UNIVERSITY OF NAIROBI

MAXIMUM POWER POINT TRACKER

FOR SOLAR CHARGE CONTROLLER

FINAL YEAR PROJECT

PROJECT NO. 64

BY: GITONGA M. JAMES

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SUPERVISOR: MR. COLLINS OMBURA

EXAMINER: MR. DHARMADHIKARY

This is a final year Project report is submitted in partial fulfillment for the award of the degree of Bachelor of Science in Electrical and Electronics Engineering

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DEDICATION

Special dedication to my dearest Parents, Brothers and Sister for their continual encouragement and relentless support towards my entire education.

May God bless you all.
ACKNOWLEDGEMENT

This project will not have been successful without the generous assistance of my supervisor Mr. C. Ombura who offered valuable information required for accomplishment of this project. My sincere acknowledgement also goes to my parents for their support throughout my study live in college.

Support offered by fellow colleagues, Lab technicians in the department of Electrical and Electronics cannot be ignored and their efforts have been greatly appreciated. Lastly my appreciation goes to God for enabling me be whom I am.
ABSTRACT

A simple but efficient Maximum Power Point Tracker (MPPT) is presented in this project, derived from nonlinear dynamics. Information from the natural switching ripple and constant voltage method is used to support the maximizing process.

The technique takes advantage of the ripples, which are automatically present in power converters. The ripple is interpreted as a perturbation from which a gradient ascent optimization is realized. The technique converges to the maximum power point without the benefit of any array parameters or measurements.

The control algorithm is first synthesized and implemented, supported by Multisim 10.0 simulations and verified by experiments. The technique has a simple circuit implementation, thus reducing the complexity of the system. The resulting system has high-tracking efficiency of 96% and 88.7% power efficiency as compared to typical voltage regulator power efficiency of 70%. The unit is low-cost and can be easily fabricated in a printed board.

Photovoltaic arrays offers an environmentally friendly renewable source of electricity but this source of electricity is relatively costly and it success largely depends on the efficiency of power extraction from the PV. The MPPT of the array therefore becomes a key control in the device operation for a successful PV application.
LIST OF ABBREVIATIONS

$PV$  í Photovoltaic Array

$V_{mpp}$  í Maximum power point Voltage

$I_{mpp}$  í Maximum power point current

$I_{sc}$  í Photovoltaic array Short Circuit current

$V_{oc}$  í Photovoltaic Open circuit voltage

$MPPT$  í Maximum Power Point Tracker

$MPP$  í Maximum power point

$P_{mpp}$  í Maximum power point power

$P&O$  í Perturb and Observe

$V_{batt}$ í Battery Voltage

$I_{ph}$ í Photo generated current

$RCC$ í Ripple correlation Control

$Vc$ í Control Voltage

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1.0 INTRODUCTION

Photovoltaic (PV) offers an environment friendly source of electricity, which is relatively costly today. The maximum power point tracking (MPPT) of the photovoltaic for all sunshine and temperature conditions is a key to keep the output power per unit cost low for successful photovoltaic applications. Hence the objective of this project to design and implement an efficient Maximum Powerpoint Tracker for Solar Charge Applications.

1.1 What is a charge controller?

A charge controller, charge regulator or battery regulator limits the rate at which electric current is added to or drawn from electric batteries. It prevents overcharging and may prevent against overvoltage, which can reduce battery performance or lifespan, and may pose a safety risk. It may also prevent completely draining ("deep discharging") a battery, or perform controlled discharges, depending on the battery technology, to protect battery life. The terms "charge controller" or "charge regulator" may refer to either a stand-alone device, or to control circuitry integrated within a battery pack, battery-powered device, or battery recharger.

1.2 What is a maximum power point tracker?

MPPT is an electronic device that makes a PV array to operate in a manner that it produces maximum power that is capable of. It can also be referred to as a high frequency DC to DC converter that takes the DC input from the solar panels, change it to high frequency AC, and convert it back down to a different DC voltage and current to exactly match the panels to the batteries voltage. In applications where photovoltaic arrays are used to provide energy, maximum power trackers are used to correct for the variations in the current-voltage characteristics of the solar cells. From the illustration of a typical silicon cell I-V curve (Fig. 1) as the output potential of the panel increases, it produces significantly less current. The current-voltage curve will move and deform depending upon temperature, illumination, and consistency of cell quality in the panel.

Figure 1.0 is an idealized curve with no deformations due to cell damage or bypass diodes kicking in.
For the array to be able to put out the maximum possible amount of power, either the operating voltage or current needs to be carefully controlled.

This so-called maximum power point is seldom located at the same voltage the main system is operating at, and even if the two were equal initially, the power point would quickly move as lighting conditions and temperature change. Hence, a device is needed that finds the maximum power point and converts that voltage to a voltage equal to the system voltage.

1.3 Reasons why use an MPPT and not a charge controller

Most PV panels are built to put out a nominal 12 volts. But in actual fact, almost all "12 volt" solar panels are designed to put out from 16 to 18 volts. The problem is that a nominal 12 volt battery is pretty close to an actual 12 volts - 10.5 to 12.7 volts, depending on state of charge. Under charge, most batteries require from around 13.2 to 14.4 volts to fully charge.

A 130 watt solar panel. (Rated at a particular voltage and current) such as the Kyocera KC-130 (rated at 7.39 amps at 17.6 volts, 7.39 amps times 17.6 volts = 130 watts).

When the KC-130 solar panel is connected to a battery through a regular charge controller, the panel puts out 7.4 amps and the battery setting is at 12 volts under charge: 7.4 amps times 12 volts = 88.8 watts. Hence 41 watts is lost, but the panel is capable of delivering 130W. The 41 watts is lost due to a poor match between the panel and the battery. With a very low battery, say
10.5 volts, it's even worse! The loss can be as much as 35% (11 volts x 7.4 amps = 81.4 watts i.e. a loss of about 48 watts.

But when utilizing the MPPT solar charge controller, the controller matches the panel voltage to the battery voltage assuming a low battery, at 12 volts. A MPPT takes that 17.6 volts at 7.4 amps and converts it down, so that what the battery gets is now 10.8 amps at 12 volts. Now you still have almost 130 watts, and thus optimization of the power output.

Ideally, for 100% power conversion you would get around 11.3 amps at 11.5 volts, but you have to feed the battery a higher voltage to force the current in. In actual fact the output of the MPPT charge controller might vary continually to adjust for getting the maximum amps into the battery.

1.4 BRIEF DESCRIPTION OF MPPT ARCHITECTURE

The device that tracks the Maximum power point are known as Maximum Power Point Trackers, also called MPPTs or trackers they differ from solar trackers in that there are electrical while solar tracker are mechanical.

Most current designs of MPPTs consist of following major components:

- A switch mode converter and a
- A tracking section/control unit

The switch-mode converter is the core of the entire supply. This allows energy at one potential to be drawn, stored as magnetic energy in an inductor, and then released at a different potential. By setting up the switch mode section in various different topologies, either high-to-low (buck converter) or low-to-high (boost) voltage converters can be constructed. Normally, the goal of a switch-mode power supply is to provide a constant output voltage or current.
1.5 RECOGNITION OF PREVIOUS WORK:

To achieve desired results of maximum tracking different researchers have proposed different schemes.

1.5.1 Comparison of various maximum power point tracking techniques

Tracking the maximum power point (MPP) of a photovoltaic (PV) array is an essential part of a PV system. Various methods of tracking have been developed and implemented. These methods vary in complexity, sensors required, convergence speed, cost and implementation hardware. Hence a need to determine which method is effective for a given PV system. From the characteristic power curve of a PV array, the problem considered by any MPPT technique is to automatically find the voltage $V_{mpp}$ or current $I_{mpp}$ at which a PV array should operate to obtain the maximum power output $P_{mpp}$ under a given temperature and irradiance and changes due to aging.

