CHAPTER 4

MAXIMUM POWER POINT TRACKER

4.1 Introduction

PV cells have a single operating point where the values of the current (I) and Voltage (V) of the cell result in a maximum power output. These values correspond to a particular resistance, which is equal to V/I as specified by Ohm's Law. A PV cell has an exponential relationship between current and voltage, and the maximum power point (MPP) occurs at the knee of the curve, where the resistance is equal to the negative of the differential resistance (V/I = -dV/dI). Maximum power point trackers utilize some type of control circuit or logic to search for this point and thus to allow the converter circuit to extract the maximum power available from a cell.

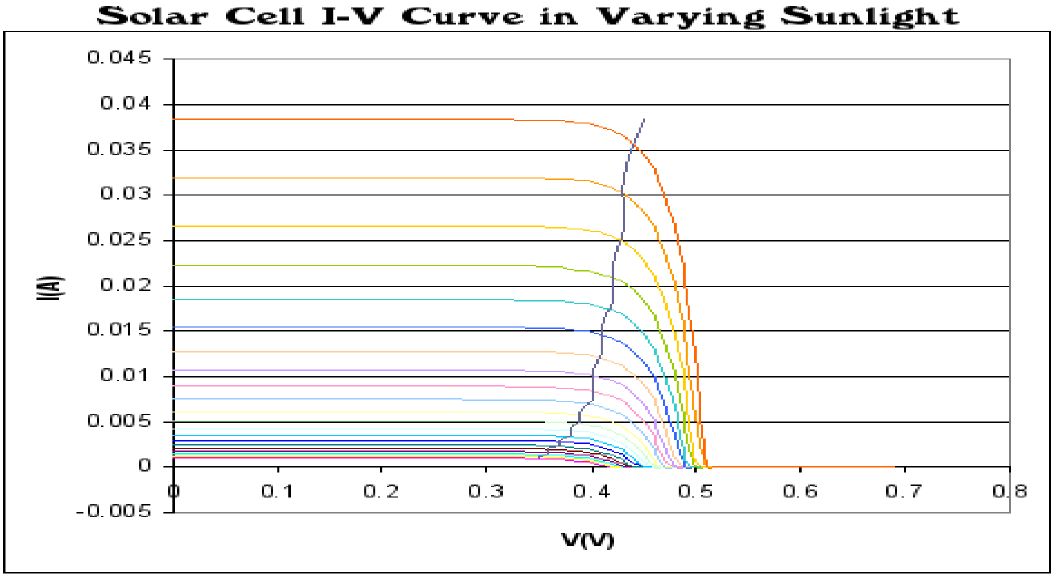


Fig 4.1 I-V Curve in varying Sunlight

4.2 Maximum Power Point Tracking

This is electronic tracking, and has nothing to do with moving the panels. Instead, the controller looks at the output of the panels, and compares it to the battery voltage. It then figures out what is the best power that the panel can put out to charge the battery. It takes this and converts it to best voltage to get maximum AMPS into the battery. (Remember, it is **Amps into the battery** that counts). Most modern MPPT's are around 92-97% efficient in the conversion. You typically get a 20 to 45% power gain in winter and 10-15% in summer. Actual gain can vary widely depending weather, temperature, battery state of charge, and other factors.

4.3 Maximum Power Point Tracker (or MPPT)

A **maximum power point tracker** (or **MPPT**) is a high efficiency DC to DC converter which functions as an optimal electrical load for a photovoltaic (PV) cell, most commonly for a solar panel or array, and converts the power to a voltage or current level which is more suitable to whatever load the system is designed to drive.

