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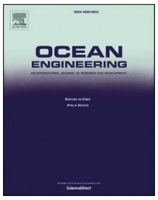

Conceptual design of a novel partially floating photovoltaic integrated with smart energy storage and management system for Egyptian North Lakes

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ABSTRACT

With the recent increase in energy demand due to social, development and economic reasons in Egypt, solar energy is one of the most abundant renewable energy resources which can be utilized to meet these needs. Although Photovoltaic (PV) technology has been used with large scale in Egypt in different applications, it's still suffering from losing its efficiency due to high temperature, dust accumulation which is common in Egypt especially in spring and summer seasons, besides the intense land requirements and power intermittency. Therefore, a novel partially floating modular PV system is proposed in this study to supply rural areas around the Egyptian North Lakes with green electricity. The PV system is integrated with a hybrid compressed air energy storage system and managed with a smart energy management strategy to extend its operating hours and enables its day and night continuous operation. The smart system also enables different operational modes of the PV system which includes sun tracking, cleaning, cooling, and surviving modes. The aim of this study is to introduce the conceptual design of the proposed concept and the smart controlling system, its different operational modes, the supporting platform and its hydrodynamics performance.

1. Introduction

The provision of an affordable, reliable, and sustainable energy supply, which is one of the UN Sustainable Development Goals, has generated significant recent research interest (Resolution, 2015). This concern is enhanced by the growing global energy demand and the environmental degradation associated with the relying on fossil fuels which provides over 80% of the global energy mix (Ahmad and Zhang, 2020). The continuously increasing energy demand is due to the population growth and urbanization accompanied with the economic development and industrialization. Therefore, a transition towards sustainable and renewable energy systems is essential to achieve energy security while preserving the environment.

For sustainable development, Egypt has developed a new strategy, *Egypt's Vision 2030*, which aims to meet the national sustainable development requirements by improving the energy efficiency and increasing the renewable energy share in the national energy mix (El-Megharbel, 2015). However, in spite of the increased utilization of renewable energy, its share in energy consumption is declining as a result of the growing national energy demand (Bank, 2021; Mondal et al., 2019). Thus, more efforts are required to meet renewable energy targets towards a more sustainable and less carbon-intensive energy system.

The offshore marine renewable sources have been extensively studied for different energy applications in Egypt. Several review studies on powering the seawater desalination applications by offshore wind power, hydrogen and solar marine renewable energy have been performed (Amin et al., 2020b, 2021b; Eshra and Amin, 2020; Amin et al., 2022a,b; Bayoumi et al., 2021). Among available renewable energy resources, Egypt has excellent solar energy potential with a radiation intensity of 2000–3200 kWh/m^2/*year* and an average theoretical potential of global horizontal irradiation of 6259 kWh/m^2 (IRENA, 2018;

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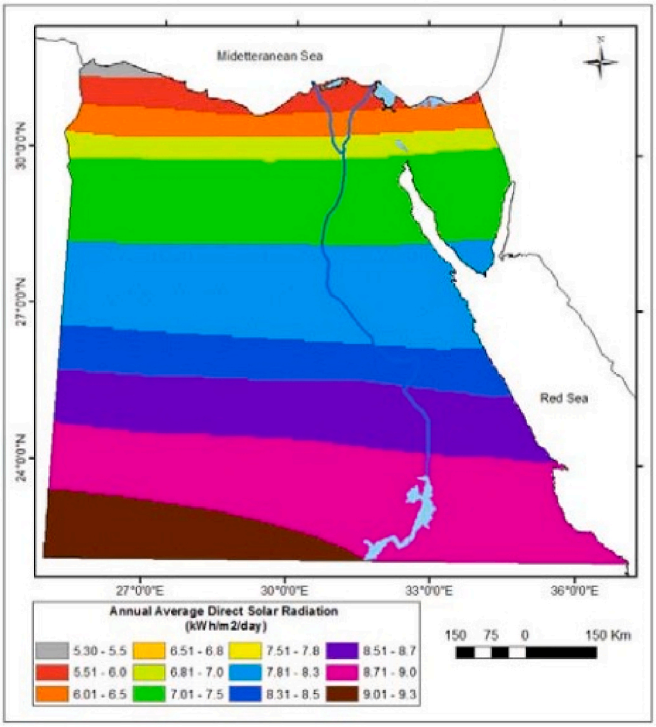

Fig. 1. Solar radiation intensity from the Atlas of Egypt (Amin et al., 2020a).

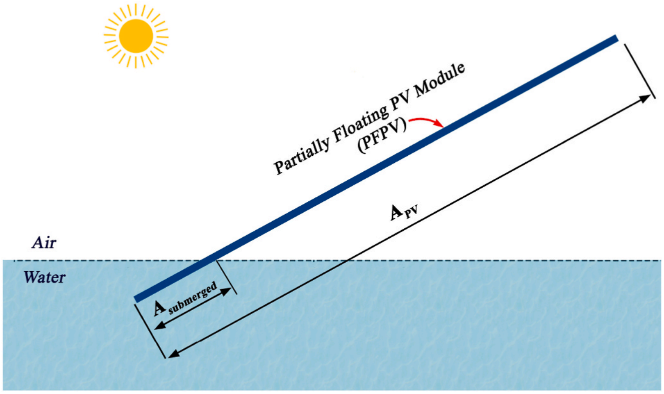

Fig. 2. Schematic diagram of the novel PFPV concept.

ESMAP, 2020). Egypt's solar atlas also shows that the solar radiation potential is well distributed across the whole country as shown in Fig. 1. Accordingly, Egypt is one of the most suitable regions for utilizing solar energy for electricity generation through photovoltaic (PV) technology which is the most commonly used solar energy application (Sahu et al., 2016). This is due to the fact that PV systems are modular, sustainable, reliable, have long life, have no moving parts and are eco-friendly since they convert sunlight into electricity directly without burning fuel or emissions and noise (Dwivedi et al., 2020; Sahu et al., 2016). However, the intermittency and fluctuation of solar energy supply, PV large land area requirements and low overall performance because of heat and reflection are still challenges that need to be effectively solved.

Various solutions have been investigated to overcome the challenges of improving the performance of PV systems and its intense space requirements. One of the promising technologies of PV systems is Floating Photovoltaic (FPV) system which refers to a PV system that mounted on top of floating structures such as rafts or pontoons assembly positioned in enclosed water bodies such as rivers, ponds, or small lakes (Sahu et al., 2016). As water bodies are located away from tall buildings, structures, and vegetation, the received sunlight by the PV panels is thus maximized. Also, FPV systems have higher efficiency and longer lifetime than land-based PV systems, due to the cooling effect of water underneath the PV panels, while having a comparable cost to that of land based plants (Cazzaniga and Rosa-Clot, 2021). Moreover, FPV systems reduce the pressure on land resources, which are limited and expensive, by exploiting the available water bodies which also reduces the water evaporation (Ranjbaran et al., 2019; Dwivedi et al., 2020; Exley et al., 2021). For example, the potentials of FPV system for power generation and water evaporation reduction were investigated by covering 5%, 10%, 15%, and 20% of four different lakes in (Mittal et al., 2017). Also, FPV systems operate in a less dusty environment which improves its operational efficiency and cleaning. Compared to conventional land-based PV system, an average efficiency improvement of 12.5% was obtained through FPV as demonstrated in (do Sacramento et al., 2015). Equipping the FPV plant with a tracking system can also increase its energy production by 15%–25% with an acceptable extra cost (Cazzaniga and Rosa-Clot, 2021).