Following is a brief discussion of the most commonly used MPPT techniques.

a) Hill-Climbing/perturb and Observe techniques

Hill-climbing involves a perturbation in the duty ratio of the power converter and P&O involves a perturbation in the operating voltage of the PV array. Perturbation of the duty ratio of power converter perturbs the PV array current and consequently perturbs the PV array voltage. Hence Hill-Climbing and P&O methods are different methods to envision the same fundamental method. From the characteristic curve of a PV array fig(1.0) it shows incrementing the voltage increases the power when operating on the left of MPP and decreases the power when operating on the right of MPP and vice versa. Therefore if there is an increase in power the subsequent perturbation should be increased and if the power decreases the perturbation should be reversed. This is summarized in a table 1.0

<table>
<thead>
<tr>
<th>Perturbation</th>
<th>Change in Power</th>
<th>Next Perturbation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive</td>
<td>Positive</td>
<td>Positive</td>
</tr>
<tr>
<td>Positive</td>
<td>Negative</td>
<td>Negative</td>
</tr>
<tr>
<td>Negative</td>
<td>Positive</td>
<td>Negative</td>
</tr>
<tr>
<td>Negative</td>
<td>Negative</td>
<td>Positive</td>
</tr>
</tbody>
</table>

Table 1.0: Perturbation Control

When the MPP is reached the system oscillates about the MPP. The oscillation can be minimized by reducing the perturbation size, but this consequently slows down the MPPT.
b) Incremental conductance

This method is based on the fact that the slope of the PV array power curve (as shown in fig (1.0) is zero at the MPP, positive on the left and negative on the right of the MPP this can be written as:

\[ \frac{dV}{dV} = 0, \text{ at MPP} \]
\[ \frac{dV}{dV} > 0, \text{ left of MPP} \]
\[ \frac{dV}{dV} < 0, \text{ right of MPP} \]

Since \( \frac{dP}{dV} = \frac{d(IV)}{dV} = I + V \frac{dI}{dV} \approx I + V \frac{\Delta}{\Delta} \) and hence the previous equations above can be rewritten as:

\[ \frac{\Delta}{\Delta} = -/ \]
\[ \frac{\Delta}{\Delta} > -/ \]
\[ \frac{\Delta}{\Delta} > -/ \]

Hence the MPP can be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance \( \frac{\Delta}{\Delta} \). Once the MPP is reached operation of the PV array is maintained at this point unless a change \( \Delta \) is noted, indicating a change in atmospheric conditions and the MPP. Increment size determines how fast the MPP is tracked. Fast tracking can be achieved with bigger increments but the system might not operate exactly at the MPP but instead oscillates around the MPP.

c) Constant reference Voltage Method

This technique is based on the linear relationship between \( V_{\text{batt}} \) and \( V_{\text{oc}} \) of the PV array, under varying irradiance and temperature levels. This can be written as:

\[ V_{\text{batt}} \approx K_1 + K_2 V_{\text{oc}} \]

Where \( K_1 \) and \( K_2 \) are constants.

d) Neural Network

Commonly in this technique, three layers are used; input layer, hidden layer and output layer. The number of nodes in each layer vary and are user dependent. The input variables can be PV array parameters like \( V_{\text{oc}} \) and \( I_{\text{sc}} \), atmospheric data like irradiance and temperature. The output data is usually one of several reference signals like duty cycle signal used to drive the power converter to operate at or close to the MPP. How close the operating point gets to the MPP depends on the algorithm used in the hidden layer and how well the neural network has been trained. The PV array is usually tested over months or years and the patterns of inputs and outputs of the neural network are recoded. Since PV arrays have different characteristics
a neural network has to be specifically trained for the PV array with which is to be used. To guarantee accuracy the neural network has to be periodically trained.

g) Ripple Correlation control (RCC)
When a PV array is connected to a power converter the switching action of the power converter imposes voltage and current ripple on the PV array. As a consequence the PV array voltage is subjected to ripple. Ripple correlation control uses the ripple to perform MPPT. RCC correlates the time derivatives of the time varying PV array power with the time derivative of the time varying PV array current or voltage to drive the power gradient to zero thus reaching the MPP. From the PV array power characteristic curve then we have if voltage \(v\) or current \(i\) is increasing and power \(p\) is increasing then the operating point is below MPP \((V < V_{MPP} \text{ or } I < I_{MPP})\) on the other hand if voltage \(v\) or current \(i\) is decreasing and power \(p\) is decreasing then the operating point is above MPP \((V > V_{MPP} \text{ or } I > I_{MPP})\)

Combining these two observation find that:

\[
\begin{align*}
\frac{dp}{dv} > 0 & \text{ if } v < V_{MPP} \\
\frac{dp}{dv} = 0 & \text{ if } v = MPP \\
\frac{dp}{dv} < 0 & \text{ if } v > V_{MPP}
\end{align*}
\]

And thus from the equations, a control strategy would be if \(\frac{dp}{dv} > 0\) then we deduce \(v < V_{MPP}\) and so we increase \(v\) so that operating point moves towards \(V_{MPP}\) and if \(\frac{dp}{dv} < 0\) then \(v > V_{MPP}\) decrease \(v\) instead but if \(v=V_{MPP}\) then we hold \(v\) constant as we are at the MPP.

h) Other MPPT techniques

- Array reconfiguration
- Current Sweep
- Fuzzy logic
- Fractional short circuit current
- Array Reconfiguration
- State based MPPT
- One Cycle Control (OCC)
- Linear Current Control
- DC Link Capacitor Droop Control
- Load I or V maximization
- Linear Reoriented Coordinates Method (LRCM)

The various MPPT techniques are analyzed in table 1.1 in Appendix 1.
CHAPTER TWO

2.0 PROJECT OVERVIEW

As the demand for electrical energy rises, extended research in electricity production from solar energy using Photovoltaic (PV) has also resulted. The basic advantage of this energy source being the environment friendliness and its abundance in nature. But despite the fact that Solar cells can be used to power a wide range of applications a solution is required to tune cost and efficiency requirement for a particular application.

The Photovoltaic array characteristic greatly influence the design of the converter and the control system needed to achieve the required design parameters, hence a need to analyze the characteristics of a PV array.

2.1 Photovoltaic Array Characteristics

The solar array is a nonlinear device it can be represented as a current source model as shown in fig (2.0)

![Photovoltaic Array equivalent circuit](image)

\[ I = I_{ph} - I_D - I_{SH} \]

Where

- \( I \) = Output current (amperes)
- \( I_{ph} \) = Photo generated current (amperes)
- \( I_D \) = Diode current (amperes)
- \( I_{SH} \) = Shunt current (amperes)
The current flowing through these elements governed by the voltage across them:

\[ V_j = V + IR_S \]

Where

\[ V = \text{Voltage across the output terminals (volts)} \]
\[ I = \text{Output current (amperes)} \]
\[ R_S = \text{Series resistance (Ω)} \]

By the Shockley diode equation, the current diverted through the diode is:

\[ I_D = I_O \left( 1 - \frac{1}{1 + e^{\frac{V_D}{kT/q}}} \right) \]

Where

\[ I_O = \text{reverse saturation current (amperes)} \]
\[ n = \text{diode ideality factor (1 for an ideal diode)} \]
\[ q = \text{elementary charge} \]
\[ k = \text{Boltzmann's constant} \]
\[ T = \text{absolute temperature} \]

