

UNIT III

DC TO DC CONVERTER

- Step-down and step-up chopper
- control strategy
- Forced commutated chopper
- Voltage commutated, Current commutated, Load commutated, Switched mode regulators
- Buck, boost, buck- boost converter
- Introduction to Resonant Converters.

DC-DC Converters

There are three basic types of dc-dc converter circuits, termed as buck, boost and buck-boost. In all of these circuits, a power device is used as a switch. This device earlier used was a thyristor, which is turned on by a pulse fed at its gate. In all these circuits, the thyristor is connected in series with load to a dc supply, or a positive (forward) voltage is applied between anode and cathode terminals. The thyristor turns off, when the current decreases below the holding current, or a reverse (negative) voltage is applied between anode and cathode terminals. So, a thyristor is to be force-commutated, for which additional circuit is to be used, where another thyristor is often used. Later, GTO's came into the market, which can also be turned off by a negative current fed at its gate, unlike thyristors, requiring proper control circuit. The turn-on and turn-off times of GTOs are lower than those of thyristors. So, the frequency used in GTO-based choppers can be increased, thus reducing the size of filters. Earlier, dc-dc converters were called 'choppers', where thyristors or GTOs are used. It may be noted here that buck converter (dc-dc) is called as 'step-down chopper', whereas boost converter (dc-dc) is a 'step-up chopper'. In the case of chopper, no buck-boost type was used.

With the advent of bipolar junction transistor (BJT), which is termed as self-commutated device, it is used as a switch, instead of thyristor, in dc-dc converters. This device (NPN transistor) is switched on by a positive current through the base and emitter, and then switched off by withdrawing the above signal. The collector is connected to a positive voltage. Now-a-days, MOSFETs are used as a switching device in low voltage and high current applications. It may be noted that, as the turn-on and turn-off time of MOSFETs are lower as compared to other switching devices, the frequency used for the dc-dc converters using it (MOSFET) is high, thus, reducing the size of filters as stated earlier. These converters are now being used for applications, one of the most important being Switched Mode Power Supply (SMPS). Similarly, when application requires high voltage, Insulated Gate Bi-polar Transistors (IGBT) are preferred over BJTs, as the turn-on and turn-off times of IGBTs are lower than those of power transistors (BJT), thus the frequency can be increased in the converters using them. So, mostly self-commutated devices of transistor family as described are being increasingly used in dc-dc converters.

Buck Converters (dc-dc)

A buck converter (dc-dc) is shown in Fig. a. Only a switch is shown, for which a device as described earlier belonging to transistor family is used. Also a diode (termed as free wheeling) is used to allow the load current to flow through it, when the switch (i.e., a device) is turned off. The load is inductive (R-L) one. In some cases, a battery (or back emf) is connected in series with the load (inductive). Due to the load inductance, the load current must be allowed a path, which is provided by the diode; otherwise, i.e., in the absence of the above diode, the high induced emf of the inductance, as the load current tends to decrease, may cause damage to the switching device. If the switching device used is a thyristor, this circuit is called as a step-down chopper, as the output voltage is normally lower than the input voltage. Similarly, this dc-dc converter is termed as buck one, due to reason given later.

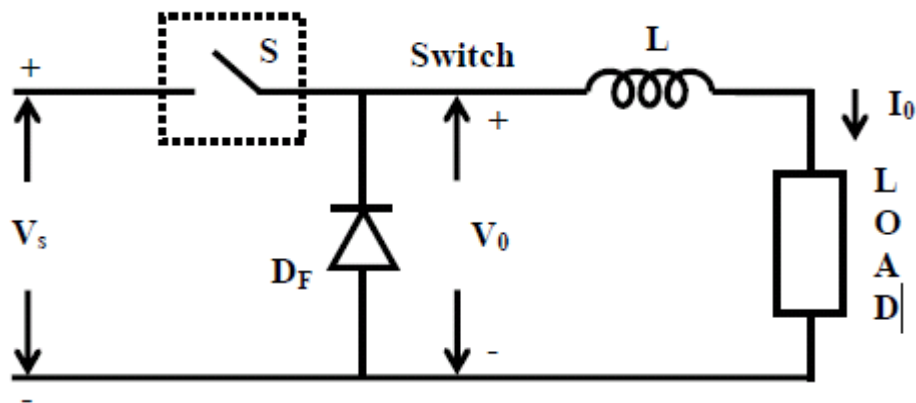


Fig. (a); Buck converter (dc-dc),

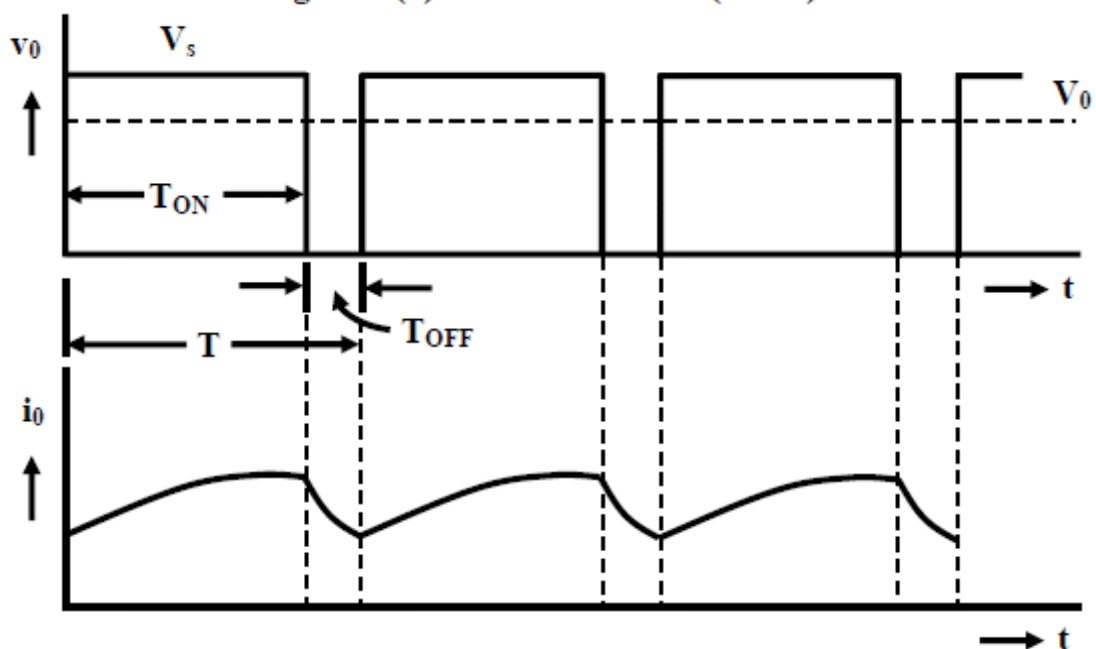


Fig. (b): Output voltage and current waveforms

The output voltage and current waveforms of the circuit (Fig. 1.10 a) are shown in Fig. 1.10 b. The output voltage is same as the input voltage, i.e., $v_0 = V_s$, when the switch is ON, during the period, $T_{ON} \geq t \geq 0$. The switch is turned on at $t = 0$, and then turned off at $t = T_{ON}$. This is

called ON period. During the next time interval, $T \geq t \geq T_{ON}$, the output voltage is zero, i.e., $v_0 = 0$, as the diode, D_F now conducts. The OFF period is $T_{OFF} = T - T_{ON}$, with the time period being $T = T_{ON} + T_{OFF}$. The frequency is $f = 1/T$. With T kept as constant, the average value of the output voltage is,

$$V_0 = \frac{1}{T} \int_0^T v_0 dt = \frac{1}{T} \int_0^{T_{ON}} V_s dt = V_s \left(\frac{T_{ON}}{T} \right) = k V_s$$

Normally, due to turn-on delay of the device used, the duty ratio (k) is not zero, but has some positive value. Similarly, due to requirement of turn-off time of the device, the duty ratio (k) is less than 1.0. So, the range of duty ratio is reduced. It may be noted that the output voltage is lower than the input voltage. Also, the average output voltage increases, as the duty ratio is increased. So, a variable dc output voltage is obtained from a constant dc input voltage. The load current is assumed to be continuous as shown in Fig. b. The load current increases in the ON period, as the input voltage appears across the load, and it (load current) decreases in the OFF period, as it flows in the diode, but is positive at the end of the time period, T.

Boost Converters (dc-dc)

A boost converter (dc-dc) is shown in Fig.a. Only a switch is shown, for which a device belonging to transistor family is generally used. Also, a diode is used in series with the load. The load is of the same type as given earlier. The inductance of the load is small. An inductance, L is assumed in series with the input supply. The position of the switch and diode in this circuit may be noted, as compared to their position in the buck converter (Fig.a).

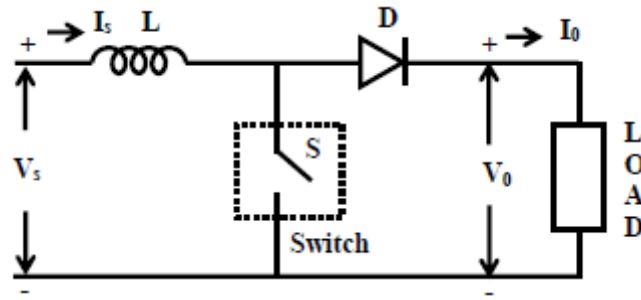


Fig. 17.2(a): Boost converter (dc-dc)

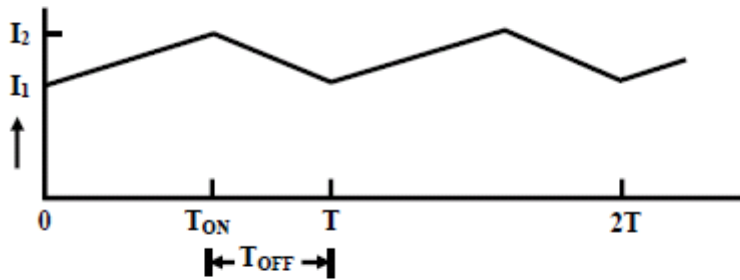


Fig. (b): Waveforms of source current (i_s)

The operation of the circuit is explained. Firstly, the switch, S (i.e., the device) is put ON (or turned ON) during the period, $T_{ON} \geq t \geq 0$, the ON period being T_{ON} . The output voltage is zero ($v_0 = 0$), if no battery (back emf) is connected in series with the load, and also as stated earlier, the load inductance is small. The current from the source (i_s) flows in the inductance L . The value of current increases linearly with time in this interval, with (di/dt) being positive. As the current through L increases, the polarity of the induced emf is taken as say, positive, the left hand side of L being +ve. The equation for the circuit is,

$$V_s = L \frac{di_s}{dt} \quad \text{or,} \quad \frac{di_s}{dt} = \frac{V_s}{L}$$

The switch, S is put OFF during the period, $T \geq t \geq T_{ON}$, the OFF period being $T_{OFF} = T - T_{ON}$. ($T = T_{ON} + T_{OFF}$) is the time period. As the current through L decreases, with its direction being in the same direction as shown (same as in the earlier case), the induced emf reverses, the left hand side of L being -ve. So, the induced emf (taken as -ve in the equation given later) is added with the supply voltage, being of the same polarity, thus, keeping the current ($i_s = i_0$) in the same direction. The current ($i_s = i_0$) decreases linearly in the time interval, T_{OFF} , as the output voltage is assumed to be nearly constant at $v_0 \approx V_0$, with (di_s/dt) being negative, as $V_s < V_0$, which is derived later.

