Recent Developments and Future Advancements in Solar Panels Technology

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Abstract. Although advancements and developments are happening on the electronics part of the solar cell, a steep boost in the research field of material and manufacturing perspective must highlight. Artificial intelligence-based maximum power point tracking algorithms are the future of solar-based circuits. Fabrication of transparent solar cells that have the potential to be used for a vast number of applications, solar cells with more than one layer of light capturing materials. Innovative photovoltaic modules that can lay on roads that can power LED lamps and can melt snow in winter are a few cutting-edge technologies from the materials as well as a manufacturing point of view. Surprisingly they have higher efficiency than traditional solar cells. This paper analyses the recent developments and the future potential of solar panel technologies in the material and manufacturing perspective.

Keywords: Transparent Solar Cells; Artificial Intelligence; Maximum Power Point Tracking; Photovoltaic Module; Light Capturing Materials.

1. Introduction

Energy is a crucial factor in economic growth and development. With an increase in demand for energy due to a growing population and expanding economy, there is a need to use renewable energy sources as their counterparts can be detrimental to our environment. Solar energy provides an optimal solution to this current situation. There has been a substantial increase in the efforts put in developing solar technology. Some of the critical issues triggered during this process include lower efficiency of silicon cells, higher processing costs, lack of proper infrastructure, and skilled workforce [1-2]. The studies in this field have paved the way for newer technologies.

The promising renewable energy source nowadays is solar energy with a PV system in which an intern got considerable attention from researchers. The Solar PV system is free from carbon emissions, environmentally friendly, readily available, and no cost for the source because of abundance in nature [3-5]. The energy conversion efficiency and the capital investment of the SPV system are very high, which are the limiting factors of this energy source.

In the past, Different kinds of semiconductor materials and technologies are there to design PV cells with less cost as well as high conversion efficiency. Traditional solar panels made from silicon crystalline wafer modules are having more weight, which makes transportation difficult. These are
generally the large-sized solar panels covered with glass sheets. A more massive and high weight solar panel requires much space and sometimes big roofs to fit these bulky and large solar panels in case of high power applications [6]-[8]. In [9], the maximum power accurately and successfully can be tracked by the maximum power tracker in all conditions tested. A comparison of different parameter performance, such as response time and tracking efficiency of the system, shows the proposed method gives better performance and efficiency than the conventional P&O (perturb and observe) method.

2. Design of PV module
The PV module consists of several PV panels with series and parallel strings of PV cells. A PV cell represented with an equivalent single diode model, as shown in fig.1, having two resistors, one in series and the other in parallel with parallel current source and series diode. On the PV panel, the incident solar energy is equal to the current source output in the equivalent circuit. The diode is the representation of a photocell without any solar incident energy. The losses inside the PV cell due to current flow represented by a parallel resistor in the equivalent circuit model.

\[ V_t = \frac{KT_{op}}{q} \]  
Where \( K \) is Boltzmann's constant,  
\( T_{op} \) is the operating temperature, and  
\( q \) is the electron charge.

The diode current:
\[ I_D = \left( \frac{V+IR_s}{e^{\frac{V}{N_sKT_{ref}}} - 1} \right) I_sN_s \]

Where,
\( n \) is the ideality factor,
\( N_s \) number of series cells,
\( C \) is the number of cells in each module and
\( I_s \) means the diode reverse saturation current.

\[ I_s = I_{rs} \left( \frac{T_c}{T_{ref}} \right)^3 e^{\frac{qE_g}{nKR} \left( \frac{1}{T_c} - \frac{1}{T_{ref}} \right)} \]

where,
\( E_g \) is the band gap and \( T_{ref} \) is the reference temperature

\[ I_{rs} = \frac{I_{sc}}{e^{\frac{qE_g}{nKR} \left( \frac{1}{T_{ref}} - 1 \right)}} \]

