3. POWER CONVERTERS

3.1 Photovoltaic (PV) Systems

Photovoltaic (PV) systems convert sunlight to electric current. You are already familiar with some simple PV applications in today’s society, such as calculators and wristwatches. More complicated systems provide power for communications satellites, water pumps, and the lights, appliances, and machines in homes and workplaces. Many road and traffic signs along highways are now powered by PV.

PV systems produce some electric current any time the sun is shining, but more power is produced when the sunlight is more intense and strikes the PV modules directly (as when rays of sunlight are perpendicular to the PV modules). While solar thermal systems use heat from the sun to heat water or air, PV does not use the sun's heat to make electricity. Instead, electrons freed by the interaction of sunlight with semiconductor materials in PV cells create an electric current. PV modules are much less tolerant of shading than are solar water-heating panels. When siting a PV system, it is most important to minimize any shading of the PV modules.

PV allows you to produce electricity—without noise or air pollution—from a clean, renewable resource. A PV system never runs out of fuel, and it won't increase oil imports.

3.2 Block Diagram of Solar Photovoltaic System

Generally there are two types of Solar Photovoltaic System they are

1. Autonomous Solar Photovoltaic system or Stand alone Solar Photovoltaic system.
2. Grid Connected PV system.
    a) Without Battery.
    b) With Battery.

3.3 Autonomous PV system (or) Stand alone Solar Photovoltaic System (SPV)

A Standalone SPV system is the one which is not connected to the power grid. Standalone PV systems usually have a provision for energy storage. This system has battery support to supply the load requirements during the night hours or even when sunshine is not adequate (Cloudy conditions) during the day.

3.3.1 Introduction

A Solar PV panel produces DC electrical power, which is different from AC power that we receive from our electrical grid supply. There are appliances that use either DC power or AC power for their operation. Most of the equipment used in our homes use AC power. Therefore it is often required to convert DC power into AC power. The conversion of DC power to AC power can be achieved using a device called inverter (or DC to AC converter). It is also possible to convert AC power into DC power using a rectifier.

3.3.2 Block Diagram

Figure 1 shows the block diagram of Standalone SPV system. Power is generated when sun light falls on the SPV module. This power is given to the MPPT or Charge controller block. The function of this block is to control the variation in the output of the SPV module and make it suitable for use at the output according to the supply required by a load. There are two types of the loads: AC and DC. DC components are directly connected to the MPPT or Charge controller block, where as the AC appliances are connected through the Battery and inverter.

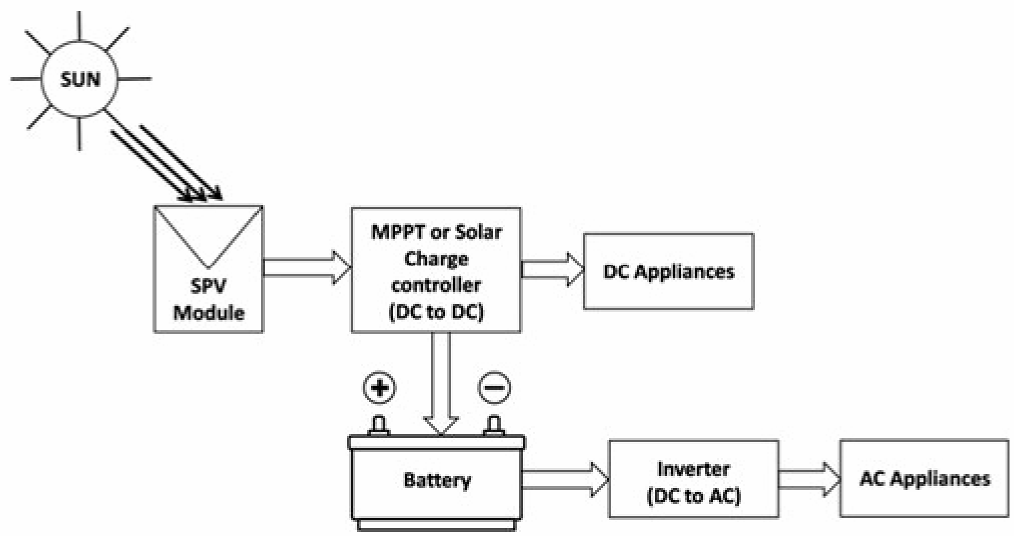
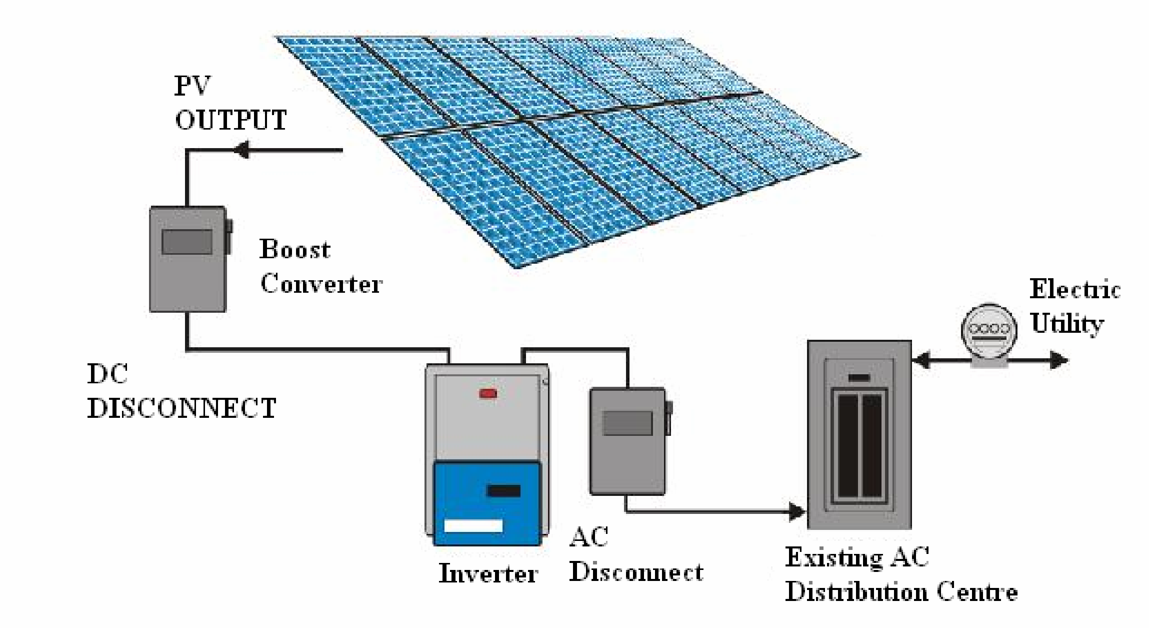


Fig 1 Simple Block Diagram of Standalone SPV system

In this way, a Standalone system is connected depending upon whether only AC load is present or both AC and DC load are present.

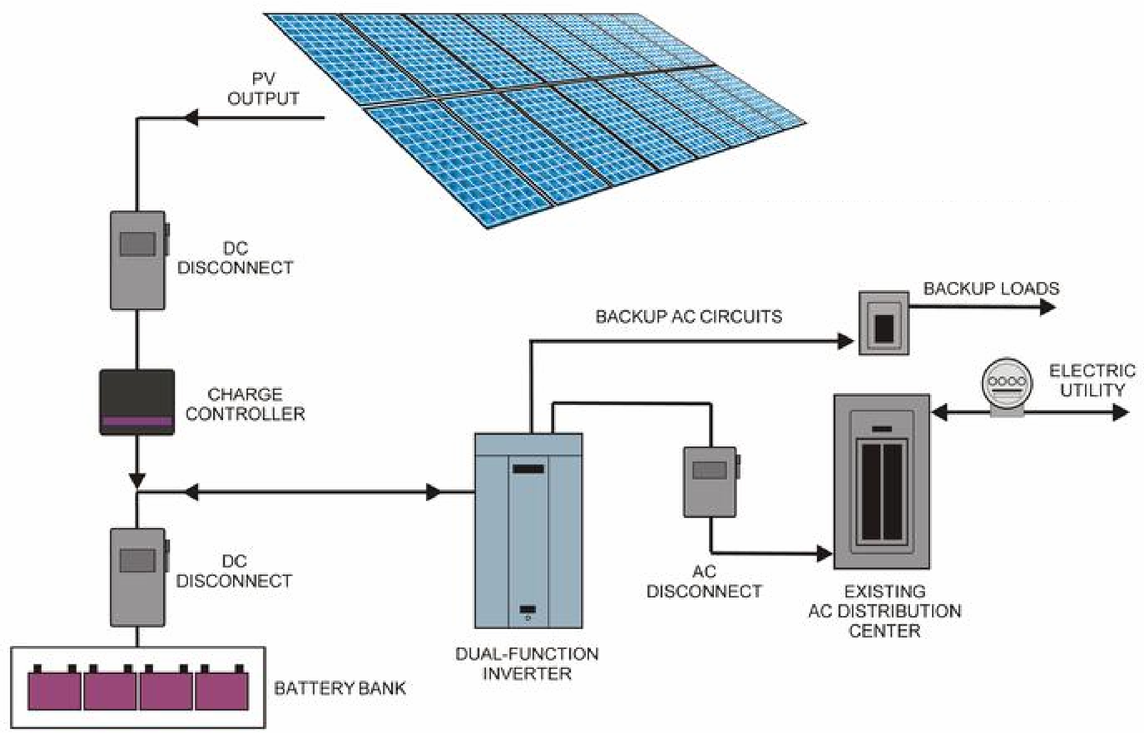
3.4 Typical Grid Tied System (Battery less)

There are no batteries to store excess power generated-the electric utility essentially stores it for you through a system called "net-metering." DC (direct current) generated by the PV panels is converted into AC (alternating current) power by the inverter (exactly the same high quality AC current delivered to your site by the utility-provided power grid). Output from the inverter is connected to your existing distribution panel (breaker panel) which feeds the rest of your site. While the system is generating electricity, power needs are provided by the PV system (up to its capacity), reducing or eliminating the power you would have drawn from the utility grid at that time. During periods when your grid-tie system is generating even more energy than your site requires, any excess is fed back into the grid for others to use and the electric utility company "buys" it from you at the retail rate. They provide credits to your account for all the power that is pushed back into the grid through the meter. And your meter will literally run backwards! When your site needs to draw more energy than it is producing (say, during cloudy conditions or at night), electricity is provided by the power grid in the normal manner and is first paid for by your accumulated credits.



3.5 Typical Grid Tied System with Battery Backup

The "Grid-Tie With Battery Backup" PV system incorporates one or more special AC circuits which are not directly connected to the electric grid like the rest of the building, but are always powered through the inverter and/or charge controller. These circuits may power a refrigerator, selected lights, computers or servers... any devices the owner deems essential. The "dual function" inverter can supply the utility grid with any excess power produced by the system like the "grid-tie" inverter, plus the inverter works with the PV modules and battery bank (through the charge controller) to provide AC power to the backup circuits when the grid is down. The charge controller manages the battery voltage, keeping them fully charged when the grid is live, and preventing them from being depleted when the system is drawing power from them.



3.6 Line Commutated Converters

3.6.1 Introduction

The three phase fully controlled bridge converter has been probably the most widely used power electronic converter in the medium to high power applications. Three phase circuits are preferable when large power is involved. The controlled rectifier can provide controllable output dc voltage in a single unit instead of a three phase autotransformer and a diode bridge rectifier. The controlled rectifier is obtained by replacing the diodes of the uncontrolled rectifier with thyristors. Control over the output dc voltage is obtained by controlling the conduction interval of each thyristor. This method is known as phase control and converters are also called "phase controlled converters". Since thyristors can block voltage in both directions it is possible to reverse the polarity of the output dc voltage and hence feed power back to the ac supply from the dc side. Under such condition the converter is said to be operating in the "inverting mode". The thyristors in the converter circuit are commutated with the help of the supply voltage in the rectifying mode of operation and are known as "Line commutated converter". The same circuit while operating in the inverter mode requires load side counter emf for commutation and is referred to as the "Load commutated inverter".

In phase controlled rectifiers though the output voltage can be varied continuously the load harmonic voltage increases considerably as the average value goes down. Of course the magnitude of harmonic voltage is lower in three phase converter compared to the single phase circuit. Since the frequency of the harmonic voltage is higher smaller load inductance leads to continuous conduction. Input current wave shape become rectangular and contain 5th and higher order odd harmonics. The displacement angle of the input current increases with firing angle. The frequency of the harmonic voltage and current can be increased by increasing the pulse number of the converter which can be achieved by series and parallel connection of basic 6 pulse converters. The control circuit become considerably complicated and the use of coupling transformer and / or inter phase reactors become mandatory.

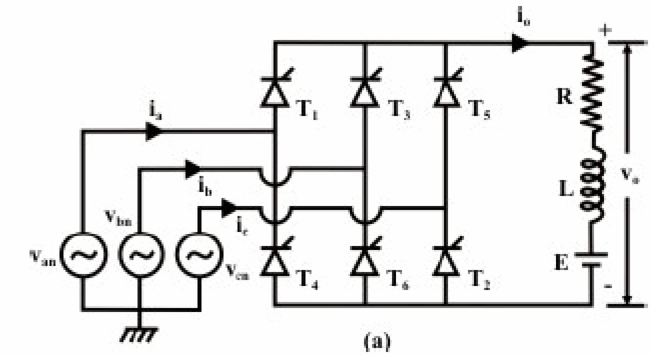
With the introduction of high power IGBTs the three phase bridge converter has all but been replaced by dc link voltage source converters in the medium to moderately high power range. However in very high power application (such as HV dc transmission system, cycloconverter drives, load commutated inverter synchronous motor drives, static scherbius drives etc.) the basic B phase bridge converter block is still used. In this lesson the operating principle and characteristic of this very important converter topology will be discussed in source depth.

