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

Muhammad Nadeem Asgher
Department of Electrical Engineering
Memorial University of Newfoundland
St. John's, NL, Canada
mnasgher@mun.ca

Mohammad Tariq Iqbal
Department of Electrical Engineering
Memorial University of Newfoundland
St. John's, NL, Canada
tariq@mun.ca

***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

I. 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.

II. 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].

This paper is presented in 32nd Annual Newfoundland Electrical and Computer Engineering Conference (NECEC-2023) IEEE

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.

III. MATHEMATICAL MODELING OF A HYBRID SYSTEM

A. 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 Fig. 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 Fig. 2. Canadian Solar-made CS6U-340M PV panels are selected, please refer to Table 1 for a list of key specifications/details of the system.

Fig. 1. Project Site (Offshore Fish Farm)

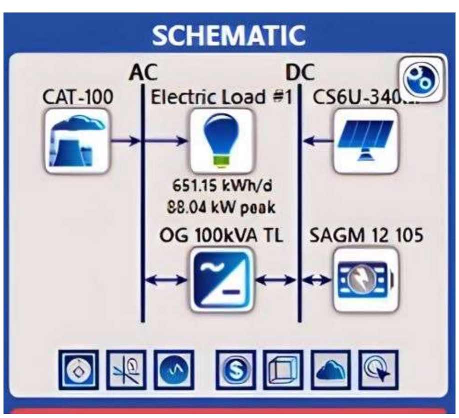

Fig. 2: Schematic of the Designed System

Table 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

B. 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 Fig. 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.

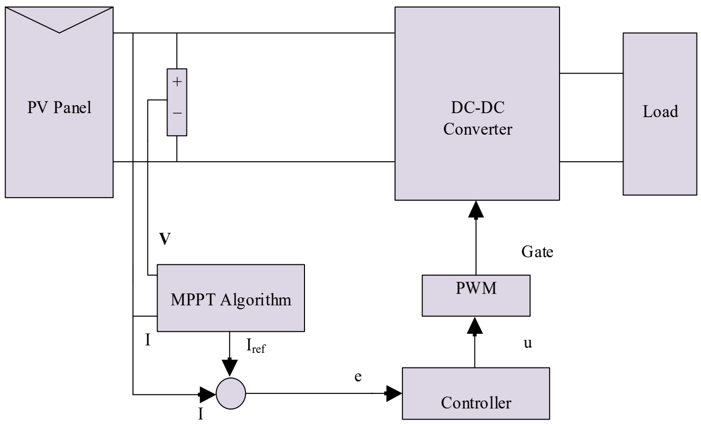

Fig. 3. PV system along with MPPT Controller

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

$$\frac{\Delta P}{\Delta V} = \frac{\Delta(VI)}{\Delta V} = I\frac{\Delta V}{\Delta V} + V\frac{\Delta I}{\Delta V} = I + V\frac{\Delta I}{\Delta V} \tag{3}$$

$$\frac{1}{V} \times \frac{\Delta P}{\Delta V} = \frac{I}{V} + \frac{\Delta I}{\Delta V} \tag{4}$$

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.

$$\frac{\Delta I}{\Delta V} = \frac{1}{V} \; at\ the\ MPP \tag{5}$$

$$\frac{\Delta I}{\Delta V} \geq \frac{1}{V} \; Left\ Side\ of\ the\ MPP \tag{6}$$

$$\frac{\Delta I}{\Delta V} \leq \frac{1}{V} \; Right\ Side\ of\ the\ MPP \tag{7}$$

The complete system consists of PV system, MPPT controller, inverter, battery bank, synchronous generator, and variable load is modeled in MATLAB/Simulink, refer to Fig. 4. Some of the key parts of the modeled system are explained below.

