The findings underscore the potential of FSPV systems as a viable and sustainable solution for powering fish farms, thereby contributing to the overall sustainability of the aquaculture industry.

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List of Abbreviations and Symbols

PV	Photovoltaic
MATLAB	Matrix Laboratory
HOMER	Hybrid Optimization Model for Electric Renewables
VSI	Voltage Source Inverter
SPWM	Sinusoidal Pulse Width Modulation
LCOE	Levelized Cost of Energy
NPC	Net Present Cost
MPPT	Maximum power point tracking
MPP	Maximum power point
SCADA	Supervisory Control and Data Acquisition
TTN	The Things Node
RTU	Remote Terminal Unit
IoT	Internet of Things
AWS	Amazon Web Services

Nomenclature

$\Delta I/\Delta V$	Incremental Conductance
I/V	Array Conductuvity
V_i	Input Voltage
V_0	Output Voltage
L	Inductance
ΔI_L	Inductor Ripple Current
f_s	Minimum Switching Frequency
C	Capacitance
U_{dc}	DC Voltage
L_g	DG side Inductor
C_f	Filter Capacitance

Chapter 1: Introduction & Literature Review

1.1 Introduction

1.1.1 Background

By developing the first civilized cities nearby the fresh waters, we can see the history of fishery and the contribution of marine foods in the human diet. The traces of fish farming history before 1000 BC indicates that the credit goes to the Chinese people. The horizon of aquaculture is also seen in the first dominant civilizations such as ancient Egypt, China, and Rome. The economy and policy of many developed countries tie to this industry since the fisheries and aquaculture sectors contribute to combat with challenges of universal food security and bring economic benefits.

According to the report of the State of World Fisheries and Aquaculture 2022 by FAO (Food and Agriculture Organization of United Nations), the world saw the historic production of 178 million tonnes of aquatic animals in the year 2020. The total production is a combination of marine and inland fish farming, contributing 63% and 37% percent, respectively [1]. The estimated value of the said production is around USD 406 Billion. The direct human consumption share in total production is dominant at 89 % and the remaining 11% is used in making fish oil etc. A positive trend in human consumption of aquatic animals is seen in the last around six decades which grew at an average annual rate of 3% from 1961 to 2019, more than the global population growth rate. Furthermore, the average global per capita consumption trend of aquatic foods over the last years has significantly increased, in 1961 it was 9kg whereas it has reached 20.2 kg in 2020 [1]. The rise in per capita consumption is influenced by income growth, inclined consumer behavior towards healthy eating, better supply/distribution network, and the introduction of better technology.

Food security is a growing challenge for the world. It will become a dilemma in the coming years because global warming and resultant natural disasters threaten world food production resources.

Therefore, the world must find ways to produce sustainable food. The 70% of the earth's surface is covered with water which provides a clear viability for aquatic animals to be served as food for the rising population.

Protein is an important part of a balanced diet and according to the World Health Organization report the protein intake ratio for an adult person should not be lower than one gram per kilogram of human body weight [2]. There can be different sources of protein but some portions of it must be through animals. The daily per capita protein requirement cannot be met by the livestock only. Therefore, adequate sources are required to meet the protein demand [2]. Regarding the amount of universal protein intake in 2019, after dairy products, aquatic food provides the largest percentage of animal protein needs, at 7%. On the other hand, the amount of greenhouse gas emissions by red meat protein production put aquatic protein in the first popular demand among high-income countries. Fish is an exceptional source of protein and superior in value to other meat sources. But the demand for fish cannot be addressed by the ocean/wild fish alone therefore, it creates an opportunity to produce fish through commercial farming. The reproduction proportion of the fish is way greater than the warm-blooded land animals and able to provide the requisite protein at mass level [3].

1.1.2 Introduction to Fish Farm

Fish are bred, raised, and harvested as part of fish farming, which is also known as aquaculture, in a setting that closely resembles their natural habitat. In a fish farm, fish production and growth are maximized/optimized by providing the right feed, maintaining water quality, and doing routine health checks on the fish. Fish farms can be developed over the oceans, rivers, lakes, or ponds. There are a variety of prevalent techniques of fish farming in different parts of the world. North America and Europe mostly have net pens where the cage is fastened to the ground in the ocean, mostly close to the coastal area. Although, fish farming/aquaculture is embracing the latest technology and there are a lot of new advancements being made to improve the yield, lower the operational cost and lower the environmental footprints. The primary division of fish farm/aquaculture is based on the salinity of species [4], seawater and freshwater are the two broad categories.

Seawater fish farming is also called offshore aquaculture, the fish is raised in a specialized and purpose-based designed enclosure (normally a cage) in the seawater. The most practical and well-liked method of offshore fish farming is open-cage aquaculture, which is being used for many years. The complete system comprises flexible but floating collars, weights tied to the bottom surface, a net, and an anchorage system connected to the seabed [5], refer to Figure 1.1. The popular species of seawater are Salmon, Cobia, and Tuna. The typical system comprises the cage, the feeding mechanism, and the energy network [6], and the production cycle takes around 24 months [7]. A balanced diet having a suitable proportion of protein, vitamins, carbohydrates, and fats is supplied through the feed lines. The mixture of diet is dependent on the farmed species. A large boat/ship called a feed barge holding the complete infrastructure comprising of power supply, feed, automated monitoring system, and crew is stationed near the cluster of net pen sites, refer to Figure 1.2. The feed is stored in the silos which are placed on the feed barge and supplied to each cage with the help of feed blowers. The offshore fish farms provide relatively better water quality and hence yield healthy fish [8]. The power supply is arranged by diesel generators because of the non-availability of the grid/transmission network at the offshore location. The power requirement is usually high because of the automated fish feeders, freezers, air compressors, lighting, and the devices used by the deployed crew [9].

Figure 1.1: Aerial View of a Seawater Fish Farm Site

(Global Seafood Alliance, Martin Fore, December 02, 2019 www.globalseafood.org/advocate/precision-fish-farming-a-new-framework-to-improve-aquaculture-part-2/)

Figure 1.2: Feed Barge

(Akva Group, https://www.akvagroup.com/sea-based/precision-feeding/feed-barges/)

1.1.3 Site Description

The site is located in Newfoundland province of Canada which has a historic association with the fish. Newfoundland is considered to be one of the best places for fishing in the world because of the gulf stream's warm waters and the chilly Labrador Current joint here, frequently resulting in extremely foggy conditions. Nutrients are lifted to the top due to the mixing of these waters and the structure of the ocean floor. The said phenomenon makes this place rich and sustainable for the fishing and seafood industry. It has a total of eight cages, seven have fish and one is kept spare. Each cage has 160,000 fish. The feed is stored in eight silos and is supplied to each cage with the help of three feed blowers, the power rating of the feed blowers is 30kW, 22kW & 22kW. The power infrastructure consists of three diesel gensets each having a power rating of 99kVA. There are two fuel tanks with a cumulative capacity of 30,000 Liters and are usually refilled after every two weeks. All the said equipment is placed on the feed barge stationed close to the cages. The dissolved oxygen and water salinity level are monitored through sensors. There are two air compressors of 30kW to collect the waste/dead fish from the cage and supply the oxygen. The cameras are installed at each cage that help the operator to monitor the fish.

Considering the bright prospects of the industry and continuous rising demand, stakeholders are keenly looking to explore ways to increase the production capacities and for that different state-of-the-art technologies are being developed such as fish globe. As we know, energy is fuel for any industry so the availability of appropriate sources of energy is inevitable to bring enhancement in the production capacity and to achieve future goals. The idea of using renewable energy to meet the energy needs of the aquaculture industry can make it a more reliable approach toward global warming concerns and will be a breakthrough in improving the sustainability of the industry, as well. As of now, wild fisheries have a greater contribution to the total production of Canada, specifically and global generally. Therefore, aquaculture business should be encouraged so that the devastating effect of overfishing on the marine environment and ecosystem can be minimized.

We must consider that energy plays a remarkable role in fish farms. For instance, components like feeders, aerators, air compressors, lighting and security, or refrigerators and cooling infrastructures operate with energy and electricity. Renewable and Non-renewable energy sources are the two different categories of energy sources in the world. The carbon emissions from renewable energy sources are very low or nonexistent, making them environmentally benign. Non-renewable resources are harmful to the environment and cause global warming. Most of the energy consumed in the world today comes from non-renewable energy sources, but the world is slowly shifting to renewables.

The sun, rain, wind, tides, and other natural phenomena can all be used to generate renewable energy, which can then be used repeatedly as needed. The energy from the sun, which is transformed into electricity, might be used as an example. Wind energy is derived from the Earth's regular weather patterns.

1.1.4 The Developing Solar PV Technologies

Continuous developments are being made to improve the efficiency of the PV modules and the following are some of the new technologies that have been introduced so far.

1.1.4.1 Bifacial PV Module

This PV module has the capability to convert solar energy to electrical energy from the front and rear side as well. On the front side, the sunlight shines directly at the PV cells whereas the sunlight which is reflected from the ground is utilized by the rear side [12], refer to Figure 1.3. The power output of the bifacial module is 50% more than the conventional PV modules.

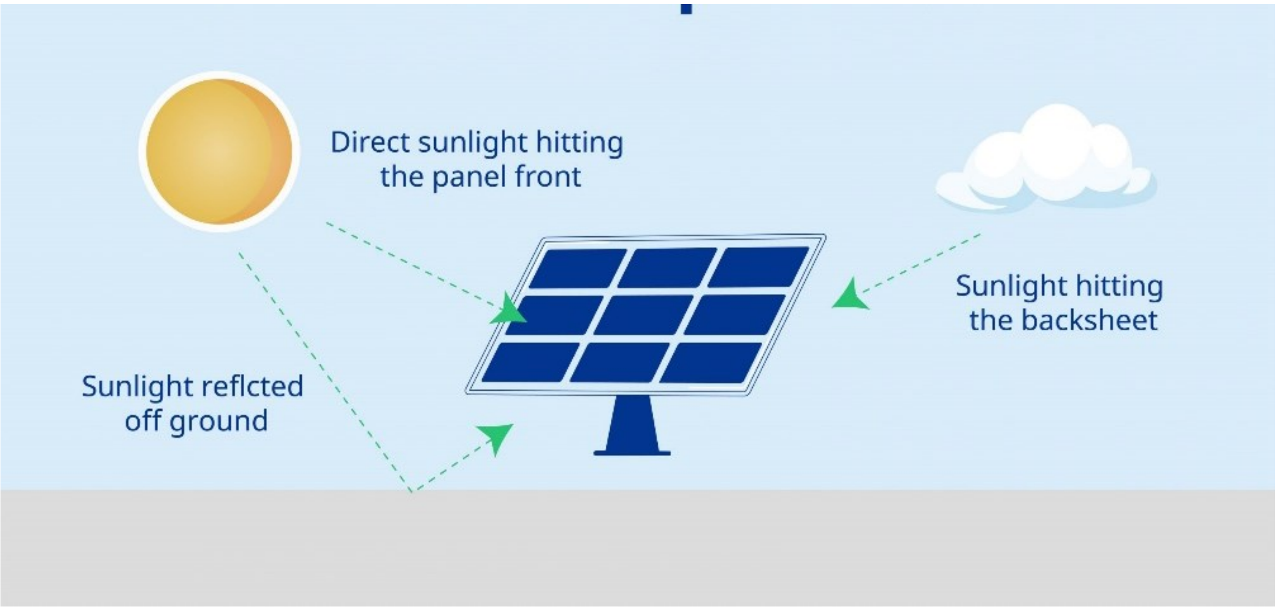

Figure 1.3: Bifacial PV Module

1.1.4.2 PERC (Passivated Emitter and Rear Cell) PV Modules

The traditional PV modules made up of crystalline silicon cells do not capture all of the wavelengths of the sunlight unless they hit the metalized rear side which leads to energy loss. With the introduction of the dielectric layer on the cell's reverse, which isolates the silicon surface and aluminum layer, the PERC technology is able to solve the issue of energy loss [12], refer to Figure 1.4. This unique feature enables this technology to improve efficiency even in low irradiance and low-temperature regions [13].

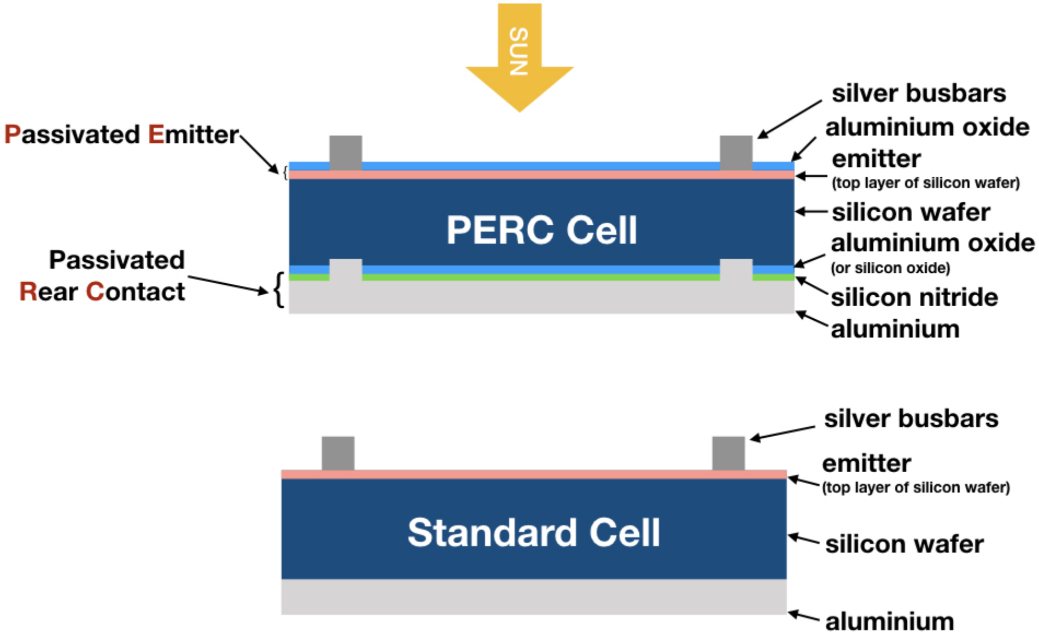

Figure 1.4: PERC PV Module

1.1.4.3 Half-Cut PV Module

The half-cut technique implements more cells per module which increases the efficiency of modules by 3% as compared to the conventional cells. The regular PV modules have 60 & 72 cells whereas the said technology uses 120 & 144 half-cells per module [12].

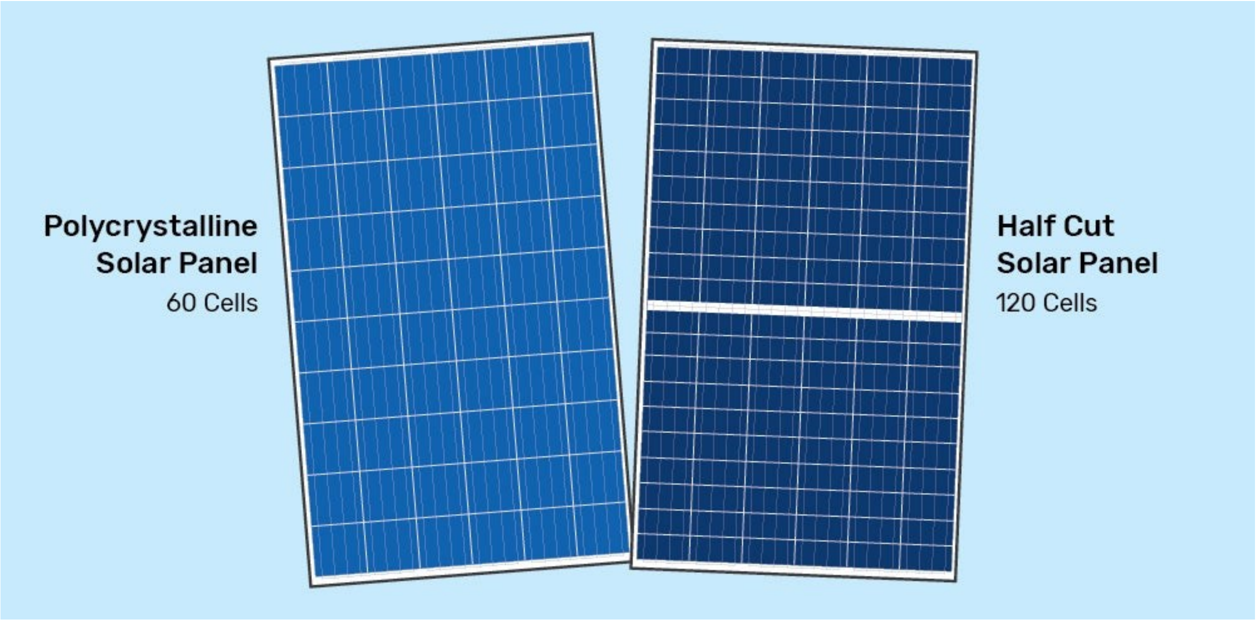

Figure 1.5: Half-Cell PV Module

The burden of extensive land requirements, which will always be a premium commodity, comes with solar photovoltaic (PV) installation. Installing Solar PV systems on water bodies including seas, lakes, lagoons, reservoirs, irrigation ponds, wastewater treatment plants, vineyards, fish farms, dams, and canals might be a desirable choice for conserving valuable land and water. When compared to solar panels that are installed on land, floating solar photovoltaic panels provide several benefits, such as fewer obstructions that block sunlight, convenience, energy efficiency, and improved power generation efficiency because of the lower temperature under the panels. Thus, the implementation of floating PV panels seems to be a complete match to expand the blue economy.

1.2 Literature Review

The world population has recently hit a new height and according to United Nations World Population Prospects Report 2022, the earth has seen 8 billion people in November 2022 which is expected to climb all-time high of 9 billion by 2050. The continuously rising population demands more food sources and fish can be an excellent source to overcome the global food security challenges. Furthermore, fish is also a richly nutritious food with abundant protein, fatty acids, minerals, and vitamins. Wild fish hunting is causing a considerable decline in the sea and rivers and is not sufficient to meet the seafood consumption rate and that’s the primary reason behind increasing fish farming activities [14].

1.2.1 Description and Operation of the Fish Farm

Aquaculture activities are broadly classified into land-based (freshwater) and offshore (seawater) fish farms. The offshore aquaculture system widely uses flexible floating cages to accommodate and raise fish. The said type of cage has a proven reputation for handling adverse weather conditions of the sea [15]. The cages are normally located at least 300 m from the seashore [16].

Robust mooring mechanisms are used to secure the cages in place. Chains, ropes, and buoys are used in these systems to keep the cages anchored in the water and from drifting away. The feed that has been specially prepared to fulfill the nutritional needs of the species being grown is typically used for feeding. The use of automated feeding devices can provide controlled and regular feeding. The feeding is done through the automated machines which are placed on the floating ship, the feed is provided through pipes in the form of homogeneous pellets [17]. The dissolved oxygen level (DO) is maintained in the cage with the help of air compressors. The DO content in water plays a pivotal role in fish survival, if it is less than 4mg/L in the water, then the fish cannot breathe and eventually dies [18]. The optimum level of DO in the water for better fish growth is 9 mg/L [14]. The amount of DO in the water is dependent on many factors like temperature, wind velocity, pollution, etc. [19]. The dissolvability of oxygen in water is inversely proportional to the temperature [14]. The fish farms located in humid, and warm areas where the atmospheric temperature is usually high, and the oxygen level in the water drops rapidly. Considering the critical role of DO in the production of fish, significant research is carried out to monitor the level of DO and implement effective techniques to maintain the level up to the requirement. The DO level in the water is artificially maintained/increased with the help of aerators (usually electric motors or air compressors) [14]. At the bottom of the fish enclosure, an aeration system diffuses air. This causes water to travel upward, which cools, purifies, and transports water rich in oxygen to the fish in the pen. The aeration system is considered to be the significant electrical load in the fish farm because in warm/humid climates the DO level drops more frequently and drastically so the electric motor/air compressor operates for 24 hours to maintain the DO level.

The automated monitoring system is an integral part of the system that helps to monitor the health, behavior, and growth of fish. The system is comprised of sensors (dissolved oxygen, salinity, pH, etc.), cameras, and a centralized monitoring/control system. The cluster of cages is formed and a feeding barge containing all the necessary operational equipment is anchored near the cages.

1.2.2 Energy Needs of Offshore Aquaculture

The offshore fish farms' operations rely heavily on electricity, feeding machines, air compressors, lighting arrangement for the cages, sensors, refrigeration, and instrumentation for monitoring are the primary consumers [20]. Further, the facilities developed for the operational staff also require electricity for lighting and heating, etc. These fish farms are not connected to the utility grid due to their remote location and rely on diesel generators for supplying electricity that runs 24/7. Energy is used in maritime fish farms in two forms i.e., fuel (for transportation) and electricity, referred to Figure 1.6. There is very limited research available on the energy assessment of offshore aquaculture however, the cumulative energy consumption (fuel used for transportation activities and generator operation) are given [20]. A study conducted on a coastal fish farm in Norway states that electricity required for carrying out the growth-phase activities is around 700kWh/day, with a peak load of 100-120kW during the feed time [21-22]. The feeding mechanism is one of the most electricity-consuming units with a share of 50% of the daily required electricity [21]. Whereas lighting, feeding, and other equipment constitute 78% of the total electricity need [22]. Another research states that the feeding machine/blowers are the leading and intensive power consumers which are placed on the deck of the feeding barge [23]. The automation trend in offshore aquaculture is increasing and companies are putting in more and more infrastructure to automate the fish feeding and remote monitoring system. Autonomous feeding systems have many advantages but have significant energy needs as well [15].

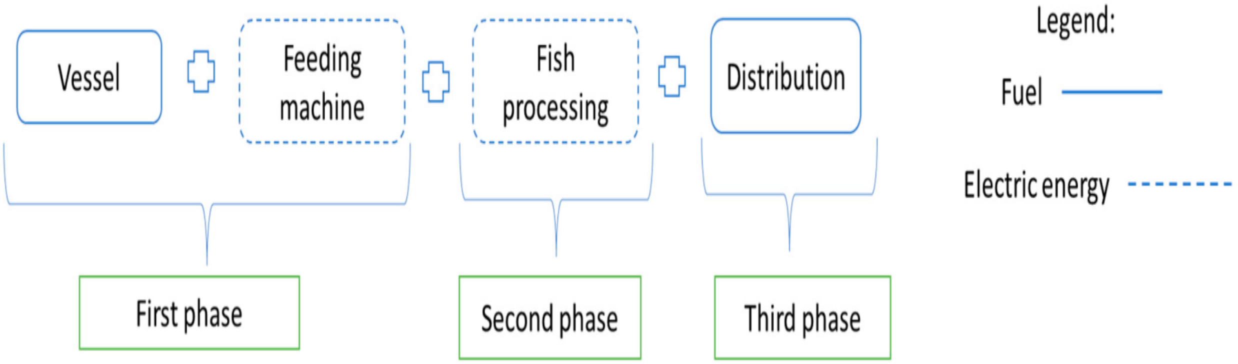

Figure 1.6: Energy used in Maritime Fish Farms

The energy demand of offshore fish farms is usually fulfilled by feed barges [15]. The feed barge is an integrated mobile setup that houses all the necessary equipment/setup to run the operations of the fish farm including the feeding system, air compressors for aeration, silos to store the feed and staff accommodation, and diesel generators. Further, the energy needs of an offshore fish farm site located in the Mediterranean Sea having underwater lighting, sensors, cameras, and remote video is recorded as 4783.88 Whr/day [15].

Energy requirement for the inland fish farms is also surveyed and found that it serves as one of the most important factors for inland aquaculture as well because of the intensive requirement of pumping the water and aeration system and the cost of electricity is going up each day. The overall production cost of the fish farms has a significant share of energy expenses, 10% to 15% [24]. The primary electrical energy-consuming equipment includes an aeration system, water pumping system, lights, etc. [25]. However, the aeration system is found to be the most energy-consuming unit [26,27]. The electricity consumption proportion is explicitly described in [27] and found to be 24% for the water pump, 57% for the aeration system, 12% for the lighting, and 7% for other auxiliary uses.

1.2.3 Review of Solar Energy for Aquaculture

Sustainable practices are the key and of paramount importance in determining the success of any business/sector. To bring more sustainability and betterment in the aquaculture industry, it is very important to apply environmentally friendly technologies that can play a role in reducing harmful impacts on the environment and bringing down the cost as well [28]. As per the FAO report [29], the aquaculture industry's share in providing seafood is more than half. Further to this, the rising population around the globe and their increasing appetite for protein give a vibrant indication that the aquaculture industry’s importance and share would be increasing in the coming days. Therefore, the discussion and research on deploying sustainable development is the need of the hour.

Solar energy is one of the most feasible and convenient renewable energy options that can bring sustainability and meet the energy demands of the aquaculture industry. According to research [30,31], in a few hours at noon in bright sunlight and clear skies, solar radiation generates roughly 1000 W/m2. The potential of solar power for aquaculture is found to be very convincing [32]. Further to this, considering the forecasted installations of solar photovoltaic panels, by 2030 solar power shall be the future energy source of aquaculture in the USA, Japan & Europe [33]. The usage of solar power for the aquaculture industry has been increasing significantly each day due to minimized operational costs, environmentally friendly nature, and low soil contamination [34]. There can be a wide variety of solar energy utilization for the aquaculture industry [35,36] like solar power generation, aeration systems powered by solar, and solar-based water heating systems [37]. The developed solar system for the fish farm can be Off-Grid and On-Grid as well. However, statistics show that most of the developed solar systems for fish farms around the globe are Off-Grid systems due to the fact that fish farms happen to be in areas where electricity is not served [38]. The On-Grid system’s presence is very rare [39-42].