*For silicon at 25°C, \( kT/q \approx 0.0259 \text{ volts.} \)*

By Ohm’s law, the current diverted through the shunt resistor is:

\[ I_{SH} = \frac{V}{R_{SH}} \]

Where \( R_{SH} = \text{shunt resistance (Ω)} \)

Substituting these into the first equation produces the characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltage:

\[ I = I_L - I_O \left( 1 - \frac{1}{1 + e^{\frac{V}{kT/q}}} \right) \]

If no load is connected with solar panel which is sitting in the sun, an open circuit voltage \( V_{oc} \) will be produced but no current follows. If the terminals of the solar panel are shorted together, the short-circuit current \( I_{SC} \) will flow but the output voltage will be zero. In both cases, no power is delivered by the solar panel. When a load is connected, we need to consider the \( I-V \) curve of the panel and the \( I-V \) curve of the load to figure out how much power can be delivered to the load. The maximum power point (MPP) is the spot near the knee of the \( I-V \) curve, and the voltage and current at the MPP are designated as \( V_{p1} \) and \( I_{p1} \). For a particular load, the maximum point is changes as the \( I-V \) curve is varies with the temperature, isolation, and shading.
2.1.2 Effects of temperature to a PV array

A good quality cell is about 15% efficient at converting solar radiation to electricity, so 85% of incident light heats the solar cell rather than contributing to electrical output. Temperature affects the characteristic equation in two ways: directly, via $T$ in the exponential term, and indirectly via its effect on $I_o$.

$$I = I_l - I_o \left( e^{q(v+J_{rs})/nkT} - 1 \right) - V + IRs/Rsh$$

While increasing $T$ reduces the magnitude of the exponent in the characteristic equation, the value of $I_o$ increases in proportion to $exp(T)$. The net effect is to reduce $V_{oc}$ linearly with increasing temperature. The magnitude of this reduction is inversely proportional to $V_{oc}$; that is, cells with higher values of $V_{oc}$ suffer smaller reductions in voltage with increasing temperature. For most crystalline silicon solar cells the reduction is about $-0.40\%/^\circ C$ [6].

The amount of photo generated current $I_{ph}$ increases slightly with increasing temperature because of an increase in the number of thermally generated carriers in the cell. This effect is slight, however, about $0.065\%/^\circ C$ for crystalline silicon cells.
Since the change in voltage is much stronger than the change in current, the overall effect on efficiency tends to be similar to that on voltage. This summarized fig. 2.2

![Fig 2.2 (a) Effect of T on PV Power](image1)

![Fig 2.2 (b) Effects of T on PV Current and Voltage](image2)

### 2.1.3 Effects of Irradiance on a solar array

Increasing the light-sensing area or light intensity per single solar cell produces a proportionate increase in the short-circuit current. The open-circuit voltage remains constant regardless of the light-sensing surface area, and is hardly changed at all even by the intensity of light. (However, it will drop drastically if the intensity of light is reduced in the extreme.)

![Fig 2.3 Effects of irradiance levels on a photovoltaic array](image3)
From above solar array analysis it shows there is a need to operate a solar panel at the MPP where the energy produced by a solar array.

2.2 BATTERY LOADS
For most renewable energy systems, the most important battery characteristics are the battery lifetime, the depth of discharge and the maintenance requirements of the battery.

Fig 2.4 Model of a Lead acid battery cell

From above model a lead acid battery terminal voltage may be given as

\[ V_{\text{batt}} = I_L R_e + V_e \]

Where \( R_e \) is the internal resistance and \( V_e \) is the induced emf.

Lead acid are the mostly widely used type of batteries for storage of electrical energy. This is largely due to their high output capacity, low self discharge rate, cheap as compared to the most common cells i.e. Nickel-Cadmium cells or Lithium. Some of its parameters will be discussed in subsequent sub topics.

2.2.1 Depth of discharge and Battery Capacity
The depth of discharge in conjunction with the battery capacity is a fundamental parameter in the design of a battery bank for a PV system, as the energy which can be extracted from the battery is found by multiplying the battery capacity by the depth of discharge. Batteries are rated either as deep-cycle or shallow-cycle batteries. A deep-cycle battery will have depth of discharge greater than 50%, and may go as high as 80%. To achieve the same useable capacity, a shallow-cycle battery bank must have a larger capacity than a deep-cycle battery bank.
2.2.2 Battery Efficiency
Lead acid batteries typically have coulombic efficiencies of 85% and energy efficiencies in the order of 70%.

2.2.3 Comparison of various lead acid battery types
Car battery - starter lighting ignition
- Designed to provide short burst of high current
- Cannot handle “deep discharge” applications

Deep discharge battery
- More rugged construction
- Bigger, thicker electrodes
- Calcium (and others) alloy: stronger plates while maintaining low leakage
- Current
- More space below electrodes for accumulation of debris before plates are shorted

2.2.4 To ensure extended battery life and safety the following are be taken into consideration when designing voltage converters for lead battery cells
- Avoid over-discharge, leads to “sulfation” and the battery is ruined. The reaction becomes irreversible when the size of the lead-sulfate formations become too large
- Avoid Overcharging as it causes other undesirable reactions to occur i.e.
  - Electrolysis of water and generation of hydrogen gas
  - Electrolysis of other compounds in electrodes and electrolyte, which can generate poisonous gasses
  - Bulging and deformation of cases of sealed batteries
- Battery charge management to extend life of battery:
  - Limit depth of discharge
  - When charged but not used, employ “float” mode to prevent leakage currents from discharging battery
  - Pulsing to break up chunks of lead sulfate
  - Trickle charging to equalize charges of series-connected cells
2.2.5 Battery Charging Control Methods

(i) Constant current charging
This is a simple charging method using constant currents for battery charging and the charging currents for the series connected batteries are equal. However, battery overcharging will result in the degradation of battery life. Small charging current will prolong the charging time.

(ii) Constant voltage charging
This constant voltage charging for battery can be easily implemented with simple and controls. During the initial stage of charging the possible large charging currents need to be limited to protect devices. When the battery voltage reaches the default value, charging voltage is held constant and charging current decreases with time. The charging will cause temperature rise and degradation of the battery life.

(iii) Two-step charging
Two-step charging method combines the constant current and constant voltage charging. In the first stage of charging, the batteries are charged by a constant current until the battery voltage reaches a preset voltage. In the second stage, a constant voltage is applied for battery charging.

(iv) Pulse charging
A pulse current is applied to the battery periodically, this provides the battery a relax time in charging process. The electrochemical reaction and neutralization of battery internal electrolyte are helpful to enhance the life cycle of battery. Using a large pulse current will shorten the battery charging time.

