A Modular Voltage-Based Maximum Power Point Tracker Photovoltaic Power Management System for Satellite Mission

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Introduction

- In recent years, there has been considerable improvement in Photovoltaic (PV)
    I. conversion efficiencies,
    II. decrease in cost of photovoltaic cells
    III. and improvement in the switching technology.
- These make solar energy one of the surest answers to the world quest for clean energy
- and it has reached its maturity when mankind needs it most.
    I. PV systems are highly reliable
    II. And they offer the lowest life-cycle cost.
- Despite its advantages, there are factors that affect its efficiency and consequently the wide application of Solar PV [Harsono, 2003].

PV Satellite

- For small satellite mission, the power requirements and challenges are common
- Especially if they are Low Earth Orbit they experience
    I. varying solar illumination characteristics
    II. and frequent eclipse periods.
- According to Craig and Alejandro (2005), there are three most common power system implementation approaches found on small satellites.
- They are;
    I. Direct Energy Transfer (DET) with Battery Bus,
    II. DET with Regulated Bus
    III. And Maximum Power Point Tracker (MPPT) with Battery Bus.
- The MPPT is most suitable when the voltage and current maximum power points of the solar array change significantly during the period of orbit.
- In low earth orbit (LEO), arrays voltage and current MPP change significantly over the sunlight period therefore making MPPT the best option for small satellites despite about 10% DC-DC conversion loss.

- Gallium arsenide-based solar cells are typically favored over silicon in industry, because they have a higher efficiency
- These use a combination of several layers of both gallium arsenide and silicon to capture the largest spectrum of light possible.
- Leading edge multi-junction cells are capable of nearly 29% efficiency under ideal conditions
- Bi-facial solar modules are now in the market

- Solar power may be used to provide all or part of a vehicle's propulsion,
- or may be used to provide power for communcations, or controls, or other auxiliary functions.

PV and Battery Sizing

$$A_{PV} = \frac{P_{PV}}{P_{BL}(1-f)^L}$$

- Where P_{PV} is the solar array power, P_{BL} is the beginning of life power, f is the array degradation factor, L is the spacecraft life ,

- The supply voltage from the solar array to the battery is determined by the number of solar cells in series (N_s).
- $V_a = N_s V_c$

The number of parallel string of solar cells determines the required current that will be supplied to the battery charging circuit.
$I_a = N_p I_c$

The total battery capacity (C_B) in Watt-hour (Wh) available for the payload can be estimated as follows:
$C_B = C \times V_B$

$$m_B = \frac{C_B}{E_B}$$

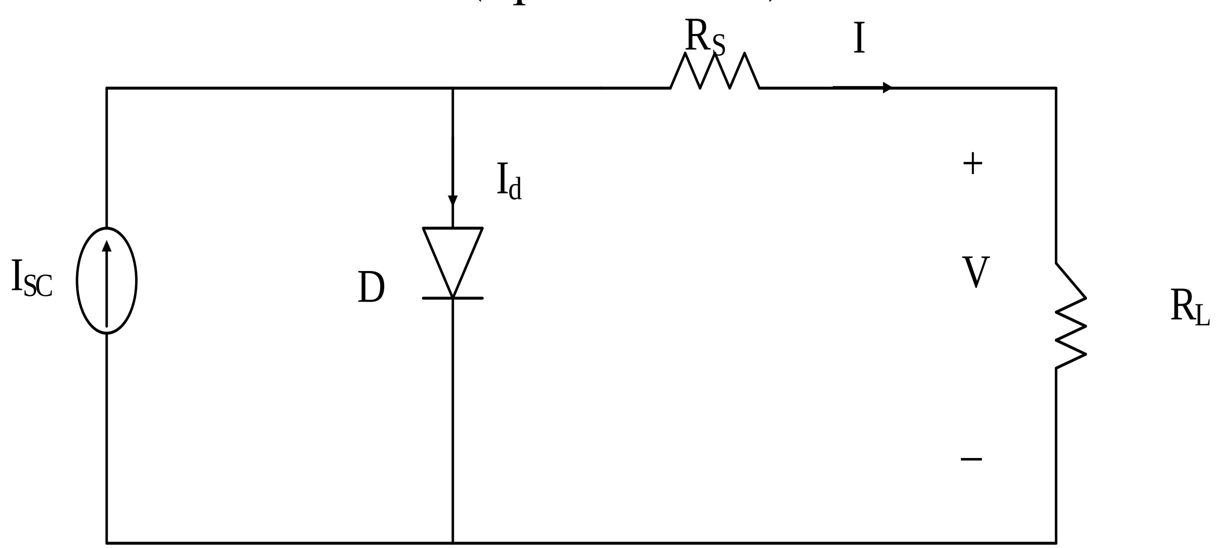
And the mass of the battery can be approximated *Where* V_B is the battery voltage, E_B is the energy density

Electrical Model of a PV Cell

- The important parameters in PV models are:

I. Short-circuit (I_{SC}) current which is the current measured from the PV when the terminals of the cell are short-circuited

II. And the open circuit voltage (V_{oc}), which is the voltage when there is no connection to the PV cell (open-circuit)