PV modules can significantly reduce the operating costs of a fish farm by providing a free and renewable source of energy. This can be especially beneficial for fish farmers who are operating in areas with high energy costs [43].

Increased independence, by using PV modules to generate electricity, fish farmers can become more independent and self-sufficient. They will not be as reliant on external energy sources, which can be unpredictable or subject to price fluctuations.

Fish can become stressed in crowded or noisy environments thus using PV-powered equipment can reduce noise levels and improve water quality, which can help reduce stress levels and enhance fish health [44] and growth, adequate lighting and aeration are essential for fish growth and health. By using PV modules to power equipment such as lights and aerators, fish farmers can create optimal conditions for fish growth and ensure the health of their fish [44]. Adequate lighting is essential for the health and growth of fish. This can help regulate fish behavior, improve feeding patterns, and enhance growth rates.

PV modules are designed to operate in all weather conditions, including cloudy days, so they can provide a reliable source of power for a fish farm. In addition, with no moving parts, they require very little maintenance, reducing downtime and increasing overall reliability [45]. Overall, the advantages of using PV modules for floating fish farms are numerous and varied and can help fish farmers improve their operations and reduce their environmental impact.

1.2.4 Survey of Solar Energy in Aquaculture

Solar energy is used to produce electricity and run fish farm operations independently without the assistance of utility power. The traces of solar power running the operations of inland fish farms are very vibrant and there are numerous literatures on this but implementation of photovoltaics to supply energy needs is scarce and a novel concept. The application of solar power for inland fish farms is described below.

An off-grid solar power system of 1.1kW is designed for a fish farm in Turkey to supply the energy and its performance is evaluated using HOMER software [46]. The aeration system is one of the most significant energy-consuming units and a solar power system is designed to run the system for a large fish farm [47]. An off-grid solar system was developed to completely power up the fish farm along with its monitoring system (PLC & HMI) [27], the yield of the fish farm is increased by maintaining the temperature of the fish cage. An automated and solar-powered fish farm management system with of aim of fish conservation is designed by Fourie [48]. Solar energy is used to trigger the operation of the water pump and aeration system when the level drops from the predetermined value [14]. Further, a study was carried out in Mexico to determine the techno-commercial feasibility of the On-grid PV system for Tilapia farms, and the positive impact of PV on the environment was also presented [38]. The study concluded that On-grid PV implementation would help to reduce the operational cost and lower the environmental impact as well. However, On-grid PV systems for aquaculture are very rare [49], because of the fact that most of the sites are located in remote areas where the power transmission infrastructure is not available [38]. An independent solar PV system with power storage (battery bank) is implemented to provide continuous electricity to the water monitoring system of fish farm in Thailand [50]. For another selected site in Thailand, different implementation topologies of PV and wind power are evaluated to meet the power needs of a shrimp farm, the results show that floating PV exhibits a positive and reliable option [51]. Another study considered the floating PV panels to power up the complete operation of a shrimp farm in Taiwan where the PV system designing is done on Helioscope, the proposed system can generate 32MWh/month by installing 896 PV panels [52]. A mega solar PV power plant having a capacity of 200MW is installed in the Zhejiang province of China which has the capability to supply electricity to many fish farms [25]. The traces of solar power use for aquaculture can also be tracked in Bangladesh where the aeration system and other critical operations of the farm are powered by solar plants [25].

1.2.5 Main Components of PV System

Solar electromagnetic radiation is converted to electricity with the help of PV (photovoltaic) panels. The PV panel, made up of semiconductor material, produces DC power which is then usually fed to an inverter to convert it to AC power. The complete solar power system consists of several PV panels, DC-DC converters equipped with appropriate MPPT (Maximum Power Point Tracking) algorithm, inverters, AC/DC cables, batteries, protecting devices (breakers, relays), and the mounting structure. DC-DC converters are used to regulate and maintain the stable supply of DC voltages to inverters and ensure the operation of PV panels at MPP. The PV panels are coupled together in parallel to form arrays to increase the power generation capacity from a few Watts to 100kW [53]. However, to maintain the specific DC bus voltage, PV panels are connected in series. The DC-DC converters have three types, described below, each type has its own utility and significance based on requirement.

- Buck Converter
- Boost Converter
- Buck-Boost Converter

Buck Converter is used when the unregulated DC input voltage is required to lower the to regulated DC output voltage, refer to Figure 1.7 for the schematic diagram. The Boost converter produces a regulated and stable DC output voltage higher than the input DC voltage and is the most commonly used converter in PV system applications. Buck-Boost Converter has the dual capability and flexibility to produce lower or higher DC output voltage than supplied DC input supply. All the said types of converters comprise the diode, MOSFET (for switching), inductor, and capacitor.

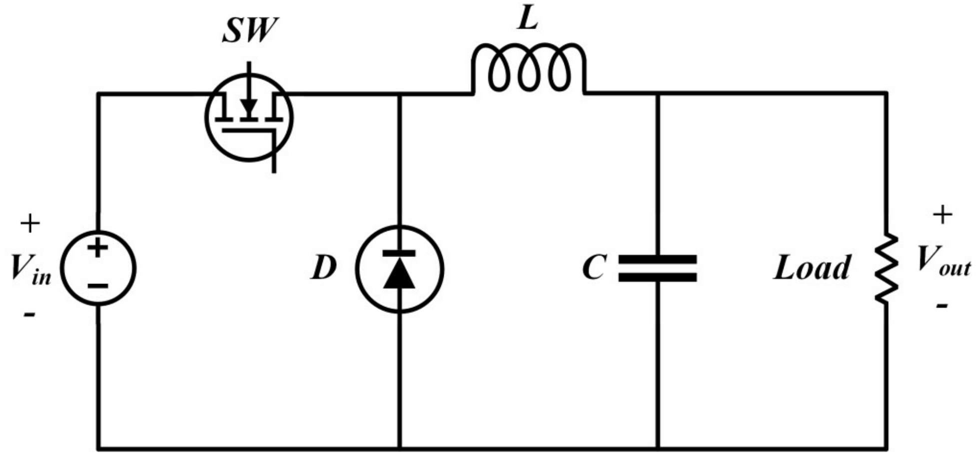

Figure 1.7: Buck Converter Schematic

The energy output of the PV cells is largely dependent on the location of the sun and the resultant sun rays' direction. Any change in the location and rays of the sun would have a direct consequence on the power produced by solar cells. The analysis of the P-V (Power-Voltage) curve of the PV cell states that there is only one specific and unique point where the most optimized power can be obtained from the module, called the "maximum power point (MPP)" and that point describes the corresponding value of voltage and current. The power produced by the cell on either side of the MPP would be less and hence it is very necessary to track that point and ensure the operation of PV cells on MPP. Therefore, an intelligent and effective DC-to-DC converter called a "maximum power point tracker" is used in PV power plants and it delivers power, voltage, or current levels that are consistent with the load level it was designed to supply. The PV system along with the MPPT converter can be seen in the block diagram in Figure 1.8. The MPPT controller pushes the PV cells to run on the voltage that is near to MPP, and it helps to get the most optimized power from the PV cells. There are many methods/algorithms to track the MPP i.e., Perturb & Observe (P&O), Hill Climbing, Incremental and Neural Network Control.

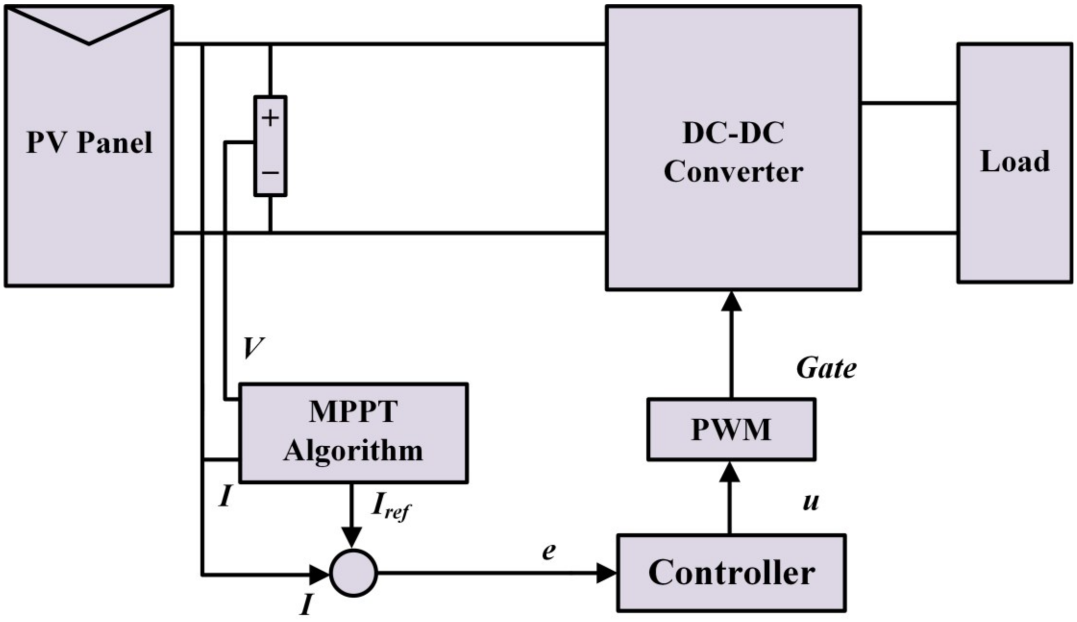

Figure 1.8: PV system along with MPPT Controller

The performance monitoring of the PV system is of paramount importance to get the maximum yield of electricity. The fish farm sites are mostly in remote areas where human presence cannot be ensured all the time. Therefore, remote monitoring of the installed PV system is inevitable to ensure healthy and safe operation. The remote monitoring of the system can be implemented by SCADA (Supervisory Control and Data Acquisition) and it brings economic advantages along with convenience and robustness in operation. The continuous advancements in this field have made it possible to monitor the performance of individual components of the whole system. This ability has improved the precision of predictive maintenance capability at each equipment level and aided to lower the probability of a sudden breakdown. The monitored/actual performance data can be compared with the OEM (Original Equipment Manufacturer) provided standards and results shall be helpful to devise the course of action.

1.2.6 Floating Solar PV

There are many types of solar systems i.e., rooftop, land-based, offshore, and floating. When compared to solar panels that are installed on land, floating solar photovoltaic panels (FSPV) provide several benefits, such as fewer obstructions that block sunlight, convenience, energy efficiency, and improved power generation efficiency because of the lower temperature under the panels. FSPV systems are similar to other kinds of PV systems. The only difference is that PV panels float on the water, the panels are anchored with the land but suspended on floats [25]. The FSPV can be constructed on dams, lakes, and even oceans [54]. The applications of FSPV can be much wider and besides serving the aquaculture industry it can also fulfill the energy needs of hydrogen production units, desalination, etc [55]. The FSPV shall be a step forward in bringing sustainability to the aquaculture industry. According to the World Bank report [56], there is an enormous potential of generating around 400 GW (gigawatts) from FSPV around the globe. So, the potential is very well reckoned. There are many countries working to harness the potential of FSPV systems and China is leading the ladder followed by Japan.

The aquatic environment benefits from solar installation because the plant's shadowing reduces algae growth, avoids excessive water evaporation, and it even improves the water quality. Installing solar photovoltaic systems over water bodies utilizing floating technology is a novel concept. The result of combining floating technology and PV plant technology is the production of electricity. The construction of photovoltaic power plants over priceless land is replaced by this. A study found that this system reduced the amount of water that evaporated. According to Australian research, evaporation might result in the loss of up to 40% of the water in open reservoirs [57]. Depending on the solar cell type and weather, a typical PV module converts 4–18% of the incident solar radiation into electricity. The remaining solar radiation that strikes the PV is transformed into heat, which sharply raises its temperature [58,59]. The power production of solar cells changes as the temperature changes. Due to this dependence on temperature, solar PV systems built on the surface of water benefit from significantly lower ambient temperatures due to the cooling action of water [60]. When floating solar PV modules are supported by aluminum frames, the cooler water temperature is also transferred to the frames, lowering the modules' overall temperature. On average efficiency of floating-type solar panels are 11% higher compared to ground-installed solar panels [45].

When compared to conventional solar panels, floating-type solar photovoltaic panels provide several benefits, including being more convenient and efficient with energy. Due to the lower temperature beneath the panels than overland mounted solar panels, floating-type solar photovoltaic panels are more efficient at generating power [44].

Reduced sunlight penetration, reduced algae growth, natural water surface reflectivity, shading effect, and lower water temperatures improve the performance of floating solar PV [43]. Preserving precious lands for farming, mining, tourism, and other land-incentive industries, and untapped and non-revenue-generating water surfaces should be converted into industrial solar power facilities. This technology has the potential to significantly reduce the cost of land and the cost of producing electricity. Water is easily accessible for washing the panels, which will increase efficiency. The widespread popularity of floating solar panels is also influenced by the benefit that water receives from the placement of solar panels above the water's surface [61]. The FSPV system can have different components and styles of implementation, however, a general representation can be seen in Figure 1.9.

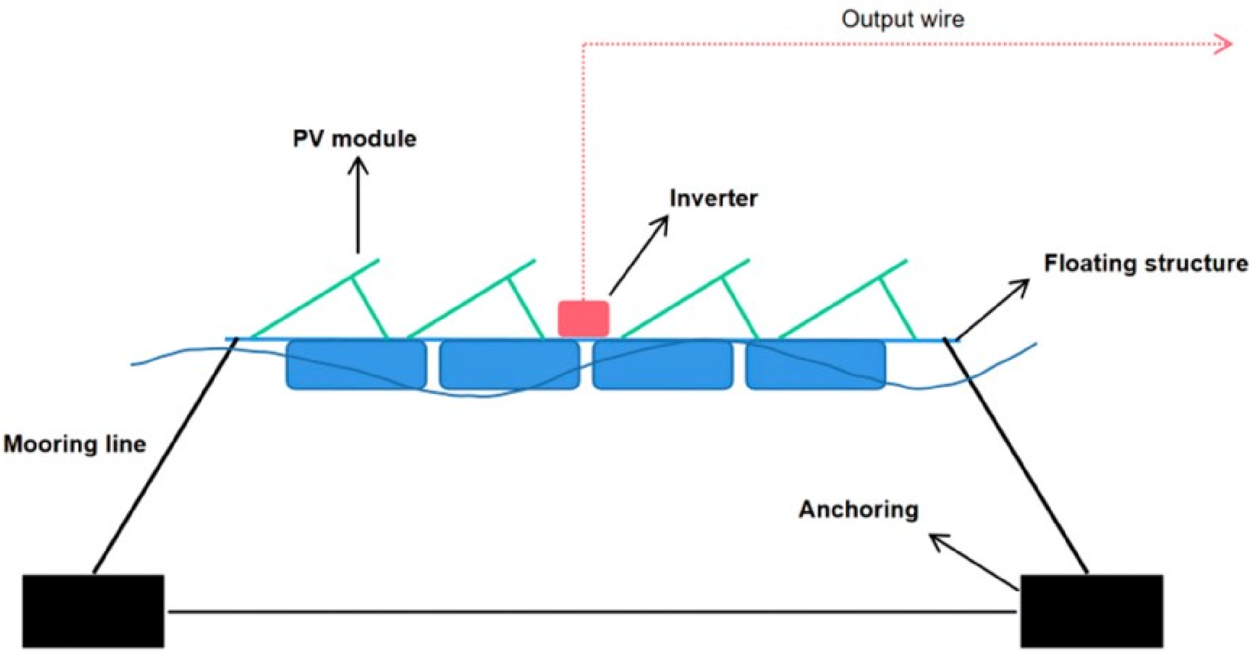

Figure 1.9: Floating Solar Photovoltaic System

1.2.7 Types of FSPV

The FSPV systems have three types primarily, based on the installation site and application, Fixed Pile-Based Photovoltaic Systems, Wave-Proof Floating Photovoltaic, Floating Platform Photovoltaic Systems, and Floating thin-film Photovoltaic systems [62]. The fixed pile-based systems are installed on fishponds, lakes, and offshore sites as well. The piles (concrete columns) are constructed at regular intervals to hold the panel and involve significant civil work. China has built many mega onshore/offshore projects using the same technology. The wave-proof floating PV is more suitable for offshore applications/sites. Offshore sites often face powerful waves that can cause damage to the FSPV. The challenge to protect the PV panels from waves is predominant here and implementation of breakwater is important. The breakwater can be of many different types including pile-permeable breakwater and single floating box type [62]. In the floating platform photovoltaic systems water is permitted to flow across the floating body and frame structure to prevent the direct impact of the waves and the PV panels are mounted at a specific height in the floating platform. This technique is duly tested in different parts of the world and is being widely used in many countries for offshore PV system applications. The floating thin-film PV systems comprise of polymer membrane retained on a circular floater to hold the PV panels.

Significant research has been done on setting up the conventional and land-based solarization of the fish farm in the past. Most of the researchers focus on converting the aeration system of fish farms to solar because of its continuous operation but very few traces are spotted where all the energy needs of fish farms are met by installed solar power. In this research, a novel concept is implemented where the floating solar PV panels are installed over the fish farm water surface and all the operational energy needs of the fish farm including freshwater pumping, aeration, etc. are supplied by the On-Grid solar power.

Therefore, selecting solar power to meet energy needs would be an advantageous option for the aquaculture industry in Canada. It would not only bring environmentally friendly energy but would reduce the operational cost and improve the profits. Hence, the sustainability of the industry shall enhance.

The stated facts are evident that solar power can be a very productive option for the aquaculture industry of Canada. It can help meet energy needs and protect the environment without any carbon footprint. The fish farms in Newfoundland, Canada are in remote areas (offshore), and power transmission infrastructure is not placed therefore, solar PV can be a great help to bring sustainable development and boost to the aquaculture industry.

1.3 Research Objectives

The idea of using FSPV for providing electricity to offshore aquaculture is unique in its nature hence, we are not able to see any traces/existence in the literature yet. Inseanergy, a Norwegian company has recently installed its first commercial project of 160kW for an aquaculture site in

Norway, refer to Figure 1.10. Considering this a revolutionary breakthrough, AKVA group (the largest aquaculture equipment producer in the world) and Inseanergy have reached an understanding to supply and install carbon-free energy solutions for the aquaculture industry. Except the example mentioned above, literature doesn't provide the details of FSPV system for aquculture. Detailed design, analysis, sizing and remote data logging of such systems are missing in the literature. In this thesis, complete details of system design analysis and data logging system are presented.

Figure 1.10: FSPV System Installed in Norway for Aquaculture Site

Based on the stated literature, the following shall be the research objectives.

- Determine the energy needs of offshore fish farms and design a FSPV system (with a backup power supply) to power up the operations completely.
- The optimization analysis of the designed FSPV system on HOMER Pro and drawing its economic viability with reference to the existing power source.

- Model the designed FSPV system's performance under different dynamic conditions to improve its reliability and performance.
- Design a low-cost solar power monitoring system having the capability of remote transmission with the aim of meeting the system requirements.

1.4 Thesis Structure

The thesis comprised five different chapters and the description of each chapter is as follows.

Chapter 1: It starts with the historical association of fisheries with humans and presents the global market review of the fish and seafood industry. It also talks about the possible driving factors of the positive trend of the industry and leading producer countries. Further, it highlights the association of fishing with Canada and its prospects. The importance and role of renewable energy to reduce GHG emissions and the possible greater share of solar power plants in the Canadian energy mix are also presented. The chapter also gives detailed insight into the literature review and the research that has happened so far on the fish farms. The importance of the FSPV system for the aquaculture industry is also emphasized with the support of past research.

Chapter 2: In this chapter, the complete PV system is designed for the specific site considering the load, and available solar resource. The power storage system is also designed along with the backup power source (generator). The designing and optimization analysis is done on HOMERPRO software. The economic viability of the designed system is also vetted.

Chapter 3: The designed PV system is modeled in MATLAB/Simulink and an analysis of the dynamic modeling of the system is done. The response and behavior of each component of the system are examined and aligned with the requisite standard. Simulation of the complete system is performed as well.

Chapter 4: A low-cost SCADA system having the capability of remote transmission is designed and demonstrated.

Chapter 5: The conclusion drawn based on the comprehensive trajectory described in the above chapters shall be presented and further future research opportunities shall also be highlighted.

1.5 References

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Co-authorship Statement

I am the primary contributor to all the research papers comprising this thesis, with my supervisor, Dr. M. Tariq Iqbal, serving as a co-author on each article. In my role as the lead author, I conducted the majority of the research work, undertook literature reviews, executed designs, implemented hardware, set up experiments, and analyzed the results for each manuscript. Additionally, I formulated the original manuscripts and later refined them based on feedback from the co-author and peer reviewers during the peer review processes. Dr. M. Tariq Iqbal, as a co-author, supervised all aspects of the research work, meticulously revised and corrected each manuscript, secured funding, provided research materials, and contributed innovative research ideas throughout the research process, playing a pivotal role in refining and updating each manuscript

Chapter 2: Design and Simulate a Floating Solar Photovoltaic System for an Offshore Aquaculture Site in Canada

Preface

A version of this manuscript has been published in the ***Jordan Journal of Electrical Engineering (JJEE)*** *Volumer-9, Number-4 (Dec 2023), where I, as the primary author, played a central role. I conducted the majority of the research, including literature reviews, system design, implementations, and results analysis. Additionally, I drafted the initial manuscript and refined it based on feedback from both the co-author and the peer review process. Dr. M. Tariq Iqbal, the co-author, supervised the research, served as a research guide, reviewed and corrected the manuscript, and contributed valuable research ideas throughout the development of the manuscript.*

Abstract

This article presents the design and commercial feasibility of a floating solar photovoltaic (FSPV) power system for an offshore fish farm site located in the Newfoundland province of Canada. The offshore fish farms are energy-intensive units, and the fish feeding system is the primary energy consumer. Due to the remote location, the grid/utility power infrastructure does not exist, and Diesel Generators fulfill energy needs, which is expensive and detrimental to the environment. A floating solar power system is proposed as a replacement for the fossil fuel energy source. A comprehensive study is conducted to investigate the actual energy requirement of a site and an appropriate hybrid solar system is designed using Homer Pro software. The designed system's techno-commercial feasibility is evaluated based on three different scenarios (Base, Ideal & Worst) The renewable energy penetration for all cases is very convincing and encouraging. The Levelized Cost of Energy (LCOE) computed by the software for all three cases is compared with the existing setup produced energy cost and found that the designed FSPV produces significantly economical power. Results demonstrate the potential of FSPV systems as a viable and sustainable solution for powering fish farms and contributing to the sustainability of the aquaculture industry.

Keywords— Aquaculture, Floating solar PV power system, HOMER Pro, LCOE

2.1 Introduction

According to the report of the State of World Fisheries and Aquaculture 2022 by FAO (Food and Agriculture Organization of United Nations), the world saw the historic production of 178 million tons of aquatic animals in the year 2020. The total production is a combination of marine and inland fish farming, contributing 63% and 37% percent, respectively [1]. The estimated value of the said production is around USD 406 Billion. The direct human consumption share in total production is dominant at 89 % and the remaining 11% is used in making fish oil etc. A positive trend in human consumption of aquatic animals is seen in the last around six decades which grew at an average annual rate of 3% from 1961 to 2019, more than the global population growth rate. Furthermore, the average global per capita consumption trend of aquatic foods over the last years has significantly increased, in 1961 it was 9kg whereas it has reached 20.2 kg in 2020 [1]. The rise in per capita consumption is influenced by income growth, inclined consumer behavior towards healthy eating, better supply/distribution network, and the introduction of better technology.

Food security is a growing challenge for the world. It will become a dilemma in the coming years because global warming and resultant natural disasters threaten world food production resources. Therefore, the world must find ways to produce sustainable food. 70% of the earth's surface is covered with water which provides a clear viability for aquatic animals to be served as food to the rising population.

Fish are bred, raised, and harvested as part of fish farming, which is also known as aquaculture, in a setting that closely resembles their natural habitat. In a fish farm, fish production and growth are maximized/optimized by providing the right feed, maintaining water quality, and doing routine health checks on the fish. Fish farms can be developed over the oceans, rivers, lakes, or ponds. There are a variety of prevalent techniques of fish farming in different parts of the world. North America and Europe mostly have net pens where the cage is fastened to the ground in the ocean, mostly close to the coastal area.

Seawater fish farming is also called offshore aquaculture, the fish is raised in a specialized and purpose-based designed enclosure (normally a cage) in the seawater. The most practical and well-liked method of offshore fish farming is open-cage aquaculture, which is being used for many years. The complete system comprises of flexible but floating collars, weights tied to the bottom surface, a net, and an anchorage system connected to the seabed [2]. The popular species of seawater are Salmon, Cobia, and Tuna. The typical system comprises the cage, the feeding mechanism, and the energy network. A balanced diet having a suitable proportion of protein, vitamins, carbohydrates, and fats is supplied through the feed lines. The mixture of diet is dependent on the farmed species. A large boat/ship called a feed barge holding the complete infrastructure comprising of power supply, feed, automated monitoring system, and crew is stationed near the cluster of net pen sites. The feed is stored in the silos which are placed on the feed barge and supplied to each cage with the help of feed blowers. The offshore fish farms provide relatively better water quality and hence yield healthy fish [3]. The power supply is arranged by diesel generators because of the non-availability of the grid/transmission network at the offshore location. The power requirement is usually high because of the automated fish feeders, freezers, air compressors, lighting, and the devices used by the deployed crew [4].