3.6.2 Operating principle of 3 phase fully controlled bridge converter

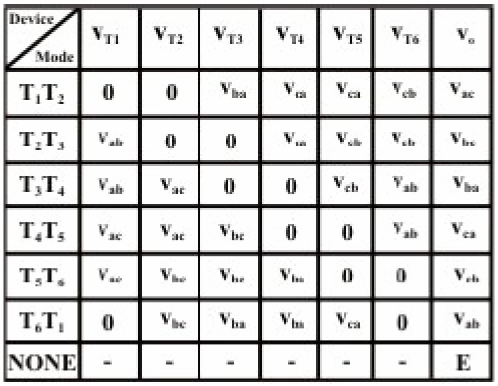
A three phase fully controlled converter is obtained by replacing all the six diodes of an uncontrolled converter by six thyristors as shown in Fig. 4 (a)

For any current to flow in the load at least one device from the top group (T_1, T_3, T_5) and one from the bottom group (T_2, T_4, T_6) must conduct. It can be argued as in the case of an uncontrolled converter only one device from these two groups will conduct.

Then from symmetry consideration it can be argued that each thyristor conducts for 120° of the input cycle. Now the thyristors are fired in the sequence $T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow T_4 \rightarrow T_5 \rightarrow T_6 \rightarrow T_1$ with 60° interval between each firing. Therefore thyristors on the same phase leg are fired at an interval of 180° and hence can not conduct simultaneously. This leaves only six possible conduction mode for the converter in the continuous conduction mode of operation. These are T_1T_2, T_2T_3, T_3T_4, T_4T_5, T_5T_6, T_6T_1. Each conduction mode is of 60° duration and appears in the sequence mentioned. The conduction table of Fig. 4 (b) shows voltage across different devices and the dc output voltage for each conduction interval. The phasor diagram of the line voltages appear in Fig. 4 (c). Each of these line voltages can be associated with the firing of a thyristor with the help of the conduction table-1. For example the thyristor T_1 is fired at the end of T_5T_6 conduction interval. During this period the voltage across T_1 was v_{ac}. Therefore T_1 is fired α angle after the positive going zero crossing of v_{ac}. Similar observation can be made about other thyristors. The phasor diagram of Fig. 4 (c) also confirms that all the thyristors are fired in the correct sequence with 60° interval between each firing.

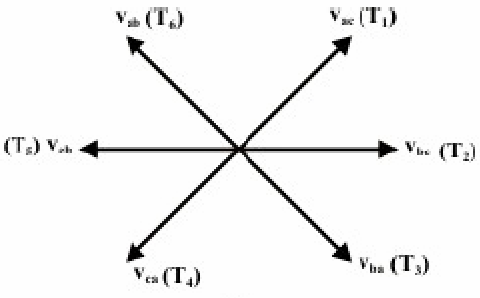


(a)



Device / Mode	v_{T1}	v_{T2}	v_{T3}	v_{T4}	v_{T5}	v_{T6}	v_o
T_1T_2	0	0	v_{ba}	v_{ca}	v_{ca}	v_{cb}	v_{ac}
T_2T_3	v_{ab}	0	0	v_{ca}	v_{cb}	v_{cb}	v_{bc}
T_3T_4	v_{ab}	v_{ac}	0	0	v_{cb}	v_{ab}	v_{ba}
T_4T_5	v_{ac}	v_{ac}	v_{bc}	0	0	v_{ab}	v_{ca}
T_5T_6	v_{ac}	v_{bc}	v_{bc}	v_{ba}	0	0	v_{cb}
T_6T_1	0	v_{bc}	v_{ba}	v_{ba}	v_{ca}	0	v_{ab}
NONE	-	-	-	-	-	-	E

(b)



(c)

Fig 4: Operation of Fully Controlled Bridge Converter (a) Circuit Diagram (b) Conduction Table

(a) Phasor Diagram of Line Voltages

Fig. 5 shows the waveforms of different variables (shown in Fig. 4.1 (a)). To arrive at the waveforms it is necessary to draw the conduction diagram which shows the interval of conduction for each thyristor and can be drawn with the help of the phasor diagram of fig. 4.1 (c). If the converter firing angle is α each thyristor is fired "α" angle after the positive going zero crossing of the line voltage with which it's firing is associated. Once the conduction diagram is drawn all other voltage waveforms can be drawn from the line voltage waveforms and from the conduction table of fig. 4.1 (b). Similarly line currents can be drawn from the output current and the conduction diagram. It is clear from the waveforms that output voltage and current waveforms are periodic over one sixth of the input cycle. Therefore this converter is also called the "six pulse" converter. The input current on the other hand contains only odds harmonics of the input frequency other than the triplex (3rd, 9th etc.) harmonics. The next section will analyze the operation of this converter in more details.

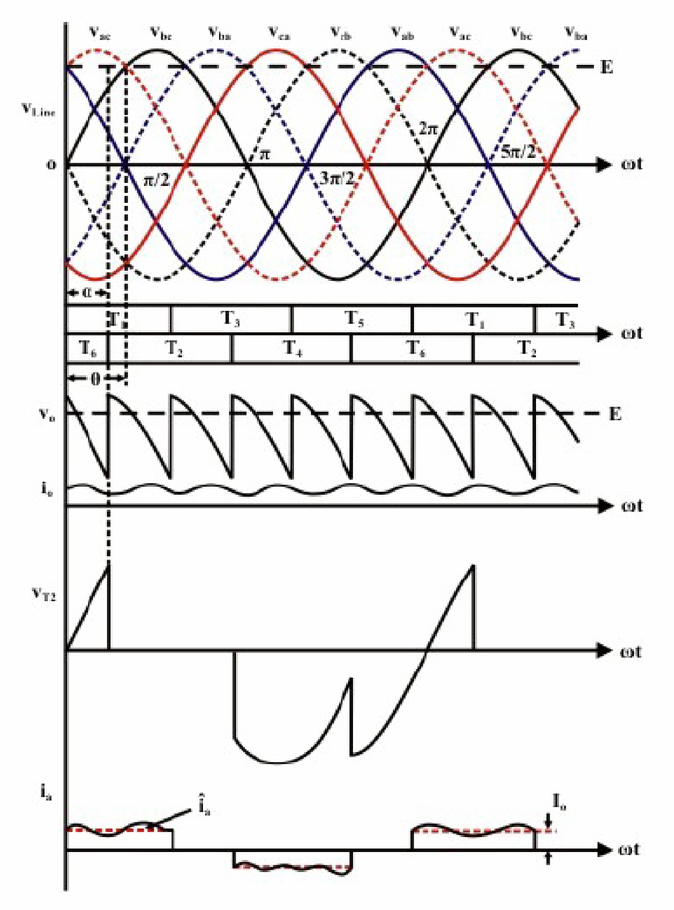


Fig 5 Waveforms of Three Phase Fully Controlled Converters in rectifier mode

3.6.3 ANALYSIS OF CONVERTER IN THE RECTIFIER MODE

The output voltage waveform can be written as

$$v_0 = V_0 + \sum_{K=1,2}^{\alpha} V_{AK} \cos 6K\omega t + \sum_{K=1,2}^{\alpha} V_{BK} \sin 6K\omega t \qquad (4.1)$$

$$V_0 = \frac{3}{\pi}\int_{\alpha}^{\alpha+\frac{\pi}{3}} v_0 \, d\omega t = \frac{3\sqrt{2}}{\pi} V_L \int_{\alpha}^{\alpha+\frac{\pi}{3}} \sin\left(\omega t + \frac{\pi}{3}\right) d\omega t$$

$$= \frac{3\sqrt{2}}{\pi} V_L \cos\alpha \qquad (4.2)$$

$$V_{AK} = \frac{6}{\pi}\int_{\alpha}^{\alpha+\frac{\pi}{3}} v_0 \cos 6K\omega t \, d\omega t$$

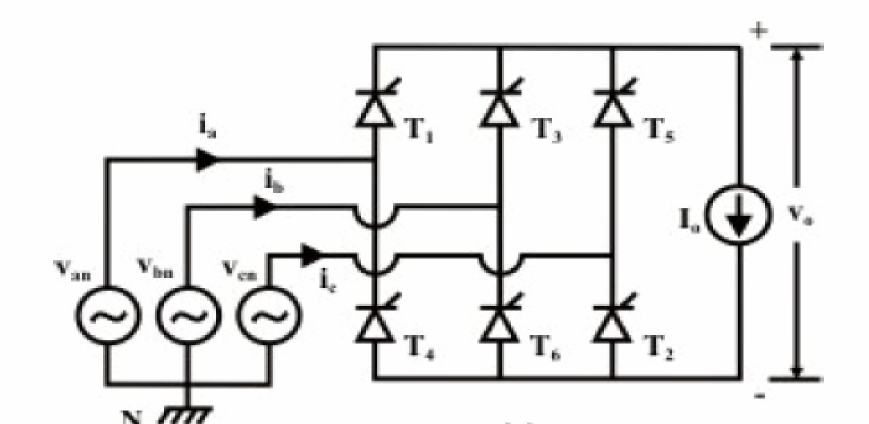
$$= \frac{6}{\pi}\int_{\alpha}^{\alpha+\frac{\pi}{3}} \sqrt{2}\, V_L \sin\left(\omega t + \frac{\pi}{3}\right) \cos 6\,\omega t \, d\omega t$$

$$= \frac{3\sqrt{2}}{\pi} V_L \left[\frac{\cos(6K+1)\alpha}{6K+1} - \frac{\cos(6K-1)\alpha}{6K-1}\right] \qquad (4.3)$$

$$
\begin{aligned}
V_{BK} &= \frac{6}{\pi}\int_{\alpha}^{\alpha+\frac{\pi}{3}} v_0 \sin 6K\omega t \, d\omega t \\
&= \frac{6}{\pi}\int_{\alpha}^{\alpha+\frac{\pi}{3}} \sqrt{2}\, V_L \sin\left(\omega t+\frac{\pi}{3}\right) \sin 6\omega t \, d\omega t \\
&= \frac{3\sqrt{2}}{\pi} V_L \left[\frac{\sin(6K+1)\alpha}{6K+1} - \frac{\sin(6K-1)\alpha}{6K-1}\right] \qquad (4.4) \\
V_{0RMS} &= \sqrt{\frac{3}{\pi}\int_{\alpha}^{\alpha+\frac{\pi}{3}} v_0^2 \, d\omega t} = V_L \left[1+\frac{3\sqrt{3}}{4\pi}\cos 2\alpha\right]^{\frac{1}{2}}
\end{aligned}
$$

3.6.4 Analysis of the converter in the inverting mode.

In all the analysis presented so far it has been assumed that α < 90°. It follows from equation 4.2 that the output dc voltage will be positive in this case and power will be flowing from the three phase ac side to the dc side. This is the rectifier mode of operation of the converter. However if α is made larger than 90° the direction of power flow through the converter will reverse provided there exists a power source in the dc side of suitable polarity. The converter in that case is said to be operating in the inverter mode. It has been explained in connection with single phase converters that the polarity of EMF source on the dc side [Fig. 4 (a)] would have to be reversed for inverter mode of operator. Fig. 6 shows the circuit connection and wave forms in the inverting mode of operation where the load current has been assumed to be continuous and ripple free.



(a)

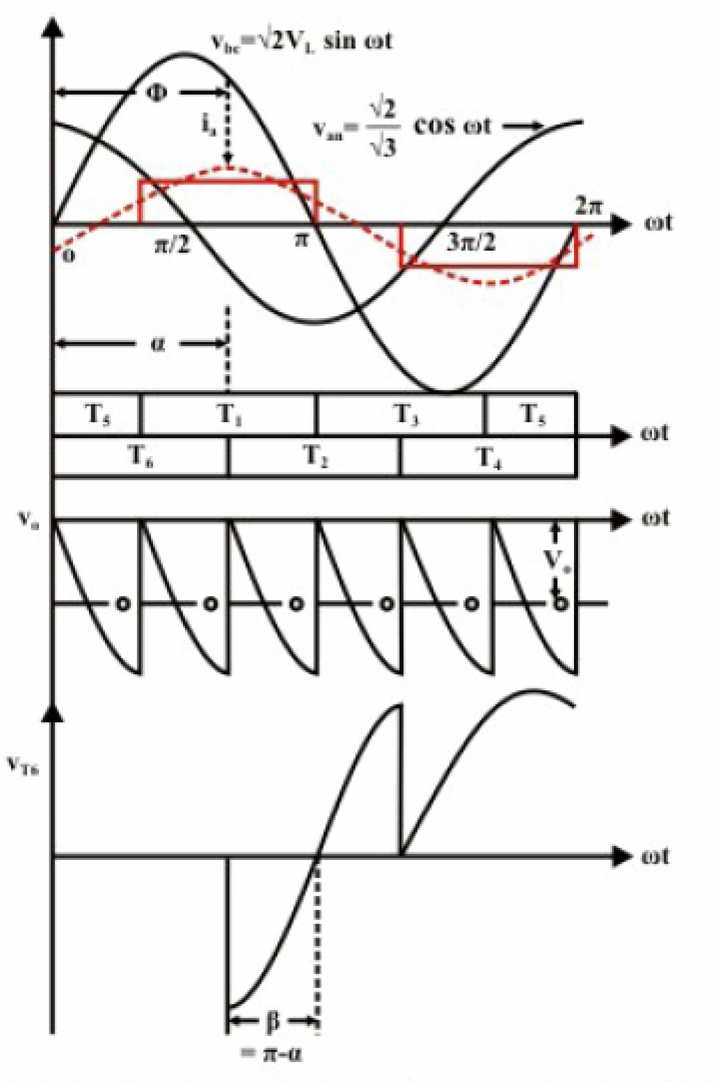


Fig 6: Invertering Mode of Operation of Three Phase Fully Controlled Converter (a) Circuit Diagram (b) Waveforms

Analysis of the converter in the inverting mode is similar to its rectifier mode of operation. The same expressions hold for the dc and harmonic compounds in the output voltage and current. In particular

$$V_0 = \frac{3\sqrt{2}}{\pi} V_L \cos\alpha \qquad (4.5)$$

$$i_{a1} = \frac{2\sqrt{3}}{\pi} I_0 \cos(\omega t - \alpha) \qquad (4.6)$$

For values of α in the range 90° < α < 180° it is observed from Fig. 6 (b) that the average dc voltage is negative and the displacement angle φ of the fundamental component of the input ac line current is equal to α > 90°. Therefore, power in the ac side flows from the converter to the source.

