Maximum power point tracking technique based on optimized adaptive differential conductance

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Abstract: Maximum power point (MPP) tracking technique based on an optimized adaptive differential conductance technique was developed in this paper. The performance of the algorithm developed in this paper was evaluated at solar irradiance of 1,000, 800 and 600 W/m² and at temperature of 298, 328 and 358 K. From the simulation results, it was observed that the impedance of the panel decreases as the irradiance increases while the impedance of the load is not affected by the irradiance. This technique was also validated with conventional incremental conductance (INC) technique. From the validation result, the resultant conductance of the optimized adaptive differential conductance technique at MPP is 0.0030 mho higher than resultant conductance at ideal condition while conventional technique has the resultant conductance of 0.0418 mho lower than the resultant conductance at ideal condition. From the analysis, the technique has a relative improvement of 6.0558% compared to the conventional INC technique. The simulation was done using Matrix Laboratory (MATLAB).

Subjects: Mathematics & Statistics; Computer Science; Engineering & Technology

Keywords: incremental conductance technique; maximum power point; maximum power point tracking; optimized adaptive differential conductance; photovoltaic

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Our research areas include digital signal processing (DSP), Digital Systems Design and Photovoltaics. They all contributed so intensively both in algorithm development and in result analysis. This project will help in the PV design for accurate tracking.

PUBLIC INTEREST STATEMENT

This paper developed a mathematical expression (model or algorithm) that will ensure optimum transfer of generated power from solar panel to load when implemented in the charge controller. The model was developed using a single diode model. When implemented in charge controller, the model will perform the function of matching the panel impedance to the load impedance to ensure optimum power transfer to the load. The significance of this model is that it will lead to the implementation of better MPPT-based charge controller for photovoltaic application. Charge controller built using this model will maximize power transfer from PV panel to the load with minimal power loss. The maximum power is transferred to load when the panel conductance is equal to the load conductance and this occurs at maximum power point. The model is very fast and accurate in matching panel impedance and load impedance.
1. Introduction

In the past few years, solar energy is one of the most important renewable energy sources that have been gaining increased attention. The amount of energy supplied to the earth by the sun in a day is sufficient to power the total energy needs of the earth in a year (Azimi, Dehkordi, & Niroomand, 2012). A comparative study of the world energy consumption released by International Energy Agency shows that in 2050, more than 45% of necessary energy in the world will be solely produced by solar arrays.

The basic structural unit of a solar system is the PV module, which consists of solar cells (Safari & Mekhilef, 2011). A solar cell converts the energy in the photons of sunlight into electricity by means of the photovoltaic phenomenon found in the certain type of semiconductors such as silicon, germanium, and selenium.

Photovoltaic (PV) systems are rated in terms of maximum power which is the highest power that can be generated by PV system under Standard Test Condition (STC). The power output efficiency of the solar module depends on many factors such as temperature, irradiance and spectral characteristics of sunlight (Safari & Mekhilef, 2011). At STC the temperature is 25°C, solar irradiance is 1,000 W/m², air mass is 1.5, wind speed is 2 m/s and solar panels tilt angle when it faces south is 30° (Eze & Olisa, 2015; Topic, Brecl, Kurnik, & Sites, 2006). Under normal operating conditions, maximum power generation from PV is not possible because the PV panel cannot always be operating at optimum power. PV systems generate the highest amount of power when the incident sun beam is perpendicular to the panel. The effective utilization of power from the sun using PV systems is improved by adding PV Efficiency Enhancement (EE) systems. Examples of EE systems are the solar tracking system and maximum power point (MPP) tracking systems.

The solar tracking system was the conventional method used to align PV panel to the direction where the solar irradiation is highest. The main drawback of this technique was that the solar tracking system is so expensive, difficult to maintain and the power generated is not well utilized due to power losses during transfer (Nguyen, Low, & Member, 2010). Due to the drawbacks of solar tracking techniques, maximum power point tracking (MPPT) was introduced. For the power generated by the PV system to be utilized well, MPPT technique is developed to enhance the utilization of power generated by the PV. Not all the power generated by PV panel is transferred to the load.