The idea of using renewable energy to meet the energy needs of the aquaculture industry can make it a more reliable approach toward global warming concerns and will be a breakthrough in improving the sustainability of the industry, as well.

Photovoltaic (PV) systems are one of the most widely used forms of renewable energy. Since it is renewable, infinite, and non-polluting, it is a desirable energy source compared to conventional fossil fuels like coal, oil, and gas. Installing solar photovoltaic systems over water bodies utilizing floating technology is a novel concept. The aquatic environment benefits from the floating solar installation since the solar plant's shadowing reduces algae growth, avoids excessive water evaporation, and it even improves the water quality.

2.2 Literature Review

The world population has recently hit a new peak and according to United Nations World Population Prospects Report 2022, the earth has seen 8 billion people in November 2022 which is expected to climb all-time high of 9 billion by 2050. The continuously rising population demands more food sources and fish can be an excellent source to overcome the global food security challenges. Furthermore, fish is also a richly nutritious food with abundant protein, fatty acids, minerals, and vitamins. Wild fish hunting is causing a considerable decline in the sea and rivers and is not sufficient to meet the seafood consumption rate and that’s the primary reason behind increasing fish farming activities [5]. Aquaculture activities are broadly classified into land-based (freshwater) and offshore (seawater) fish farms. The offshore aquaculture system widely uses flexible floating cages to accommodate and raise fish. The said type of cage has a proven reputation for handling adverse weather conditions of the sea. The cages are normally located at least 300 m from the seashore. Robust mooring mechanisms are used to secure the cages in place. Chains, ropes, and buoys are used in these systems to keep the cages anchored in the water and from drifting away. The feed that has been specially prepared to fulfill the nutritional needs of the species being grown is typically used for feeding. The use of automated feeding devices can provide controlled and regular feeding. The feeding is done through the automated machines which are placed on the floating ship, the feed is provided through pipes in the form of homogeneous pellets. The Dissolved Oxygen level (DO) is maintained in the cage with the help of air compressors. The DO content in water plays a pivotal role in fish survival, if it is less than 4mg/L in the water, then the fish cannot breathe and eventually dies. The optimum level of DO in the water for better fish growth is 9 mg/L [5]. The DO level in the water is artificially maintained/increased with the help of aerators (usually electric motors or air compressors).

The offshore fish farms' operations rely heavily on electricity, feeding machines, air compressors, lighting arrangement for the cages, sensors, refrigeration, and instrumentation for monitoring are the primary energy consumers [6]. Further, the facilities developed for the operational staff also require electricity for lighting and heating, etc. These fish farms are not connected to the utility grid due to their remote location and rely on diesel generators for supplying electricity that runs 24/7.

Energy is used in maritime fish farms in two forms i.e., fuel (for transportation) and electricity. There is very limited research available on the energy assessment of offshore aquaculture in the form of electricity however, the cumulative energy consumption (fuel used for transportation activities and generator operation) is given [6]. A study conducted on a coastal fish farm in Norway states that electricity required for carrying out the growth-phase activities is around 700kWh/day, with a peak load of 100-120kW during the feed time [7]. The feeding mechanism is one of the most electricity-consuming units with a share of 50% of the daily required electricity [7]. Another research states that the feeding machine/blowers are the leading and intensive power consumers which are placed on the deck of the feeding barge [8]. The automation trend in offshore aquaculture is increasing and companies are putting in more and more infrastructure to automate the fish feeding and remote monitoring system. Autonomous feeding systems have many advantages but have significant energy needs as well [9].

Solar energy is one of the most feasible and convenient renewable energy options that can bring sustainability and meet the energy demands of the aquaculture industry. According to research [10], in a few hours at noon in bright sunlight and clear skies, solar radiation generates roughly 1000 W/m2. The potential of solar power for aquaculture is found to be very convincing.

The traces of solar power running the operations of inland fish farms are very vibrant however, we cannot find any evidence of solar power installation for offshore aquaculture. Some of the literature found on utilizing solar power for inland fish farms is described below.

An off-grid solar power system of 1.1kW is designed for a fish farm in Turkey to supply the energy and its performance is evaluated using HOMER software [11]. The aeration system is one of the most significant energy-consuming units in inland fish farms and a solar power system is designed to run the system for a large fish farm [12]. Another study considered the floating PV panels to power up the complete operation of a shrimp farm in Taiwan where the PV system designing is done on Helioscope, the proposed system can generate 32MWh/month by installing 896 PV panels [13].

There are many types of solar systems i.e., rooftop, land-based, offshore, and floating. When compared to solar panels that are installed on land, floating solar photovoltaic panels (FSPV) provide several benefits, such as fewer obstructions that block sunlight, convenience, energy efficiency, and improved power generation efficiency because of the lower temperature under the panels. FSPV systems are similar to other kinds of PV systems. The only difference is that PV panels float on the water, the panels are anchored with the land but suspended on floats. The FSPV can be constructed on dams, lakes, and even oceans. The FSPV shall be a step forward in bringing sustainability to the aquaculture industry. According to the World Bank report [14], there is an enormous potential of generating around 400 GW (gigawatts) from FSPV around the globe. So, the potential is very well reckoned. Many countries working to harness the potential of FSPV systems and China is leading the ladder followed by Japan.

Due to this dependence on temperature, solar PV systems built on the surface of water benefit from significantly lower ambient temperatures due to the cooling action of water [15]. On average efficiency of floating-type solar panels are 11% higher compared to ground-installed solar panels [16]. This technology has the potential to significantly reduce the cost of land and the cost of producing electricity.

Significant research has been done on setting up solar power plants for land-based fish farms. In this article, a novel concept is implemented where the floating solar PV panels are installed over an offshore fish farm water surface and all the operational energy needs of the fish farm are supplied by the Off-Grid solar power.

2.3 Project Site Particulars

2.3.1 Site Description

The site is located near Red Island, Placentia Bay, North of the Atlantic Ocean, Newfoundland, province of Canada which has a historic association with the fish. Newfoundland is considered to be one of the best places for fishing in the world because of the gulf stream's warm waters and the chilly Labrador Current joint here. Nutrients are lifted to the top due to the mixing of these waters and the ocean floor’s structure. The said phenomenon makes this place rich and sustainable for the fishing and seafood industry. The selected site is in the Atlantic Ocean, around 2 km from the land. It has a total of eight cages, seven have fish and one is kept spare. The circumference of each cage is 160m, diameter of 50.95m. Each cage accommodates 160,000 Salmon fish. There is one feed barge, two cages are on one side of the feed barge whilst the other six are on the opposite side, the said orientation can be seen in Figure 2.1.

Figure 2.1: Project Site (Offshore Fish Farm)

2.3.2 Load Profile/Energy Demand

The primary load of the offshore fish farm is the fish feeding system. The feed is stored in the form of homogenous pellets in eight silos and is supplied to each cage with the help of three feed blowers, the rated power of the feed blowers is 30kW, 22kW & 22kW. The operational hours of the feed blowers depend on the season and size of the fish. The Salmon growth rate in summer is high as compared to winter as the seawater temperature has a deep correlation with the growth of Salmon [17]. In summer, three meals are served in a day typically, breakfast, lunch, and dinner. Therefore, longer operational hours of the fish feeding system (8-10 hours) are observed in summer, posing high average electricity demand per day. During winter only lunch is provided, and fish remains in hibernation mode usually. The feed blowers run for 4-6 hours a day which means lower average electricity demand per day. On average, feed blowers run at 70% of their rated power.

There is one air compressor of 30kW to collect the waste/dead fish from the cage and supply the oxygen, in case of need. The usual operation of the air compressor is 3-4 hours a day. Since the feed barge houses all the equipment, it is a multistory (3 floors) ship, and the lighting load is significant there. The indoor LED lights are 12W each and 60Nos whilst the outdoor area has 20Nos, 100W LED lights. The dissolved oxygen and salinity sensors are placed in each cage which are powered uninterruptedly. The cameras are also installed at each cage to monitor the health and activities of fish. There is a centralized control room where the input of all the sensors is received, and fish feed operation is also monitored. The control room is equipped with multiple power sockets, computers, lights, and automation equipment. All the load of equipment placed in the control room and other loads experienced by the staff (fridge, oven, TV, etc.) is combined as auxiliary load.

Table 1 shows the energy consumption of a typical day for June, the highest consumption month, the average energy demand per day is 721.7 kWh and the peak power is 79 kW. During the winter season, the temperature drops from -10ºC to -15ºC at the site, and the heating load is also added to the list. Further to this, the duration of the outdoor lights is also increased to 15 hours. Since the primary load (feeding system) is laid off relatively in winter so the accumulative demand remains lower than in summer. The energy demand in a typical day of winter is 575 kWh and the peak load is 82 kW. The Single Line Diagram (SLD) of the existing electricity network at the project site can be seen in Figure 2.2.

Table 2-1: Load Profile

Sr	**Load**	**Rated Power (kW)**	**Avg. Power (kW)**	**Op. Time (Hrs)**	**Consumed Power (kWh/day)**
1	Feed Blower-1	30	21	10	210
2	Feed Blower-2	22	15.4	10	154
3	Feed Blower-3	22	15.4	10	154
4	Air Compressor (Aeration & Mud Collect)	30	21	4	84
5	Indoor LED Lights: (60Nos)	0.72	0.72	24	17.28
6	Outdoor LED Lights: (20Nos)	2	2	9	18
7	DO Sensors (8Nos)	0.008	0.008	24	0.192
8	Salinity Sensors (8Nos)	0.008	0.008	24	0.192
9	Fridge	0.8	0.8	24	19.2
10	Microwave Oven	0.9	0.9	0.5	0.45
11	LED TV (2 Nos)	0.17	0.17	8	1.36
12	Electrical Crane	50kW	10	1.5	15
13	Control and Automation Equipment	3kW	2	24	48
14	**Total**	**110.2**	**79**	**115**	**721.7**

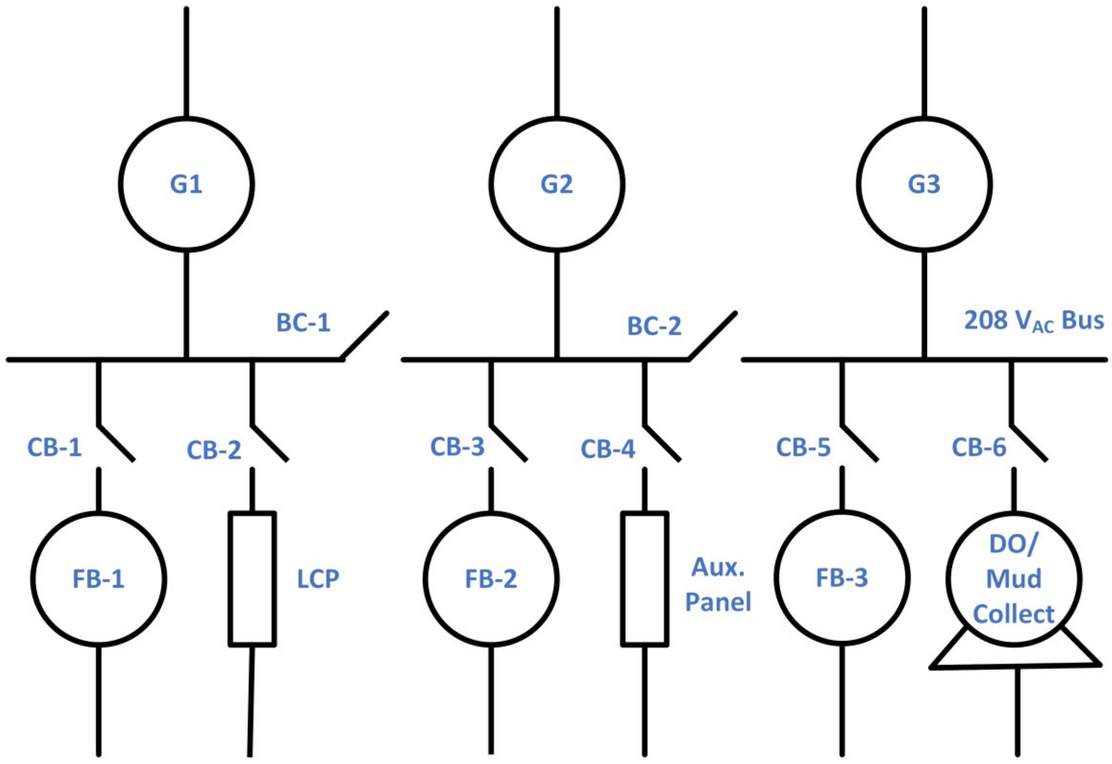


Figure 2.2: Existing System SLD

2.3.3 Solar Resource

The determination of solar resources is the most fundamental step while designing the solar system for a particular site and it also helps to verify the techno-commercial feasibility of the project. The Homer Pro software provides reliable calculation while computing the monthly Global Horizontal Irradiance (GHI) based on the average of 22-year data taken from NASA meteorology. The GHI is a measure of the total radiations received by the ground, it is the summation of two components i.e. DNI (Direct Normal Irradiance) & DHI (Diffuse Horizontal Irradiance). The solar irradiation that comes directly from the sun in a straight line to the surface is termed DNI whilst the irradiation that doesn't follow the direct path and is dispersed in the environment and received from all directions is called DHI.

It can be seen in Figure 2.3 that the highest solar resource is available in June (5.1 kWh/m2/day) followed by May and July. Whereas the annual average available GHI is 3 kWh/m2/day.

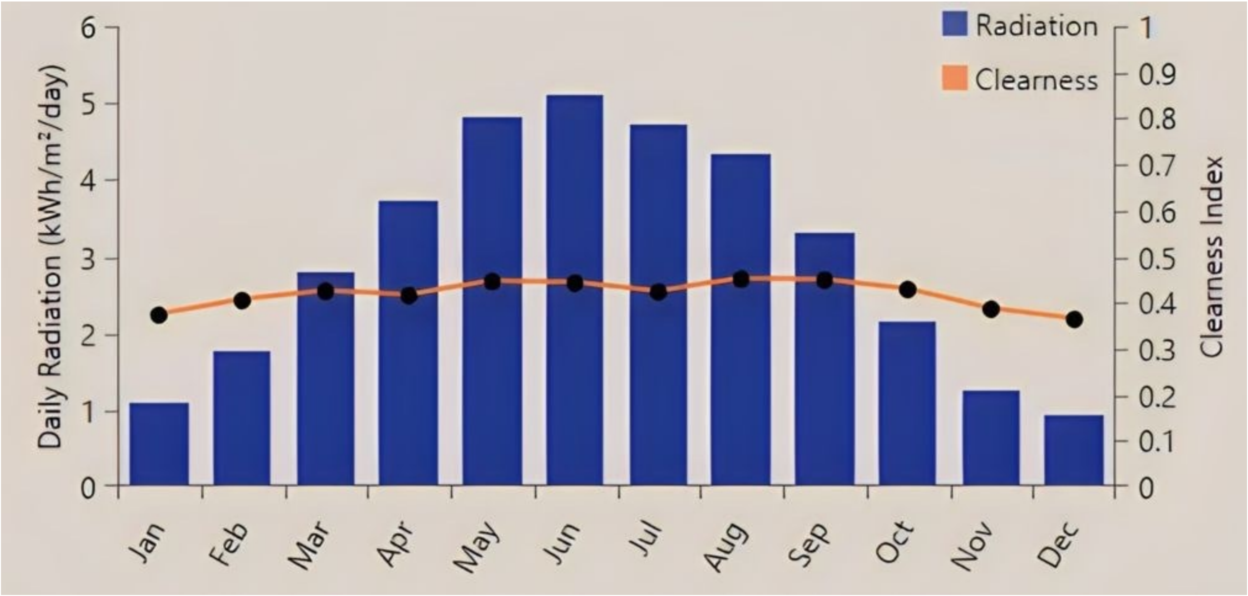


Figure 2.3: Solar Resource at the Site

2.4 System Design

The design of the Floating Solar PV system for the fish farm is done using the Homer Pro tool Developed by the National Renewable Energy Laboratory (NREL) in the United States [18]. HOMER stands for Hybrid Optimization of Multiple Energy Resources. It is a software application used to design and analyze a power system's technical and financial aspects for stand-alone, remote, and distributed generation applications. HOMER Pro is simple to use, detailed, and takes in all the necessary variables when analyzing a power system.

The load profile determined above for the summer and winter months is given as input to the said tool. The hourly load is distributed based on the information collected from the site and the annual average load per day is computed as 651.15 kWh/day. There are two buses i.e. AC & DC. AC bus operates at 208V whilst DC bus voltage is 360V. The load and diesel generator are directly connected to the AC bus whereas PV panels and battery bank is connected to the DC bus, refer to Figure 2.4.

Two different sensitivity variables are introduced to determine the techno-commercial feasibility of the designed system. The variation (10%) in solar resource and annual average per day load is assumed, and three different cases ideal, base & worst case are developed.

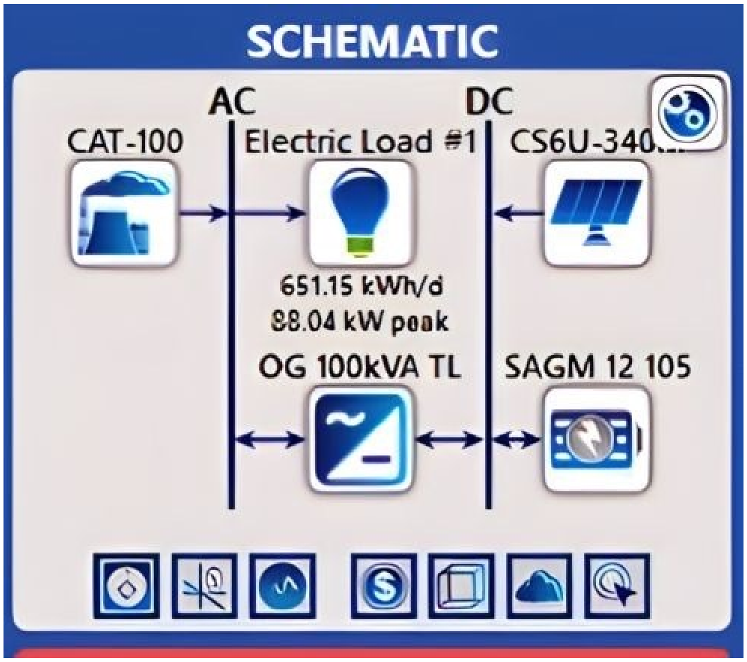


Figure 2.4: Schematic of the designed system

2.4.1 Component Selection

The PV panels of Canadian Solar, model CS6U-340M, a tier 1 and one of the most reputed PV panel manufacturers, are selected. The selected PV modules have 25 years performance warranty. Solar SAGM 12 105 models of the battery is chosen. The battery is manufactured by Trojan, USA, and enjoys distinguished reliability of performance. SOCOMEC-made inverter having model name SUNSYS PCS² OG 100kVA TL has opted. 100kVA Diesel Generator made by Caterpillar is considered.

2.4.2 Base Case

The base case is the actual prevailing scenario at the project site which is based on the following two fundamental inputs.

- The annual average per day solar resource is 3.00 kWh/m2/day and the annual average per day load is 651.5 kWh/day.

Homer Optimizer tool computed the best possible solution for the above-said inputs and recommended a solar PV power plant of 366kW, 1077 No of modules each of 340 W. The monthly electricity production, referred to in Figure 2.5, is a clear indication that solar production is largely dominant and fulfilling the load requirement comfortably with a share of more than 88%. Considering the financial and environmental challenges associated with diesel generators, it is kept as low priority source and to cope with the non-availability of solar energy, a sizeable battery bank of 542.1 kWhr is designed. The said battery bank consists of 390 batteries and can serve the critical load of the fish farm for one whole day. There are 13 strings, and each string has 30 batteries with a nominal capacity of 1.39 kWh. The configuration of the complete system is shown in Figure 2.6.

Production	KWh/yr	%
CanadianSolar MaxPower CS6U-340M	417,172	88.6
CAT-100kVA	55,260	11.4
Total	472,431	100

Consumption	KWh/yr	%
AC Primary Load	237,670	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	237,670	100

Quantity	KWh/yr	%
Excess Electricity	221,047	46.8
Unmet Electric Load	0.181	0
Capacity Shortage	93.5	0.04

Quantity	Value	Units
Renewable Fraction	76.7	%
Max Renew Penetration	5,039	%

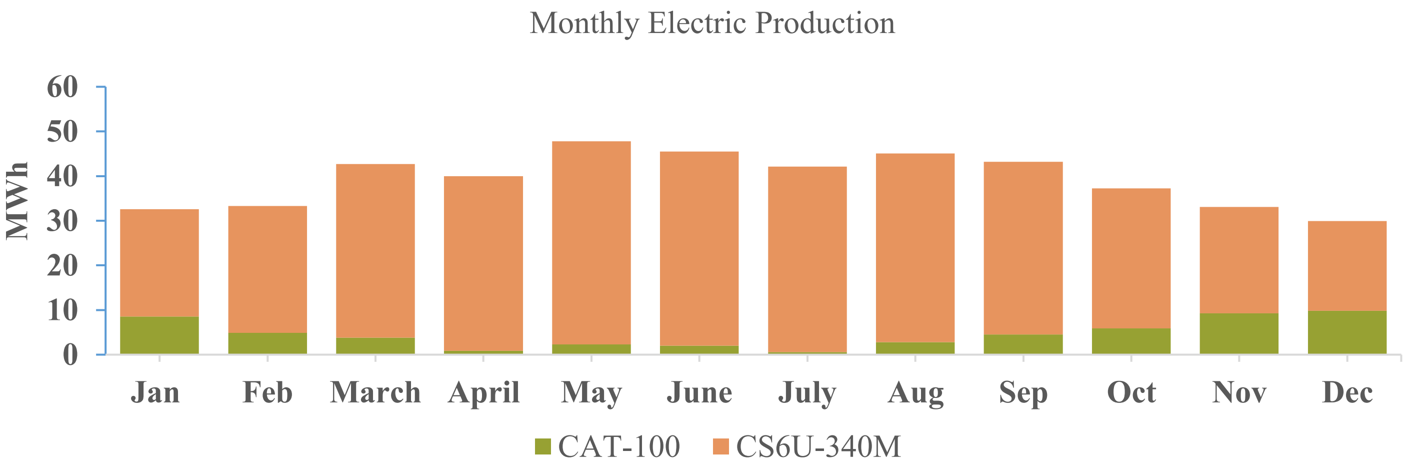


Figure 2.5: Monthly Electricity Production by PV & Generator

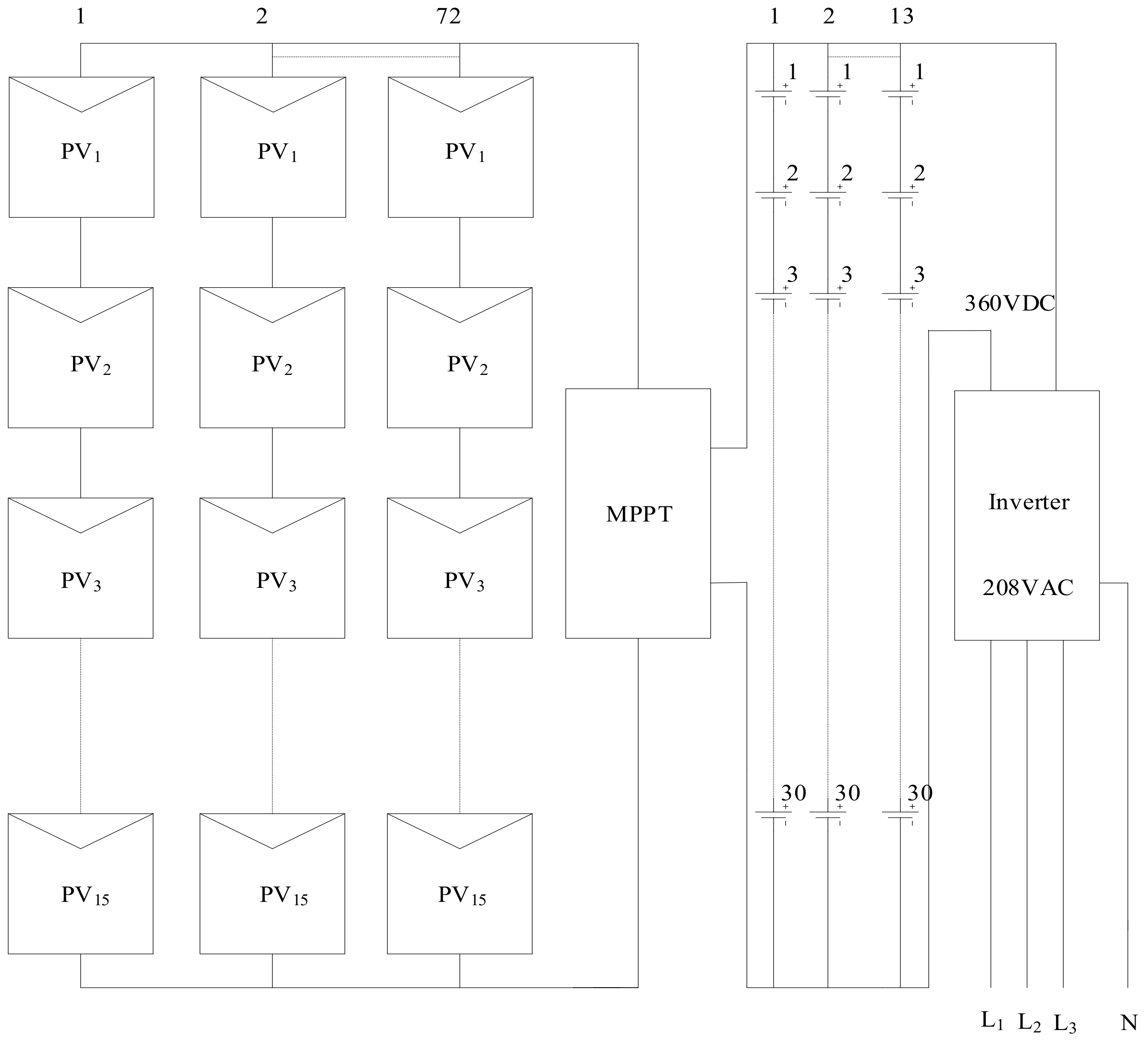


Figure 2.6: Configuration of PV System

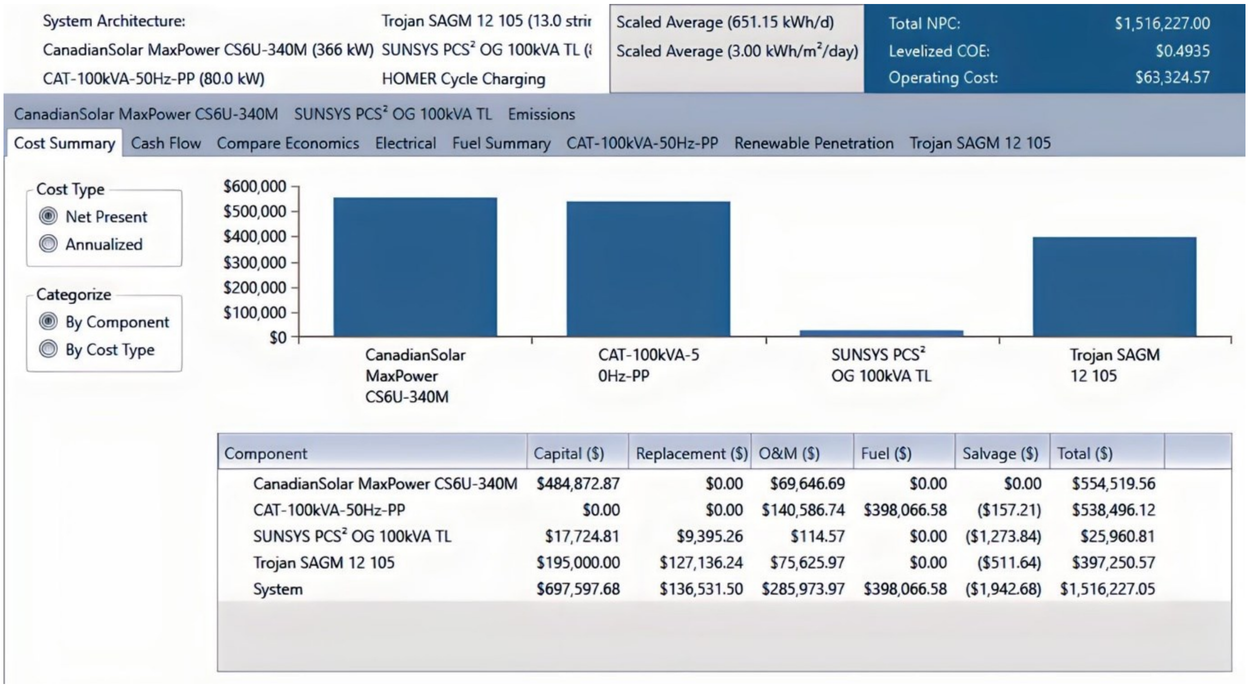
The renewable penetration at every time step is calculated by Homer Pro using the following formulae (referred to as Eq 1). It indicates the proportion of the total produced energy from renewable energy resources.

$$pren \quad = \frac{Pren}{Lserved} \tag{1}$$

Pren is the energy generated by renewable energy resources and Lserved is the load served at a particular time step. The renewable penetration is found to be at 82.1% which depicts a very convincing and encouraging solution for the project site.