**TABLE 2.0: Lead acid Battery Characteristics**

<table>
<thead>
<tr>
<th></th>
<th>Fully Completely Charged</th>
<th>Discharged</th>
</tr>
</thead>
<tbody>
<tr>
<td>State of charge:</td>
<td>100%</td>
<td>0%</td>
</tr>
<tr>
<td>Depth of discharge:</td>
<td>0%</td>
<td>100%</td>
</tr>
<tr>
<td>Electrolyte concentration:</td>
<td>~6 molar</td>
<td>~2 molar</td>
</tr>
<tr>
<td>Electrolyte specific gravity:</td>
<td>~1.3</td>
<td>~1.1</td>
</tr>
<tr>
<td>No-load voltage:</td>
<td>12.6V-12.8V</td>
<td>11.7 V-12.0V</td>
</tr>
</tbody>
</table>

*(Specific battery types characteristics may vary)*
CHAPTER THREE

3.0 DESIGN SYNTHESIS

From analysis of the various MPP tracking techniques analysis (Appendix 1, Table 1.1) the techniques vary in many aspects, including simplicity, speed of convergence, digital versus analog implementation, sensors required, and need for parameterization. It is from these factors that the ripple control method blended with constant reference voltage method was chosen as the basis of realization of this project. Ripple control Correlation has the following characteristics:

- RCC has simple circuit implementations.
- Converges asymptotically to the maximum power point (MPP).
- Uses array current and voltage ripple, which must already be present if a switching converter, is used, to determine gradient information; no artificial perturbation is required.
- Achieves convergence at a rate limited by switching period and the controller gain.
- Does not rely on assumptions or characterization of the array or an individual cell.
- Have several straightforward circuit implementations, some of which are very inexpensive, analog versions.
- High reliability and tracking efficiency
- Due to the inherent low cost of implementation, RCC would be well suited for a modular application, which would use many small converters rather than a few large, expensive.

These features taken together make RCC the technique of choice. Many factors must be considered when designing a photovoltaic converter, so that no single method can be claimed to be the best converters. RCC is also appropriate for applications requiring a high rate of convergence, such as mobile systems that encounter rapidly changing light conditions (e.g. solar cars).
3.1 Synthesis of the control algorithm

The various control equation of the MPPT discussed in this project are synthesized as follows

3.1.1 Ripple correlation Control

The MPP of photovoltaic array varies with illumination temperature, radiation levels, ageing and other factors. By denoting these time varying parameters as \((\emptyset, \emptyset, \dot{\emptyset}..)\) from chain rule we \(\frac{dp}{dt}\) can be written as:

\[
\frac{dp}{dt} = \frac{\partial p}{\partial \emptyset} \cdot \dot{\emptyset} + \frac{\partial p}{\partial \emptyset} \cdot \dot{\emptyset} + \ldots
\]

\(\dot{\emptyset} \dot{\emptyset} \dot{\emptyset} \ldots\) (eqn. 1)

The noise terms \((\emptyset, \emptyset, \dot{\emptyset}..)\) in the equation above makes estimation of \(V_{MPP}\) difficult and requires \(V\) to be continually adjusted. By considering the unvarying \(V-P\) characteristic i.e. by neglecting the noise terms in the equation (1) above then differentiating the v-p curve we

\[
\begin{align*}
> 0 & < \\
= & = \\
< 0 & >
\end{align*}
\]

\(\dot{\emptyset} \dot{\emptyset} \dot{\emptyset} \ldots\) eqn 2

From the above a control strategy would to increase \(V\) when / > 0 for \(V < V_{MPP}\) and hence increasing \(V\) will bring it close to \(V_{MPP}\), similarly when / < 0 we decrease \(V\), as \(V > V_{MPP}\) but if / > 0 that is \(V=V_{MPP}\) then we hold \(V\) constant as we are at the MPP. Writing equation (eqn 2) in differential form:

\[
\begin{align*}
> 0 & < \\
= & = \\
< 0 & >
\end{align*}
\]

\(\dot{\emptyset} \dot{\emptyset} \dot{\emptyset} \ldots\) eqn 3

Which can know be represented in simple function \(= -k(V-V_{mpp})\) where \(k\) is positive coefficient associated with speed. (Larger \(K\), faster dynamic response) Observing that (eqn 1) and (eqn 2) have similar forms then we can deduce a simple control equation

\[
= k / , \text{where} \ K > 0
\]

Information on \(dp/dv\) neglecting noise terms in (eqn 1) then we need \((dp/dt)/(dv/dt) = / \) .

A suitable control algorithm would be:

\[
= / 
\]

But from the equation above an algebraic loop results as \(\text{ is found on both sides this equation has the following setbacks:}

i. Analogue dividers have many imperfections

ii. When \(= 0\) then control equation fails to hold point
By rearranging the equation as \( = \) this will destroy the sign in function

Because what we are interested in is getting the sign of the \( / \) then we can utilize the signum function to retrieve the signs. i.e. \( \text{sgn} \ x = -1 \) if \( x < 0 \)

\[
\text{sgn} \ x = +1 \quad \text{if} \quad x > 0
\]

\[
\text{sgn} \ x = 0 \quad \text{if} \quad x = 0
\]

Using modified signum where \( \text{sgn} \ x = -1 \) if \( x < 0 \)

\[
\text{sgn} \ x = +1 \quad \text{if} \quad x \geq 0
\]

from which the singularity problem is solved i.e. by utilizing a signum function that never return a zero.

Then we can rewrite \( / \) as \( \text{sgn}( \ / \ ) \equiv \text{sgn}( \ ) / \ ( ) \) which can also be written as

\[
\text{sgn}( \ ) / \ ( ) \equiv \text{sgn}( \ ) \ ( )
\]

Hence the final control equation becomes

\[
\text{Sgn}( \ ) \leftarrow \text{sgn}( \ ) \ ( )
\]

← denotes the assignment of information held on RHS of the control equation to the LHS of the control equation.

From the equation we conclude that the RHS of the control equation contains information on whether to increase or decrease \( ( \ ) \) to approach the MPP. But due to the fact that the signum function used have a discontinuity at the MPP then the system oscillates around the MPP.

\[
\text{Fig 3.1 Ripple Control block diagram}
\]

From the block diagram fig. (3.1), the photovoltaic array voltage and current are sensed and forms the inputs of the control loop. Power of the Panel is approximated by an analog multiplier. Two differentiators, an analog multiplier, two comparator and a XOR forms the control circuit of the Ripple control method.
3.1.2 Constant reference voltage control equation synthesis

In the constant reference voltage mode control (fig 3.2), instead of measuring both current and voltage parameters, only PV panel voltage is measured. The measured voltage \( V_{pv} \) multiplied by a constant and then added to fixed reference voltage \( V_{ref} \) in an error amplifier. The error signal \( (Vc) \) is compared to a sawtooth waveform to generate pulses with the required duty cycle. These pulses are then used to drive the MOSFET switch of the buck converter. This control mode is utilized when using battery loads.

A sawtooth waveform of magnitude 5 Volts raised by a constant dc voltage of 5 volts was used in the generation of Pulse width modulated Pulses.

![Block Diagram](image)

**Fig 3.2 Constant reference Voltage Control Method block diagram**

The required control voltages for the various duty cycles were calculated and tabulated. (12 volts lead acid battery, charged using Constant voltage charging method was assumed in the calculations).

24
Table: 3.1 Control voltage determination (Charging voltage = 14 Volts)

<table>
<thead>
<tr>
<th>PV array Voltage</th>
<th>Required Duty Cycle</th>
<th>Required Control Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>14.74</td>
<td>0.95</td>
<td>5.25</td>
</tr>
<tr>
<td>15.55</td>
<td>0.90</td>
<td>5.5</td>
</tr>
<tr>
<td>16.47</td>
<td>0.85</td>
<td>5.75</td>
</tr>
<tr>
<td>17.5</td>
<td>0.80</td>
<td>6</td>
</tr>
<tr>
<td>18.7</td>
<td>0.75</td>
<td>6.25</td>
</tr>
<tr>
<td>20</td>
<td>0.70</td>
<td>6.5</td>
</tr>
<tr>
<td>21.54</td>
<td>0.65</td>
<td>6.75</td>
</tr>
<tr>
<td>23.4</td>
<td>0.60</td>
<td>7</td>
</tr>
<tr>
<td>25.45</td>
<td>0.55</td>
<td>7.25</td>
</tr>
</tbody>
</table>

From the data in table 3.1 a graph was plotted for the Duty cycle against PV array voltage.