PV modules transfer the highest percentage of power generated to the load at MPP. MPP is a point along the P-V characteristic of a PV panel where the photovoltaic impedance is equal to the load impedance. It is also a point where there is negligible energy loss in the transmission of the generated power to the load. MPP along the P-V curve is detected using MPPT techniques. MPPT is the method of operating the photovoltaic system in a manner that allows the modules to transfer most of the power generated to the load. It is implemented in charge controllers alongside battery charge level monitoring system. MPPT varies the electrical operating point of the PV system so that the module will deliver nearly all the generated power to the load. It ensures that maximum power is transferred from the photovoltaic (PV) panel to the load (Chafle & Vaidya, 2013).

An example of MPP technique is incremental conductance (INC) method. INC method makes use of instantaneous conductance (panel) and INC (load) to determine the MPP. Resultant conductance is determined by the instantaneous conductance \( \frac{1}{v} \) and INC \( \frac{dv}{dv} \) as shown in Equation (1). For an ideal INC, the resultant conductance (the slope of the P-V curve) at MPPT is zero as in (2). For a perfect condition to be achieved in MPPT based on INC technique, Equation (2) must be satisfied (Chafle & Vaidya, 2013).
Figure 1 shows the plot of power and resultant conductance against voltage for an ideal maximum power point tracking technique. Figure 1 shows that power is at its maximum when the resultant conductance (\(\Upsilon\)) is zero and it occurs at \(V_{mpp}\). It is also observed from Figure 1 that power at MPP (\(P_{mpp}\)) occurs at \(V_{mpp}\). Any MPPT technique with resultant conductance equals to zero at \(V_{mpp}\) and maximum power at \(V_{mpp}\) is an ideal maximum point tracking technique. Ideally, maximum power occurs when the resultant conductance is equal to zero.

\[
\Upsilon = \frac{dI}{dv} + \frac{I}{v}
\]

(1)

The objective of this paper is to develop an optimized adaptive differential conductance technique that will accurately track the MPP. This technique was developed to solve the problem of conventional INC technique such as tracking accuracy.

The difference between optimized adaptive differential conductance technique and the conventional incremental technique is the replacement of \(\frac{I}{V}\) with \(\frac{I_{mpp}}{V_{mpp}}\). In this paper, \(\frac{I}{V}\) as replaced with \(\frac{I_{mpp}}{V_{mpp}}\) to ensure that MPP is tracked with better accuracy.

2. Derivation of optimized adaptive differential conductance technique

Optimized adaptive differential conductance technique is a modified INC technique that is developed using a single diode model of the solar cells. A single diode model is given in Figure 2. The circuit consists of the series resistor (\(R_s\)) and a shunt resistor (\(R_{sh}\)). A large value of series resistor leads to the large voltage drop across it and this leads to drop in terminal voltage for the same current. Series resistance losses are most important at high illumination intensities (Mahapatro, 2013). \(R_{sh}\) are added to the circuit which limits the performance of the cell and also accounts for the dissipative phenomena at the cell internal losses. This implies that very high value of \(R_{sh}\) leads to significant reduction in short circuit current. The parallel resistance takes care of the recombination losses,
mainly due to thickness, surface effect and the non-ideality of the junction. The circuit also consists of the photovoltaic currents \( I_{ph} \), the diode current \( I_D \) and shunt current \( I_{sh} \). The value of \( R_s \) and \( R_{sh} \) modifies shunt circuit current of the cell in a single diode equivalent circuit of PV, Photo generated \( I_{ph} \) and the following equivalent electrical circuit results as in Figure 2.