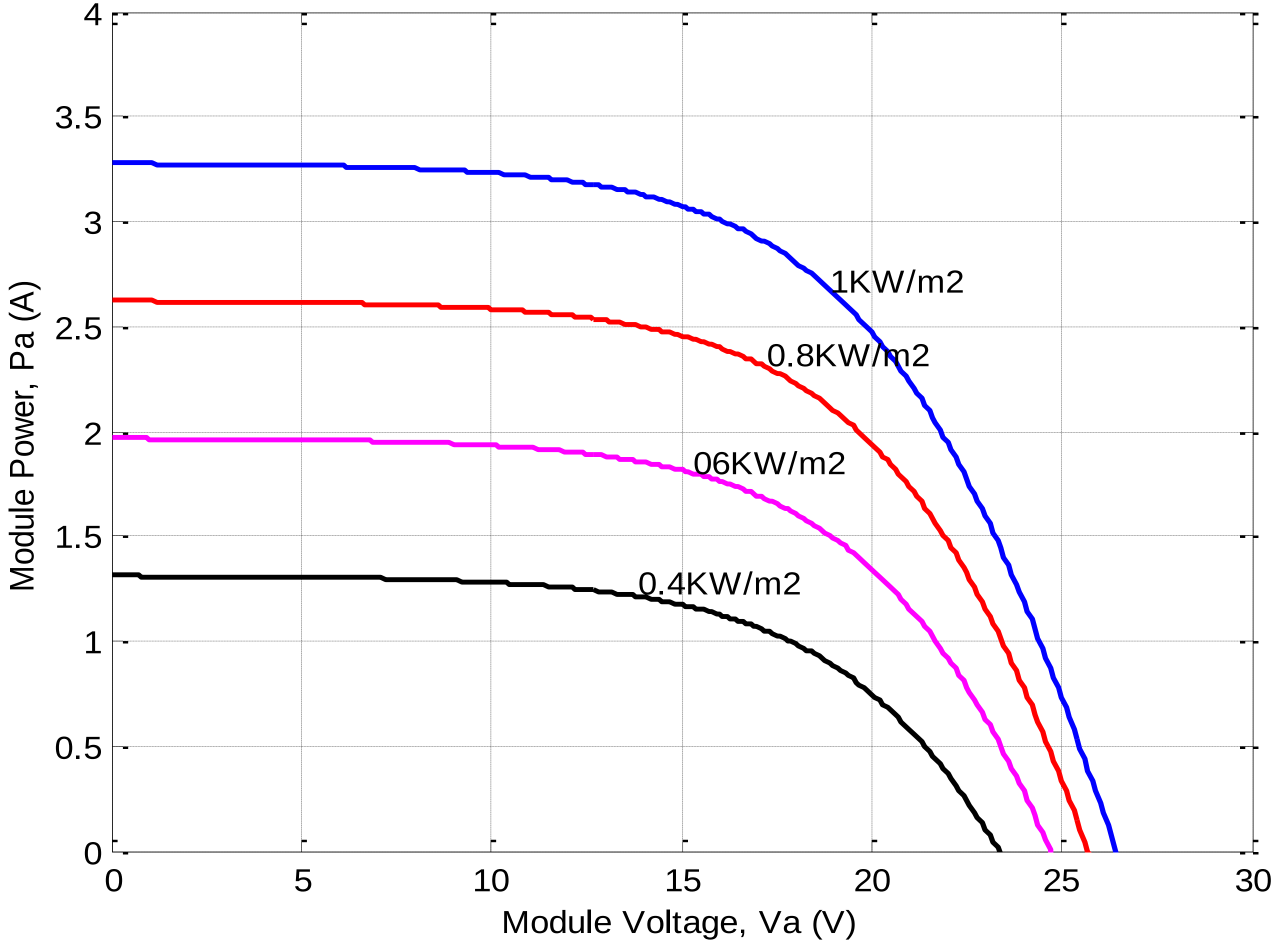


$$I_o = \frac{I_{SC}}{\left(e^{\frac{qV_d}{kT}} - 1\right)}$$

The photon generated current I_{sc}, is directly proportional to the irradiance, the intensity of illumination, to PV cell