![Duty cycle versus PV array voltage](image)

**Fig 3.3** Duty cycle versus PV array voltage

Using the data in table 3.1 a graph of required control voltage versus PV Voltage was also plotted.
Fig 3.4 Required Voltage versus PV array voltage

From graph figure 3.4 a linear equation was extracted using linear regression for PV voltage range of 14 volts- 25 volts. PV voltage was used as the independent variable and the required voltage as the dependent variable. From the linear regression equation the following results were obtained,  $A = 2.4669$,  $B = 0.19525$

And hence the control equation  

$Y = 2.4 + 0.19525X$

Where $Y$ is the required control voltage and $X$ is the PV array Voltage,

Thus the control equation becomes

$V_c = 2.5 + 0.2V_{ph}$
3.2 PRACTICAL REALIZATION OF THE CONTROL EQUATION

The following MPPT sub-systems shall be discussed in details:

- Power Converter (Buck converter)
- Square wave generator
- Voltage Sensor
- Current Sensor
- Comparators
- Differentiators
- FET analog multiplier
- Constant Voltage control Circuit

3.2.1 BUCK CONVERTER

The MPPT designed uses a Buck converter shown in fig (3.1)

Considering a solar array, a buck dc-dc converter and a battery in the load stage, a circuit diagram was drawn as shown in fig 3.1.

![Buck Converter Diagram](image)

Fig 3.5 Buck Converter

A buck converter interrupts the line and provides a variable pulse width square wave to a simple averaging filter such that the voltage applied to the inductor \( L \) is either \( V_{in} \) or 0.

The dc output voltage is the average applied to \( L \). Hence considering time when switch is closed and time when switch is open then:

\[
V_{out} = V_{in} \frac{t_{on}}{T}
\]

\[
Where \ t_{on} + t_{off} = T = \text{period}
\]

Therefore

\[
V_o = \frac{V_{in}}{T} = V_{in}D
\]

Where \( D \) is the duty cycle.
From the above equation we can conclude that for a buck converter the output voltage is always less than the input voltage and the output voltage depends only on the duty cycle and input voltage only.

### 3.2.2 Output Voltage Ripple

Output voltage ripple is the name given to the phenomenon where the output voltage rises during the On-state and falls during the Off-state. Several factors contribute to this including, but not limited to, switching frequency, output capacitance, inductor, load and any current limiting features of the control circuitry. At the most basic level the output voltage will rise, and fall as a result of the output capacitor charging and discharging:

\[
\frac{dV_o}{dt} = \frac{I_L}{C}
\]

During the Off-state, the current in this equation is the load current. In the On-state the current is the difference between the switch current (or source current) and the load current. The duration of time \((dT)\) is defined by the duty cycle and by the switching frequency.

Qualitatively, as the output capacitor or switching frequency increase, the magnitude of the ripple decreases. Output voltage ripple is typically a design specification for the power supply. Capacitor selection is normally determined based on cost, physical size and non-idealities of various capacitor types. Switching frequency selection is typically determined based on efficiency requirements, which tends to decrease at higher operating frequencies. The ripples inherent in the converter are taken advantage of in the design of the MPPT in this project.

### 3.2.3 Calculation of converter component values

Taking into consideration following design specification of a Converter

\[
\begin{align*}
E_{in} &= 25V_{max} \\
E_{out} &= 14.0V \\
I_L &= 4.5A \\
\text{Ripple} &= 100mV_{p-p} \\
\text{Operating frequency} &= 26.7Khz \\
\text{Let} \ I_{L_{max}} &= 5
\end{align*}
\]
Calculation

**Inductor size**

\[ L = \left( \frac{\text{ }}{\text{}} \right) = \left( \frac{\text{ }}{\text{}} \right) = 0.12 \text{m} \]

**Capacitor Size**

\[ C = \left( \frac{\text{ }}{\text{}} \right) = \left( \frac{\text{ }}{\text{}} \right) = 98 \]

**3.2.4 Converter Switch**

The switch is constructed from a P-channel power MOSFET (IRF9540) transistor because of the following reasons:

- MOSFETs have low leakage currents
- Have very low power consumption (small control current)
- Have high OFF resistance
- Have high switching speeds as compared to power BJT
- Low On resistance \(< 0.117 \Omega\)
- Have a high \(dv/dt\) capability

The P channel MOSFET used handle large current drains \((23A)\) and has fast switching speeds. It is turned on by a zero gate voltage, and off by a positive gate voltage. Unlike the Bipolar Junction Transistor (BJT) which has a negative temperature coefficient, the MOSFET has a positive temperature coefficient. This means that as the MOSFET heats up under high current conditions or a fast increasing current between drain and source, the impedance of the device increases thus limiting any further increase in current. Secondary breakdown is therefore not possible with a MOSFET.
3.3 MPPT CONTROL UNIT REALIZATION

3.3.1 Square wave generator (Pulse generator)
To generate a 10 KHz square wave a 555 timer LM555 IC was used in an astable multivibrator connection as shown in figure:

![Square wave generator](image)

*Fig 3.6 Square wave generator*

3.3.2 Determination of Pulse Generator Component Values
Synthesis of clock signal; 60% duty cycle and a frequency of 26.7 KHz , with C2= 0.01µF

Period $T = \frac{1}{f} = 37.4\mu\text{S}$

Time on $t_{on}= d \times T$ and time off $(t_{off}) = T - t_{i}$

Using the equation $C = \frac{1}{a+bf}$

Where $a = -1.2905 \times 10^6$, $b = 0.05890049$

Computing the value of $R_2$

$R_2 = \frac{(t_{off})}{(0.693xC)}$

$= 14.97 \times 10^6 s/ 0.010 \times 10^{-6} x 0.693 = 2.2K\Omega$

Computing value of $R_1$

$R_1 = \frac{(t_{off})}{(0.693xC)-R_3}$

$= 22.45 \times 10^6/(0.01 \times 10^{-6} x 0.693) - 2.2K = 1K\Omega$
To achieve control of the duty cycle of the pulse generator a gated oscillator circuit was connected as shown in figure 3.3.

**Fig 3.7 Gated oscillator circuit**

The square wave output of the 555 timer is fed to a D-flip flop as a clock. The output of the D flip flop is thus a function of the clock pulse and the output of the control unit.

### 3.3.3 Voltage sensor

The voltage sensor was synthesized using a buffer/voltage follower and a voltage divider at the non inverting input of an Op amp:

**Fig 3.8 Voltage sensor**
The output voltage is given as

\[ Av = \frac{R_f}{R_1} + 1; \text{ but } R_f = 0 \text{ and } R_1 = \infty \text{ thus } Av = 1 \]

Hence

\[ V_o = \left[ \frac{R_2}{(R_1+R_2)} \right] V_{in} \]

The output voltage follows the input signal voltage

### 3.3.4 Current sensor

The current sensor is achieved by using the circuit shown in the figure 3.4.