The Net Present Cost (NPC) calculated for the project is $1,516,227, refer to Fig 2.7. The NPC accounts for all the possible costs incurred to procure and set up the complete power plant, replacement cost of the new equipment, operation & maintenance (O&M) expenses, and Fuel. The computed NPC is dominated by the system set-up cost, 46%, followed by diesel fuel expenses which stood at 26%. The fuel and the O&M cost are much higher than the general standard due to the offshore location of the fish farm. The accessibility of resources at the remote site is a challenging task, so the cost is considered accordingly. Levelized Cost of Energy is the analysis that looks at the lifetime energy cost and lifetime energy production from an economic perspective [19]. The LCOE considers all costs associated with a power generation facility, including initial capital expenditures, ongoing operating and maintenance expenses, fuel costs, and estimated lifespan energy output. The LCOE offers a standardized technique to compare the cost-competitiveness of various energy sources or technologies by dividing the total costs by the total energy generated. LCOE computed for this case is $0.4935 and can be represented as an equation as follows [20].

$$LCOE = \frac{Total\ Cost}{AC\ Load + DC\ Load} \tag{2}$$



System Architecture:
CanadianSolar MaxPower CS6U-340M (366 kW)
CAT-100kVA-50Hz-PP (80.0 kW)
Trojan SAGM 12 105 (13.0 strir
SUNSYS PCS^2 OG 100kVA TL (
HOMER Cycle Charging
Scaled Average (651.15 kWh/d)
Scaled Average (3.00 kWh/m^2/day)

Total NPC: $1,516,227.00
Levelized COE: $0.4935
Operating Cost: $63,324.57

Cost Type: ● Net Present ○ Annualized
Categorize: ● By Component ○ By Cost Type

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
CanadianSolar MaxPower CS6U-340M	$484,872.87	$0.00	$69,646.69	$0.00	$0.00	$554,519.56
CAT-100kVA-50Hz-PP	$0.00	$0.00	$140,586.74	$398,066.58	($157.21)	$538,496.12
SUNSYS PCS^2 OG 100kVA TL	$17,724.81	$9,395.26	$114.57	$0.00	($1,273.84)	$25,960.81
Trojan SAGM 12 105	$195,000.00	$127,136.24	$75,625.97	$0.00	($511.64)	$397,250.57
System	$697,597.68	$136,531.50	$285,973.97	$398,066.58	($1,942.68)	$1,516,227.05

Figure 2.7: Cost Summary

The cashflow summary, referred to in Figure 2.8, gives a snapshot of the amount required to establish and run the project expended over the lifetime of the project i.e. 25 years.

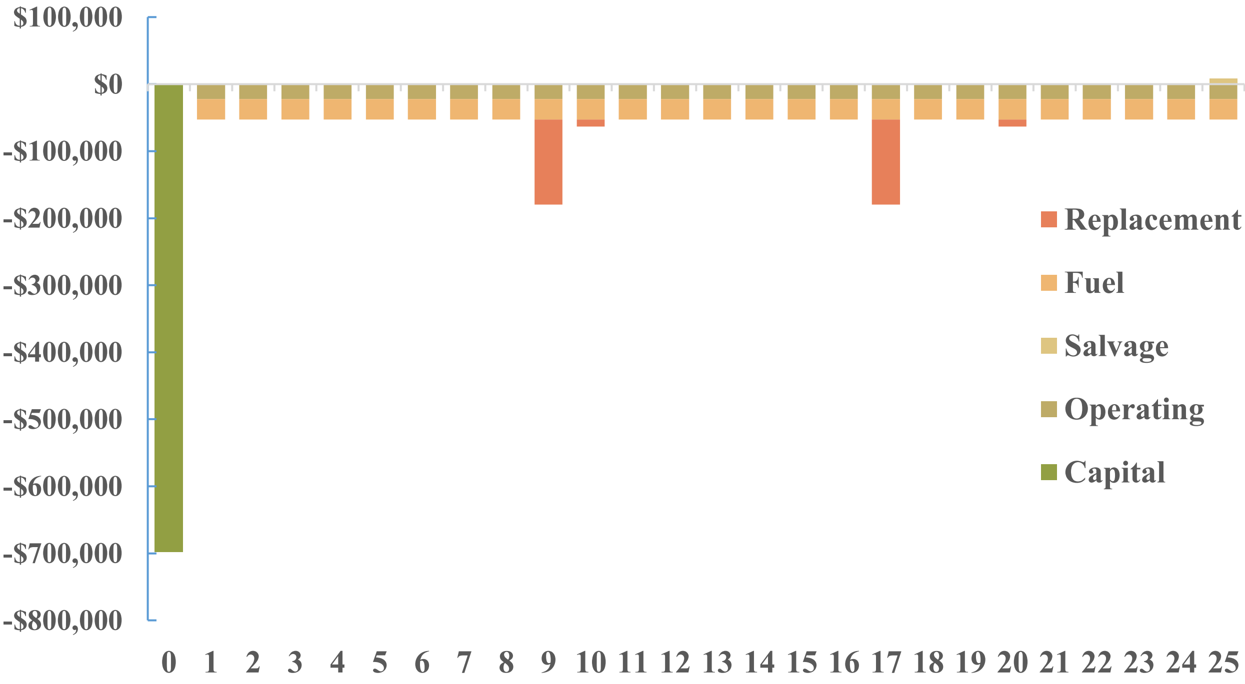


Figure 2.8: Cashflow Summary

2.4.3 Ideal Case

The description of the Ideal case is as follows.

- The annual average per day solar resource is increased to 10% (3.30 kWh/m2/day) and the annual average per day load is decreased by 10% (586 kWh/day).

The monthly electricity production referred to in Figure 2.9, shows that more than 89% of the power is generated by the installed solar plant and only 10% of power reliance is on diesel generator. The renewable penetration is found to be 78.3%. The total computed PV capacity is 289kW, 850 No. of Panels of 340 W. The battery bank is 500.4 kWh, consisting of 12 parallel strings with each string having 30 batteries. The NPC of the system is $1,278,775 with LCOE **of** $0.4624.

2.4.4 Worst Case

The worst-case scenario has the following assumptions.

- The annual average per day solar resource decreased to 10% (2.70 kWh/m2/day) and the annual average per day load increased by 10% (716 kWh/day).

The monthly electricity production referred to in Figure 2.10, shows that more than 91% of the power is generated by the installed solar plant and only 8% of power reliance is on diesel generator. The renewable penetration is found to be 85%. The total computed PV capacity is 461 kW, 1356 No. of Panels of 340 W. The battery bank is 1000.8 kWh, consisting of 24 parallel strings with each string having 30 batteries. The NPC of the system is $1,764,691 with LCOE of $0.5223.

System Architecture:
CanadianSolar MaxPower CS6U-340M (289 kW)
CAT-100kVA-50Hz-PP (80.0 kW)
Trojan SAGM 12 105 (12.0 stri
SUNSYS PCS² OG 100kVA TL (
HOMER Load Following

Scaled Average (586.04 kWh/d)
Scaled Average (3.30 kWh/m²/day)

Total NPC:	$1,278,775.00
Levelized COE:	$0.4624
Operating Cost:	$54,137.19

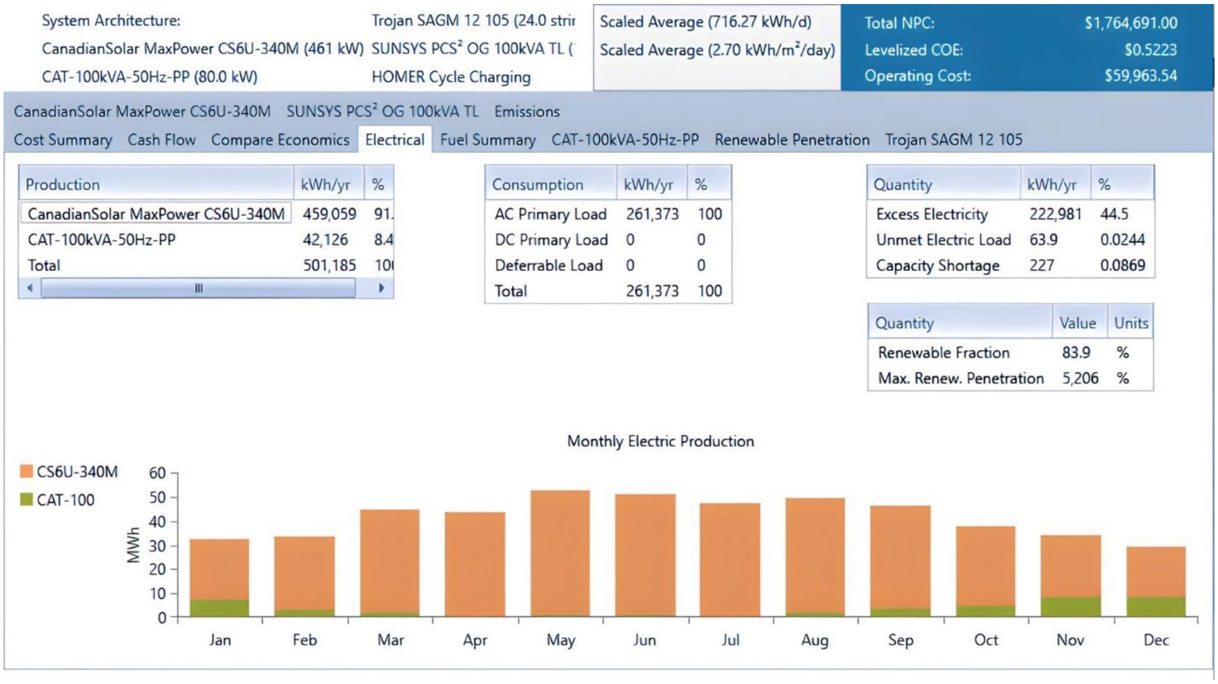
Production	kWh/yr	%
CanadianSolar MaxPower CS6U-340M	368,654	89.
CAT-100kVA-50Hz-PP	44,805	10.
Total	413,460	10

Consumption	kWh/yr	%
AC Primary Load	213,903	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	213,903	100

Quantity	kWh/yr	%
Excess Electricity	186,566	45.1
Unmet Electric Load	0	0
Capacity Shortage	0	0

Quantity	Value	Units
Renewable Fraction	79.1	%
Max. Renew. Penetration	4,542	%

Figure 2.9: Monthly Electricity Production by PV & Gen (10% Less Load & 10% more Solar Insolation Level)



System Architecture:
CanadianSolar MaxPower CS6U-340M (461 kW)
CAT-100kVA-50Hz-PP (80.0 kW)
Trojan SAGM 12 105 (24.0 stri
SUNSYS PCS² OG 100kVA TL (
HOMER Cycle Charging

Scaled Average (716.27 kWh/d)
Scaled Average (2.70 kWh/m²/day)

Total NPC:	$1,764,691.00
Levelized COE:	$0.5223
Operating Cost:	$59,963.54

Production	kWh/yr	%
CanadianSolar MaxPower CS6U-340M	459,059	91.
CAT-100kVA-50Hz-PP	42,126	8.4
Total	501,185	10

Consumption	kWh/yr	%
AC Primary Load	261,373	100
DC Primary Load	0	0
Deferrable Load	0	0
Total	261,373	100

Quantity	kWh/yr	%
Excess Electricity	222,981	44.5
Unmet Electric Load	63.9	0.0244
Capacity Shortage	227	0.0869

Quantity	Value	Units
Renewable Fraction	83.9	%
Max. Renew. Penetration	5,206	%

Figure 2.10: Monthly Electricity Production by PV & Gen (10% more Load & 10% less Solar Insolation Level)

2.5 Discussion

The designed system's production capability is tested under various conditions and all three cases prove that it has the absolute capability to provide electricity to the offshore fish farm. Further, the renewable penetration in all three cases is substantial and it is evident that energy reliance of offshore aquaculture can easily be shifted from fossil fuel to environmentally friendly energy resources. The usage of renewable energy sources shall be a great step to protect the environment and a significant help to reduce global warming.

The diameter of one fish cage is 50.95 m and its area is 2039 m^2. The dimensions of the selected PV plate are 1960x992x40 mm and the area of one plate is $2m^2$. Considering the Base Case, 1077 No of PV panels shall be required which can be installed comfortably on two cages following the scheme referred to in Figure 2.11.

Figure 2.11: FSPV Installation Scheme

The economic viability of the proposed system is also investigated by analyzing and comparing the cost of electricity production of existing (three diesel generators each of 99 kVA) and the proposed power system infrastructure. The actual fuel consumption data of these generators for different months of the year 2022 is taken from the project site to calculate the Cost of Electricity (COE), refer to Table 2. Since the price of diesel varies so, the average price prevailing in the vicinity of St. John's for March 2023-June 12, 2023 is taken. There is a colossal cost associated with the transportation of diesel at fish a farm site therefore, its impact is also accounted for in the calculations.

Table 2-2 Cost of Electricity (COE) with Existing System i.e., Three Diesel Gen each 99kVA

Sr	**Description**	**Jan 22**	**Feb 22**	**May 22**	**Jun 22**	**Jul 22**	**Dec 22**
1	Monthly Fuel Consumption of Three Gen (Liters)	8970	9034	9246	9600	9660	9142
2	Per day Fuel Consumption of Three Gen (Liters)	299	301	308	320	322	305
3	Fuel Cost per liter (USD)	1.80					
4	Per day fuel cost (USD)	538	542	555	576	580	548
5	Average Load (kWh)	651.5					
6	**COE/kWh (USD)**	**0.83**	**0.83**	**0.85**	**0.88**	**0.89**	**0.84**

The annual average Cost of Electricity (COE)/kWh comes out to 0.85 USD whereas if we take the base case of the proposed system the LCOE is 0.4935 USD. An important point to focus on is that while calculating the (COE)/kWh for the existing system, the capital, replacement, auxiliary equipment (cables, switchgear, etc.), and O&M cost are not considered and only fuel cost is taken into calculation. Whereas LCOE accounts for all the said costs. Despite this significant leverage and ignorance of cost extended to the current system, the proposed FSPV system is 42% cost-effective, which portrays a difference that cannot be overlooked. Due to the remote/offshore location of the fish farm, the replacement and O&M cost of the diesel generators is way higher than general prevailing standards and if that is included then the gap is expected to widen up to 50%.

2.6 Conclusion

The above-stated analysis provides a strong basis to conclude that the floating solar photovoltaic (FSPV) systems can be a great source to provide economical and environmentally friendly energy to the offshore fish farm which is located in Newfoundland, Canada. By using FSPV systems, fish farms can reduce their carbon footprint and contribute to a more sustainable environment. In addition to that FSPV systems require minimal maintenance and can last for several years with proper upkeep, making them a reliable and low-maintenance source of energy for fish farms.

Offshore fish farming requires a reliable source of electricity to power feed blowers, aerators, and other equipment necessary for fish growth and maintenance. The provision of low-cost energy shall be a pinnacle transformation to bring sustainability, improve profitability, and expand the Canadian aquaculture industry that will proceed to assist in boosting the economy and meeting the food security challenges for the ever-growing population.

The FSPV can be a game-changer for the aquaculture industry, and it has all the potential to improve the sustainability of the business by providing economical and environmentally friendly energy.

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Chapter 3: Dynamic Modelling and Analysis of a Hybrid Power System of Floating Solar PV System for an Offshore Aquaculture Site in Newfoundland

Preface

The manuscript has been accepted and presented in the conference proceedings of the ***2023 IEEE 32nd Annual Newfoundland Electrical and Computer Engineering Conference (NECEC),*** *the paper shall be available in MUN research repository.Serving as the primary author, I took a leading role in conducting the research, encompassing literature reviews, system design, modeling, and results analysis. Additionally, I initiated the manuscript's first draft and subsequently refined it based on feedback from the co-author and the peer review process. Dr. M. Tariq Iqbal, the co-author, provided research supervision, acted as a guide, reviewed and corrected the manuscript, and contributed valuable research ideas throughout the manuscript's development.*

Abstract

In this article a hybrid power system, a combination of solar and diesel generator (DG) is modeled in MATLAB and the dynamic performance of the system are analyzed considering the design parameters. The said system is designed for an offshore aquaculture site located in Newfoundland, Canada. The paper presents a novel concept of evaluating the dynamic performance of floating solar PV panels over the water surface of the fish farm. The sizing and economic feasibility of the system were carried out on HomerPro. Design is modeled in MATLAB to analyze the impact of dynamic changes on system performance. The system is exposed to variable irradiance, temperature, and load side variations and simulated under each condition. The results presented here confirm the satisfactory and reliable response of the system in all scenarios. The designed system shall replace the existing power source (diesel gen) with green and economical energy resources and will be a great help to bring sustainability in the Canadian aquaculture industry.

Keywords—Hybrid power system, Aquaculture, Floating solar PV power system, HomerPro, dynamic modeling

3.1 Introduction

By developing the first civilized cities nearby the fresh waters, we can see the history of fishery and the contribution of marine foods in the human diet. The economy and policy of many developed countries tie to this industry since the fisheries and aquaculture sectors contribute to combat with challenges of universal food security and bring economic benefits.

As of now, wild fisheries have a greater contribution to the total production. Therefore, aquaculture business should be encouraged so that the devastating effect of overfishing on the marine environment and ecosystem can be minimized. Aquaculture is embracing the latest technologies and many new advancements are being made to improve the yield and lower the operational cost and the environmental footprints. The availability of appropriate energy sources is inevitable to bring enhancement in the production capacity, and sustainability to achieve future goals.

We must consider that energy plays a major role in fish farms. For instance, components like feeders, aerators, air compressors, lighting, and refrigerators are energy-intensive and need electricity to operate. Renewable and Non-renewable energy sources are the two different categories of energy sources in the world. The carbon emissions from renewable energy sources are very low or nonexistent, making them environmentally benign. Non-renewable resources are harmful to the environment and cause global warming.

3.2 Literature Review

Land-based (freshwater) and offshore (seawater) fish farms are the two main categories of aquaculture activities. The offshore fish farm cages are located inside the sea from 2km to 25km from the coast. The cluster of cages is formed and a feeding barge containing all the necessary operational equipment is anchored near the cages. The automated monitoring and feed system form an integral part of offshore aquaculture that provides regulated feed and helps to monitor the health, and growth of fish inside the cages. The system is primarily comprised of feed blowers, sensors (dissolved oxygen (DO), salinity, pH, etc.), cameras, and a centralized monitoring/control system. At the bottom of the fish enclosure, an aeration system is deployed which diffuses air and causes oxygen-rich water to travel upward in the pen.

The energy demand of offshore fish farms is usually fulfilled by feed barges [1]. The feed barge is an integrated mobile setup that houses all the necessary equipment/setup to run the operations of the fish farm including the feeding system, air compressors for aeration, silos to store the feed and staff accommodation, and DGs. Further, the energy needs of an offshore fish farm site located in the Mediterranean Sea having underwater lighting, sensors, cameras, and remote video is recorded as 4783.88 Whr/day [1].

The usage of solar power for the aquaculture industry has been increasing significantly each day due to minimized operational costs, environmentally friendly nature, and low soil contamination [2]. The presence of solar energy systems in land-based fish farms is quite convincing and discussed here. An off-grid solar system was developed to completely power up the fish farm along with its monitoring system (PLC & HMI) [3], the yield of the fish farm is increased by maintaining the temperature of the fish cage. An automated and solar-powered fish farm management system with of aim of fish conservation is designed by Fourie [4].

Installing solar photovoltaic systems over water bodies utilizing floating technology is a novel concept. Depending on the solar cell type and weather, a typical PV module converts 4–18% of the incident solar radiation into electricity. The remaining solar radiation that strikes the PV is transformed into heat, which sharply raises its temperature. The power production of solar cells changes as the temperature changes. Due to this dependence on temperature, solar PV systems built on the surface of water benefit from significantly lower ambient temperatures due to the cooling action of water. On average efficiency of floating-type solar panels are 11% higher compared to ground-installed solar panels [5]. Thus, the implementation of floating PV panels seems to be a complete match to expand the blue economy.

3.3 Mathematical Modeling of Hybrid System

3.3.1 System Sizing

A location for an offshore fish farm project has been chosen in Newfoundland, Canada, close to Red Island in Placentia Bay, refer to Figure 3.1. It has a total of eight fish cages and circumference of each cage is 160 m. The actual energy demand (kWh/day) is collected from the site, given as input to HomerPro software and the techno-commercial feasibility of the designed system is carried [6]. The schematic of the designed system can be seen in Figure 3.2. Canadian Solar-made CS6U-340M PV panels are selected, please refer to Table 3.1 for a list of key specifications/details of the system.