The maximum power is transferred from a solar panel when the impedance of the load it is driving is optimally matched to its source impedance. As you might expect, the panel’s source impedance also varies as the operating conditions change, and so more sophisticated systems use a Maximum Power Point Tracker (MPPT) to optimise the panel’s load conditions to its peak power transfer level. In operation the voltage generated at the PV panel terminals will vary as the MPPT automatically adjusts the power taken from the panel, maintaining that power at a maximum for the prevailing conditions

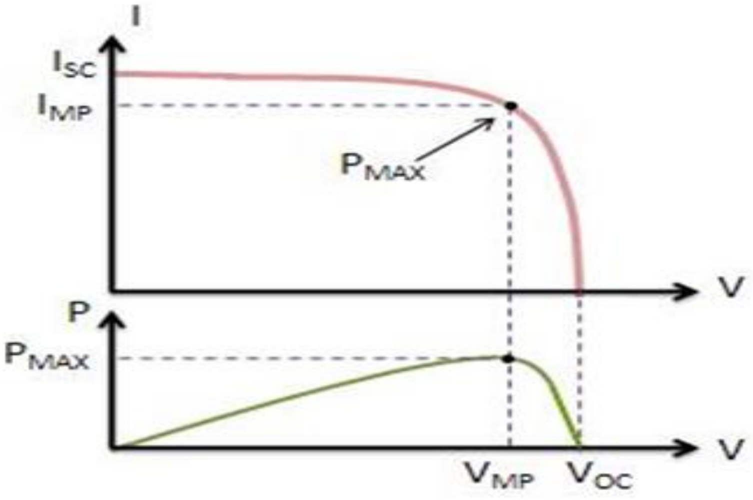


Fig 4.2 I-V Curve & P-V Curve

4.4 Uses of MPPT

Battery-less grid-tied PV inverters utilize MPPTs to extract the maximum power from a PV array, convert this to alternating current (AC) and sell excess energy back to the operators of the power grid.

Off-grid power systems also use MPPT charge controllers to extract the maximum power from a PV array. When the immediate power requirements for other devices plugged into the power system are less than the power currently available, the MPPT stores the "extra" energy -- energy that is not immediately consumed during the day -- in batteries. When other devices plugged into the power system require more power than is currently available from the PV array, the MPPT drains energy from those batteries in order to make up the lack. MPPT charge controllers are quickly becoming more affordable and are more common in use now than ever before.

The uses of MPPT regulators are greatest during cold weather, on cloudy or hazy days or when the battery is deeply discharged. Solar MPPTs can also be used to drive motors directly from solar panels. The benefits seen are huge, especially if the motor load is continuously changing. This is due to the fact that the AC impedance across the motor is related to the motor's speed. The MPPT will switch the power to match the varying resistance.

4.5 Solar tracker

A solar tracker is a device that keeps an array of solar modules (solar panels) or a concentrating collector facing toward the sun. The use of a tracker ensures that the amount of sunlight falling directly onto the modules throughout the day, and hence the amount of electricity produced, is much greater than in the case of a static set-up. Solar trackers can boost the power output of an array by 30 to 50%. Their cost is relatively low compared to that of the solar modules themselves, and can, in any case, be recouped quite quickly through the extra electricity generated.

Fig 4.3 Solar Tracker

4.5.1 Types of solar tracker

The two basic types of solar tracker are single-axis and double-axis. A single-axis tracker can only pivot in one plane – either horizontally or vertically. This makes it less complicated and generally cheaper than a two-axis tracker, but also less effective at harvesting the total solar energy available at a site.

A horizontal-axis tracker consists of a long horizontal tube to which solar modules are attached. The tube is aligned in a north-south direction, is supported on bearings mounted on pylons or frames, and rotates slowly on its axis to follow the sun's motion across the sky. This kind of tracker is most effective at equatorial latitudes where the sun is more or less overhead at noon. In general, it is effective wherever the solar path is high in the sky for substantial parts of the year, but, for this very reason, does not perform well at higher latitudes.