Applying Kirchhoff's law to the nodes of the circuit of Figure 2 yields (3) (Al-hamadi, 2014).

\[
I = I_{ph} - I_D - I_{sh} \tag{3}
\]

where, \( I \) = Output current (load current), \( I_{ph} \) = Photo generated current, \( I_D \) = Diode current and \( I_{sh} \) = Shunt current

For all environmental conditions, current generated by the photovoltaic cell \( I_{ph} \) is expressed by (4) (Chouder, Silvestre, Sadaoui, & Rahmani, 2012).

\[
I_{ph} = I_{sc} \left[ 1 + k_i (T - T_{ref}) \right] \frac{G}{G_{ref}} \tag{4}
\]

where, \( I_{sc} \) = Short circuit current (A), \( k_i \) = Shunt circuit current temperature coefficient of the cell (°C), \( T \) and \( T_{ref} \) are the working temperatures of the cell and the reference temperature of the cell respectively in Kelvin, and \( G \) and \( G_{ref} \) are the solar radiation on the cell surface and reference solar radiation respectively in W/m².

However, at STC, Equation (4) becomes \( I_{ph} = I_{sc} \).

The current passing through the diode \( I_D \) in this type of system is given by (5).

\[
I_D = I_0 \left( \frac{qV}{A n k T} - 1 \right) \tag{5}
\]

where, \( q \) = Electron charge \((1.602 \times 10^{-19} \text{C})\), \( k \) = Boltzmann’s constant \((1.3865 \times 10^{-23} \text{J/K})\), \( T \) = Cell temperature in Kelvin, \( A \) = Diode ideality constant \((A = 2 \text{ for Silicon, 1 for Germanium})\), \( n \) = Number of PV cells in series, and \( I_0 \) = Reverse saturation current of the diode and is given by (6)

\[
I_0 = I_{is} \left[ \frac{T}{T_{ref}} \right]^3 \text{Exp} \left[ \left( \frac{q E_{gap}}{A k} \right) \left( \frac{1}{T_{ref}} - \frac{1}{T} \right) \right] \tag{6}
\]

where, \( E_{gap} \) = Energy band gap of the semiconductor material (Andalibi, Rostami, & Darvish, 2016; Bellia, Youcef, & Fatima, 2014), and \( I_{is} \) = Diode saturation current and it is given by (7)

\[
I_{is} = \frac{I_{sc}}{\text{Exp} \left( \frac{E_{gap}}{A k T_{ref}} - 1 \right)} \tag{7}
\]

where \( I_{sc} \) and \( V_{oc} \) are the short circuit current and open circuit voltage respectively.

\( I_{sh} \) is the saturation current through the shunt resistance and using current division rule it becomes

\[
I_{sh} = \frac{V_D}{R_{sh}} = \frac{V + IR_s}{R_{sh}} \tag{8}
\]

Substituting (5) and (8) into (3), then (3) yields Equation (9)

\[
I = I_{ph} - I_0 \left( \frac{q(V + IR_s)}{A n k T} - 1 \right) - \frac{V + IR_s}{R_{sh}} \tag{9}
\]
Equation (9) is a general I-V characteristic equation of PV cell based on single diode model (Kumar, Shaktawat, Kumar, & Lal, 2013).

2.1. Assumption and approximations of some parameters made in this work

In this research work, Equations (10) to (19) are general equations that lead to successful development of the model. Equations (20), (21) and (23) are the models developed in this paper. They are used for calculating the voltage at the MPP, current at MPP and optimized adaptive differential conductance respectively.

