

Cardiff University School of Engineering

The Buck-Boost Converter

The Design and Application of Buck Boost Converters

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Abstract

This paper looks at the buck boost converter, a power electronic device that can step up and step down voltages for applications where voltage control is required. The study in this report analyses and confirms through simulations the voltages and currents through the converter based on various switching sequences. Moreover, this report outlines the design of a buck boost converter using the specific design equations. Lastly, an isolated version, known as the fly back converter, was developed to show the various applications that can arise from said configuration.

Introduction

Power electronics are widely used to control power and convert it to different forms. There are many different forms of power electronic devices that serve different purposes. Some may convert AC electrical power to DC electrical power whilst others amplify the power. This report focuses on DC/DC converters and their applications. DC/DC converters are a switched mode power supply (SMPS) device. These devices convert one DC voltage level to another DC voltage level when supplied with power of a few kilowatts. Depending on whether the voltage level is going up, down, or both, either a boost, buck, or buck-boost converter will be used, respectively. These converters can also be isolated which will be discussed in further detail in this report. Particularly, the isolated buck-boost converter, the flyback converter will be discussed.

Switched Mode Power Supply

SMPS devices using high switching frequencies to control the voltage levels in a circuit. The time differences between the on and off states of the circuit characterises what type of SMPS device it is. This characteristic is known as the duty ratio δ ; the duty cycle ratio is the ratio of the on-time period against the total time period cycle. By working the SMPS at high switching frequencies, little energy is dissipated by the switch in either starts therefore low loss components may be used for the filtering aspect of this circuit. (Billings and Morey, 2010)

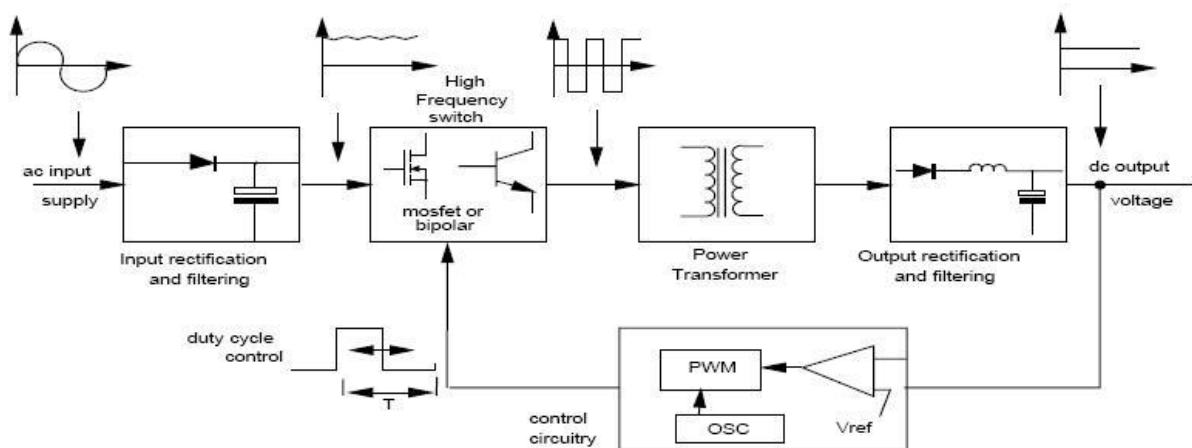


Figure 1- Block Diagram of SMPS (Agarwal, 2013)

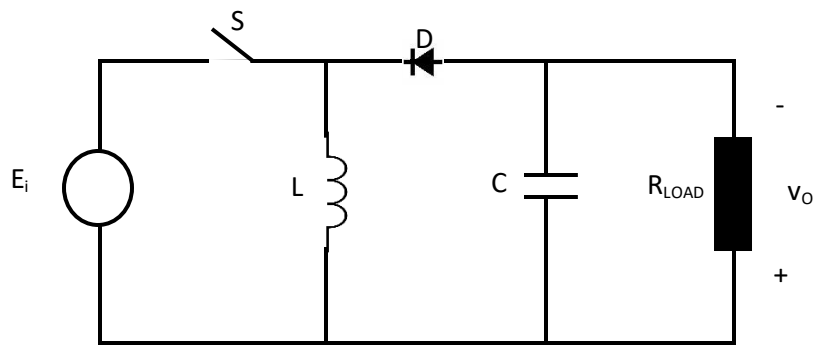
Figure 1(Agarwal, 2013), shows a block diagram of how a SMPS works. The device is fed an AC voltage (V_{AC}) which is first converted to a DC voltage (E_i) using a rectifier. This DC voltage will then flow through the switching circuit which can be either buck, boost or buck-boost. This voltage is then filtered using an LC filter circuit to get rid of any undesirable harmonics and there is a feedback component to control the voltage output. SMPS devices can work in either Continuous Conduction Mode (CCM) or

Discontinuous Conduction Mode (DCM). The major difference between the two is that in CCM, the current that is seen in the inductor does not go below zero during switching cycles however in DCM, it can be seen that the current does go below zero.