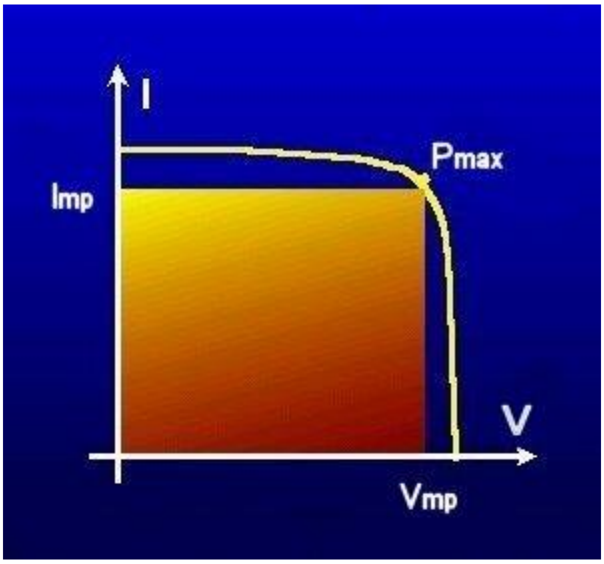
For higher latitude, a vertical-axis tracker is better suited. This works well wherever the sun is typically lower in the sky and, at least in the summer months, the days are long.

Double-axis solar trackers, as the same suggest, can both simultaneously in horizontal and vertical directions, and so are able to point exactly at the sun at all times in any location. They use they same principle as the mountings of astronomical telescopes; consequently there is no shortage of software to run on the computers that control movement of such devices.

4.6 Maximum power point (MPP)

The point on the current-voltage (I-V) curve of a solar module under illumination, where the product of current and voltage is maximum (P_{max}, measured in watts). The points on the I and V scales which describe this curve point are named I_{mp} (current at maximum power) and V_{mp} (voltage at maximum power.)

For a typical silicon cell panel, the maximum power point (MPP) is about 17 volts for a 36-cell configuration.



4.6.1 Variation of MPP

The I-V characteristics curve of a photovoltaic array is shown in fig 4.17. The variation of maximum power point is also shown in this figure. The maximum power points of different I-V curves are joined by a dotted line. Actually the variation of MPP is not linear ,but can be considered to be linear for practical purposes. The voltage across the PV array terminals is to be kept at V1, V2, V3 and V4 for insulation L1, L2, L3 and L4 respectively for the extraction of maximum PV power. A straight line is drawn the maximum power points P1, P2, P3, P4. A middle point “P” is chosen, which lies between P1 and P4. If the PV array voltage is kept at V0, which corresponds to “P” apparently maximum power will always be supplied to the load. Though it will not track the MPP accurately, the performance can be thought to be quite adequate for many practical purposes, e.g, motor driving, battery charging etc.

In this proposed maximum power point tracker circuit, a Buck or step down DC-TO-DC converter is used to provide adequate modulation to the switch in order to maintain the photovoltaic generator voltage at its optimum value Vm. Since the operating conditions are highly variable (e.g. with illumination, temperature etc.), the circuit has to be a closed-loop control (Fig. **4.17**).

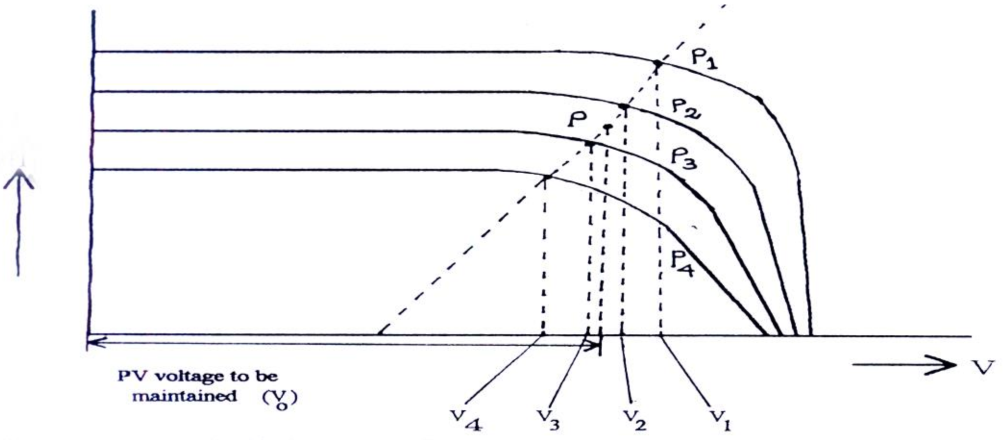


Fig . 4 . 17 Variation of MPP

4.7. Buck Regulators

In buck regulators, the average output voltage V_a is less than the input voltage, V_s – hence the name ‘bucks' a very popular regulator . The circuit diagram of a buck regulator is given below,

