

Module 3

DC to DC Converters

Lesson

17

Types of Basic DC-DC Converters

Instructional Objectives

Study of the following:

- Three basic types of dc-dc converter circuits – buck, boost and buck-boost
- The expressions for the output voltage in the above circuits, with inductive (R-L) and battery (or back emf = E) load

Introduction

In the last module (#2) consisting of eight lessons, the various types of circuits used in both single-phase and three-phase ac-dc converters, were discussed in detail. This includes half-wave and full-wave, and also half-controlled and full-controlled ones.

In this lesson – the first one in this module (#3), firstly, three basic types of dc-dc converter circuits – buck, boost and buck-boost, are presented. Then, the expressions for the output voltage in the above circuits, with inductive (R-L) and battery (or back emf = E), i.e., R-L-E, load, are derived, assuming continuous conduction. The different control strategies employed are briefly described.

Keywords: DC-DC converter circuits, Thyristor choppers, Buck, boost and buck-boost converters (dc-dc), Step-down (buck) and step-up (boost) choppers, Output voltage and current.

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. 17.1a. 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.

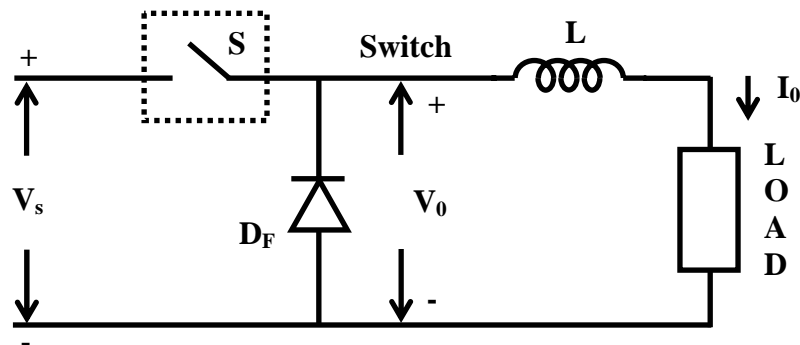


Fig. 17.1(a): Buck converter (dc-dc)

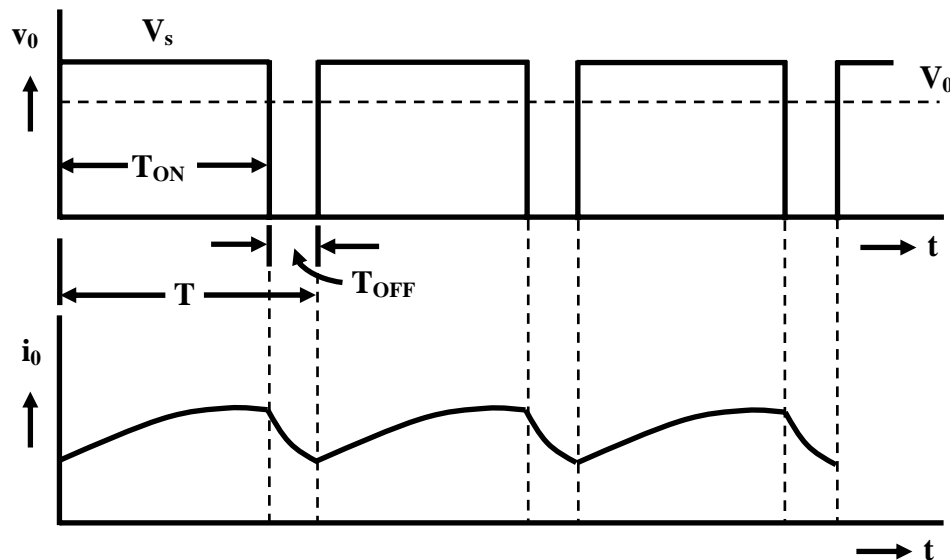


Fig. 17.1(b): Output voltage and current waveforms

The output voltage and current waveforms of the circuit (Fig. 17.1a) are shown in Fig. 17.1b. 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,

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

The duty ratio is $k = (T_{ON} / T) = [T_{ON} / (T_{ON} + T_{OFF})]$, its range being $1.0 \geq k \geq 0.0$. 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. 17.1b. 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. 17.2a. 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. 17.1a).

