CHAPTER 3

SWITCHED CONVERTER TOPOLOGIES OVERVIEW

3.1 INTRODUCTION

Switching regulators are preferred over linear regulators for their high efficiency and providing step up, step down or inverter output unlike linear regulator which does only step down operation. In practice, the conversion efficiency of linear regulators is limited to only 30% and they find application in analog circuits to ensure nearly constant supply voltage providing high power supply rejection ratio (PSRR).

In switching regulator circuits, semiconductor switches control the dynamic transfer of power from input to output with very short transition times. Because of this switching action there is ripple added to output voltage. The output requirement is a dc voltage with a minimum superimposition of ac ripple. Pulse width modulation (PWM) is the most widely used method for controlling the output voltage. It maintains a constant switching frequency and varies the duty cycle. Duty cycle is defined as the ratio of switch on time to reciprocal of the switching frequency \( f_s \). Since the switching frequency is fixed, this modulation scheme has a relatively narrow noise spectrum allowing a simple low pass filter to sharply reduce peak-to-peak ripple at output voltage. This requirement is achieved by arranging an inductor and capacitor in the converter in such a manner as to form a low pass filter network. This
requires the frequency of low pass filter to be much less than switching frequency (f_s).

The following section discusses various converter topologies and their operation. Idealized circuits are considered for ease of understanding and explanation. The key difference between each is the arrangement of the switch and output filter inductor and capacitor.

### 3.2 BUCK CONVERTER

The buck converter is used for step down operation. A buck converter with its output filter arrangement is as shown in figure 3.1

![Figure 3.1 Buck Converter.](image)

When the transistor Q1 is on and Q2 is off, the input voltage appears across the inductor and current in inductor increases linearly. In the same cycle the capacitor is charged. When the transistor Q2 is on and Q1 is off, the voltage across the inductor is reversed. However, current in the inductor cannot change instantaneously and the current starts decreasing linearly. In this cycle also the capacitor is also charged with the energy stored in the inductor.

There is the possibility of two modes of operation namely
continuous and discontinuous mode. In continuous mode, the inductor current never reaches zero and in discontinuous mode the inductor current reaches zero in one switching cycle. At lighter load currents the converter operates in discontinuous mode. The regulated output voltage in discontinuous mode no longer has a linear relationship with the input voltage as in continuous conduction mode operation.

### 3.2.1 SYNCHRONOUS RECTIFICATION

The transistor Q2 is used instead of a diode for higher efficiency. This is synchronous rectification. The forward voltage drop across a diode during the second cycle is appreciable and reduces the converter efficiency. To the contrary in a well-designed circuit transistor voltage is much less than the forward diode voltages drop. However, synchronous rectification requires non-overlap logic to avoid supply shunt currents which results when both transistors are on.

### 3.2.2 INDUCTOR VOLT-SECOND BALANCE

Analyzing the inductor current waveform determines the relationship between output and input voltage in terms of duty cycle. In a well-designed converter, the main objective is to have small percentage of ripple at the output. As a result, the output voltage can be approximated by its DC component. Inductor current is found by integrating the inductor voltage waveform. Inductor voltage and current waveforms for a buck converter are as shown in figure 3.2.
In steady state, the observation over one switching period the net change in inductor current is zero is the principle of inductor volt second balance. The inductor voltage definition is given by equation 3.1;

$$V_L(t) = L \frac{di_L(t)}{dt}$$  \hspace{1cm} (3.1)

Integration over one complete switching period yields,

$$i_L(T_{sw}) - i_L(0) = \frac{1}{L} \int_{0}^{T_{sw}} V_L(t) dt$$  \hspace{1cm} (3.2)

The left hand side of above equation is zero. As a result 3.2 can be written as in the form of equation 3.3;
\[
\int_{0}^{T_{sw}} V_L(t) \, dt = 0 
\]  \quad (3.3)

The equation 3.3 has the unit of volt-seconds or flux-linkages. Alternatively, total area under the \(v_L(t)\) waveform over one switching period must be zero. Area under the \(v_L(t)\) curve is given by equation 3.4;

\[
A = \int_{0}^{T_{sw}} V_L(t) \, dt = (V_G - V_0)(D T_{sw}) + (-V_0)(D' T_{sw})
\]  \quad (3.4)

Average value of inductor voltage is given by equation 3.5;

\[
\langle V_L \rangle = \frac{A}{T_{sw}} = D(V_G - V_0) + D'(-V_0)
\]  \quad (3.5)

By equating \(\langle v_L \rangle\) to zero and using relation \(d + d' = 1\), and solving for \(V_{OUT}\) yields equation 3.6;

\[
V_0 = D \cdot V_G
\]  \quad (3.6)

### 3.2.3 CAPACITOR CHARGE BALANCE

Similar to the inductor volt-second balance, the defining equation for capacitors is given by 3.7;

\[
\dot{i}_C(t) = C \frac{d\dot{i}_C(t)}{dt}
\]  \quad (3.7)

Integration over one complete switching period yields equation 3.8;
\[ V_c(T_{sw}) - V_c(0) = \frac{1}{C} \int_0^{T_{sw}} ic(t) \, dt \]  

(3.8)

In steady state, the net change over one switching period of the capacitor voltage must be zero, so that the left hand side of the above equation is zero. Equivalently stated the average value or the DC component of the capacitor must be zero at equilibrium as given in equation 3.9;

\[ \langle ic \rangle = \frac{1}{T_{sw}} \int_0^{T_{sw}} ic(t) \, dt = 0 \]  

(3.9)

Thus the principle of capacitor charge balance can be used to find the steady state currents in a switching converter.

### 3.3 BOOST CONVERTER

The boost converter is capable of producing a dc output voltage greater in magnitude than the dc input voltage. The circuit topology for a boost converter is as shown in figure 3.3.