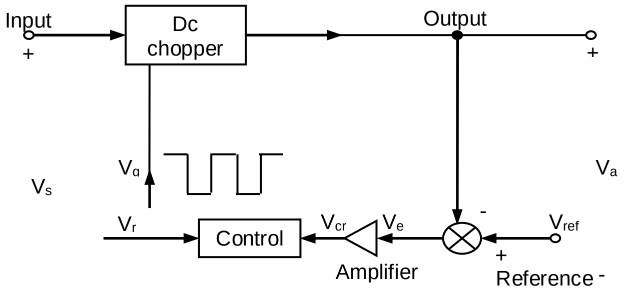


Fig 4.5 Elements regulators of switching-mode

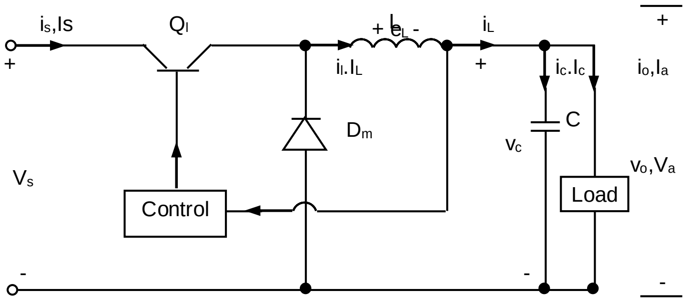
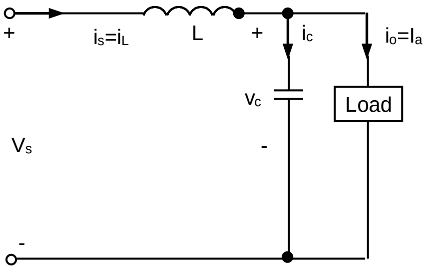
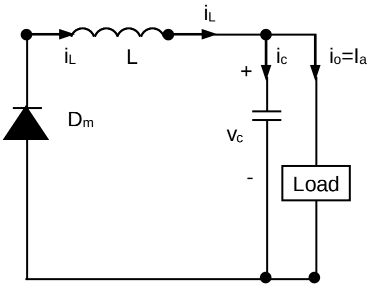


Fig 4.6 Circuit diagram



Mode 1



Mode 2

Regulator using a power BJT is shown in Figure 5.15a, and this is like a step-down converter. The circuit operation can be divided into two modes. Mode I begins when transistor Q_1 is switched on at $t = 0$. The input current, with rises, flows through filter inductor L, filter capacitor C, and load resistor R. Mode 2 begins when transistor Q_1 is switched off at $t = t_1$. The freewheeling diode D_m conducts due to energy stored in the inductor; and the inductor current continues to flow through L, C, load and diode D_m the inductor current falls until transistor Q_1 is switched on again in the next cycle. The equivalent circuits for the modes of operation are shown in Figure 5.16b. The wave-forms for the voltage and currents are shown in Figure 5.16c for a continuous current flow in the inductor L. It is assumed that the current rises and falls linearly. In practical circuits the switch has finite, nonlinear resistances. Its effect can generally be negligible in most applications. Depending on the switching frequency, filter inductance, and capacitance, the inductor current could be discontinuous.

The voltage across the inductor L is, in general,

$$eL = L\frac{di}{dt}$$

Assuming that the inductor current rises linearly from I_1 to I_2 in time t_1,

$$V_s - V_a = L\frac{I_2 - I_1}{t_1} = L\frac{\Delta I}{t_1} \qquad (1)$$

or

$$t_1 = \frac{\Delta IL}{V_s - V_a} \tag{2}$$

and the inductor current falls linearly form I_1 to I_2 in time t_2,

$$-V_a = L\frac{\Delta I}{t_2} \tag{3}$$

Where $\Delta I = I_2 - I_1$ is the pack-to-peak ripple current of the inductor L. Equating the value of Δ I in Eqs. (1) and (2) gives

