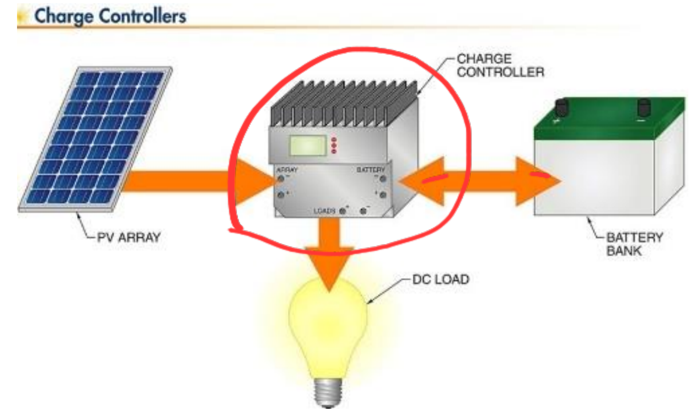
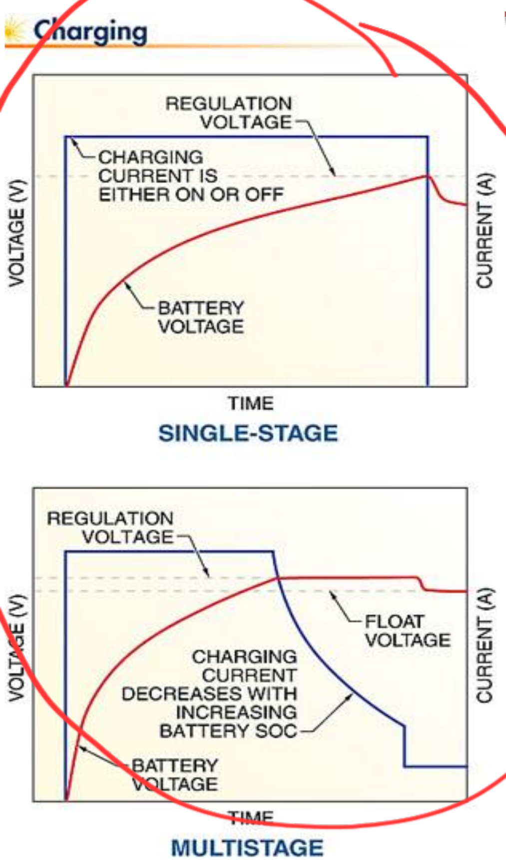
Maximum Power Point Trackers (MPPTs) and Charge Controllers

L16 /part 2





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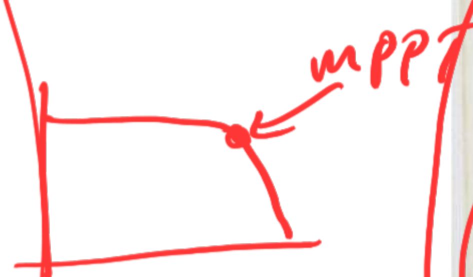
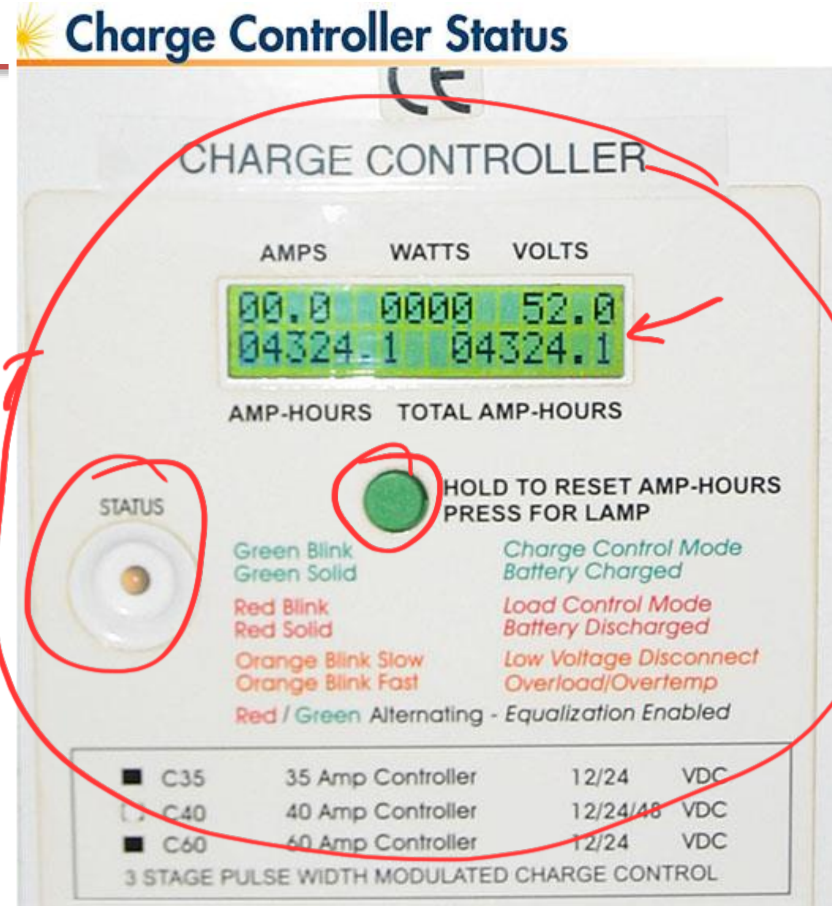
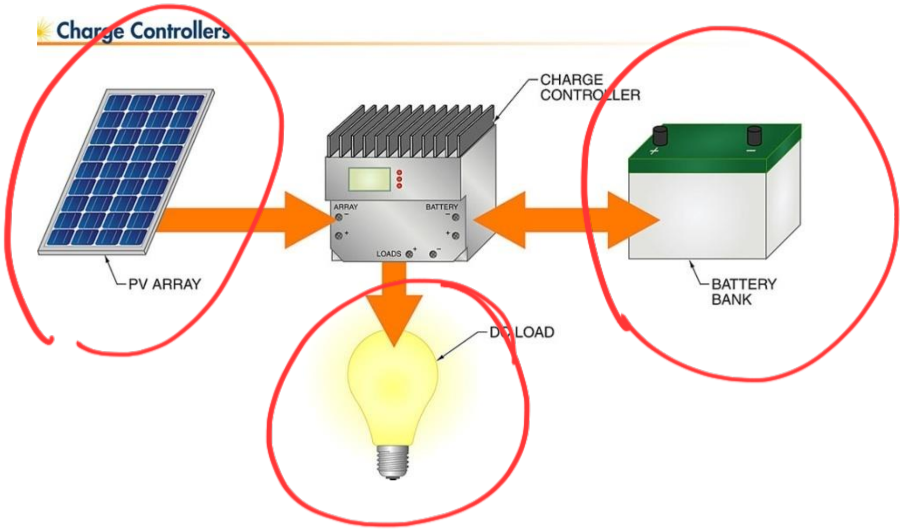




Charge Controller Function

- In applications where batteries are used , it is critical to prevent overcharging or deep-discharging of batteries to preserve their life and ensure good performance
- This is achieved using what is called charge controllers
- Charge controllers manage interactions and energy flows between a PV array, battery bank, and electrical load.

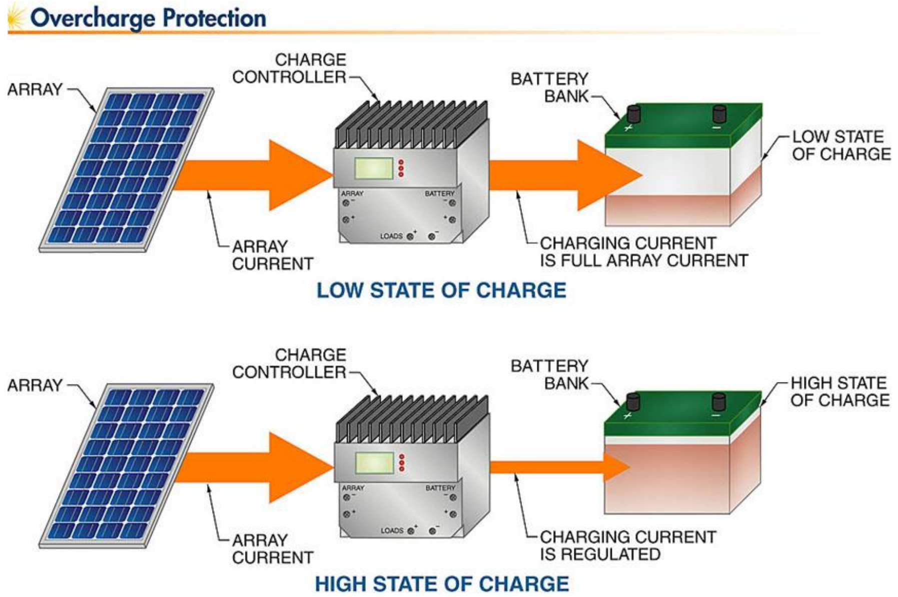


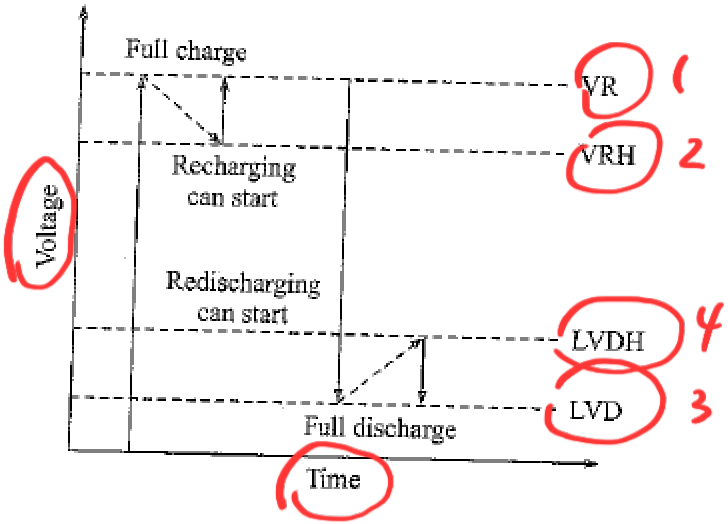
Set Points

- Charge controllers regulate the charging and discharging of a battery
- Charge controllers senses the voltage of the battery (or State Off Charge "SOC") and decides either to disconnect it from the source (PV array) to prevent from overcharging
- It also prevent deep discharging by disconnecting the load
- The charge control algorithm has set points (threshold values) depending upon which it takes the decisions

Commonly used Set points

- **Voltage Regulation (VR) set-point:** It is the maximum voltage up to which a battery can be charged (without getting overcharged).
- If this threshold is reached, the controller either disconnects the battery from the source or starts regulating the current delivered to the battery

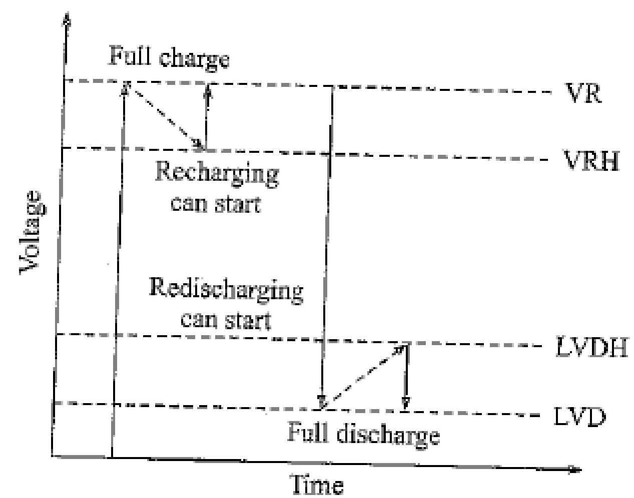




Charge controllers protect batteries from overcharge by terminating or limiting charging current

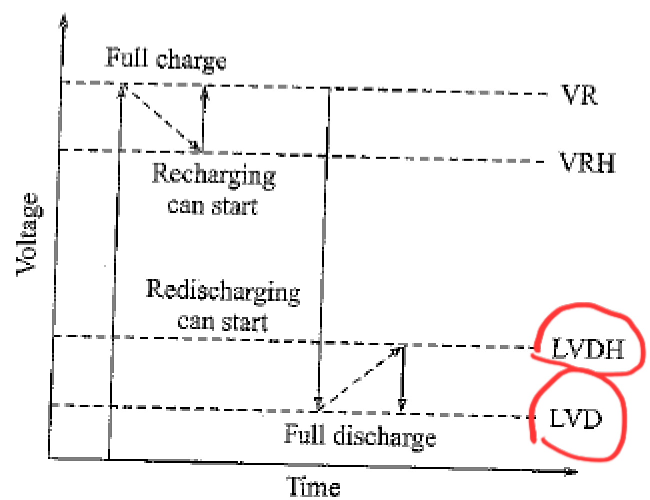
Commonly used Set points

- **Voltage Regulation Hysterisis (VRH):** It is the difference between VR and the voltage at which the controller reconnects the battery to the PV source and starts charging
- If VRH is too small , it will result in tighter regulation but the control will be oscillatory and may affect the battery life.
- At the same time , a large value of VRH may lead to slight overcharging every cycle
- VRH is important in determining how effectively the controller charges the battery
- In practice a trade-off is reached for VRH