**Case 1**: Using a single diode model, for \( n \)-cell PV with \( R_{sh} \) very large and \( R_s \) very small, \( I_{sh} \) will tend to zero and therefore (4) can be rewritten as in (10) (Abd, Wooi, & Selvaraj, 2013; Visweswara, 2013).

\[
I = I_{ph} - I_0 \left( \exp \frac{q(V + IR_s)}{AnkT} - 1 \right) - 0 \tag{10}
\]

Equation (10) can be further simplified as shown in (11).

\[
I = I_{ph} - I_0 \left( \exp \frac{q(V + IR_s)}{AnkT} \right) \tag{11}
\]

**Case 2**: At open circuit, \( I = 0 \) and \( V = V_{oc} \), therefore (11) becomes (12) (Kumar et al., 2013).

\[
I_{ph} = I_0 \left[ \exp \left( \frac{qV_{oc}}{AnkT} \right) \right] \tag{12}
\]

Substituting (4) in (12), the open circuit voltage \( (V_{oc}) \) is rewritten as (13).

\[
V_{oc} = \frac{AnkT}{q} \log_e \left[ \frac{I_{sc} \left( 1 + k_i \left( T - T_{ref} \right) \right) G_{ref}}{I_0} \right] \tag{13}
\]

**Case 3**: At short circuit current \( V = 0 \) and \( I_{sc} \) will be written as in (16) (Mahapatro, 2013). Equation (14) can be rewritten as in (15).

\[
I_0 \left( \exp \frac{qI_{sc}R_s}{AnkT} \right) = \left[ I_0 + \frac{1}{1000} \right] \tag{14}
\]

\[
\exp \frac{qI_{sc}R_s}{AnkT} = 1 + \frac{1}{1000} \tag{15}
\]

To obtain the short circuit current of a single diode model, Equation (15) can be rewritten as in (16). Substituting (16) and (4) in (11), the load current of the PV cell is given as in (17).

\[
I_{sc} = \frac{AnkT}{qR_s} \log_e \left( 1 + \frac{1}{1000I_0} \right) \tag{16}
\]

The power delivered to the load by the PV system is given by (18). Substituting (17) in (18) and differentiating with respect to \( V \) gives (19).

\[
P = VI \tag{18}
\]
\[ \frac{dp}{dv} = \left( \frac{AnkT}{qR_s} \right) \log_e \left( 1 + \frac{1}{1000I_0} \right) \left[ 1 + \frac{k_i(T - T_{ref})}{G_{ref}} \right] \frac{G}{G_{ref}} - I_0 \exp \left( \frac{qV}{AnkT} \right) \left[ \frac{qV}{AnkT} + 1 \right] \]  \hspace{1cm} (19)

At MPP \( \frac{dp}{dv} = 0 \). Solving Equation (19) for \( V \) at MPP, Equation (20) is obtained.

\[ V_{mpp} = \frac{AnkT}{q} \log_e \left( \frac{AnkT}{qR_s} \log_e \left( 1 + \frac{1}{1000I_0} \right) \left[ 1 + \frac{k_i(T - T_{ref})}{G_{ref}} \right] \frac{G}{G_{ref}} \right) - I_0 \exp \left( \frac{qV_{mpp}}{AnkT} \right) \]  \hspace{1cm} (20)

To determine the current of the PV cell at MPP (\( I_{mpp} \)), (20) is substituted in (11) and (21) is obtained.

\[ I_{mpp} = \left( \frac{AnkT}{qR_s} \log_e \left( 1 + \frac{1}{1000I_0} \right) \left[ 1 + \frac{k_i(T - T_{ref})}{G_{ref}} \right] \frac{G}{G_{ref}} \right) - I_0 \left[ \exp \left( \frac{qV_{mpp}}{AnkT} \right) \right] \]  \hspace{1cm} (21)

Equation (20) and (21) represents the voltage and current at MPP of a PV panel respectively.