It is observed form Fig. 6 (b) that an outgoing thyristor (thyristor T_6 in Fig. 6(b)) after commutation is impressed with a negative voltage of duration β = π – α. For successful commutation of the outgoing thyristor it is essential that this interval is larger than the turn off time of the thyristor i.e.,

$$\beta \geq \omega t_q, \text{ tq is the thyristor turn off time}$$

Therefore $\pi-\alpha \geq \omega t_q$ or $\alpha \leq \pi-\omega t_q$.

This imposes an upper limit on the value of α. In practice this upper value of α is further reduced due to commutation overlap.

3.7 BOOST CONVERTER

The boost converter, also known as the step-up converter, is another switching converter that has the same components as the buck converter, but this converter produces an output voltage greater than the source. The ideal boost converter has the five basic components, namely a power semiconductor switch, a diode, an inductor, a capacitor and a PWM controller. The placement of the inductor, the switch and the diode in the boost converter is different from that of the buck converter. The basic circuit of the boost converter is shown in Fig. 7.

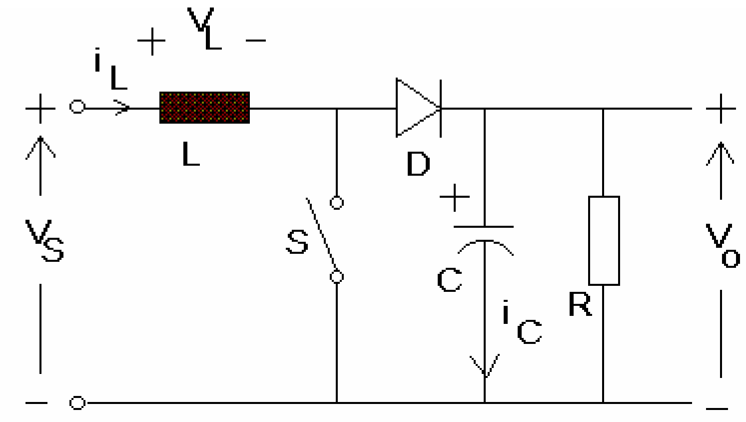


Fig 7 Boost Converter

The operation of the circuit is explained now. The essential control mechanism of the circuit in Fig. 7 is turning the power semiconductor switch on and off. When the switch is ON, the current through the inductor increases and the energy stored in the inductor builds up. When the switch is off, current through the inductor continues to flow via the diode D, the RC network and back to the source. The inductor is discharging its energy and the polarity of inductor voltage is such that its terminal connected to the diode is positive with respect to its other terminal connected to the source. It can be seen then the capacitor voltage has to be higher than the source voltage and hence this converter is known as the boost converter. It can be seen that the inductor acts like a pump, receiving energy when the switch is closed and transferring it to the RC network when the switch is open.

When the switch is closed, the diode does not conduct and the capacitor sustains the output voltage. The circuit can be split into two parts, as shown in Fig. 8. As long as the RC time constant is very much larger than the on-period of the switch, the output voltage would remain more or less constant.

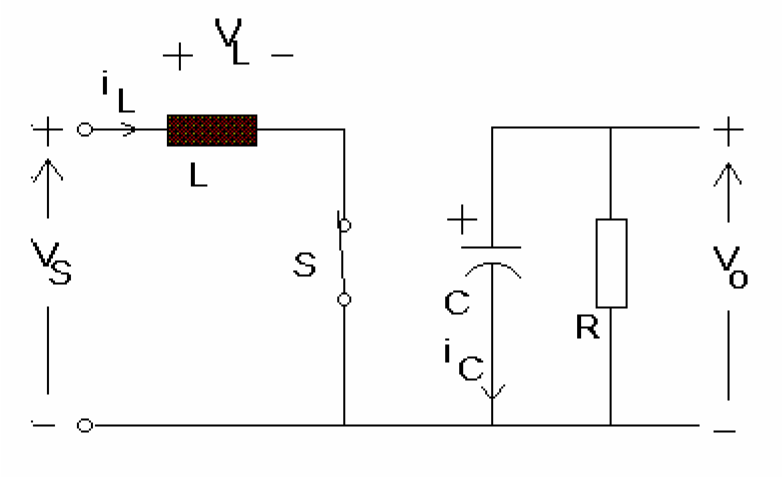


Fig 8 When Switch S is closed

When the switch is open, the equivalent circuit that is applicable is shown in Fig. 9. There is a single connected circuit in this case.

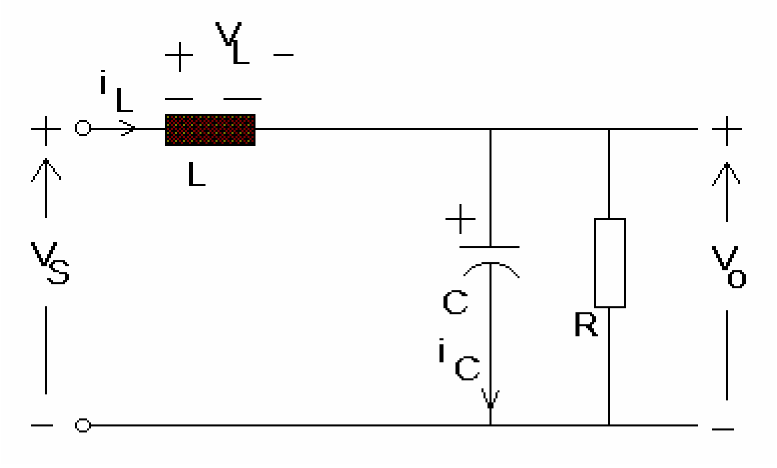


Fig 9 When Switch S is open

3.7.1 ANALYSIS OF THE IDEAL CIRCUIT

Analysis of the circuit is carried out based on the following assumptions. The circuit is ideal. It means when the switch is ON, the drop across it is zero and the current through it is zero when it is open. The diode has zero voltages drop in the conducting state and zero current in the reverse-bias mode. The time delays in switching on and off the switch and the diode are assumed to be negligible. The inductor and the capacitor are assumed to be lossless.

1. The responses in the circuit are periodic. It means especially that the inductor current is periodic. Its value at the start and end of a switching cycle is the same. The net increase in inductor current over a cycle is zero. If it is non-zero, it would mean that the average inductor current should either be gradually increasing or decreasing and then the inductor current is in a transient state and has not become periodic.
2. It is assumed that the switch is made ON and OFF at a fixed frequency and let the period corresponding to the switching frequency be T. Given that the duty cycle is D, the switch is on for a period equal to DT, and the switch is off for a time interval equal to (1 - D)T.
3. The inductor current is continuous and is greater than zero.
4. The capacitor is relatively large. The RC time constant is so large, that the changes in capacitor voltage when the switch is ON or OFF can be neglected for calculating the change in inductor current and the average output voltage. The

average output voltage is assumed to remain steady, excepting when the change in output voltage is calculated.

5. The source voltage V_S remains constant.

3.7.2 Inductor Current with Switch Closed

When the switch is closed, the equivalent circuit that is applicable is shown in Fig. 8. The source voltage is applied across the inductor and the rate of rise of inductor current is dependent on the source voltage V_S and inductance L. The differential equation describing this condition is:

$$L\frac{di_L}{dt} = v_S(t) \quad (1)$$

If the source voltage remains constant, the rate of rise of inductor current is positive and remains fixed, so long as the inductor is not saturated. Then equation (1) can be expressed as :

$$\frac{\Delta i_L}{\Delta t} = \frac{V_S}{L} \qquad (2)$$

The switch remains ON for a time interval of DT in one switching cycle and hence DT can be used for ΔT. The net increase in inductor current when the switch is ON can be obtained from equation (2) to be:

$$\Delta I_L = \frac{V_S}{L}\times(DT) \qquad (3)$$

3.7.3 Inductor Current with Switch Open

When the switch is open, the circuit that is applicable is shown in Fig. 9. Now the voltage across the inductor is:

$$v_L = V_S - V_o \quad (4)$$

Given that the output voltage is larger than the source voltage, the voltage across the inductor is negative and the rate of rise of inductor current, described by equation (5), is negative. Hence if the switch is held OFF for a time interval equal to (1 - D) T, the change in inductor current can be computed as shown in equation (6)

$$\frac{di_L}{dt} = \frac{V_S - V_o}{L} \quad (5)$$

$$\Delta I_L = \frac{V_S - V_o}{L} \times (1 - D)T \quad (6)$$

The change in inductor current reflected by equation (6) is a negative value, since $V_o > V_S$. Since the net change in inductor current over a cycle period is zero when the response $i_L(t)$ is periodic, the sum of changes in inductor current expressed by (4) and (6) should be zero. That is,

$$\frac{V_S}{L} \times DT + \frac{V_S - V_o}{L} \times (1 - D)T \quad = 0 \quad (7)$$

On simplifying equation (7), we get that

$$V_o = \frac{V_S}{1 - D} \quad (8)$$

It has been stated that when $i_L(t)$ is periodic, the net change in inductor current over a cycle is zero. Since change in inductor current is related to its volt-seconds, the net volt-seconds of the inductor has to be zero. The expression for the net volt-seconds can be obtained from equation (7) and it can be seen that the numerator of equation (7) should be zero. That is,

$$V_S \times DT + \left(V_S - V_o\right) \times (1 - D)T \quad = 0 \quad (9)$$

The value of D varies such that $0 < D < 1$ and it can be seen from equation (8) that output voltage is greater than the source voltage, and hence this circuit is called the boost converter. The output voltage has its lowest value when $D = 0$ and then the output voltage equals the source voltage. When D approaches unity, output voltage tends to infinity. Usually D is varied such that $0.1 < D < 0.9$.

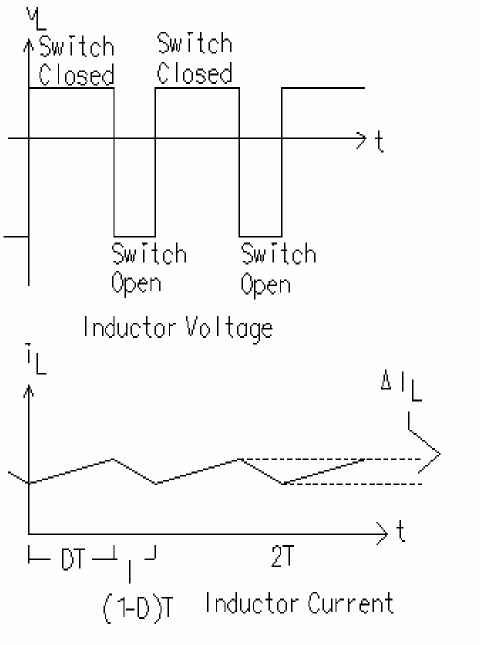


Fig 10

The waveforms of inductor voltage and inductor current are shown in Fig. 10. These waveforms are drawn assuming that both the output and the source voltage remain steady. These waveforms illustrate how the inductor voltage is related to its current.