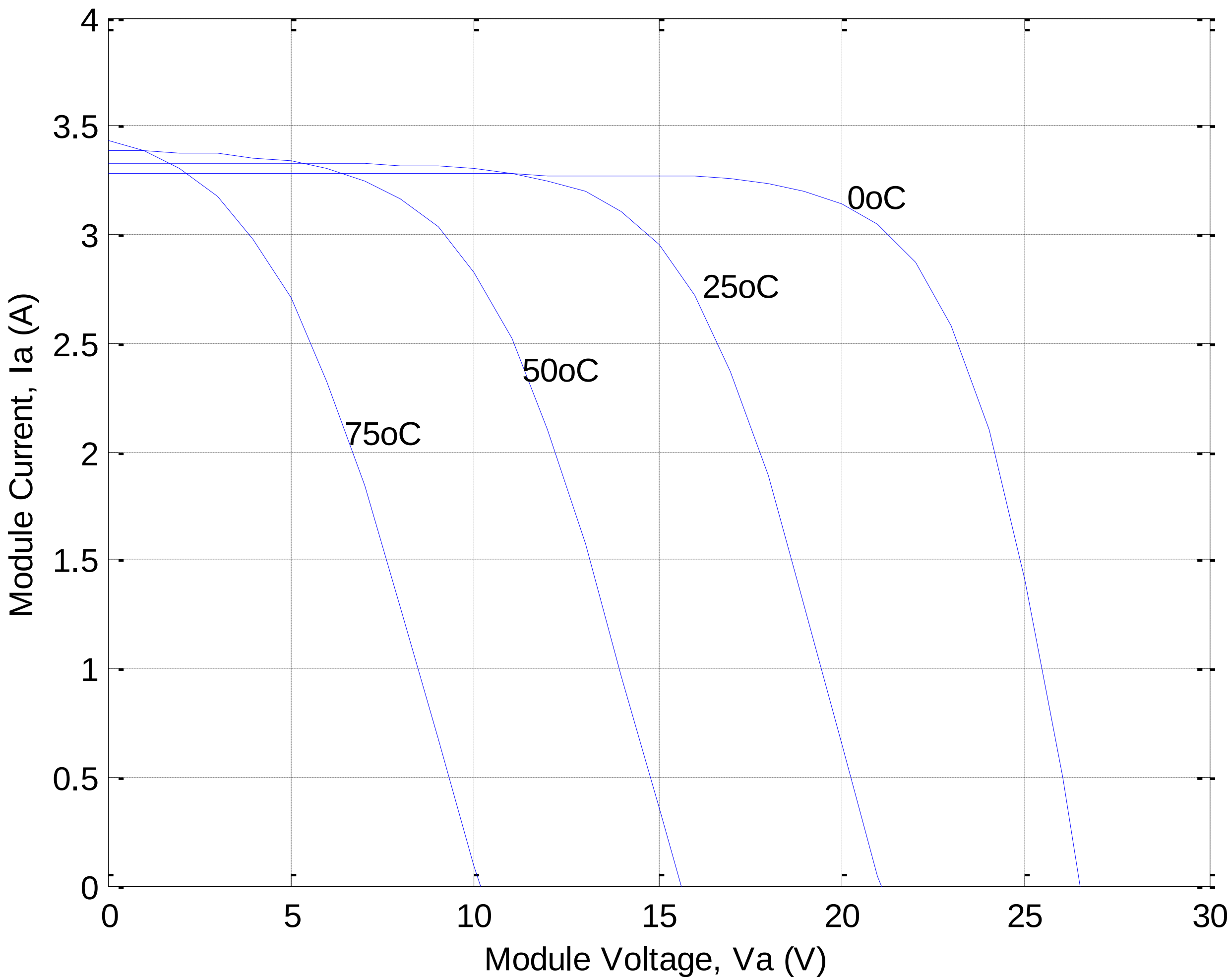
Irradiance

- Approximately, the photon generated current, which is equal to I_{sc}, is directly proportional to the irradiance, the intensity of illumination on a PV cell