Where,
\( V_{oc} \) open-circuit voltage and \( I_{sc} \) is the short circuit current.
\( V_{oc}, I_{sc} \) can be determined from the PV array that modeled.
$$I_{sh} = \frac{V_{dc} + IR_{dc}}{R_{sh}}$$  \hspace{1cm} (5)

$$I_{ph} = Gk[I_{SSC} + K(T_c - T_{ref})]$$  \hspace{1cm} (6)

$$I = N_pI_{ph} - I_d - I_{sh}$$  \hspace{1cm} (7)

3. Types of solar cells

![Diagram of solar cell types]

**Fig.2: Types of solar cells**

3.1 *First Generation Solar Cell*
Wafer Based As it already mentioned, the first-generation solar cells produced on silicon wafers. It is the oldest and the most popular technology due to high power efficiencies. The silicon wafer-based technology further categorized into two subgroups named as:
- Single/ Mono-crystalline silicon solar cell.
- Poly/Multi-crystalline silicon solar cell.

3.2 *Second Generation Solar Cells*
Thin Film Solar Cells Most of the thin-film solar cells and a-Si are second-generation solar cells, and are more economical as compared to the first generation silicon wafer solar cells. Thin-film solar cells classified as:
- Amorphous Silicon Thin Film (a-Si)
- Cadmium Telluride (CdTe) Thin Film Solar Cell
- Copper Indium Gallium Di-Selenide (CIGS) Solar

3.3 *Third Generation Solar Cells*
Third generation cells are the new promising technologies but not commercially investigated in detail. Most of the developed 3rd generation solar cell types are:
- Nano crystal-based solar cells
- Polymer-based solar cells
- Dye-sensitized solar cells
- Concentrated solar cells

3.4 *Transparent solar cell technologies*
There are approximately nine technologies that apply to the fabrication of transparent solar cells, and they are a focal point of current research due to market demand and the potential applications of transparent solar cells (TSC). The centers of research that report some success with TSC are in Japan,
Germany, the USA, and India. The observation that has 90% of these technologies use an FTO or ITO conductor on glass, which has a layer with almost 10 Ω/sq resistance, using a thin film with a thickness of less than 20 nm. Combined with intrinsic optical losses of the glass itself, the layers of PV reduce the transparency by approximately 15–20% before the deposition of any other materials. Thus, the best transparency achieved currently is less than 80%. The technologies that achieved more than 20% transmittance with at least 1% efficiency elaborated in chronological order below.

**Thin film photovoltaics (TPVs)**
- Near-Infrared transparent solar cell
- Polymer solar cell (PSC)
- Transparent luminescent solar concentrator (TLSC)
- Perovskite solar cell
- Electrophoretic deposition (EPD)
  - Dip-coater
  - Sputtering deposition
  - Quantum dot (QD) solar cell

4. Technologies used for MPPT control of solar cells till date:

4.1 MPPT by P&O method:
Conventional Perturb & Observe algorithm has been extensively used due to ease of implementation, as explained in the flowchart in Fig. 3. MPPT is a continuous process of observation and perturbation until the operating point converges at the MPP.

The algorithm compares the power and voltages of time (K) with the sample at a time (K-1) and predicts the time to approach to MPP. A small voltage perturbation changes the power of the solar panel if the power alteration is positive; voltage perturbation continued on the same track. But if delta power is negative, it indicates that the MPP is far away, and the perturbation decreased to reach the MPP. Thus, in this way, the whole PV curve is checked by small perturbations to find the MPP that increases the response time of the algorithm.

Conversely, if the perturbation size enlarged, it generates steady-state oscillations about the MPP. Many researchers have proposed modifications in the P&O algorithm to overcome the response time problem and steady-state oscillations. After this, so many modified P & O MPPT algorithms came into the analysis of solar PV cells.

![Fig.3: P & O algorithm Flow Chart](image-url)
4.2 MPPT by ANN methods: Reinforcement learning algorithms have to learn from the environment on-line. ANN is a quite advantage as photovoltaic systems operate under different climate and weather conditions. The temporal difference Q-learning algorithm also proposed for the MPPT technology of PV cells.