$$\Delta I = \frac{(V_s - V_a)t_1}{L} = \frac{V_a t_2}{L}$$

Substituting $t_1 = kT$ and $t_2 - (1-k)T$ yields the average output Voltage as

$$V_a = V_s\frac{t_1}{T} = kV_s \tag{4}$$

Assuming a lossless circuit, $V_s I_s = V_a I_a = kV_s I_a$ and the average input current

$$I_s = kI_a \tag{5}$$

The switching period T can be expressed as

$$T = \frac{1}{f} = t_1 + t_2 = \frac{\Delta IL}{V_s - V_a} + \frac{\Delta IL}{V_a} = \frac{\Delta ILV_s}{V_a(V_s - V_a)} \tag{6}$$

which gives the peak-to-peak ripple current as

$$\Delta I = \frac{V_a(V_s - V_a)}{fLV_s} \tag{7}$$

or

$$\Delta I = \frac{V_s k(1-k)}{fL} \tag{8}$$

Using Kerchief's current law, we can write the inductor current i_L as

If we assume that the load ripple current Δi_o is very small and negligible, $\Delta i_L = \Delta i_c$.

The average capacitor current, which flows into for $t_1/2 + t_2/2 = T/2$, is

$$I_c = \frac{\Delta I}{4}$$

The capacitor voltage is expressed as

$$u_c = \frac{1}{C}\int i_c dt + u_c(t=0)$$

and the peak-to-peak ripple voltage of the capacitor is

$$\Delta V_c = u_c - v_c(t=0) = \frac{I}{C}\int_0^{T/2}\frac{\Delta I}{4}dt = \frac{\Delta IT}{8C} = \frac{\Delta I}{8fC} \tag{9}$$

Substituting the value of ΔI from Eq. (7) or (8) in Eq. (9) yields

$$\Delta V_c = \frac{V_a(V_s - V_a)}{8LCf^2V_s} \tag{10}$$

$$\Delta V_c = \frac{V_s k(1-k)}{8LCf^2} \tag{11}$$

Condition of continuous inductor current and capacitor voltage. If I_L is the average inductor current, the inductor ripple current $\Delta I = 2I_L$.

Using Eqs. (8) and (12), we get

$$\frac{V_s(t-k)k}{fL} = 2I_L = 2I_a = \frac{2kV_s}{R}$$

which gives the critical value of the inductor L_c as

$$L_c = L = \frac{(1-k)R}{2f} \tag{12}$$

If V_c is the average capacitor voltage, the capacitor ripple voltage $\Delta V_c = 2V_a$ Using Eqs. (4) and (8), we get

$$\frac{V_s(I-k)k}{8LCf^2} = 2V_a = 2kV_s$$

which gives the critical value of the capacitor C_c as

$$C_c = C = \frac{1-k}{16Lf^2} \tag{13}$$

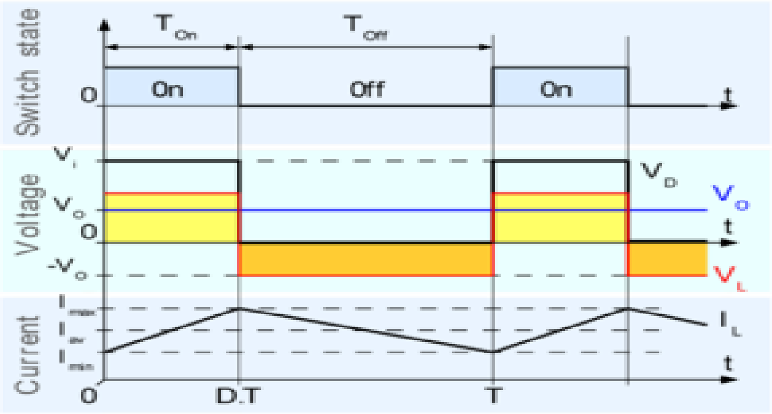


Fig 4.7 Continuous Mode of Operation

The buck regulator requires only one transistor, is simple, and has high efficiency greater than 90%. The di/dt of the load current is limited by inductor L. However, the input current is discontinuous and a smoothing input filter is normally required. It provides one polarity of output voltage and unidirectional output current. It requires a protection circuit in case of possible short circuit across the diode path.