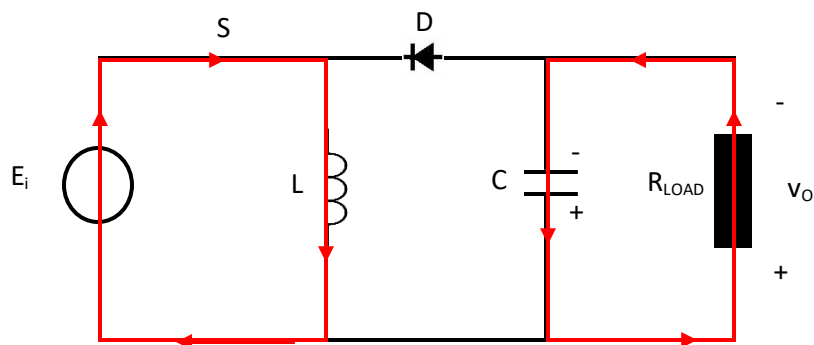
Buck-Boost Converter

The buck-boost converter is a hybrid of two other types of converters. The buck converter, which steps down a voltage, and the boost converter which steps up the voltage. The input voltage will have the opposite polarity of the output voltage. It can both step up and step down a voltage. As a buck-boost converter can function as either converter, it is a popular device used in power electronics. It can be used for all the applications stated for the buck and boost converter. They will commonly be used in self-regulating power systems to ensure that the power stays consistent. The buck-boost converter is used in battery powered applications as it can keep a steady power supply even when the battery power is depleting over time. It can also step down the voltage when the battery has full charge as this might be more than what is required for the application. (Roberts, 2014)

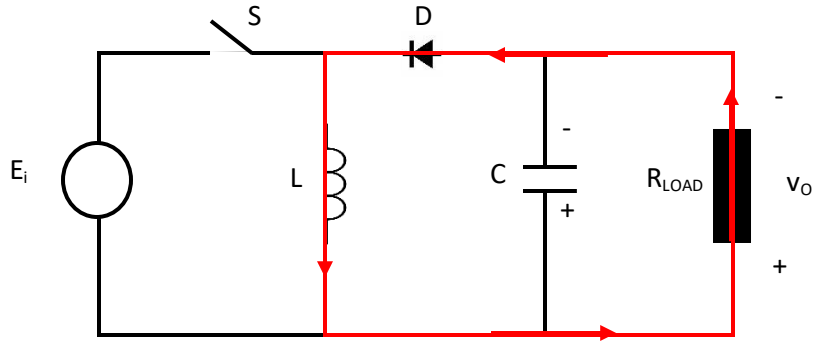
Topology



(a)



(b)



(c)

Figure 2 - (a) Topology of a Buck/Boost Converter, (b) Current flow when Switch S is ON, (c) Current flow when Switch S is OFF

When the switch is turned on, current flows into to inductor L. Current will also flow in opposite direction on the output side. As this voltage is negative, and a positive voltage is flowing through the inductor, the diode will block any current passing. When the switch is opened, the inductor discharges current which flows through the load and capacitor. At this point, the diode is forward biased.

As the buck-boost converter is able to operate it both modes, it is popular in power electronics. However, there is a disadvantage of having an inverted output voltage which can limit its application possibilities. With the buck-boost converter, it has discontinuous current at both the input and output which means it cannot be used for Power Factor Correction(PFC) applications. For PFC, normally a boost converter will be used as it can provide a smooth continuous current at the input side. (Abdel-Rahman, 2014)

Simulation

DC/DC converters can either work in continuous conduction mode, or discontinuous conduction mode. The difference between the two modes is that in DCM, the current reaches zero before the switch is turned on again. The period for which the current is at zero for is known as the 'dead time'. Ideally, a buck-boost converter will work in CCM. To ensure the circuit works in CCM, the inductance must be above a certain value. This can be calculated using the equation:

$$L \geq \frac{(1-\delta)^2 R}{2f_s} \quad (1)$$

Where δ = Duty cycle ratio

R = Load Resistance

f_s = switching frequency.

The following simulation was done using MATLAB. The following schematic is for a buck-boost converter to work as a boost converter in CCM.