![Figure 3.3 Boost Converter](image)

When the transistor Q1 is on the current in inductor L, rises linearly and at this time capacitor C, supplies the load current, and it is
partially discharged. During the second interval when transistor Q1 is off, the diode D1 is on and the inductor L, supplies the load and additionally, recharges the capacitor C. The steady state inductor current and voltage waveform is shown in figure 3.4.

Figure 3.4 Steady-state inductor voltage and current waveform of boost converter

Using the inductor volt balance principle to get the steady state output voltage equation yields equation 2.10 and 2.11;

\[ V_G \cdot T_{ON} + (V_G - V_o) \cdot T_{OFF} = 0 \]  \hspace{1cm} (2.10)

\[ \frac{V_o}{V_G} = \frac{T_{ON}}{T_{OFF}} = \frac{1}{1 - D} \]  \hspace{1cm} (2.11)

Since the converter output voltage is greater than the input voltage, the input current which is also the inductor current is greater than
output current. In practice the inductor current flowing through, semiconductors Q1 and D1, the inductor winding resistance becomes very large and with the result being that component non-idealities may lead to large power loss. As the duty cycle approaches one, the inductor current becomes very large and these component non-idealities lead to large power losses. Consequently, the efficiency of the boost converter decreases rapidly at high duty cycles. The detailed analysis of boost converter is beyond the scope of this thesis. The guidelines to select the inductor and capacitor for boost converter are discussed in reference. The small signal model of boost converter and its control to output transfer function are explained in detail in reference.

3.4 BUCK-BOOST CONVERTER

The buck-boost converter is capable of producing a dc output voltage which is either greater or smaller in magnitude than the dc input voltage. The arrangement for the buck-boost converter is as shown in figure 3.5.

![Buck-boost converter diagram](image)

Figure 3.5 Buck-boost converter

When the transistor Q1 is on, input voltage is applied across the inductor and the current in inductor L rises linearly. At this time the capacitor C, supplies the load current, and it is partially discharged.
During the second interval when the transistor is off, the voltage across the inductor reverses in polarity and the diode conducts. During this interval the energy stored in the inductor supplies the load and additionally, recharges the capacitor. The steady state inductor current and voltage waveform is shown in figure 3.6

![Figure 3.6 Steady-state inductor voltage and current waveform of buck-boost converter](image)

Using the inductor volt balance principle to find the steady state output voltage equation yields equation 3.12 and 3.13;

\[
V_G \cdot T_{\text{ON}} + V_o \cdot T_{\text{OFF}} = 0
\]

\[
\frac{V_o}{V_G} = \frac{T_{\text{ON}}}{T_{\text{OFF}}} = \frac{D}{1 - D}
\]

The D varies between 0 and 1 and thus output voltage can be lower or higher than the input voltage in magnitude but opposite in
polarity.

3.5 CuK CONVERTER

CuK converters are derived from the cascading of buck and boost converters. The buck, boost and buck-boost converter all transfer energy between input and output using the inductor and analysis is based on voltage balance across the inductor. The CuK converter as shown in Figure 3.7 utilizes capacitive energy transfer and analysis is based on current balance of the capacitor.

Figure 3.7 CuK Converter

When the diode is on, the capacitor is connected to input through L1 and source energy is stored in capacitor. During this cycle the current in C1 is $I_{IN}$. When transistor Q1 is on, the energy stored in the capacitor is transferred to the load through inductor L2. During this cycle the current in C1 is $I_{OUT}$. The capacitive charge balance principle is used to obtain steady state solution given by the equations 3.14 and 3.15;

$$I_g \cdot T_{OFF} + (-I_o) \cdot T_{ON} = 0$$  \hspace{1cm} (3.14)
Using the power conservation rule, the voltage ratio is given by the equation 3.16:

\[
\frac{V_0}{V_G} = \frac{D}{1-D}
\]  

(3.16)

This voltage ratio is the same as the buck-boost converter.

### 3.6 ISOLATED DC-DC CONVERTER

#### 3.6.1 TRANSFORMER ISOLATION

The use of a transformer allows dc isolation and multiple outputs in a dc-dc converter. Since the transformer size and weight vary inversely with frequency, significant improvements can be made by incorporating the transformer into the converter. Through a proper choice of transformer turns ratio and switching frequency stresses imposed on the transistors and diodes can be minimized. This leads to improved efficiency at lower cost.

Multiple dc outputs are obtained by adding multiple secondary windings and converter secondary side circuits. The secondary turns ratios are appropriately chosen to get the desired output voltages.

#### 3.6.2 FLYBACK CONVERTER

When the transistor Q1 is turned on, the energy is stored in the power transformer while the load current is supplied from output capacitor C. When the transistor is turned off, the energy stored in transformer is
transferred to output as load current and to recharge the capacitor as shown in figure 3.8 of flyback converter.

![Flyback Converter Diagram](image)

**Figure 3.8 Flyback converter**

One of the major advantages of Flyback converter is that they don’t require an output filter inductor, thus saving cost and volume. This also makes Flyback converters valuable for high output voltages unlike forward converters which have an output inductor potentially causing problems as the inductor must sustain large voltages. Flyback also doesn’t require a high voltage freewheeling diode.

The filter capacitor at the output is typically larger in Flyback converters as it alone supplies the load current when the transistor is ON. Equivalently the full DC current flows from ground through the capacitor to the load during the transistor ON time. Thus the ripple current rating of the capacitor and output ripple voltage requirement collectively determines the final choice of output filter capacitor.

**3.7 SUMMARY**

This chapter discusses about the basic topologies of switching regulator and shows their output to input voltage relationship with duty
cycle. The analysis can be modified for any converter topology.