To determine the ratio of output current to the output voltage of the PV cell, differentiate (11) with respect to cell output voltage and Equation (22) is obtained.

\[ \frac{dI}{dV} = \frac{qI_0}{AnkT} \exp \left( \frac{qV}{AnkT} \right) \]  \hspace{1cm} (22)

But the resultant conductance of the system is given by (23) where \( \Upsilon \) is the resultant conductance (in mho) and \( \frac{dI}{dV} \) the slope in A/V.

\[ \Upsilon = \left( \frac{I_{mpp}}{V_{mpp}} - \frac{dI}{dV} \right) \]  \hspace{1cm} (23)

When (20), (21) and (22) are substituted in (23), Equation (24) is obtained.

\[ \Upsilon = \left( \frac{AnkT}{qR_s} \log_e \left( 1 + \frac{1}{1000I_0} \right) \left[ 1 + \frac{k_i(T - T_{ref})}{G_{ref}} \right] \frac{G}{G_{ref}} \right) - I_0 \left[ \exp \left( \frac{qV_{mpp}}{AnkT} \right) \right] - \frac{qI_0}{AnkT} \exp \left( \frac{qV}{AnkT} \right) \]  \hspace{1cm} (24)

Equation (24) is the model developed in this paper. This model can be compared with the conventional INC model represented in (2). This technique differs from the conventional INC technique as it considered \( \frac{1}{V_{mpp}} \) instead of \( \frac{1}{V} \) and this leads to better accuracy.

From (24), the conductance of the PV panel \( \left( \frac{1}{Z_{panel}} \right) \) and conductance of the load \( \left( \frac{1}{Z_{load}} \right) \) are represented as in (25) and (26) respectively.

\[ \frac{1}{Z_{panel}} = \left( \frac{AnkT}{qR_s} \log_e \left( 1 + \frac{1}{1000I_0} \right) \left[ 1 + \frac{k_i(T - T_{ref})}{G_{ref}} \right] \frac{G}{G_{ref}} \right) - I_0 \left[ \exp \left( \frac{qV_{mpp}}{AnkT} \right) \right] \]  \hspace{1cm} (25)

\[ \frac{1}{Z_{load}} = \frac{qI_0}{AnkT} \exp \left( \frac{qV}{AnkT} \right) \]  \hspace{1cm} (26)

For maximum power transfer to be achieved, \( \Upsilon \) must be equal to zero and therefore, \( \frac{1}{Z_{panel}} = \frac{1}{Z_{load}} \).

This technique achieves this by balancing the impedance of the photovoltaic panel with that of the...
Comparing Equation (2) and (23), it is observed that (2) differentiated only the voltage and current but (23) differentiated the voltage and current at MPP which will give accurate MPP.

2.2. Performance metrics
Performance metrics are measurement standard that is used to evaluate the performance of models. Ideal MPPT Accuracy (IMTA) will be used to evaluate the effectiveness of the proposed model. This is obtained by taking the absolute difference of the average mean of new and old techniques, dividing it by the old technique and taking the percentage as shown in Equation (27) where \( N \) is the number of data points.

\[
\text{IMTA} = \left( \frac{\frac{1}{N} \sum Y_{\text{old}} - \frac{1}{N} \sum Y_{\text{new}}}{\frac{1}{N} \sum Y_{\text{old}}} \right) \times 100
\]  

(27)

The performance of proposed model was validated using conventional incremental conductance. The conventional incremental conductance technique is selected because it has good performance, low cost and easy to implement (Safari & Mekhilef, 2011).

2.3. Parameters and definitions
The input and output parameters used in the model development are explained as shown in Table 1.

| Table 1. The input and output parameters |
|-----------------------------------------|
| **Input data**                          | **Output data**                         |
| Names of parameter | Symbol | Value | Names of parameter | Symbol |
| Reverse saturation current | \( I_0 \) | 0.07 A | Output power | \( P \) |
| Series resistance | \( R_s \) | 0.008 Ω | Open circuit voltage | \( V_{oc} \) |
| Diode ideality factor | \( A \) | 2 | Short circuit current | \( I_{sc} \) |
| Number of cells | \( n \) | 100 | Output current | \( I \) |
| Electron charge | \( Q \) | \( 1.6 \times 10^{-19} \) C | Resultant conductance | \( \Upsilon \) |
| Boltzmann’s constant | \( k \) | \( 1.3805 \times 10^{-23} \) J/K | Current maximum power point | \( I_{mpp} \) |
| Reference temperature | \( T_{ref} \) | 298 K | Load conductance (slope) | \( \frac{dI}{dV} \) |
| Working temperatures | \( T \) | 298, 328, 358 K | Voltage maximum power point | \( V_{mpp} \) |
| Reference irradiance | \( G_{ref} \) | 1,000 W/m\(^2\) | Photovoltaic current | \( I_{ph} \) |
| Working irradiance | \( G \) | 1,000, 800, 600 W/m\(^2\) | Panel conductance | \( \frac{I_{mpp}}{G_{mpp}} \) |
| Voltage | \( V \) | 0–\( V_{oc} \) | | |