C. 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

$$V_0 = D.V_i \tag{8}$$

$$L = \frac{V_0 \times (V_i - V_0)}{\Delta I_L \times f_s \times V_i} \tag{9}$$

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.

$$C = \frac{\Delta I_L}{8 \times f_s \times \Delta V_o} \tag{10}$$

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

D. 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].

E. 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.

$$L_i = \frac{U_{dc}}{16 \times f_s \times \Delta I_L} \tag{11}$$

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.

$$\Delta I = \frac{0.1 \times Pn \times \sqrt{2}}{V} \tag{12}$$

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

$$L_g = 0.6 \times L_i \tag{13}$$

$$C_f = \frac{Pn}{\omega_g \times V_{Ph-g}} \tag{14}$$

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

IV. MODELING OF COMPLTE 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 Fig. 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.

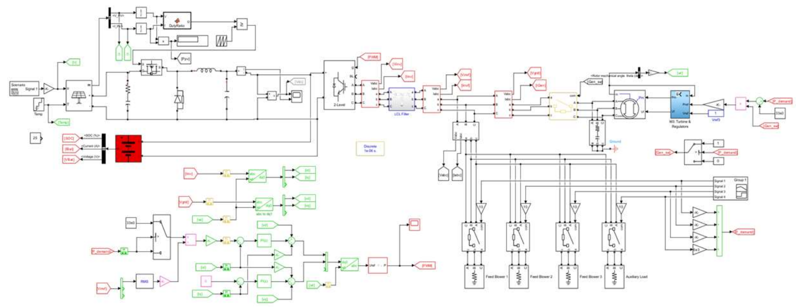

Fig. 4. Complete System Modelled in MATLAB/Simulink

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 Fig 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 Fig. 6.

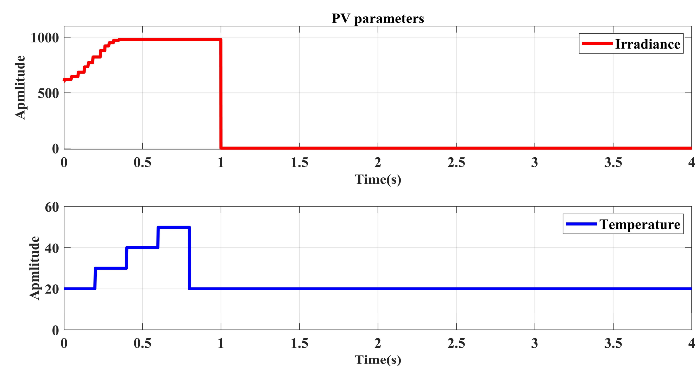

Fig. 5. Variable Irradiance and Temperature

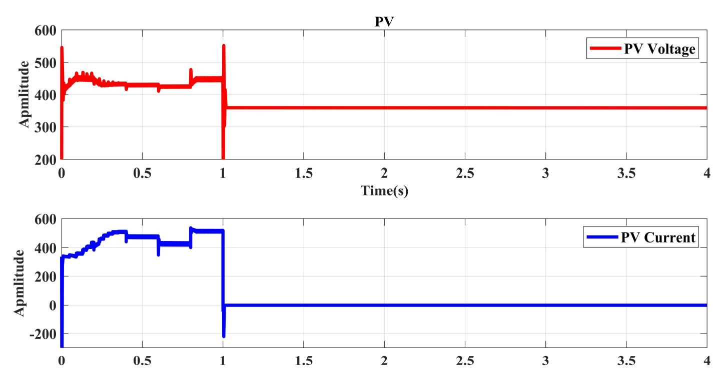

Fig. 6. PV Voltage and Current due to inputs shown in Fig. 5

This paper is presented in 32nd Annual Newfoundland Electrical and Computer Engineering Conference (NECEC-2023) IEEE