Low Voltage Disconnect (LVD):

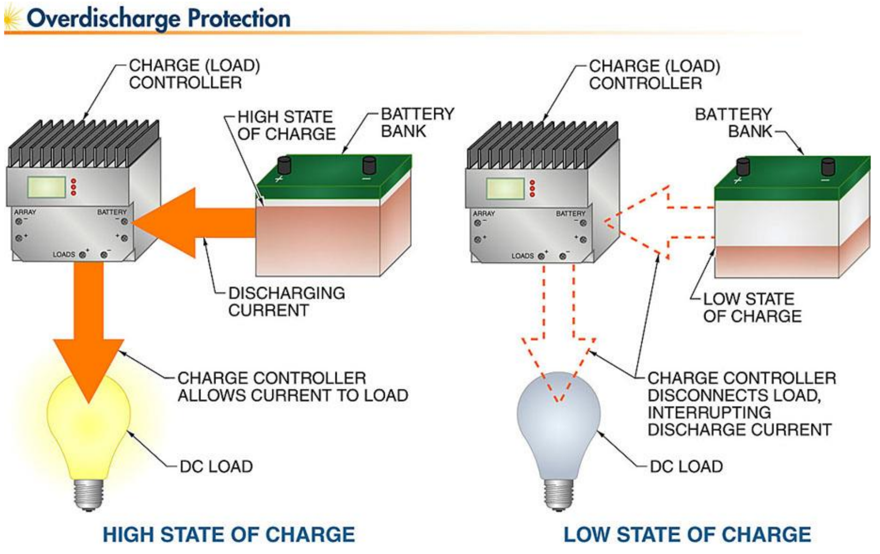
- **Low Voltage Disconnect (LVD):** It is the minimum voltage up to which the battery can be allowed to discharge, without getting deep discharged, it is also defined as the maximum Depth Of Discharge “DOD” of the battery
- The charge controller disconnects the load from the battery terminals as soon as the battery voltage touches LVD to prevent it from over-discharging



Load Disconnect

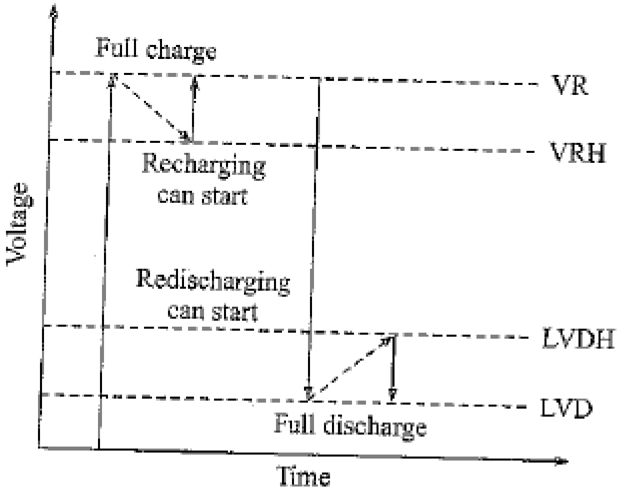
(protect from Overdischarge)

•Charge controllers protect batteries from over-discharge by disconnecting loads at low battery voltage.

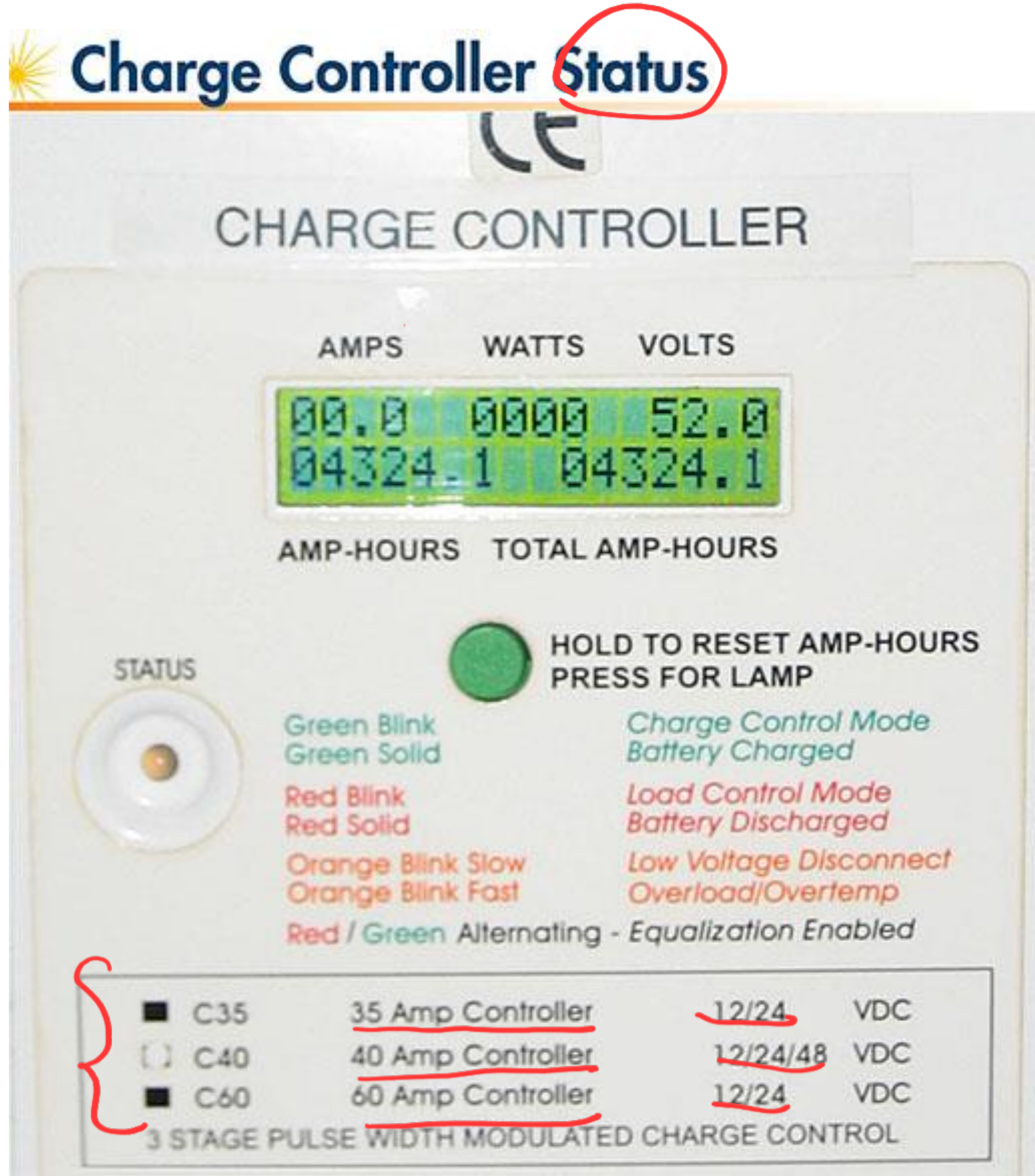


Low Voltage Disconnect Hysterisis

- **Low Voltage Disconnect Hysterisis (LVDH):** It is the difference between LVD value and the battery voltage at which load can be reconnected to the battery terminals
- If LVDH is too small the load will be switched on and off more frequently which can affect the battery and the load adversely



- Most commercial charge controllers include displays or LEDs to indicate battery voltage, state of charge, and/or present operating mode.

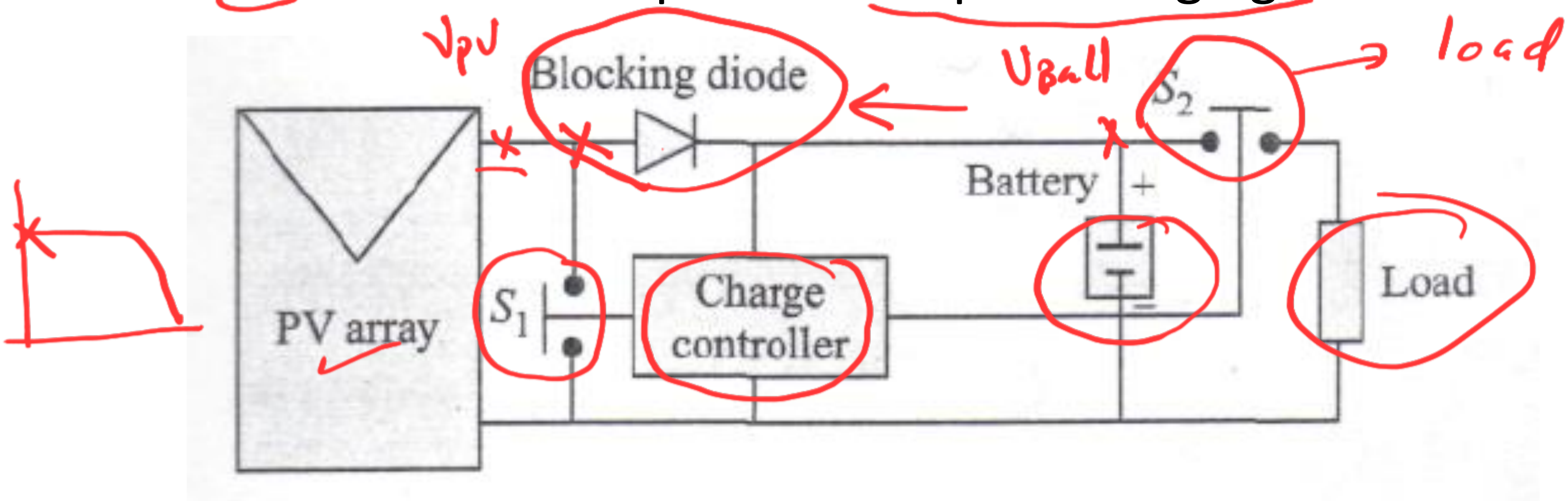


Types of Charge Controllers

- There are 4 types:
  - Shunt (Linear)
  - Series (Linear)
  - Switching (DC-DC converter)
  - MPPT

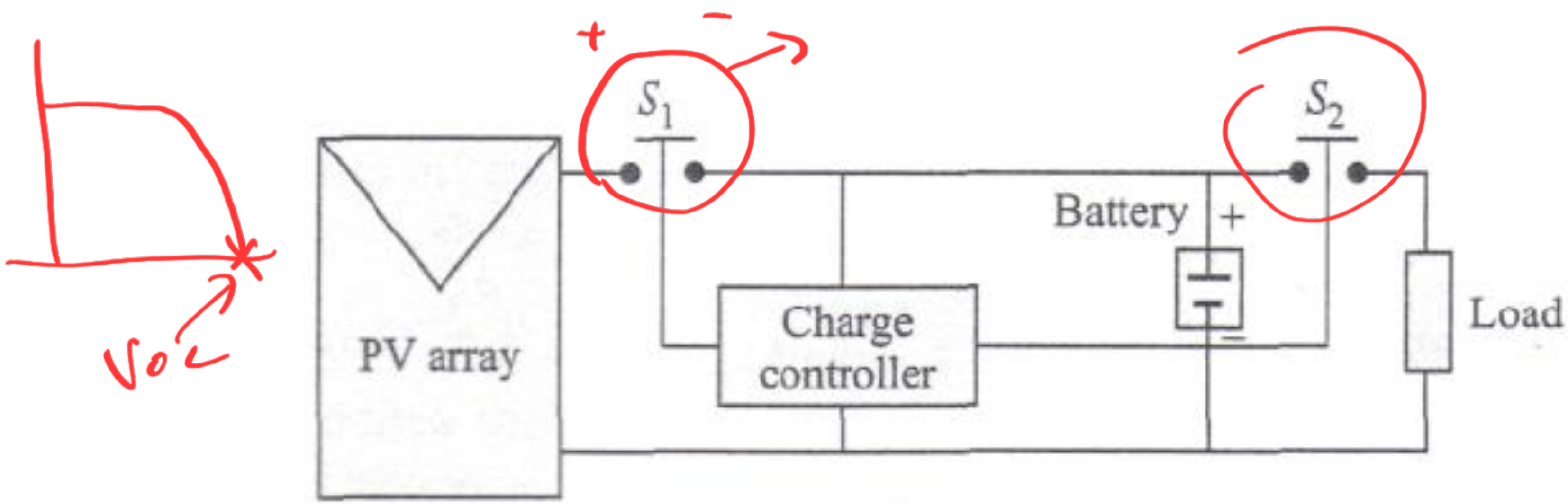
Shunt type

- Switch *S1* is connected in shunt with the PV panel, which is turned on when the battery voltage reaches its over voltage limit (VR).
- The PV array is short-circuited and it no more feeds the battery.
- The blocking diode prevents short circuiting of the battery and also prevents the battery to discharge through the PV array during the nights and low insolation periods.
- The switch *S2* allows the battery to discharge **through the** load.
- When the battery voltage reaches the threshold value (LVD), the switch *S2* is turned off to prevent deep discharging



