Design and development of dual axis sun tracking system for floating PV plant

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Abstract. Increase in need of non-renewable energy sources has directed to the installation of PV plants in many areas. But considering the availability of land and the charges, the PV plant can be installed on water bodies like dams, reservoirs, lake, waste water treatment plants, canals etc. Floating type PV panels has a number of advantages compared to the land-based PV plant; its efficiency can be increased by effective cooling and tracking mechanism. The installation in water bodies offers additional advantages to the aquatic environment like reducing the evaporation rate of the water body, reduces unwanted plant growth in water body; improving the water quality. In this paper, detailed description of floating and the rotating structures in the plant. For higher efficiency the solar panel should be tracking in two axes, that is, tracking of azimuthal and altitude axis. Hence, dual axis tracking system is adopted and the mechanism is explained. Torque calculations are made for selection of correct stepper motor and hybrid linear actuator. Different materials for the platform are compared. A prototype made of wood was design and developed in NIT Puducherry.

Keywords: Solar, Photovoltaics, Floating, Dual axis tracking.

1. Introduction
In the current scenario, the renewable energy sources are substituting the non-renewable energy sources and also fulfilling the energy demands all over the world. Among all the available renewable energy sources, solar energy is the most predominant and most promising energy alternative due to its ubiquity and also it is freely available all over the world. Solar thermal and Solar Photovoltaics (PV) are the applications of the solar energy where solar PV is the most common application of solar energy. Many developments have been evolved int eh realm of solar PV cells from early 1800s to present day first [1–7]. The establishment of solar PV panels has the prerequisite difficulty of more land which will always be an expensive. The immediate solution for this economic glitch is installing the solar PV on the water body which can reduce the acquirement of land with high price. Floating solar PV has its own advantages when compared to ground mounted solar PV or roof mounted solar PV panels like more efficiency because of cooling effect of water. Also, this floating solar PV enables the decrease in water evaporation from the water bodies and prevents the water pollution by restricting the formation of algae etc. The platforms used for floating solar PVs are completely recyclable and withstand to effect of ultraviolet
rays, corrosion etc., by using high-density polyethylene. So, with these advantages floating solar PV systems became very logical substitute for existing solar PV systems by utilizing the waterbodies and also these systems are economically viable compared to other solar PV systems [8–12]. The floating solar PV systems can be more efficient if they are equipped with solar tracing system. This solar tracking system enables the floating PV to find the Sun’s position and tilt according to it. These tracking and tilting can be done by various methods. Also, this tracking of different types like single axis and double axis tracking with open loop and closed loop. These systems are mainly done by MATLAB or Arduino programming to track the exact position of sun [13–22]. In the current paper, we designed a floating solar PV system with some selection criteria for materials and tracked the sun for double axis i.e, azimuthal and elevation tracking system with the Arduino programming.

2. Floating PV
The floating PV installed on as floating system on the water bodies is the current trending technology in solar PV system which reduces the economic difficulty of installing solar PV system on the expensive and valuable land. This floating system arrangement consists of floating and rotating platforms which solar PV panels are mounted and connected to tracking system through cables.

i. Floating platform – A floating platform should have adequate buoyancy enough to float itself as well as with a substantial load. It should be designed in such a way that it accommodates no. of solar cells connected in series and parallel combination and also along with tracking system.

ii. Rotating platform – It is basically placed above the floating platform; the PV panels are actually placed in this and sits on the latter with rollers. This has gear at its circumference and it is rotated by motor.

iii. Mooring system – A mooring system typically indicates to any perpetual structure to which a container may be protected. In this floating solar PV system, this mooring system safeguards the panels from turning or floating away by keeping in the same position.

iv. Solar PV module – The crystalline PV modules have proved to be efficient compared to the amorphous, so we are using crystalline type in our project. The commercially available panels have aluminum frames, which on years starts to corrode so alternatives such as polymers can be adopted.

v. Cables and Connectors – The generated electricity from the floating system is transferred to land through cables and connectors. In this case, we used floating cables for transfer of generated electricity.

2.1. Design of floating platform.
The primary requirements of a floating platform are:

1. Efficient – the consumption of power by the motor is reduced by use of worm gear drive and due to high transmission ratio, providing high torque with the use of frictionless bearing the efficiency can be increased.

2. Economical – by adopting plastic gears the cost is reduced compared to the steel frames.

3. Low manufacturing Cost – simplicity of the design and the low cost for the manufacturing process.

4. Maintenance Free – plastic gears with the self-lubricating property and corrosion resistant makes it maintenance free

5. Less Installation Resources – modular structure and easy assembling of components make it portable to transfer and also requires less man power and assembling equipment.