3.7.4 Output Voltage Ripple with Switch Closed

In this sub-section, the change in output voltage is calculated. It needs to be emphasized that the peak-to-peak ripple in output voltage is quite small for a well-designed circuit. For the inductor, the net change in inductor current over a cycle is zero when $i_L(t)$ is periodic. For the capacitor, the net change in capacitor voltage over a cycle is zero when it is periodic. When the switch is closed, the equivalent circuit in Fig. 8 shows that the boost converter is split into two sub-circuits, with the loop currents decoupled from each other. When the switch is closed, the output voltage is sustained by the capacitor. During this period, the capacitor discharges part of its stored energy and it re-acquires this energy when the switch is open. When the switch is open, part of the inductor current charges the capacitor since the inductor current usually remains larger than the current through the load resistor. From Fig. 8,

$$i_C(t) = C\frac{dv_o(t)}{dt} \quad (10)$$

When current through a capacitor charges it up, its rate of rise of capacitor voltage is positive since the capacitor voltage is increasing. When the switch is open, the capacitor is discharging its energy with its voltage falling and the current through the capacitor is then a negative value. The output voltage remains positive and hence the output current is positive and it is the negative of the capacitor current, as can be seen from Fig. 8. Since the change in output voltage is quite small, it can be assumed that the load current remains constant at its average value and equation (10) can be now expressed as:

$$i_C(t) \approx -\frac{V_o}{R} \quad (11)$$

When the capacitor current is constant, its voltage changes linearly with time. Here the period for which the switch is closed is DT and the DT can be used in place of ΔT. The peak-to-peak ripple in output voltage expressed as ΔV_o and it is then expressed as:

$$\Delta v_o = i_C \times (DT) = -\frac{V_o}{R} \times (DT) = -\frac{DV_o}{fR} \quad (12)$$

Equation (12) yields the value of the peak-to-peak ripple in output voltage. In equation (12), 1/f replaces T since T is the reciprocal of switching frequency.

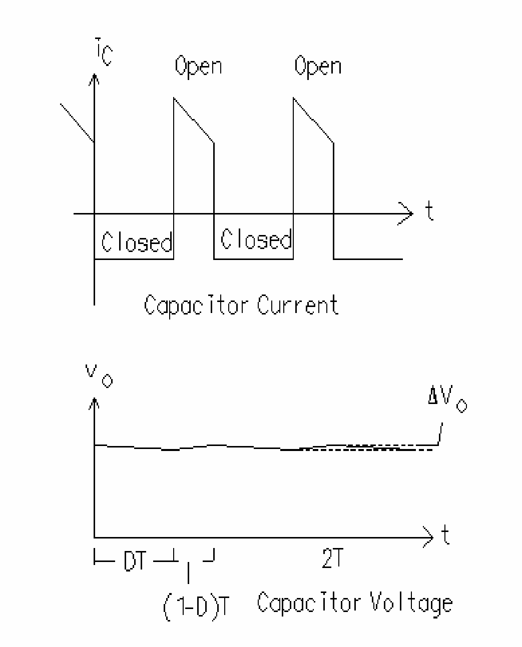


Fig 11

Figure 11 shows how the capacitor current and voltage vary over a cycle. The ripple in output voltage is exaggerated in Fig. 11, whereas in practice it would be much smaller. If the output voltage is drawn to scale, the ripple in output voltage would not be noticeable.

3.7.5 Expression for Average Inductor Current

The average inductor current can be found out by equating the power drawn from the source to the power delivered to the load resistor. Again the ripple in output voltage is ignored and it is assumed justifiably that the output voltage remains steady at its average value. Power P_o absorbed by load resistor is then:

$$P_o = \frac{(V_o)^2}{R} \quad (13)$$

It can be seen from the circuit in Fig. 7 that the current drawn from the source flows through the inductor. Hence the average value of inductor current is also the average value of source current. Let the average inductor current be I_L. Then power P_S supplied by the source is then:

$$P_S = V_S \times I_L \quad (14)$$

After equating equations (13) and (14), we get the average inductor current as:

$$I_L = \frac{(V_o)^2}{V_S \times R} \quad (15)$$

Since load current I_o is:

$$I_o = \frac{V_o}{R} \quad (16)$$

Using equations (8) and (16), equation (15) can be re-presented as:

$$I_L = \frac{I_o}{1 - D} \quad (17)$$

Since $0 < D < 1$, it can be seen from equation (17) that $I_L > I_o$.

3.7.6 CONTINUOUS CONDUCTION

The analysis thus far is based on the assumption that the current through the inductor is continuous. The inductor current varies over a cycle, varying between a minimum value and a maximum value. The minimum and maximum values can be expressed in terms of its mean value and its change as expressed in equation (3). That is,

$$I_{L,\max} = I_L + \left(\frac{\Delta I_L}{2}\right) \quad (18)$$

and

$$I_{L,\min} = I_L - \left(\frac{\Delta I_L}{2}\right) \quad (19)$$

It is shown in Fig. 6 how the maximum and the minimum inductor current can be obtained. It is also shown that as the load resistor becomes greater, the average inductor current reduces, but the peak-to-peak ripple in inductor current does not change. It has to be so and expression for ΔI_L in equation (3) does not indicate any term reflecting the load resistor.

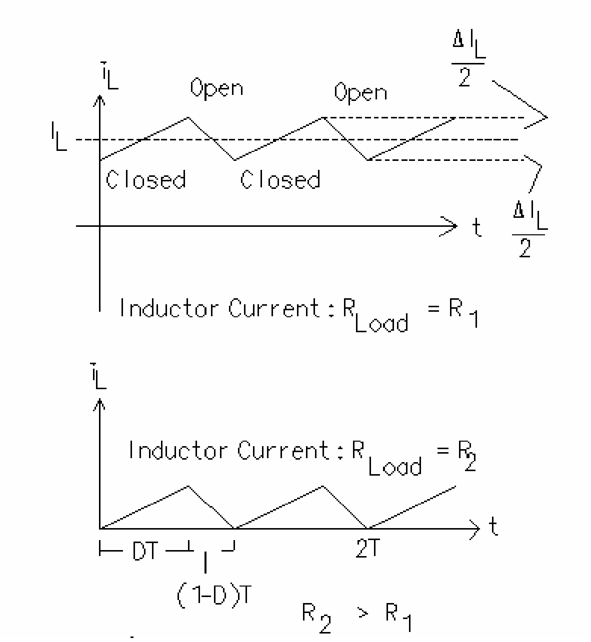


Fig 12

For continuous conduction,

$$I_L > \frac{\Delta I_L}{2} \quad (20)$$

At the boundary of continuous and discontinuous conduction,

$$I_L = \frac{\Delta I_L}{2} \quad (21)$$

Another expression for I_L is now obtained. Substituting for V_o in equation (15) the expression in equation (8), we obtain that

$$I_L = \frac{V_S}{(1-D)^2 \times R} \quad (22)$$

Substituting for I_L from the equation above and for Δi_L from equation (3), equation (18) becomes:

$$I_{L,\max} = \frac{V_S}{[1-D]^2 R} + \left(\frac{(DT)V_S}{2L}\right) \quad (23)$$

and

$$I_{L,\min} = \frac{V_S}{[1-D]^2 R} - \left(\frac{(DT)V_S}{2L}\right) \quad (24)$$

From equations (23) and (24), the condition for continuous conduction is:

$$\frac{V_S}{[1-D]^2 R} > \left(\frac{(DT)V_S}{2L}\right) \quad , or$$

$$f > \frac{RD[1-D]^2}{2L}, where\ fT = 1 \quad (25)$$

Equation (25) can be interpreted as follows, assuming that only one of the four parameters is varied at a given time with the other three parameters remaining unchanged.

The circuit tends to become discontinuous,

i. if the switching frequency f is decreased, or
ii. if the duty cycle D is reduced, or
iii. if the load resistance increases, or
iv. if the inductance used has lower value.

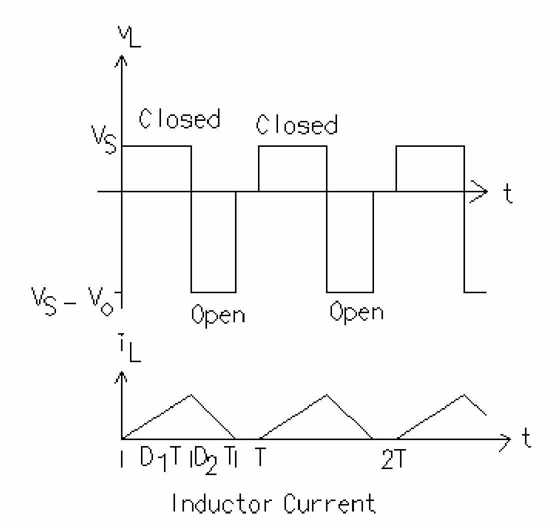


Fig 13

When the conduction is discontinuous, the voltage across the inductor is zero for part of the cycle since there is no current through the inductor. Let D_1T be the time for which the switch is ON in one cycle and let D_2T be the period for which the diode conducts. Since the conduction is discontinuous,

$$(D_1 + D_2) < 1 \quad (26)$$

An expression for the output voltage can be obtained in terms of source voltage, duty cycle D_1 of the switch and duty cycle D_2 of the diode. Since the net change in inductor current is over a cycle, the net volt-seconds area associated with the inductor is zero. The waveforms relevant to the inductor when the conduction is discontinuous are shown in Fig. 13. From Fig. 13,

$$V_S \times D_1T + (V_S - V_o) \times D_2T \quad = 0 \quad (27)$$

On simplifying, an expression for V_o can be obtained. Then

$$V_o = V_S \times \left[\frac{D_1 + D_2}{D_2}\right] \quad (28)$$

The value of D_1, the duty cycle of the switch, is usually known, but the period for which the diode conducts is an unknown quantity depending on the other circuit parameters. The value of D_2can be determined in several ways. Here it is determined using the power balance between the input and output. When the circuit is ideal, the input power equals output power. Let the average source current be I_S and the average output current be I_o. Then

$$V_S \times I_S = V_o \times I_o \quad (29)$$

Using equation (28), we get that

$$I_S = I_0 \times \left[\frac{D_1 + D_2}{D_2}\right] = \frac{V_0}{R} \times \left[\frac{D_1 + D_2}{D_2}\right] = \frac{V_S}{R} \times \left[\frac{D_1 + D_2}{D_2}\right]^2 \quad (30)$$

The average source current be I_S can be obtained from Fig. 7. The average source current is the same as the average inductor current. Let the peak inductor current be ΔI_L and the period for which this current flows is ($D_1T + D_2T$). This period is the base of the triangle that defines the inductor current. The average inductor current is obtained as the area of this triangle divided by the cycle period. We have that

$$I_S = \Delta I_L \times \left[\frac{D_1 + D_2}{2}\right] \quad (31)$$

Equating equations (30) and (31),

$$\Delta I_L \times \left[\frac{D_1 + D_2}{2}\right] = \frac{V_S}{R} \times \left[\frac{D_1 + D_2}{D_2}\right]^2 \quad (32)$$

From equation (3),

$$\Delta I_L = \frac{D_1 T V_S}{L} = \frac{D_1 V_S}{fL} \quad (33)$$

Substituting for ΔI_L from equation (33) in equation (32), we get that

$$\frac{D_1}{2fL} = \frac{(D_1 + D_2)}{R \times (D_2)^2} \quad (34)$$

Equation (34) can be re-written as:

$$(D_2)^2 = \frac{2fL}{RD_1} \times (D_1 + D_2) \quad (35)$$

Solving for D_2,

$$D_2 = \frac{fL}{RD_1} \times \left[1 + \sqrt{1 + \frac{2RD_1^{\,2}}{fL}}\right] \quad (36)$$

Equation (36) states how D_2 varies as a function of R, D_1, f and L. Once D_2 is known, V_o can be obtained from equation (28).

It is possible to get an expression for V_o as a function of R, D_1, f and L. For this, we equate the average load current with the average diode current. The average output current can be obtained from the average output voltage and the load resistor. The average diode current is:

$$I_{D,avg} = \Delta I_L \times \frac{D_2}{2} \quad (37)$$

Using the expression for ΔI_L from equation (33), and replacing the L.H.S. by the average load current,

$$\frac{V_o}{R} = \frac{V_S D_1 D_2}{2fL}, \; where \; fT = 1 \quad (38)$$

Hence we obtain that

$$D_2 = \frac{2fL}{RD_1} \times \frac{V_o}{V_S} \quad (39)$$

By substituting for D_2 from equation (36) in the above equation, we can get an expression for V_o/V_S. Alternatively, equation (28) can be re-written as:

$$\frac{V_o}{V_S} = 1 + \frac{D_1}{D_2} \quad (40)$$

Using the expression for D_2 from equation (39) in equation (40),

$$\frac{V_o}{V_S} = 1 + \frac{RD_1^{\,2}}{2fL \times \left({}^{V_o}\!/\!{}_{V_S} \right)} \quad (41)$$

That is,

$$\left[\frac{V_o}{V_S}\right]^2 - \frac{V_o}{V_S} = \frac{RD_1^{\,2}}{2fL} \quad (42)$$

Solving for the ratio of output to source voltage and taking the positive root of the expression on the R.H.S. of equation (42),

$$\frac{V_o}{V_S} = \frac{1}{2} \times \left[1 + \sqrt{1 + \frac{2RD_1^{\ 2}}{fL}} \right] \quad (43)$$

Equation (43) states how (V_o/V_S) varies as a function of R, D_1, f and L

3.8 BUCK BOOST CONVERTER

3.8.1 Introduction

The buck–boost converter is a type of DC-to-DC converter that has an output voltage magnitude that is either greater than or less than the input voltage magnitude. It is a switched-mode power supply with a similar circuit topology to the boost converter and the buck converter. The output voltage is adjustable based on the duty cycle of the switching transistor. One possible drawback of this converter is that the switch does not have a terminal at ground; this complicates the driving circuitry. Also, the polarity of the output voltage is opposite the input voltage. Neither drawback is of any consequence if the power supply is isolated from the load circuit (if, for example, the supply is a battery) as the supply and diode polarity can simply be reversed. The switch can be on either the ground side or the supply side.