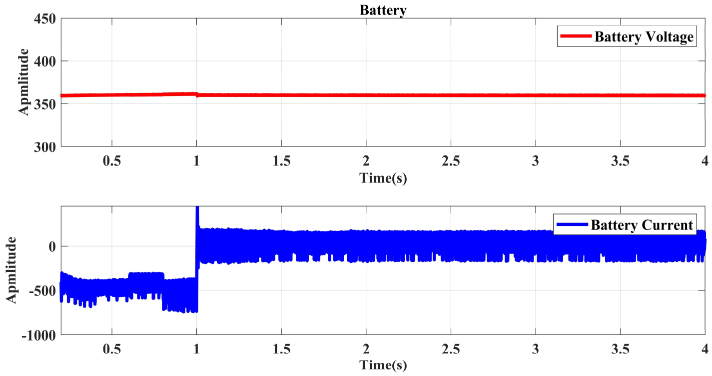

Fig. 7. Battery Charging and Discharging

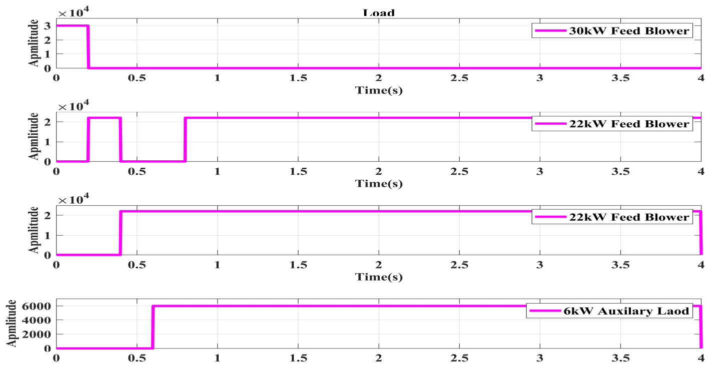

Fig. 8. Variable Load (Load Switching)

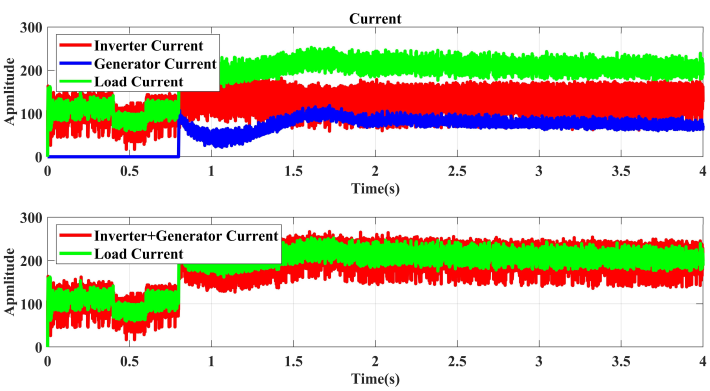

Fig. 9. PV, Generator and Load Current

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 Fig. 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%.

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 Fig. 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 Fig 9. The load demand is primarily fulfilled by PV (inverter current).

V. 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.

REFERENCES

[1] Menicou, M., & Vassiliou, V. (2010). Prospective energy needs in Mediterranean offshore aquaculture: Renewable and sustainable energy solutions. Renewable and Sustainable Energy Reviews, 14(9), 3084–3091. https://doi.org/10.1016/j.rser.2010.06.013

[2] Al-Saidi, M.; Lahham, N. Solar energy farming as a development innovation for vulnerable water basins. Dev. Pract. 2019, 29,619–634

[3] Bayrak G, LebeliM(2011) A PV based automation system for fish farms: an application study. *In 2011 7th International conference on electrical and electronics engineering (ELECO). IEEE*

[4] Fourie CM et al (2017) A solar-powered fish pond management system for fish farming conservation. *In 2017 IEEE 26th International symposium on industrial electronics (ISIE). IEEE*

[5] Choi Young-Kwan. A study on power generation analysis of floating PV system considering environmental impact. 2014;8(1):75–84.

[6] Asgher, M.N., Iqbal, M.T. (2023). Design and Simulate a Floating Solar Photovoltaic System for an Offshore Aquaculture Site in Canada. *Jordan Journal of Electrical Engineering*

[7] H. B. Massawe, "Grid Connected Photovoltaic Systems with SmartGrid functionality," M.S. Thesis, Dept.ElKraft, NTNU, Trondheim, Norway, 2013

[8] Sahoo, Sarat Kumar, A. Ramulu, Saachi Batta, and Shweta Duggal."Performance analysis and simulation of three phase voltage source inverter using basic PWM techniques." *In International Conference on Sustainable Energy and Intelligent System. SEISCON 2012, IET 2012, pp.257-263.*

This paper is presented in 32nd Annual Newfoundland Electrical and Computer Engineering Conference (NECEC-2023) IEEE