6. Lesser Resistance towards wind force.
We have chosen hexagonal structure because, when arranging the hexagons together the empty spaces or gap is nil and compared to other shapes the material required in this case is less. This reduces the overall cost of the project. In the platform slots are made in each side for the wind flow throughout the wind can destroy the stability of the plant.
2.2. **Design of rotating platform.**
The rotating platform is placed above the floating platform. It is joined with rollers in the bottom for the easy movement. It has spur gear tooth profile in its circumference which is in turn rotated by another spur gear with smaller radius which is connected in parallel with stepper motor using shafts. It has another structure fixed to it using a hybrid linear actuator and the panels are kept in this structure. The panels are kept in such a way that the shadow of one panel does not fall on the other.

2.3. **Arduino Program for Sun Tracking Mechanism.**
There are two types of tracking,
1. The Sun’s position based on the collected data can be fed to the Arduino and the panel position is predetermined.
2. The other one is by using LDR (Light Dependent Resistor), the sun’s position can be calculated instantly and this can be fed to Arduino.

**Pin Diagram of Arduino:** Arduino Uno is the representative illustration of Arduino board. It comprises of ATmega328—a 28 pin microcontrollers. This is made up of 14 digital input/output pins of which 6 can be used as Pulse Width Modulation (PWM) outputs, 6 analog inputs, a 16 MHz crystal oscillator, a Universal Serial Bus (USB) connection, a power jack, an In-Circuit Serial Programming (ICSP) header, and a reset button.

**Power Jack:** It is powered either by pc through an USB or by an external source such as battery or adapter.

**Digital Inputs:** It comprises of 14 digital inputs/output (I/O) pins, in which each pin provide or take up current of 40mA. Some of them have special functions such as pins 0 and 1, which act as Rx and Tx respectively. For serial communication, pins 2 and 3—which are external interrupts and subsequently pins 3,5,6,9,11 provides PWM output and pin 13 where LED is connected.

**Analog inputs:** It has 6 analog input/output pins, in which each pin is able to provide a resolution of 10 bits.

**ARef:** It offers reference to the analog inputs

**Reset:** It is used to reset the microcontroller.
2.3.1. Light Dependent Resistor (LDR): An LDR is a light sensitive instrument whose resistivity is a function of the incident electromagnetic radiation and it is also called as photo conductive cells, photo conductors, or simply photocells. These devices are made up of high resistive semiconductor materials. There are various indications for LDR, in which one of the most usually used symbols is shown in the figure below. The arrow shows light incident on the device. As said earlier, LDRs are light dependent devices whose resistance is declined when light falls on them and amplified when there is no light or in darkness. This resistance is called as dark resistance and it has a range of 10^12 Ω. If a constant voltage is applied and magnitude of incident light is increased then the current starts increasing.

![Figure3. LDR and graph shows resistance vs. illumination curve for a particular LDR.](https://www.electrical4u.com/light-dependent-resistor-ldr-working-principle-of-ldr)

2.4. Working of dual axis sun tracking mechanism
Initially the panel is fixed approximately at 11° (since the latitude of Karaikal is 10.9254° N). The sun’s position is tracked using LDR sensors. Here we have employed dual axis tracking system, azimuthal and elevation tracking. 4 LDR sensors are used. The sensors are separated from each other, so that they are hidden from each other. They are placed in small piece of cardboard on four sides and separated using cardboard. As we all know as the light falls on LDR the resistance starts decreasing, the value of resistance from all the sensors are sent to the Arduino and the program is made in such a way that it compares the data and generates an output. The Arduino sends signal to the stepper motor. The stepper motor is connected with the driver gear. This driver gear drives the rotating platform which itself is a spur gear. As the stepper motor turns one step it rotates the driver gear to a particular angle and this in turn rotates the rotating platform. This tracking enables the plant to track sun every hour, that is, tracks the sun as it moves from east to west. The Arduino not only sends signal to the stepper motor but also to the hybrid linear actuator. The linear actuator connects the rotating platform and the base where the panels are kept. Hence according to the signal, the linear actuator lifts the base upwards. We all know that, the sun’s declination angle varies from -23.5° to 23.5° no longer the sun path remains the same so, this elevation tracking can track the sun on daily basis.