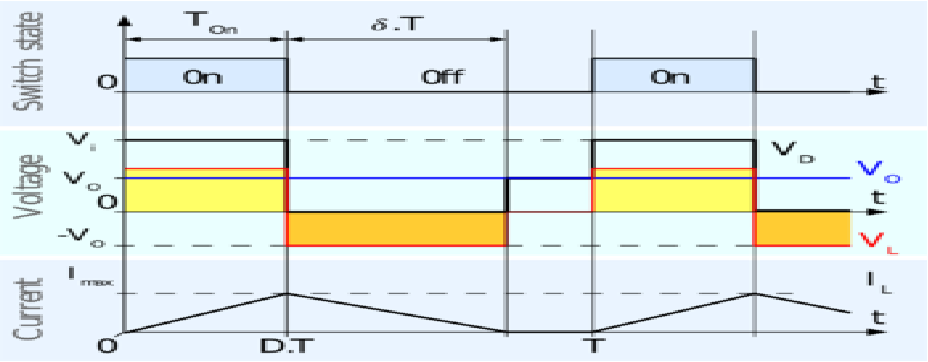


Fig 4.8 Discontinues Mode of Operation

4.8 Boost Regulators

In a boost regulators the output voltage is greater than the input voltage --- hence the name 'boost'. A boost regulator using a power MOSFET is shown in Figure 4.9. The circuit operation can be divided into two modes. Mode I begins when transistor in on.

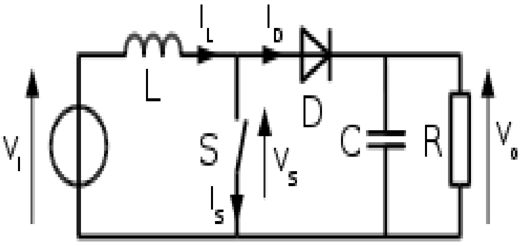
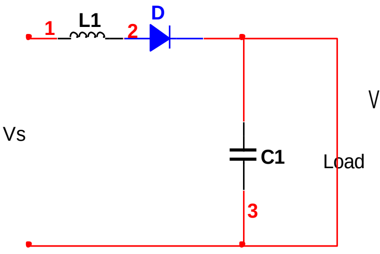
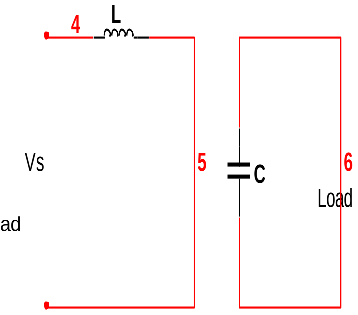


Fig 4.9 Circuit diagram



Mode 1



Mode 2

Boost regulator with continuous mode

M_1 is switched on at $t = 0$. The input current, which rises, flows though inductor L and transistor Q_1. Mode 2 begins when transistor M_1 is switched off at $t = t_1$. The current that was following through the transistor would now flow $L, C,$ load, and diode D_m The inductor current falls until transistor M_1 is turned on again in the next cycle. The energy stored in inductor L is transferred to the load. The equivalent circuits for the moods of operation are shown Figure 5.17b. The waveforms for voltages and currents are shown in 5.17c. for continuous load current, assuming that the current rises or falls linearly.