Water beneath the FPV plant can be used to further cool the PV modules by generating a water veil on the PV panel surface using a low pressure pumping system which can achieve a net efficiency gain of 8–9% as studied in (Krauter, 2004). Also, high pressure water pumping systems can be used in a sprinkler cooling system as studied experimentally in (Nižetić et al., 2016) that achieved about 6% effective increase in the PV panel electrical efficiency. The PV electrical efficiency improvement can also reach 15% by water spray cooling in extreme weather conditions as reported in (Dwivedi et al., 2020). Meanwhile, spraying water on both sides of the PV modules can result in an electrical efficiency increase of up to 16.3% (Nižetić et al., 2016). Furthermore, the water spray flow rate and angle have been investigated experimentally to study their effect on the PV performance in (Nateqi et al., 2021) which shows that a maximum increase of about 26% of the PV panel electrical efficiency can be obtained compared to non-cooled PV panels. To further cool the PV panels, submerged PV systems have been introduced as well which can achieve about 20% more efficiency in summer than conventional exposed to air PV systems (Sahu et al., 2016). Several experimental studies have been conducted to evaluate the performance of submerged PV modules which can be smoothly integrated with existing structures such as pools and fountains (Clot et al., 2017).

In this study, a new concept of Partially Floating Photovoltaic (PFPV) plant is implemented to generate electricity and overcome the energy efficiency and security issues in rural areas around the Egyptian North Lakes. In a PFPV plant, a continuous direct contact between the PV modules and the water body is made to offer an efficient and costless cooling and maintain a permanent thermal equilibrium of the PFPV system with the water body as shown in Fig. 2 (Elminshawy et al., 2021, 2022). The potential of deploying the novel PFPV concept to cool the PV panels and enhance its performance can be further improved by altering the ratio of the submerged area of the PV module ($A_{submerged}$) to the total surface area (A_{PV}) and the PV tilt angle which needs to be investigated. The novel PFPV system is also equipped with a network of extended fins embedded in the local water to make the best use of the surrounding environment for further cooling. This method has the advantage of regulating the temperature of the PFPV system through direct contact with the water which offers a continuous heat transfer between the PFPV submerged portion and the local water and consequently increases its electric output and efficiency.

Regarding the solar power intermittent supply, Energy Storage Systems (ESS) have the potential for addressing this issue. By incorporating an ESS to a PV plant, excess energy at low demand periods can be stored and discharged during peak load demand which improves the plant efficiency, reliability, stability, and increases its penetration rate (Rahman et al., 2020). Energy storage includes many technologies with different scales where PV electricity can be stored in different forms such as chemical, electrical, thermal or kinetic media. Among the available energy storage technologies, electrochemical energy storage is the main technology for PV systems such as batteries due to their efficiency, maturity, and the continuous reduction of their costs (Bullich-Massagué et al., 2020; Ranjbaran et al., 2019; Cazzaniga et al., 2017). However, batteries are not suitable for large scale applications with their limited lifetime and the hazardous wastes that requires recycling (Rahman et al., 2020; Cazzaniga et al., 2017). Therefore, other energy storage technologies such as hydrogen energy storage using an electrolyzer has been studied for a FPV plant in (Temiz and Javani, 2020). Furthermore, mechanical Pumped Hydro Storage (PHS) system (Al-Masri et al., 2020) or hybridizing the FPV with a hydropower plant (Lee et al., 2020) have been considered but both methods are geographically restrictive and have high capital cost (Bullich-Massagué et al., 2020). In order to overcome the PHS geographical limitations, a novel hydro-pneumatic energy storage system for a FPV plant has been experimentally investigated at small scale in (Buhagiar et al., 2019) where pumped water are used to compress air. Mechanical energy storage also includes Compressed Air Energy Storage (CAES) system which has been investigated for FPV plant in (Cazzaniga et al., 2017) due to its lower environmental impacts and higher total amount of stored energy over its lifetime compared to batteries. Moreover, CAES systems have high reliability and durability with long lifetime and size flexibility which makes them one of the most promising solutions for FPV plants (Cazzaniga et al., 2018). However, the managing of the system thermal balance is the main challenge with CAES systems. Therefore, a CAES system hybridized with a Thermal Energy Storage (TES) is selected for the electrical energy storage of the proposed PFPV in this study.

The presence of a PV generation system and the energy storage system besides the required load and the national grid, in case of a grid connected PV application, requires a smart Energy Management Strategy (EMS) to improve the electrical integration of the system and match the electricity generation with demand which further increases the overall system efficiency. Therefore, the development of a suitable EMS is a basic issue for these systems. Several EMS have been reported in the literature for hybrid renewable energy systems with different objectives but the main objective is still satisfying the load requirements (Tamalouzt et al., 2016; Dahbi et al., 2018). Other EMS objectives include reducing and preventing deep discharge of the ESS (Tamalouzt et al., 2016; Guentri et al., 2021), extending the ESS lifetime (Boukettaya and Krichen, 2014; Olatomiwa et al., 2016), controlling the grid voltage (Naik et al., 2021; Guentri et al., 2021), avoiding excess PV power dump (Bonkile and Ramadesigan, 2019), reducing energy cost and emissions (Boukettaya and Krichen, 2014), and enhancing the system overall efficiency and reliability (Guentri et al., 2021; Olatomiwa et al., 2016). For the proposed hybrid PFPV plant in this article, an efficient EMS is developed that takes into consideration the operational limits of the system components while controlling the energy flow in order to maintain the system efficiency and increase the lifetime of the energy system components.

From the previous literature survey, it has been found that most researchers' works were concerned with land-based PV systems which have been integrated with various cooling techniques whether active or passive. Some of these studies were experimental in actual outdoor conditions and others were theoretical research aided with the help of computational programming simulation for optimal performance. However, by a deep insight into these systems, the percentage improvement in the performance of the enhanced PV system does not compensate for the economic value of the huge flatted smooth land area for large scale PV installation. Lately, the trend of the floating PV systems predominates the land installed ones globally with its cooling effect and evaporation reduction potentials. Accordingly, it is clear that the FPV systems have gained more attention in the last decade. However, little work about FPV systems has been reported in the Middle East region which is known for high steady solar radiation and clear sky, especially in Egypt. Moreover, the majority of FPV studies rarely focus on using cooling to enhance the performance of the FPV system. Finally, rare experiments have been reported concerning the effect of the tilting angle on the optimal performance of the floating PV system, so the authors attempt to cover the gap. The aim of this paper is to introduce the design of a prototype model for the field-testing of the novel PFPV concept integrated with a smart energy storage and management systems. The paper is organized as follow; Section 2 introduces the selected site for installing the proposed PFPV system. Section 3 describes the proposed prototype, its main subsystems, its different operational modes, and the hydrodynamic performance of the developed concept is also presented. Finally, Section 4 presents the work conclusions.

Fig. 3. Egyptian northern delta lakes (Balah, 2012).

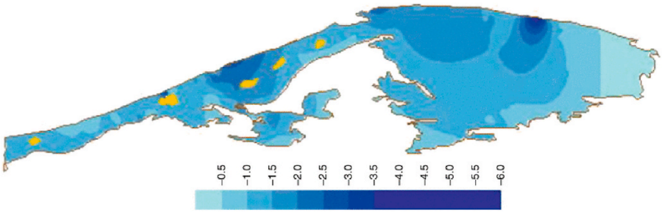

Fig. 4. The bathymetric map of Bardawil Lagoon (Balah, 2012).

2. Site selection

Egypt has 1150 km of coastline along the Mediterranean Sea (Amin et al., 2021a). For the sake of improving the energy security and welfare in rural areas around the Egyptian north lakes, a novel PFPV concept equipped with a smart energy storage and energy management systems is proposed. The Egyptian northern coast on the Mediterranean Sea has five lakes which are, from east to west, Bardawil, Manzala, Burullus, Idku, and Maryut as shown in Fig. 3. Due to its depth potential and strategic location, Bardawil lake is the most favorable region for the installation of the proposed PFPV plant.