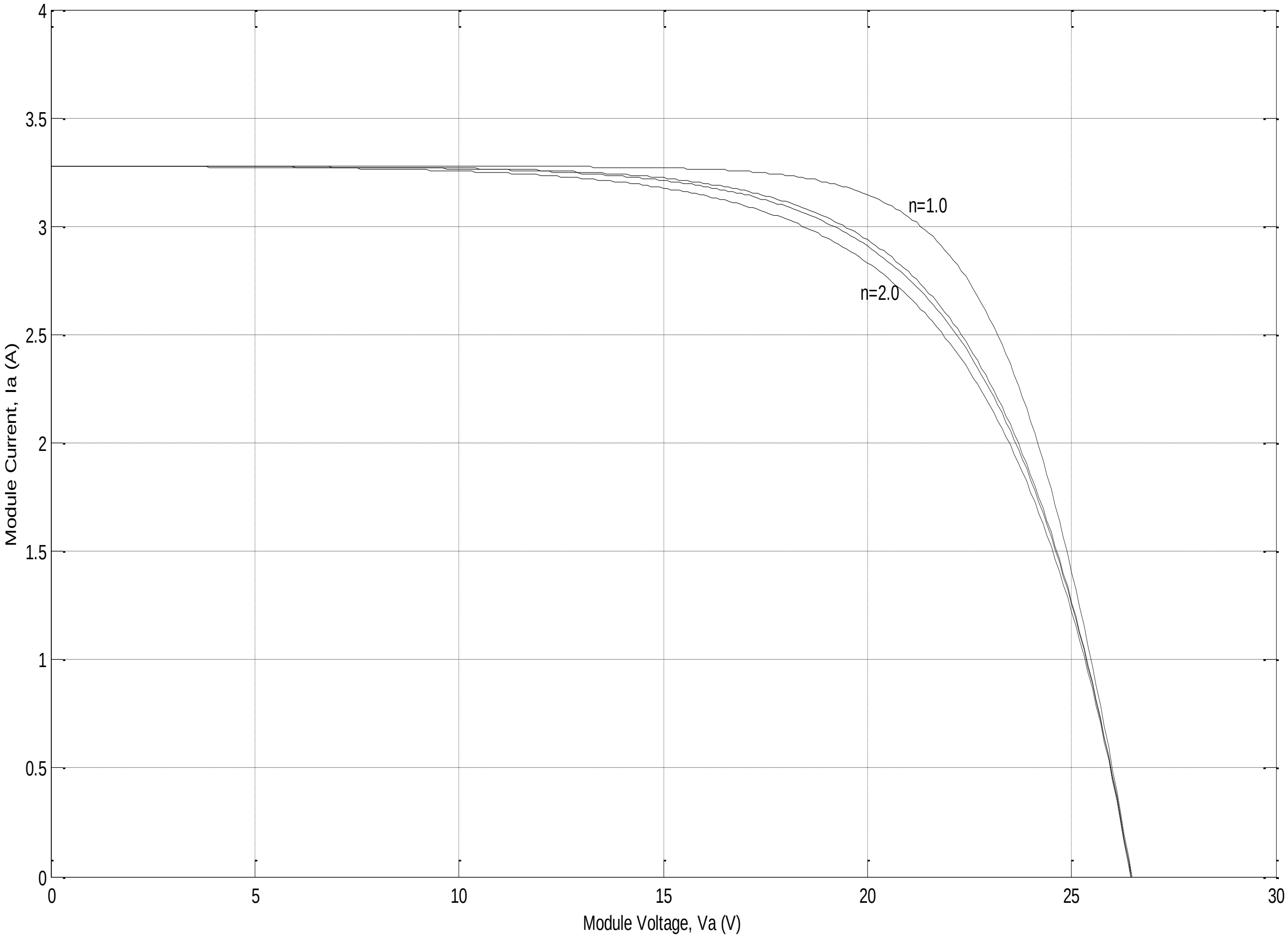
Effect of Temperature on PV Cells

- Since only a small fraction of the insolation hitting a module is converted to electricity and carried away, most of that incident energy is absorbed and converted to heat.



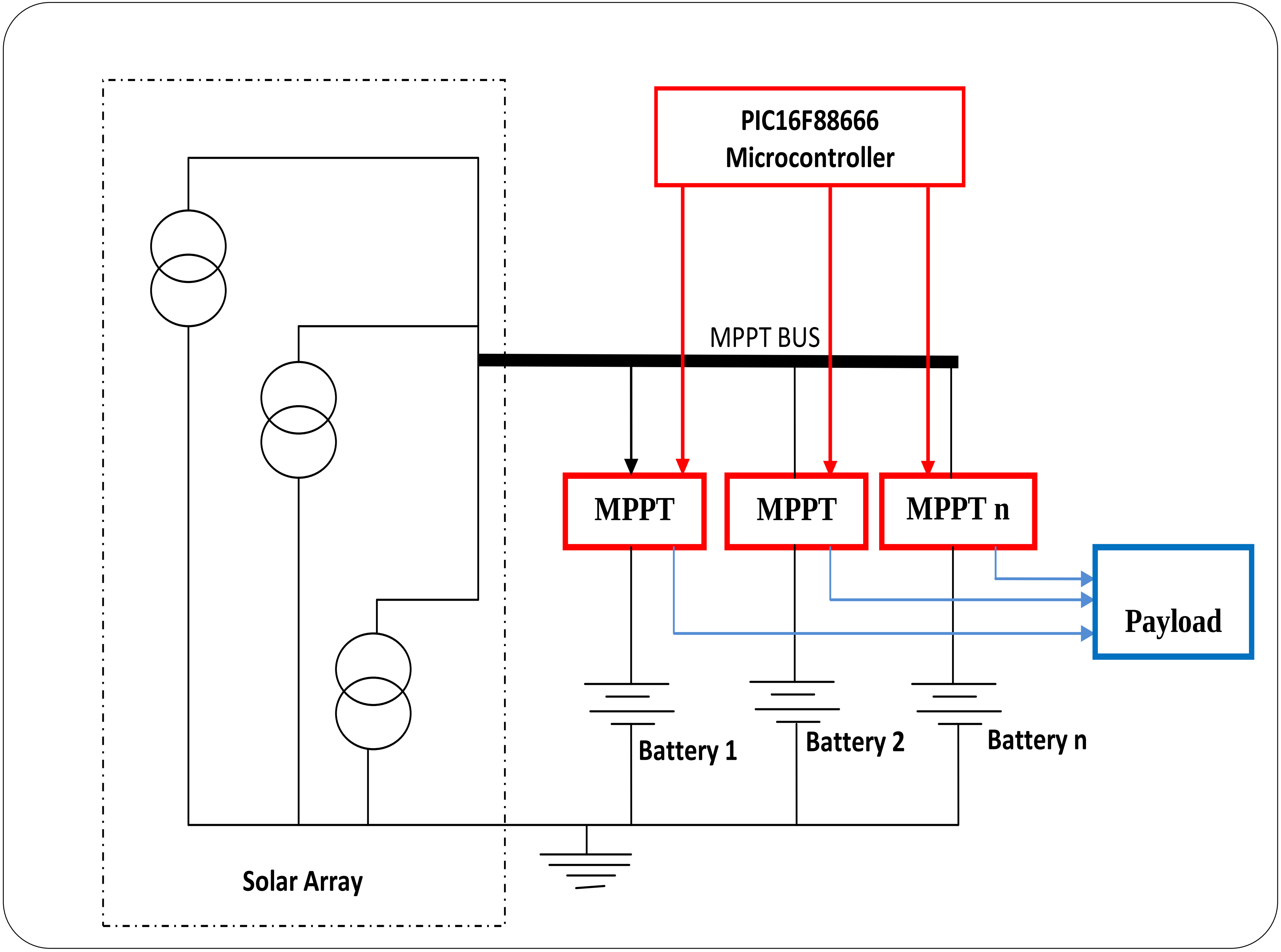
Effect of Diode Ideality Factor

- Ideality factor takes a value between 1 and 2, being near one at high currents, rising towards two at low currents.
- A value of 1.3 is suggested as typical in normal operation