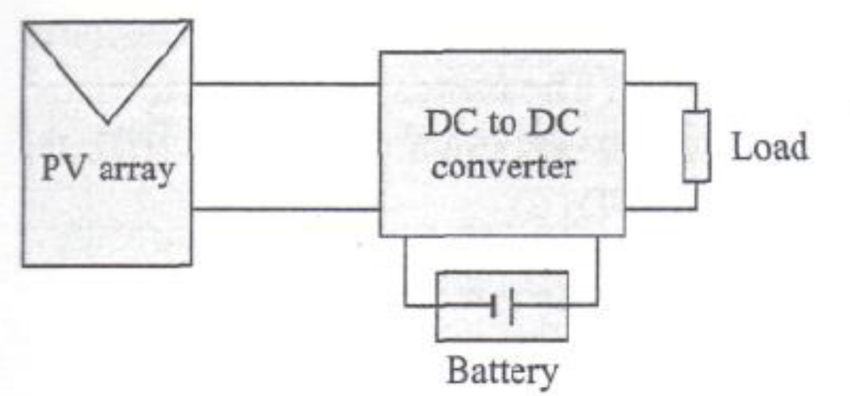
Series type charge controller

- The switch S1 is turned off to prevent the battery from getting overcharged. A major drawback of this method is the additional loss in the switch *S1 which* now carries the PV output current charging the battery.
- Depending on the application and type of battery used, different charge controller configurations are used which either completely disconnect the array from the battery or allow a regulated current to flow through the battery to maintain the battery voltage.



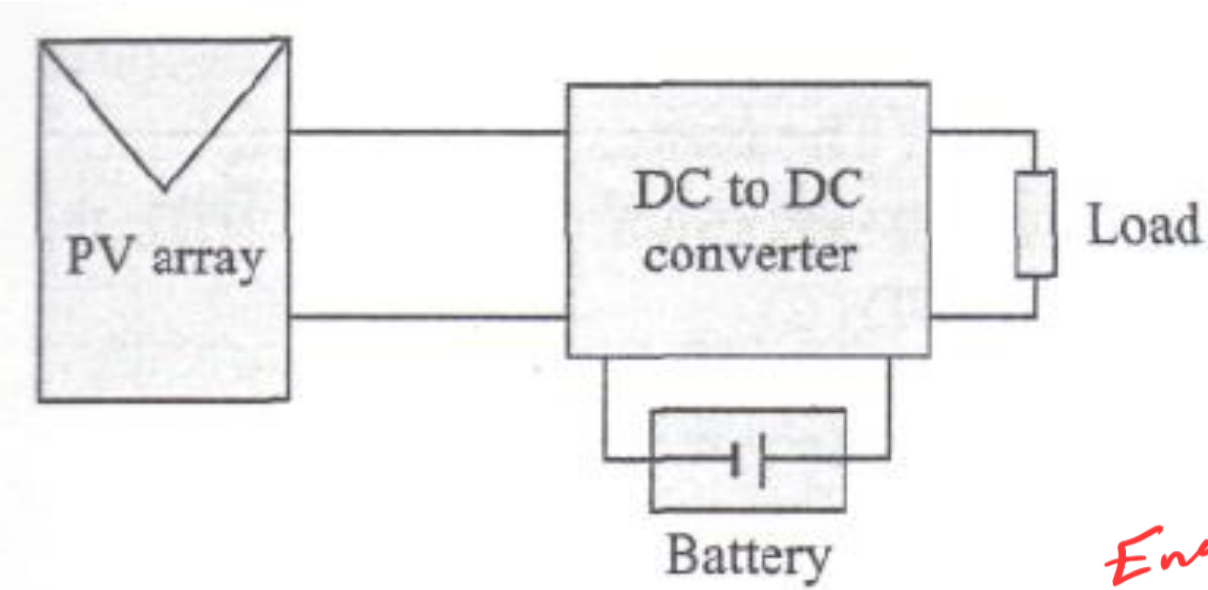
DC to DC converter type charge controller (Switching)

- The series and shunt type of charge controllers are not efficient
- if a DC to DC converter is used to interface the battery- and load combination with the PV array, it provides a smoother control and efficient and optimum use of the PV source.
- **A buck,** boost or buck-boost type DC to DC converter can be used to regulate the output of the PV array to feed the load. The DC to DC converter offers **the following advantages:**
- (a) There are no additional losses due to the conduction of switches such as *Sl* and S2.



DC to DC converter type charge controller

- (b) The regulation of battery charging current and battery voltage is superior.
- (c) The output voltage of the PV array and the battery voltage need not be identical now. So the PV" can be operated at the MPP



End of L16/P2
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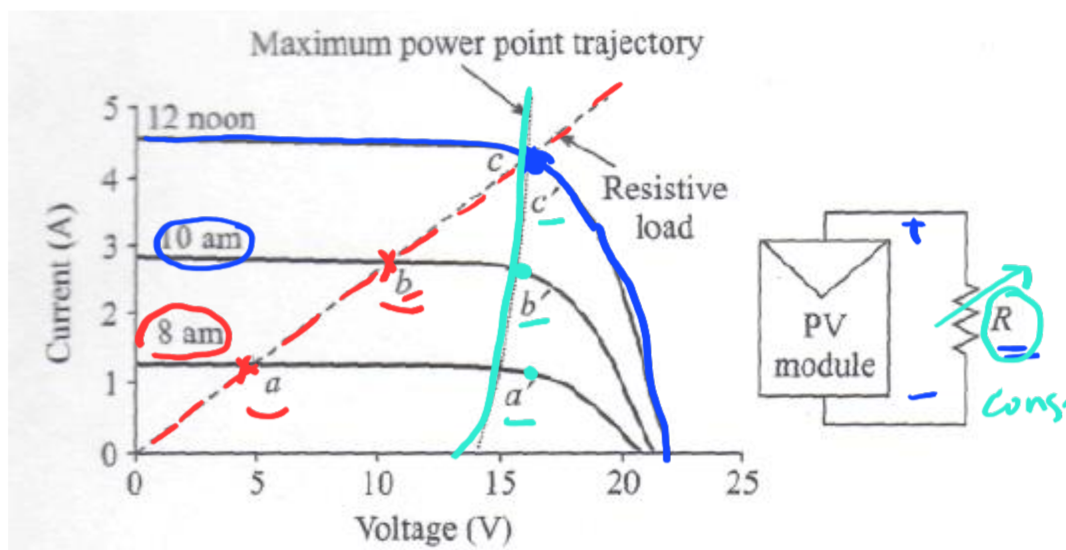
MPPT Charge controllers

L17 10/5/2021

- The battery charging methods described above pump whatever energy is coming out from the PV array into the battery.
- To charge battery in a more efficient manner, the PV array is operated at a point where the **PV output power is maximum**.
- The output power of the PV array changes with the change in voltage across it.
- To extract maximum power from the PV array, a DC to DC converter is used between the PV array and the battery.
- **The duty cycle of the DC to DC converter is controlled to impose optimum voltage across the PV array which corresponds to maximum power point (MPP).**

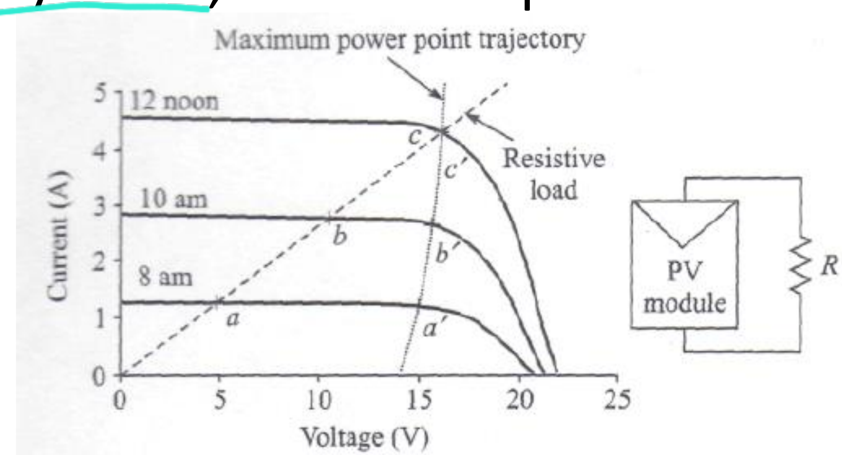
MAXIMUM POWER POINT TRACKING (MPPT)

- When a solar PV module is used in a system, its operating point is decided by the load to which it is connected.
- Also, since solar radiation falling on a PV module varies throughout the day, the operating point of module also changes throughout the day.
- As an example, the operating point of a PV module and a resistive load for 12 noon, 10 am and 8 am is schematically shown in Fig. denoted by *a, b* and c.



MAXIMUM POWER POINT TRACKING (MPPT)

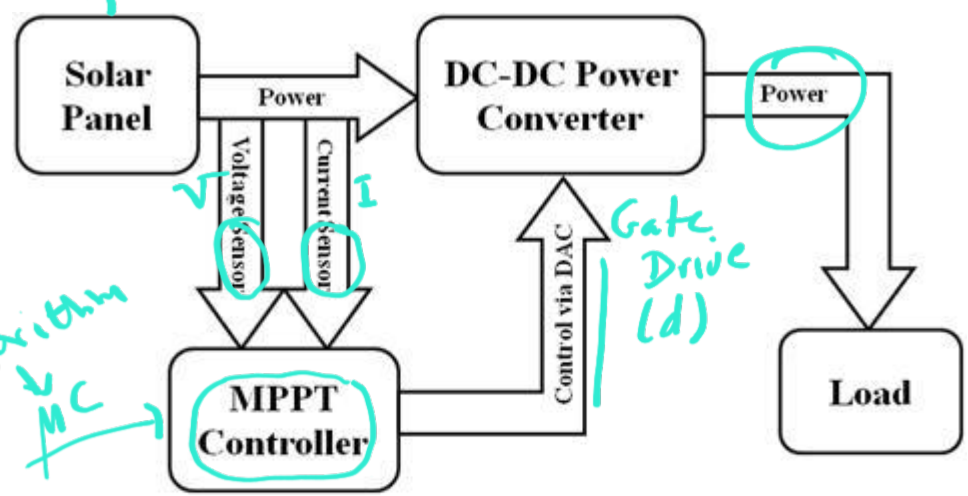
- Ideally, under all operating conditions, we would like to transfer maximum power from a PV module to the load.
- In Fig. the trajectory of a point at which the solar PV module will give maximum power is also shown.
- Thus, for maximum power transfer, instead of operating at points *a, b* and *c* the module should be operating at points *a ' b'* and *c'.*
- In order to ensure the operation of PV modules for maximum power transfer, a special method called Maximum Power Point Tracking (MPPT) is employed in PV systems, which is explained in the following paragraphs.



MPPT and Sun Tracking

- Here it should be noted that the MPPT is not the same as the mechanical tracking (also called sun-tracking, discussed earlier) of solar PV modules.
- In the case of sun-tracking. PV modules are rotated mechanically so that the radiation intercepted by a module is maximum (hence maximizing power generation) under a given condition, while in the case of MPPT, electronic circuitry is used to ensure that maximum amount of generated power is transferred to the load.

- The maximum power tracking mechanism makes use of an algorithm and an electronic circuitry.
- **The mechanism is based on the principle of impedance matching between load and PV module, which is necessary for maximum power transfer**.
- This impedance matching is done by using a DC to DC converter, the impedance is matched by changing the duty cycle *(d)*
- Figure shows a simple block diagram for MPPT.