Design Calculations

When the switch is turned on, for a time period of t_{ON} , the supply voltage E_i is applied across inductor L and the current change of the inductor will be:

$$\Delta i_L = \frac{E_i}{L} t_{ON} \quad (2)$$

When the switch is turned off, the time period can be found by subtracting the time period of one cycle, T by t_{ON} . The current stored in the inductor begins to decrease as it discharges and this decrease, the voltage across it will equate to the output voltage v_o and the current change is:

$$-\Delta i_L = \frac{v_o}{L}(T - t_{ON}) \quad (3)$$

By equating the two above equations, the voltage ratio can be obtained to be:

$$\frac{v_o}{E_i} = -\frac{\delta}{1-\delta} \quad (4)$$

Therefore, if the duty ratio is greater than 0.5, the voltage ratio will be greater than 1 which means the output voltage is greater than the input voltage. This means that the buck-boost converter will work as a boost converter. If the duty ratio is less than 0.5, then the converter will work as a buck converter.

For this simulation, the duty ratio is chosen to be 70% to ensure that the converter steps up the voltage.

Arbitrary values were chosen for resistance, capacitance, input voltage and switching frequency. These are 10Ω , $47\mu\text{F}$, 100V and 10kHz , respectively. From this the inductance requirements can be found. Using Eq (1):

$$L \geq \frac{(1-0.7)^2 10}{2 * 10000} \quad (5)$$

$$L \geq 0.000045 = 45\mu\text{H}$$

To ensure CCM, $L = 100\mu\text{H}$ was chosen.

Schematic

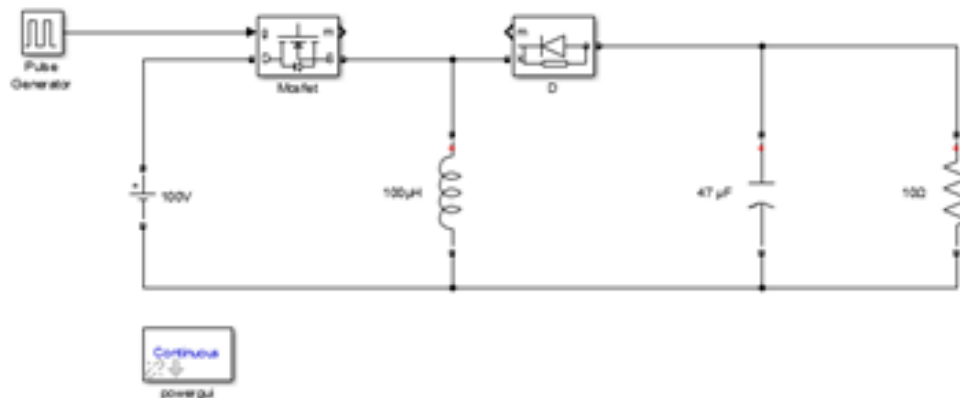
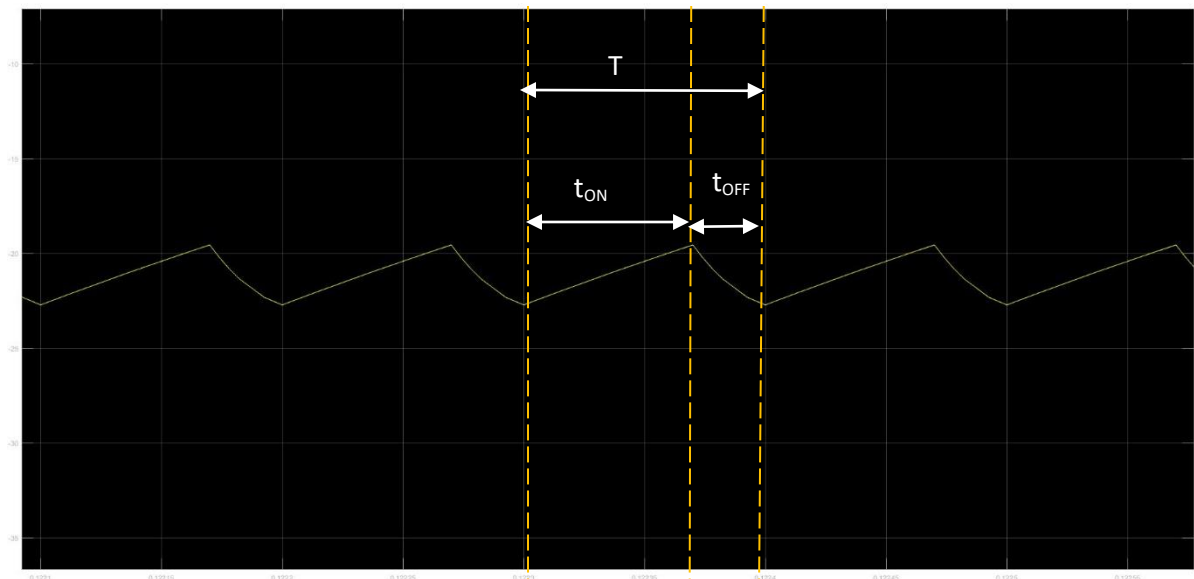