Bardawil lake is situated at the southeastern Mediterranean coast in the north of Sinai Peninsula and it is part of the Egyptian government strategy of Sinai development as well as the Egyptian lakes development national project. This includes many investments such as tourism development and agriculture reclamation projects (Balah, 2012). Moreover, Bardawil lake has an irregular bottom topography as shown in Fig. 4 with a water depth varies between 0.3m and 6.5m. The PFPV plant will be located near to the lake inlet at the extreme eastern region with the highest water depth.

Regarding the lake climate conditions, air temperature ranges from $13.7^{\circ}C$ to $27^{\circ}C$ while the mean wind speed is in the range of 4.5–6.3 m/s throughout the year mostly from the north direction. Also, water temperature varies between $13.9^{\circ}C$ and $24.6^{\circ}C$ and relative humidity ranges between 48.5% and 57.1% (Balah, 2012). The developed PFPV plant will be equipped with different measuring devices for collecting climate data as well as operational data.

Table 1
Principal particulars of the selected PV module.

Parameter	Value
Panel type	Polycrystalline
Maximum power	325 *W*
Open-circuit voltage	45.8–46.2 *V*
Short circuit current	9–10 *A*
Efficiency	16–17%

Table 2
Principal particulars of the pilot-scale PFPV floating platform.

Parameter	Value
Length	8.6 *m*
Breadth	8.6 *m*
Depth	1.3 *m*
Draft	0.6–0.92 *m*
Weight	7 *tons*

Table 3
Floater operational loads cases.

Draft **(m)**	Displacement **(tons)**	Required ballast **capacity (Liter)**	Intact/ damaged	PV panels **condition**
0.60	8.186	0	Lightship condition	Lightship condition
0.70	9.547	1324	Dry operation mode	
0.75	10.23	1986	Dry operation mode	
0.81	11.04	2780	Dry operation mode	Touching PV Panels (approx.)
0.90	12.26	3972	Cooling mode	
0.96	13.07	4766	Cooling mode	partially submerged PV (10+ cm approx.)
1.00	13.61	5296	Cooling mode	partially submerged PV (15+ cm approx.)
1.05	14.29	5958	Cooling mode	partially submerged PV (20+ cm approx.)
1.10	14.96	6620	Cleaning mode (Max draft)	partially submerged PV (25+ cm approx.) or fully submerged by closing tilling angle to zero
1.15	15.63		Survival mode	partially submerged PV (30+ cm approx.)
1.20	16.29		Survival mode	partially submerged PV (35+ cm approx.)
1.25	16.96		Survival mode	partially submerged PV (40+ cm approx.)
1.30	17.73		Damaged condition	Max PV submergence (45+ cm approx.)

3. The proposed system

The design of a pilot-scale station is introduced in this work to be constructed and tested as a prototype model of the proposed PFPV concept. A field-testing of the novel concept is then performed in a water basin built at the Port Said Faculty of Engineering's campus in Egypt to measure its performance and quantify the surrounding meteorological conditions effects on the PV system. The performance of the integrated smart energy storage and management systems will be also investigated experimentally. Next, the main components of the developed prototype will be briefly described.

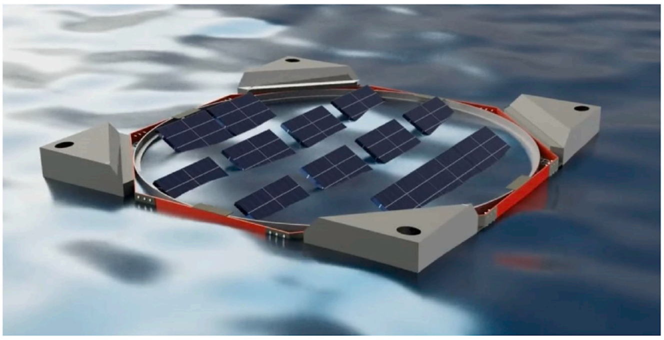

Fig. 5. Proposed partially submerged photovoltaic system.

3.1. Photovoltaic solar system

The PFPV plant built for this study consists of 13 solar panels of 4 rows with a sufficient distance between these rows to eliminate the shading effect of one row to its adjacent panels. Polycrystalline PV modules were chosen and its main specifications under standard conditions are shown in Table 1. As explained earlier, the PV panels will be partially submerged in the water body for costless and continuous cooling and cleaning of the PV cells which accordingly improves its performance. In this project, the PV modules submergence ratio is controlled by ballasting and de-ballasting the floating platform to achieve the desired trim. Experimental investigation of different submergence ratios is planned to be carried out to trace its effect on the PV performance.

To further enhance the PV power production, the PV panels are surrounded by a circular confining structure capable of rotating the PV panels to track the Sun between sunrise and sunset as shown in Fig. 5. For less complex and expensive system, a single-axis solar tracking system with the tilted PV panels is used to move the PV panels on a trajectory relative to the position of the Sun and it is driven from the control unit. Moreover, the PV tilt angle, which is the vertical angle between the PV module and horizontal level, can significantly affect the PV performance. Therefore, different values of PV tilt angles are also experimentally investigated to find the optimum tilt angle corresponding to the novel PFPV system with the respect to various submerged area ratio examined.

The performance of the proposed PFPV concept and the efficiency enhancement can be evaluated as a function of its electrical power output P_{PFPV} and electrical efficiency η_{PFPV} as follows;

$$P_{PFPV} = V_{max} \times I_{max} \tag{1}$$

$$\eta_{PFPV} = \frac{P_{PFPV}}{G \times A_s} \tag{2}$$

where $V_{\max}$ and $I_{\max}$ are the maximum voltage and current of the PV modules, A_s is the module surface area, and G is the solar radiation intensity. The PFPV performance is then compared to the land-based PV module power P_{LPV} and efficiency η_{LPV} to calculate the percentage of power and efficiency enhancement P_{enh} and η_{enh} respectively as follows;

$$P_{enh} = \frac{P_{PFPV} - P_{LPV}}{P_{LPV}} \times 100\% \tag{3}$$

$$\eta_{enh} = \frac{\eta_{PFPV} - \eta_{LPV}}{\eta_{LPV}} \times 100\% \tag{4}$$

Another parameter that can be used for evaluating the PFPV concept is the normalized power output efficiency η_P (Bashir et al., 2014) calculated as follows as a function of the standard test condition power P_{STC} which is read from the nameplate of the module.

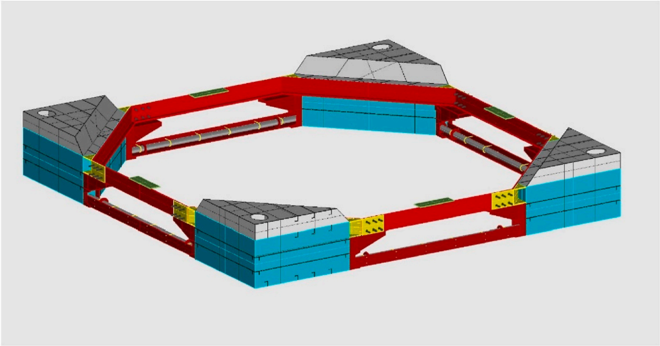

Fig. 6. Assembly and construction of the pilot-scale PFPV floating platform.