The equation for the circuit is,

$$V_s = V_0 + L \frac{di_s}{dt} \quad \text{or,} \quad \frac{di_s}{dt} = \frac{(V_s - V_0)}{L}$$

In this case, the output voltage is higher than the input voltage, as contrasted with the previous case of buck converter (dc-dc). So, this is called boost converter (dc-dc), when a self-commutated device is used as a switch. Instead, if thyristor is used in its place, this is termed as step-up chopper. The variation (range) of the output voltage can be easily computed.

The source current waveform is shown in Fig. 17.2b. As stated earlier, the current varies linearly from I_1 ($I_{\min}$) to I_2 ($I_{\max}$) during the time interval, T_{ON} .

So, using the expression for di_s/dt during this time interval,

$$I_2 - I_1 = I_{\max} - I_{\min} = (V_s / L) T_{ON}.$$

Similarly, the current varies linearly from I_2 ($I_{\max}$) to I_1 ($I_{\min}$) during the time interval, T_{OFF} .

So, using the expression for di_s/dt during this time interval,

$$I_2 - I_1 = I_{\max} - I_{\min} = [(V_0 - V_s) / L] T_{OFF}.$$

Equating the two equations, $(V_s / L) T_{ON} = [(V_0 - V_s) / L] T_{OFF}$, from which the average value of the output voltage is,

$$V_0 = V_s \left(\frac{T}{T_{OFF}} \right) = V_s \left(\frac{T}{T - T_{ON}} \right) = V_s \left(\frac{1}{1 - (T_{ON} / T)} \right) = V_s \left(\frac{1}{1 - k} \right)$$

The time period is $T = T_{ON} + T_{OFF}$, and the duty ratio is,

$k = (T_{ON} / T) = [T_{ON} / (T_{ON} + T_{OFF})]$, with its range as $1.0 \geq k \geq 0.0$. The ON time interval is $T_{ON} = kT$. As stated in the previous case, the range of k is reduced. This is, because the minimum value is higher than the minimum (0.0), and the maximum value is lower than the maximum (1.0), for reasons given there, which are also valid here. As shown, the source current is assumed to be continuous. The expression for the output voltage can be obtained by using other procedures.

Buck-Boost Converters (dc-dc)

A buck-boost converter (dc-dc) is shown in Fig. Only a switch is shown, for which a device belonging to transistor family is generally used. Also, a diode is used in series with the load. The connection of the diode may be noted, as compared with its connection in a boost converter (Fig.a). The inductor, L is connected in parallel after the switch and before the diode. The load is of the same type as given earlier. A capacitor, C is connected in parallel with the load. The polarity of the output voltage is opposite to that of input voltage here.

When the switch, S is put ON, the supply current (i_s) flows through the path, V_s , S and L, during the time interval, T_{ON} . The currents through both source and inductor (i_L) increase and are same, with (di_L/dt) being positive. The polarity of the induced voltage is same as that of the input voltage. The equation for the circuit is,

$$V_s = L \frac{di_L}{dt} \quad \text{or,} \quad \frac{di_L}{dt} = \frac{V_s}{L}$$

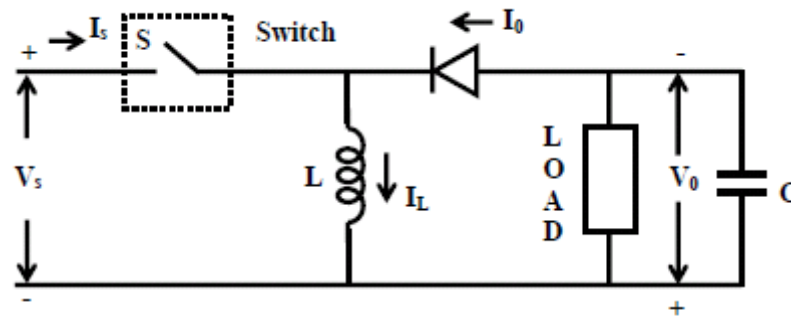


Fig. 1 (a): Buck-boost converter (dc-dc)

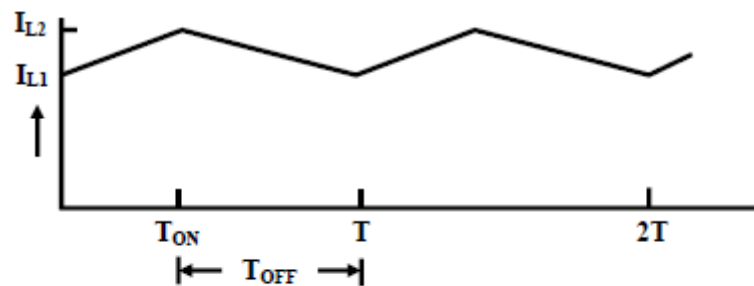


Fig. 1 (b): Inductor current (i_L) waveform

Then, the switch, S is put OFF. The inductor current tends to decrease, with the polarity of the induced emf reversing. (di_L/dt) is negative now, the polarity of the output voltage, V_0 being opposite to that of the input voltage, V_s . The path of the current is through L, parallel combination of load & C, and diode D, during the time interval, T_{OFF} . The output voltage remains nearly constant, as the capacitor is connected across the load.

The equation for the circuit is,

$$L \frac{di_L}{dt} = V_0 \quad \text{or,} \quad \frac{di_L}{dt} = \frac{V_0}{L}$$

The inductor current waveform is shown in Fig. 17.3b. As stated earlier, the current varies linearly from I_{L1} to I_{L2} during the time interval, T_{ON} . Note that I_{L1} and I_{L2} are the minimum and maximum values of the inductor current respectively. So, using the expression for di_L/dt during this time interval, $I_{L2} - I_{L1} = (V_s / L) T_{ON}$.

Similarly, the current varies linearly from I_{L2} to I_{L1} during the time interval, T_{OFF} . So, using the expression for di_L/dt during this time interval, $I_{L2} - I_{L1} = (V_0 / L) T_{OFF}$.

Equating the two equations, $(V_s / L) T_{ON} = (V_0 / L) T_{OFF}$, from which the average value of the output voltage is,

$$V_0 = V_s \left(\frac{T_{ON}}{T_{OFF}} \right) = V_s \left(\frac{T_{ON}}{T - T_{ON}} \right) = V_s \left(\frac{(T_{ON} / T)}{1 - (T_{ON} / T)} \right) = V_s \left(\frac{k}{1 - k} \right)$$

The time period is $T = T_{ON} + T_{OFF}$, and the duty ratio is,

$k = (T_{ON} / T) = [T_{ON} / (T_{ON} + T_{OFF})]$. The ON time interval is $T_{ON} = kT$. It may be observed that, for the range $0 \leq k < 0.5$, the output voltage is lower than the input voltage, thus, making it a buck converter (dc-dc). For the range $0.5 < k \leq 1.0$, the output voltage is higher than the input voltage, thus, making it a boost converter (dc-dc). For $k = 0.5$, the output voltage is equal to the input voltage. So, this circuit can be termed as a buck-boost converter. Also it may be called as step-up/down chopper. It may be noted that the inductor current is assumed to be continuous. The range of k is somewhat reduced due to the reasons given earlier. The expression for the output voltage can be obtained by using other procedures.

Control Strategies

In all cases, it is shown that the average value of the output voltage can be varied. The two types of control strategies (schemes) are employed in all cases. These are:

(a) Time-ratio control, and (b) Current limit control.

Time-ratio Control

In the time ratio control the value of the duty ratio, Tk_{ON}/T is varied. There are two ways, which are constant frequency operation, and variable frequency operation.