Voltage-Based Modular MPPT Bus

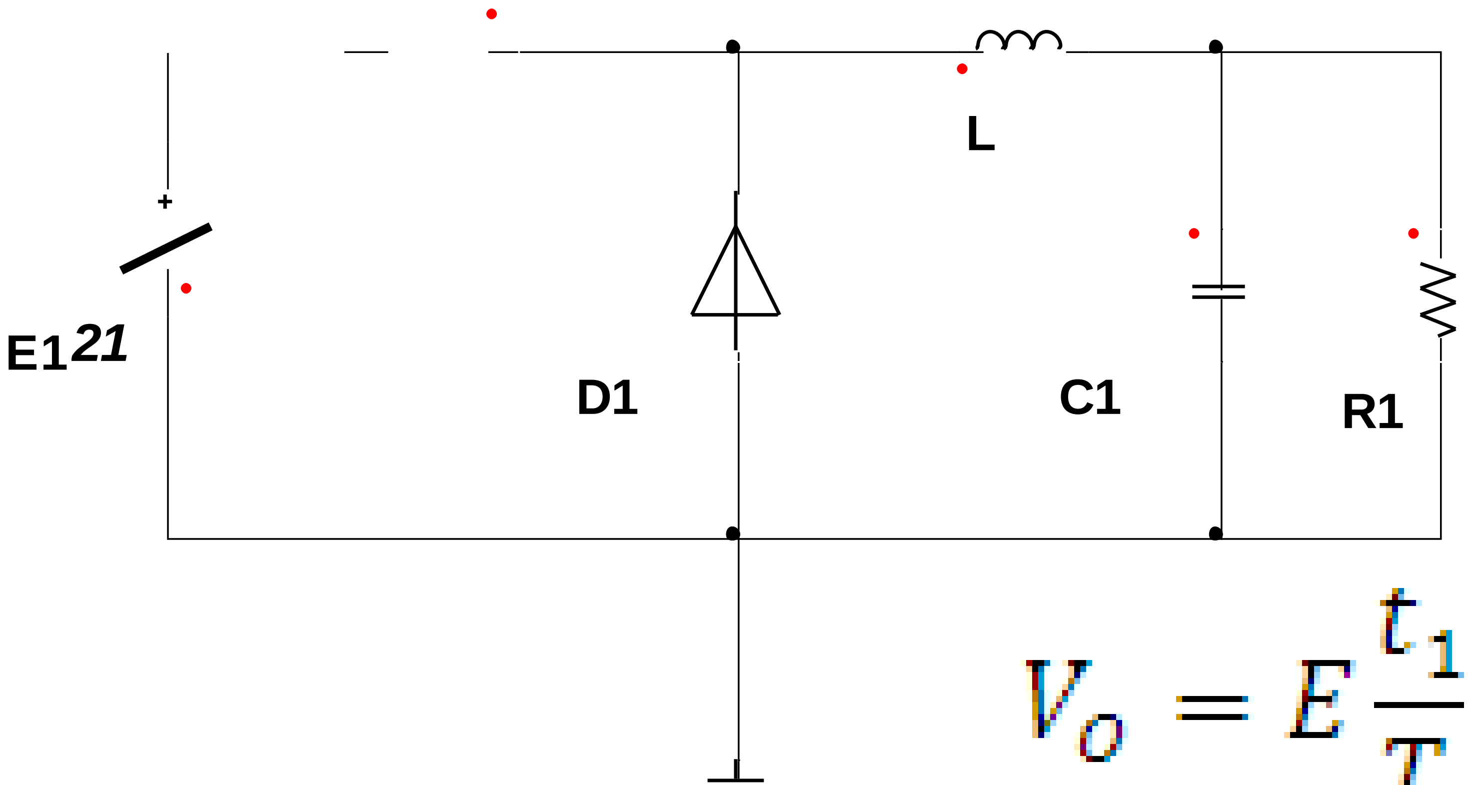
- MPPT is the most ideal topology for small satellites because of its ability to track both current and voltage variations due to
- irradiation, temperature and cell characteristics.
- In practice, the solar panels are likely not to operate at the same temperature, the degradation of the panels may vary with the cell characteristics
- And the solar cells may be made of different technologies therefore varying the maximum power point which will lead to system inefficiency.
- The Modular MPP maintains the bus voltage at solar array MPP during battery charging and high power demand by the payload.
- This regulator is designed for the charge controller to have the array bus at either MPP or backed-off voltage of the array.
- It has the advantage of allowing the use of different solar cell technologies and the MPP of an individual panel can be tracked over the changing thermal conditions whilst in sunlight.
- The most important advantage of the MPPT bus is the fact that it will create redundancy and improve both reliability and availability of the system.