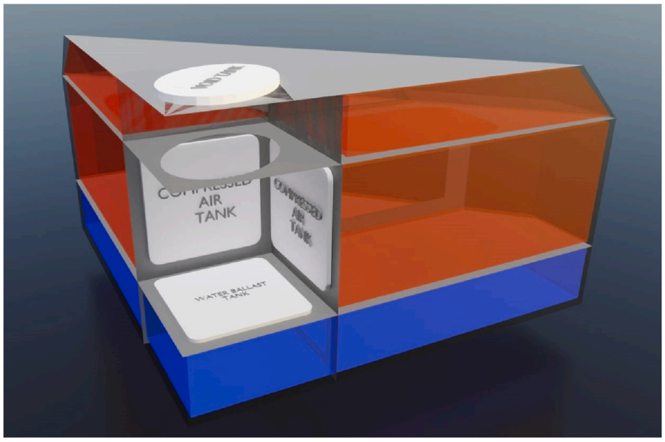

Fig. 7. Corner tank configuration of the pilot-scale PFPV floating platform.

$$\eta_P = \frac{P_{PFPV}}{P_{STC}} \times 100\% \tag{5}$$

3.2. *Floating platform*

A floating platform is designed to support the whole PFPV plant components by its buoyancy and stability features. Therefore, due to its large capacity, stability, and relocatability, a semisubmersible platform type is chosen for this project. Semisubmersibles are also not limited to a specific water depth range and can be easily integrated for quayside operation. Moreover, a variety of mooring lines layouts and patterns can be used with semisubmersibles which depends on the location and the platform characteristics.

As illustrated in Fig. 6, the PFPV plant platform has a square layout due to its suitability for the PV tracking system with the main particulars shown in Table 2. These dimensions are suitable for the built water basin. The platform consists mainly of 4 corner tanks with sufficient capacity for buoyancy, stability, and ballasting according to the required operational parameters. By filling the platform corner tanks with water, a submergence of up to 32 cm can be made to partially submerge the PV panels and study the water cooling effect on the PV performance. Also, a piping system is equipped in the platform to connect the four corner pontoons together to maintain the same water level inside which prevents the platform to heel or trim. Part of the space available in these corner tanks will be used for compressed air storage as shown in Fig. 7.

Ring Z frames are used to stiffen the platform and support the PV panels weight and the walkway modules for operation and maintenance. An octagon supporter web frame is also used to connect the 4 corner tanks and hold the rotating ring frame. A conventional mooring system of four lines at the platform corners is selected to keep the floating platform in position which is found suitable for the testing site conditions.

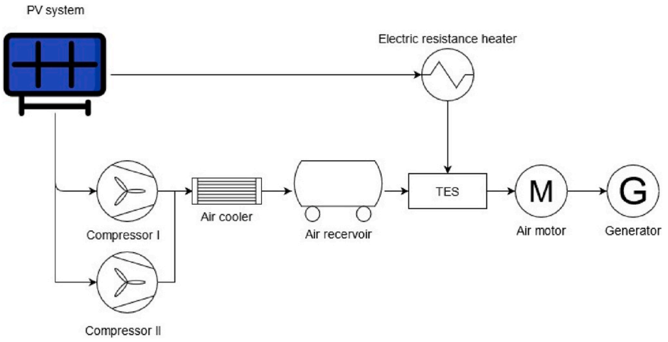

Fig. 8. Proposed hybrid energy storage system.

3.3. *Energy storage system*

Due to its high power and energy capacity, economic feasibility, reliability, durability, and flexibility, compressed air energy storage (CAES) systems have been proposed for energy storage in grid and standalone renewable solar energy applications. In CAES systems, extra and off-peak generated electricity is used to compress air and store it for later use during peak demands or when the renewable energy is not available or insufficient. During energy discharge, the compressed air is heated before expanding in a turbine or motor to generate electricity. In conventional CAES, heat is added to the compressed air by burning conventional fuels such as natural gas in a combustion chamber which affects the system efficiency and its environmental performance. Therefore, in order to eliminate the system emissions, fuel dependence, and increase its efficiency, the conventional CAES system can be hybridized with a thermal energy storage (TES) system to provide the compressed air with the required expansion heat as proposed in (Lemofouet-Gatsi, 2006).

The proposed hybrid ESS in this project consists of two main subsystem; a CAES system integrated with a TES system. As illustrated in Fig. 8, the CAES system is composed of two independent variable speed air compressors to charge air in a conventional air receiver using the surplus energy from the PV plant. By using multiple small air compressors, more effective utilization of the PV energy can be achieved and lower start up power is required compared with the operation with a single air compressor as shown in Fig. 9. Also, using multiple compressors offer a wider operational control range and a better handling of the PV power production variation between summer and winter which results in higher system efficiency. Moreover, using variable speed compressors allows more flexible and efficient operation since it can vary its operational load with the fluctuation of the PV available energy. These compressors are integrated with coolers to reduce the compressed air temperature for higher air density and better storage efficiency.

Regarding the TES system, it also utilizes a part of the available off-peak PV generated electricity and stores it as heat in a medium using an electric resistance heater. Water is considered as the most commonly used medium in TES systems due to its availability, low cost, high specific heat, and it is environmentally friendly (Koçak et al., 2020). Also, water can be easily stored in an insulated steel or stainless steel tank and heated using electric heaters in a sensible heat TES system. Then, during energy discharge, the compressed air passes through the TES to be heated before expanding in the air motor to generate electricity using the generator. However, in order to properly operate this hybrid ESS, an energy management strategy is required as discussed in the following section.

3.4. *Energy management strategy*

For hybrid energy storage systems, the proper split of the required

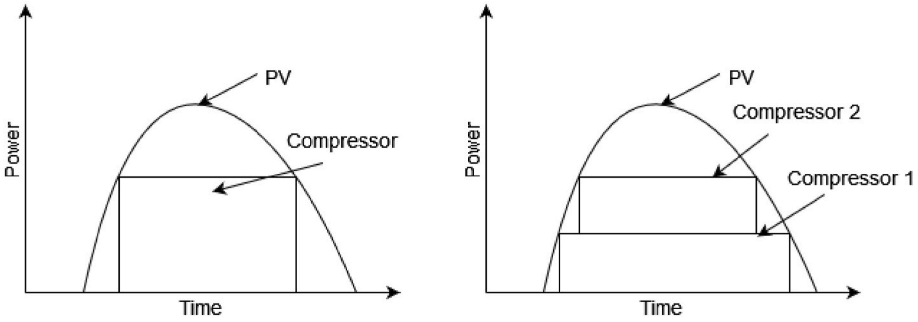

Fig. 9. Multiple compressors operation compared to single compressor operation.

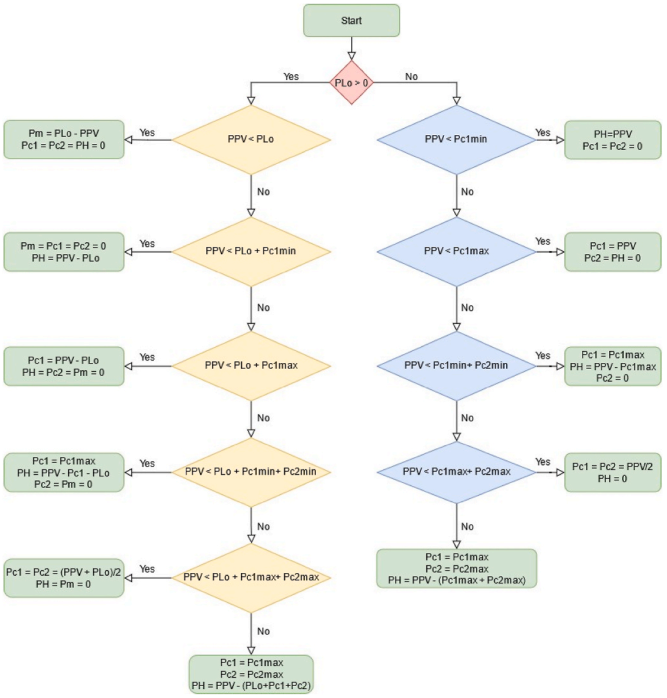

Fig. 10. Proposed energy management strategy algorithm for the developed PFPV prototype.