3.8.2 Principle of Operation

The basic principle of the buck–boost converter is fairly simple (see figure 14 and 15):

- ✓ While in the On-state, the input voltage source is directly connected to the inductor (L). This results in accumulating energy in L. In this stage, the capacitor supplies energy to the output load.
- ✓ While in the Off-state, the inductor is connected to the output load and capacitor, so energy is transferred from L to C and R.

Compared to the buck and boost converters, the characteristics of the buck–boost converter are mainly:

- ✓ Polarity of the output voltage is opposite to that of the input;
- ✓ The output voltage can vary continuously from 0 to $-\infty$ (for an ideal converter). The output voltage ranges for a buck and a boost converter are respectively 0 to V_i and V_i to ∞.

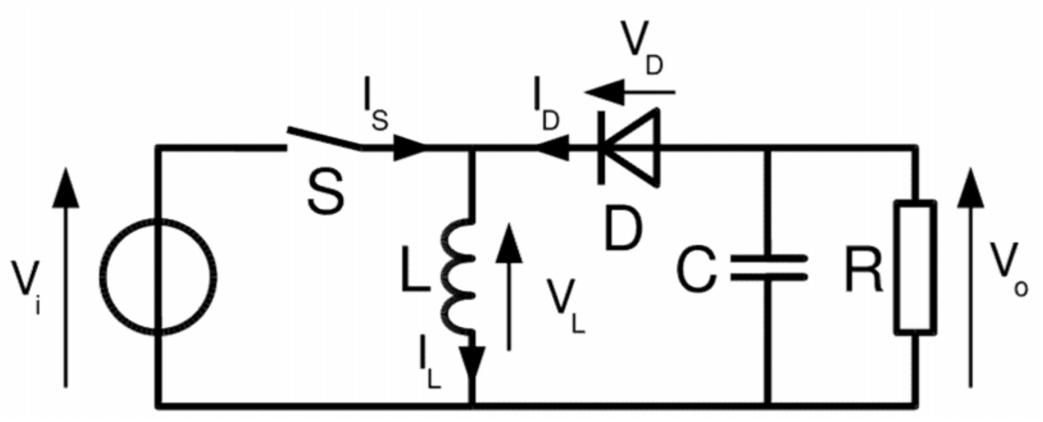


Fig 14 Buck Boost Converter

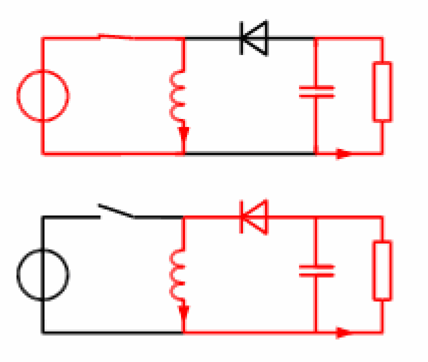


Fig. 15: The two operating states of a buck–boost converter: When the switch is turned-on, the input voltage source supplies current to the inductor, and the capacitor supplies current to the resistor (output load). When the switch is opened, the inductor supplies current to the load via the diode D.

3.8.3 Continuous Conduction Mode

If the current through the inductor *L* never falls to zero during a commutation cycle, the converter is said to operate in continuous mode. The current and voltage waveforms in an ideal converter can be seen in Figure 16.

From $t=0$ to $t=DT$, the converter is in On-State, so the switch *S* is closed. The rate of change in the inductor current (I_L) is therefore given by

$$\frac{dI_L}{dt} = \frac{V_i}{L}$$

At the end of the On-state, the increase of I_L is therefore:

$$\Delta I_{L_{On}} = \int_0^{DT} dI_L = \int_0^{DT} \frac{V_i}{L} dt = \frac{V_i DT}{L}$$

D is the duty cycle. It represents the fraction of the commutation period *T* during which the switch is on. Therefore *D* ranges between 0 (*S* is never on) and 1 (*S* is always on).

During the Off-state, the switch *S* is open, so the inductor current flows through the load. If we assume zero voltage drop in the diode, and a capacitor large enough for its voltage to remain constant, the evolution of I_L is:

$$\frac{\mathrm{d}I_\mathrm{L}}{\mathrm{d}t} = \frac{V_o}{L}$$

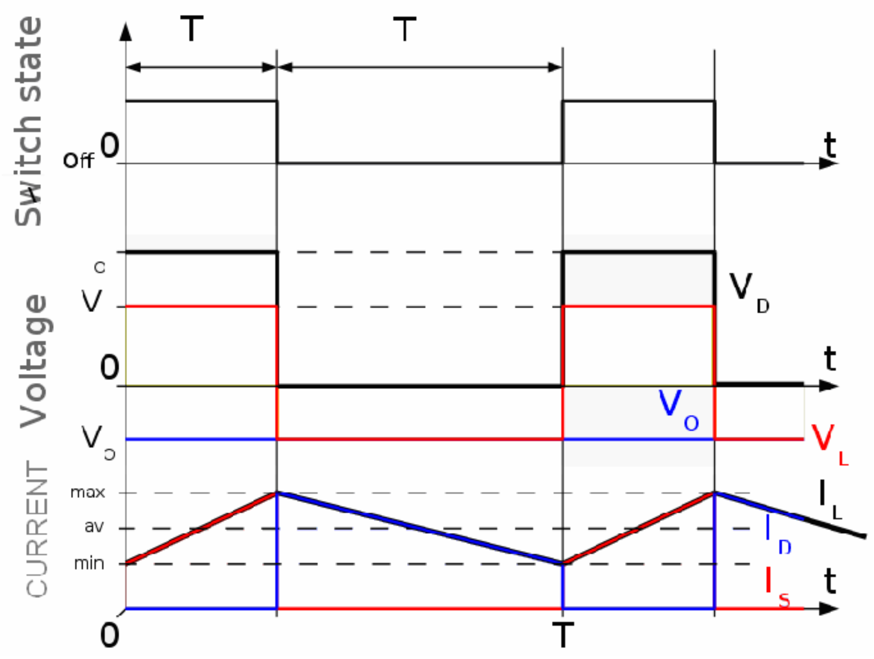


Fig 16: Waveforms of current and voltage in a buck–boost converter operating in continuous mode.

Therefore, the variation of I_L during the Off-period is:

$$\Delta I_{\mathrm{L_{Off}}} = \int_0^{(1-D)T} \mathrm{d}I_\mathrm{L} = \int_0^{(1-D)T} \frac{V_o\,\mathrm{d}t}{L} = \frac{V_o\,(1-D)\,T}{L}$$

As we consider that the converter operates in steady-state conditions, the amount of energy stored in each of its components has to be the same at the beginning and at the end of a commutation cycle. As the energy in an inductor is given by:

$$E = \frac{1}{2} L\, I_\mathrm{L}^2$$

It is obvious that the value of I_L at the end of the off state must be the same as the value of I_L at the beginning of the On-state, i.e. the sum of the variations of I_L during the on and the off states must be zero:

$$\Delta I_{\mathrm{L_{On}}} + \Delta I_{\mathrm{L_{Off}}} = 0$$

Substituting $\Delta I_{\mathrm{L_{On}}}$ and $\Delta I_{\mathrm{L_{Off}}}$ by their expressions yields:

$$\Delta I_{\mathrm{L_{On}}} + \Delta I_{\mathrm{L_{Off}}} = \frac{V_i\, D\, T}{L} + \frac{V_o\,(1-D)\,T}{L} = 0$$

This can be written as:

$$\frac{V_o}{V_i} = \left(\frac{-D}{1-D}\right)$$

This in return yields that:

$$D = \frac{V_o}{V_o - V_i}$$

From the above expression it can be seen that the polarity of the output voltage is always negative (as the duty cycle goes from 0 to 1), and that its absolute value increases with D, theoretically up to minus infinity as D approaches 1. Apart from the polarity, this converter is either step-up (as a boost converter) or step-down (as a buck converter). This is why it is referred to as a buck–boost converter.

3.8.4 Discontinuous Conduction Mode

In some cases, the amount of energy required by the load is small enough to be transferred in a time smaller than the whole commutation period. In this case, the current through the inductor falls to zero during part of the period. The only difference in the principle described above is that the inductor is completely discharged at the end of the commutation cycle (see waveforms in figure 17). Although slight, the difference has a strong effect on the output voltage equation. It can be calculated as follows:

As the inductor current at the beginning of the cycle is zero, its maximum value $I_{L_{\mathrm{max}}}$ (at $t = DT$) is

$$I_{L_{\mathrm{max}}} = \frac{V_i\, D\, T}{L}$$

During the off-period, I_L falls to zero after δ.T:

$$I_{L_{\mathrm{max}}} + \frac{V_o\, \delta\, T}{L} = 0$$

Using the two previous equations, δ is:

$$\delta = -\frac{V_i\,D}{V_o}$$

The load current I_o is equal to the average diode current (I_D). As can be seen on figure 17, the diode current is equal to the inductor current during the off-state. Therefore, the output current can be written as:

$$I_o = \bar{I_D} = \frac{I_{L_{\max}}}{2}\delta$$

Replacing $I_{L_{\max}}$ and δ by their respective expressions yields:

$$I_o = -\frac{V_i\,D\,T}{2L}\frac{V_i\,D}{V_o} = -\frac{V_i^2\,D^2\,T}{2L\,V_o}$$

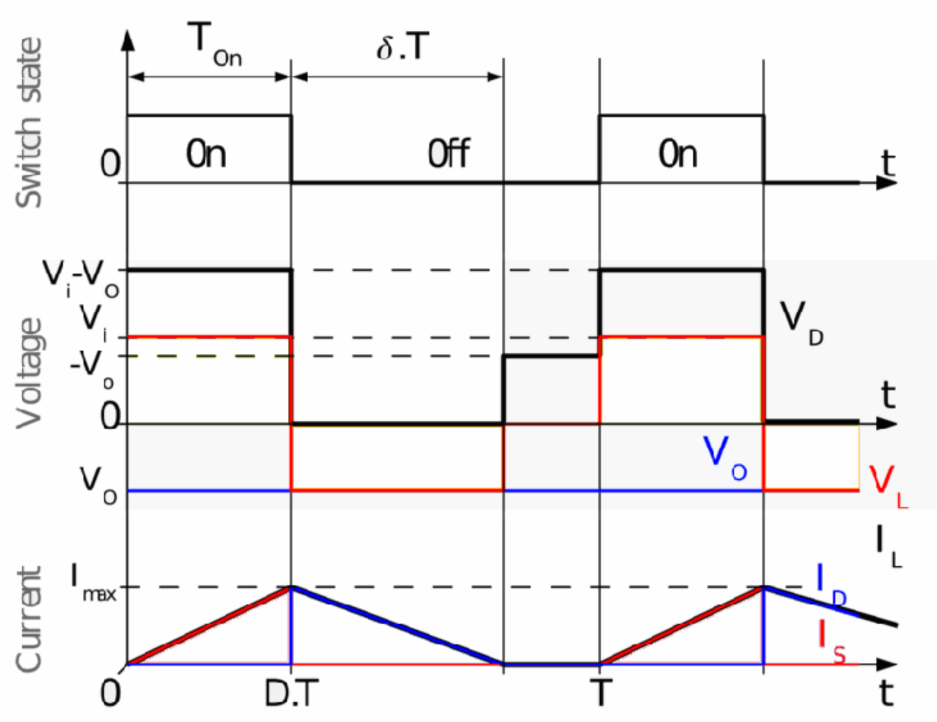


Fig 17: Waveforms of current and voltage in a buck–boost converter operating in discontinuous mode

Therefore, the output voltage gain can be written as:

$$\frac{V_o}{V_i} = -\frac{V_i\,D^2\,T}{2L\,I_o}$$

Compared to the expression of the output voltage gain for the continuous mode, this expression is much more complicated. Furthermore, in discontinuous operation, the output voltage not only depends on the duty cycle, but also on the inductor value, the input voltage and the output current.

3.9 Designing of PV system (Sizing of Inverter, Battery and Array)

It is very important for a photovoltaic designer to know how to find the suitable size of photovoltaic array to be installed in a certain building. To do this, he needs to take some factors into considerations and do some calculations.

Here are some basic principles to follow when designing a quality PV system:-

1. Select a packaged system that meets the owner's needs. Customer criteria for a system may include reduction in monthly electricity bill, environmental benefits, desire for backup power, initial budget constraints, etc. Size and orient the PV array to provide the expected electrical power and energy.
2. Ensure the roof area or other installation site is capable of handling the desired system size.
3. Specify sunlight and weather resistant materials for all outdoor equipment.
4. Locate the array to minimize shading from foliage, vent pipes, and adjacent structures.
5. Design the system in compliance with all applicable building and electrical codes.
6. Design the system with a minimum of electrical losses due to wiring, fuses, switches, and inverters.
7. Properly house and manage the battery system, should batteries be required.
8. Ensure the design meets local utility interconnection requirements.

3.9.2 Basic steps to be followed when installing a PV system:

1. Ensure the roof area or other installation site is capable of handling the desired system size.
2. If roof mounted, verify that the roof is capable of handling additional weight of PV system. Augment roof structure as necessary.
3. Properly seal any roof penetrations with roofing industry approved sealing methods.
4. Install equipment according to manufacturer’s specifications, using installation requirements and procedures from the manufacturers' specifications.
5. Properly ground the system parts to reduce the threat of shock hazards and induced surges.
6. Check for proper PV system operation by following the checkout procedures on the PV System Installation Checklist.