Constant Frequency Operation

In this control strategy, the ON time, T_{ON} is varied, keeping the frequency, or time period ($f=1/T$) constant. This is also called as *pulse width modulation control* (PWM). Two cases with duty ratios, as (a) 0.25 (25%), and (b) 0.75 (75%) are shown in Fig. Hence, the output voltage can be varied by varying ON time, T_{ON}

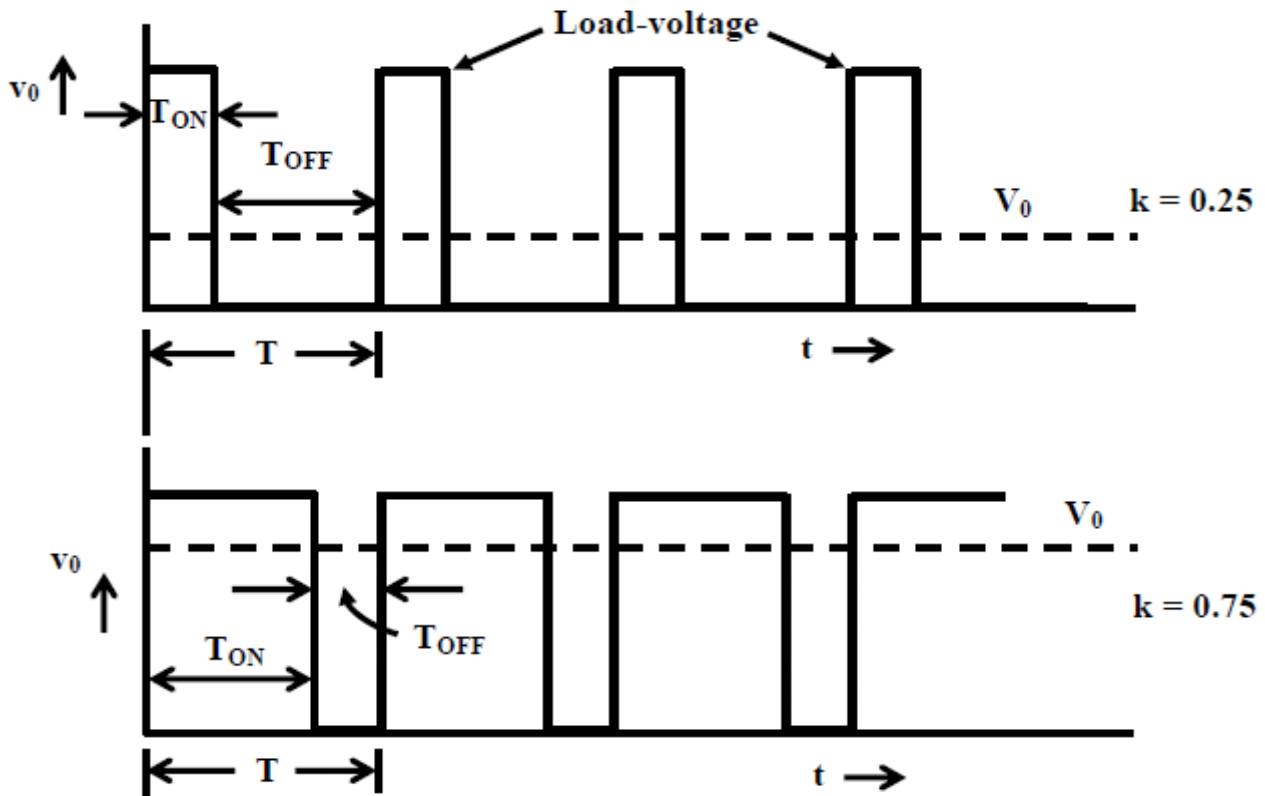


Fig. : Pulse-width modulation control (constant frequency)

Variable Frequency Operation

In this control strategy, the frequency ($f=1/T$), or time period T is varied, keeping either (a) the ON time, constant, or (b) the OFF time, constant. This is also called as *frequency modulation control*. Two cases with (a) the ON time, constant, and (b) the OFF time, constant, with variable frequency or time period are shown in Fig. The output voltage can be varied in both cases, with the change in duty ratio,

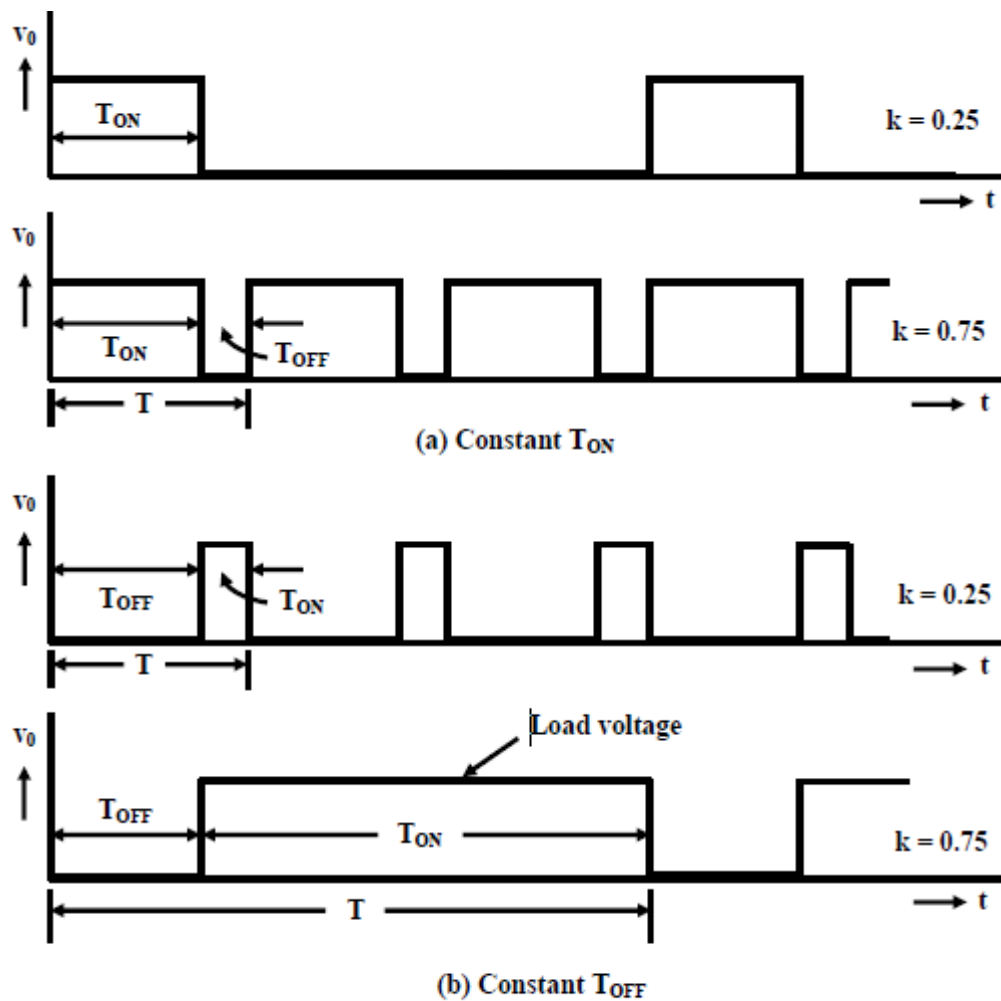


Fig. 1 : Output voltage waveforms for variable frequency system

There are major disadvantages in this control strategy. These are:

- (a) The frequency has to be varied over a wide range for the control of output voltage in frequency modulation. Filter design for such wide frequency variation is, therefore, quite difficult.
- (b) For the control of a duty ratio, frequency variation would be wide. As such, there is a possibility of interference with systems using certain frequencies, such as signaling and telephone line, in frequency modulation technique.
- (c) The large OFF time in frequency modulation technique, may make the load current discontinuous, which is undesirable.

Thus, the constant frequency system using PWM is the preferred scheme for dc-dc converters.

Current Limit Control

As can be observed from the current waveforms for the types of dc-dc converters described earlier, the current changes between the maximum and minimum values, if it (current) is continuous. In the current limit control strategy, the switch in dc-dc converter (chopper) is turned ON and OFF, so that the current is maintained between two (upper and lower) limits. When the current exceeds upper (maximum) limit, the switch is turned OFF. During OFF period, the current freewheels in say, buck converter (dc-dc) through the diode, and decreases exponentially. When it reaches lower (minimum) limit, the switch is turned ON. This type of control is possible, either with constant frequency, or constant ON time, . This is used only, when the load has energy storage elements, i.e. inductance, L . The reference values are load current or load voltage. This is shown in Fig. In this case, the current is continuous, varying between and , which decides the frequency used for switching. The ripple in the load current can be reduced, if the difference between the upper and lower limits is reduced, thereby making it minimum. This in turn increases the frequency, thereby increasing the switching losses.

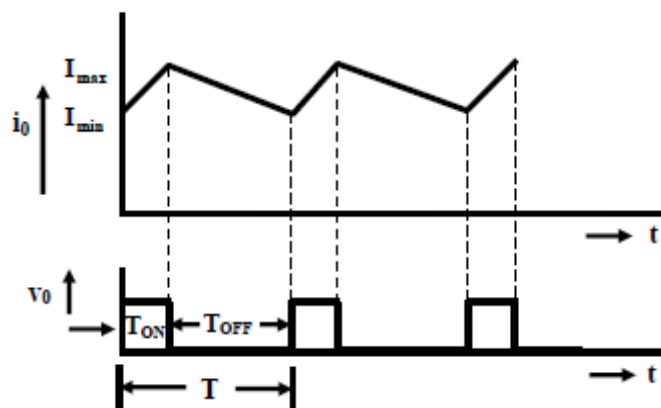
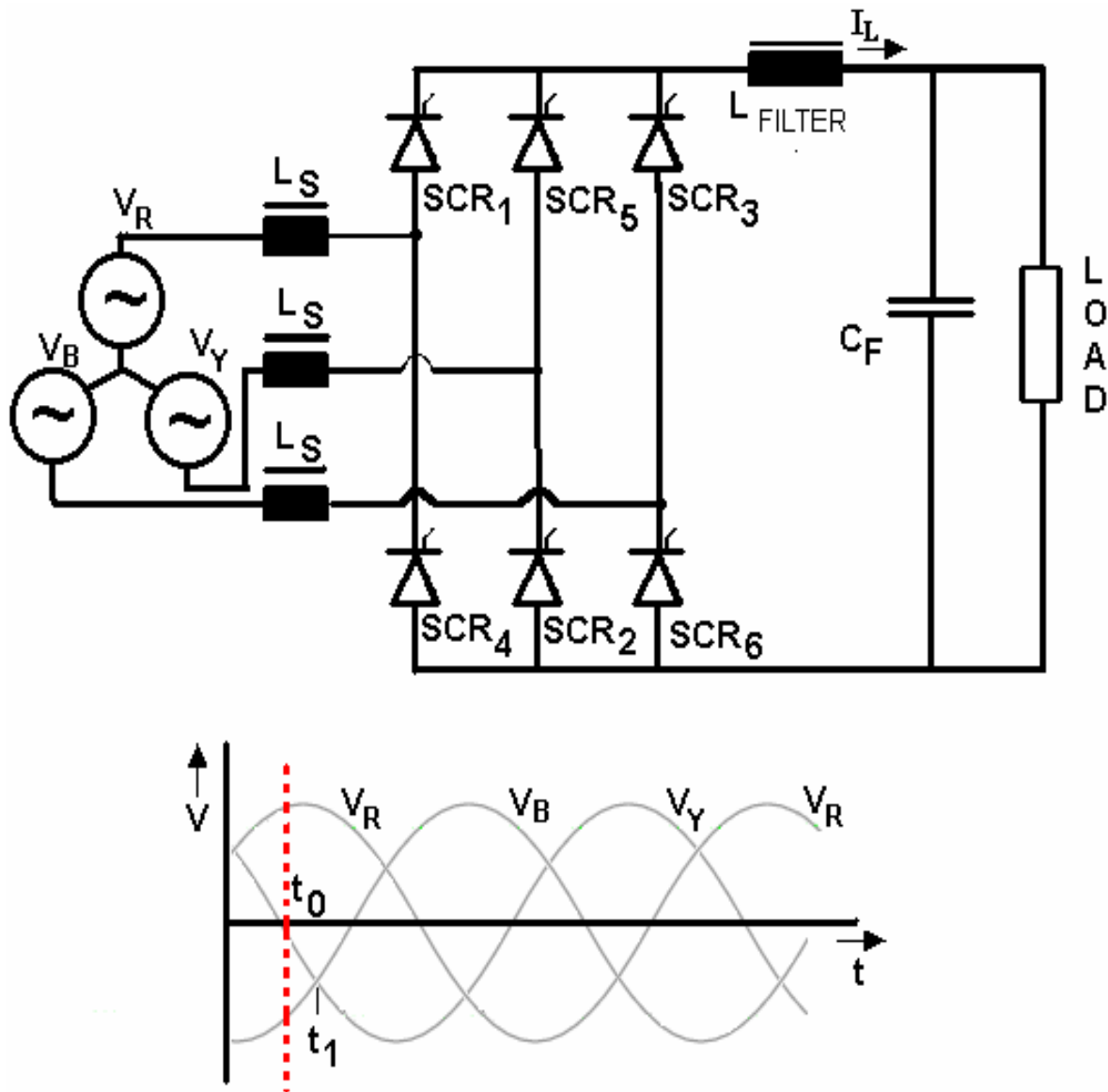