Assuming that the inductor current rises linearly from I_1 to I_2 in time t_1,

$$V_s = L\frac{I_2 - I_1}{t_1} = L\frac{\Delta I}{t_1} \tag{14}$$

or

$$t_1 = \frac{\Delta IL}{V_s} \tag{15}$$

and the inductor current falls linearly form I_1 to I_2 in time t_2,

$$V_s = V_a = -L\frac{\Delta I}{t_2} \tag{16}$$

or

$$t_2 = \frac{\Delta IL}{V_a - V_s} \tag{17}$$

Where $\Delta I = I_2 - I_1$ is the pack-to-peak ripple current of the inductor L. Eqs. (14) and (16)

$$\Delta I = \frac{V_s t_1}{L} = \frac{(V_a - V_s)t_2}{L}$$

Substituting $t_1 = kT$ and $t_2 = (1-k)T$ yields the average output Voltage,

$$V_a = V_s\frac{T}{t_2} = \frac{V_s}{1-k} \tag{18}$$

which gives

$$(1-k) = \frac{V_s}{V_a} \tag{19}$$

Substituting $k = t_1/T = t_1 f$ into Eq. (19) yields

$$t_1 = \frac{V_a - V_s}{V_a f} \tag{20}$$

Assuming a lossless circuit, $V_s I_s = V_a I_a = V_s I_a (1-k)$ and the average input current

$$I_s = \frac{Ia}{1-k} \tag{21}$$

The switching period T can be expressed from

$$T = \frac{1}{f} = t_1 + t_2 = \frac{\Delta IL}{V_s} + \frac{\Delta IL}{V_a - V_s} = \frac{\Delta ILV}{V_s(V_a - V_s)} \qquad (22)$$

and this gives the peak-to-peak ripple current.

$$\Delta I = \frac{V_s(V_a - V_s)}{fLV_a} \qquad (23)$$

or

$$\Delta I = \frac{V_s k}{fL} \qquad (24)$$

When the transistor is on, the capacitor supplies the load current for $t = t_1$. The average capacitor current during time t_1 is $I_c = I_a$ and the peak-topeak ripple voltage of the capacitor is

$$\Delta V_c = u_c - v_c(t = 0) = \frac{I}{C}\int_0^{t_1} I_c dt = \frac{I}{C}\int_0^{t_1} I_a = \frac{I_a t_1}{C} \qquad (25)$$

Substituting $t_1 = (V_a - V_s)/(V_a f)$ from Eq (21) gives

$$\Delta V_c = \frac{I_a(V_a - V_s)}{V_a f_c} \qquad (26)$$

or

$$\Delta V_c = \frac{I_a k}{fC^2} \qquad (27)$$

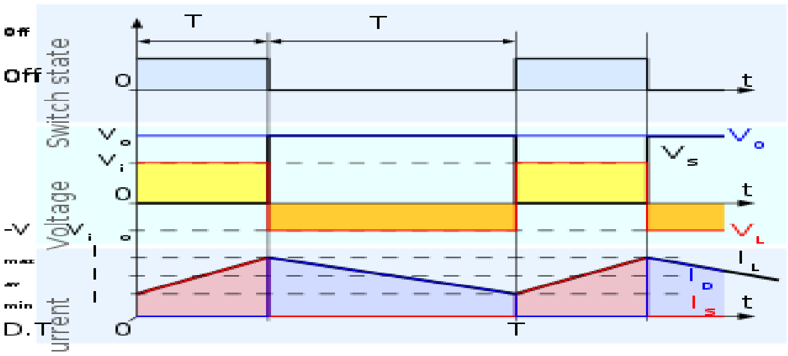


Fig 4.10 Continuous Mode of Operation

Condition of continuous inductor current and capacitor voltage. If I_L is the average inductor current, the inductor ripple current $\Delta I = 2I_L$.

Using Eqs. (18) and (24), we get

$$\frac{kV_s}{fL} 2I_L = 2Ia = \frac{2V_s}{(1-k)R}$$

which gives the critical value of the inductor L_c as

$$L_c = L = \frac{k(1-k)R}{2f} \qquad (28)$$

If V_c is the average capacitor voltage, the capacitor ripple voltage $\Delta V_c = 2V_a$ Using Eq. (27) we get

$$\frac{I_a k}{Cf} = 2V_a = 2I_a R$$

which gives the critical value of the capacitor C_c as

$$C_c = C = \frac{k}{2fR}$$

(29)

The boost regulator can step up the output voltage without transformer. Due to a single transistor, it has a high efficiency. The input current is continuous. However, a high-peak current has to flow through the power transistor. The output voltage is very sensitive to changes in duty cycle k and it might be difficult to stabilize the regulator. The average output currents is less than the average inductor current by a factor of (1-k), and a much higher rms current would flow through the filter capacitor, re-sulting in the use of a larger filter capacitor and a larger inductor than those of a buck regulator.