Figure 3.1: Project Site (Offshore Fish Farm)

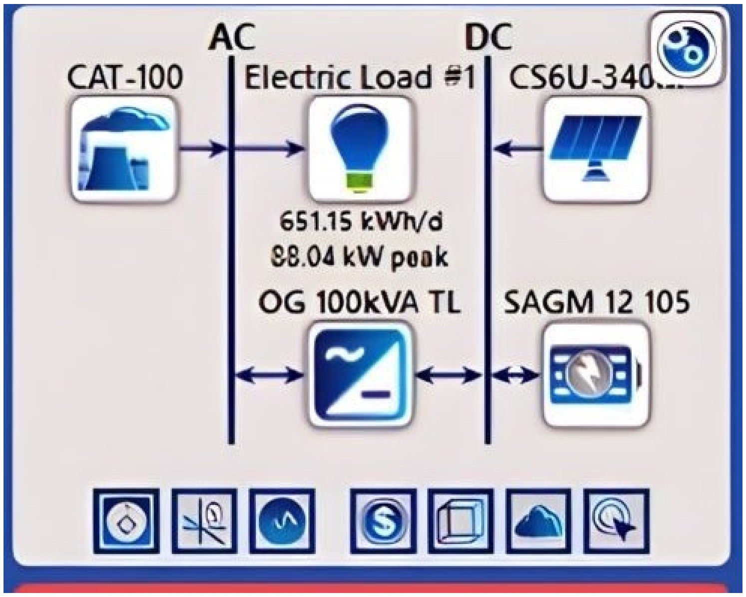

Figure 3.2: Schematic of the Designed System

Table 3-1 List of key Specifications of System

Sr	Description	Unit/Symbol	Value
1	Total Designed Solar Power by HomerPro	kW	366
2	Nominal Max. Power of Single PV Module	W/Pmax	340
3	Total No. of PV Modules	No	1077
4	Battery Bank Size	kWhr	542.1
5	Nominal Capacity of One Battery Cell	kWhr	1.39
6	Total No. of Battery Cells	No	390
7	DC Bus Voltage	V_{DC}	360
8	AC Bus Voltage (Phase-Phase)	V_{AC}	208
9	Total Load	kW	80
10	Diesel Generator Rating	kVA	99

3.3.2 Maximum Power Point Tracking

The energy output of the PV cells is largely dependent on the location of the sun and the resultant sun rays' direction. Any change in the location and rays of the sun would have a direct consequence on the power produced by solar cells. Further to this, the relation between I-V and P-V is not linear in the case of PV cells. Therefore, the output of the PV cells is constantly changing. The analysis of the P-V & I-V curve of the PV states that there is only one specific and unique point where the most optimized power can be obtained from the module, called the "maximum power point (MPP). The power produced by the cell on either side of the MPP would be less and hence to improve the conversion efficiency of PV installation it is very necessary to track that point and ensure the operation of PV cells on MPP.

The maximum power point tracker (MPPT) is a device, essentially a DC-DC converter, equipped with an intelligent algorithm in a microprocessor that helps to track the output power of a PV array, the MPPT finds the optimal power output point and ensures the operation of the PV cells at that particular point. Since PV cells are exposed to fairly changing irradiance and temperature, MPPT remains constantly busy in finding the MPP with respect to changing weather. Further to this, any change in load (resistance) also causes MPP to change and the power output of PV cells is no longer optimized. The model of the PV system along with a MPPT controller is shown in Figure 3.3. There are many prevalent techniques/algorithms to track the MPP i.e., Perturb & Observe (P&O), Hill Climbing, Incremental Conductance (INC), and Neural Network Control. The INC algorithm is applied in this paper considering its superior performance in tracking the MPP in changing weather conditions, reliable robustness, and accuracy. In addition, INC offers better efficiency and is easy to implement, as well.

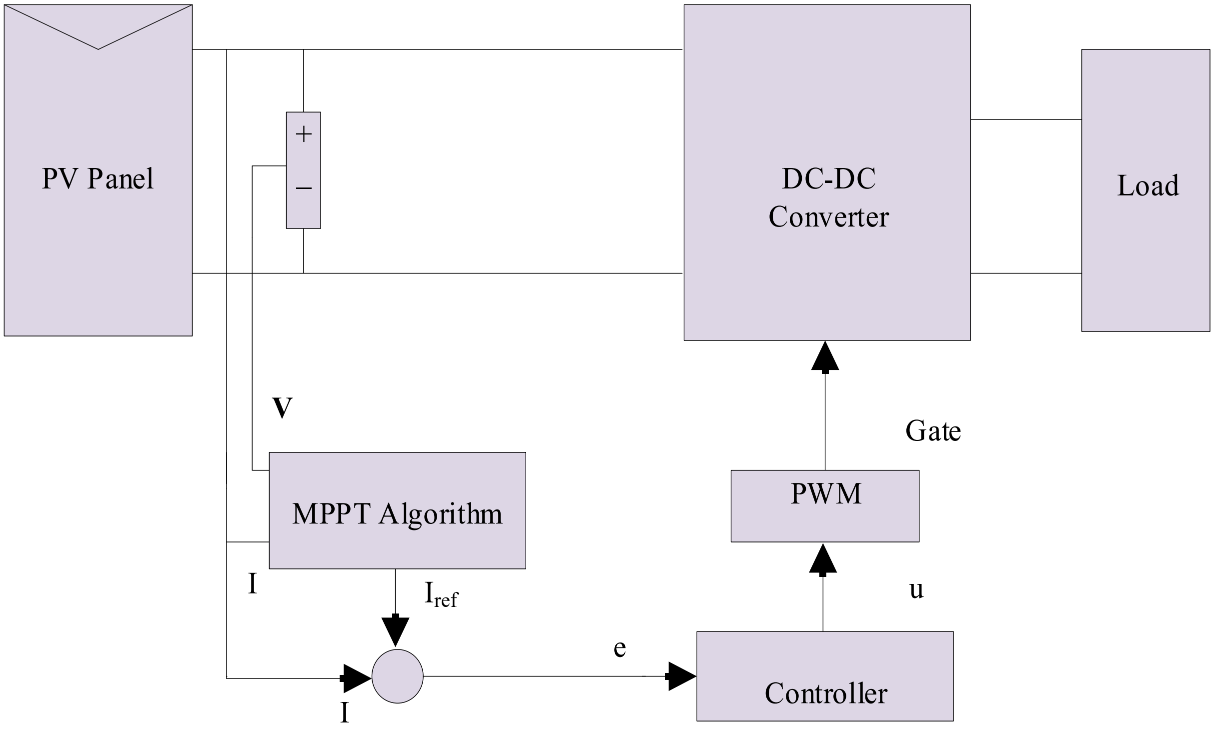

Figure 3.3: PV system along with MPPT Controller

INC algorithm follows a key point that the slope of the P-V curve of the PV module is zero at MPP ($\frac{\Delta P}{\Delta V} = 0$). To find the MPP, the algorithm is designed to compare the incremental conductance ($\frac{\Delta I}{\Delta V}$) with the array conductivity ($\frac{I}{V}$). The fundamental equation driving the operation of INC is as follows

$$\frac{\Delta P}{\Delta V} = \frac{\Delta (VI)}{\Delta V} = I\frac{\Delta V}{\Delta V} + V\frac{\Delta I}{\Delta V} = I + V\frac{\Delta I}{\Delta V} \tag{3.1}$$

$$\frac{1}{V} \times \frac{\Delta P}{\Delta V} = \frac{I}{V} + \frac{\Delta I}{\Delta V} \tag{3.2}$$

The PV Module’s output power is differentiated with respect to voltage and equated to zero to get the Incremental Conductance.

Following are the key relationships that derive the operation of the INC algorithm.

$$\frac{\Delta I}{\Delta V} = \frac{1}{V} \ at\ the\ MPP \tag{3.3}$$

$$\frac{\Delta I}{\Delta V} \geq \frac{1}{V} \ Left\ Side\ of\ the\ MPP \tag{3.4}$$

$$\frac{\Delta I}{\Delta V} \leq \frac{1}{V} \ Right\ Side\ of\ the\ MPP \tag{3.5}$$

The complete system consists of PV system, MPPT controller, inverter, battery bank, synchronous generator, and variable load is modeled in MATLAB/Simulink, refer to Figure 3.4. Some of the key parts of the modeled system are explained below.

3.3.3 DC-DC Converter

DC-DC converter is implied in the system as part of the multi-stage power processing system. The converter has a pivotal role in achieving the MPP of PV modules, the output is DC voltage, and it is exposed to handle small power only [7]. DC-DC converter along with the DC-AC inverter forms the multi-stage system and this configuration offers the freedom of operation of PV voltage in a wide range. Further, it also uncouples the direct connection between AC output and PV module so that a double-line-frequency ripple of PV voltage is not induced by AC power swell.

The buck converter is used as a DC-DC converter due to its high efficiency, simple configuration, and low voltage ripple. The DC output voltage level in accordance with the inverter DC link is maintained by the buck converted which is 360V DC in our case. The output voltage (V_0) is lower than the input voltage (V_i) and this is achieved by controlling the duty cycle (D) of switch S, the duty cycle is a scalar that has a value between 0 & 1. The important equations describing the operation and designing of Buck converter are as follows

$$V_0 = D.V_i \tag{3.6}$$

$$L = \frac{V_0 \times (V_i - V_0)}{\Delta I_L \times f_s \times V_i} \tag{3.7}$$

ΔI_L is the inductor ripple current which is taken as any value between 0.2-0.4 of maximum output current. The output capacitor is designed to lower down the ripples on the output voltage and it is designed considering the following expression.

$$C = \frac{\Delta I_L}{8 \times f_s \times \Delta V_o} \tag{3.8}$$

The values of the inductor and capacitor computed according to the above-said equations are 0.346mH & 1.2mF, respectively.

3.3.4 DC-AC Inverter

Stable DC output from the buck converter is fed to the three-phase Voltage Source Inverter (VSI) which converts it to the desired AC voltage i.e. 208V (phase-phase). Among various available PWM techniques, Sinusoidal Pulse Width Modulation Technique (SPWM) is used because of its unique offerings i.e. low Total Harmonic Distortion (THD), simplicity and better controlling schemes. The desired output voltage waveform and reduction in THD is achieved by controlling the width of SPWM pulses. THD is a very relevant and concerned parameter when non-linear components are involved, most of the semiconductor devices which are the heart of renewable energy systems, depict non-linear behavior. Therefore, the combination of SPWM and filters provides a great solution in the reduction of harmonics and resultant losses. SPWM reduces the low-order harmonics and filters are used to reduce high-order harmonics [8].

3.3.5 LCL Filter

The level of power quality supplied to the load is gaining more and more attention due to its direct effects on the performance of the connected load. Higher the power quality, lower the losses and better the performance of load. As discussed above, filters are necessary to control and eliminate the higher-order harmonics. LCL filter is used to reduce the harmonic distortion in the inverter output waveform and low ratings of inductor and capacitor are used to make the system more economical.

Designing of LCL filter is a complex process and it starts with computing the inverter side inductor with the help of the following equation.

$$L_i = \frac{U_{dc}}{16 \times f_s \times \Delta I_L} \tag{3.9}$$

f_s is the frequency of the system and DC bus voltage is represented by U_{dc}. ΔI_L is referred to as current ripple and can be computed by following equation.

$$\Delta I = \frac{0.1 \times Pn \times \sqrt{2}}{V} \tag{3.10}$$

The value of DG side inductor Lg and filter Capacitor C_f, are computed according to the following equations.

$$L_g = 0.6 \times L_i \tag{3.11}$$

$$C_f = \frac{Pn}{\omega_g \times V_{Ph-g}} \tag{3.12}$$

The value of the inductor and capacitor computed according to above-said equations are 0.450mH & 0.081mF, respectively.

3.4 Modeling of Complete System in Matlab/Simulink

The individual modeling of all the components described above in section III is put together and a complete model is assembled on MATLAB/Simulink, refer to Figure 3.4, which is a very useful tool to model the actual behavior of components/equipment through block-based programming and mathematical relationship.

The complete PV system consists of 72 parallel and 15 series strings, each module is of 340W (CanadianSolar CS6U-340M). The battery bank comprised of 1365Ah (542.1kWh), each battery is 12V & 105Ah (1.39kWh). There are 30 batteries connected in series and 15 parallel strings.

Although the PV system can fulfil the energy demand of the selected site but due to the intermittent nature of renewable energy sources, a backup DG is also considered to improve the reliability of the power system. Although the originally system doesn't need such a large rating of DG but the existing infrastructure of the site has 99kVA synchronous DG so, the same is considered in the model. The real-time model of the synchronous DG is developed in MATLAB to address the possible constraints of synchronization with PV system and smooth power flow to the variable load. The control system is developed for the DG to regulate its operation and to gain more precise control on active power generation according to design parameters. Further, the controller also ensures a robust response against all possible real-time load variations.

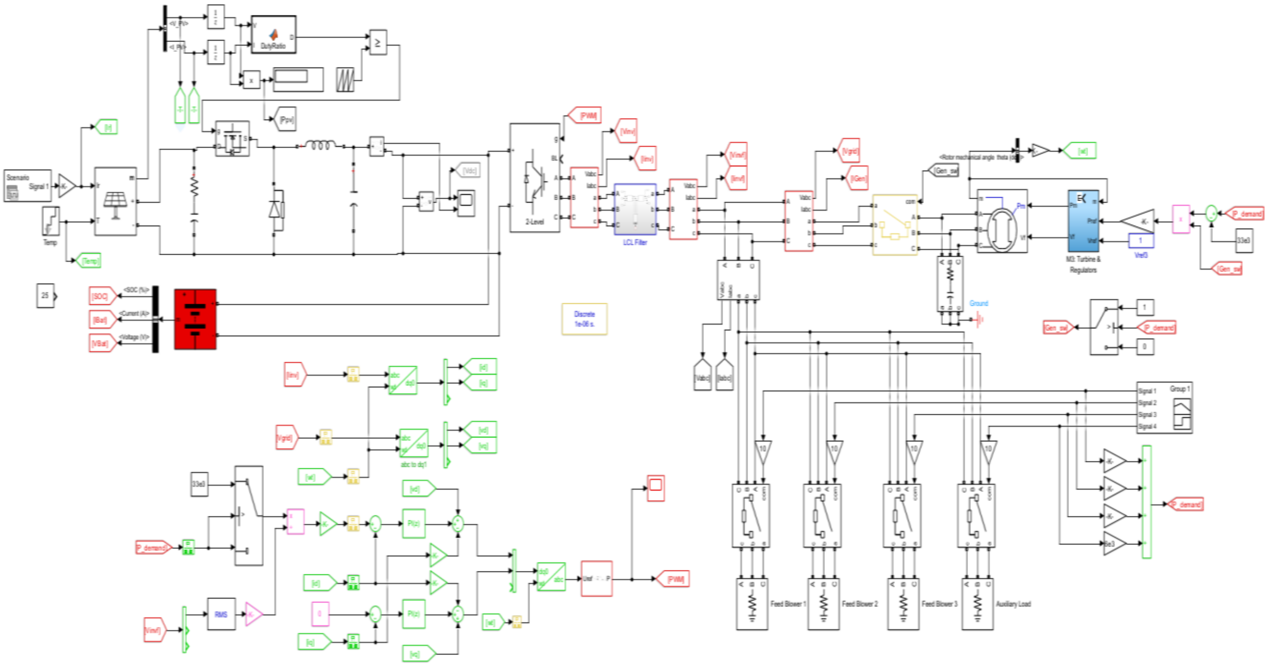

Figure 3.4: Complete System Modelled in MATLAB/Simulink

Since power output of PV is largely dependant on weather (irradiance and temperature), which is always changing, therefore, the analysis of changing weather on PV power output and its corresponding affect on whole power system network is very necessary. The dynamic response of system is evaluated by exposing it to variable irradiance and temperature, refer to Figure 3.5. The response time and behaviour of system is found satisfactory. MPPT controller is efficiently achieving MPP despite of drastic changes in weather and ensuring maximum power generation from PV in all cases. The PV power generation following the variable irradiance and temperature can be seen in Figure 3.6.

The power flow from PV to load is the priority and in case of excess power, the battery bank is charged. If PV is not producing enough power to meet the load demand then DG is capable of supplying the deficit and excess power shall again charge the battery bank, refer to Figure 3.7. Synchronization of PV and DG is achieved using Phase-Lock Loop (PLL). But to ensure fuel optimization, DG only comes to action if the load is more than 30%.

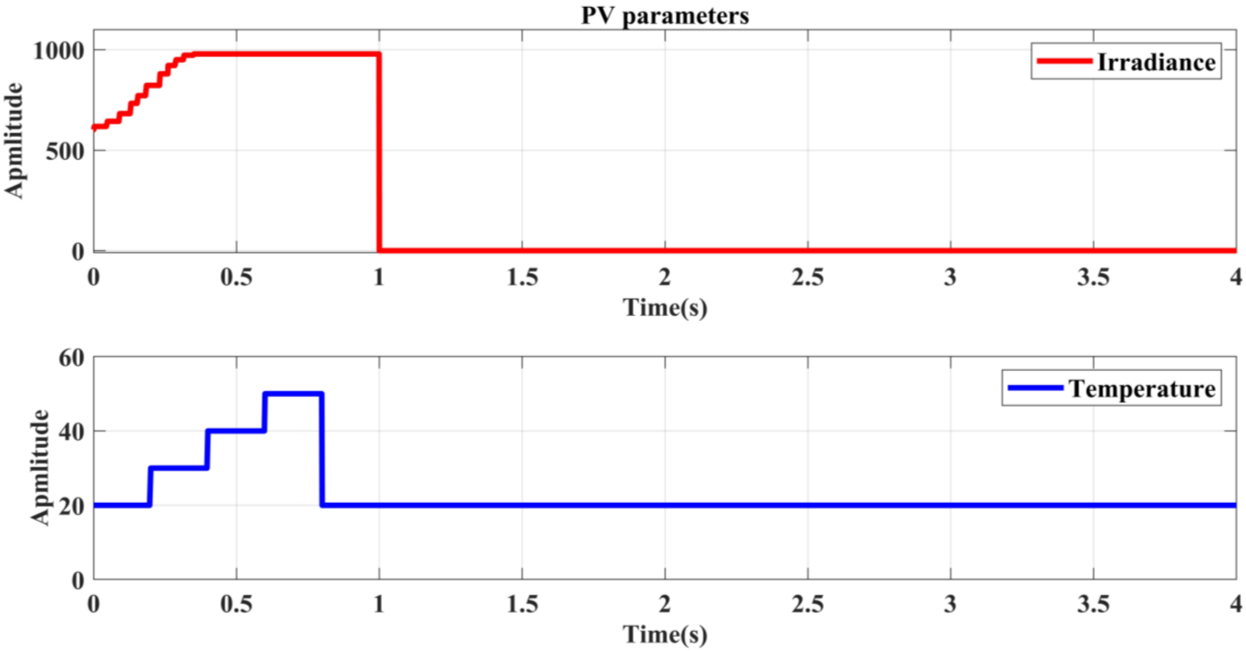

Figure 3.5: Variable Irradiance and Temperature

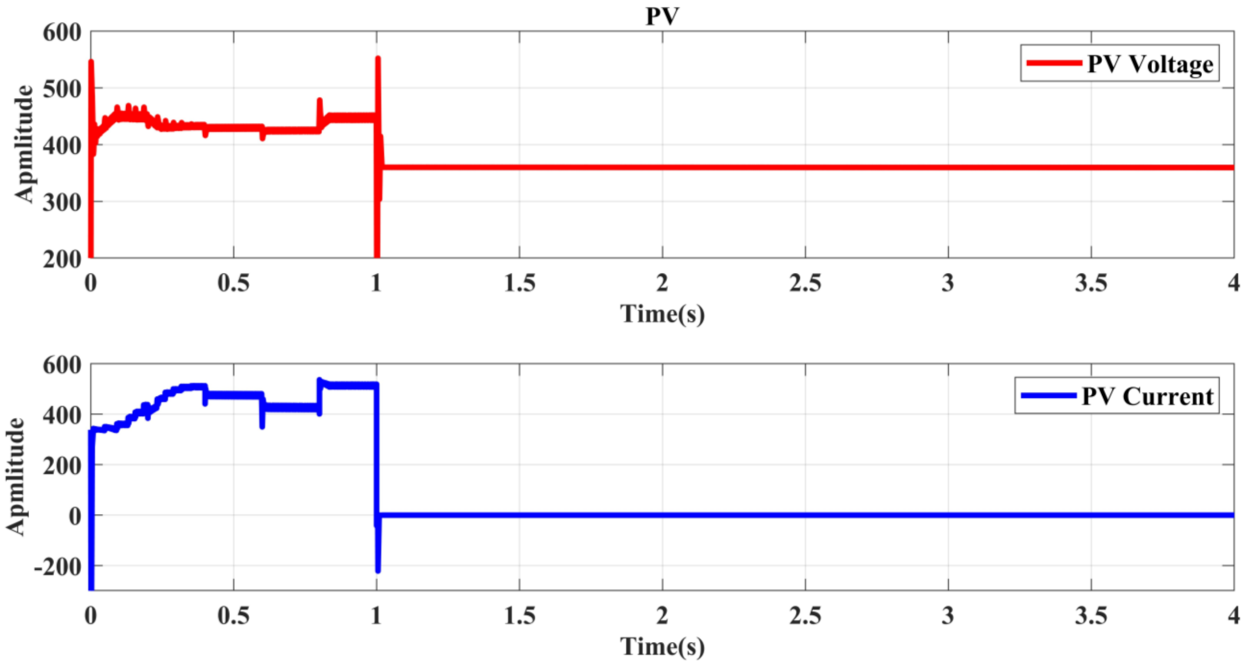

Figure 3.6: PV Voltage and Current due to inputs shown in Figure 3.5

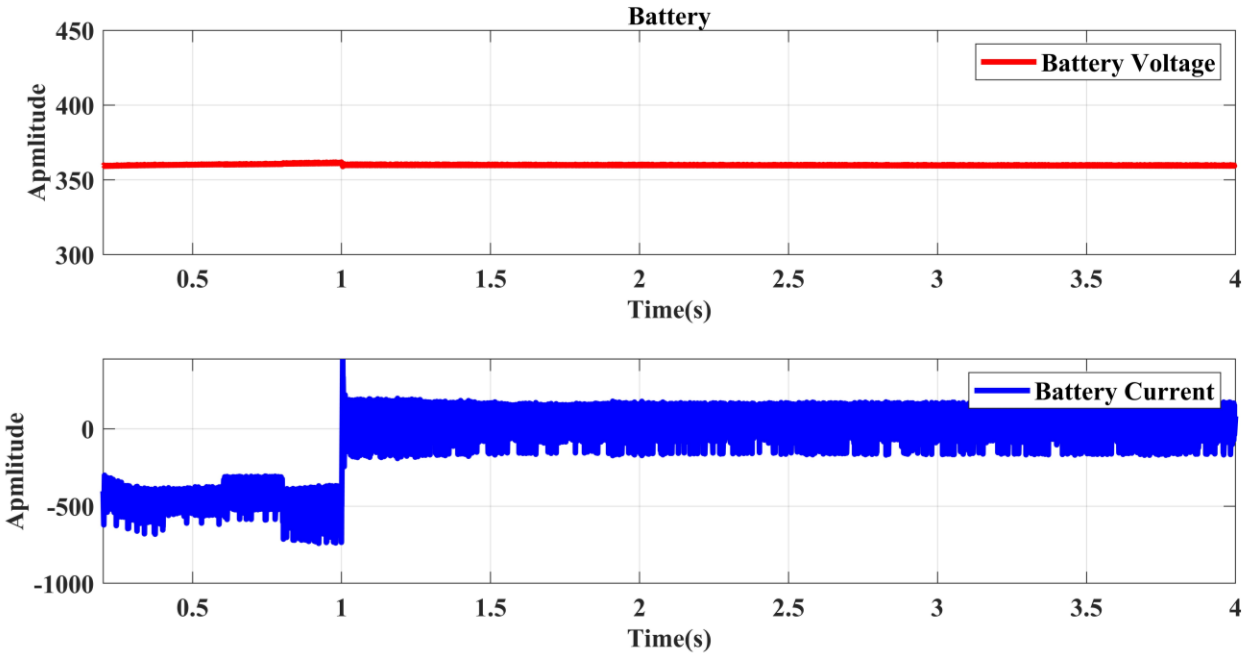

Figure 3.7: Battery Charging and Discharging

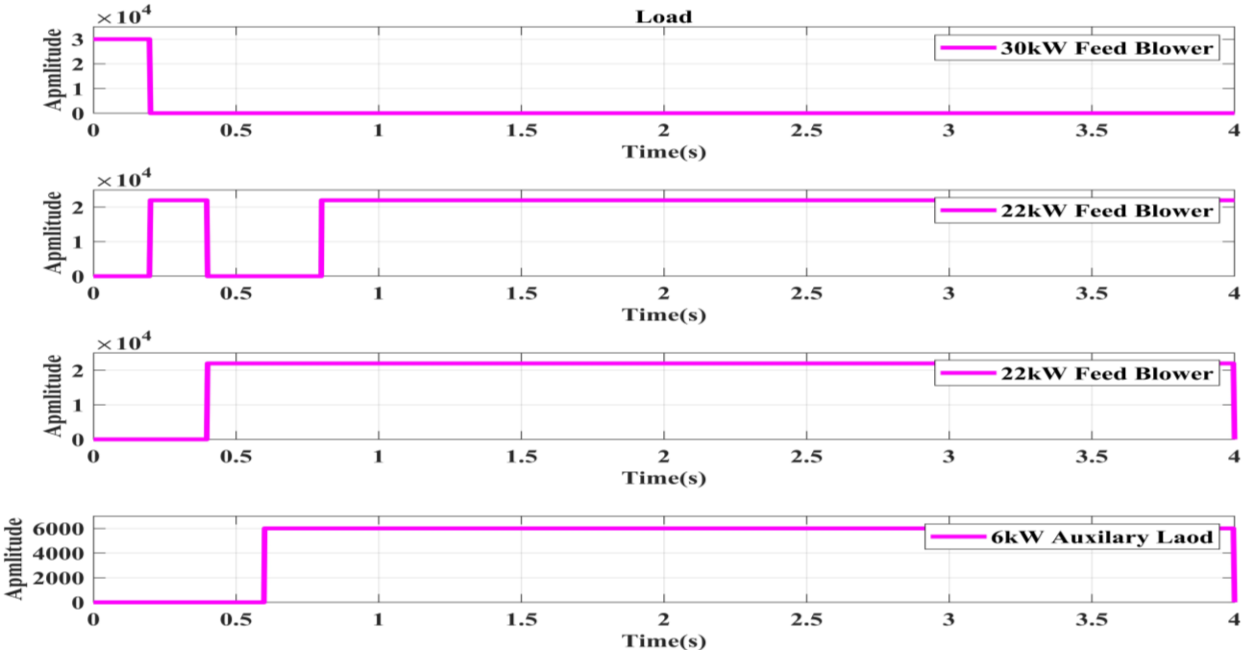

Figure 3.8: Variable Load (Load Switching)

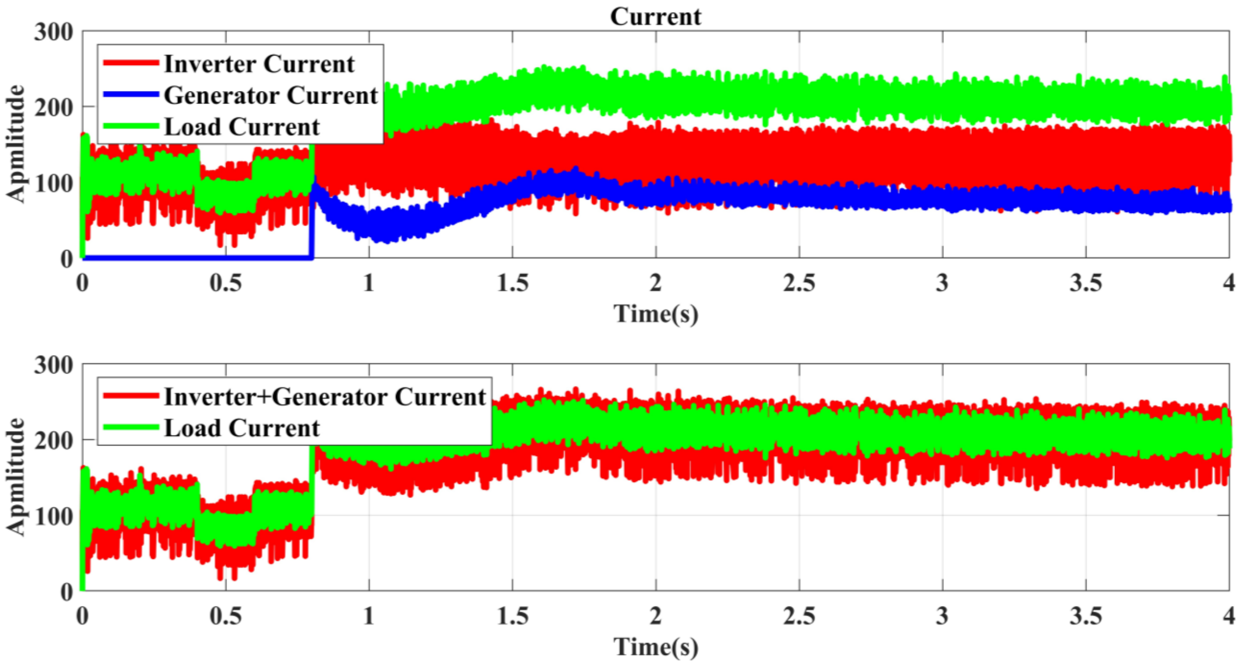

Figure 3.9: PV, Generator and Load Current

The total load of the aquaculture site is 80 kW which is a combination of three feed blowers (30kW, 22kW & 22kW) and 6kW is the auxiliary load (lights, sensors, etc).In the real world, the load is always changing as well and variation of load could also impact and disturb the operation of power sources and network Therefore, the variability of load is applied, refer to Figure 3.8 and its impact is analyzed. The response time of the system is found satisfactory and both power sources (PV and Gen) are capable of supplying power smoothly to the variable load in changing weather conditions, refer to Figure 3.9. The load demand is primarily fulfilled by PV (inverter current).