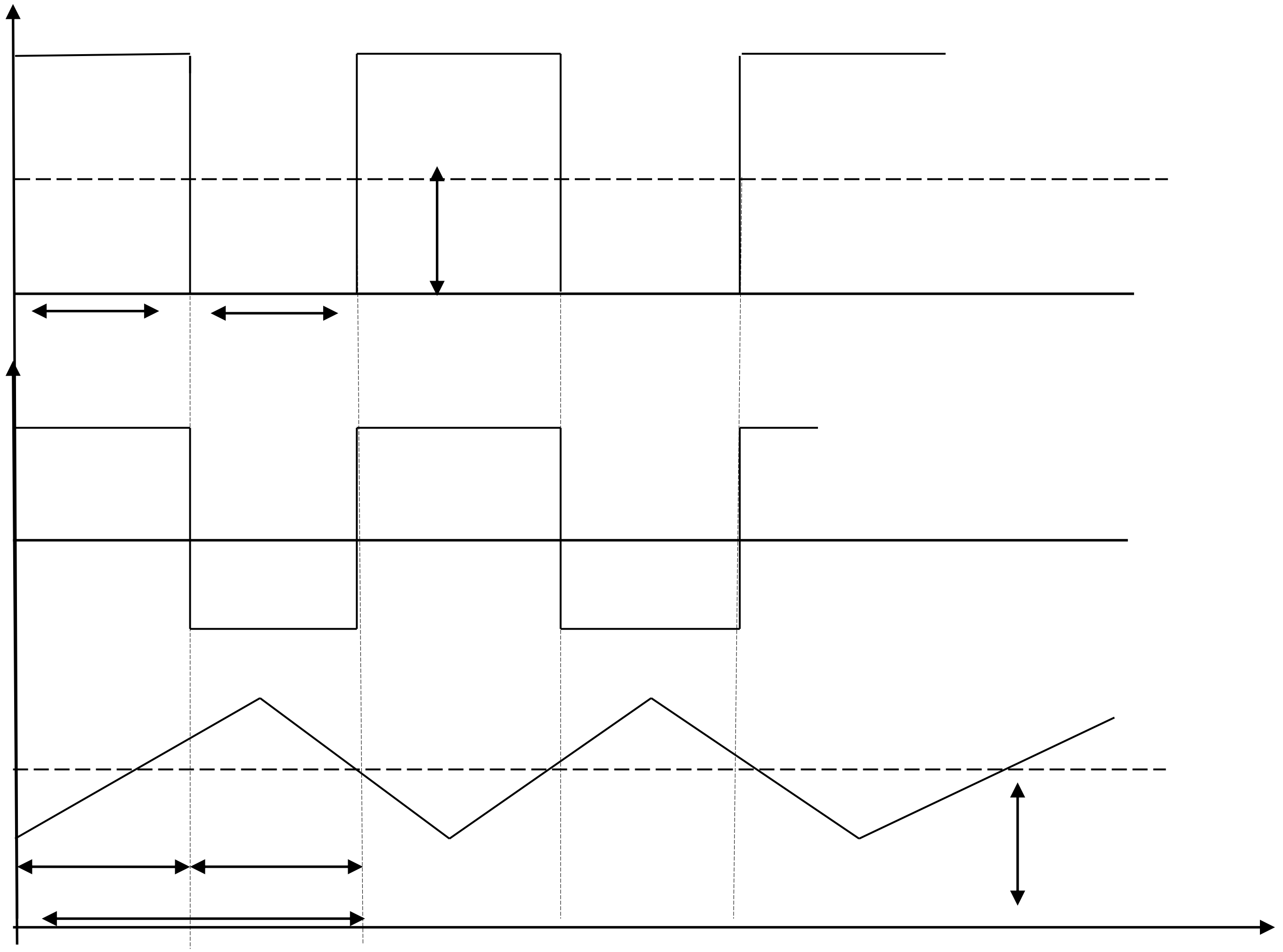
PIC16F88666
Microcontroller
MPPT BUS
MPPT
MPPT
MPPT n
Payload
Battery 1
Battery 2
Battery n
Solar Array

Buck Converter

- The buck converter is the main power management circuit in the voltage-controlled MPPT bus.
- It consists of four main components: switch, diode, inductor and an output capacitor for filtering.
- A switching control circuit made up of a PIC microcontroller is used to monitor the output voltage within the desired voltage.