![Figure4. Circuit connection for the program](https://www.electrical4u.com/light-dependent-resistor-ldr-working-principle-of-ldr)
2.5. Torque calculation
For azimuthal tracking of PV panel, we are adopting worm gears. 
Radius of spur gear $(R) = 0.3$ m 
Mass of the total rotating platform $(m) = 30$ kg 
Torque required rotate the worm gear $(T) = I \times \alpha$

Moment of Inertia,

$$I = \frac{1}{2} \times m \times R \times R$$

$$= \frac{1}{2} \times 30 \times 0.3 \times 0.3$$

$$= 1.35 \text{ m}^2$$

To rotate $180^\circ$ in $12$ hours, $\omega = 0.25 \text{ rad/sec}$

$$\alpha = \frac{\omega}{t}$$

$$= \frac{0.25}{1}$$

$$= 0.25 \text{ rad/s}^2$$

Required torque,

$$T = 1.35 \times 0.25$$

$$= 0.3375 \text{ N-m}$$

Selection of stepper motor based on $0.3375 \text{ N-m}$ torque

2.6. Selection of stepper motor
Stepper motor selected is OMHT17-275 (High Torque Stepper Motor)
FRAME SIZE: NEMA 17
STEP ANGLE: $1.8^\circ$

2.6.1. Features and Benefits:
- High Torque
- Cost effective
- Up to $0.44 \text{ N-m}$ Holding Torque

| Table 1. Standard Motor Specifications. |
|-----------------------------------------|
| Step Angle $(^\circ)$ | 1.8 |
| Frame Size            | NEMA 17 |
| Body Length (m)       | 0.048 |
| Current (A)           | 1.7 |
| Holding Torque (N-m)  | 0.44 |
| Resistance (Ω)        | 1.7 |
| Voltage (V)           | 2.8 |
| Rotor Inertia (g-cm$^2$) | 82 |
| Number of leads       | 8 |
| Connection            | Parallel |
| Weight (kg)           | 0.357 |
| Branding              | Power Step High Torque |

Maximum power rating of the stepper motor $= V \times I$

$$= 2.8 \times 1.7$$

$$= 4.76\text{W}$$

2.6.2. Torque Calculation for Hybrid Linear Actuator.
For elevation axis tracking hybrid linear actuators connected to motor are,
\[ F = \frac{Q(2\pi\mu r - P)}{(2\pi r + \mu P)} \]

Where,
\( \mu \) = Frictional coefficient
\( r \) = Pitch circle radius of lead screw
\( Q \) = Perpendicular load acting
\( P \) = Pitch of lead screw
\( F \) = Perpendicular force acting

Expected weight of the rotating platform = 30 kg (including wind force)
\( Q = 15 \text{ kg} = 147\text{N} \)
\( \mu = 0.35 \)
\( r = 2.97\text{mm} \)

\[ F = \frac{147[(2 \times 3.14 \times 0.35 \times 0.00297) - 0.000305]}{[2 \times 3.14 \times 0.00297] + 0.35 \times 0.000305} \]

\( F = 162.833\text{N} \)

Torque = 5.478 kg-cm

### 2.7. Selection of Material for The Platform

A comparison is made between the plastic materials and material is selected. The three materials opted for comparison were:

1. POLYETHER ETHER KETONE (PEEK)
2. NYLON 6/6 GF-30
3. HIGH DENSITY POLYETHYLENE (HDPE)

### Table 2. Comparison of Properties

| Physical Properties | PEEK | HDPE | NYLON 6,6 |
|---------------------|------|------|-----------|
| Density (g/cc)      | 1.49 | 0.94-1.0 | 1.36 |
| Moisture Absorption at Equilibrium (%) | 0.2 | 0.01-0.03 | 1.6 |
| Mechanical Properties | | | |
| Tensile Strength at Break (MPa) | 156 | 113 | 140 |
| Elongation at Break (%) | 3.0 | 1.0-2.9 | 5.0 |
| Flexural Strength (MPa) | 250 | 215 | 315 |
| Flexural Modulus (GPa) | 10.0 | 11.7 | 10.8 |

### 2.8. Advantages of High-Density Polyethylene

Based on the above comparison high density polyethylene (HDPE) is selected for the below mentioned reason.