Figure 3 - Schematic of buck-boost converter in MATLAB

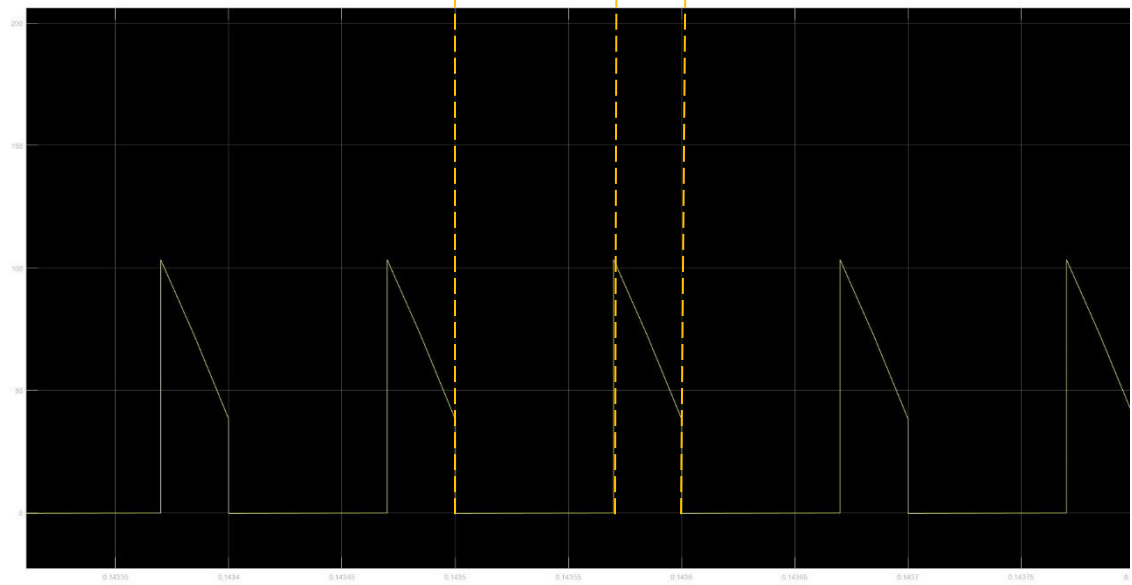
A summary of the circuit values are:

$V_{in} = 100\text{V}$	$L = 100\mu\text{H}$	$C = 47\mu\text{F}$	$R = 10\Omega$
$f_s = 10\text{kHz}$	$T = 100\mu\text{s}$	$\delta = 70\%$	