Fig. . : Current limit control

In this lesson, first one in this module (#3), the three basic circuits – buck, boost and buck-boost, of dc-dc converters (choppers) are presented, along with the operation and the derivation of the expressions for the output voltage in each case, assuming continuous conduction. The different strategies employed for their control are discussed. In the next lesson – second one, the expression for the maximum and currents for continuous conduction in buck dc-dc converter will be derived

commutation process

The commutation process plays an important role in the operation and control of both naturally commutated (or line commutated) and forced commutated SCR based converters. These converters may be either AC-DC, DC-DC or DC-AC converters. The AC-DC Phase



**Fig Top: A three-phase Phase Angle Converter;
bottom: The input three-phase voltage waveforms**

Angle Converter, (PAC) continues to be used in much high power and very high power converters where the application is non-critical or the non-state-of-the-art is preferred for operational advantages. The following section discusses commutation with respect to this application,

Voltage Commutation

In a voltage commutated thyristor circuit a voltage source is impressed across the SCR to be turned off, mostly by an auxiliary SCR. This voltage is comparable in magnitude to the operating voltages. The current in the conducting SCR is immediately quenched, however the reverse-biasing voltage must be maintained for a period greater than that required for the device to turn-off. With a large reverse voltage turning it off, the device offers the fastest turn-off time obtainable from that particular device. It is an exposition of 'hard' turn-off where the reverse biasing stress is maximum.

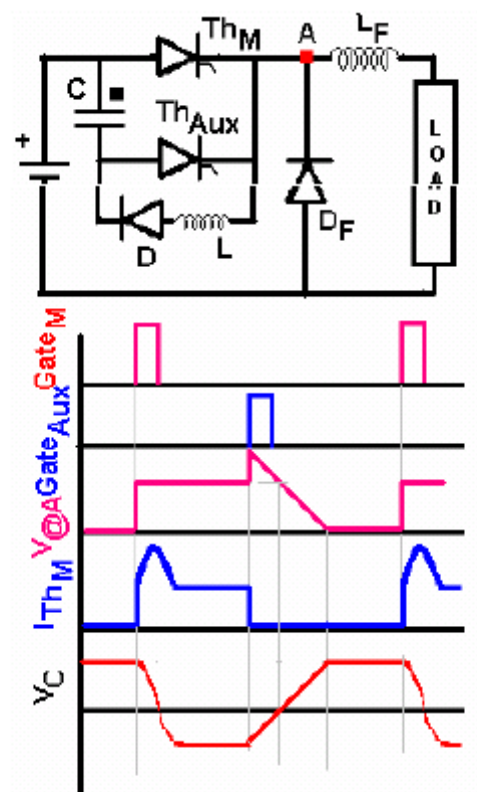


Fig. A voltage commutated DC-DC Chopper and most significant waveforms

Fig. illustrates voltage commutation. Th_M is the main SCR and Th_{Aux} is the Auxiliary. As a consequence of the previous cycle, Capacitor C is charged with the dot as positive. When the Main SCR is triggered, it carries the load current, which is held practically level by the large filter inductance, L_F and the Free-wheeling diode. Additionally, the charged Capacitor swings half a cycle through Th_M , L and D ending with a negative at the dot. The reverse voltage may be less than its positive value as some energy is lost in the various components in the path. The half cycle capacitor current adds to the load current and is taken by the Main SCR.

With the negative at the dot C- $T_{h_{Aux}}$ is enabled to commutate T_{h_M} . When $T_{h_{Aux}}$ is triggered the negative charge of the capacitor is impressed onto T_{h_M} and it immediately turns off. The SCR does take the reverse recovery current in the process. Thereafter, the level load current charges the capacitor linearly to the supply voltage with the dot again as positive.

The Load voltage peaks by the addition of the capacitor voltage to the supply when $T_{h_{Aux}}$ is triggered. The voltage falls as the capacitor discharges both changes being linear because of the level load current. When the Capacitor voltage returns to zero, the load voltage equals supply voltage. The turn-off time offered by the commutation circuit to the SCR lasts till this stage starting from the triggering of $T_{h_{Aux}}$. Now the capacitor is progressively positively charged and the load voltage is equally diminished from the supply voltage. $T_{h_{Aux}}$ is naturally commutated when the capacitor is fully charged and a small excess voltage switches on the free wheeling diode. With the positive at the dot the capacitor is again ready for the next cycle. Here $T_{h_{Aux}}$ must be switched before T_{h_M} to charge C to desired polarity.

Voltage commutation may be chosen for comparatively fast switching and it can be identified from the steep fall of the SCR current. There is no overlapping operation between the incoming and the outgoing devices and both currents fall and rise sharply. Stresses on all the three semiconductors can be expected to be high here.

Current commutation

The circuit of Fig.can be converted into a current commuted one just by interchanging the positions of the diode and the capacitor. Here the Capacitor is automatically charged through D-L- L_F -Load with the dot as positive. Any of the SCRs can thus be switched on first.

If T_{h_M} is triggered first, it immediately takes the load current turning off D_F . When $T_{h_{Aux}}$ is triggered, it takes a half cycle of the ringing current in the L-C circuit and the polarity of the charge across the capacitor reverses. As it swings back, $T_{h_{Aux}}$ is turned off and the path through D-C-L shares the load current which may again be considered to be reasonably level. The Current-share of T_{h_M} is thus reduced in a sinusoidal (damped) manner. Turn-off process is consequently accompanied by an overlap between T_{h_M} and the diode D in the D-C-L path. Once the main SCR is turned off, the capacitor current becomes level and the voltage decreases linearly. A voltage spike appears across the load when the voltage across the commutating inductance collapses and the capacitance voltage adds to the supply voltage.

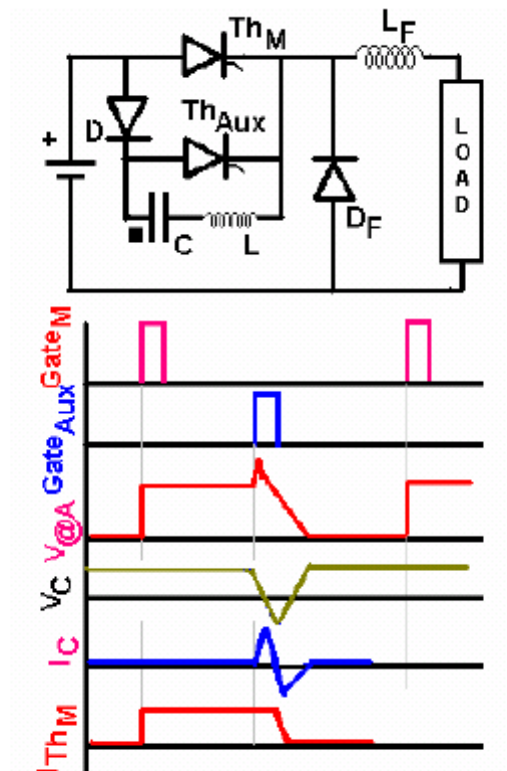


Fig. A current commutated DC-DC Chopper and most significant waveforms

The free-wheeling diode also turns on through a overlap with D when the capacitor voltage just exceeds the supply voltage and this extra voltage drives the commutating current through the path D -Supply- D_F - L . Thus there is soft switching of all devices during this period. Further an additional diode may be connected across the main SCR. It ensures 'soft' turn-off by conducting the excess current in the ringing L - C circuit. The low forward voltage appearing across the SCR causes it to turn-off slowly. Consequently switching frequencies have to be low.

Load Commutation

The circuit in Fig is called a load-commutated chopper. Conduction paths are alternately through the diagonal SCR pairs. Conduction patterns of these two groups are symmetrical. Each pair of SCRs conduct with the capacitor in series. The current thus automatically is extinguished when the capacitor achieves supply voltage level and the free-wheeling diode is turned on. Any value of capacitor will suffice for commutation. In fact it is chosen to satisfy the load current requirement. This commutation method permits fastest switching of the SCRs. Currents through the SCRs rise and fall sharply without any inductance regulating it .