The data obtained from the Equations (2), (18) and (24) were shown in Tables 2–5. Considering Table 2, results showed how resultant conductance and output power of PV system varies with PV voltage at STC. From table, it was observed that the power output increased with increase in voltage (\( V \)) for \( V \leq V_{mpp} \) and decreased with increase in \( V \) for \( V > V_{mpp} \). On the other hand, the resultant conductance varied inversely as \( V \) for \( 0 \leq V \leq V_{oc} \). For \( V \leq V_{mpp} \) the resultant conductance is positive and this implies that the model is forwardly tracking the MPP. For \( V > V_{mpp} \) the resultant conductance is negative and this implies that the model is backwardly tracking MPP.

The relationship in Table 2 was clearly shown in Figure 3. From Figure 3, resultant conductance is positive and it varies inversely with voltage for \( V \leq V_{mpp} \). On the other hand, as the power is increasing, the voltage is also increasing for \( V \leq V_{mpp} \). From the point that \( V_{mpp} \) is attained, the power started varying inversely with the voltage. However, the resultant conductance continues to be inversely proportional to the voltage, though, it is negative in this region. The change in sign of the resultant conductance about the MPP makes the model adaptive in tracking MPP.
Table 3 showed how resultant conductance and power varies with the voltage at different irradiance. It was observed from the table that the resultant conductance was directly proportional to the received irradiance for all values of the input voltage. The results showed that the higher the value of irradiance, the higher the value of resultant conductance. This is because the impedance of panel falls with the increase in irradiance while the impedance of the load is constant. The relationship in Table 3 was clearly shown in Figure 4.

Figure 4 showed the resultant conductance-voltage relationship at 298 K and 600, 800 and 1,000 W/m². From figure, it was observed that the resultant conductance increases as the irradiance increases and vice versa. This is because the impedance of the panel decreased as the irradiance is increasing while the impedance of the load is not affected by the irradiance. This showed that matching of panel impedance with load impedance using this model is faster at low irradiance but less accurate.

### Table 2. The resultant conductance (ϒ) and power varies with voltage at 1,000 W/m² and 298 K (STC) for the proposed model

| Data point | ϒ (mho) | Power (W) | Voltage (V) |
|------------|---------|-----------|-------------|
| 1          | 0.3903  | 0         | 0           |
| 2          | 0.3832  | 19.5811   | 2.1758      |
| 3          | 0.3722  | 38.9168   | 4.3516      |
| 4          | 0.3554  | 57.8128   | 6.5274      |
| 5          | 0.3298  | 75.9383   | 8.7032      |
| 6          | 0.2906  | 92.7358   | 10.879      |
| 7          | 0.2308  | 107.274   | 13.0548     |
| 8          | 0.1395  | 118.009   | 15.2306     |
| 9          | −8.3243 x 10⁻⁶ | 122.395 | 17.4064     |
| 10         | −0.2131 | 116.262   | 19.5822     |
| 11         | −0.5386 | 92.8034   | 21.758      |
| 12         | −1.0359 | 40.9619   | 23.9338     |