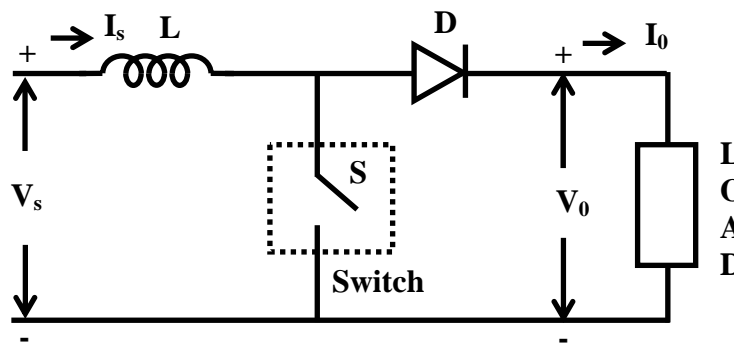


Fig. 17.2(a): Boost converter (dc-dc)

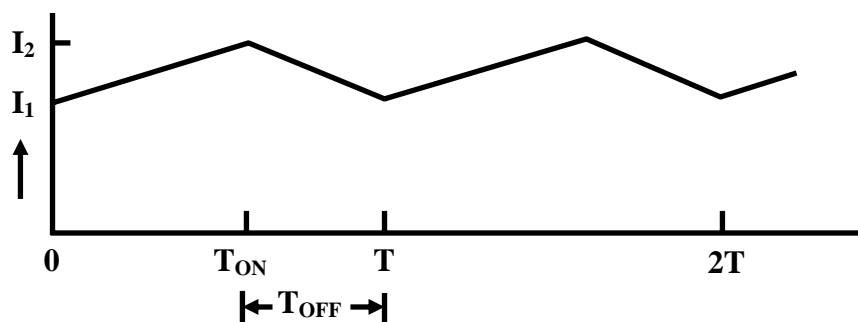


Fig. 17.2(b): Waveforms of source current (i_s)

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,

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

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.

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.

Buck-Boost Converters (dc-dc)

A buck-boost converter (dc-dc) is shown in Fig. 17.3. 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. 17.2a). 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,

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

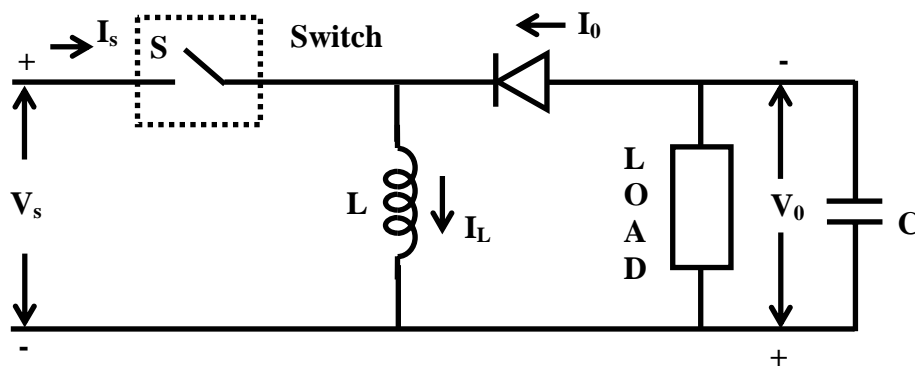


Fig. 17.3(a): Buck-boost converter (dc-dc)

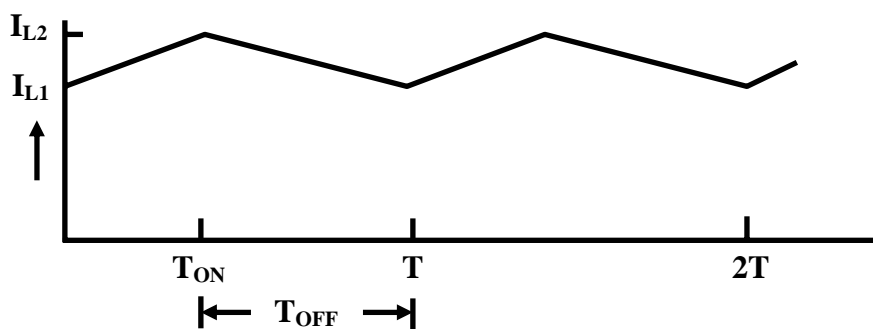


Fig. 17.3(b): Inductor current (i_L) waveform

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, $k = T_{ON} / T$ 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 ($f = 1/T$), or time period T constant. This is also called as *pulse width modulation control* (PWM). Two cases with duty ratios, k as (a) 0.25 (25%), and (b) 0.75 (75%) are shown in Fig. 17.4. Hence, the output voltage can be varied by varying ON time, T_{ON} .