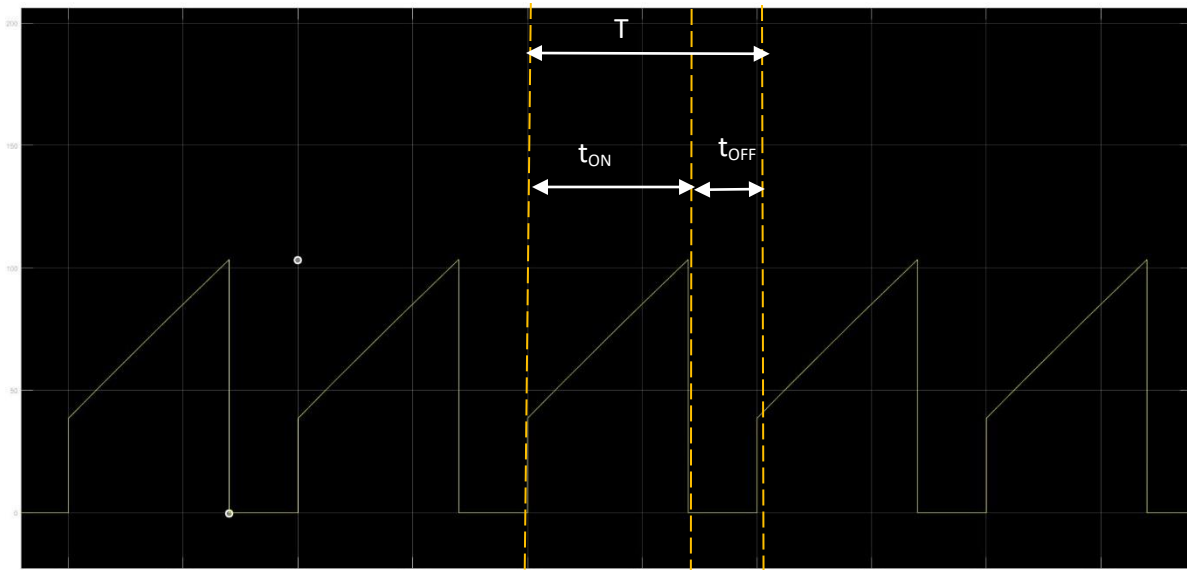
Simulation Results



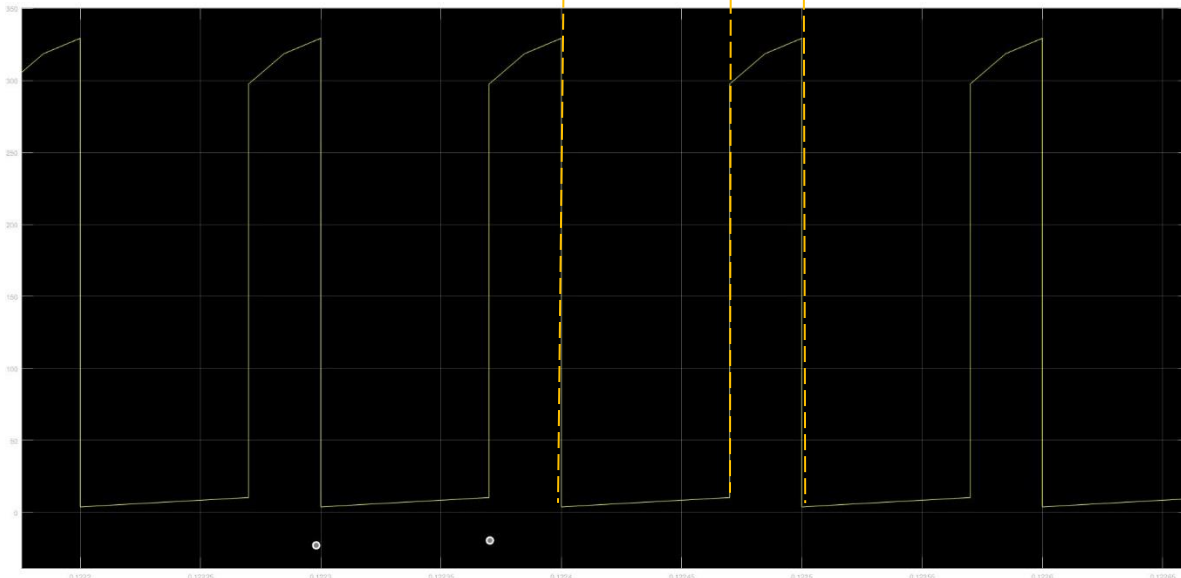
(a)



(b)



(c)



(d)

Figure 4 - (a) Load Current, (b) Diode Current, (c) Switching Current, (d) Switching Voltage

Simulation Analysis

The simulation resulted in an output voltage of 240V. This meant that the circuit is working correctly as a boost converter. From the simulation results, in each graph, the time period for one cycle was $100\mu\text{s}$. Fig 4(c) shows the current across the switch. The current increased for $70\mu\text{s}$ and then went to zero as it was switched off. The time period of the current being zero was around $30\mu\text{s}$. When the switch was turned on, the current went up to 38A and then gradually increased to 102A. The opposite of this can be seen in Fig 4(b) which shows the current through the diode. For the time period t_{ON} , the diode is not letting any current flow as it is reverse biased. When the switch is turned off, the diode forward biased and the current increases from 38A to 103A.

Figure 4(a) is a combination of Fig 4(b) and Fig 4(c) as it is the current seen flowing through the load. As this is continuous mode, there is always current flowing through the load and the current never reaches zero. For $70\mu\text{s}$, the current increases and then for the remaining $30\mu\text{s}$ when the switch is turned off, the current begins to decrease.