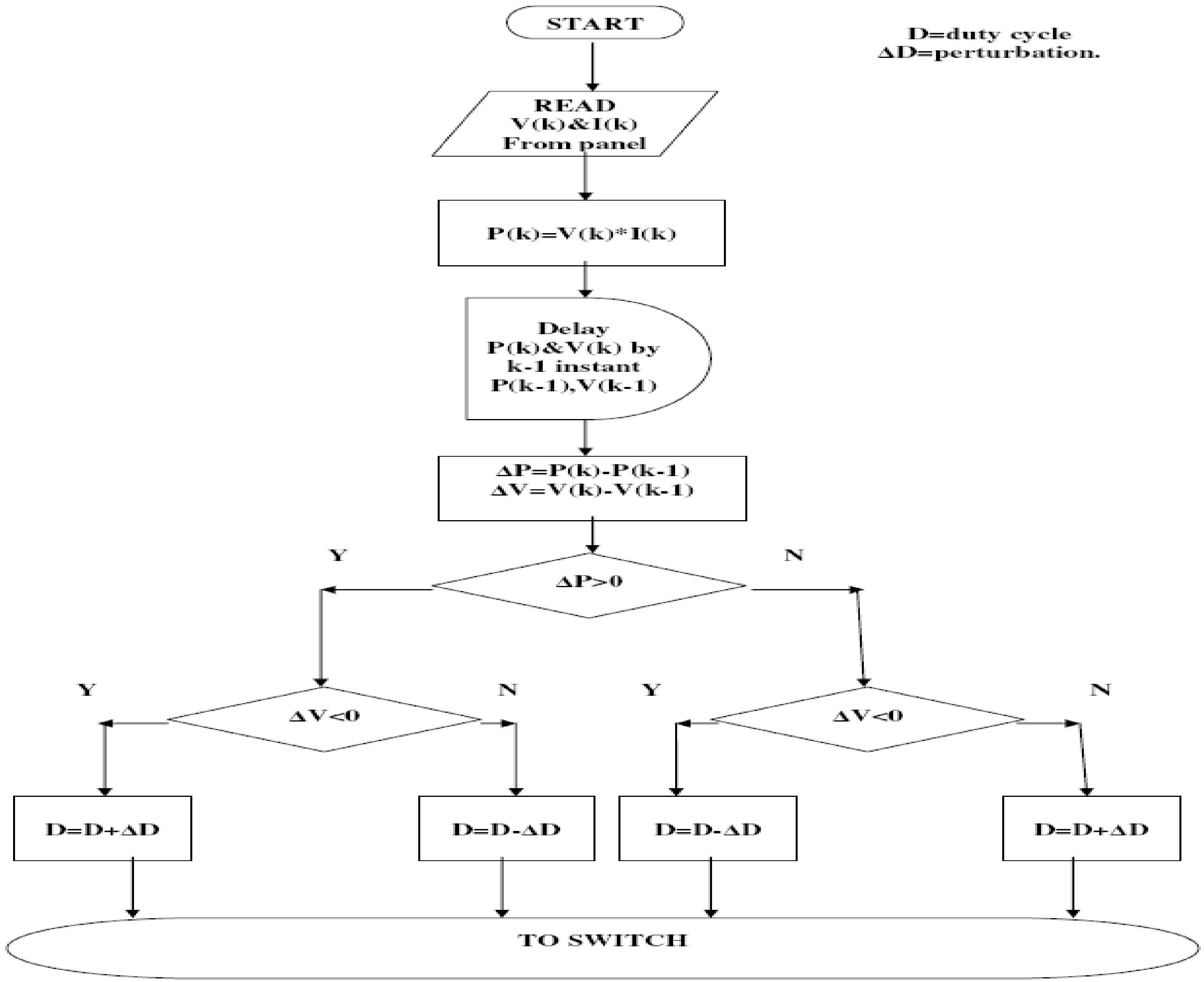


$$V_o = E\frac{t_1}{T} = DE$$



The Control Circuit Algorithm of the MPPT

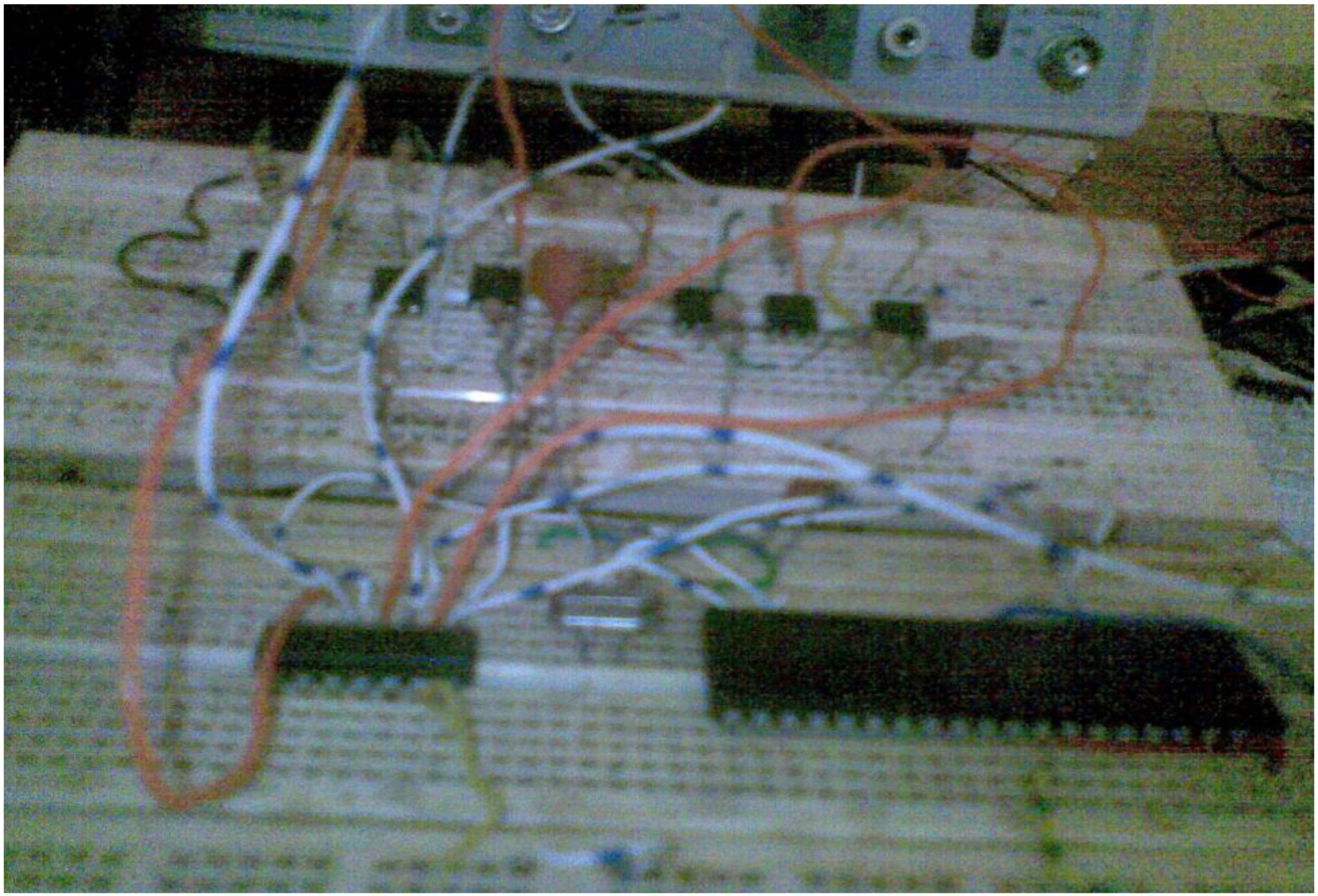
- The Peak Power point of a solar module is attained at 76% of the module open circuit voltage
- This value is fixed and does not vary much with the changes in the environmental conditions except temperature.
- By measuring the Voc as a feedback to adjust the solar module voltage to about 76% of the Voc, the peak power can be tracked.
- Likewise manner, the Peak Power current of the module lies at about 95% of its short circuit current Ish
- And by measuring the short circuit current Isc as a feedback and adjusting the operating current of the converter at 95% of Isc the module can be made to operate at Peak power.
- The values of the peak voltage and current are used to compute the maximum power point.
- This is used to develop the algorithm for tracking the maximum power point the duty cycle D, and perturbation ΔD.