1. Super buoyancy (lighter than water) – The density is in the range of 930 to 970 kg/m³ which makes HDPE lighter than water.
2. Zero corrosion – Oxygen, salt and water have no effect on HDPE. It is not affected by the ravages of time. HDPE offers zero corrosion and zero maintenance.
3. Resistance to marine growth – no anti fouling needed.
4. High impact resistance – Its viscous and elastic characteristics prevent it from deformation. It is tough and flexible.
5. Black strength (UV resistant) – One can use black HDPE because of its resistance to Ultraviolet (UV) rays. Black HDPE is mixed with carbon, which avoids the material to turn out to be as brittle due to climatic conditions.
6. Production flexibility – Can be constructed by plate welding, giving great flexibility.
7. Easy of repair.
8. Low carbon footprint – The carbon footprints of HDPE making is 5 times lesser than Aluminium in terms of durability. HDPE is indestructible; it may stay up to 40 years.
9. Durability: 100% recyclable.

2.9. Selection of Reinforcement
Reinforcing the structure increases the physical properties. There is much reinforcement available in the market; some of them are discussed below.

i. Carbon – fiber reinforcement
   a) Very light results in light weight structures
   b) Impact strength
   c) Expensive, the price will be decreased when there is advancement in the production technology
   d) Thermal expansion is zero
   e) Temperature resistant
   f) Corrosion resistant
   g) Very stiff and brittle
   h) High strength to weight ratio

ii. Natural – fiber reinforcement
   a) Low density
   b) Less expensive and Biodegradable
   c) Tensile modulus and flexural modulus
   d) Renewable resources
   e) Moisture absorption is more
   f) Coupling between natural fiber and polymer is difficult

iii. Glass – fiber reinforcement
   a) High modulus of elasticity and Higher elongation at break
   b) It is cheap
   c) Good chemical resistant to acids and solvents
   d) Electrically insulated
   e) Relatively Higher temperature resistant
   f) Low moisture absorption
   g) Higher strength to weight ratio
   h) It’s not stiff, but this can overcome by designing sandwich structure, light weight core can be sandwiched between two glass skins and then the end is stiff.

Based on the above comparison on properties and reliability glass - fiber reinforcement is used.

2.10. Design of Gears
Spur gears are selected and their design is as follows:
Pressure angle is chosen as 20° (mostly preferred for plastic gears)
Pitch Diameter of the gear, D = 60 cm
Taking the no. of teeth, N = 120
Diametral pitch = N / D
       =120 / 60
       =2 / cm
Addendum = 1 / P
       =1 / 2 = 0.5cm
Whole depth = addendum + dedendum
hₜ = 2.33 / P
     = 2.33 / 2 =1.165 cm
Standard circular tooth thickness,
Cₜ = π / 2P = 0.785 cm
Root diameter, \( d_r = D - 2h_t \)
\[ = 60 - (2 \times 1.165) \]
\[ = 57.67 \text{ cm} \]

Module, \( m = \frac{D}{N} \)
\[ = 0.5 \text{ cm} \]

Tangential Force = \( 2000 \times \frac{T}{d} \)
\[ = 2000 \times 0.3375 / 0.6 \]
\[ = 1.125 \text{ kN} = 11036 \text{ kgf} \]

Calculation for pinion
Pitch diameter = 6 cm
Pressure angle = 20°
No. of teeth = 12

Bending Stress (\( \sigma_b \))
\[ = \frac{F}{(m \times y \times b)} \]
\[ = \frac{1125}{(30 \times 0.7658 \times 3.5)} \]
\[ = 13.99 \text{ N/m} \]

By considering all the design calculations, using selected materials and components driven by Arduino program, the floating PV is developed as shown in figure,

![Figure 5. Developed prototype in front and side views](image)

![Figure 6. Panel in lifted position](image)

3. Conclusions
1. From the several proposed design for floating platform, the hexagonal structure was found to be efficient, cost effective and easy installation.
2. Dual-axis sun tracking mechanism was explained, the azimuthal tracking was controlled by stepper motor and the elevation tracking was controlled by hybrid linear actuator.
3. The selection of the stepper motor and hybrid linear actuator was made by calculating the torque produced by the structure.
4. An Arduino program was developed to control Arduino which in turn controls the stepper motor and the hybrid linear actuator.
5. From Polyether ether ketone, nylon 6,6 and High-density polyethylene (HDPE) materials, HDPE was found to reliable with 10% of glass fiber reinforcement as it increases the strength of the structure.
6. The gear parameters of spur gear were calculated and the design was made according to the calculation.
7. Prototype with optimum tracking was fabricated.

4. Future Scope
1. The efficiency of the floating PV plant can be compared with the land-based PV plant experimentally for some duration and results and graphs can be made based on the observations made.
2. The original model with high density polyethylene can be made and tested.

3. The project can further be expanded to make it work in saltwater lagoons where waves would be present by using dampers or secondary reflectors.

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