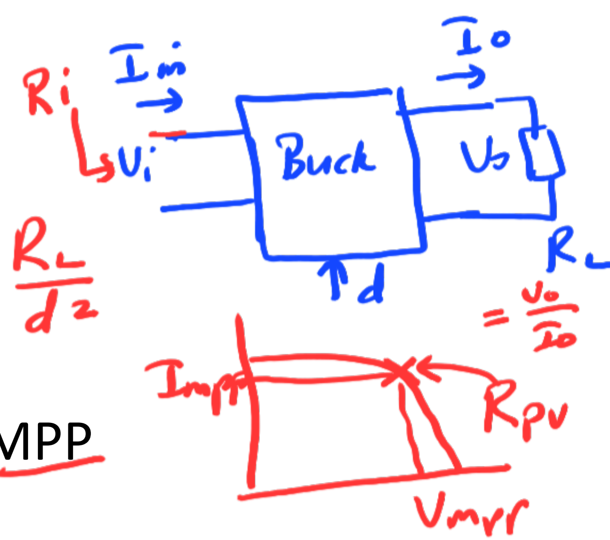
Impedance Matching

- The power from the solar module is calculated by measuring the voltage and current.
- This power is an input to the algorithm which then adjusts the duty cycle of the switch, resulting in the adjustment of the reflected load impedance according to the power output of PV module.
- For instance, the relation between the input voltage (Vi) and the output voltage *(Vo)* and impedance of load *(RL)* reflected at the input side (Ri) of a **buck type DC to DC converter** can be given as:

$$V_o = d\, V_i \quad \text{and} \quad Io=Iin/d$$

$$Ri=Vi/Ii=(Vo/d)/(dIo);\ Vo/Io=RL$$

$$R_i = \frac{R_L}{d^2}$$



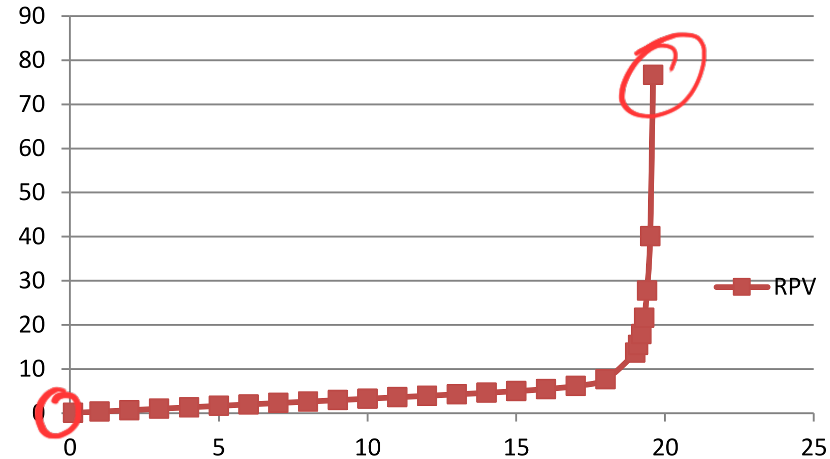
d is duty cycle,

- By varying d , Ri is changed to match Rpv at the MPP

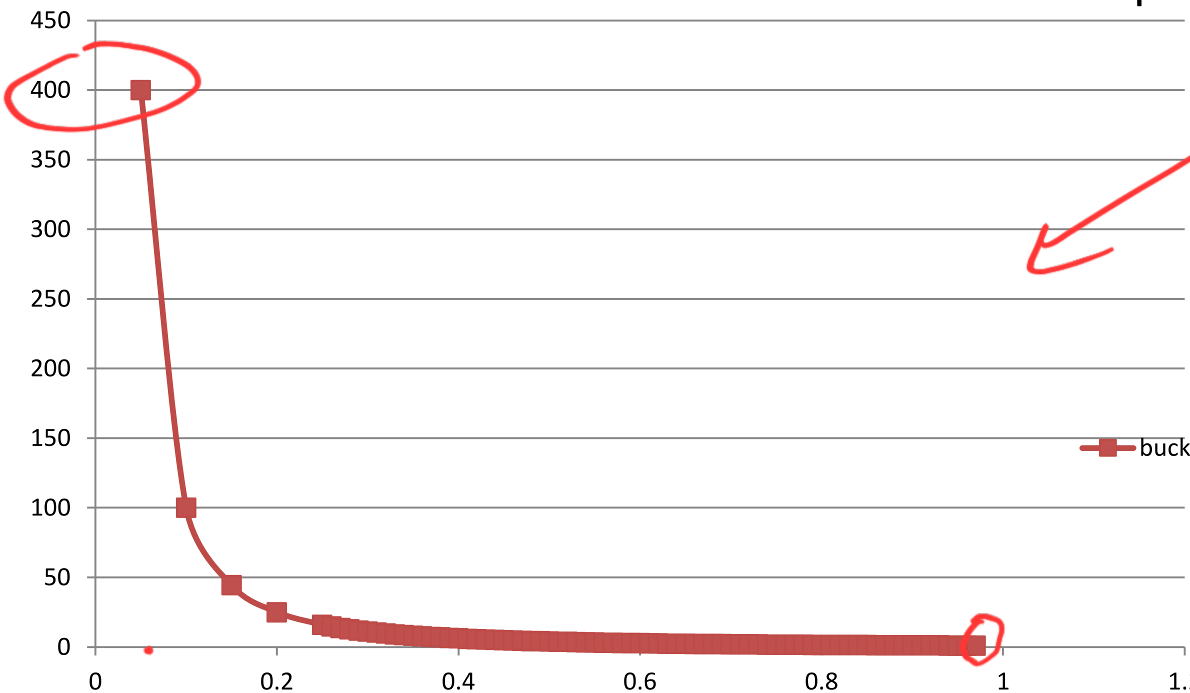
Input Impedance for DC-DC Converters

Converter Type	Input Impedance
Buck	$R_{in} = R_L \left[\frac{1}{d}\right]^2$
Boost	$R_{in} = R_L[1-d]^2$
Buck-Boost	$R_{in} = R_L \left[\frac{1-d}{d}\right]^2$

- d can be varied from 0 to 1, input impedance also varies
- For Buck the reflected impedance is higher than load impedance, for the boost it is lower and for buck boost it can be lower or higher



Output Impedance for PV module



$$R_{in} = \frac{V_i}{I_i} = R_L \left(\frac{1}{d}\right)^2$$

For R_L=1

Input Impedance for Buck

MPPT Mehods

- There are some conventional methods for MPPT.
- These methods include:

1. Constant Voltage method
2. Open Circuit Voltage method
3. Short Circuit Current method
4. **Perturb and Observe method***
5. **Incremental Conductance method***
6. Temperature method
7. Temperature Parametric method

Details of some MPPT algorithms are discussed

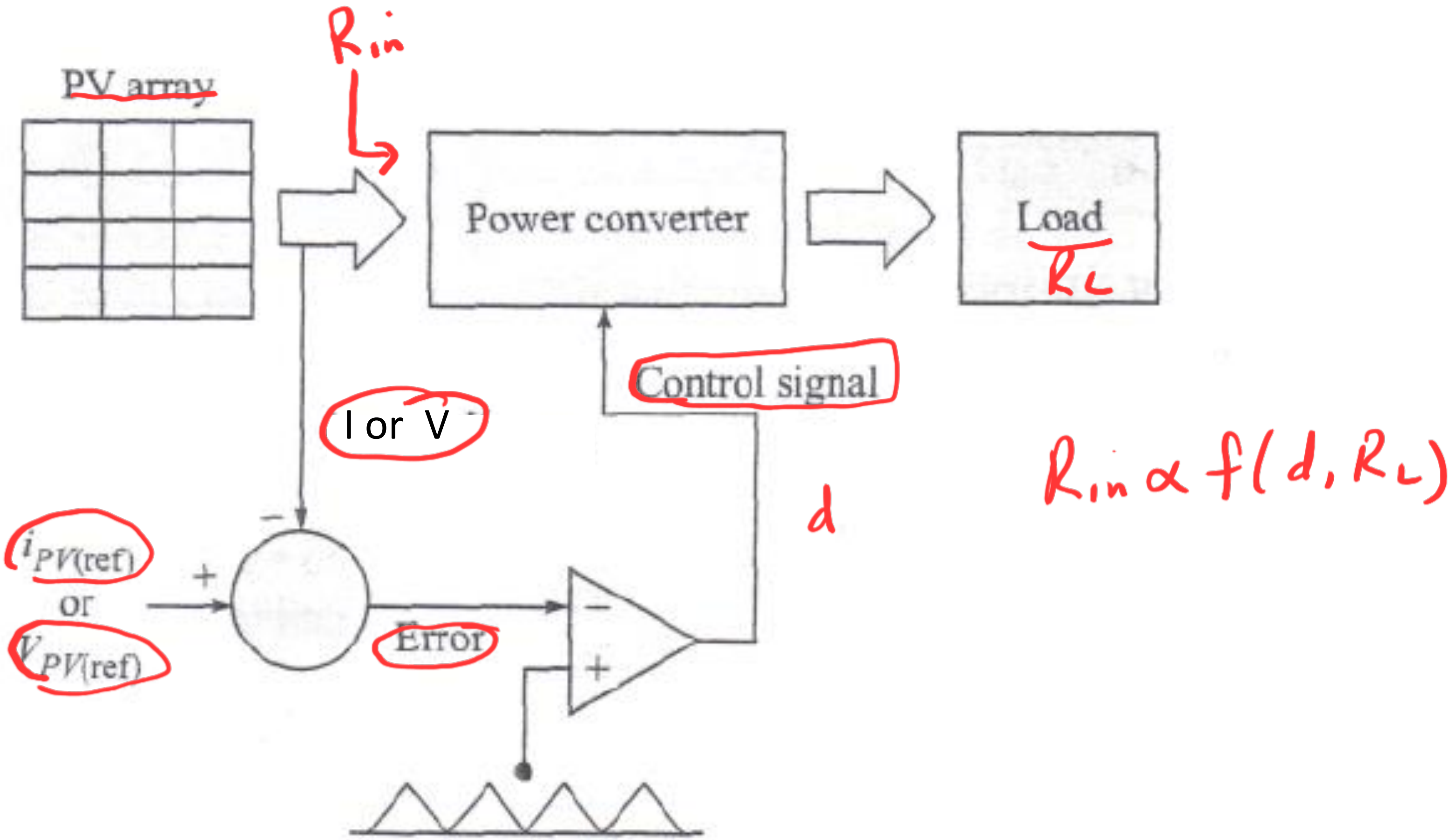
Constant Voltage Method

- This method simply uses single voltage to represent the Vmp.
- In some cases this value is programmed by an external resistor connected to a current source pin of the control IC.
- In this case, this resistor can be part of a network that includes a NTC thermistor so the value can be temperature compensated.
- For the various different irradiance variations, the method will collect about 80% of the available maximum power.
- The actual performance will be determined by the average level of irradiance.
- In the cases of low levels of irradiance the results can be better.

Open Circuit Voltage Method

- An improvement on this method uses Voc to calculate Vmp.
- Once the system obtains the Voc value, Vmp is calculated by,
- $$Vmp = kVoc$$
- The k value is typically between to 0.7 to 0.8. It is necessary to update Voc occasionally to compensate for any temperature change.
- Sampling the Voc value can also help correct for temperature changes and to some degree changes in irradiance.
- Monitoring the input current can indicate when the Voc should be re-measured.
- The k value is a function of the logarithmic function of the irradiance, increasing in value as the irradiance increases.
- An improvement to the Voc method is to also take this into account

MPPT circuit for constant current/constant voltage method



Incremental Conductance Method

$$\frac{dp}{dv} = 0, \text{ at MPP}$$

$$\frac{dp}{dv} > 0, \text{ at left of MPP}$$

$$\frac{dp}{dv} < 0, \text{ at right of MPP}$$

$$\frac{dp}{dv} = \frac{d(IV)}{dv}$$

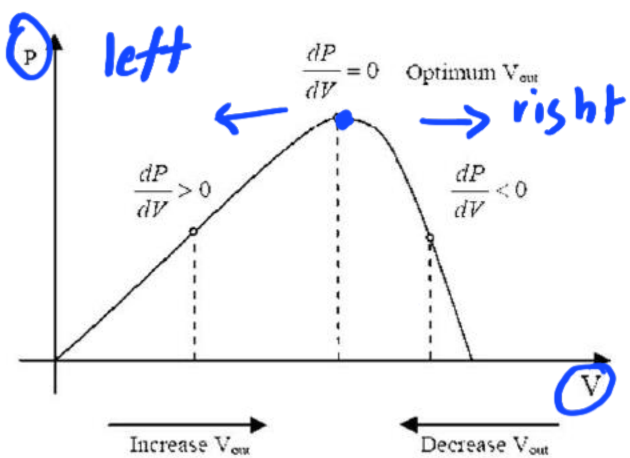
$$= I + V\frac{dI}{dV}$$

$$= I + V\frac{\Delta I}{\Delta V}$$

- The incremental conductance method based on the fact that, **the slope of the PV array power curve is zero at the MPP,** positive on the left of the MPP.