### Table 3. The resultant conductance (ϒ) varies with voltage at varying Solar irradiance and temperature of 298 K for the proposed model

| 600 W/m² | 800 W/m² | 1,000 W/m² | Voltage (V) |
|----------|----------|------------|-------------|
| ϒ (mho)  | ϒ (mho)  | ϒ (mho)    |             |
| 0.2539   | 0.3235   | 0.3903     | 0.0000      |
| 0.2467   | 0.3163   | 0.3832     | 2.1758      |
| 0.2357   | 0.3053   | 0.3722     | 4.3516      |
| 0.2189   | 0.2885   | 0.3554     | 6.5274      |
| 0.1933   | 0.2629   | 0.3298     | 8.7032      |
| 0.1542   | 0.2237   | 0.2906     | 10.879      |
| 0.0944   | 0.1639   | 0.2308     | 13.0548     |
| 0.003    | 0.0726   | 0.1395     | 15.2306     |
| −0.1365  | −0.0669  | −8.3243 x 10⁻⁶ | 17.4064   |
| −0.3496  | −0.28    | −0.2131    | 19.5822     |
| −0.6751  | −0.6055  | −0.5386    | 21.7580     |

Table 3 showed how resultant conductance and power varies with the voltage at different irradiance. It was observed from table that the resultant conductance was directly proportional to the received irradiance for all values of the input voltage. The results showed that the higher the value of irradiance, the higher the value of resultant conductance. This is because the impedance of panel falls with the increase in irradiance while the impedance of the load is constant. The relationship in Table 3 was clearly shown in Figure 4.
**Table 4. Variation of resultant conductance with voltage at 1,000 W/m² irradiance for varying temperatures for the proposed model**

| Temperature | Voltage (V) | Resultant Conductance (mho) |
|-------------|-------------|------------------------------|
| 298 K       |             | 0.3903, 0.3832, 0.3722, 0.3554, 0.3298, 0.3006, 0.2308, 0.1395, $-8.3243 \times 10^{-6}$ | 0.0000, 2.1758, 4.3516, 6.5274, 8.7032, 10.8790, 13.0548, 15.2306, 17.4064, 19.5822, 21.7580, 23.9338 |
| 328 K       |             | 0.3403, 0.3345, 0.3259, 0.3134, 0.2949, 0.2678, 0.2280, 0.1694, 0.0834 | 2.1758, 4.3516, 6.5274, 8.7032, 10.8790, 13.0548, 15.2306, 17.4064, 19.5822, 21.7580, 23.9338 |
| 358 K       |             | 0.2909, 0.2861, 0.2793, 0.2696, 0.2557, 0.2361, 0.2081, 0.1683, 0.1117 | 2.1758, 4.3516, 6.5274, 8.7032, 10.8790, 13.0548, 15.2306, 17.4064, 19.5822, 21.7580, 23.9338 |

**Figure 3.** Plot of resultant conductance and power against voltage for the proposed model.

**Figure 4.** Plot of resultant conductance against voltage at different irradiance for the proposed model.
Table 4 showed how the resultant conductance varies with the voltage at 1,000 W/m² irradiance at 298, 328 and 358 K. From table, it was observed that resultant conductance varied inversely with the temperature for \( V \leq V_{mpp} \). However, for \( V > V_{mpp} \), the resultant conductance is directly proportional to the temperature. This is because panel impedance decreases with the increase in panel temperature (this behaviour is right since the panel is made from semiconductor) and panel temperature has no effect on the load impedance. Table 4 also showed that the model tracks MPP faster and more accurately at low temperature. The relationship in Table 4 was clearly shown in Figure 5.

Figure 5 showed how the resultant conductance varies with voltage for temperatures of 289, 328 and 358 K. The characteristic behaviour in Figure 5 showed that the resultant conductance was inversely proportional to the temperature of the PV panel for \( V \leq V_{mpp} \) and directly proportional to the temperature for \( V > V_{mpp} \). Figure also showed that the model tracks MPP faster and more accurately at low temperature.