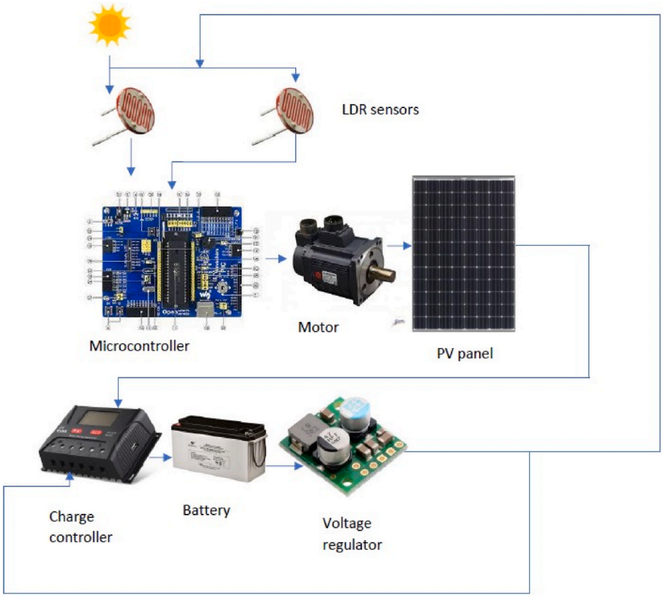

Fig. 11. Automatic sun tracking subsystem.

load demands or the available power to be stored between the storage system components is a challenging problem which requires the design of an Energy Management Strategy (EMS). This EMS controls the dynamic behavior of the system which affects its efficiency, operational stresses, and lifetime of its components. Therefore, designing a suitable EMS for the developed prototype is a fundamental issue to manage the energy flow between the PFPV system and the power consumers which includes the CAES system, TES system, and the required electrical load supplied through the air motor and generator.

A high level supervisory control system based on the deterministic Rule-Based (RB) approach is designed for the energy management and storage of the developed PFPV system. In deterministic RB control, engineering knowledge and human expertise are used to design a set of deterministic rules that decide the operating points of the system components taking into consideration the operational limits of the system components. These rules can be easily realized and tuned with low computational cost and complexity which makes this strategy type suitable for real-time applications (Tie and Tan, 2013).

The main objective of the proposed EMS for the developed prototype is to satisfy the required load (PLo) by the motor (Pm) and the available PV power (PPV) while taking into consideration the minimum and maximum operational limits of the air compressors (Pc1min, Pc2min, Pc1max, and Pc2max) and the TES electric heater power (PH) while storing any excess energy. As illustrated in Fig. 10, when there is a load to be satisfied, if the required PLo is higher than the available PPV, the motor will supply the missing power while the two compressors and the heater are not working. If the PPV exceeds the required PLo or there is no load to be satisfied, the excess power will be stored using one compressor or two compressors or one compressor and the TES heater, or the two compressors and the TES heater taking into consideration the components operational limits and the pressure and temperature safety limits of the CAES and TES systems.

3.5. *Operating modes*

The PFPV power system presented in this study is proposed to operate in five integrated modes. These modes are named as automatic sunlight tracking mode, cleaning mode, cooling mode, surviving mode and energy storage mode. The description of each mode and function are discussed in the following sections.

3.5.1. *Automatic sunlight tracking mode*

Since the output power of PV system depends on intensity of the sun radiation and the angle of incidence, it's important to remain the solar cells perpendicular to sun light to obtain the maximum efficiency. According to our proposed automatic sunlight tracking subsystem shown in Fig. 11, we assume that the photovoltaic PV panel rotates automatically depending on the sun irradiance during the day while at night; the

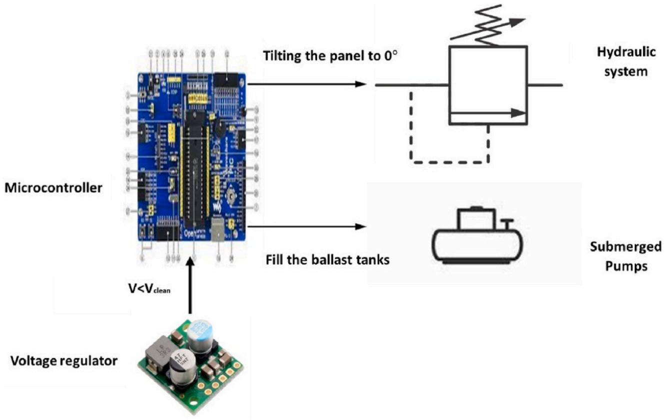

Fig. 12. Cleaning subsystem.

system is in sleep mode to minimize the energy consumption.

The stand-alone system consists of the PV panels and the rotating ring, two light dependent resistors (LDR)sensors, a microcontroller, a DC gear motor, a lead acid battery, a voltage regulator and a charge controller (Chin et al., 2011). The ideal tracker allows the PV cells to point to the sun according to both changes of altitude angle (during the day) and latitudinal offset of the sun (during seasonal changes) and changes in azimuth angle. As a microprocessor based solar tracker system, the controller is connected to a DC gear motor controlling the motion of the rotating ring. Once the location is chosen, the azimuth elevation range is determined, and the angular steps are calculated. A photo-sensor called light dependent resistor (LDR) is used to indicate the intensity of radiation. A microcontroller is then capturing the signals of the LDRs to give the right signal to the motor to rotate the rotating ring.

According to studies on the previously used automatic sun tracking systems, the power consumption by the tracking system is only about 2–3% of the increased energy (Chin et al., 2011). The annual energy available to the two-axis tracker was about 72% higher than the fixed surface and 30% higher for the single axis east-to-west tracker.

The position of the sun is detected by two LDRs located at the surface of the PV panel. The signals coming from the sensors are fed into a microprocessor based electronic control system that operates a DC gear motor to rotate the rotating ring and gives the hydraulic system the suitable signal to tilting the panel. During the day, the solar tracker rotates at a pre-determined angle from sunrise to sunset. At night, a return algorithm is used to reposition the panel at its home position for the next day.

The electrical energy is then stored in the lead acid battery. The charge controller prevents the battery overcharging. The battery provides all the electronic components with the required voltage levels (Jinayim et al., 2007).

3.5.2. *Cleaning mode*

The performance of PV production is highly affected by the deployment area weather conditions. A previous experimental study on the effect of dust particles on PV panels in the same lighting conditions was conducted by (Sulaiman et al., 2011) using artificial dust from mud and talcum. The study concluded that the accumulated dust on the surface of PV can reduce the PV efficiency and output power by 50%. According to another study in real weather condition in United Arab Emirates, the dust accumulation was found to be in a linear relationship with dust density and the tilt angle. In this study, the PV power production was reduced from 37.6% to 12.7% in outdoor experiments depending on tilt angle and dust density (Semaoui et al., 2015). Accordingly, proper functionality of PV module requires some special cleaning arrangements that should be done to maintain its efficiency (Samman and Latief, 2017).

In our study, seeking integration between the operating modes, the voltage input level V to the voltage regulator used in the automatic sun tracking subsystem will be used as an indicator of the PV output power and efficiency. A significant drop in this voltage level below a chosen threshold V_{clean} will be considered by the microcontroller as an initiation for the cleaning mode. Accordingly, the microcontroller gives the hydraulic system the suitable signal to tilting the panel to zero degree. At the same time, submerged pumps are directed to fill the ballast tanks. Streams of water filling the tanks will clean the panels of suspended dust, as shown in Fig. 12. The cleaning time could be controlled by the microprocessor program.

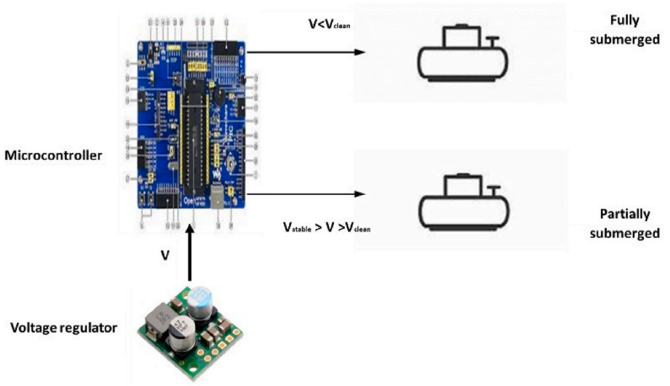

Fig. 13. Cooling subsystem.