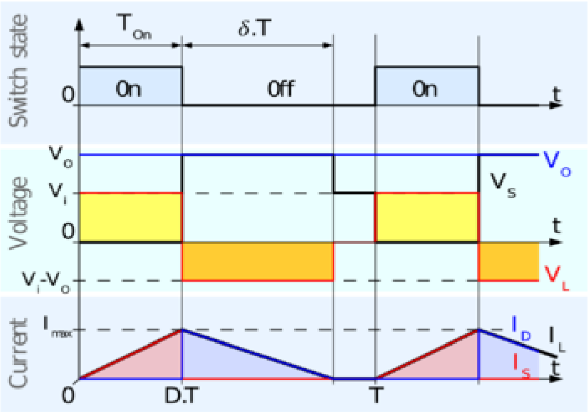


Fig 4.11 Discontinuous Mode of Operation

4.9 MAXIMUM POWER POINT TRACKER CIRCUIT

The MPPT control circuit is feed by a signal which is the image of generator power. usually this signal is the output of an analog multiplier(fig-4.18), the inputs being the generator voltage and generator current measure through a series shunt.

The maximum power point tracker circuit applies the fact that at the maximum power point, the steady state condition is expressed as dP=0. As shown in fig-4.18, a differentiating amplifier provides a signal proportional to dP/dt.

a ramp generator provides a continuous variation of the PV array through the PWM that acts on Ton. if the subsequent power variation dP/dt is positive, the operating point moves continuously to the maximum power point(MPP). When the power reaches maximum value (dP/dt=0), the output of the differentiator is zero, which stop the linear ramp generator to increase. At this state, PWM signal, corresponding to maximum operating point of the PV array settles. The PWM signal for the optimum condition drives the load through the DC- To -DC converter.

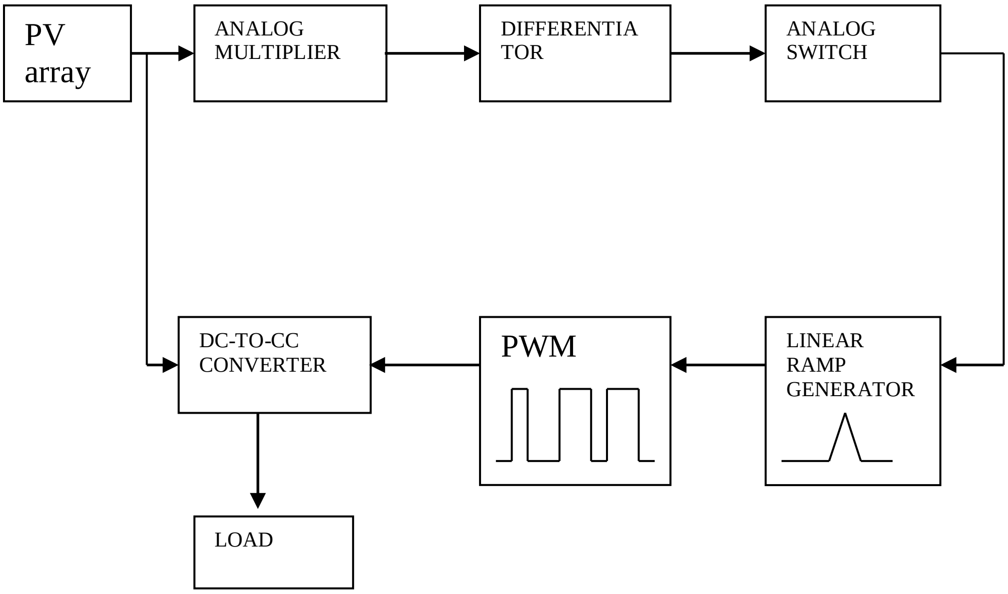


Fig.4.12. The block diagram of Maximum Power Point Tracker (MPPT) System.