And negative on the right on the MPP.

This can be given by,



$$\frac{dP}{dV} = I + V\frac{dI}{dV} = 0$$

$$= I + V\frac{\Delta I}{\Delta V} = 0$$

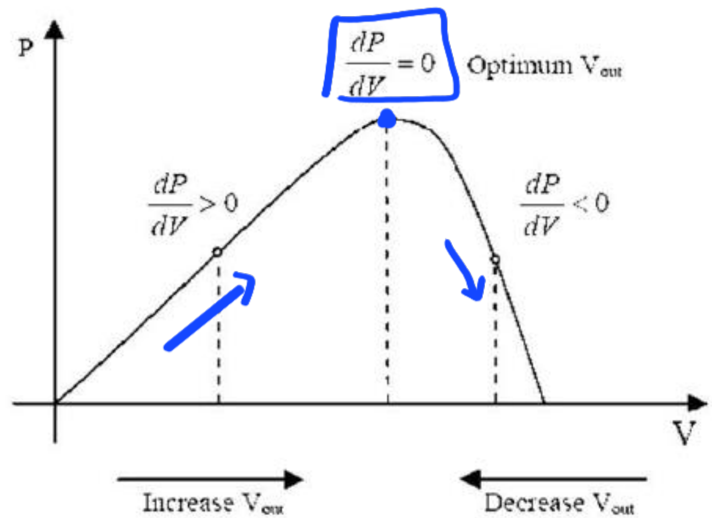
So that,

$$\frac{\Delta I}{\Delta V} = \frac{-I}{V} \text{ at MPP} \quad (3.1)$$

$$\frac{\Delta I}{\Delta V} > \frac{-I}{V}, \text{ at left of the MPP} \quad (3.2)$$

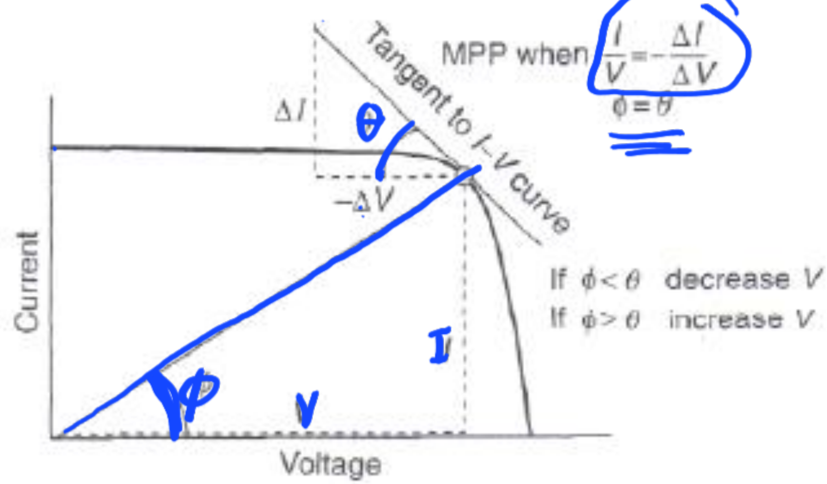
$$\frac{\Delta I}{\Delta V} < \frac{-I}{V}, \text{ at right of the MPP} \quad (3.3)$$

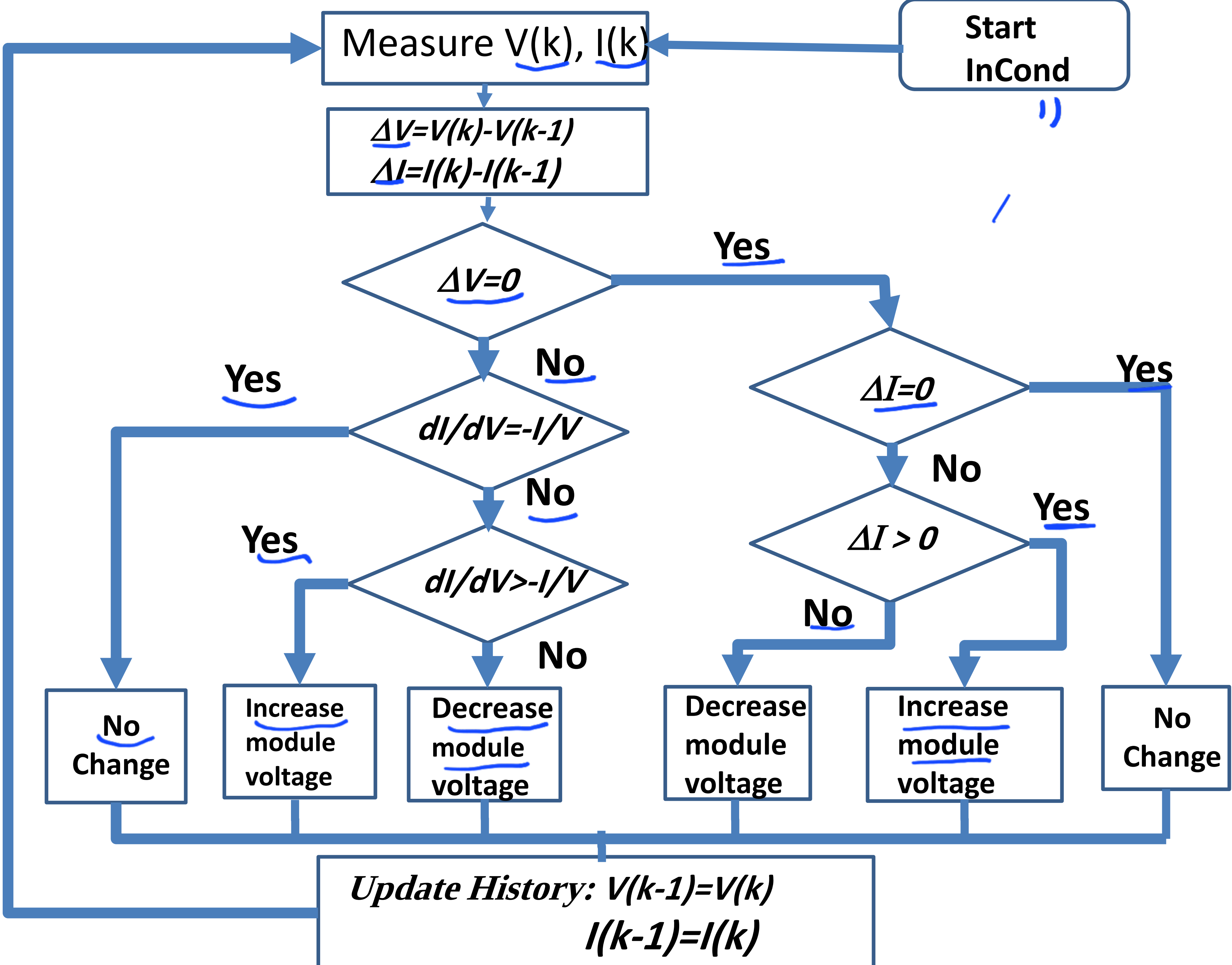
- **The ratio of I/V, called the instantaneous conductance, is based on measurements of PV current and voltage taken at fixed increments of time.**
- **The ratio ΔI /ΔV, called the incremental conductance, refers to changes that might have occurred in I and V during one of those time steps.**
- Figure shows one interpretation of these conductance's on a PV I-V curve.
- The instantaneous conductance is the slope of a line drawn from the origin to the operating point.
- The incremental conductance is the negative slope of the I-V curve at that same operating point.



$$\begin{cases} dP/dV < 0 & \text{right of MPP,} \\ dP/dV = 0 & \text{at MPP,} \\ dP/dV > 0 & \text{left of MPP.} \end{cases}$$

- **We could imagine, therefore, that the MPP can be found by incrementing the duty cycle of the converter until the ratio of the incremental changes ΔV and ΔI equals I/V; that is, until the angles ϕ and θ are equal.**
- Having located the MPP, the duty cycle of the converter remains fixed until subsequent I and V measurements indicate that a change is needed.
- That change may be the result of temperature or insolation shifts in the I-V curve, which move the MPP.
- For example, if insolation increases, the MPP will move somewhat to the right. At the next time step, the sensors will indicate an increase in current ΔI, but until the duty cycle changes, Δ V is still zero.
- That increase in insolation has moved the MPP to the right so the PV voltage needs to increase: that is. the dutv cvcle needs to increase.



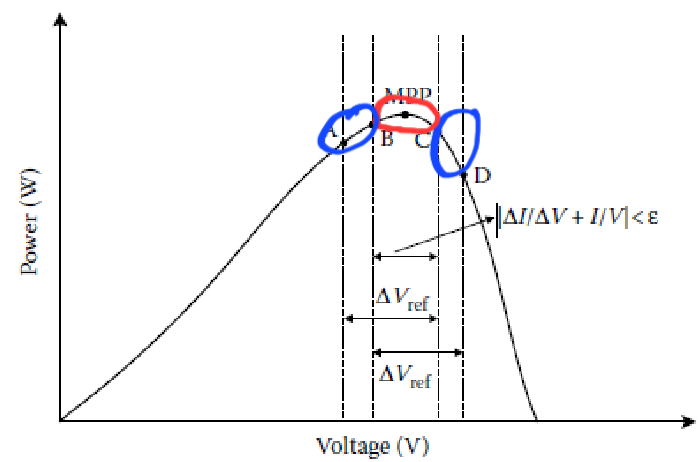


Start
InCond
Measure V(k), I(k)
ΔV=V(k)-V(k-1)
ΔI=I(k)-I(k-1)
ΔV=0
Yes
No
dI/dV=-I/V
Yes
No
dI/dV>-I/V
Yes
No
ΔI=0
Yes
No
ΔI > 0
Yes
No
No Change
Increase module voltage
Decrease module voltage
Decrease module voltage
Increase module voltage
No Change
Update History: V(k-1)=V(k)
I(k-1)=I(k)

Practical Implementation

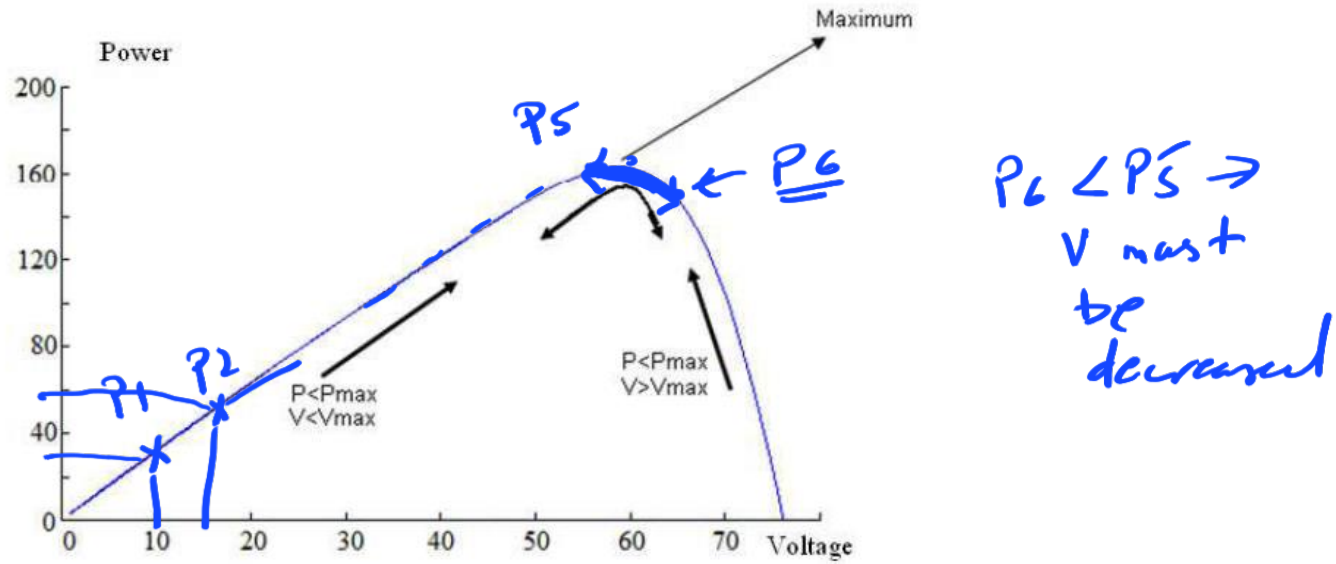
- Practically, due to the noise and errors, satisfying the condition of $\Delta I/\Delta V = -I/V$ may be very difficult .
- Therefore, this condition can be satisfied with good approximation by
- $|\Delta I/\Delta V + I/V| < \varepsilon$, where ε is a positive small value.
- Based on this algorithm, the operating point is either located in the BC interval or
- oscillating among the AB and CD intervals, Selecting the step size $(\Delta V ref)$, shown in, is a trade-off between accurate steady tracking and dynamic response.
- If larger step sizes are used for quicker dynamic responses, the tracking accuracy decreases and the tracking point oscillates around the MPP.
- On the other hand, when small step sizes are selected, the tracking accuracy will increase. In the meantime, the time duration required to reach the MPP will increase

→ $d \pm \Delta d$



Perturb and Observe (P&O) Method or "Hill Climbing method"

- **In this method the controller adjusts the voltage by a small amount from the array and measures power, if the power increases, further adjustments in the direction are tried until power no longer increases.**
- This is called P&O method. Due to ease of implementation it is one of the most commonly used MPPT method.
- The voltage to a cell is increased initially, if the output power increase, the voltage is continually increased until the output power starts decreasing.
- Once the output power starts decreasing, the voltage to the cell decreased until maximum power is reached. This process is continued until the MPPT is attained.
- This result is an oscillation of the output power around the MPP.