The Reinforcement Learning Model: The general model of a reinforcement learning algorithm includes agent, environment, state, action, and reward. The agent explores the environment and the appropriate actions to achieve a predefined goal. The agent learns from the environment through the reward function. The agent maintains an average reward value for a specific state-action pair. When the agent finishes exploration, it starts the exploitation phase.

4.3 MPPT by the fuzzy logic approach: Fuzzy systems (FS) works based on fuzzy set theory and associated techniques pioneered by LotfiZadeh[10]. It is a non-linear method, which attempts to apply the expert knowledge of an experienced user to the design of a fuzzy-based controller. Generally, as shown in figure 5, FLC contains four main components:
   a) The fuzzifier that maps crisp values into fuzzy input sets to activate rules.
   b) The rule-based system defines the controller behavior by using a set of IF-THEN statements.
   c) The inference engine which maps fuzzy input sets into fuzzy output sets by applying the rules, and
   d) The de-fuzzifier in FIS maps output fuzzy values into crisp values.

The rules describing the FLC operation expressed as linguistic variables represented by fuzzy sets. The controller output obtained by applying an inference mechanism [10, 11]. In the case of fuzzy
controllers hardware implementation, which is of interest here, the shapes of the membership functions associated with the FLC linguistic variables are often piecewise linear functions (triangular or trapezoidal). The number & shape of the membership functions of every set, as well as the fuzzy logic inference mechanism, was initially selected based on trial-and-error methods, with the region of interest covered appropriately by data inputs.

The idea behind the reasoning was; the last chance of the control signal (D) caused the power to rise, keep moving in the same direction; otherwise, if it has caused the power to drop move it in the opposite direction [1, 4, 7, 17]. The MPPT using the Mamdani's FLC approach, which uses the min-max operation fuzzy combination law, is designed in a manner that the control task tries to continuously move the operation point of the solar array as close as possible to the maximum power point (MPP) [12]. The two inputs of the fuzzy controller are the tracking error (E) and ∆E), which defined as:

$E(n) = \frac{p(n) - p(n-1)}{V(n) - V(n-1)}$  \hspace{1cm} (8)

$\Delta E(n) = E(n) - E(n-1)$  \hspace{1cm} (9)

Where:
E and ∆E are the error and change in error, n is the sampling time, p(n) is the instant power of the PV generator and V(n) is the instant corresponding voltage. These inputs choose to have the instant value of E(n) shows if the load operation power point is located on the right or in the left compared to the Pmax actual position. While ∆E(n) expresses the moving direction of this operation point.

The output variable is the pulse width modulation (PWM) signal called D, which is transmitted to the boost DC/DC converter to drive the load. After the rules have applied, the center of the area as the defuzzification method used to find the actual value of (D) as a crisp output. The membership functions and fuzzy inference values for D found to make MPPT possibilities in the PV cell.

5. Recent developments:
The possibility of a two-in-one or duplex solar panel that generates electricity and heats water, occupying only 170 square feet on the terrace. In 2017, the co-founders spotted a small proof of concept clay model of the duplex solar panel at IIT Madras. "It was a 10 x 15 cm model designed for academic demonstration. Praneeth and Harsha have plans for further innovations, one of them being incorporating micro concentrators within solar panels, negating the need for large mirrors to focus the sun rays on to the panel, for industrial use.

![Fig.6: Residential 2 in 1 panel](image1)

![Fig.7: Industrial 2 in 1 panel](image2)

**MPPT by ANFIS control**
ANFIS Technique The adaptive neural-fuzzy interference system (ANFIS) technique is considered a hybrid method based on the architecture of a neural network and fuzzy logic inference. The ANFIS technique has several nonlinear applications in many sectors, such as engineering, chemistry, manufacturing, and physics. Mainly, in the areas of electrical engineering, there are a PV array and a
wind turbine. The ANFIS structure consists of five layers: fuzzification, rules, normalization, consequent, and addition, as shown in Figure 5.