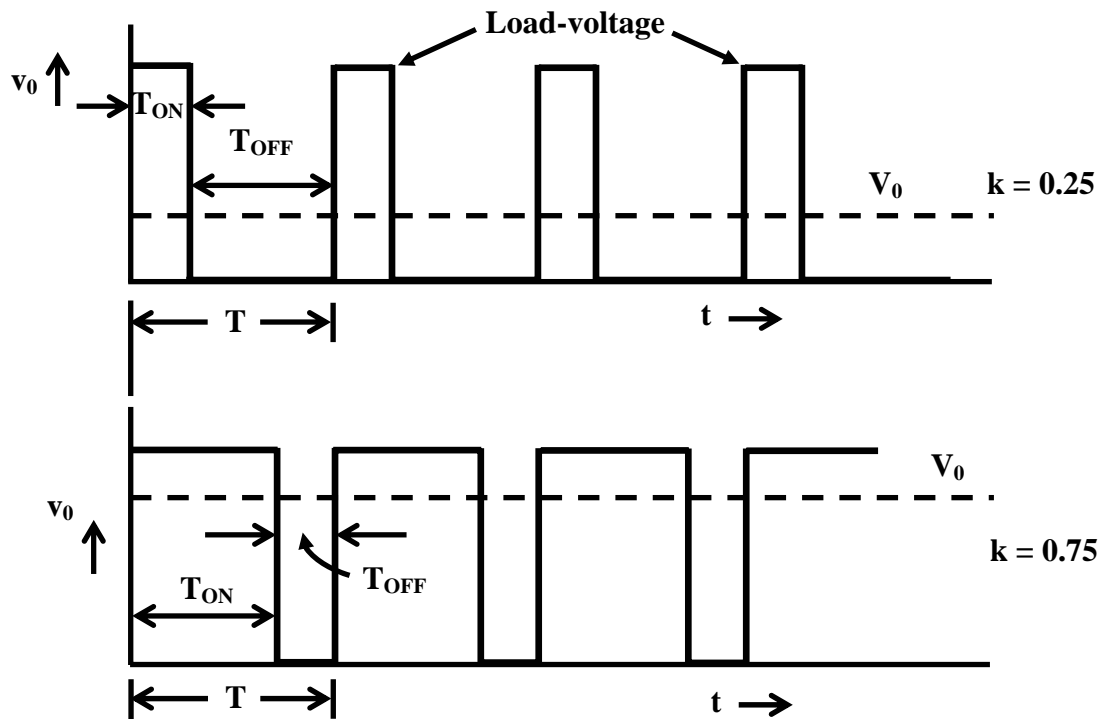


Fig. 17.4: Pulse-width modulation control (constant frequency)

Variable Frequency Operation

In this control strategy, the frequency ($f = 1/T$), or time period T is varied, keeping either (a) the ON time, T_{ON} constant, or (b) the OFF time, T_{OFF} constant. This is also called as *frequency modulation control*. Two cases with (a) the ON time, T_{ON} constant, and (b) the OFF time, T_{OFF} constant, with variable frequency or time period (T), are shown in Fig. 17.5. The output voltage can be varied in both cases, with the change in duty ratio, $k = T_{ON}/T$.