**Fig 3.9 Current Sensor**

A small resistor connected in series with the Photovoltaic array is used to convert the array current to a voltage which is proportional to the PV array current. This voltage signal is fed to inverting input a an Op-amp with a gain given by

\[ AV = \frac{R_f}{R_1} = \frac{36}{1} = 36 \]

### 3.3.5 Differentiators

The two differentiators used in the implementation of the project are synthesized by use of a high pass filter as shown below. A capacitor \( C \) is connected between \( V_{in} \), at the inverting Op-amp input. As shown in figure (3.5)

**Fig 3.10 Differentiator**
The current through the capacitor is proportional to the time derivative of the voltage across it, which is equal to the input voltage. This current flows through the feedback resistor $R$, producing a voltage at the output proportional to the capacitor current, which is proportional to the time rate of change of the input voltage. In terms of equations,

$$I_1 = C_1 \frac{dV}{dt}$$

$$V_o = -R_4 I_2$$

The critical frequency of the differentiator is given by:

$$f_c = \frac{1}{2\pi R_4 C_1} = \frac{1}{159.1343 \text{ Hz}} \approx 1.6 \text{ KHz}$$

Is used to limit the high frequency gain

### 3.3.6 Comparators and the XOR gate

A comparator compares two input signals. Its output has two possible levels i.e. $V_{CC}$ and $0V$. The outputs of the differentiators are fed into the comparator and compared with a zero reference voltage. The comparator also eliminates the high frequency harmonics. The comparator output provides a digital signal which indicates whether the power time derivative is positive or negative and also if the voltage time derivative is positive or negative. The outputs of the comparators are introduced to an XOR gate which does the multiplication of the two signs from the comparator outputs. The XOR yields a binary signal which indicates whether $V_{pv}$ should be increased or decreased.

**Fig 3.11 Decision making circuit**

The output of the comparators are given as

- If $V2$ is positive the output voltage $= 0$
- If $V2$ is negative then output voltage $= 5V$
Similarly for the second comparator

*If* $V1$ *is positive the output voltage* $= 0$

*If* $V1$ *is negative then output voltage* $= 5V$

The output of the XOR is the Boolean algebraic solution of the outputs of the comparators.

### 3.3.7 The analog Multiplier

The approximation of the output power of the PV array is approximated by computing the product of the outputs of the voltage and current sensors.

The analog multiplier was designed from two FET transistors. By utilizing the characteristic of a FET transistor to behave like a voltage controlled resistor in the region just before pinch off then, as circuit was designed as in fig (3.6)

![Simple FET Multiplier](image)

*Fig 3.12 Simple FET Multiplier*

Operating the FET in the region below pinch off the

From the FET characteristic i.e. voltage controlled resistor then

$$R_{ds} \propto -$$, \quad \quad \quad \quad \quad \quad R_{ds} =$$

Hence

$$V_{out} = - \quad = -$$

Hence the required function to calculate the approximate power $P = IV$
3.4.8 Constant reference voltage output control circuit

When the MPPT is operating in fixed output voltage mode i.e. when charging a battery only the Voltage of the Photovoltaic is sensed. The sensed voltage forms an error signal which is then applied in the constant reference voltage control method equation i.e. $V_c = 2.4 + V_{ph} \times 0.2$ which generates the control voltage. The control voltage is then compared with a constant magnitude sawtooth waveform to give out the required Pulse duty cycle which is used to control the MOSFET switch.

![Control voltage generator circuit](image)

**Fig 3.13 Control voltage generator circuit**

![Constant Reference voltage, Duty cycle generator circuit](image)

**Fig 3.14 Constant Reference voltage, Duty cycle generator circuit**
3.5 OPERATION OF THE MPPT CIRCUIT

The Controller computes the PV array power, using an analogue multiplier and the using two differentiators the time derivative of power and Voltage are computed which are the fed to two comparators which extract the information about the sign of the derivatives. Multiplication of the two derivatives is achieved through the use of an Exclusive OR-gate (XOR). The output of the XOR yields a binary signal, indicating whether $V$ should be increased or decreased.

To increase the output voltage $V$ across the $PV$ array, the MOSFET power switch is opened this leads to the capacitor across the array to charge up and hence the voltage increase. To decrease the impressed voltage across the array the MOSFET power switch is crossed and hence the capacitor discharges and consequently the voltage $V$ decreases. The opening and closing of the switch is made to correspond to the output of the XOR gate. This output is sampled by the D flip-flop which is clocked at a constant frequency. The output of the D flip-flop is used to drive the MOSFET power switch. The D-flip-flop prevents high frequency chattering of the switch and avoids interference generated by the buck converter's switch action. This is summarized in table 3.1. In constant output voltage mode i.e. battery charging mode the MPPT outputs a constant voltage of 14 volts. The voltage is used in to charge a 12 volts Lead acid battery, in Constant Voltage charging method.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Comparator Output</th>
<th>XOR output</th>
<th>Switch Condition</th>
<th>Effects on $V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V \leq$</td>
<td>$dv/dt$</td>
<td>$X_P$</td>
<td>$X_V$</td>
<td>0</td>
</tr>
<tr>
<td>$V \leq$</td>
<td>$&gt; 0$</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>$V &gt;$</td>
<td>$\leq 0$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$V &gt;$</td>
<td>$&gt; 0$</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3.1 MPPT Operation
CHAPTER FOUR

4.0 SIMULATION AND EXPERIMENTAL RESULTS
The validity of the working of the designed MPPT was done in Multisim simulations and in the laboratory where the following tests were done.

1. Verification of a typical Solar Panel Characteristics (Silicon Solar Cell)
2. Tracker working Verification

Solar Panel characteristics Verification
This was done using small solar panel unit set at various angles of inclination to the source of solar radiation i.e. different isolation strengths. The following parameter were measured Photovoltaic array Voltage ($V_{ph}$) and Photovoltaic array current ($I_{ph}$)

4.1.0 Verification Solar Panel characteristics

Experimental Results

Table 4.0: Photovoltaic Array Voltage and Current Measurement (Panel at an angle $\varnothing$ with sun rays ($0^\circ < \varnothing < 90^\circ$))

<table>
<thead>
<tr>
<th>Photovoltaic Array Characteristic (Panel Flat)</th>
<th>Array Voltage</th>
<th>Array Current</th>
<th>power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.24</td>
<td>22.4</td>
<td>5.376</td>
</tr>
<tr>
<td></td>
<td>1.07</td>
<td>21.3</td>
<td>22.791</td>
</tr>
<tr>
<td></td>
<td>2.22</td>
<td>20.5</td>
<td>45.51</td>
</tr>
<tr>
<td></td>
<td>3.18</td>
<td>20.4</td>
<td>64.872</td>
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<tr>
<td></td>
<td>3.78</td>
<td>20.3</td>
<td>76.734</td>
</tr>
<tr>
<td></td>
<td>3.78</td>
<td>20.3</td>
<td>76.734</td>
</tr>
<tr>
<td></td>
<td>4.11</td>
<td>19.8</td>
<td>81.378</td>
</tr>
<tr>
<td></td>
<td>4.15</td>
<td>19.9</td>
<td>82.585</td>
</tr>
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<td></td>
<td>4.52</td>
<td>19.9</td>
<td>89.948</td>
</tr>
<tr>
<td></td>
<td>5.74</td>
<td>17.2</td>
<td>98.728</td>
</tr>
<tr>
<td></td>
<td>6.27</td>
<td>14.3</td>
<td>89.661</td>
</tr>
<tr>
<td></td>
<td>6.27</td>
<td>14.3</td>
<td>89.661</td>
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<td></td>
<td>6.49</td>
<td>13.2</td>
<td>85.668</td>
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<td></td>
<td>6.93</td>
<td>8.4</td>
<td>58.212</td>
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<td>7.07</td>
<td>7.3</td>
<td>51.611</td>
</tr>
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<td></td>
<td>7.22</td>
<td>5.5</td>
<td>39.71</td>
</tr>
<tr>
<td></td>
<td>7.43</td>
<td>2.9</td>
<td>21.547</td>
</tr>
<tr>
<td></td>
<td>7.5</td>
<td>1.9</td>
<td>14.25</td>
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<tr>
<td></td>
<td>7.55</td>
<td>1</td>
<td>7.55</td>
</tr>
<tr>
<td></td>
<td>7.57</td>
<td>0.6</td>
<td>4.542</td>
</tr>
<tr>
<td></td>
<td>7.58</td>
<td>0.4</td>
<td>3.032</td>
</tr>
</tbody>
</table>
Fig 4.0 Photovoltaic array Voltage/Current characteristic (Panel at an angle with the sun)