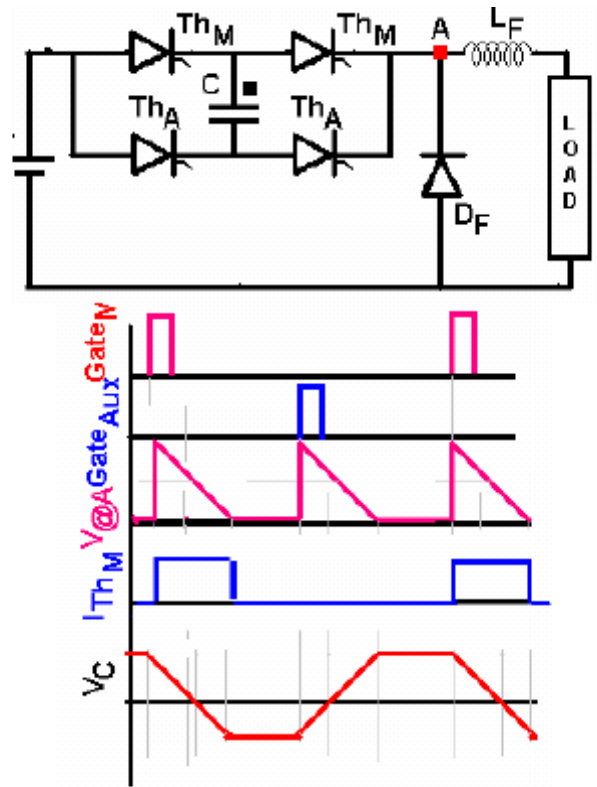


Fig. A load-commutated DC-DC Chopper and most significant waveforms

The free wheeling diode current also behaves similarly and all devices are stressed by sharp di/dt. The load voltage is of triangular shape with a peak equal to double the supply voltage (average equal to supply voltage for the conduction interval). The capacitor has a symmetric trapezoidal voltage across itself.

Classification of forced commutation methods

The six distinct classes by which the SCR can be turned off are:

Class A Self commutated by a resonating load

Class B Self commutated by an L-C circuit

Class C C or L-C switched by another load carrying SCR

Class D C or L-C switched by an auxiliary SCR

Class E An external pulse source for commutation

Class F AC line commutation

These examples show the classes as choppers. The commutation classes may be used in practice in configurations other than choppers.

Class A, Self commutated by resonating the load

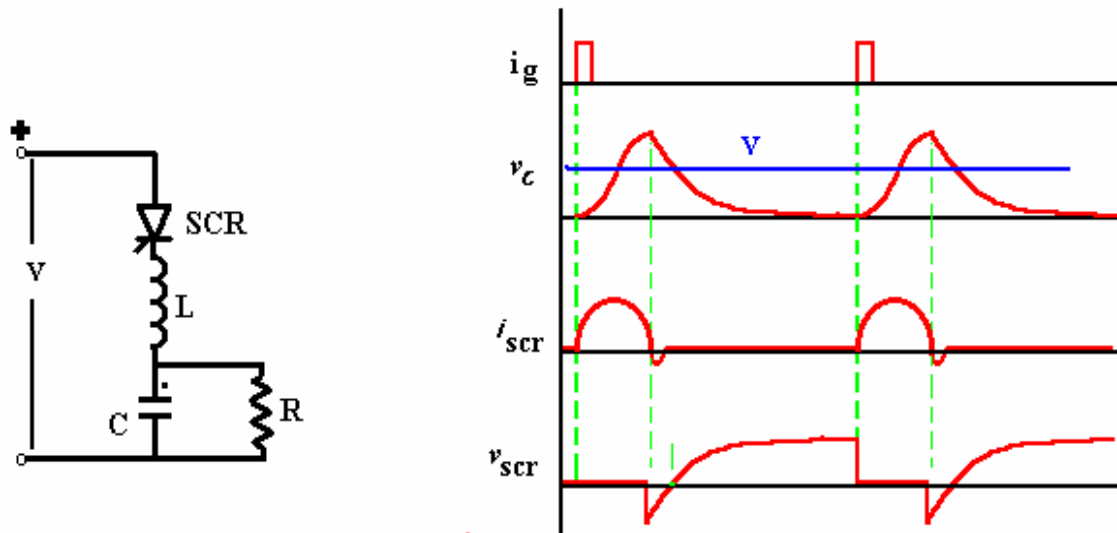


Fig.A resonant load commutated SCR and the corresponding waveforms

When the SCR is triggered, anode current flows and charges up C with the dot as positive. The L-C-R form a second order under-damped circuit. The current through the SCR builds up and completes a half cycle. The inductor current will then attempt to flow through the SCR in the reverse direction and the SCR will be turned off.

The current may be expressed as

$$I(s) = V \frac{1}{s(Ls + \frac{R}{1+RCs})} = V \frac{1+RCs}{LRCs^3 + Ls^2 + Rs}$$

The solution of the above equation is of the form

$$i(t) = \frac{V}{R} \left[1 + \frac{1}{\sqrt{1-\xi^2}} \frac{\omega_n^2}{\xi} e^{-\eta RC} \sin(\omega t + \phi) \right]$$

where,

$$\xi = \frac{1}{2R} \sqrt{\frac{L}{C}}, \quad \omega_n = \sqrt{\frac{L}{C}}, \quad \omega = \omega_n \sqrt{1-\xi^2}, \quad \phi = \tan^{-1} 2RC\omega$$

and

$$v(t) = V \left[\frac{\omega_n^2}{\sqrt{1-\xi^2}} e^{-\eta 2RC} \sin(\omega t) + 1 \right]$$

The capacitor voltage is at its peak when the SCR turns off and the capacitor discharges into the resistance in an exponential manner. The SCR is reverse-biased till the capacitor voltage returns to the level of the supply voltage V .

Class B, Self commutated by an L-C circuit

The Capacitor C charges up in the dot as positive before a gate pulse is applied to the SCR. When SCR is triggered, the resulting current has two components.

The constant load current I_{load} flows through R - L load. This is ensured by the large reactance in series with the load and the freewheeling diode clamping it. A sinusoidal current flows through the resonant L-C circuit to charge-up C with the dot as negative at the end of the half cycle. This current will then reverse and flow through the SCR in opposition to the load current for a small fraction of the negative swing till the total current through the SCR becomes zero. The SCR will turn off when the resonant-circuit (reverse) current is just greater than the load current.

The SCR is turned off if the SCR remains reversed biased for $t_q > t_{off}$, and the rate of rise of the reapplied voltage $<$ the rated value.

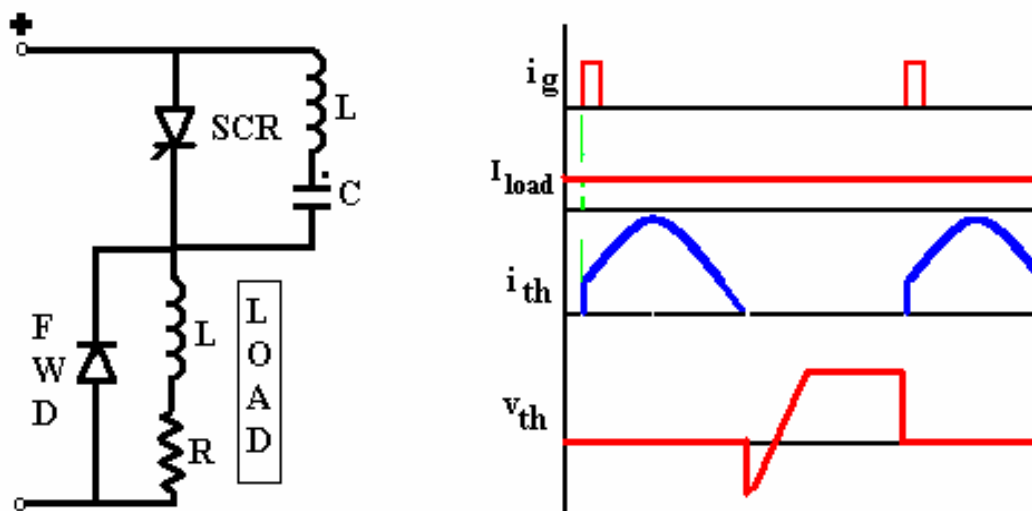


Fig Class B, L-C turn-off

Class C, C or L-C switched by another load-carrying SCR

This configuration has two SCRs. One of them may be the main SCR and the other auxiliary. Both may be load current carrying main SCRs. The configuration may have four SCRs with the load across the capacitor, with the integral converter supplied from a current source. Assume SCR_2 is conducting. C then charges up in the polarity shown. When SCR_1 is triggered, C is switched across SCR_2 via SCR_1 and the discharge current of C opposes the flow of load current in SCR_2 .

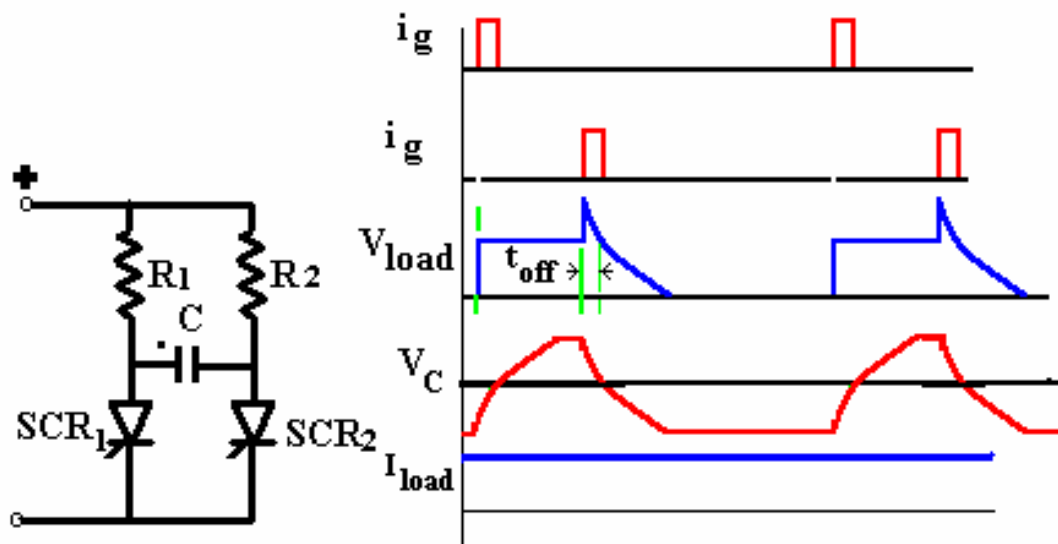


Fig. Class C turn-off, SCR switched off by another load-carrying SCR

Class D, L-C or C switched by an auxiliary SCR

The circuit shown in Figure (Class C) can be converted to Class D if the load current is carried by only one of the SCR's, the other acting as an auxiliary turn-off SCR. The auxiliary SCR would have a resistor in its anode lead of say ten times the load resistance.