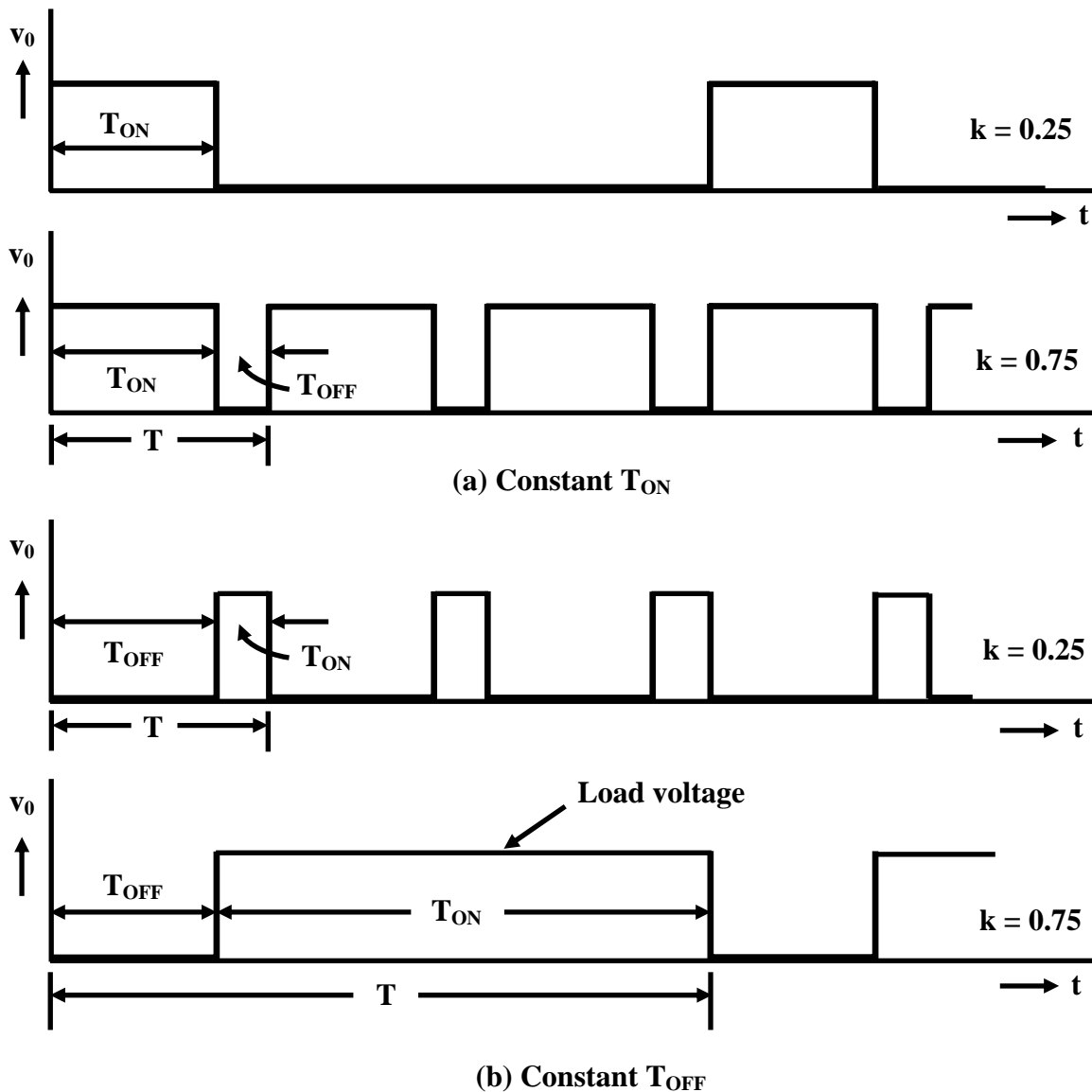


Fig. 17.5: Output voltage waveforms for variable frequency system

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 (choppers).

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 exceed upper (maximum) limit, the switch is turned OFF. During OFF period, the current freewheels in say, buck converter (dc-dc) through the diode, D_F , 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, T_{ON} . 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. 17.6. In this case, the current is continuous, varying between I_{max} and I_{min} , 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.

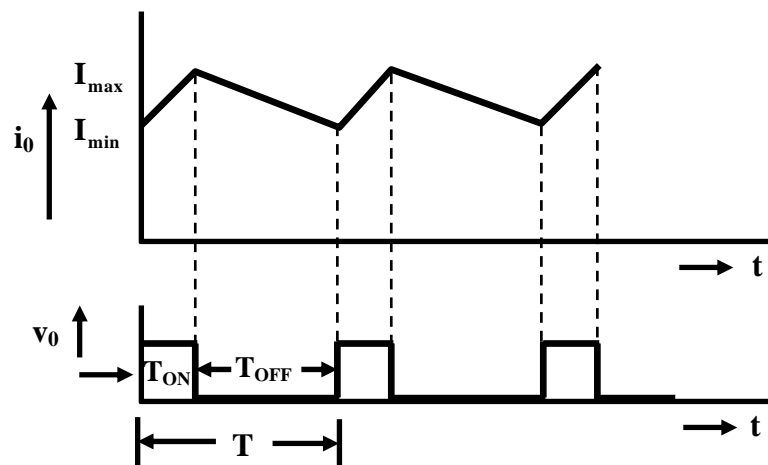


Fig. 17.6: Current limit control

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.