3.5 Conclusion

The results presented here prove the satisfactory response of the designed system against all possible dynamic changes. The MPPT is found very efficient in tracking and achieving the MPP despite of variations in weather. The controller for the synchronous generator is very robust to respond to the changes in load, managing the mechanical inertia of DG accordingly, and coordinating with PLL to ensure smooth synchronization with the PV system. The results endorse the profoundness of the overall performance of the designed system and further confirms the capability of the designed PV system to fully meet the energy needs of fish farm and reliance on DGs can be minimized to the lowest possible value. It would not only bring environmentally friendly and economical energy but would reduce the operational cost and enhance the sustainability of Canadian aquaculture industry.

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Chapter 4: Development of a Low-Cost, Open-Source LoRA based SCADA System for Remote Monitoring of Hybrid Power System for an Offshore Aquaculture Site in Newfoundland

Preface

A version of this manuscript has been published in the ***European Journal of Electrical Engineering & Computer Science (EJECE)*** *Voulme-7, Issue-6 (2023). As the primary author, I undertook the majority of the research, including literature reviews, system design, hardware assembling, and results analysis. Additionally, I authored the initial manuscript draft and later refined the final version based on feedback from the supervisor. Dr. M. Tariq Iqbal, the co-author, provided research supervision, acted as a guide, reviewed and corrected the manuscript, and contributed research ideas to enhance the overall development of the manuscript.*

Abstract

In this article a low-cost and open-source Internet of Things (IoT) based Supervisory, Control and Data Acquisition (SCADA) system for remote monitoring of the hybrid power system for an offshore aquaculture site is presented. The selected site is situated 2km away from the coastline where there is no electrical utility infrastructure and limited communication options are available. The hardware of the designed system primarily consists of six field sensors, Arduino Leonardo as Remote Terminal Unit (RTU), LoRA (Long Range) gateway, cables, AC/DC current and voltage supplies. Arduino IDE, AWS, Influx DB, and Grafana provide the software support. The field sensors are responsible for measuring the solar, battery, inverter & generator currents, along with battery voltage and temperature. All of the field sensors except the temperature sensor send the data to RTU which further delivers it to The Things Network (TTN) cloud. With the help of influx DB, AWS cloud computing services, and Grafana, the data can be stored and visualized through interactive yet informative graphs. The graphs display the historical and live data of each sensor. Further, it also gives the option to set alarms and alerts on user-defined conditions to improve control over the hybrid power system. The complete hardware is assembled and tested in Memorial University's Power lab. The developed system was supplied with variable current/voltage supplies and the data was logged for three continuous hours. However, the data can be stored for a much longer duration as per user's requirement. The hardware and the results presented here are a testament that the proposed design system is capable to provide a remote monitoring solution for the offshore aquaculture site.

Keywords—IoT, LoRA, Hybrid power system, Aquaculture

4.1 Introduction

The reliance on renewable energy to meet the energy needs of industrial, commercial, and residential installations is increasing each day due to its unparalleled competitiveness on economic and environmental grounds. Amongst available renewable energy resources, solar PV provides great flexibility to be installed over a variety of places i.e. rooftop, ground, and over water bodies. This distinguished convenience attached to solar PV systems are a beacon of hope to bring vast transformation in the global energy mix and has the capability to realize the vision of reduced emission in coming years. The monitoring of PV power systems is of paramount importance to ensure optimal performance, timely maintenance of the system, and fault diagnosis.

The robust and cost-effective monitoring of PV systems forms an integral part of improving the resilience of the overall system. SCADA system, which is a combination of software and hardware, provides the liberty to supervise, collect, transmit, and log the data [1]. The SCADA system primarily comprises Field Sensors, Remote Terminal Unit (RTU), Communication Equipment/protocols, Human Machine Interface (HMI), and Servers. Sensors act as the eyes and ears of the whole system, have direct interaction with the system to be monitored and data is collected for onward transmission. RTU is like the heart of the system, is essentially a microcontroller, receives the data from field sensors, processes it in meaningful form, and transmits it to the central system. The data from RTU is sent to a central monitoring system/cloud/website using an appropriate communication channel [2]. HMI receives the data and displays it according to the user’s required format. Finally, Servers log the historical data for analysis and decision-making.

As of now, four generations of SCADA have been witnessed and it is continuously evolving considering the industry demands, refer to Figure 4.1. Its first generation came to the surface in the

1960s and primarily focused on hardware-based solutions. The second generation adopted the power of emerging software and also improved the graphical user interface to make its usage friendlier. The third generation improved HMI for better data visualization and provided better connectivity with interfacing equipment. Whilst the fourth generation improved its interoperability with other systems, security, and ability to access data remotely.

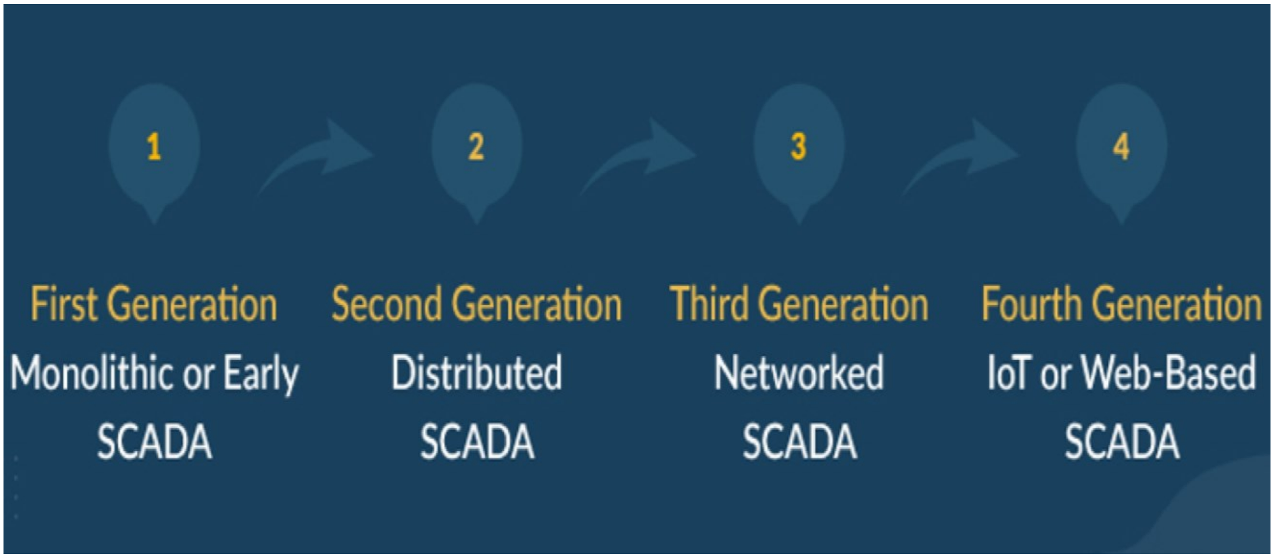


Figure 4.1: Evolution of SCADA

The open-source SCADA systems offer a unique and competitive offering by combining different low-cost but compatible equipment together to provide similar services as a proprietary system. The cost is always a concern in proprietary SCADA systems and often they are not very welcoming in interfacing with the other manufacturer’s equipment. Amongst the variety of prevalent communication technologies to transmit data from RTUs, LoRA (Long Range) is preferred for long-range communication. Further to this, it is also energy efficient (low power consumption) and offers wide area coverage where conventional technologies like Wi-Fi or cellular service is not feasible.

4.2 Literature Review

Solar energy has been adopted as the preferred source around the globe and its vibrant presence can be felt everywhere. The solar installations' pyramid is achieving new heights every day and now the more important concern is to look for possibilities to improve the performance, efficiency, reliability, and convenience of the system. The implementation of a SCADA system to monitor and record the operational performance of output power and other parameters is certainly an avenue that can bring the above-mentioned attributes to solar installations.

In [3], an IoT-based open-source low-cost SCADA system comprising current/voltage sensors mounted on Arduino UNO, Raspberry Pi2, and EmonCMS is implemented. The sensors took the actual data from PV panels and data was logged for 2 weeks. The sensors sent the data to Arduino attached to Raspberry Pi and Node-RED is used to communicate data to EmonCMS. The operator can see the live data and take the required action. A SCADA system was implemented to monitor the electrical parameters (power, voltage, current) of a hybrid system comprising wind, PV, and energy storage systems [4]. The real-time data is monitored using the ThingsSpeak platform. The developed SCADA system also has the capability to interface with MATLAB and low-cost components (Arduino & ATMega2560 RTU) are used. The hybrid system model is developed on MATLAB and its corresponding prototype is implemented, the effectiveness of the SCADA system is verified by comparing the actual results shown on ThingsSpeak with MATLAB simulation. In another research, an open-source SCADA system is implemented to monitor and control the environmental parameters [5]. Based on the environmental parameters, the operation of home appliances is controlled. The atmospheric sensors and light-dependent resistor are connected to ESP32, the local server is made using Raspberry Pi2, and the data is sent over the web using MQTT protocol and Node-Red. In [6], the author implemented an IoT-based application where data is collected using a temperature and humidity sensor, Node-Red acts as a server and data is stored in its internal database. Finally, the data is sent to the IBM Bluemix cloud. The air quality monitoring system is implemented to measure the presence of carbon monoxide, ozone gas, and temperature. ESP8266 is used as RTU and data is sent using MQTT Broker. Node-Red receives the data and sends it to a web-based application dashboard [7].

A SCADA system is developed for the renewable energy-based microgrid that has ability to send data to a server using LoRA gateway [8]. The data encryption is implemented with the AES algorithm to ensure data security. The mesh topology was used to enhance the communication range of the LoRA ESP32 gateway and 500m coverage is increased. The comparative analysis of ESP32 and Dragino-UNO-based gateways is presented, and both are used to upload the data to the server. A very sophisticated and cost-effective alternative is presented in [9], to calculate the sag and temperature of the transmission line by utilizing the vision system. The cameras installed on poles took photos, process them, and sent to the SCADA system using LoRA communication to determine the sag and other transmission line parameters. The data transfer between microgrids is achieved using LoRA communication. The electrical parameters of the individual generation system are collected by the local controllers and then transmitted to a central station using LoRA, the range testing of data transmission is done up to 4km [10]. Further, the author explained the competitive advantage of LoRA technology and its applications in SCADA [11]. LoRAWAN allows communication over long distances by maintaining low power requirements that can lead to cost-effective and reliable SCADA/IoT applications. It also states that a 2400mAh battery can provide backup for 4 hours to a device that sends one byte of message after every 30 minutes.

It is quite reasonable to establish that the remote monitoring of the system is inevitable to ensure healthy operation, timely maintenance, avoid downtime, and maintain the efficiency of any power system. In this paper, the LoRA-based low-cost and open-source SCADA is designed and tested considering the actual constraints of the offshore aquaculture site, and the complete setup is explained here in the following sections.

4.3 Proposed System Description

A hybrid power system dominated by floating solar PV panels is designed for an offshore aquaculture site located near Red Island, Placentia Bay, North of the Atlantic Ocean, Newfoundland, province of Canada. It has a total of eight cages refer to Figure 4.2. The selected site is in the Atlantic Ocean, around 2 km from the land. There is no presence of electrical infrastructure and only limited options of communication technologies are available. Therefore, the long-range based communication setup is selected which can communicate the data to the control room located a few kilometers away on land. The hybrid power system consists of a Diesel Generator (DG) 99kVA, PV (363kW), and battery bank (542.1kWh), the complete details of the designed hybrid power system can be found in [12].

Figure 4.2: Project Site (Offshore Fish Farm)

The output of the DG, PV, and battery bank is measured through sensors. Arduino Leonardo is the RTU that collects data from sensors and has the capability to transmit it to TTN through an in-built

LoRAWAN module without any additional hardware. To receive the data from RTU at TTN, the LoRA gateway is registered at TTN, and Arduino Leonardo is also registered as an application to the TTN network. Once the data is received on TTN, it has multiple options to send it to the cloud or store it on the local server. Using the MQTT communication protocol, the data is pushed to Influx DB for storage. Amazon Web Services provided virtual cloud computing services (EC2), Telegraf and Grafana are used to receive, process, and display historical and live data through interactive charts. The orientation/schematic of the proposed system is shown in Figure 4.3. The scope of this research paper is limited to the development of a prototype in accordance with the actual system and hence it is prepared accordingly. Details of the hardware and software used to compile the presented architecture are explained explicitly in the following sections. Further, the algorithm and flow chart to measure, collect, store, and display the field measurements are explained in the following sections of this paper.

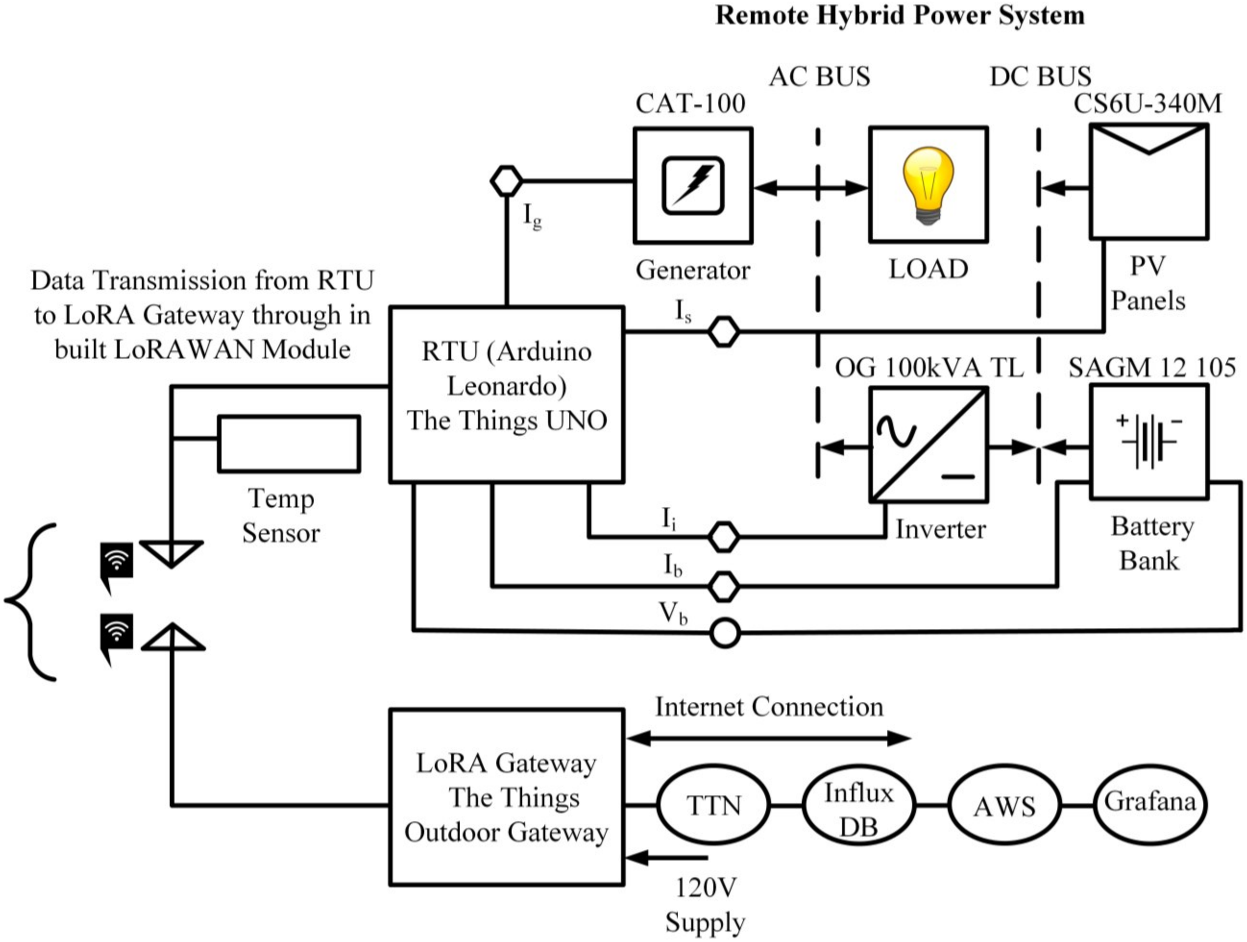


Figure 4.3: Proposed System's Design Block Diagram

4.4 Components of The System

The development of low-cost and open-source SCADA system for remote monitoring system can be primarily divided into three following different sections.

- Field Measurement
- Receipt and Transmission of field data
- Graphical User Interface (GUI) development

The components selected to achieve the above-said milestones are explained in this section.

4.4.1 Sensors

Sensors are the front-line warriors for the system and play a pivotal role in the safety and monitoring of the system. The real-time data of the desired parameter is provided by the sensor which provides the basis for subsequent decision/action. In this project, predominantly three types of sensors are used.

- Current Sensor
- Voltage Sensor
- Environmental Sensor

4.4.1.1 Current Sensor

The currents of PV solar modules, battery bank, inverter, and generator are measured. The solar modules and battery current are essentially required to be measured with a DC current sensor whilst the inverter and generator current is need to be measured with an AC current sensor. ACS712 Hall effect sensor is selected for the prototype development. This sensor can measure AC & DC current and has three different types based on its current measurement rating, 05A, 20A & 30A. For the sake of prototype development, the 05A sensor is selected. It needs a $5V_{DC}$ supply and ground connection to power up. It's a linear current sensor that makes measurement easier. Further, it also provides the isolation from the actual current-carrying conductor and enhances safety of the sensor and subsequent connected equipment. The sensors required for the actual hybrid system are also worked out here.

PV Modules

There are a total 72 parallel strings of panels and the short circuit current of each sensor is 9.48A. The total current of the PV installation shall be 683A. In order to improve the reliability of the system, we can use four CR5210 DC current sensors, each has current range of $200A_{DC.}$

Battery Bank

The battery bank consists of 13 parallel strings and each cell is of 105Ah. One CR5210 sensor can measure the current.

For the inverter and Generator, CSCA-A Series Hall effect-based sensor manufactured by Honeywell can be used.

4.4.1.2 Voltage Sensor

The voltage sensor is used to measure the output voltage of the battery bank. A very simple but precise voltage sensor having a range of 0-25VDC is used for our prototype. It works on the principle of voltage divider and reduces the input voltage with a factor of 5. It is made using two resistors of 30kΩ & 7kΩ. The DC bus voltage of the actual system is 360VDC therefore, CR5310 having a voltage range of 0-600VDC can be used.

4.4.1.3 Environmental Sensor

The performance of the PV modules depends greatly on the temperature they are exposed to. With the increase in temperature, the open circuit voltage of the panel decreases and its short circuit increases, refer to Figure 4.4.

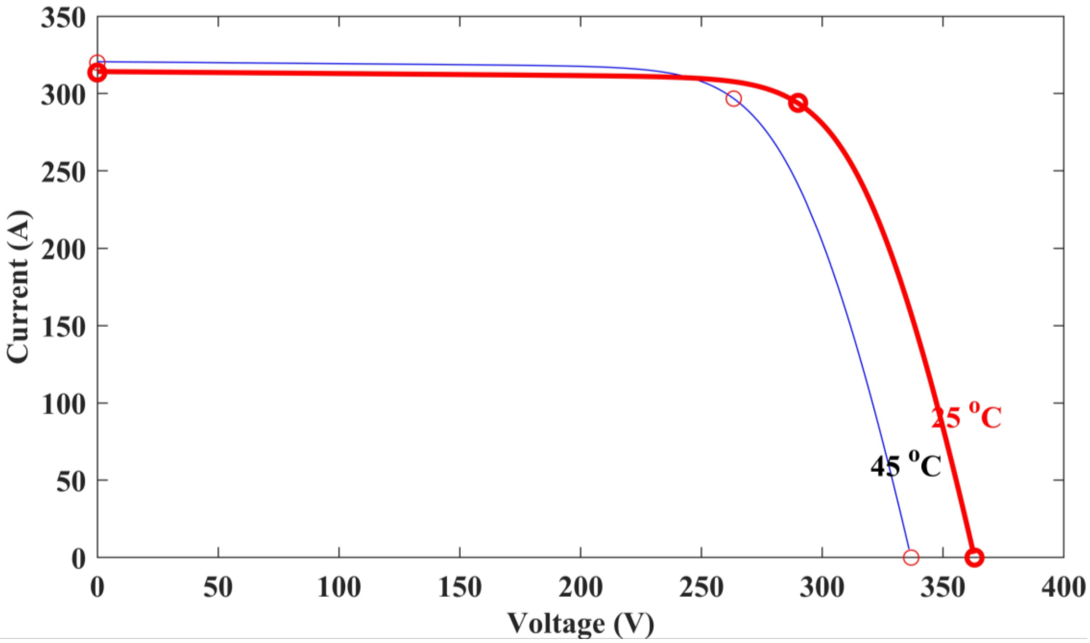


Figure 4.4: Temperature relation with PV performance

The Things Node which is a smart temperature sensor with in-built LoRAWAN module is used here [13]. The Things Node is a very friendly device and can be added as an end device to (TTN) under applications. Once it is connected, it monitors the real time temperature and sends to the TTN cloud.

4.4.2 Arduino Leonardo

Arduino Leonardo is a very useful, widespread and open-source microcontroller used in developing IoT-based projects. It is from the family of Arduino that offers user-friendly hardware and software for constructing a wide range of applications. The microcontroller used here is also called The Things UNO which is based on Arduino Leonardo added with a Microchip LoRAWAN module and is a product of The Things Network [14]. The product is programmed through IDE, installed on a PC, and can help to take off the measurements provided by the sensors. This powerful microcontroller is serving as RTU, taking the field measurements from sensors and sending it to the TTN cloud with the help of LoRA gateway. The pin layout is shown in Figure 4.5, all the sensors are connected on ADC pins (from A0 to A4). The ground and VCC (+5V) is kept common for all the sensors.