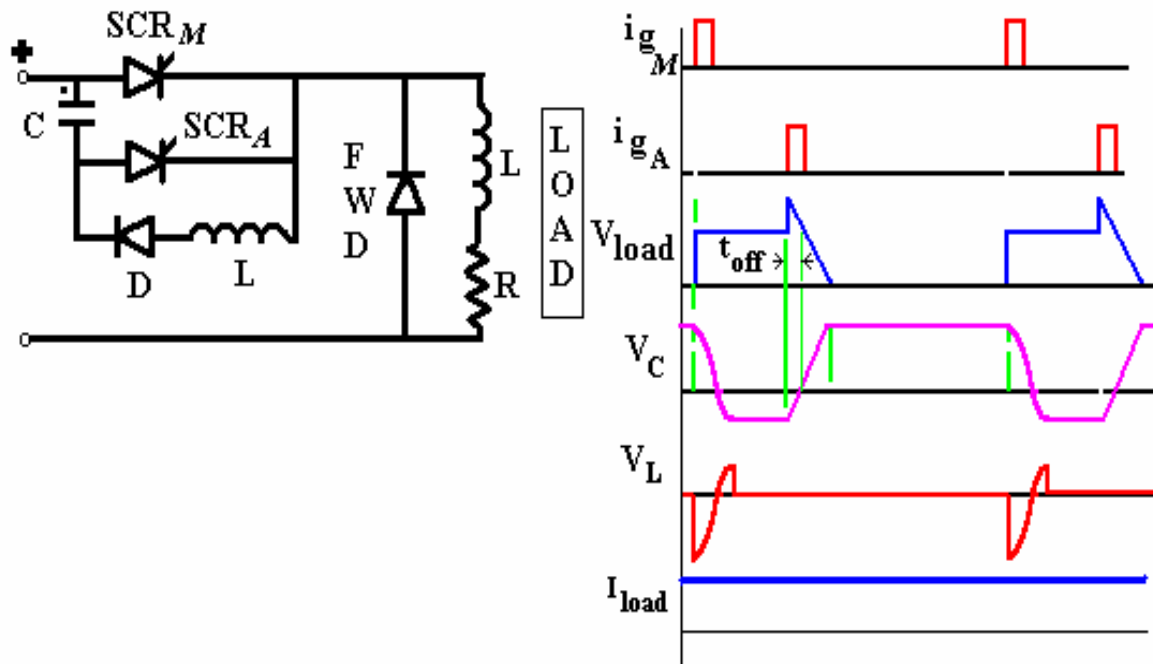


Fig. Class D turn-off. Class D commutation by a C (or LC) switched by an Auxiliary SCR.

SCR_A must be triggered first in order to charge the upper terminal of the capacitor as positive. As soon as C is charged to the supply voltage, SCR_A will turn off. If there is substantial inductance in the input lines, the capacitor may charge to voltages in excess of the supply voltage. This extra voltage would discharge through the diode-inductor-load circuit.

When SCR_M is triggered the current flows in two paths: Load current flows through the load and the commutating current flows through C - SCR_M - L - D network. The charge on C is reversed and held at that level by the diode D . When SCR_A is re-triggered, the voltage across C appears across SCR_M via SCR_A and SCR_M is turned off. If the load carries a constant current as in Fig., the capacitor again charges linearly to the dot as positive.

Class E – External pulse source for commutation

The transformer is designed with sufficient iron and air gap so as not to saturate. It is capable of carrying the load current with a small voltage drop compared with the supply voltage.

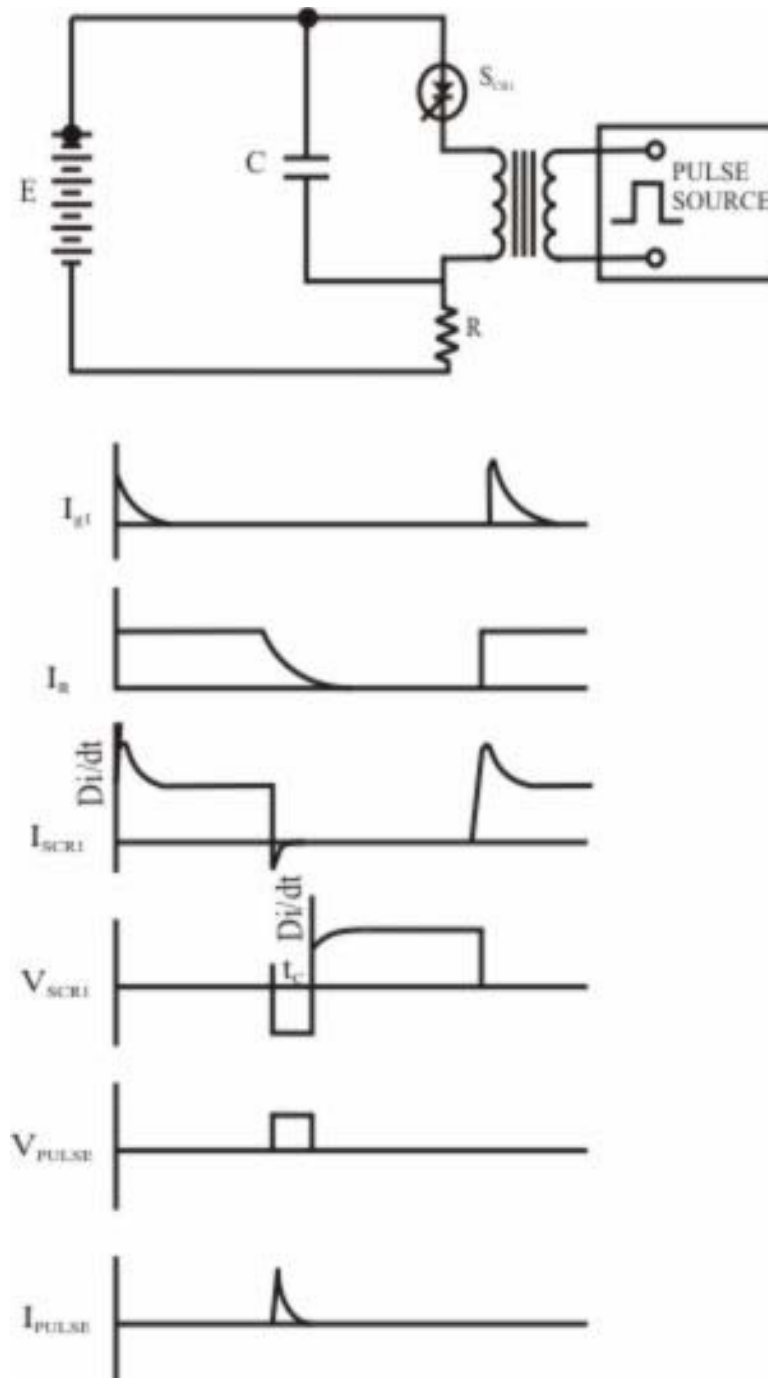


Figure Class E Commutation (Example 2)

When SCR1 is triggered, current flows through the load and pulse transformer. To turn SCR₁ off a positive pulse is applied to the cathode of the SCR from an external pulse generator via the pulse transformer. The capacitor C is only charged to about 1 volt and for the duration of the turn-off pulse it can be considered to have zero impedance. Thus the pulse from the transformer reverses the voltage across the SCR, and it supplies the reverse recovery current and holds the voltage negative for the required turn-off time.

Class F, AC line commutated

If the supply is an alternating voltage, load current will flow during the positive half cycle. With a highly inductive load, the current may remain continuous for some time till the

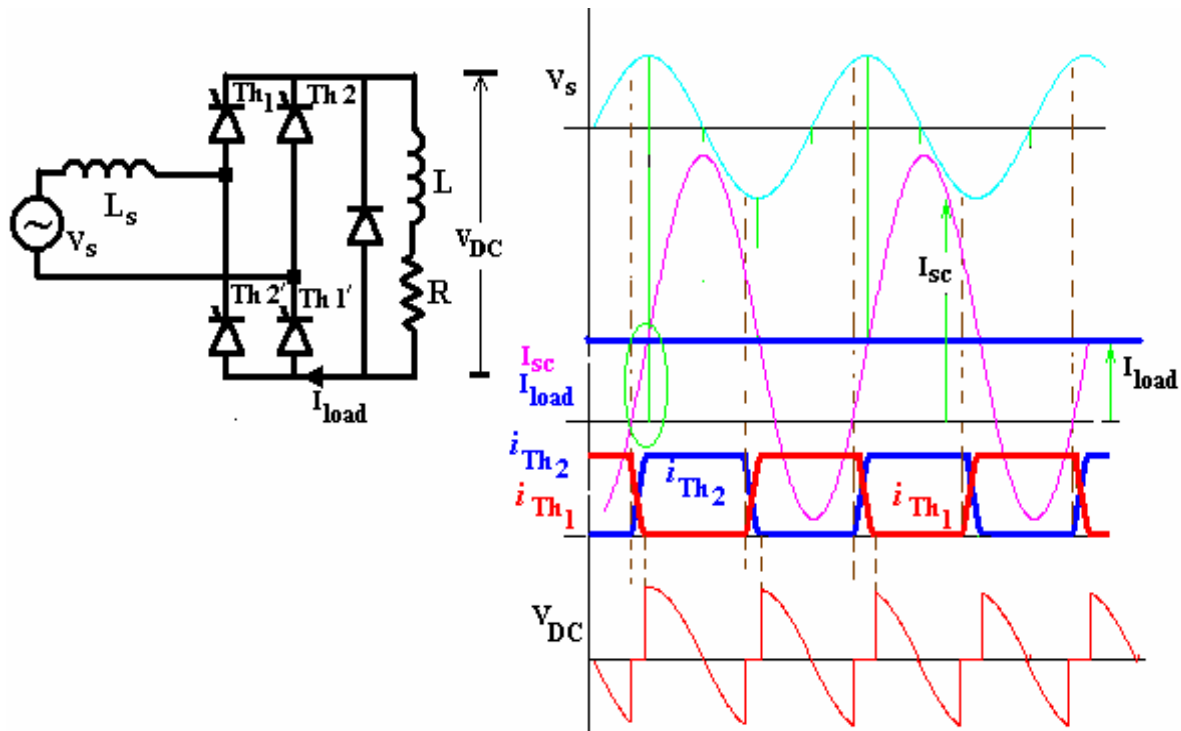


Fig. Class F, natural commutation by supply voltage

energy trapped in the load inductance is dissipated. During the negative half cycle, therefore, the SCR will turn off when the load current becomes zero 'naturally'. The negative polarity of the voltage appearing across the outgoing SCR turns it off if the voltage persists for the rated turn-off period of the device. The duration of the half cycle must be definitely longer than the turn-off time of the SCR.