Fig. 4.1 Photovoltaic array Voltage/Power characteristic (Panel at an angle with the sun)
Table 4.1: Photovoltaic Array Voltage and Current Measurement (Panel at an angle $\phi$ with sun rays ($\phi = 90^\circ$))

<table>
<thead>
<tr>
<th>Photovoltaic Array Characteristics (Panel at an angle)</th>
<th>Array Voltage</th>
<th>Array Current</th>
<th>power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array Voltage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.35</td>
<td>0.4</td>
<td></td>
<td>3.34</td>
</tr>
<tr>
<td>8.32</td>
<td>0.9</td>
<td></td>
<td>7.488</td>
</tr>
<tr>
<td>8.29</td>
<td>1.5</td>
<td></td>
<td>12.435</td>
</tr>
<tr>
<td>8.23</td>
<td>3</td>
<td></td>
<td>24.69</td>
</tr>
<tr>
<td>8.16</td>
<td>5.8</td>
<td></td>
<td>47.328</td>
</tr>
<tr>
<td>8.02</td>
<td>10.4</td>
<td></td>
<td>83.408</td>
</tr>
<tr>
<td>7.77</td>
<td>21.5</td>
<td></td>
<td>167.055</td>
</tr>
<tr>
<td>6.64</td>
<td>48.3</td>
<td></td>
<td>320.712</td>
</tr>
<tr>
<td>5.3</td>
<td>62.5</td>
<td></td>
<td>331.25</td>
</tr>
<tr>
<td>2.35</td>
<td>73.6</td>
<td></td>
<td>172.96</td>
</tr>
<tr>
<td>0.68</td>
<td>78.1</td>
<td></td>
<td>53.108</td>
</tr>
<tr>
<td>0.2</td>
<td>80</td>
<td></td>
<td>16</td>
</tr>
</tbody>
</table>

Fig 4.3 Photovoltaic array Voltage/Current characteristic (Panel facing the sun)
4.1.1 Analysis

From the above plots the typical characteristic curves of a PV array were verified and hence their use in the derivation of the control algorithm of the MPPT tracker. It shows that depending on the level of isolation a PV array has a point where power derived from the array is maximum. This point is the (maximum power point) MPP. From the plots:

**Panel facing the sun:**
- $MPP = 340mW$
- $V_{mpp} = 6V$
- $I_{mpp} = 56mA$

**Panel at an angle with the sun:**
- $MPP = 98.728mW$
- $V_{mpp} = 5.74V$
- $I_{mpp} = 17.2mA$
4.2. Tracker working verification
4.2.1 Multism simulation results

Fig 4.5 Multisim simulations showing buck converter Power (Blue), Voltage ripples, (orange) Clock pulses (Dark Blue) and gated clock pulses light (green)

The waveforms in fig 4.5 show the cell behavior reflected in both shape and of phase relationships in Ripple Correlation Control operation.

4.2.2 Experimental observations Waveforms Fixed output Voltage mode

Fig 4.6 Sawtooth waveform used in generation Pulse width modulated pulses
Fig 4.7 Pulse observed at input voltage of $V_{pv} = 16$ volts, duty cycle = 0.85 (theoretical 0.88)

Fig 4.7 Pulse observed at input voltage of $V_{pv} = 18$ volts, duty cycle = 0.75 (theoretical 0.78)
Fig 4.8 Pulse observed at input voltage of $V_{pv} = 23$ volts, duty cycle = 0.58 (theoretical 0.61)

Fig 4.9 Pulse observed at input voltage of $V_{pv} = 20$ volts, duty cycle = 0.69 (theoretical 0.70)
Fig 4.10 Buck converter switching ripples (Operating in discontinuous mode)

Fig 4.10 Buck converter switching ripples $V_{pk} = 30$ mV (Load 12.7V battery)
4.3 DESIGNED MPPT EFFICIENCY

Table: 4.2 efficiency measurement

<table>
<thead>
<tr>
<th>Panel Voltage</th>
<th>Observed Duty Cycle</th>
<th>Theoretical Duty Cycle</th>
<th>Tracking Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>0.85</td>
<td>0.88</td>
<td>3.41%</td>
</tr>
<tr>
<td>18</td>
<td>0.75</td>
<td>0.78</td>
<td>3.85%</td>
</tr>
<tr>
<td>20</td>
<td>0.69</td>
<td>0.70</td>
<td>1.43%</td>
</tr>
<tr>
<td>23</td>
<td>0.58</td>
<td>0.61</td>
<td>4.92%</td>
</tr>
</tbody>
</table>

From table 4.4 the average tracking error is 3.40 % hence with an efficient DC-DC converter it is possible to extract up to 96% of the PV array. Compared with a typical Charge controller efficiency of 70% the MPPT discussed in this project can output 26% more power than a typical charge controller. In practical scenario this is not generally the case due to power losses in control circuit and the MOSFET switch.

4.3.1 Converter efficiency

For the MPPT discussed in the project the following losses considered.

Choke Losses \[ = I^2 R_{ch} = 20.25 \times 0.1 = 2.0W \]

MOSFET switch Losses \[ = R_{ds} \text{(ON)} \times I^2 = 0.117 \times 20.25 = 2.4W \]

Diode Losses \[ = E_d I_l (E_{in} - E_{out})/E_{in} + f I_p E_{in} t_{d(off)} \]
\[= 0.6(4.5)(25-14)/25 + 0.134 = 1.34W \]

Total losses \[ = 5.74W \]

Hence Converter efficiency becomes \( \eta = (70)/(75.74) \)
\( \eta = 92.4\% \)

Where

- \( E_{in} \) = Dc input voltage
- \( E_{out} \) = Dc output voltage
- \( E_d \) = Diode forward voltage drop
- \( f \) = Operating frequency in Hertz
- \( I_l \) = Dc load current
- \( R_{ch} \) = Choke Dc resistance
- \( t_{T(off)} \) = Transistor turn off time
- \( t_{d(off)} \) = Diode turn off time
- \( R_{ds(on)} \) = MOSFET switch on resistance

Thus with the designed MPPT an efficiency of 88.7% is approximated.

The designed MPPT power efficiency mainly depends on the converter design, and not the control unit algorithm, since only a few low power ICs are used in the implementation.
CHAPTER FIVE

5.0. CONCLUSION

The PV array output power delivered to the load can be maximized using MPPT control method. In this project Ripple Correlation Control and Constant Voltage reference method was presented. And From the various tests it was clear that without the prior knowledge of the array parameters it was possible to track the maximum power point of a Photovoltaic Array. The technique utilized is simple to implement and low cost using analog circuits. Experiments based on the parameters used shows excellent tracking effectiveness of 96% with a power efficiency of 88.7%. Hence the designed MPPT is more efficient than the typical charge controllers which have a power efficiency of 70%.

5.1 Further work and recommendations

Though the objectives of the project were achieved. Future work has been proposed in the following areas so as to achieve a highly effective and commercial device.