3.5.3. *Cooling mode*

Photovoltaic panel temperature is considered as one of the critical issues effecting the output power efficiency, since solar cell performance decreases with increasing temperature. Depending on the type of PV panel, a typical PV panel converts about 20% of the incident solar radiation into electricity and the rest 80% is converted into heat (Dubey et al., 2013). The optimum operating temperature for a conventional PV modular is 25°. Above this limit, the temperature begins to negatively affect the output power. Each solar cell temperature rise of 1° above 25 °C, will reduce the cell energy production by 0.4% (Pujotomo and Diantari, 2018).

Depending on the mechanical characteristics of our proposed design, partially submerging as a partially cooling mode shown in Fig. 5 and fully submerging as a fully cooling mode could be applied. Again the voltage level of the voltage regulator will be used as an indicator of the PV temperature. As the voltage level decreases, the PV cell temperature is expected to be increased (Shukla et al., 2017). As shown in Fig. 13, if V is less than V_{clean}, fully submerged scenario will be in action. If V is between V_{clean} and V_{stable}, where V_{stable} is the voltage level corresponding to 25 °C, partially submerged scenario will be considered.

3.5.4. *Surviving mode*

For land-based PV systems, the risk of damage due to strong winds directed onto the underside of PV panels, is one of the main concerns. The damage risk increases by increasing the panel tilting angle which causes large wind forces onto the PV panels. Several failure cases of floating solar PV plants under severe weather conditions in Japan were also reported (Jeremy Ong, 2020). Recently a floating solar PV plant was significantly damaged after Typhoon Faxai at Yamakura Dam in Japan. The storm reportedly came in at an average wind speed of 41 m/s, which is apparently higher than the local code required. Therefore, the PV systems are sensitive to both wind speed and direction (Uematsu et al., 2021). The effect of the wind in PV panels have been experimentally investigated by (Schubauer and Dryden, 1937). Many research works offer wind-resistance arrangements to reduce the wind damage risks (Kuwahara, 1973).

Inspired with offshore structures for oil and gas platforms, surviving mode technique is implemented into the proposed PV modular. Like the

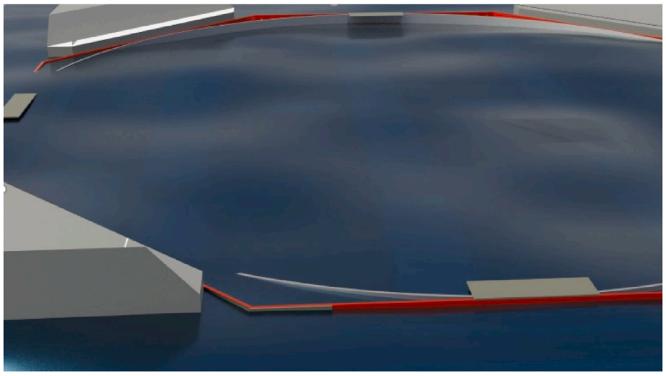

Fig. 14. Fully submerged mode for surviving from bad weather and strong winds.

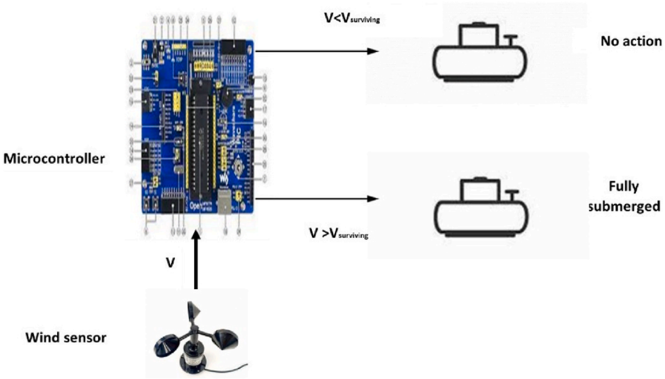

Fig. 15. Surviving subsystem.

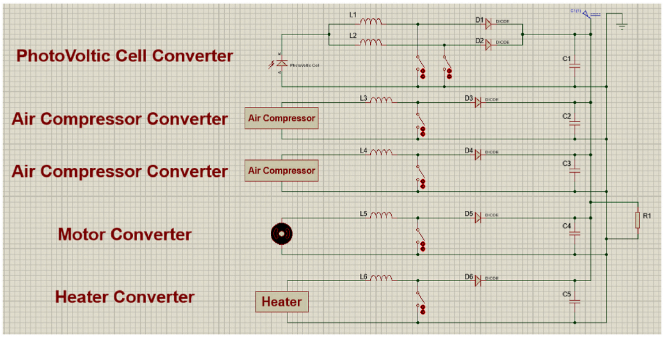

Fig. 16. Structure of the proposed electric system.

offshore platform when it meets strong wind, all ballast tanks are used to increase the vessel draft and reduce the freeboard area which is subjected to wind force. Following the same technique, in gust wind, all PV panels will automatically be closed with tilting angle until zero degree and pumping the seawater into ballast tanks to submerge the PV system and reduce the four corners draft as shown in Fig. 14. The value of the output voltage of the wind sensor V is compared to the threshold voltage $V_{\text{surviving}}$ which is the base of the full submergence decision as shown in Fig. 15.

3.5.5. *Energy management mode*

Promoting the highest level of energy conservation and sustainability, the proposed PFPV system is incorporated with a hybrid energy storage system shown in Fig. 8. In order to manage properly the operation of this system, a management strategy is developed as discussed in Section 3.4. The proposed EMS structure could be considered as a microgrid. As explained earlier, the structure consists of a PV source, two air compressors' converters, a heater, and a motor associated with an Interleaved Boost Converter (IBC) and bidirectional converters to the DC link, and a DC load linked at the DC link terminals. These converters are operated in current-controlled mode. A voltage controller is used to sustain the reference voltage across the load at the DC link. The structure of the proposed electric system is shown in Fig. 16.

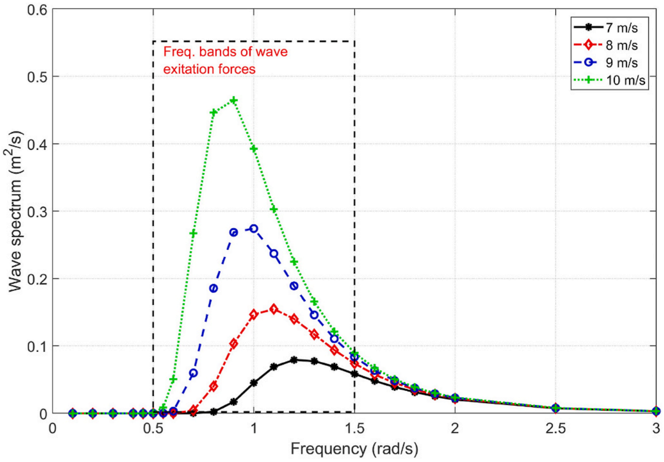

Fig. 17. The wave spectrum of the selected location for different wind speeds.

3.6. *Hydrodynamic performance of the proposed concept*

A novel floating photovoltaic power station is proposed in this study. The proposed system is integrated with a hybrid compressed air energy storage system in order to cover the night period and extend the working hours of the proposed system. As the proposed floating system deploys in a marine environment and faces different loading conditions, the hydrodynamic performance is a critical aspect. In this section, the environmental loads rising from exciting wave force are calculated, then the stability and motion behavior are evaluated based on a numerical approach using DVN-GL SeSam software package.