7. Ensure the design meets local utility interconnection requirements
8. Have final inspections completed by the Authority Having Jurisdiction (AHJ) and the utility (if required).

3.9.3 Sizing of Solar Electric System

When we consider using solar electricity, we have to know exactly how many appliances have to power. Sizing is about calculating the number of solar modules and batteries that are needed to run the required number of appliances.

To do sizing, there are several steps to be followed. The first step is to add up the daily requirement for electricity of each of the appliances. This is based on the power rating of each appliances and the average length time it will be used in one day.

The next step is to calculate how much electricity will be produced by one module. This calculation uses weather records of sunshine for the site and the current output from one module. For big countries that sit on huge range of latitude (e.g. United States, Australia, China, and Africa) and countries that have 4 seasons a year, the records of sunshine will vary accordingly to the latitude and seasons. However, India sits on latitude of 6 ° 15 ' N and has only hot and humid climate. The sunshine record would be more constant. Next, the number of modules is calculated using the daily requirements of appliances and the daily output expected from one module.

Batteries are used to store electricity generated during sunny days for use during and after cloudy days. Sizing batteries are based on the daily requirement for electricity and the number of day’s storage that is needed. Besides, it also depends on the recommended cycle depth for the type of battery to be used.

3.9.3.1 Limitations of Sizing

It is very important to realize that there is no sizing procedure is perfect. Therefore, the calculations that we get cannot be relied upon totally. The main problems with sizing are as follow:

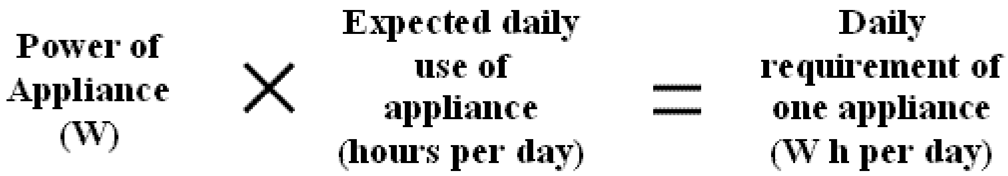
1. The weather records for the site may not be detailed enough to do an accurate calculation of the module output.
2. Since the weather records are the summary of the past, they can only suggest what may happen on the future when the solar electricity will be used each day. After all, it is the law of the nature that the weather is unpredictable.

3. It is difficult to predict accurately how much electricity will be used each day.

One way of overcoming these limitations is to have extra modules and batteries which allow for periods of very bad weather. However, extra features will add on the cost of the project. Therefore, we have to balance the cost and the performance of the system in order to create the best application as possible.

3.10 Units of Consumption of Electricity

The unit that we measure for the consumption of electricity of a typical electrical appliance is kilo-watt hours (KWh) or watt hours (Wh) for small appliances. To calculate the daily requirement in Wh per day, we as the designer must first list down all the appliances that are expected to be used in the system. For each appliance, first find its power and decide the amount of time in hours that it will be used each day. The calculation of daily requirement for each appliance is as follow:-



$$\text{Power of Appliance (W)} \times \text{Expected daily use of appliance (hours per day)} = \text{Daily requirement of one appliance (W h per day)}$$

The power or wattage of an appliance can be found somewhere on the outside of the appliance, electrical tag attached to the cable or in the instruction book. Sometimes there are some appliances that has no power figure but only numbers with units of "V" and "A". Multiply these two numbers together to get the power of the appliance in W.

3.10.1 Calculation of Daily requirements of Appliances

Now, let us look at one example of calculation using the equation discussed above.

Mr. X decides to install a stand-alone PV system in his house. The first step that he has to do is to determine the total daily requirement of appliances of his house.

The appliances in his house are as follow:

- 8 fluorescent tubes, 20 W each (4 hours per day)
- 2 filament bulbs, 50 W each (2 Hours per day)
- One 10 W-DVD player (2 hours per day)
- One 80 W-color television (4 hours per day)
- 2 cooling fans, 40 W each (6 hours per day)

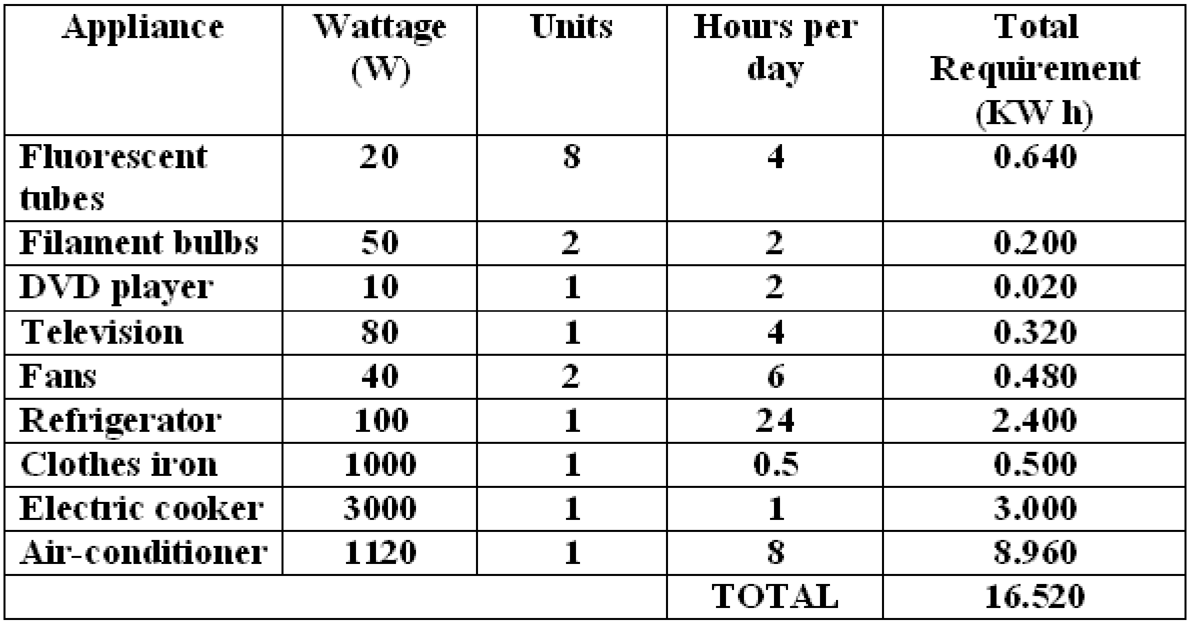
- Refrigerator, 100 W (24 hours per day)
- Clothes iron, 1KW (30 minutes per day)
- Electric cooker, 3KW (1 hour per day)
- Air-conditioner 1.5hp (8 hours per day)

Calculate the total daily electricity requirement of all the appliances in Mr. X's house.

(1 hp = 0.7457 KW)

Solution

1.5 hp = 1.5 X 0.7457 K = 1.12KW



Appliance	Wattage (W)	Units	Hours per day	Total Requirement (KW h)
Fluorescent tubes	20	8	4	0.640
Filament bulbs	50	2	2	0.200
DVD player	10	1	2	0.020
Television	80	1	4	0.320
Fans	40	2	6	0.480
Refrigerator	100	1	24	2.400
Clothes iron	1000	1	0.5	0.500
Electric cooker	3000	1	1	3.000
Air-conditioner	1120	1	8	8.960
			TOTAL	16.520

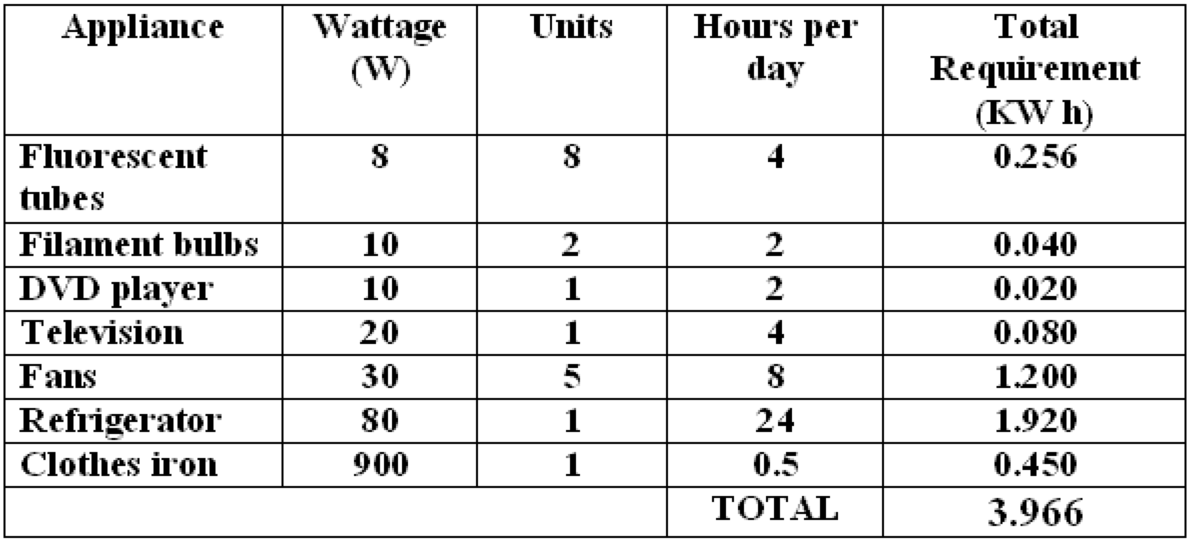
3.10.2 Estimating the consumption for a PV system

The output from a solar cell module of 40 W peak output can reach about 150 W h per day. Recall that the total daily requirement of electricity for Mr. X's house is 16.52 KW h. Therefore at least 110 modules (16.52K / 150 = 110.1 modules) are required to meet a daily requirement of 16.52 KW h per day. This is a very large number of solar modules for just one home.

Clearly it is not economical to use solar electricity for running some of the appliances that are found in a home connected to the mains or a generator. When sizing for a solar system, the daily requirement can be significantly reduced the values in the previous example. Reductions are made by carefully decided which appliances need to be run on solar electricity and for how long they really need to be used each day.

For Mr. X's case, it is very obvious that air-conditioner is not suitable to be run using solar electricity. Therefore, we have to replace the air-conditioner by adding more low-power cooling fans. Electric cooker has to be eliminated from this system as the power consumed is too high.

Now, let us recalculate the requirement of solar electricity of Mr. X's house after considering the consumption of power for every appliances. The summary of calculation is shown below:



Appliance	Wattage (W)	Units	Hours per day	Total Requirement (KW h)
Fluorescent tubes	8	8	4	0.256
Filament bulbs	10	2	2	0.040
DVD player	10	1	2	0.020
Television	20	1	4	0.080
Fans	30	5	8	1.200
Refrigerator	80	1	24	1.920
Clothes iron	900	1	0.5	0.450
			TOTAL	3.966

Table 2 after Reduction of Power Consumption

Therefore, the total daily requirement of electricity for Mr. X's house is **about 4 KW h**. The requirement has reduced about 75% from 16.52 KW h to 4 KW h. If using the solar module that can produce 150 W h per day, the minimum number of solar modules needed is about 27 (4 K / 150 = 27) for stand-alone photovoltaic system. The number of modules can be reduced if we choose modules that can produce higher power but certainly it will cost more.

In conclusion, the large reduction in requirement can be achieved by removing the high-power appliances and changing to the low-power appliances.

3.11 Average Daily Output from One Module

For a system with a generator, sizing is simple because the power output of the generator is constant. For photovoltaic system, sizing is much more complicated. This is because the amount of electricity generated each day depends on the rating solar module and on the amount of sunlight reaching the modules through the day.

3.11.1 Units of Daily Insolation

We know that the irradiance that reaching the surface of a module can be measured in units of watts per square meter (W/m^2). A different unit is used when measuring the total amount of light reaching the ground over a period of time.

For calculating the daily output of a solar module, the unit that we use is *peak-hours per day*. Peak hours are equivalent to the number of hours of sunlight at an irradiance of 1000 W/m^2. This value of irradiance is chosen because it is the same value as the Standard Test Conditions (STC) under which the electrical specifications of solar modules are measured. The value of 1000 W/m^2 also happens to be the highest irradiance that can be received on a surface facing the sun directly and when the sun is more than 45° above the horizon. Peak hours can also be given as KW/m^2 per days which are the same size.

3.11.2 Standard Test Conditions (STC)

1. Irradiance of 1000 W/m^2
2. Cell temperature of 25°C

3.11.3 Module Tilt

A solar module is always mounted at a certain angle of tilt from horizontal. The tilt angle should be at least 15° or more to ensure that the rain-water can drain off easily, and wash the dust away.