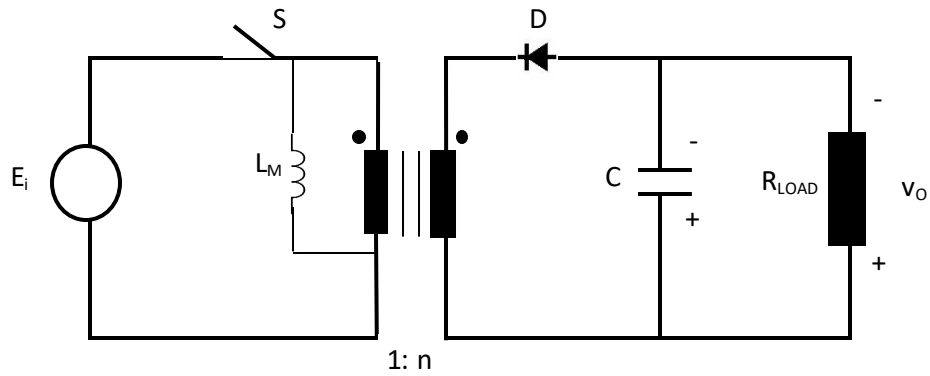
Fig 4(d) shows the voltage across the switch during the time periods. When the switch is on, there is not voltage across the switch. When the switch is turned off, the voltage increases to 330V. This value is expected as the voltage seen across the switch is a sum of the supply voltage E_i (100V) and the output voltage v_o (230V).

Isolation

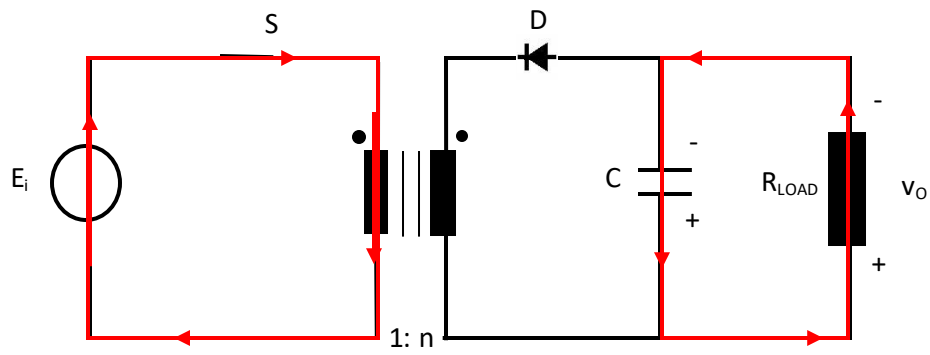
The above DC/DC converter is cheap and simple to use however in high voltage situations; it provides little protection to the load. In high voltage applications, the converter can be electrically isolated to ensure that high input voltage will not damage the load. Another issue with non-isolated DC/DC converters is that the efficiency of the converter decreases if it has to step up or down big voltages to small voltages e.g. 500V to 4V. Isolated converters are able to do this and can support multiple outputs. Isolated converters also have low Electromagnetic Interference (EMI) which contributes to its efficiency and ability to function (Luo and Ye, 2003). All three converters can be modified to become isolated converters and by designing the circuit in MATLAB, the output voltage and current waveforms can be analysed.

Flyback Converter (Isolated Buck-Boost Converter)

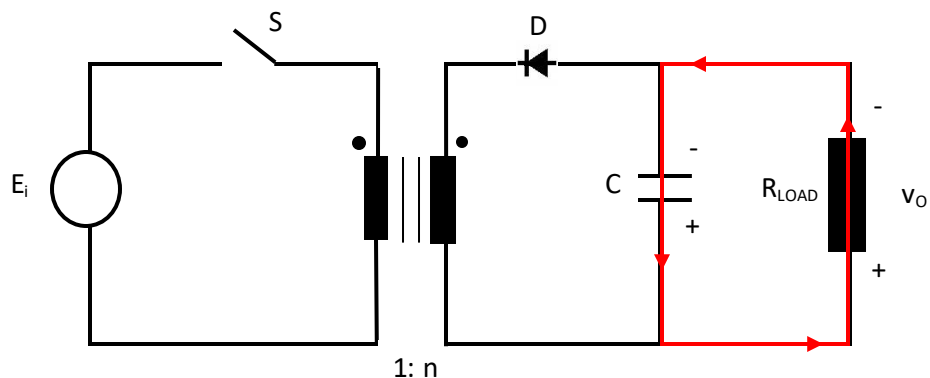
The flyback converter is based on the buck-boost converter. It is mainly used in low power applications and has a greater efficiency than the boost converter. Fig 5 shows the topology of the flyback converter. The inductor winding is split into two creating an isolated topology. The two windings will be separate but closely spaced together, making this a bifilar inductor coil. This two winding inductor function is seen as a transformer therefore it is also known as a flyback transformer. The flyback transformer however will only have current flowing in either the primary winding or the secondary winding (Scloccchi, 2016). There cannot be current flowing through both windings simultaneously. The switching function is carried out by switch S and the diode D. The windings will have a turns ratio meaning that the current going through them will be different. As this converter is based on the buck-boost converter, there will be a negative voltage output. To ensure a positive voltage at the output, the polarities of the winding can be reversed.