3.6.1. *Environmental loads*

Floating photovoltaic systems are deployed in a water body environment, which increases the design challenges compared with land-based system. Different design concepts were constructed in different marine environments such as shallow tropical lagoons in Maldives, offshore protected platforms in Norway, rough open see in North Sea (Netherlands) and nearshore in the Arabic Gulf in Dubai (Hooper et al., 2021). The floating photovoltaic system is subjected to different marine environment forces such as wind, wave and current forces that makes the interaction between the system and its marine environment a very critical issue. In order to understand the hydrodynamic performance of the proposed platform, the Mediterranean Sea wave spectrum $S(w)$ can be estimated using Equation (6) as follows;

$$S(w) = \frac{\alpha\, g^2}{w^5} \exp\left[-0.74 \left(\frac{w\, V_w}{g} \right)^{-4} \right] \tag{6}$$

where w is the frequency, g is the acceleration of gravity, V_w is the wind speed, and α is a constant equals to 0.0081 (Bai and Jin, 2015). As shown in Fig. 17, the results show that Mediterranean Sea's wave band peaks are in the range of 0.8–1.2 rad/s in this area at average wind speed ranges from 7 to 10 m/s. Therefore, the natural frequency of the proposed PFPV concept should be outside of the wave band range to avoid resonance response.

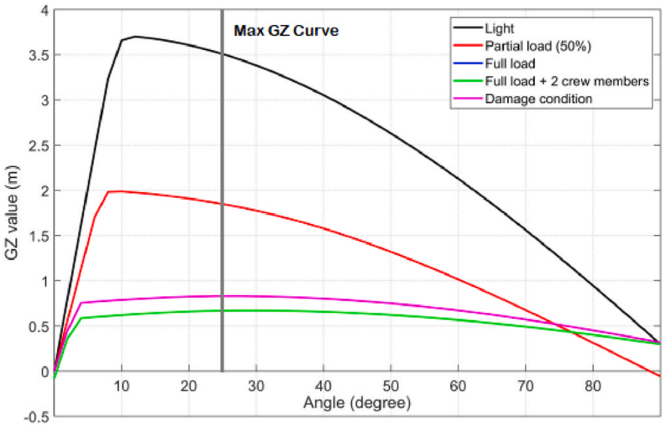

Fig. 18. GZ curve at different operational load cases.

3.6.2. *Stability*

The proposed floater is subjected to different load cases during its operation. The load cases are summarized in Table 3; namely light-ship case, dry PV mode, cooling mode (partially PV submergence), cleaning mode and finally survival mode. The floater must have a sufficient stability to keep the PFPV and the floater itself upright at all operating modes. The floater must also be capable of returning back quickly to its equilibrium position after any excitation is applied and ended. Stability requirements for floating platforms are usually evaluated through positive metacentric height (GM) and righting lever (GZ) curves. Static stability results for the proposed operational modes, from HydroD module, are presented in Fig. 18. Based on the general criteria rising from the International Maritime Organization (IMO), the minimum operational GM should be larger than 1 m. The maximum GZ must occur at an angle of heel not less than 25°. The area under the GZ curve must not be less than 0.055 m.radians up to an angle of heel 40°. According to the static stability results, the proposed PFPV satisfies the IMO criteria. More details about the stability criteria for different load cases is shown in Table 4.

3.6.3. *Motion behavior*

The wave-induced motions and internal responses of the floating photovoltaic concept are investigated and presented in this section. Wave-induced response amplitude operators (RAOs) of motion were calculated for the proposed floater. The presented results were obtained from frequency-domain simulations using DNV-GL Sesam software package, HydroD version 4.9–02. The motion response and hydrodynamic performance at six degrees of freedom were evaluated to ensure that the motion was restricted within the allowable limits for the Egyptian environmental loading conditions, and the results are presented in Figs. 19–24.

Generally, one of the main criteria for a successful floater design is the avoidance of experiencing large amplitude of motion during operations. The RAOs are dependent not only on the wave frequency, but also the wave direction. In the present case, different wave directions are included from 0 to 45°, due to the platform quarter symmetry. Figs. 19–24 present the heave, pitch, roll, surge, sway, and yaw motions of RAOs, respectively. Fig. 19 shows that the RAO peak of the heave motion occurs at 2.8 rad/s for wave incident zero and 15°. The heave peak shifted for incident wave equal of 30 and 45° to 3.3 rad/s. Heave response cancellation phenomena happen for all wave incident angle around 2.1 rad/s wave frequency. The largest heave response

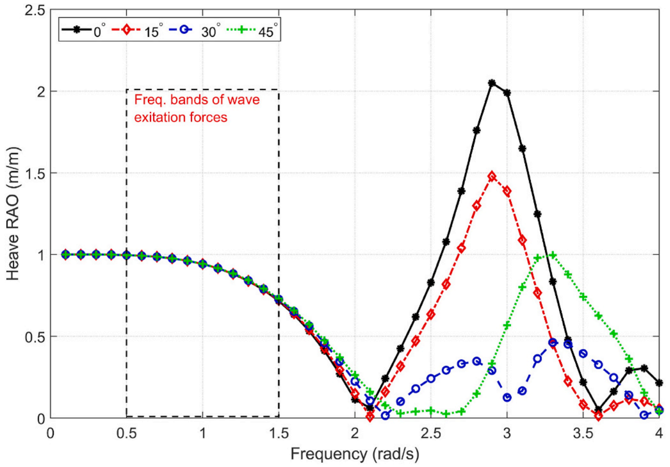

Fig. 19. The heave motion response for the proposed FPV concept at different incident wave directions.

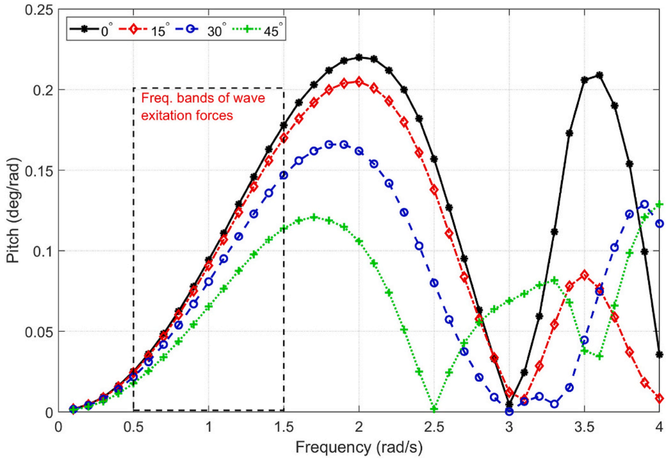

Fig. 20. The pitch motion response for the proposed FPV concept at different incident wave directions.

Table 4
Stability criteria for different load cases.