Here are 2 simple steps that can be followed to determine the tilt angle and the direction of the modules:-

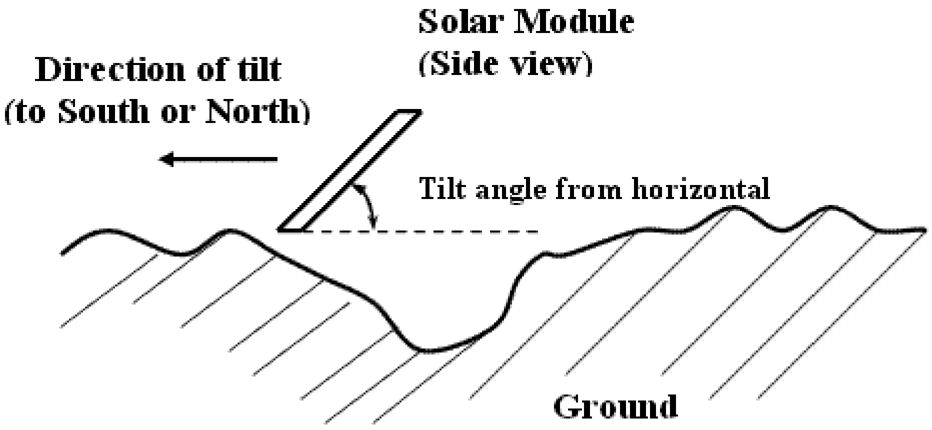
a) ***Set the tilt angle at the latitude angle of the site***.

For sites at higher latitudes than 30°, the tilt angle can be set at the latitude angle plus 15°. This helps to even out the daily electrical output over the year by optimizing the tilt angle for the winter months.

For sites at latitudes between 15°S and 15°N (for Example, Malaysia), a tilt angle of 15° is used.

b) ***The direction of tilt should be set towards equator.***

For countries at the North hemisphere of the earth (China, Malaysia, Japan etc.), the module should face South and for countries located at the South hemisphere of the earth (Australia, New Zealand etc.), the direction of the module should be North.



3.12 Selecting Suitable Modules for the Application

The number of cells needed in a module depends on the type of charge regulation to be used and the local temperature. Self-regulating modules with thirty o thirty-two cells are good for small solar systems. A separate charge-regulating unit is not needed, which keeps the system simple and low cost.

Modules with thirty-three or thirty-four cells and a charge regulator make better use of the available sunshine to charge batteries in the shortest time. Extra cells are needed in hot climates and in systems with large system losses to the batteries.

Table below shows a selection of a module for various types of systems and climates based on open circuit voltage in volts (V_{oc}) under Standard Test Conditions (STC) or number of cells in the module.

Application	Local Climate			
	Mild (below 30 °C at midday)		Hot (above 30 °C at midday)	
	Crystalline Silicon	Thin-film Silicon	Crystalline Silicon	Thin-film Silicon
Self-regulating, no diode	18 V (30 cells)	20 V	19 V (32 cells)	21 V
Self-regulating, with a diode	19 V (32 cells)	21 V	20 V (34 cells)	22 V
With a charge regulator	≥ 20 V (32 cells)	≥ 22 V	≥ 21 V (> 34 cells)	≥ 23 V

From the table we can find that V_{oc} for thin-film silicon is higher in each application. The number of cells for crystalline silicon is also increased in hot climate. However, both type of silicon produce higher voltages during hot weather compared to mild climate. This is because more power is absorbed during hot weather and thus higher voltage can be generated.

Besides, additional of 2 cells is needed for self-regulating crystalline-type with diode because it has to compensate voltage drop in the diode. Diode is used to avoid current from flowing back to the cells when the batteries are fully charged.

We have known that thin-film silicon cells can perform better than crystalline silicon cells. However, it is much more expensive than crystalline silicon cells. Therefore, we have to choose the suitable type of cells not only based on the performance but also our budget of the project. This section teaches us to choose suitable type of cells. The following section will teach us how to determine the daily output from the module that we have chosen here.

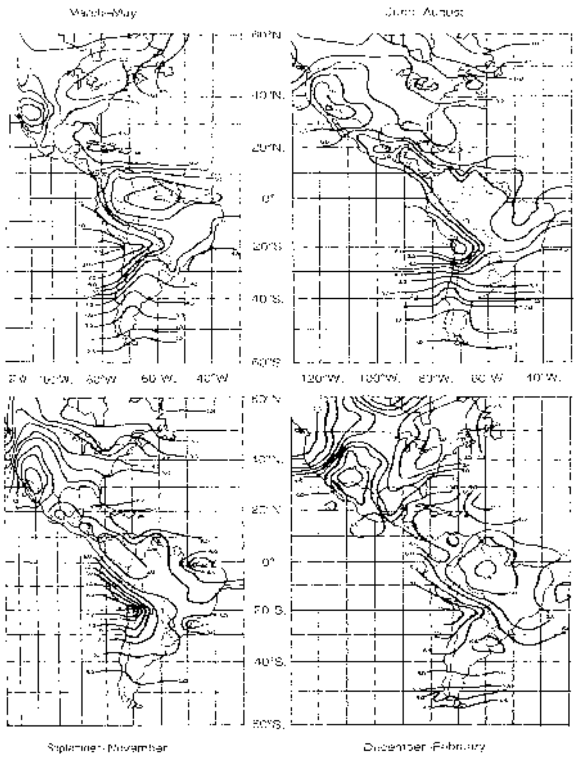
3.13 Determining the Daily Output from One Module

The maps shown below have sets of average daily insolation for most countries of the world. The averages are over three month periods and apply to modules tilted at the same angle as their angle of latitude.

For some sites, the country can be found directly on the maps. Otherwise, we can use a pencil to draw lines for the angles of latitude and longitude of the site so that the site is located where the lines cross. For each quarter of the year, choose the nearest curve of daily insolation and follow along this curve to the value of peak-hours per day. A more accurate estimate of daily insolation can be made by judging the position of the site between two curves. We will practice this method in the example on next section.

The daily electrical output from one module in units of *W h per day at 12 V* is calculated using the following formula:

$$\boxed{\begin{array}{c}\textbf{Current at}\\ \textbf{load or}\\ \textbf{other}\\ \textbf{current}\\ \textbf{specification}\\ \textbf{of module}\\ \textbf{(A)}\end{array}} \times \boxed{\begin{array}{c}\textbf{Daily peak}\\ \textbf{insolation}\\ \textbf{(Peak-hours}\\ \textbf{per day)}\end{array}} \times \boxed{\textbf{12 V}} = \boxed{\begin{array}{c}\textbf{Daily output}\\ \textbf{of one}\\ \textbf{module}\\ \textbf{(W h per day}\\ \textbf{at 12 V)}\end{array}}$$



b. North and South America (longitudes 130°W. to 30°W.).

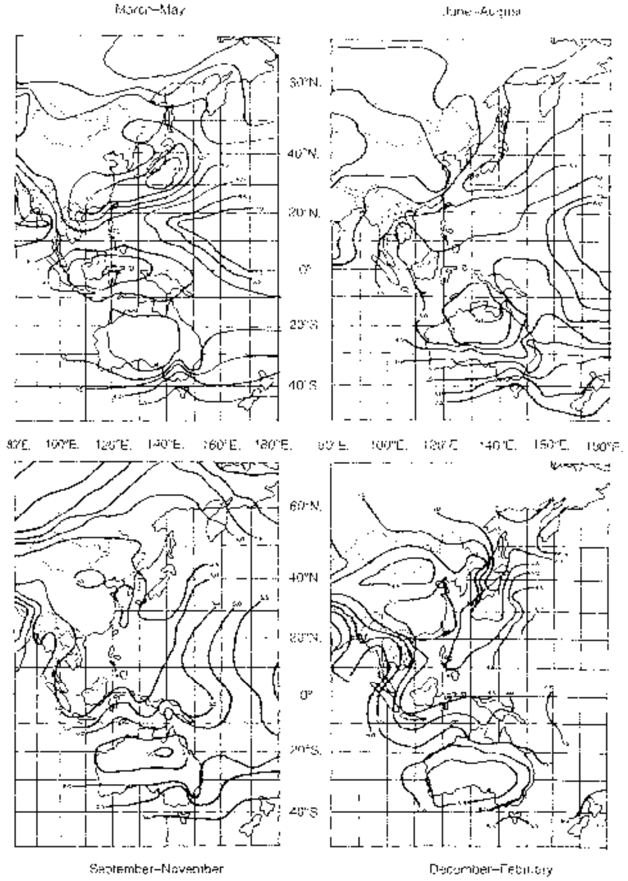


Figure 8.4(c) Far East, Australia, and New Zealand (longitudes 80°E. to 180°E.).

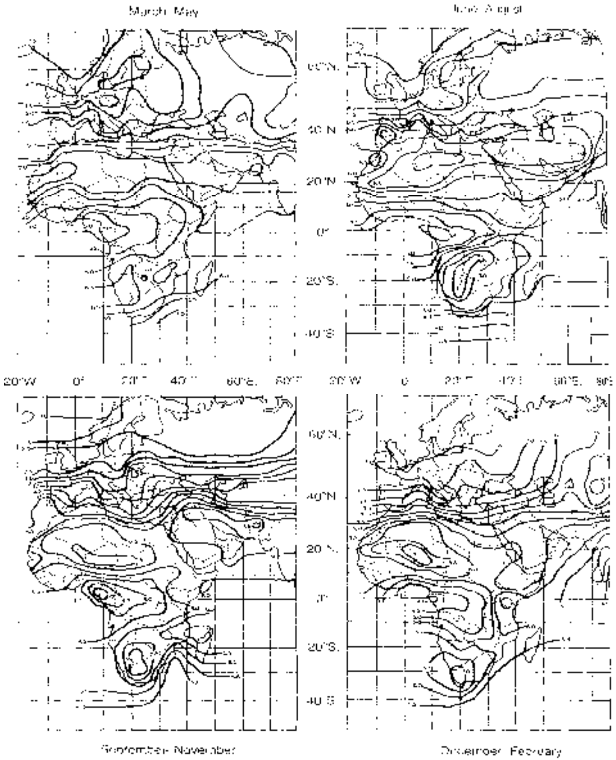


Figure 8.4(b) Europe, Middle East, and Africa (longitudes 20°W. to 60°E.)

The value of 12 V is chosen because it is the voltage at which the electricity is actually used by the appliances. For 24 V systems, 12 is still used because allowance for the higher voltage is made later when sizing the number of modules.

Example

From previous example, Mr. X has decided to install modules with a current at load of 4.5 A under STC in his house. His house is located in Kuala Lumpur. What will be the lowest daily electrical output of one module averaged over a three-month period?

Solution

Kuala Lumpur is at latitude of 3 ° 8 ' N. Based on the map, we can calculate the average output of a module over a three-month period using above Equation. The calculations are as follow:-

March - May

Average output = 4.5 X 5.5 X 12 = 297 W h per day at 12 V.

June - August

Average output = 4.5 X 4.6 X 12 = 248.4 W h per day at 12 V.

September - November

Average output = 4.5 X 5.0 X 12 = 270 W h per day at 12 V.

December - February

Average output = 4.5 X 5.4 X 12 = 294.6 W h per day at 12 V.

Therefore, we have determined that the lowest average daily output for Mr. X's module is 248.4 W h per day at 12 V for June to August. As Kuala Lumpur is located at latitude of 3 ° 8 ' N, the modules should be tilted at 15° from horizontal and facing South to generate electrical output.

There are some weaknesses to determine the average output of a module using the maps of daily insolation. The information given from the maps only gives an approximate indication of daily insolation. The values on the curves are averaged over three-month periods. There is no indication of how long the daily electrical output might get for one month.

Besides, setting the tilt angle of the module at the same angle as the latitude of the site may not be the optimum. On the small scale of the maps, they cannot take into account local variations which can be significant for some sites.

The suggestion to overcome the limitation is determine the average daily insolation for every month at the site. If meteorological records are available for the area of interest, they can be used to give a better estimate of daily electrical output expected from a module.

3.14 Sizing the Number of Modules Needed

Most appliances are used at night. Therefore they draw power from the batteries in stead of directly from the solar modules. When sizing the number of modules that are needed, the small loss of electricity when charging the batteries must be included. This is the current or A h charging efficiency. Typical values to use are 80% for lead-acid batteries and 70% for nickel-cadmium batteries.

The formula for sizing the minimum number of modules is as follow:

$$\boxed{\text{Minimum Number of Modules needed}} = \frac{\boxed{\text{Daily Requirement of Appliances (W h per day)}}}{\boxed{\text{Daily output of one module (W h per day at 12 V)}} \times \boxed{\text{Charging Efficiency of battery (\%)}}} \times \boxed{100\ \%}$$

Example

Calculate the minimum number of modules needed by Mr. X from the values that we have determined from previous examples if he uses lead-acid batteries.

Solution

Daily requirement of appliances = 3.966 K W h

Daily output of one module = 248.4 W h

Therefore, minimum number of solar modules needed by Mr. Lee is

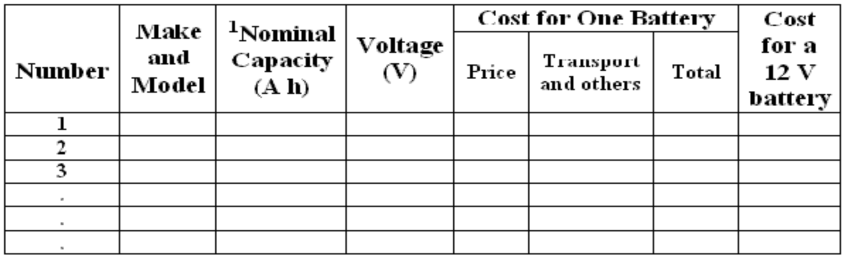
= (3.966 K X 100) / (248.4 X 80)

= 19.96

That is 20 modules

3.15 Choosing the Right Battery

The first step in choosing a battery is to find out which ones are available. Then their details, specifications and price should be listed in a table. The price should include the cost of delivery to the site and all other incidental costs for each battery. The voltage supplied by a battery depends on the number and type of cells from which it is made. Batteries should be compared at the same voltage of 12 V. Below shows two tables we have to make and equations to help us to determine certain parameters in the table.