The rectifier in Fig is supplied from an single phase AC supply. The commutation process involved here is representative of that in a three phase converter. The converter has an input inductance L_s arising mainly out of the leakage reactance of the supply transformer. Initially, SCRs Th_1 and Th_1 , are considered to be conducting. The triggering angle for the converter is around 60^0 . The converter is operating in the continuous conduction mode aided by the highly-inductive load.

When the incoming SCRs, Th_2 and Th_2 , are triggered, the current through the incoming devices cannot rise instantaneously to the load current level. A circulating current I_{sc} builds up in the short-circuited path including the supply voltage, V_s - L_s - Th_1 ,- Th_2 and V_s - L_s - Th_2 ,- Th_1 paths. This current can be described by:

$$I_{sc} = \frac{V_s \sin(\omega t - 90^0)}{\omega L_s} + \frac{V_s}{\omega L_s} \cos \alpha = \frac{V_s \cos(\omega t)}{\omega L_s} + \frac{V_s}{\omega L_s} \cos \alpha$$

where α the triggering angle and I_{sc} and V_s as shown in Fig.

This expression is obtained with the simplifying assumption that the input inductance contains no resistances. When the current rises in the incoming SCRs, which in the outgoing ones fall such that the total current remains constant at the load current level. When the current in the incoming ones reach load current level, the turn-off process of the outgoing ones is initiated. The reverse biasing voltage of these SCRs must continue till they reach their forward blocking state. As is evident from the above expression, the overlap period is a function of the triggering angle. It is lowest when $\alpha \sim 90^0$. These SCRs being 'Converter grade', they have a larger turn-off time requirement of about 30-50 μ secs.

The period when both the devices conduct is known as the 'overlap period'. Since all SCRs are in conduction, the output voltage for this period is zero. If the 'fully-controlled' converter in Fig. is used as an inverter with triggering angles $> 90^0$, the converter triggering can be delayed till the 'margin angle' which includes the overlap angle and the turn-off time of the SCR - both dependent on the supply voltages.

Introduction to regulated dc power supplies

Power supply is a broad term but this lesson is restricted to discussion of circuits that generate a fixed or controllable magnitude dc voltage from the available form of input voltage. Integrated-circuit (IC) chips used in the electronic circuits need standard dc voltage of fixed magnitude. Many of these circuits need well-regulated dc supply for their proper operation. In majority of the cases the required voltages are of magnitudes varying between -18 to +18 volts. Some equipment may need **multiple output power supplies**. For example, in a Personal Computer one may need 3.3 volt, ± 5 volt and ± 12 volt power supplies. The digital ICs may need 3.3volt supply and the hard disk driver or the floppy driver may need ± 5 and ± 12 volts supplies. The individual output voltages from the multiple output power supply may have different current ratings and different voltage regulation requirements. Almost invariably these outputs are **isolated dc voltages** where the dc output is ohmically isolated from the input supply. In case of multiple output supplies ohmic isolation between two or more outputs may be desired. The input connection to these power supplies is often taken from the standard utility power plug point (ac voltage of 115V / 60Hz or 230V / 50Hz). It may not be unusual, though, to have a power supply working from any other voltage level which could be of either ac or dc type.

There are two broad categories of power supplies: **Linear regulated power supply** and **switched mode power supply (SMPS)**. In some cases one may use a combination of switched mode and linear power supplies to gain some desired advantages of both the types.

Linear regulated power supply

shows the basic block for a linear power supply operating from an unregulated dc input. This kind of unregulated dc voltage is most often derived from the utility ac source. The utility ac voltage is first stepped down using a utility frequency transformer, then it is rectified using diode rectifier and filtered by placing a capacitor across the rectifier output. The voltage across the capacitor is still fairly unregulated and is load dependent. The ripple in the capacitor voltage is not only dependent on the capacitance magnitude but also depends on load and supply voltage variations. The unregulated capacitor voltage becomes the input to the linear type power supply circuit. The filter capacitor size is chosen to optimize the overall cost and volume. However, unless the capacitor is sufficiently large the capacitor voltage may have unacceptably large ripple. The representative rectifier and capacitor voltage waveforms, where a 100 volts (peak), 50 Hz ac voltage is rectified and filtered using a capacitor of 1000 micro-farad and fed to a load of 100 ohms is shown in **Fig.** For proper operation of the voltage regulator, the instantaneous value of unregulated input voltage must always be few volts more than the desired regulated voltage at the output. Thus the ripple across the capacitor voltage (difference between the maximum and minimum instantaneous magnitudes) must not be large or else the minimum voltage level may fall below the required level for output voltage regulation. The magnitude of voltage-ripple across the input capacitor increases with increase in load connected at the output.

The step down transformer talked above should be chosen such that the peak value of rectified voltage is always larger than the sum of bare minimum voltage required at the input of the regulator and the worst-case ripple in the capacitor voltage. Thus the transformer turns ratio is chosen on the basis of minimum specified supply voltage magnitude. The end user of the power supply will like to have a regulated output voltage (with voltage ripple within some specified range) while the load and supply voltage fluctuations remain within the allowable limit. To achieve this the unregulated dc voltage is fed to a voltage regulator circuit. The circuit in Fig. shows, schematically, a linear regulator circuit where a transistor is placed in between the unregulated dc voltage and the desired regulated dc output. Difference between the instantaneous input voltage and the regulated output voltage is blocked across the collector - emitter terminals of the transistor.

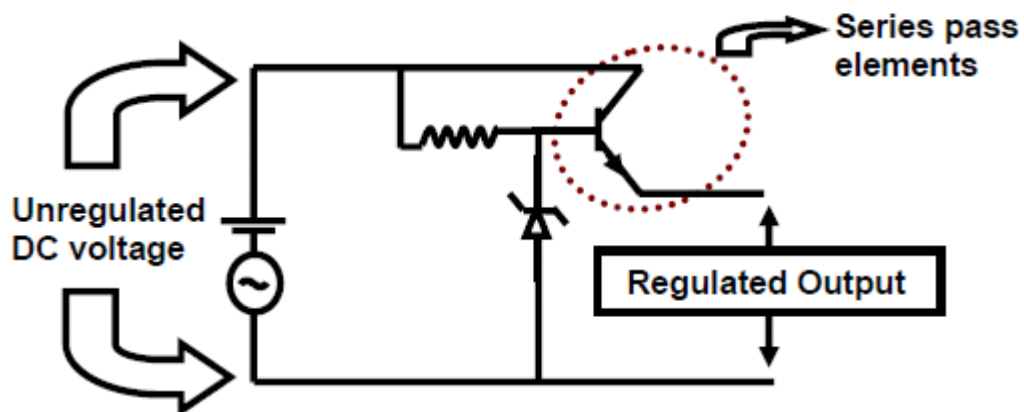


Fig. : Schematic linear voltage regulator

As discussed previously, in such circuits the lowest instantaneous magnitude of the unregulated dc voltage must be slightly greater than the desired output voltage (to allow some voltage for transistor biasing circuit). The power dissipation in the transistor and the useful output power will be in the ratio of voltage drops across the transistor and the load (here the control power dissipated in the base drive circuit of the transistor is assumed to be relatively small and is neglected). The worst-case series voltage drop across the transistor maybe quite large if the allowed variation in supply magnitude is large. Worst-case power dissipation in the transistor will correspond to maximum supply voltage and maximum load condition (load voltage is assumed to be well regulated). Efficiency of linear voltage regulator circuits will be quite low when supply voltage is on the higher side of the nominal voltage.

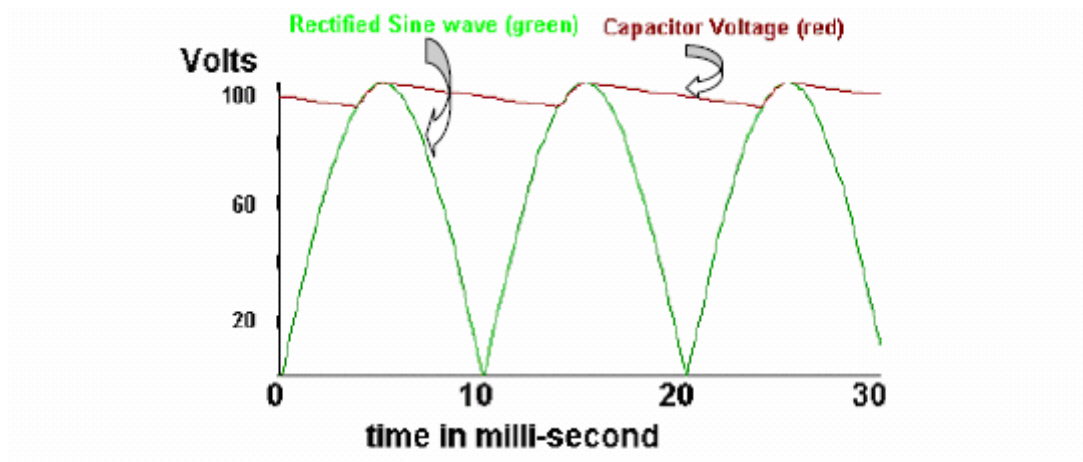


Fig. : Typical voltage output from rectifier-capacitor combination

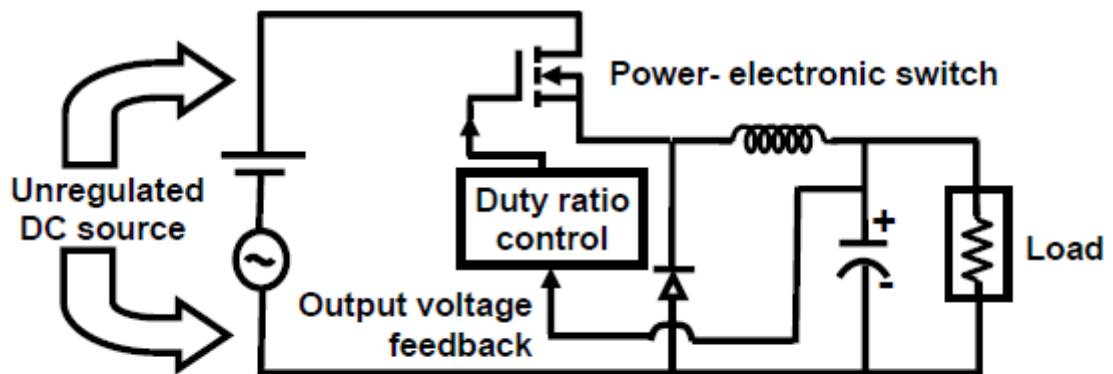


Fig. : A schematic switched mode dc to dc chopper circuit

Switched Mode Power Supply (SMPS)