(a)



(b)



(c)

Figure 5 - (a) Topology of a Flyback Converter, (b) Current flow when switch S is on, (c) Current flow when switch S is off

Operation

To look at the operation of the flyback converter, the polarities of the windings have been reversed to ensure a positive output voltage. The windings will be modelled as an ideal transformer and the inductance is represented by an inductor connected in parallel to the transformer. This inductor L_M will have the same currents and voltage flowing through it as the primary inductor winding. This is shown in Fig 6.

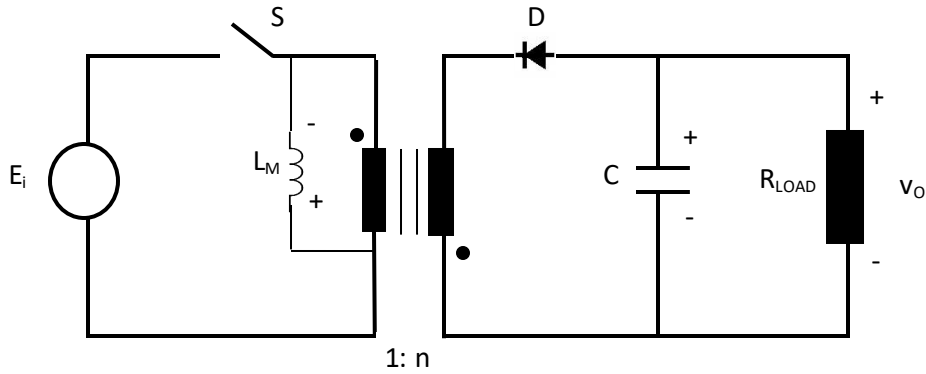


Figure 6 - Topology of a flyback converter with reversed polarity and magnetising inductance represented

When the switch is turned on, energy is stored in the magnetising inductor. During this period known as T_{ON} , the diode will be reverse biased. At this point current will flow as shown in Fig4 (b). The voltage seen at L_M will be equivalent to the input voltage therefore:

$$v_L = E_i \quad (6)$$

The current at the L_M will be equivalent to the source current:

$$i_L = i_i \quad (7)$$

The current seen at the capacitor will be equivalent to the negative current of the load so:

$$i_C = -\frac{V_O}{R_{LOAD}} \quad (8)$$

Assuming CCM and small ripple approximation (Erickson, 2013), the circuit can be represented by its DC components which give the above equations as:

$$v_L = E_i \quad (9)$$

$$I = i_i \quad (10)$$

$$i_C = -\frac{V_O}{R_{LOAD}} \quad (11)$$

When the switch is turned off, this energy is transferred to the secondary inductor winding at a ratio of 1: n and goes to the load and output capacitor. As the switch is off, the input current will be 0A. The magnetising current will flow through the transformer and into the secondary winding. The voltage seen at the magnetising inductor is the same as the output voltage but multiplied by the turns ratio:

$$v_L = -\frac{V_O}{n} \quad (12)$$

The current of the capacitor will be the difference between the secondary winding current and the current across the load:

$$i_C = \frac{i}{n} - \frac{v_O}{R_{LOAD}} \quad (13)$$

These can be represented by its DC components which helps simplify these equations:

$$v_L = -\frac{V_O}{n} \quad (14)$$

$$i_C = \frac{I}{n} - \frac{V_O}{R_{LOAD}} \quad (15)$$

When the switch is on again, there is current flowing in the primary winding, and in the loop of the load and capacitor as the capacitor discharged energy into the load. This process can be seen in Fig 4 (Suntio, 2009).

Designing a Flyback Converter

Fig 7 shows the waveforms that can be seen for a flyback converter. Equations to find the values of the components can be found using the volt-second balance principle and the capacitor charge balance principle. The volt-second balance principle is used for the inductor which says that over one cycle, the average voltage across that inductor is zero. Similarly, the capacitor charge balance principle states that the average current over one cycle for a capacitor is zero.