Number	Make and Model	[1]Nominal Capacity (A h)	Voltage (V)	Cost for One Battery			Cost for a 12 V battery
				Price	Transport and others	Total	
1							
2							
3							
.							
.							
.							

[1] At C/100 or C_{100} (measured for a full discharge over 100 hours)

Where

$$\text{Cost for a 12 V battery (Local Currency)} = \frac{\text{Total Cost of one battery (Local Currency)} \times \text{12 V}}{\text{Nominal Voltage of one battery (V)}}$$

We can also use the following table to compare batteries by value for money of various aspects.

Number	Nominal Capacity (A h)	Cost for a 12 V battery	Usable cycle depth (%)	Cycle Life (Cycles)	Capacity (A h)		Relative value for money		
					Usable	Total Usable	One cycle	Cycle Life	Life
1									
2									
3 .									
.									
.									

Table 5 comparing batteries by value for money of various aspects

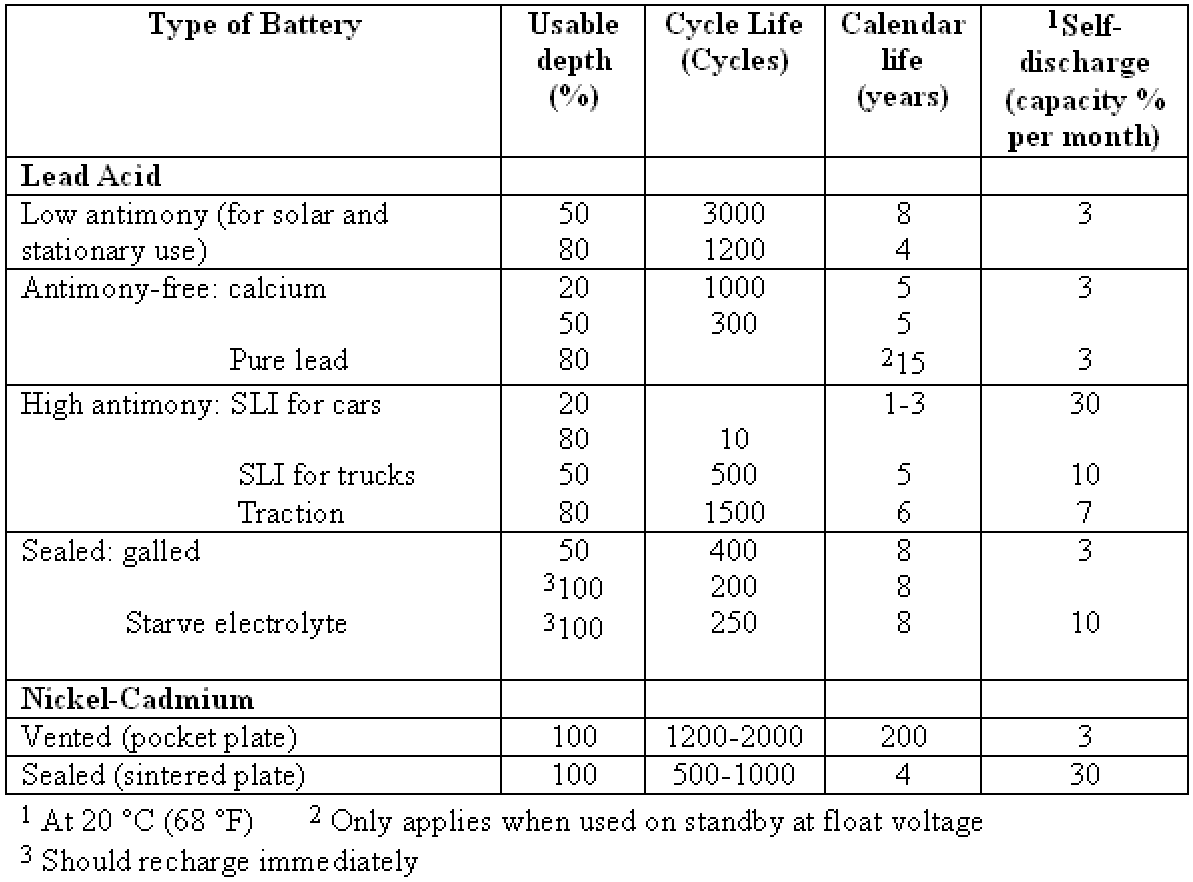
Where

$$\text{Usable Capacity (A h)} = \text{Nominal Capacity (A h)} \times \frac{\text{Usable depth (\%)}}{\text{100 \%}}$$

$$\text{Total usable capacity over cycle life (A h)} = \text{Usable capacity (A h)} \times \text{Cycle Life at usable depth (Cycle)}$$

At the last column of Table 5, each capacity figures is divided by price and to give a number which is "value for money". The higher the answer, the better value for money of battery.

Often the full specifications are not given to enable Table 5 to be completed. Table 6 lists typical specifications of various types of rechargeable batteries. This can be used a guide to complete the calculation of capacity figures. However, when comparing individual brands of batteries, always use the specifications for that brand provided by the supplier.



Type of Battery	Usable depth (%)	Cycle Life (Cycles)	Calendar life (years)	[1]Self-discharge (capacity % per month)
Lead Acid				
Low antimony (for solar and stationary use)	50 80	3000 1200	8 4	3
Antimony-free: calcium	20 50	1000 300	5 5	3
Pure lead	80		[2]15	3
High antimony: SLI for cars	20 80	 10	1-3	30
SLI for trucks	50	500	5	10
Traction	80	1500	6	7
Sealed: galled	50 [3]100	400 200	8 8	3
Starve electrolyte	[3]100	250	8	10
Nickel-Cadmium				
Vented (pocket plate)	100	1200-2000	200	3
Sealed (sintered plate)	100	500-1000	4	30

[1] At 20 °C (68 °F) [2] Only applies when used on standby at float voltage

[3] Should recharge immediately

Table 6 Specifications for various types of rechargeable batteries that can be used in solar electric systems. The values are given for the purpose of comparison only. Please refer to the specifications from individual suppliers where possible

There are two approaches to balancing the starting and running costs of a system:

1. To minimize the system cost at the start, aim for high usable capacity. However, the battery may have a short life.

2. To minimize the cost over the life of the battery, aim for a high value of total usable capacity over cycle life.

3.15.1 Sizing the Number of Batteries Needed

Batteries charge up during the day and ready to use at night. They also smooth out the variations of insolation. They do this by storing the excess charge received during sunny days and ready for use during cloudy days that follow. Therefore, the period of storage required should be based on the maximum number of consecutive days with rain or heavy cloud.

Another purpose of batteries can be to provide seasonal storage and smooth out variations of daily insolation between months. A battery with low rate of self-discharge is essential for this purpose.

The usable capacity required is calculated from the daily electrical requirement and period of storage as follow:-

$$\textbf{Total Usable capacity needed (A h at 12 V)} = \frac{\textbf{Daily requirement of appliances (W h per day)} \times \textbf{Period of storage required (days)}}{\textbf{12 V}}$$

We have learnt how to select a rechargeable battery from those that are available at the previous section. For sizing, two specifications are required about the battery which we have selected. The specifications are:-

1. The full capacity in A h units.
2. The usable depth of discharge recommended for that type of battery, in percentage.

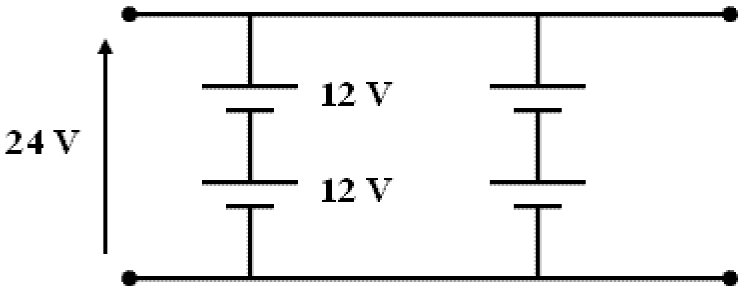
The full capacity of a battery is measured as it is discharged to a specified voltage. However, most types of lead-acid battery should not be cycled over their full capacity or else their life is severely shortened. The percentage of charge used on each cycle of a battery is called cycle depth. To obtain the full life of a battery, the cycle depth should not exceed the depth recommended for that type of battery.

The number of batteries that are needed is calculated from the usable capacity and cycle depth as shown in equation below:-

$$\textbf{Minimum number of 12 V batteries needed} = \frac{\textbf{Total Usable capacity needed (A h in 12 V)}}{\textbf{Maximum depth of cycles (\%)} \times \textbf{Full Capacity specified for one 12 V battery (A h)}} \times \textbf{100 \%}$$

This calculation is based on nominal 12 V batteries. When batteries have a lower nominal voltage, they are connected in series to form 12 V batteries. Their voltages add for series connection while the over all capacity in A h is the same as for one battery.

For systems operating at 24 V, the wiring arrangement is to connect 12 V batteries in series pairs. The circuit is as shown bellow:-



In these 24 V systems, equation 7.8 still applies but the nearest even number above the answer should be used.

Example

We know that the daily requirement of appliances for Mr. Lee house is 4 KW h per day. Mr. Lee has decided to choose batteries which have a capacity of 500 A h. They are lead-acid batteries intended for deep-cycle operation and can be discharged to a depth of 65 %. What is the smallest number of batteries that can be used?

Solution

Since the estimate of period for storage is not given, we assume that 4 days of storage is adequate in Kuala Lumpur. Using Equation 7.7, the total usable battery capacity needed is:

(4 K X 4) / 12 = 1333.33A h at 12 V

Thus using Equation 7.8, the minimum number of batteries needed is:-

(1333.33 X 100) / (500 X 65) = 4.103

Therefore, the minimum number of batteries that are needed is 5. If the system is running on 24 V, we take 6 batteries for the storage of the electricity for the system.

3.16 SELECTION OF INVERTER

AC Voltage:

In the US, we can face a multitude of AC operating voltages as well as single or three-phase systems;

1. 120/240- single phase is used in residential applications. Inverters would connect to 240VAC in this application.
2. 240- three-phase is used for power loads in commercial and industrial buildings. This is a delta configuration. Across any one (of 3 transformers) there's 240V. On one side (only) of the delta. There is a center-tapped transformer which is connected to neutral. Thus providing 2x 120VAC for outlets.
3. 208Y/120-V three-phase four wire distribution is commonly used in commercial buildings with limited electrical loads. 120V is available between a pole and ground, while 208V is available between any two poles.
4. 480- Three phase delta is commonly used in commercial and industrial buildings with substantial motor loads.
5. 480Y/277- is used to supply commercial and industrial buildings. Between any two poles there's 480V, and between any pole and neutral there's 277V. The 277V is used for ballasted lighting. Local step-down transformers are typically inserted to provide 208Y/120-V power for lighting, appliances and outlets.

DC Voltage:

For inverters we have the following parameters when considering DC voltages;

1. The Maximum Power Point Transfer (MPPT or MPP) voltage range. This is the voltage range where the inverter employs its software algorithm to adjust its DC input impedance to that of the solar system. A solar PV string should be sized such that the inverter can normally operate within this range.
2. Maximum DC voltage; a solar PV string with no load (Vo) must under no circumstance ever exceed an inverters maximum DV voltage. When considering this factor, one must assume the lowest possible solar PV panel temperature while exposed to bright sunlight. This usually happens on a winter day with cumulus clouds. Here in Los Altos California, it is safe to assume a T (min) of -10C.

3. Minimum DC voltage; for tracking systems, the minimum DC voltage at which the inverter remains on-line is particularly critical to concentrated solar PV tracker performance. During cloud cover, a solar PV string’s DC voltage can drop to a very low level. At some point, the inverter will decide to all-together stop production, and proceed with shutdown. Upon cloud clearing, a shut-down inverter, must now go through a start-up procedure during which it must monitor the AC voltage and frequency for a given time interval before going on-line.

String sizing:

Solar PV panels or receivers should be connected in series to form “strings”. Strings should be connected in parallel to match an inverters power rating. A 10KW inverter should not be used together with a 1KW solar PV plant, because the inverter will never operate at its peak efficiency level. Inversely, a 10KW solar PV string should not be used to power a 1KW inverter. In this case, assuming VDC is not being violated, the inverter will simply produce 1KW.

String considerations for tracker operations:

A single tracker in an open field has no special requirements to string layout. On the other hand, as more trackers are added to a field, and the spacing between trackers become denser, trackers will inevitably shade their partners during early morning and late afternoons. This is a particularly important time because is happens to be at the time of day where;

1) The largest gain is made by using tracking vs. non-tracking

2) In the late afternoon, the energy costs are at their highest

While shading ultimately is inevitable, designing the proper string layout can mitigate the shading issue. Consider a simple heliostat, ie. a solar PV-panel-equipped-plane with 3 rows, which is pointed perpendicular to the sun. Rather than having a given solar PV string run zigzag between top, middle and bottom rows, it would be better to have a top, middle and bottom string. For commercial fields where 3-phase wiring is used, one may even consider installing 3 distinct inverters for each of the rows, where each inverter feeding 1 of 3 phases. Thus affording a dedicated MPP unit for each string.

A solar PV’s DC circuit should feed one and only one inverter.