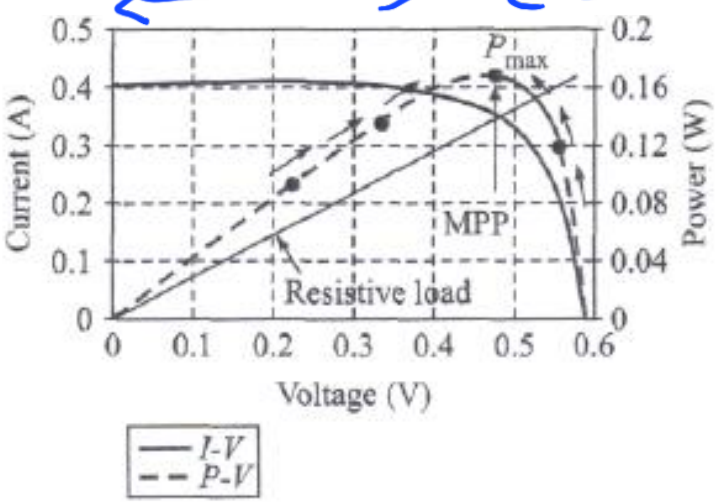


- In this algorithm the operating voltage of the PV module is perturbed by a small increment, and the resulting change of power, P is observed.
- If the P is positive, then it is supposed that it has moved the operating point closer to the MPP.
- Thus, further voltage perturbations in the same direction should move the operating point toward the MPP.
- If the P is negative, the operating point has moved away from the MPP, and the direction of perturbation should be reversed to move back toward the MPP.

Hill Climbing method (perturb and observe) Buck Converter

- The algorithm of this scheme is described below along with the help of mathematical expressions

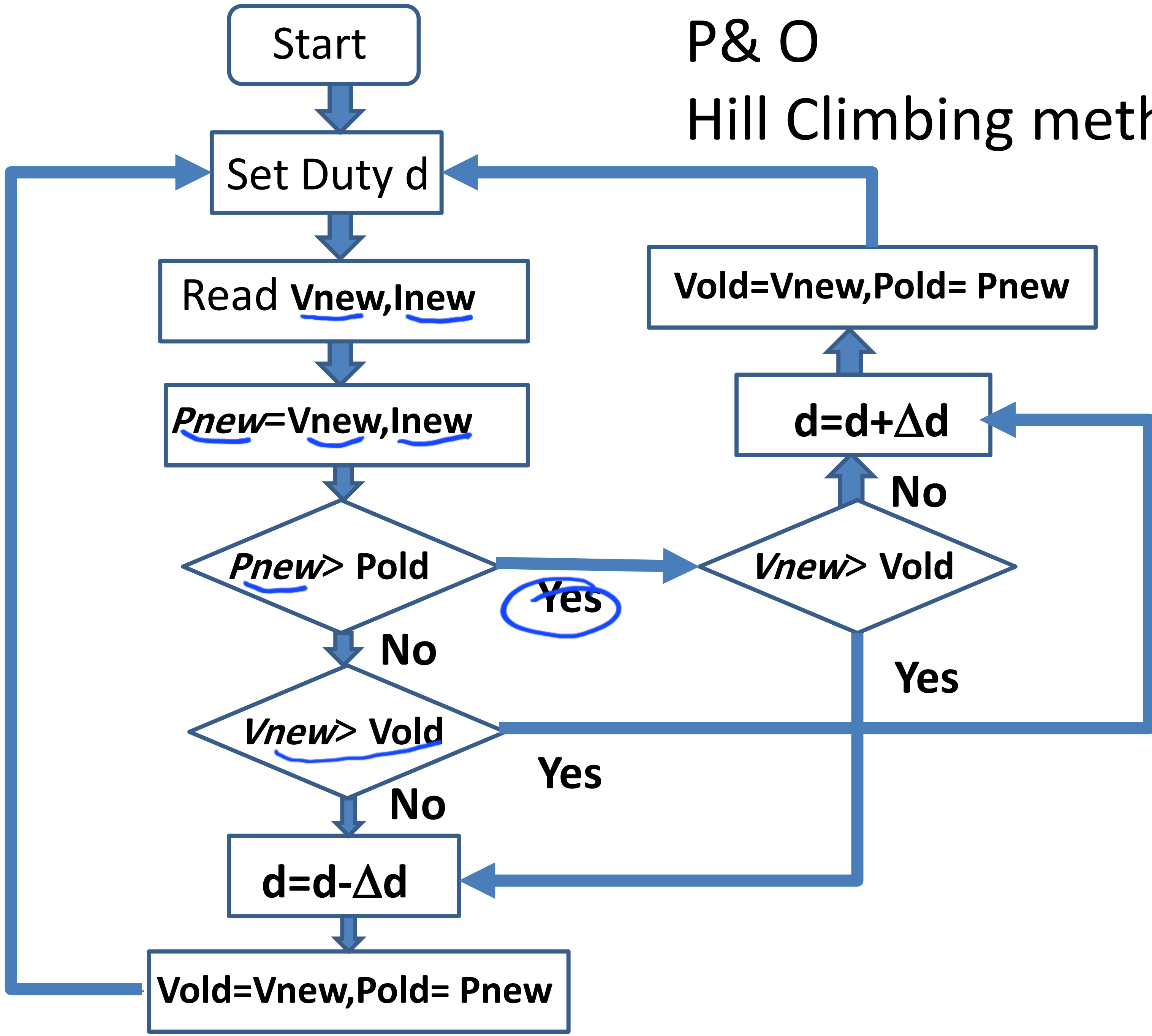
$$\left.\begin{array}{l}\text{In the voltage source region, } \dfrac{\partial P_{PV}}{\partial V_{PV}} > 0 \Rightarrow d = d + \Delta d \text{ (i.e., increment } d\text{)} \\ \text{In the current source region, } \dfrac{\partial P_{PV}}{\partial V_{PV}} < 0 \Rightarrow d = d - \Delta d \text{ (i.e., decrement } d\text{)} \\ \text{At MPP, } \dfrac{\partial P_{PV}}{\partial V_{PV}} = 0 \Rightarrow d = d \text{ or } \Delta d = 0 \text{ (i.e., retain } d\text{)}\end{array}\right\}$$



- if the slope is positive (Pnew > Pold) the duty cycle is increased *($d = d + \Delta d$).*
- This means that the slope is positive and the module is operating in the constant current region.
- In case of the slope being negative (Pnew < *Pold)* then the duty cycle is reduced

  ($d = d - \Delta d$), as the operating region in this
case is the constant voltage region.
- This algorithm can be implemented using a microcontroller.

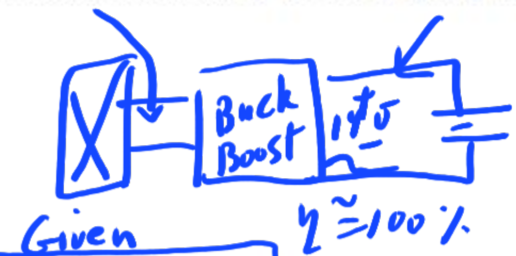
P& O
Hill Climbing method



5.13 Consider a single 87.5 W, First Solar CdTe module (Table 5.3) used to charge a 12-V battery.

a. What duty cycle should be provided to a maximum-power-point, buck-boost converter to deliver 14-V to the battery when the module is working at standard test conditions (STC)? How many amps will it deliver to the battery under those conditions?

b. Suppose ambient temperature is 25°C with 1-sun of insolation. Recalculate the amps delivered to the battery.



SOLN:

a. The First Solar module has an STC MPP of 1.78 A, 49.2 V. So the converter needs to drop the 49.2 V down to 14 V. From (5.36)

$$\frac{D}{1-D} = \frac{14V}{49.2V}$$

$$14 - 14D = 49.2D \quad .... \quad D = \frac{14}{14+49.2} = 0.2215$$

Since we assume power in equals power out,

$$49.2x1.78 = 14xI_B$$

$$I_B = \frac{49.2x1.78}{14} = 6.255A$$

SOLN:

b. First find cell temperature. From the table, NOCT = 45°C so from (5.23):

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20}{0.8}\right)S = 25 + \left(\frac{45 - 20}{0.8}\right)1 = 56.25^{o}$$

These cells have a - 0.25%/°C power degradation, so at 25°C:

Power loss = 0.25%/°C x (56.25-25)°C = 7.8125%

Power @ 25°C = 87.5 (1 - 0.078125) = 80.39 W

Again, with power in equal power out:

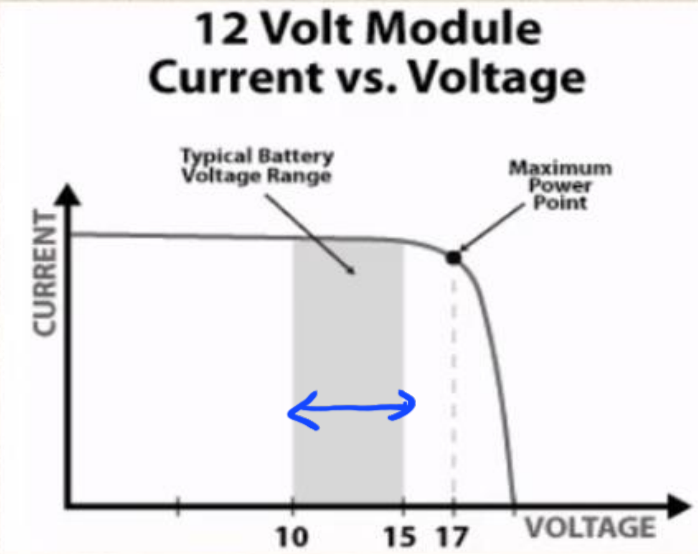
80.39 = 14V x I A   Charging current = 80.39/14 = 5.74 A

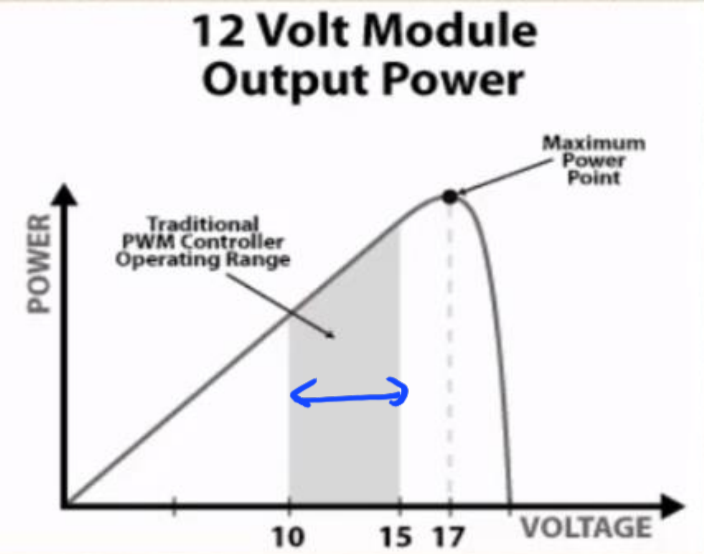
That's a loss of 8.2% due to temperature.