- Implementing the control algorithms using microcontrollers this will not only reduce component count but also add more functionality to the device such as charging timing and implementation of various battery charging methods.
- Designing and construction of battery management system to ensure long life of batteries and reduce cost of battery maintenance.
- Designing efficient solid state protection circuits
- Implementation of the Device using High speed op-amps and comparators so as to allow operation of the circuit at frequencies well above the audio range.
- Research on ways of integrating the designed MPPT to dynamic systems such as solar powered vehicles.
- Research on integrating the MPPT discussed in this paper with Wind power
- Design and implement a circuitry to integrate solar power extracted using the designed MPPT with Mains power.
REFERENCES


[4] Yan Hong Lim and David C. Hamill, “Synthesis, simulation and Experimental Verification of a maximum Power Point Tracker from Nonlinear Dynamics” Surrey Space Centre, University of Surrey, United Kingdom GU2 7XH.


## APPENDIX 1

### Table 1.1: Common MPPT techniques characteristics

<table>
<thead>
<tr>
<th>MPPT technique</th>
<th>PV array Dependent</th>
<th>True MPPT</th>
<th>Analog or Digital</th>
<th>Periodic Tuning</th>
<th>Convergence speed</th>
<th>Implementation Complexity</th>
<th>Sensed parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hill climbing /P&amp;O</td>
<td>No</td>
<td>Yes</td>
<td>Both</td>
<td>No</td>
<td>Varies</td>
<td>Low</td>
<td>Voltage, Current</td>
</tr>
<tr>
<td>IncCond</td>
<td>No</td>
<td>Yes</td>
<td>Digital</td>
<td>No</td>
<td>Varies</td>
<td>Medium</td>
<td>Voltage, Current</td>
</tr>
<tr>
<td>Fractional $I_{sc}$</td>
<td>Yes</td>
<td>No</td>
<td>Both</td>
<td>Yes</td>
<td>Medium</td>
<td>Medium</td>
<td>Current</td>
</tr>
<tr>
<td>Fractional $V_{oc}$</td>
<td>Yes</td>
<td>No</td>
<td>Both</td>
<td>Yes</td>
<td>Medium</td>
<td>Low</td>
<td>Voltage</td>
</tr>
<tr>
<td>Fuzzy logic control</td>
<td>Yes</td>
<td>Yes</td>
<td>Digital</td>
<td>Yes</td>
<td>Fast</td>
<td>High</td>
<td>Varies</td>
</tr>
<tr>
<td>Neural Network</td>
<td>Yes</td>
<td>Yes</td>
<td>Digital</td>
<td>Yes</td>
<td>Fast</td>
<td>High</td>
<td>Varies</td>
</tr>
<tr>
<td>RCC</td>
<td>No</td>
<td>Yes</td>
<td>Analog</td>
<td>No</td>
<td>Fast</td>
<td>Low</td>
<td>Voltage, Current</td>
</tr>
<tr>
<td>Current Sweep</td>
<td>Yes</td>
<td>Yes</td>
<td>Digital</td>
<td>Yes</td>
<td>Slow</td>
<td>High</td>
<td>Voltage, Current</td>
</tr>
<tr>
<td>Array Reconfiguration</td>
<td>Yes</td>
<td>No</td>
<td>Digital</td>
<td>Yes</td>
<td>Slow</td>
<td>High</td>
<td>Voltage, Current</td>
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<tr>
<td>Best fixed Voltage</td>
<td>Yes</td>
<td>No</td>
<td>Both</td>
<td>Yes</td>
<td>N/A</td>
<td>Low</td>
<td>None</td>
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<tr>
<td>Linear Reoriented</td>
<td>Yes</td>
<td>No</td>
<td>Digital</td>
<td>No</td>
<td>N/A</td>
<td>High</td>
<td>Voltage/ Current</td>
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<tr>
<td>Coordinates Method</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Linear current control</td>
<td>Yes</td>
<td>No</td>
<td>Digital</td>
<td>Yes</td>
<td>Fast</td>
<td>Medium</td>
<td>Irradiance</td>
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</table>
APPENDIX 2

IRF9540N DATASHEET
APPENDIX 3

BC107 DATASHEET

APPENDIX 4

COMPLETE CIRCUIT DIAGRAM
### APPENDIX 5

**BILL OF MATERIALS**

<table>
<thead>
<tr>
<th>RESISTORS</th>
<th>Quantity</th>
<th>Value</th>
<th>Cost</th>
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</thead>
<tbody>
<tr>
<td>4</td>
<td>1k</td>
<td></td>
<td>20/=</td>
</tr>
<tr>
<td>2</td>
<td>2k2</td>
<td></td>
<td>10/=</td>
</tr>
<tr>
<td>2</td>
<td>4.7k</td>
<td></td>
<td>10/=</td>
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<tr>
<td>12</td>
<td>100k</td>
<td></td>
<td>60/=</td>
</tr>
<tr>
<td>1</td>
<td>2k</td>
<td></td>
<td>5/=</td>
</tr>
<tr>
<td>1</td>
<td>51k</td>
<td></td>
<td>5/=</td>
</tr>
<tr>
<td>1</td>
<td>200k</td>
<td></td>
<td>5/=</td>
</tr>
<tr>
<td>1</td>
<td>0.5</td>
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<td>5/=</td>
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<td>1</td>
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<td></td>
<td>5/=</td>
</tr>
<tr>
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<td>20k</td>
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<td>5/=</td>
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<th>CAPACITORS</th>
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<th>Cost</th>
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<tbody>
<tr>
<td>2</td>
<td>10nF</td>
<td></td>
<td>5=</td>
</tr>
<tr>
<td>1</td>
<td>100nF</td>
<td></td>
<td>5/=</td>
</tr>
<tr>
<td>2</td>
<td>1nF</td>
<td></td>
<td>5=</td>
</tr>
<tr>
<td>1</td>
<td>68uf</td>
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<td>10/=</td>
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<tr>
<th>INTEGRATED CIRCUITS</th>
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<th>Value</th>
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<tbody>
<tr>
<td>2</td>
<td>555</td>
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</tr>
<tr>
<td>1</td>
<td>74S74</td>
<td>50/=</td>
</tr>
<tr>
<td>2</td>
<td>LP311</td>
<td>30/=</td>
</tr>
<tr>
<td>1</td>
<td>74LS86</td>
<td>50/=</td>
</tr>
<tr>
<td>3</td>
<td>LM324</td>
<td>30/=</td>
</tr>
<tr>
<td>1</td>
<td>7815</td>
<td>30/=</td>
</tr>
<tr>
<td>1</td>
<td>7805</td>
<td>30/=</td>
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</table>

<table>
<thead>
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<th>TRANSISTORS</th>
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<tr>
<td>1</td>
<td>BC107</td>
<td>30/=</td>
</tr>
<tr>
<td>1</td>
<td>IRF9540N</td>
<td>80/=</td>
</tr>
<tr>
<td>1</td>
<td>2N3819</td>
<td>200/=</td>
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<table>
<thead>
<tr>
<th>DIODES</th>
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<th>Value</th>
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<tr>
<td>2</td>
<td>RF207</td>
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</tr>
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<td>1</td>
<td>2.4V Zener diode</td>
<td>20/=</td>
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</table>

<table>
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<tr>
<th>OTHERS</th>
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<th>Value</th>
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<tbody>
<tr>
<td>1</td>
<td>12V BATTERY</td>
<td>1000/=</td>
</tr>
<tr>
<td>1</td>
<td>9mH inductor</td>
<td>60/=</td>
</tr>
<tr>
<td>1</td>
<td>SPDT switch</td>
<td>30/=</td>
</tr>
<tr>
<td>1</td>
<td>PCB BOARD</td>
<td>800/=</td>
</tr>
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</table>

**TOTAL COST** | **2650/=**