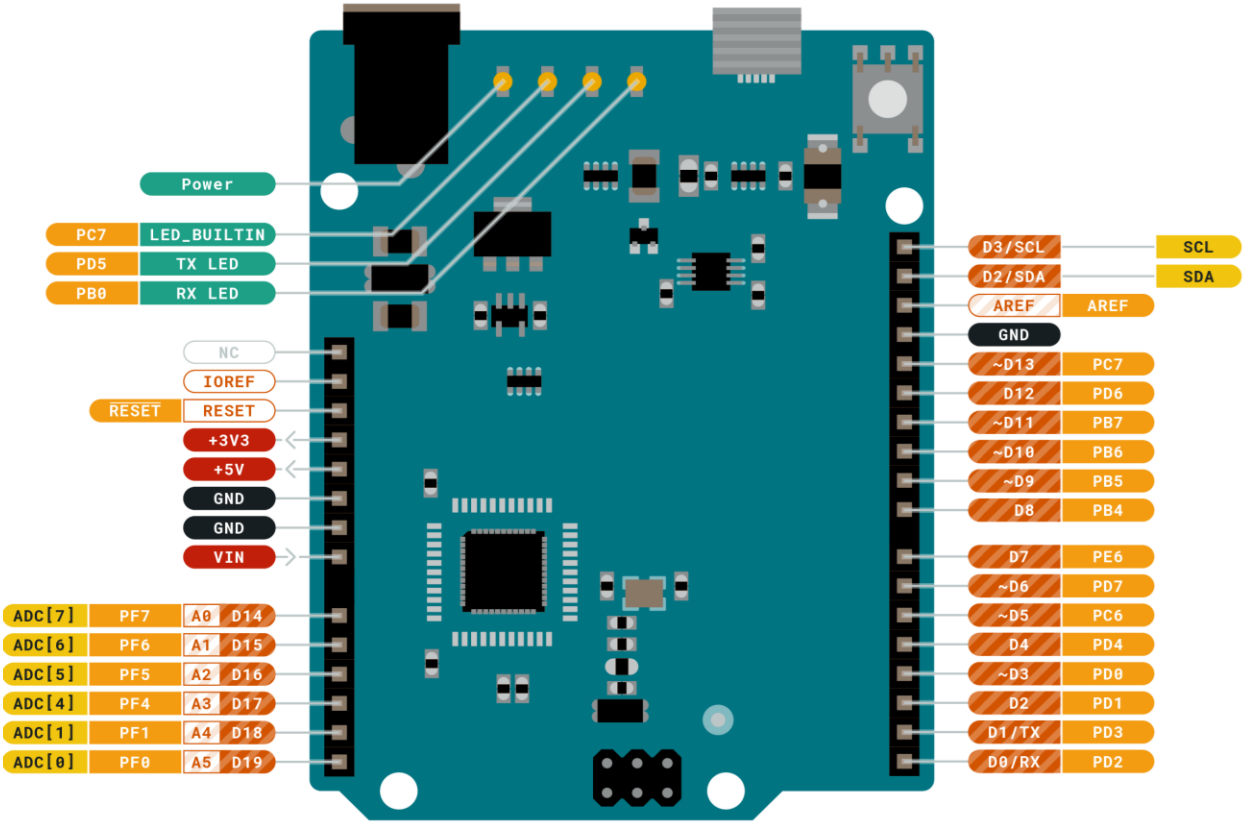


Figure 4.5: Pin Layout of Arduino Leonardo

4.4.3 LoRA Gateway

There are many communication technologies that exist now a days but most of them are not energy efficient and also has limitation in coverage area [11]. Low Power Wide Area (LPWA) technologies offer a great solution when it comes to transferring the small amount of data over a long range with minimum power consumption. This is the primary difference of LPWA from other prevalent wireless technologies [15]. The comparison for the range of wireless networks is given in Figure 4.6.

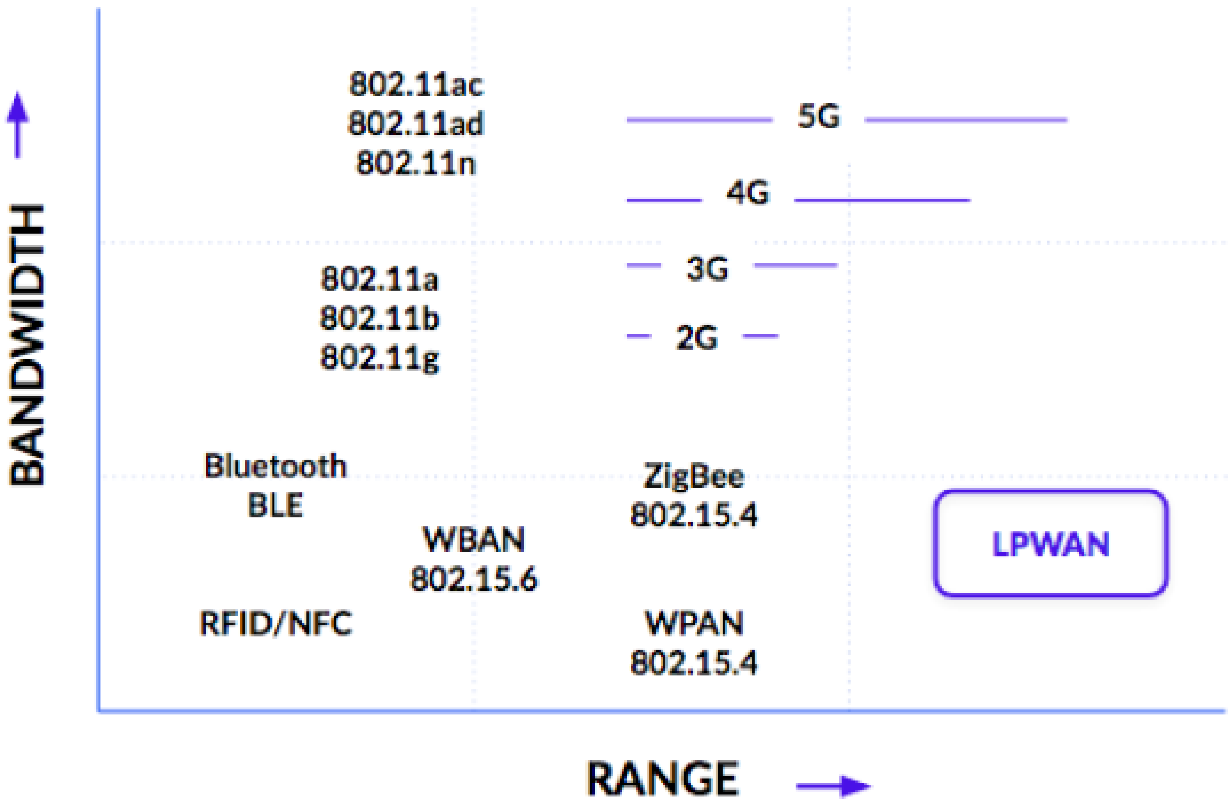


Figure 4.6: Range Comparison of Wireless Networks

LoRAWAN is a type of LPWAN network which uses chirp spread spectrum (CSS) modulation that helps it to achieve long communication range with minimum power needs. The Things Network manufactured LoRA gateway is used here which helps to build web-based setup. It provides a convenient and robust way to communicate the sensors' output to internet [16]. The outdoor gateway is available to function at 868MHZ (EU) and 915MHZ (US) and its range is up to 10km.

4.4.4 InfluxDB

InfluxDB is frequently used in a variety of sectors and applications, including IT operations for monitoring and alerting, IoT for collecting and analyzing sensor data, and applications that need analysis of historical data. Both open-source and commercial versions are available, the open-source version is used for this project that stores the data for 30 days. Further, it's very compatible with other applications and provides stored data as input for smart data visualization.

4.4.5 Amazon Web Services (AWS)

AWS is a globally recognized, popular, and comprehensive cloud computing service provided under the banner of Amazon. It offers a vast range of cloud services including storage and data analytics. It is very adaptive and provides convenient access to a wide range of technologies to build according to requirements. Amazon Elastic Compute Cloud (EC2) which offers the freedom of developing virtual servers in the cloud is used in our project to provide the platform to store and visualize the data coming from TTN.

4.4.6 Grafana

Grafana is a free, open-source analytics and interactive visualization tool that offers graphs, charts, and other visual representations [17]. It is widely used in various industries and domains for monitoring, observability, and data visualization. Users can create customized dashboards by adding multiple panels and visualizations, making it easy to monitor and analyze different aspects of data in one place. Grafana provides alerting capabilities, allowing users to set up alert conditions and receive notifications when certain conditions are met. This is crucial for monitoring and responding to critical events or anomalies.

4.5 Algorithm and Flowchart of The Proposed System

The data of the field sensors is sent to RTU and is processed by it to show at the serial monitor of Arduino IDE by following the below described algorithm and flowchart referred in Figure 4.7.

Algorithm for sensor data reading at Arduino (RTU)

1. Add the appEUI and appKey of RTU from TTN.
2. Define the analog inputs of RTU.
3. Set the floats for resistor values in voltage sensor.
4. Define and set the sensitivity of ACS712.

5. Determine samples of measurement from sensors and take the average.
6. Convert the average value of measurement to the actual value considering the sensitivity of sensor.
7. Print the live measurements at serial monitor.
8. Go to step 5 and repeat.

Algorithm for sending data from RTU to Grafana

TTN

1. Register LoRA gateway and RTU on TTN
2. Set the Payload format at TTN
3. Create API key in TTN
4. Get MQTT Credentials from TTN

Influx DB

1. Sign up for Influx DB Account.
2. Create the database for TTN Data.
3. Setup Telegraf Config by entering the MQTT Credentials you got from TTN.

AWS EC2 with Grafana and Telegraf

1. Sign up for AWS Free Account
2. Setup an AWS EC2 Instance with Amazon Linux
3. Connect to AWS EC2.
4. Install Docker
5. Install Telegraf and run the Telegraf configuration set in InfluxDB. This should run in the background.
6. In docker, run an image of Grafana Cloud on a container.
7. Access Grafana Cloud by using the EC2 IP and port set to run the container.
8. In Grafana, go to Data Sources and select Influx DB.

9. Choose Flux for your query language.
10. Input the Influx DB Credentials and Database.
11. Create the dashboard in Grafana.
12. In the dashboard using InfluxDB as the data source set up the charts and visualization
13. Go to Dashboard to visualize the data.

The flowchart describing the data transmission and visualization can be seen in Figure 4.7.

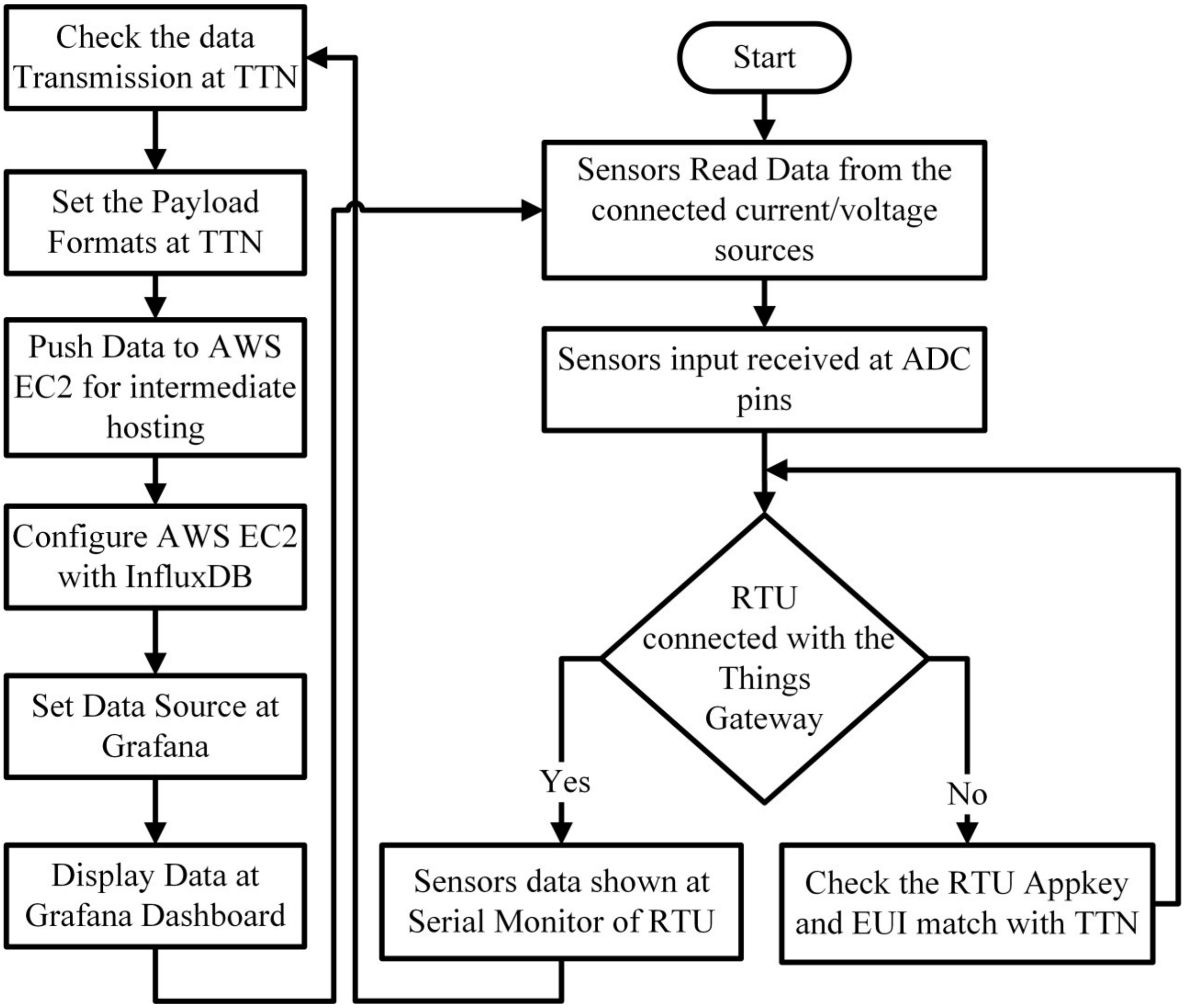


Figure 4.7: Flow Chart of Complete System

4.6 Implementation Methodology

The implementation of the IoT-based SCADA system starts from the configuration of the LoRa gateway which requires to make an account on the Things network and then registering the gateway by providing its unique EUI, ID, and the suitable frequency plan prevalent in your area (we use 915MHZ). Then the gateway is connected to the internet through local Wi-Fi, it can be connected through ethernet as well. After that, the RTU (Arduino Leonardo) is registered with the TTN under applications. To do that, RTU is connected with HMI (laptop) through USB 2.0, and the device EUI (Extended Unique Identifier) is retrieved through IDE software. The device EUI is used to register the RTU at TTN as the End Device under the applications tab. Then the RTU configuration is verified by using OTAA, once it is done successfully the data packets' transmission from RTU to TTN cloud is verified. Since the LoRA gateway has a range up to 10km we did the range testing as well. The RTU and the Things Node were taken away from the gateway for 3km, and they were successfully transmitting data at TTN.

There are a total of five field sensors used to measure the electrical parameters of the hybrid power system. Solar current, Battery Current, Generator Current, Inverter Current, and Battery Voltage sensors are connected at RTU ADC pins A0, A1, A2, A3 & A4, respectively. The current sensors are connected in series while the voltage sensor is connected in parallel. For convenience, all the sensors are mounted on a breadboard. The VCC (+5V) and ground are supplied to all the sensors (ACS712) sensors through the common wires from the RTU's respective ports. Solar and Battery current sensors are supplied with the DC current source through a shunt resistor having a power rating of 7W and 2.2Ω. Whereas, the generator and inverter current sensors are supplied the AC current via autotransformer, model no is 3PN1010B. The autotransformer can supply the variable voltage/current, the output voltage can be 0-140V and the corresponding current also varies from 0-10A. The AC current is supplied to sensors via a rheostat of 10Ω & 300W of power rating. The voltage sensor which has the capability to measure voltage in the range of 0-25V is connected in parallel to the fixed DC voltage source. The common ground from the RTU is connected to the voltage sensor and its analog pin is connected to the ADC pin of the RTU. Although the readings taken from sensors can be seen at HMI but to check the accuracy of the developed system, multimeters are connected at several points to take the continuous and live readings of current and voltage of all the sensors to ensure the accuracy of sensors and subsequent deployed system. The complete hardware setup is implemented in Memorial University's power lab, refer to Figure 4.8. The temperature is measured through the Things Node and it was added as an end device to the TTN cloud similar to the RTU.

The RTU takes the readings from the sensors and reports it to the Arduino IDE software, the readings from the sensors can be seen on the serial monitor of the IDE by following the steps outlined in Section V. Since the RTU is configured as end device as TTN so the live data reported by RTU can be seen at the cloud that can be accessed by the authorized users on internet anywhere in the world. TTN offers a variety of communication protocols under the integration tab (MQTT, Webhooks etc.) to transmit and visualize the data on several compatible platforms [18]. We took advantage of the remarkable virtual server AWS and combined it with Influx DB and Grafana to store and plot the data. The detailed steps to push, store, and plot the IoT data are outlined in the above section.

The data is logged for three continuous hours, all the sensors were connected with the explained setup and continuously sending data. The sensors sends the live readings at IDE after every 40 seconds and the same readings are reported at TTN after one second on average, refer to Fig. 9. The data received at TTN is saved at InfluxDB and 30 days of storage is supported in a free version. InfluxDB offers great flexibility in accessing the periodic data. Further, a graphical user interface is developed on Grafana and the graphs of each current sensor can be seen under the dashboard.

Grafana allows a wide window to see the historical data according to the user's requirement for analysis and decision-making.

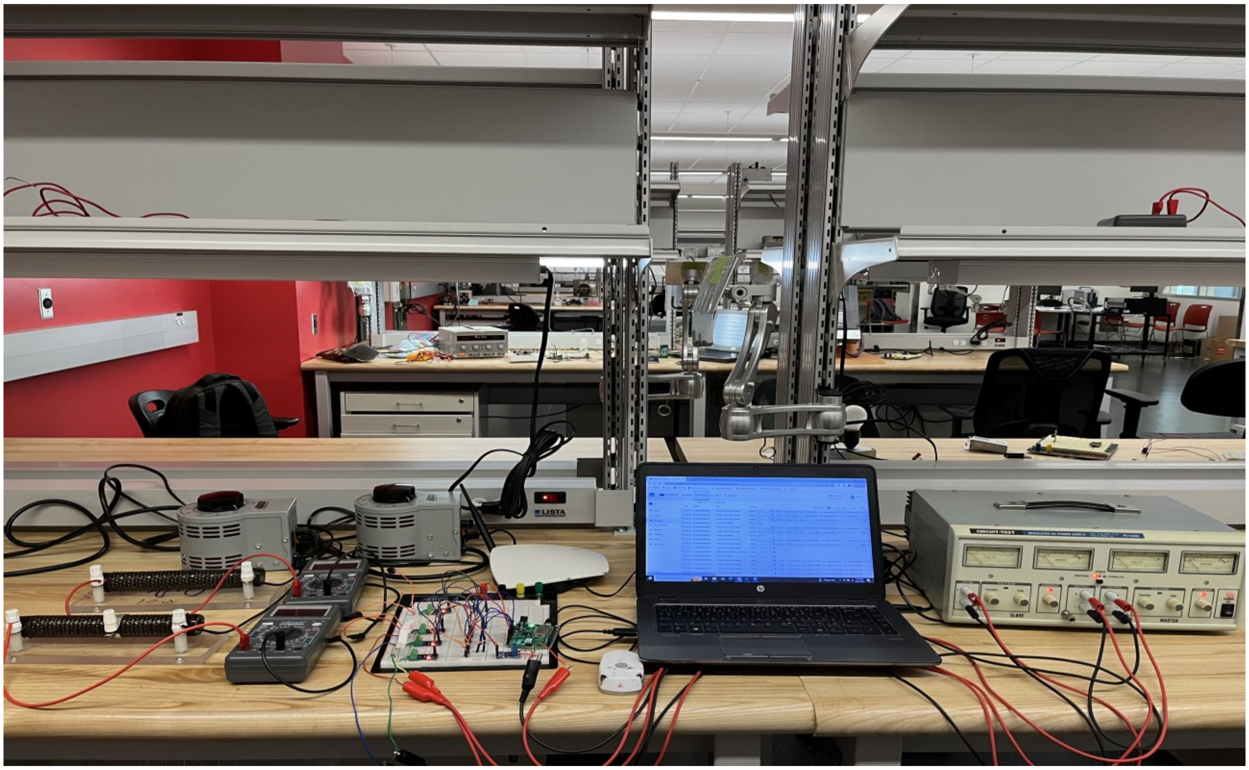
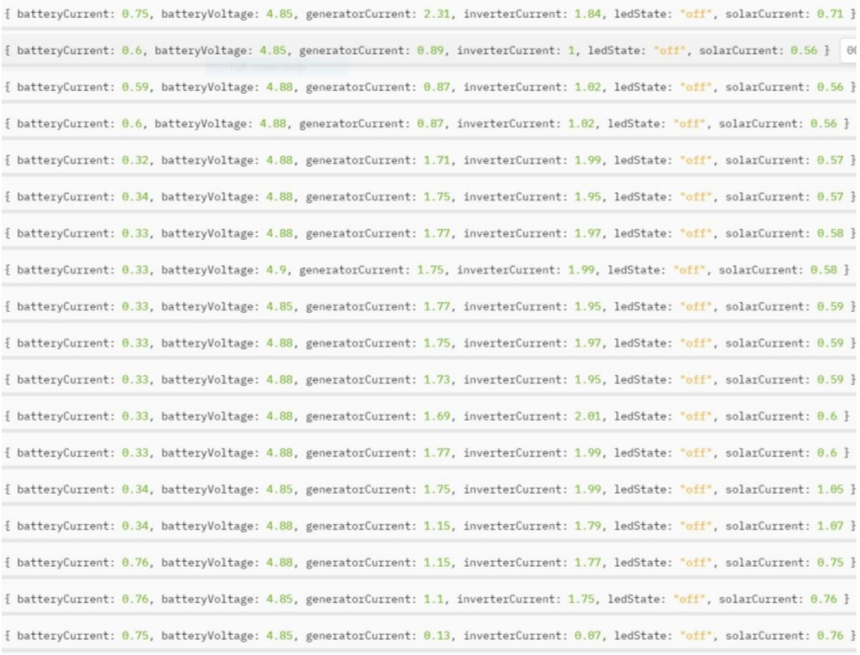


Figure 4.8: Prototype Hardware Setup at Memorial University's Power Lab

TTN allows to set the payload formatting of the received data as per the user's requirement. The payload formatting of the sensors' data received at TTN is set in accordance with the connection of sensors with RTU ADC pins, as defined above in this section, to ensure compliance with RTU serial monitor readings. The raw data of each individual sensor is received at TTN cloud after an average of 40 seconds with its unique name (matching with RTU serial monitor) and can be seen in Figure 4.9. The raw data of sensors is stored at InfluxDB and graphical user interface of each sensor is developed on Grafana to show the historical/live data.



```
{ batteryCurrent: 0.75, batteryVoltage: 4.85, generatorCurrent: 2.31, inverterCurrent: 1.84, ledState: "off", solarCurrent: 0.71 }
{ batteryCurrent: 0.6, batteryVoltage: 4.85, generatorCurrent: 0.89, inverterCurrent: 1, ledState: "off", solarCurrent: 0.56 }
{ batteryCurrent: 0.59, batteryVoltage: 4.88, generatorCurrent: 0.87, inverterCurrent: 1.02, ledState: "off", solarCurrent: 0.56 }
{ batteryCurrent: 0.6, batteryVoltage: 4.88, generatorCurrent: 0.87, inverterCurrent: 1.02, ledState: "off", solarCurrent: 0.56 }
{ batteryCurrent: 0.32, batteryVoltage: 4.88, generatorCurrent: 1.71, inverterCurrent: 1.99, ledState: "off", solarCurrent: 0.57 }
{ batteryCurrent: 0.34, batteryVoltage: 4.88, generatorCurrent: 1.75, inverterCurrent: 1.95, ledState: "off", solarCurrent: 0.57 }
{ batteryCurrent: 0.33, batteryVoltage: 4.88, generatorCurrent: 1.77, inverterCurrent: 1.97, ledState: "off", solarCurrent: 0.58 }
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{ batteryCurrent: 0.33, batteryVoltage: 4.88, generatorCurrent: 1.75, inverterCurrent: 1.97, ledState: "off", solarCurrent: 0.59 }
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{ batteryCurrent: 0.76, batteryVoltage: 4.88, generatorCurrent: 1.15, inverterCurrent: 1.77, ledState: "off", solarCurrent: 0.75 }
{ batteryCurrent: 0.76, batteryVoltage: 4.85, generatorCurrent: 1.1, inverterCurrent: 1.75, ledState: "off", solarCurrent: 0.76 }
{ batteryCurrent: 0.75, batteryVoltage: 4.85, generatorCurrent: 0.13, inverterCurrent: 0.07, ledState: "off", solarCurrent: 0.76 }
```

Figure 4.9: Raw Sensors Data Received at TTN

Figure 10 & 11 shows the current value and data log for three hours (from 14:00-17:00 hours) of solar and battery current on the Grafana dashboard. The solar and battery current sensors are supposed to measure the DC current output of PV modules and battery bank so to resemble the actual power system scenario, the sensors were connected with the DC power supply through the resistance (particulars discussed above). The y-axis shows the magnitude of the measured current whilst the x-axis shows the time range. Since the selected sensor model can measure a maximum of 05A, the maximum range of the y-axis is selected accordingly. The average value of solar and battery current calculated in a three-hour duration was around 0.7A while the peak value was 1.5A. Some sudden changes in current magnitude (increase/decrease) can be seen in the said figures which were intentional and brought in current inputs to have some visible movements in the graph. Further, the temperature of the connected resistances was continuously monitored, and it was observed that at the peak current (1.5A), the resistance was getting heated abnormally therefore, the magnitude of the current was reduced immediately to avoid any damage to the resistors.