Applicable for all ships	Criteria		Light		Full load		Partial load (50%)		Full load + crew	
	Value	Unites	Actual	Unites	Actual	Unites	Actual	Unites	Actual	Unites
Area 0 to 30				Pass		Pass		Pass		Pass
Shall not be less than (≥)	3.1513	m.deg	90.9966	Pass	19.915	Pass	47.5729	Pass	15.2474	Pass
Area 0 to 40				Pass		Pass		Pass		Pass
Shall not be less than (≥)	5.1566	m.deg	123.1344	Pass	27.1596	Pass	63.2378	Pass	20.9939	Pass
Area 30 to 40				Pass		Pass		Pass		Pass
Shall not be less than (≥)	1.7189	m.deg	32.1378	Pass	7.2446	Pass	15.6657	Pass	5.7466	Pass
Max GZ at 30 or greater				Pass		Pass		Pass		Pass
Shall not be less than (≥)	25	deg	11.6	Fail	28.2	Pass	8.7	Fail	32.4	Pass
Initial GM_t				Pass		Pass		Pass		Pass
Shall not be less than (≥)	0.15	m	22.517	Pass	12.623	Pass	15.749	Pass	12.363	Pass

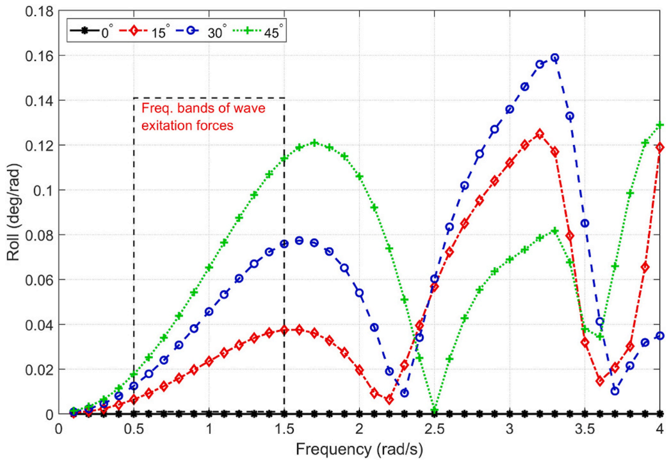

Fig. 21. The roll motion response for the proposed FPV concept at different incident wave directions.

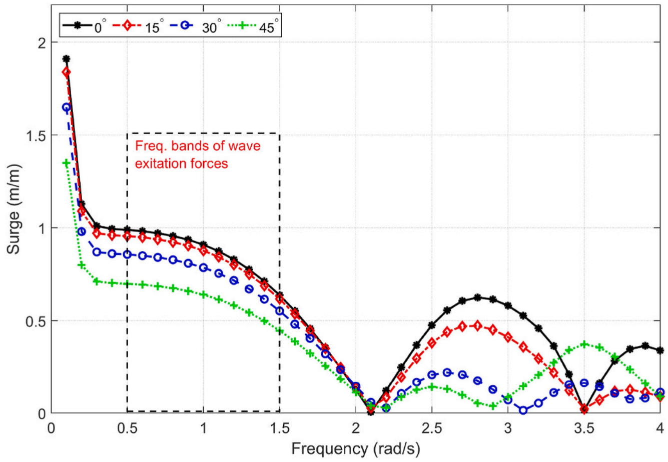

Fig. 22. The surge motion response for the proposed FPV concept at different incident wave directions.

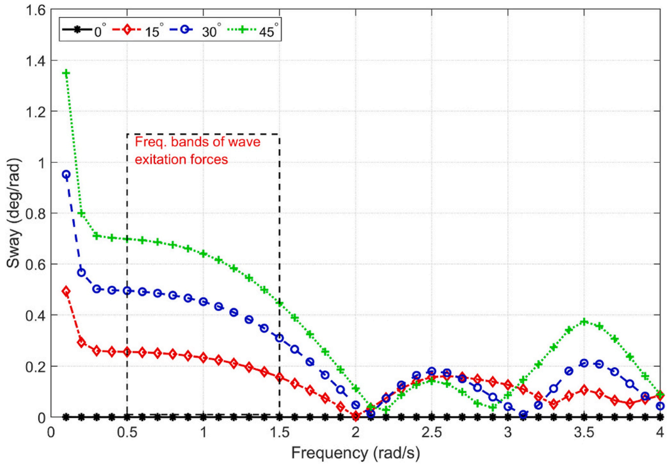

Fig. 23. The sway motion response for the proposed FPV concept at different incident wave directions.

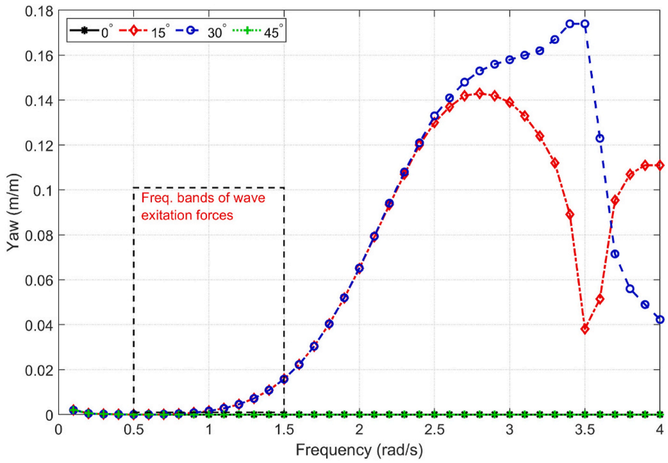

Fig. 24. The yaw motion response for the proposed FPV concept at different incident wave directions.

cancellation was happened for wave incident of 45° from wave frequency range of 2.2–2.7 rad/s.

Fig. 20 shows the pitch RAOs of the PFPV floater, where the peak of the pitch motion occurs at 2 rad/s. The pitch response cancellation point happens at 3 rad/s for all incident wave angles except at 45° happens at 2.5 rad/s. For heave, pitch and surge motions, the highest motion responses for the proposed PFPV were happened for incident wave equals to zero, while the lowest was happened for incident wave equals to 45°.

Fig. 21 shows the roll RAOs of the PFPV floater, where the peak of the roll motion occurs at 1.7 rad/s. The roll response cancellation zone happens in range of 2.2–2.5 rad/s for all incident waves directions. Fig. 22 shows the surge RAOs, where the peak occurs between 2.6 and 2.8 rad/s. The surge response cancellation point happens at 2.1 rad/s. Fig. 23 shows the sway RAOs, where the minimum response happens for zero incident wave and the maximum response happens for 45° wave incident.

The floater's global motions responses frequencies should be outside of the high energy excitation range of the wave's frequencies. The black dashed box presents the high energy excitation range of waves in the Mediterranean Sea based on the data shown in Fig. 17. This box presents the unsafe design zone for the proposed floater (0.5–1.5 rad/s) where the motion responses frequencies of the selected platform must be out of it. According to the heave RAO's results, all RAO peaks are out of the unsafe zone and the lowest motion responses happen for 45° incident angles.

4. Conclusions

This paper presents the conceptual design of an innovative partially floating PV (PFPV) system for the use in the Egyptian north lakes to meet the continuously increasing energy demand due to the recent population growth and economic development in Egypt. The proposed PFPV concept employs a novel passive cooling approach where the partially submerged PV panels are in continuous contact with the water body which regulates its temperature and significantly enhance its performance. A suitable floating platform has been designed to support the PFPV system and enable its different operational modes which includes sun tracking, cooling, cleaning, and surviving modes. The hydrodynamic performance and motion response of the floating platform has been investigated numerically using DNV-GL SeSam software package. The results show that the proposed platform satisfied the IMO stability criteria and the platform response in the six degrees of freedom is in the safe zone far from resonance taking into consideration the environmental loads of the selected location. To overcome the intermittency and discontinuity issues of solar energy, a compressed air energy storage system hybridized with a thermal energy storage system is proposed in this study. Also, a novel energy management strategy is designed to properly manage the operation of the proposed PFPV system and control its dynamic behavior. The proposed innovative PFPV system is feasible, modular in design and suitable for deployment in appropriate water reservoirs and coastal areas. Therefore, it can contribute to the sustainable and socio-economic development targeted by the Egyptian government and help in decarbonizing the national electricity grid and supply rural areas around the Egyptian North Lakes with green electricity.

CRediT authorship contribution statement

Ameen M. Bassam: Conceptualization, Methodology, Software, Writing – original draft. **Islam Amin:** Methodology, Software, Writing – review & editing. **Ayman Mohamed:** Conceptualization, Methodology. **Nabil A.S. Elminshawy:** Conceptualization, Methodology. **Heba Y.M. Soliman:** Conceptualization, Methodology. **Yasser Elhenawy:** Conceptualization, Methodology. **Andrew Premchander:** Conceptualization, Software. **Selda Oterkus:** Conceptualization, Methodology. **Erkan Oterkus:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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