Like a linear power supply, the switched mode power supply too converts the available unregulated ac or dc input voltage to a regulated dc output voltage. However in case of SMPS with input supply drawn from the ac mains, the input voltage is first rectified and filtered using a capacitor at the rectifier output. The unregulated dc voltage across the capacitor is then fed to a high frequency dc-to-dc converter. Most of the dc-to-dc converters used in SMPS circuits have an intermediate high frequency ac conversion stage to facilitate the use of a high frequency transformer for voltage scaling and isolation. In contrast, in linear power supplies with input voltage drawn from ac mains, the mains voltage is first stepped down (and isolated) to the desired magnitude using a mains frequency transformer, followed by rectification and filtering. The high frequency transformer used in a SMPS circuit is much smaller in size and weight compared to the low frequency transformer of the linear power supply circuit.

The 'Switched Mode Power Supply' owes its name to the dc-to-dc switching converter for conversion from unregulated dc input voltage to regulated dc output voltage. The switch employed is turned 'ON' and 'OFF' (referred as switching) at a high frequency. During 'ON' mode the switch is in saturation mode with negligible voltage drop across the collector and emitter terminals of the switch where as in 'OFF' mode the switch is in cut-off mode with negligible current through the collector and emitter terminals. On the contrary the voltage-regulating switch, in a linear regulator circuit, always remains in the active region.

Details of some popular SMPS circuits, with provisions for incorporating high frequency transformer for voltage scaling and isolation, have been discussed in next few lessons. In this lesson a simplified schematic switching arrangement is described that omits the transformer action. In fact there are several other switched mode dc-to-dc converter circuits that do not use a high frequency transformer. In such SMPS circuits the unregulated input dc voltage is fed to a high frequency voltage chopping circuit such that when the chopping circuit (often called **dc to dc chopper**) is in ON state, the unregulated voltage is applied to the output circuit that includes the load and some filtering circuit. When the chopper is in OFF state, zero magnitude of voltage is applied to the output side. The ON and OFF durations are suitably controlled such that the average dc voltage applied to the output circuit equals the desired magnitude of output voltage. The ratio of ON time to cycle time (ON + OFF time) is known as duty ratio of the chopper circuit. A high switching frequency (of the order of 100 KHz) and a fast control over the duty ratio results in application of the desired mean voltage along with ripple voltage of a very high frequency to the output side, consisting of a low pass filter circuit followed by the load.

Hybrid (SMPS followed by linear) power supply

A comparison of linear and switched mode power supplies tells about the advantages and disadvantages of the two. Linear power supply is highly inefficient if it has to work over large variations in input voltage, is more bulky because of the use of low frequency transformer and filter elements (inductors and capacitors). On the other hand linear power supplies give better output voltage regulation. It may sometimes be required to have output voltage regulation similar to the one provided by linear supplies and compactness and better efficiency of a switched mode supply. For this, the linear power supply may be put in tandem with a switched mode supply.

Let us consider a case where one needs an isolated and well-regulated 5 volts output while input power is drawn from utility supply that has large voltage fluctuation. In such a situation one may generate an isolated 7.5 volts from an SMPS and follow it by a 5 volts linear power supply set to work with 7.5 volts input. The input to linear power supply must be few volts more than the required output (for proper biasing of the switches) and hence SMPS tries to maintain around 7.5 volts input. It can be seen that the linear power supply now does not have large input voltage variation in spite of large variations in the utility rms voltage. The SMPS portion of the power supply efficiently performs the job of voltage isolation and conversion from widely varying utility voltage to fairly regulated 7.5 volts dc. Under the given condition it may not be difficult to see that the overall efficiency of this hybrid power supply will lie between that of a SMPS and a linear supply. The overall cost may or may not increase even though two supplies in tandem

are used. It is to be kept in mind that to achieve the same output voltage specification by an SMPS circuit alone, the control and filtering circuit may become more costly and complex (than the one used in the hybrid power supply unit). Similarly if the linear supply has to be designed for larger fluctuation in input voltage the component ratings, including heat-sink ratings, will be higher and may cost as much as the hybrid unit.

Multiple output SMPS

A single power supply unit may need to output several different voltages. The individual output voltages may have different ratings in terms of output current, voltage regulation and ripple voltages. These outputs may need isolation between them. Generally a common high frequency transformer links the input and output windings and in spite of output voltage feedback all the outputs can not have same regulation because of different loads connected to different outputs and hence different ohmic (resistive) drops in the output windings (loads are generally variable and user dependent). Also the coupling between the different secondary windings and the primary winding may not be same causing different voltage drops across the respective leakage inductances. Barring this mismatch in the voltage drops across the resistances and leakage inductances of the secondary windings their output voltages are in proportional to their turns ratios. The turns ratios are properly chosen to give fairly regulated individual output voltages (even if only one output voltage feedback is used for SMPS switch control). The output that needs to have tighter voltage regulation may be used for output voltage feedback. In case another output needs to have similarly tight regulation then that particular output may be passed through an additional linear regulator circuit as in the case of hybrid power supply circuit .

Resonant Mode Power Supplies

Resonant mode power supplies are a variation over SMPS circuits where the switching losses are significantly reduced by adapting zero-voltage or zero-current switching techniques. In non-resonant mode SMPS circuits the switches are subjected to hard switching (during hard-switching, both the voltage and current in the switch are of considerable magnitude resulting in large instantaneous switching power loss). Efficiency of resonant mode power supplies is generally higher than non-resonant mode supplies.

Power supply specifications

Power supplies may have several specifications to be met, including their voltage and current ratings. There may be short time ratings of higher magnitudes of current and continuous ratings of somewhat lower magnitudes. One needs to specify the tolerable limits on the ripple voltages, short-circuit protection level of current (if any) and the nature of output volt-current curve during over-current or short circuit (the output voltage magnitude should reduce or fold back towards zero, gradually, depending on the severity of over-current). The fuse requirement (if any) on the input and the output side may need to be specified. One needs to specify the type of input supply (whether ac or dc) or whether the power supply can work both from ac or dc input voltages.

Acceptable range of variation in input voltage magnitude, supply frequency (in case of ac input) are also to be specified. Efficiency, weight and volume are some other important specifications. Some applications require the electro-magnetic compatibility standards to be met. By electromagnetic compatibility it is meant that the level of EMI generation by power supply should be within tolerable limits and at the same time the power supply should have the ability to work satisfactorily in a limited noisy environment. It is quite common to have output voltage isolation and it is specified in terms of isolation breakdown voltage. In case of multiple power supplies it needs to be specified whether all the outputs need to be isolated or not and what should be the acceptable ripple voltage range for each.

In majority of the cases the available source of input power is the alternating type utility voltage of 50 or 60 Hz. The voltage levels commonly used are 115V (common in countries like, USA) and 230 volts (common in India and many of the European countries). Most utility (mains) power supplies are expected to have $\pm 10\%$ voltage regulation but for additional precaution the SMPS circuits must work even if input voltages have $\pm 20\%$ variation. Now-a-days universal power supplies that work satisfactorily and efficiently both on 115 V and 230 V input are quite popular. These power supplies are very convenient for international travelers who can simply plug-on their equipments, like laptop computer and shaving machine, without having to pay much attention on the exact voltage and frequency levels of the utility supply. In contrast some of the other power supplies have a selector switch and the user is required to adjust the switch position to match the utility voltage. In case user forgets to keep the selector switch at correct position, the equipment attached may get damaged.

frequency ripple in voltage is effectively filtered using small values of filter capacitors and inductors. A schematic chopper circuit along with the output filter is shown in **Fig.21.3**. Some other switched mode power supply circuits work in a slightly different manner than the dc-to-dc chopper circuit discussed above. Details of some of these circuits have been discussed in following lessons.

SMPS versus linear power supply

As discussed above, in a linear regulator circuit the excess voltage from the unregulated dc input supply drops across a series element (and hence there is power loss in proportion to this voltage drop) whereas in switched mode circuit the unregulated portion of the voltage is removed by modulating the switch duty ratio. The switching losses in modern switches (like: MOSFETs) are much less compared to the loss in the linear element.

In most of the switched mode power supplies it is possible to insert a high frequency transformer to isolate the output and to scale the output voltage magnitude. In linear power supply the isolation and voltage-scaling transformer can be put only across the low frequency utility supply. The low frequency transformer is very heavy and bulky in comparison to the high frequency transformer of similar VA rating. Similarly the output voltage filtering circuit, in case of low frequency ripples is much bulkier than if the ripple is of high frequency. The switched mode circuit produces ripple of high frequency that can be filtered easily using smaller volume of filtering elements.

Linear power supply though more bulky and less efficient has some advantages too when compared with the switched mode power supply. Generally the control of the linear power supply circuit is much simpler than that of SMPS circuit. Since there is no high frequency switching, the switching related electro-magnetic interference (EMI) is practically absent in linear power supplies but is of some concern in SMPS circuits. Also, as far as output voltage regulation is concerned the linear power supplies are superior to SMPS. One can more easily meet tighter specifications on output voltage ripples by using linear power supplies.