In the first layer, every node of the training data is an adaptive node, with the node function using Equations (7) and (8):

\[ A_{1,i} = \mu x_i(x) \quad \text{for } i = 1, 2 \quad (10) \]
\[ A_{1,i} = \mu y_{i-2}(y) \quad \text{for } i = 3, 4 \quad (11) \]

Where \( \mu \) is the defined membership function and \( A_{1,i} \) is the defined membership value for the inputs \( x \) and \( y \). The subscripted 1 and \( i \) is the layer number and node number of the training data, respectively.

The defined membership functions can be any shaped function, such as triangular, trapezoidal, or Gaussian. The best membership functions achieve less training error. In Layer 2, every node is a fixed node based on one fuzzy rule. The output value is given by Equation (9):

\[ A_{2,i} = \omega_i = \mu x_i(x) \mu y_i(y) \quad \text{for } i = 1, 2 \quad (12) \]

In Layer 3, every node is fixed based on the normalization of the firing strength, using Equation (10):

\[ A_{3,1} = \omega_i = \omega_i / (\omega_1 + \omega_2) \quad (13) \]

In Layer 4, every node is adapted and calculated based on the rule consequent, as given in Equation (11):

\[ A_{4,1} = \omega_i f_i = \omega_i (p_1 x + q_1 y + r_1) \quad (14) \]

where \( p_i, q_i, \) and \( r_i \) are the following parameters that require optimized in the training operation. In Layer 5, all input nodes are summed together to get the final output signal, as given in Equation (12):

\[ A_{5,1} = \sum_i \omega_i f_i = \sum_i \omega_i f_i / \sum \omega_i \quad (15) \]

The traditional ANFIS-MPPT method usually has two inputs and one output, such as in [13]. The operating temperature and irradiance level usually used as inputs to the training data of the ANFIS method, and the output is the reference power. Under the same weather conditions, the actual PV power calculated using the sensed voltage and current of the PV operation. These two power readings compared, and the error is given to a PI controller to generate the signal of a DC-DC convertor by a PWM generator to adjust the operating MPP of the PV module.

In general, the MPPT technique based on ANFIS has designed to solve the limitations of an intelligent system. Besides, it can adjust its elements to give a faster response and less fluctuation under different weather conditions due to less time consumed in the defuzzification stage. However, accurate training data and tuning the ANFIS model are significant challenges when designing an efficient ANFIS-MPPT.

![Fig.8: Block diagram of ANFIS model](image)
6. Future advancement
Semi-transparent solar cells: a window to the future?

- Windows have been ubiquitous in society for centuries, filling our homes and workplaces with natural light. But what if they could also generate electricity?
- One of the critical parameters is known as the average visible transmittance (AVT). AVT is the % of visible light (as opposes to other wavelengths, like infrared or ultraviolet) hitting the window that travels through it and emerges on the other side.
- We don't want the solar window to absorb so much light that we can no longer see it out. Nor do I want it to let so little light through it hardly generates solar power. The scientists have been trying to find a happy medium between high electrical efficiency and a high AVT.

Problems involved in a semi-transparent Solar Cell:

- An AVT of 25% generally considered the benchmark for a solar window. But letting a quarter of the light travel through the solar cell makes it hard to generate much current(gives low output).
- If your friend was wearing a red shirt, when you view them through a window, their shirt should appear red. But because semi-transparent solar PV absorbs some of the light we see in the visible spectrum, we need to think more carefully about this color-rendering property. We can find how well the cell can accurately present an image by calculating what's called the color rendering index, or CRI.
- An approach that can lead to good CRIs is to replace organic absorber materials ith one that absorbs energy from the sun outside the visible range, which the cell appear as ordinary glass to the human eye. However, this place limitations on the efficiency of the cells.
- The transparent electrode used to collect a charge from these cells can be brittle and contain rare elements, such as indium.

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