PWM Charging:

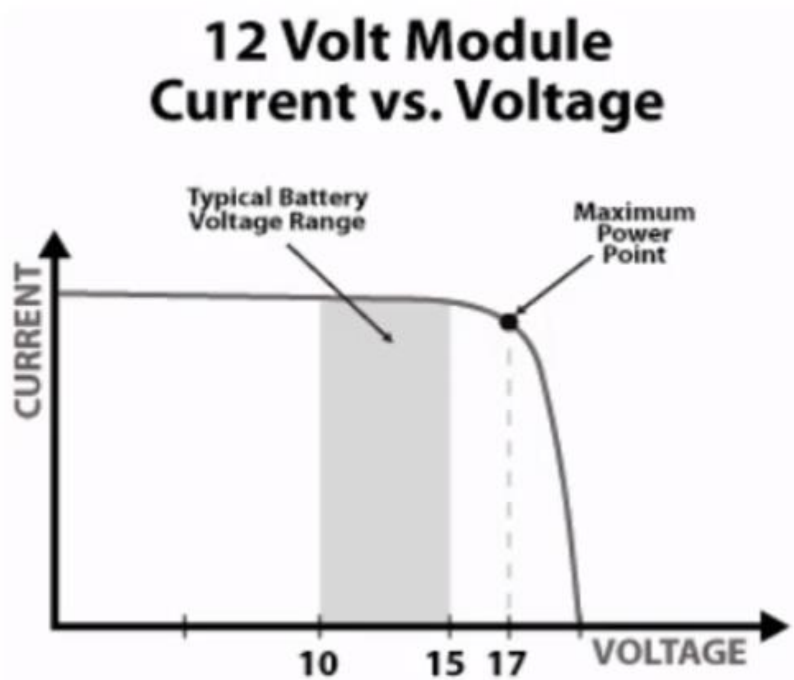
Traditional solar regulators featuring PWM (pulse width modulation) charging operate by connecting the solar array directly to the battery bank. When the array is connected directly to the battery bank, the array output voltage is 'pulled down' to the battery voltage. This occurs because the batteries are a very large load for the limited current sourcing capability of a solar array.

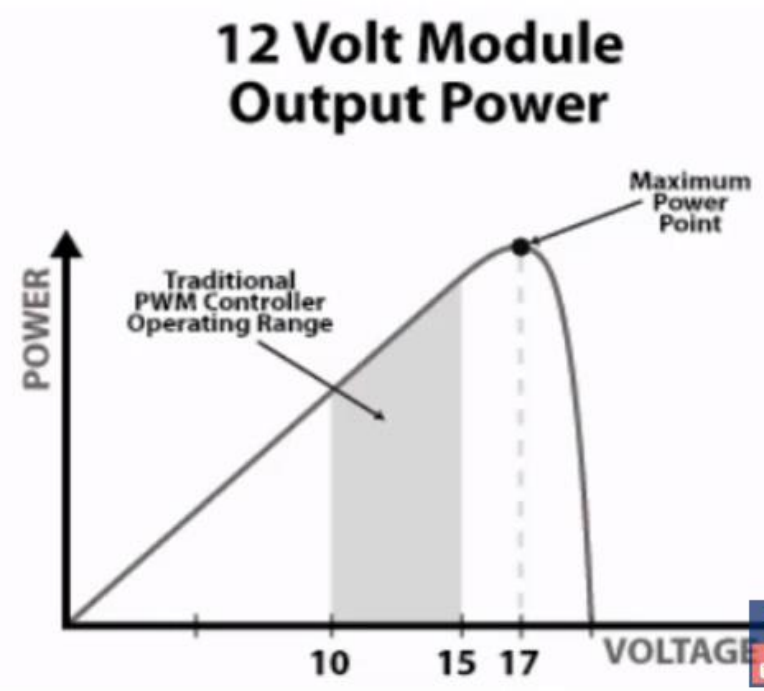
The V_{mp} (maximum power voltage) rating is the voltage where the product of the output current and output voltage (amps * volts) is greatest and output power (watts = amps * volts) is maximized. Module wattage ratings (i.e. 100W, 205W) are normally specified at the V_{mp}.





Using a nominal 12V system as an example, the battery voltage will normally be somewhere between 10 – 15 Vdc. However, 12V nominal solar modules commonly have a V_{mp} of about 17V. When the array (having V_{mp} of 17V) is connected to the batteries for charging, the batteries pull down the output voltage of the array. Thus, the array is not operating at its most efficient voltage of 17V, but rather at somewhere between 10 and 15V. The following graphs illustrate this phenomenon:



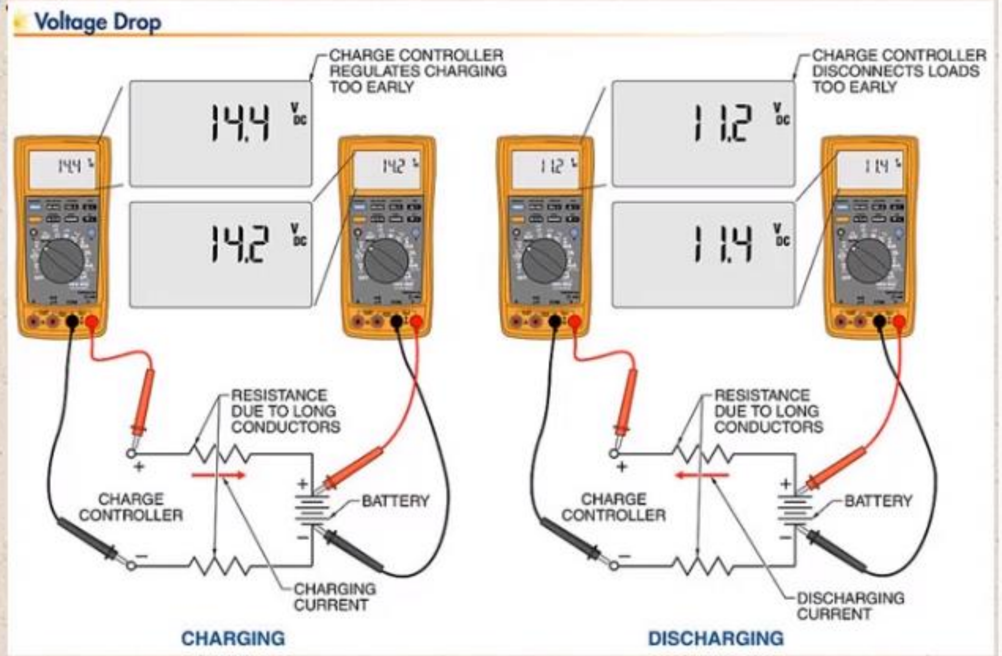


Set points?

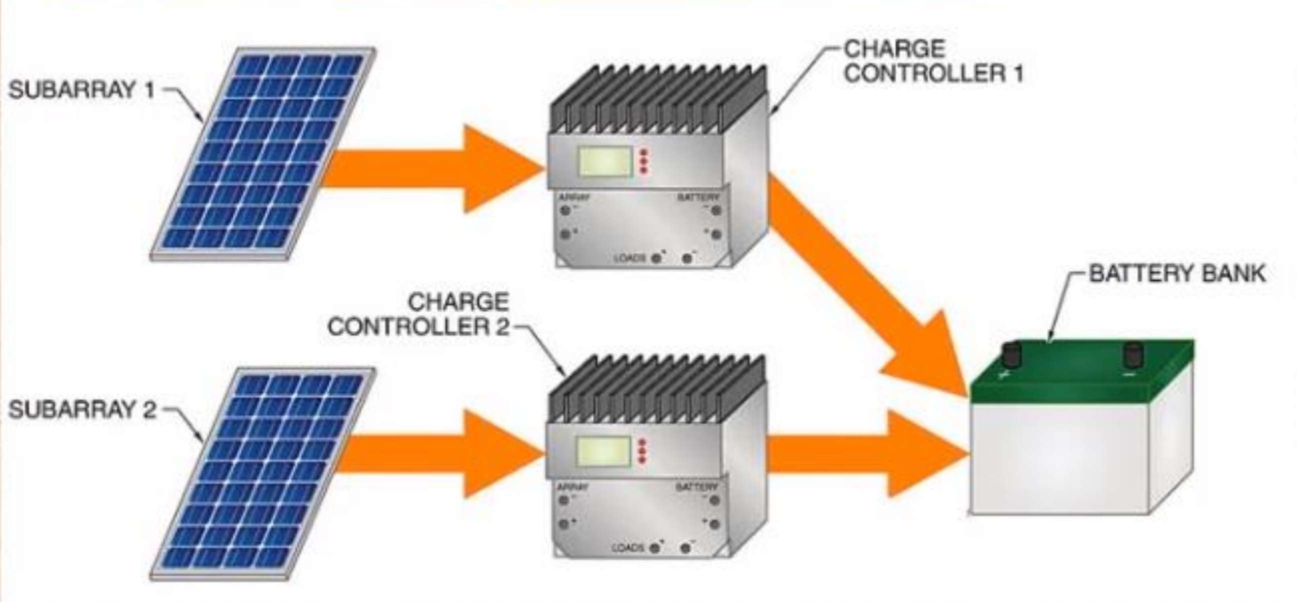
The voltages at which the controller changes the charge rate are called **set points**. When determining the ideal set points, there is some compromise between charging quickly before the sun goes down, and mildly overcharging the battery. The determination of set points depends on the anticipated patterns of usage, the type of battery, and to some extent, the experience and philosophy of the system designer or operator. Some controllers have adjustable set points, while others do not.

Cables and voltage drop

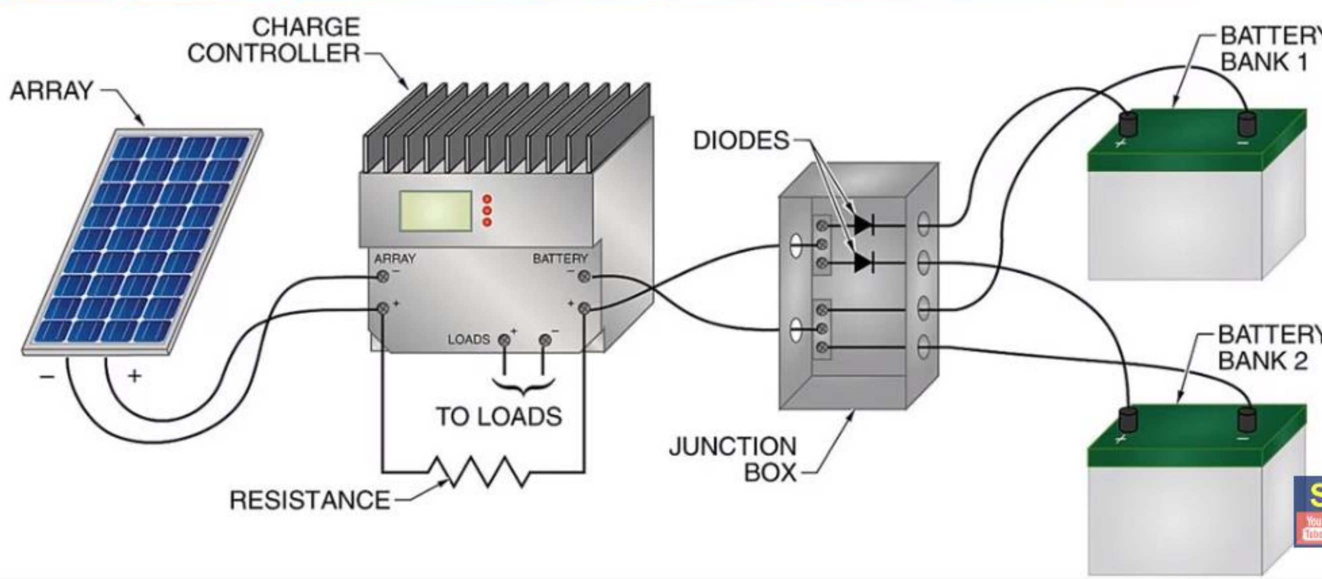
Installing charge controllers close to batteries also minimizes voltage drop. As charging current increases on the conductors between the charge controller and battery terminals, the voltage drop increases. Since many charge controllers sense battery voltage with the conductors used to deliver charging current, the measured voltage is slightly higher than the actual battery voltage. This prematurely activates charge regulation, causing the battery to be undercharged.