The inverter and generator current sensors' readings are also logged for three continuous hours, refer to Figure 12 & 13, respectively. The sensors are connected to the regulated AC power supply (autotransformer, as described above). The average current value recorded during the duration was 2A while the peak current was 3.5A. The rheostat was of higher power rating relatively therefore we had the margin to increase the magnitude of currents comparatively. The magnitude of the current was changed periodically to have visible effects in the graph. The temperature of the rheostats was monitored continuously, and it was observed that at a peak current of 3.5A rheostats get heated abnormally therefore, the current was reduced near to the average value. The battery voltage is measured through the voltage sensor connected in parallel to the DC voltage source and data is logged, refer to Figure 14. The temperature is monitored by the Things Node which senses the environmental temperature and sends data directly to TTN cloud without the involvement of RTU. The historical and current temperature is also shown on Grafana, refer to Figure 4.15.

Figure 4.10: Solar Current

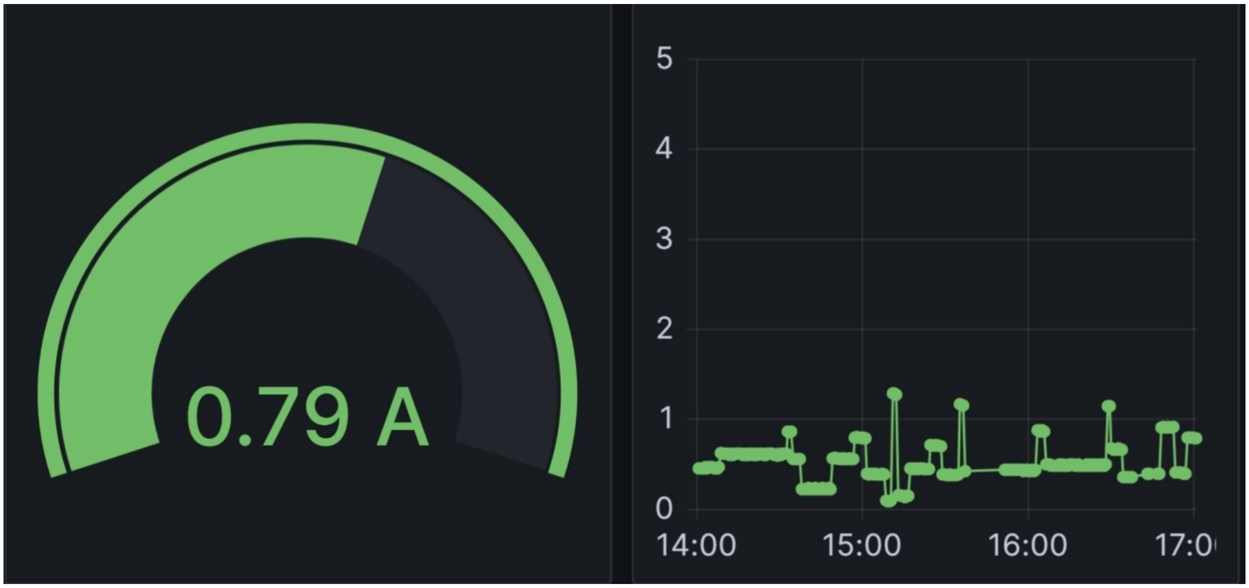

Figure 4.11: Battery Current

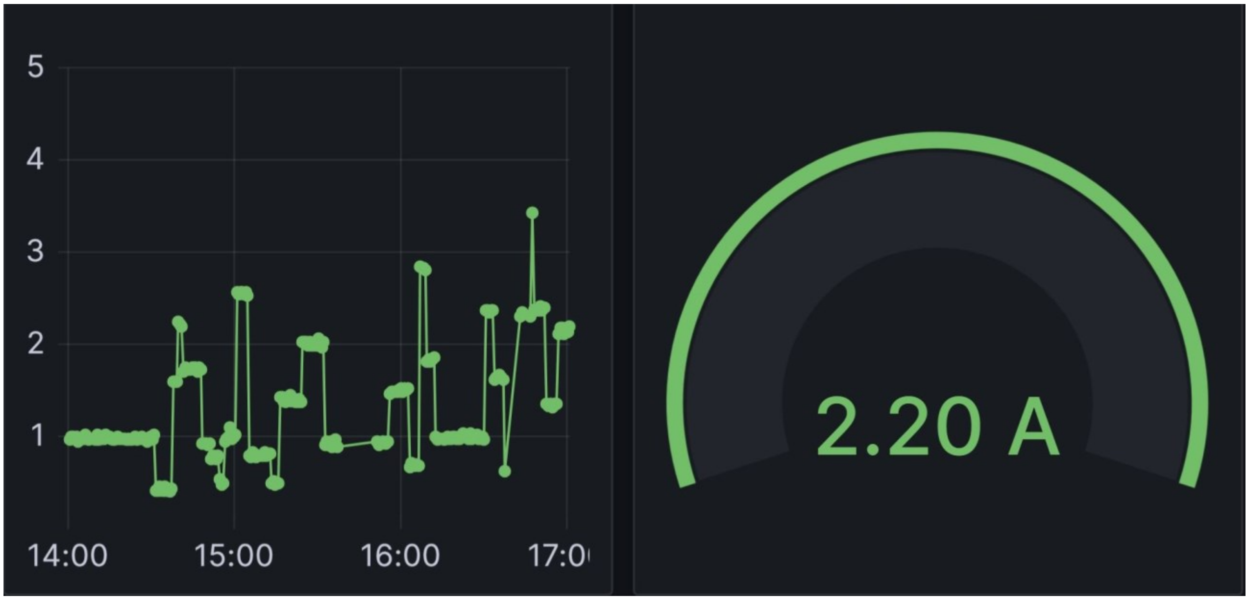

Figure 4.12: Inverter Current

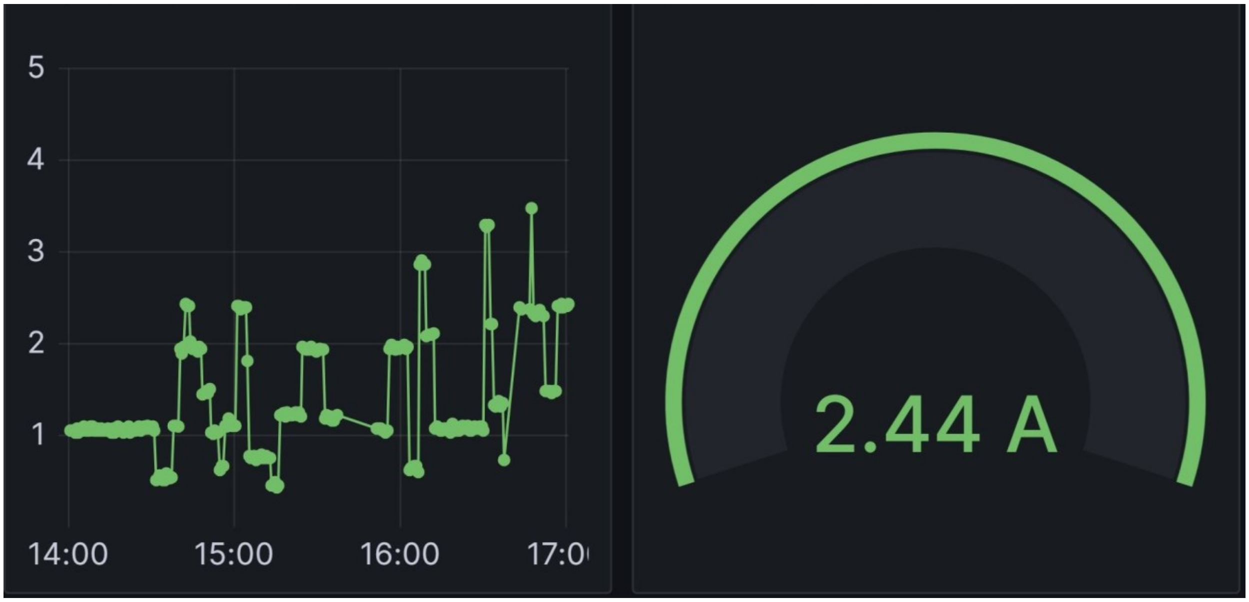

Figure 4.13: Generator Current

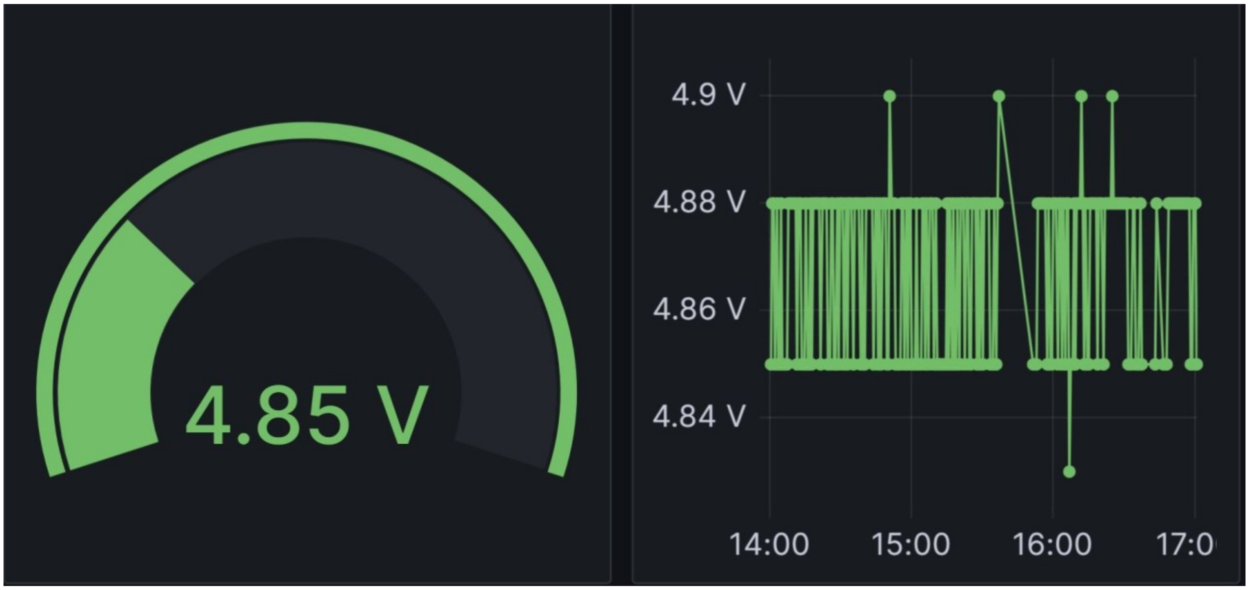

Figure 4.14: Battery Voltage

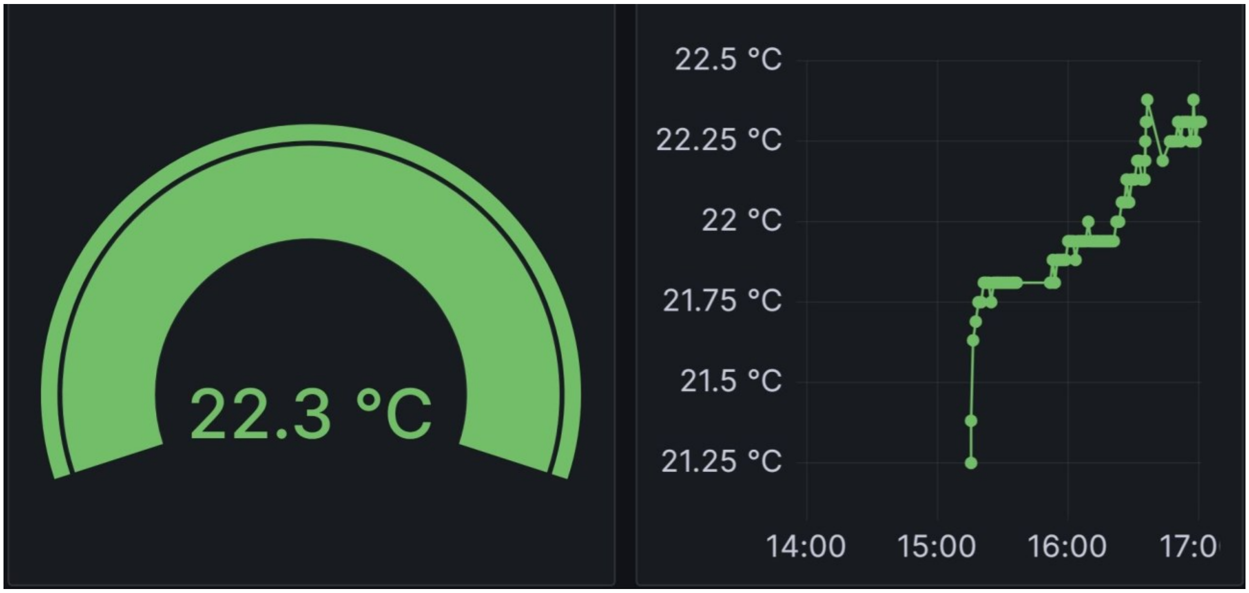

Figure 4.15: Temperature Measurement

4.7 Discussion

The unique offerings and features of the designed system can be summarized as follows.

1. The designed system is capable to collect, transmit, process, storage and display the live/historic data so it is an IoT-based SCADA system.
2. The field sensors take the actual and precise measurements from the respective equipment and transmit it to the RTU, which pushes the raw data to TTN cloud (refer to Fig. 9), using its inbuilt LoRAWAN module. Further, the database of TTN data is created at InfluxDB and Telegraf is configured by entering the MQQT credentials of TTN. AWS account is created to connect it to the elastic compute cloud (EC2) which allows users to run virtual servers. The telegraf is configured with AWS EC2 and Grafana cloud is accessed by using the EC2 IP. Further, the data source is set as “InfluxDB” in Grafana, and under the dashboard the historical and live data of all the sensors can be viewed with multiple options of charts (bar, line, etc.). The guideline for connecting the TTN to InfluxDB and InfluxDB to Grafana can be accessed at [20], [21], respectively.

3. The sensors are measuring and reporting the data to RTU after an average of every 40 seconds which is pushed to Grafana dashboard by following the steps outlined above. The data logging of all the sensors is done for three continuous hours and can be seen in the Figure 9-15.
4. The hybrid power system designed for the offshore aquaculture site to supply the energy needs consists of solar (363kW), battery backup (542.1kWh), inverter (100kVA), and a diesel generator (99kVA). But the scope of this research paper is to develop a prototype for the remote monitoring of the hybrid system therefore a lab test setup is developed to demonstrate and highlight the required combination of hardware and software to achieve remote monitoring. The SCADA system can be designed and implemented for the actual hybrid power system by following the steps mentioned in this research paper.
5. A low magnitude of current is supplied to sensors to ensure the safety of equipment and continuous operation without any damage.
6. Low-cost and open-source components are used to build the SCADA system therefore, small businesses can also get its benefits and monitor the aquaculture sites remotely.
7. We verified that remote monitoring is conveniently possible, the control room away from the project site (up to 10km) will be able to acquire and store the live/historical data. Further, authorized users can view the performance data anywhere in the world on TTN and Grafana.
8. The data can be visualized based on the user’s requirement, the designed and deployed system offers a flexible and wide array of options.
9. The data can be stored for a considerable time and if it is required to increase the storage period, can be done at a competitive cost.

10. The Grafana dashboard is very user-friendly and provides the liberty to adjust the viewing of data according to requirements.

4.8 Conclusion

The aquaculture project sites mostly happen to be in remote areas around the globe whether they are inland (pond/lake-based) or offshore sites. The Canadian aquaculture industry is dominated by offshore project sites where the fish cages are inside the ocean (from 0.5km to 5km from land). The electrical supply from utility and communication infrastructure is very scarce and its approachability always remains a challenge. The development of a low-cost and LoRA-based SCADA system enabling the remote monitoring of an offshore aquaculture site would be a great help to the industry. Aquaculture is a big industry in Canada that has a considerable share in the Canadian economy. The industry is a mix of big and small businesses. Due to the proprietary nature of the SCADA system, it always becomes a hefty cost to deploy it, and maybe big players of the industry can afford it only. The developed system has its unique offering of providing all the requisite features of a SCADA system but at a very low cost than OEM-owned systems. Thus, it will enable the small and big players of the industry to enjoy the benefits of remote monitoring equally.

LoRA-based open-source low-cost SACDA system primarily comprising of filed sensors, RTU (Arduino Leonardo), LoRA gateway, and HMI was developed and tested in the Memorial University's Power lab. The DC current sensors measure the solar and battery current whereas AC current sensors measure the inverter and generator current installed. The variable current and voltage sources are connected to check the behavior of the system. The temperature is measured using the Things Node. The RTU collects the data from all the sensors and successfully transmits it to the TTN cloud. The data storage and its visualization are also performed with the help of open-source platforms. The live and historic data can be visualized at the Grafana dashboard, and the auto-refresh is enabled which helps to see the current and historic data side by side. The data is stored for 30 days and can be accessed in CSV format.

The designed SCADA system is not only compatible with power system monitoring but can be implemented for the remote monitoring of any industry with minor adjustments. However, it is fully capable and shall be a pinnacle transformation to bring sustainability and improve the operational performance in the offshore aquaculture industry.

4.9 References

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Chapter 5: Conclusion and Future Work

5.1 Conclusion

Canada has a leading and progressive aquaculture sector where companies are eagerly finding ways to increase sustainability and expansion in business. The fish are raised in offshore sites where the provision of cost-competitive energy resources becomes a real challenge and companies are bound to rely on expensive and carbon emission-based sources i.e. DGs. A consistent and dependable supply of electricity is essential for offshore fish farming to operate essential equipment such as feed blowers and aerators that are crucial for the growth and maintenance of the fish.

In this thesis, an offshore aquaculture site located in the Atlantic Ocean, Newfoundland, Canada is selected, and the actual energy needs for its day-to-day operations were collected. The said data was given as input to the HomerPro software to design the required renewable energy resource i.e., the PV system. Three scenarios (base, ideal, worst) were developed, by varying the solar resource and average load, to investigate the techno-commercial viability of the designed power system. For the base case, the annual average per day solar resource for the particular project site was 3.00 kWh/m2/day and the annual average per day load was 651.5 kWh/day. The PV system considering the said input calculated by the software was 366kW with a battery bank of 542.1kWh and renewable penetration of 88%. The estimated NPC and LCOE were $1,516,227, and $0.4935, respectively. In the ideal case, the average per day solar resource was increased to 10% (3.30 kWh/m2/day) and the annual average per day load was decreased by 10% (586 kWh/day). A 289kW PV system with a battery backup of 500.4kWh was proposed by the software. The NPC comes out to be $1,278,775 and the LCOE of $0.4624 with a renewable penetration of 78.3%. The worst-case considerations were opposite to the ideal case which yielded the NPC and LCOE $1,764,691, $0.5223, respectively. The calculated photovoltaic (PV) capacity amounted to 461 kW, while the battery bank stored 1000.8 kWh. Further, the cost of electricity produced by the existing source DGs and the base case of the designed system were compared and it was found that the designed hybrid power system can produce the required electricity at a significantly lower cost than the conventionally prevalent setup. This analysis establishes a robust rationale for asserting that floating solar photovoltaic (FSPV) systems can serve as an excellent resource for delivering both cost-effective and environmentally friendly energy to offshore fish farms.

In the next stage, the dynamic performance of the designed hybrid power system was evaluated. The system was modeled in MATLAB/Simulink using the customized and pre-defined block sets. As the PV panels face the continuously changing weather which has a direct effect on the PV modules' performance. The incremental conductance algorithm was implied to maximize the output and performance of the PV system. A buck converter was used to get the stable DC output voltage from PV arrays ($360V_{DC}$) and the inverter converted the DC to three-phase AC power i.e. $208V_{AC}$ (three-phase). The utilization of the SPWM technique in the inverter's switching operation was chosen due to its simplicity and superior control methods. Further, LCL filter was deployed to remove the THD and improve the power quality. The synchronous generator was also modeled along with the speed governor and a robust controller to handle the changes in load and to exhibit the real behavior of a generator. Further, the synchronization of the PV system and generator was achieved using the PLL. The battery backup system designed in HomerPro was also modeled in MATLAB along with its charge controller and it was charged by PV and generator in case of excess power.

The variable load was connected to observe its effects on the performance of sources. The system's designed configuration underwent testing under varying irradiance and temperature conditions to evaluate its dynamic performance.

The simulation results showcased that the designed system effectively responds to a wide range of dynamic variations. The controller employed for the synchronous generator exhibits remarkable resilience in adapting to load variations, effectively handling the mechanical inertia of distributed generation, and collaborating with the phase-locked loop (PLL) to ensure seamless synchronization with the photovoltaic (PV) system. The findings strongly support the exceptional performance of the entire system and further substantiate the ability of the designed PV system to entirely fulfill the energy requirements of the fish farm, thereby reducing reliance on DGs to a minimum.

Finally, a remote monitoring system comprising of open source and low-cost SCADA system is developed to monitor and control the performance of the designed hybrid power system. As discussed, the chosen location for the offshore fish farm is located 2 kilometers from the shore in the sea. This site faces limited availability of electrical supply and communication infrastructure, making it difficult to access. In the Canadian aquaculture sector, there is a combination of both large and small enterprises. Deploying the SCADA system has traditionally been expensive due to its proprietary nature, making it accessible mainly to larger industry players. The newly developed system offers all the essential SCADA features at a significantly lower cost compared to OEM-owned systems. As a result, it levels the playing field, allowing both small and large businesses in the industry to enjoy the advantages of remote monitoring on an equal footing. An open-source, low-cost SCADA system based on LoRA technology was developed and tested in Memorial University's Power lab. This system primarily comprises field sensors, an RTU (Arduino Leonardo), a LoRA gateway, and HMI. The DC current sensors measure solar and battery currents, while AC current sensors monitor inverter and generator currents. Variable current and voltage sources are connected to assess the system's performance. Temperature is measured using the Things Node. The RTU collects data from all sensors and effectively transmits it to the TTN cloud. Data storage and visualization are carried out using open-source platforms. The Grafana dashboard allows for the visualization of live and historical data with auto-refresh functionality, enabling concurrent examination of current and past data. Data is retained for 30 days and can be accessed in CSV format. The results confirmed that remote monitoring is easily achievable, as the control room located up to 10 kilometers away from the project site can efficiently obtain and archive both real-time and historical data. Moreover, authorized users have the capability to access performance data from anywhere in the world through TTN and Grafana.

The thesis presents a comprehensive solution aimed at addressing the complex challenges associated with providing a reliable, cost-effective, and environmentally sustainable power source for offshore aquaculture sites. By focusing on the development and implementation of floating solar photovoltaic (FSPV) systems, the research offers a promising avenue for enhancing the sustainability, profitability, and overall growth of the Canadian aquaculture sector. The affordability and accessibility of energy play a pivotal role in driving the sector's sustainability efforts while also catering to the escalating food demands of a growing population. The adoption of FSPV systems represents a significant advancement with the potential to revolutionize the aquaculture industry. By leveraging renewable energy sources, such as solar power, fish farms can significantly reduce their environmental footprint while simultaneously contributing to broader sustainability goals. Moreover, the low-maintenance nature of FSPV systems ensures their suitability for long-term use, providing a reliable energy source for aquaculture operations over extended periods. In summary, the research underscores the critical importance of sustainable energy solutions in fostering the resilience and growth of the aquaculture sector. By embracing innovative technologies like FSPV systems, fish farms can not only mitigate their environmental impact but also contribute to the overall sustainability agenda thus positioning themselves as key players in the drive towards a more sustainable future.

5.2 Research Contributions

- Assesment of the daily energy requirement of an offshore aqualcuture site in Newfoundland, Canada.
- Sizing/designing of the FSPV system to lower the reliance on fossil fuel sources to minimum, selection of the reliable and compatible componets of the system.
- Develop the economic analysis of the designed FSPV system with the existing power system infrastructure.
- Determine the dynamic response of the designed system and tested under different varying conditions to ensure the system stability in real life.
- Designed a low cost and open-source LoRA based SCADA system for remote monitoring of the designed hybrid power system.

5.3 Future Work

There is no doubt to establish that the FSPV systems have great and convincing potential to fulfill the rising energy requirements of the world. FSPV systems can be installed over water bodies i.e. ocean, lake, pond etc. The reliable buoying mechanism development to hold and ensure the safety of equipment against the tides is crucial thing. The Development of secure anchoring and mooring systems to prevent drifting or dislocation of the floating platform during storms or adverse weather conditions is an important task that needs to be focused in the future. Further, on the front of remote monitoring systems, the advancement to ensure data privacy and advanced data analytics using machine learning techniques could be further explored. Strategies and appropriate systems should be developed to protect the system from cyber threats and ensure the confidentiality and integrity of data. The data analytic techniques shall help to detect anomalies and bring performance optimizations. The following could be the next steps for this research

- A full feasibility study of the FSPV system that include detailed installation cost, mooring cost, cabling cost, fuel shipment cost etc.
- Impact of ocean waves on FSPV system needs be investigated.
- Impact of snow load on FSPV system needs to be studied.
- More sensors such as each PV and battery string current sensor should be added.
- FSPV motion sensors could be added.
- LoRA private data server without using The Things Network could be added.

Above mentioned steps shall be necessary and pave the way to installation of the proposed FSPV system at offshore aquaculture site.

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Articles in Conference Publications

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