START
D=duty cycle
ΔD=perturbation.
READ
V(k)&I(k)
From panel
P(k)=V(k)*I(k)
Delay
P(k)&V(k) by
k-1 instant
P(k-1),V(k-1)
ΔP=P(k)-P(k-1)
ΔV=V(k)-V(k-1)
Y
N
ΔP>0
Y
N
ΔV<0
Y
N
ΔV<0
D=D+ΔD
D=D-ΔD
D=D-ΔD
D=D+ΔD
TO SWITCH

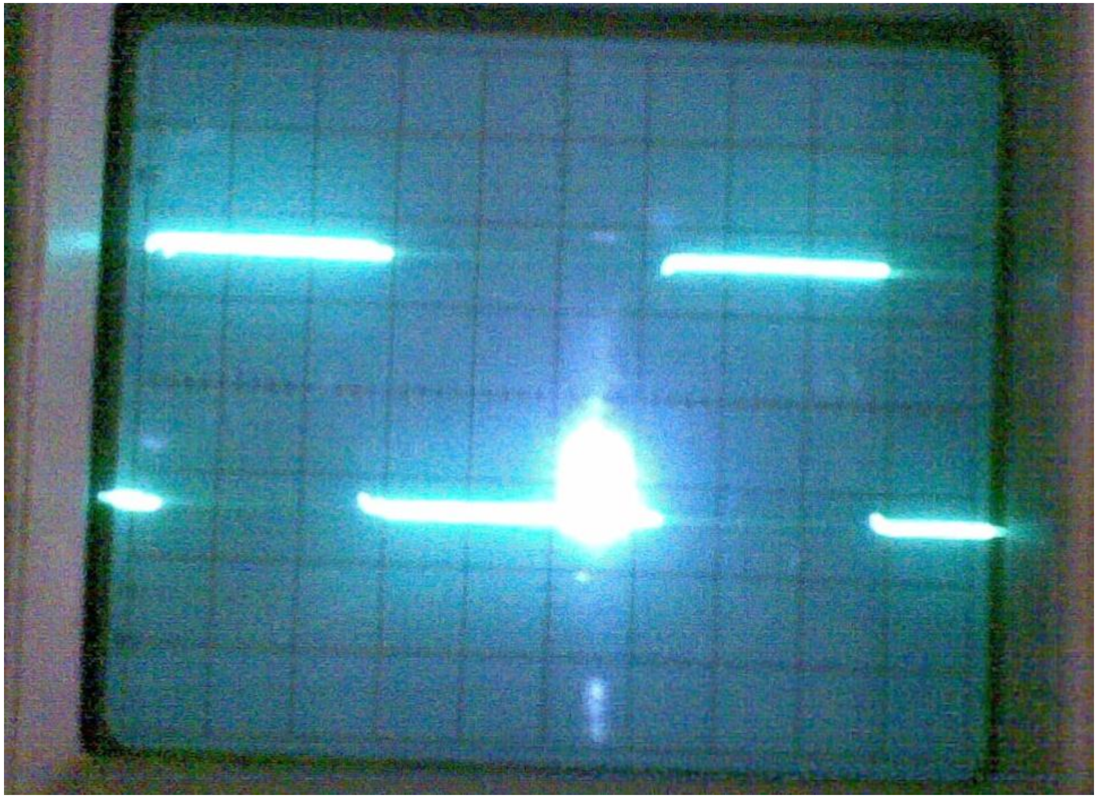
Construction of an Experimental Voltage-Based Modular MPPT Bus

- For the experimental purpose a PIC16F886 microcontroller was used to continuous control the switching of the DC/DC Buck converter,
- A feedback to monitor the Voc of the module, continuously match the load to the MPP and keep adjusting the MPP using pulse width modulation (PWM).
- The power circuit is switching at 80% duty cycle
- The power components used are:
- Module MPP voltage = 18 V
- Module MPP Current = 3.2 A
- Inductor (L) = 5.58 mH
- Average ripple current = 0.12 A
- Filter capacitor = 10 μF
- This PWM controller was operated at a 5 kHz.

The Constructed Circuit of the Voltage Based Modular MPPT



Modulated Signals from the Microcontroller Output



Conclusion

- This paper has proposed a voltage-based modular MPPT for optimal tracking operating conditions of PV power.
- Measurement from the constructed circuit returned MPP voltage of 72% of the open circuit voltage with a resistive load regardless of the operating condition.
- The modular MPPT bus allows for redundancy and improved reliability of the overall system.