Multiple Subarrays and Charge Controllers



Multiple Battery Banks with One Charge Controller



BlueSolar PWM-Pro	12/24-5	12/24-10	12/24-20	12/24-30
Battery Voltage	12/24V with automatic system voltage detection			
Rated charge current	5A	10A	20A	30A
Automatic load disconnect	Yes			
Maximum solar voltage	28V / 55V (1)			
Self-consumption	< 10mA			
Load output	Manual control + low voltage disconnect			
Protection	Battery reverse polarity (fuse)		Output short circuit	Over temperature
Battery temperature sensor	Optional (article SCC940100100)			
Temperature compensation	-30 mV / °C resp. -60 mV / °C (if temperature sensor installed)			
Remote panel	Optional (article SCC900300000)			
Grounding	Common positive			
Operating temp. range	-20 to +50°C			
Humidity (non-condensing)	Max 98%			

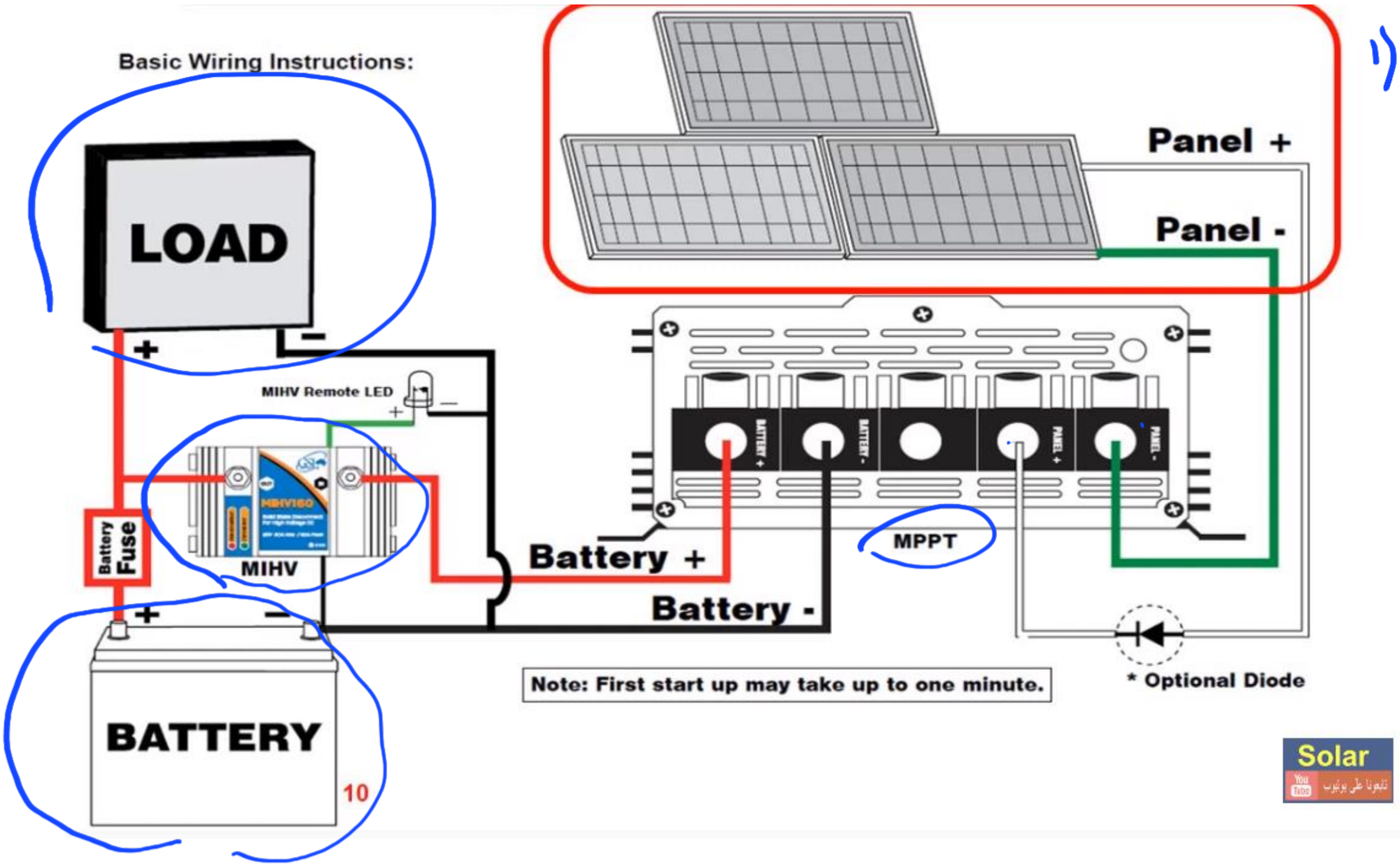
DEFAULT SETTINGS				
Absorption charge (2)	14.4V / 28,8V			
Float charge (2)	13.8V / 27,6V			
Equalization charge (2)	14,6V / 29,2V			
Low voltage load disconnect	11,1V / 22,2V			
Low voltage load reconnect	12,6V / 25,2V			
ENCLOSURE				
Terminal size	4mm²	4mm²	10mm²	10mm²
Protection category	IP30			
Weight	0,13kg	0,13kg	0,3kg	0,5kg
Dimensions (h x w x d)	138x70x37 mm 5.4x2.7x1.4 inch	138x70x37 mm 5.4x2.7x1.4 inch	160x82x48 mm 6.3x3.2x1.9 inch	200x100x57 mm 7.9x4.0x2.3 inch
STANDARDS				
Safety	IEC 62109-1			
Emission	EN 61000-6-1, EN 61000-6-3, ISO 7637-2			

1) For 12V use 36 cell Solar panels
For 24V use 72 cell Solar panels

Type of Charge Controller

7. The latest generation of charge controllers incorporates a technology called maximum power point tracking, or MPPT. This function is designed to increase the efficiency of the PV array by converting the typically higher voltage (17-21 VDC in a 12 VDC nominal system) to the 14 VDC or so required to charge the battery. Stated simply, the un-useable high-end voltage is converted to useable extra amps. Remember the relationship between volts, amps, and watts: watts = amps x volts. An MPPT charge controller takes advantage of this relationship to deliver more useable power from the PV array to the batteries. The electronics

Basic Wiring Instructions:



MPPT is most effective under these conditions:

Cold weather, cloudy or hazy days:

Normally, PV module works better at colder temperatures and MPPT is utilized to extract maximum power available from them.

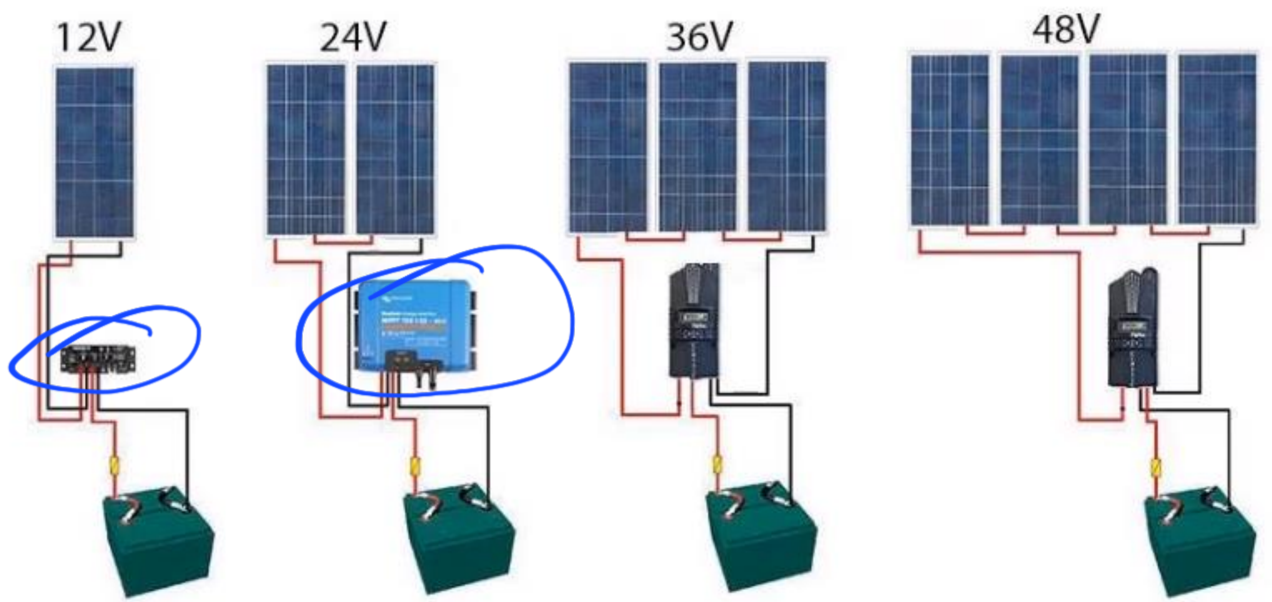
When battery is deeply discharged:

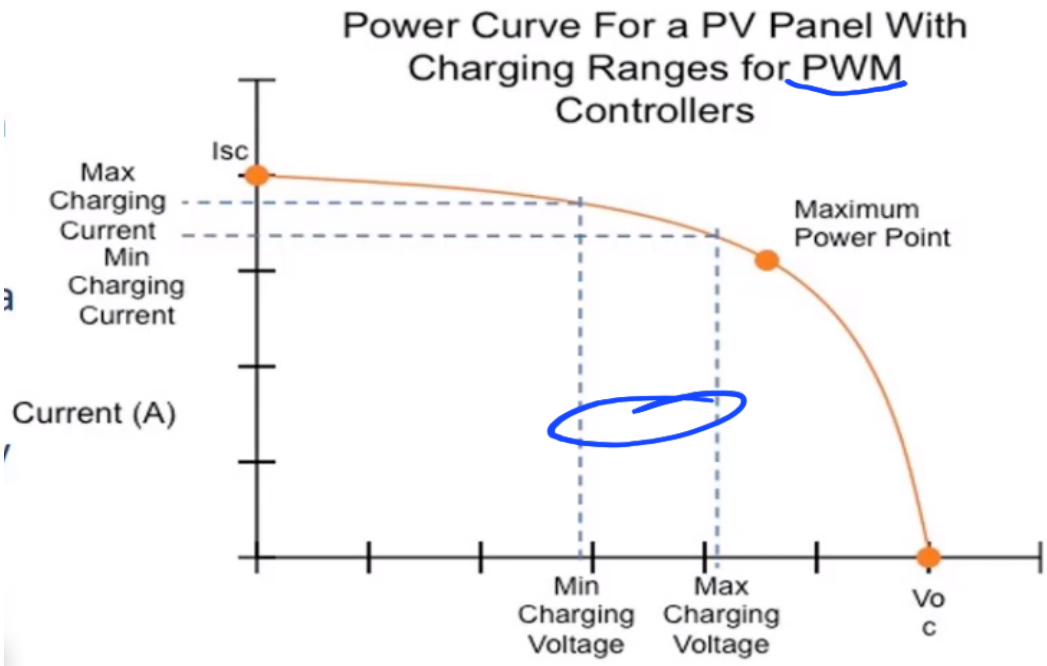
MPPT can extract more current and charge the battery if the state of charge in the battery is lowers.

Maximum Power Point Tracking Controllers

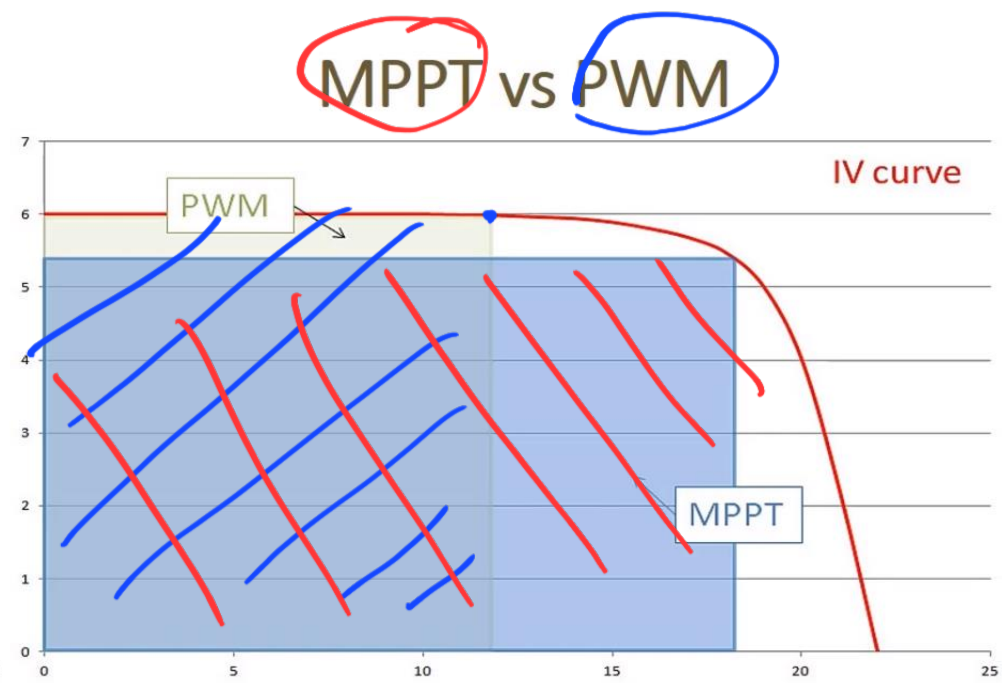
- A MPPT controller adjusts the voltage output to take advantage of the Vpp and charge the battery more

- *Peak Power Voltage* (Vpp) is the maximum power point that a PV system can deliver; varies with temperature and sunlight intensity





Only voltage control



End of charge controllers
& MPPT Topic