Table 5. Variation of resultant conductance with voltage at 600 W/m² and 298 K for the proposed model and conventional incremental conductance technique

| Data point | Optimized adaptive differential conductance (OADC) at 600 W/m² | Conventional incremental conductance at 600 W/m² | Powers at 600 W/m² | Voltage (V) |
|------------|---------------------------------------------------------------|--------------------------------------------------|-------------------|------------|
|            | Resultant conductance (mho)                                   | Resultant conductance (mho)                      | P (W)             |            |
| 1          | 0.2539                                                        | 0.2090                                           | 0.0000            | 0.0000     |
| 2          | 0.2467                                                        | 0.2018                                           | 11.6556           | 2.1758     |
| 3          | 0.2357                                                        | 0.1909                                           | 23.0658           | 4.3516     |
| 4          | 0.2189                                                        | 0.1741                                           | 34.0363           | 6.5274     |
| 5          | 0.1933                                                        | 0.1485                                           | 44.2363           | 8.7032     |
| 6          | 0.1542                                                        | 0.1093                                           | 53.1083           | 10.8790    |
| 7          | 0.0944                                                        | 0.0495                                           | 59.7210           | 13.0548    |
| 8          | 0.0030                                                        | −0.0418                                          | 62.5302           | 15.2306    |
| 9          | −0.1365                                                       | −0.1813                                          | 58.9910           | 17.4064    |
| 10         | −0.3496                                                       | −0.3944                                          | 44.9322           | 19.5822    |
| 11         | −0.6751                                                       | −0.7199                                          | 13.5483           | 21.7580    |
Table 5 showed how the resultant conductance varies with the voltage at 600 W/m² and 298 K for the proposed and conventional INC technique. From table, it was observed that at 600 W/m² and 298 K, the resultant conductance of optimized adaptive differential conductance was larger than the resultant conductance of conventional INC technique. It was also observed that at \( V_{mpp} \), the resultant conductance of the proposed technique is closer to the value for the ideal model (zero) compared to the resultant conductance of the INC technique. Using Equation (27), it was observed that the proposed model has accuracy improvement of 6.0558% over the conventional INC technique. However, the speed of tracking the MPP is the same for both models. This is because the MPP occurs at data point eight for the two models.

The results in Table 5 were clearly presented in Figure 6. From figure, it was observed that the plot of the resultant conductance of the proposed technique against voltage intersected the plot of power against the voltage at the \( V_{mpp} \) while that of the INC technique intersected the power plot at a point far from \( V_{mpp} \). This also showed that the developed technique has better accuracy. However, the data point plots of each model correspond showing that the two models have the same speed (Table 6).

![Figure 6. Plot of resultant conductance and power against voltage.](image-url)

### Table 6. Symbols and its nomenclatures

| Symbol | Nomenclature | Lowercase | Uppercase |
|--------|--------------|-----------|-----------|
| A      | alpha        | alpha     |           |
| N      | nu           | nu        |           |
| Q      | qu           | qu        |           |
| k      | kappa        | kappa     |           |
| \( \rho \) | rho   | rho       |           |
| V      | Nu           | Nu        |           |
| T      | tau          | tau       |           |
| \( \iota \) | lota | lota      |           |
| \( \Upsilon \) | Gamma | Gamma     |           |
5. Conclusion
In this paper, optimized adaptive differential conductance technique was successfully developed.

The model developed was simulated using MATLAB. From the result, it was observed that the new model was very accurate. It tracks the MPP faster and more accurately at low temperature. On the other hand, the MPP is tracked faster at low irradiance but the tracking is more accurate at higher irradiance. In comparison with conventional INC technique, it was noticed that the optimized adaptive differential conductance technique developed was 6.0558% more accurate. The importance of the result obtained in this research is that it showed the expected performance of the techniques developed. The result will act as a lookup table and chart for designers as it concerns some input and expected out parameters. The significance of the method developed in this paper is that it will lead to the implementation of better MPPT-based charge controller for photovoltaic application. Charge controller developed using this method will maximize the transfer of power from the PV panel to the load with minimal loss.

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