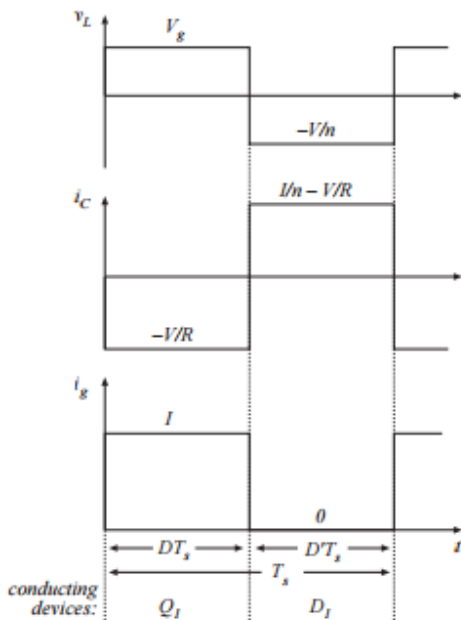


Figure 7 - Voltage and Current waveforms

This equation then gives us the voltage ratio as:

$$\frac{V}{E_i} = \frac{D}{1-D} \cdot n \quad (19)$$

Using the Capacitor charge balance, the magnetising current can be found to be:

$$I = \frac{V}{(1-D)R} \cdot n \quad (20)$$

Where D is the duty cycle of the circuit. (Dekker, 2004)

Leakage Inductance

When designing a flyback converter, consideration must be taken into account for the leakage inductance of the transformer. This is seen on the primary side and can reduce the efficiency of the

circuit. Leakage inductances can cause voltage overshoots which means that higher voltage rated power switches will be needed which increase costs. To ensure that this leakage is at a minimum, a snubber can be added to the circuit. The snubber circuit effectively clamps the voltage and current across the switch along with limiting the rate of voltage rise and rate of current rise (V L and George, 2014).

Selecting Inductances

The selected values of inductance are crucial to ensure that the converter operates in continuous mode. The calculation of inductances must also take into consideration the maximum secondary ripple current and to ensure the right half plane (RHP) zero (Scloclchi, 2016) is as high as possible. RHP is an undesirable feature of the flyback converter which only occurs in continuous mode. It results in the crossover frequency being a lower value by decreasing the conduction of the diode which can affect the dynamic response of the circuit. (V L and George, 2014)

The secondary conductance can be calculated by using the following equation:

$$L_{SEC} = \frac{(V_O + V_{d_{fw}}) \cdot (1-D)}{\Delta I_{SEC} \cdot f_s} \quad (21)$$

Where $V_{d_{fw}}$ is the forward drop voltage of the diode, f_s is the switching frequency, ΔI_{SEC} is the allowed secondary ripple current (usually set to 30-50% of rms output current):

$$\Delta I_{SEC} = \frac{I_{O_MAX}}{(1-D_{MAX})} \quad (22)$$

The equivalent primary inductance is found by:

$$L_p = L_s \cdot n^2 \quad (23)$$

The RHP effect often results in the maximum crossover frequency being a quarter of the RHP frequency. The worst case of the RHP frequency must be determined and this can be done so by using:

$$F_{RHPZ} = \frac{V_O}{I_O} \cdot \frac{(1-D)^2}{D \cdot 2\pi \cdot L_s} \quad (24)$$

The values of primary and secondary inductance can be chosen to ensure that RHP is minimised. (V L and George, 2014)

Simulation

A simple simulation was made to show how the flyback converter can work like a buck-boost converter even with an airgap. The schematic is shown in Fig 8. The circuit was connected to a voltage measurement to display the voltage output of the circuit.

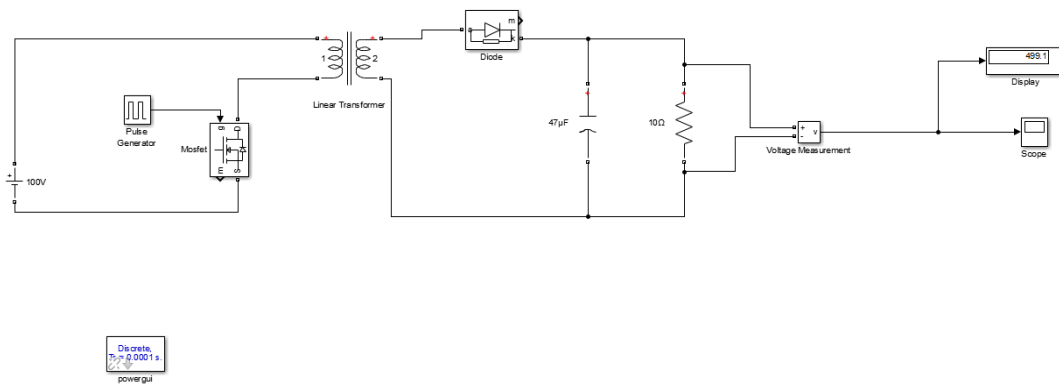


Figure 8 - Flyback Converter Diagram in MATLAB

The values for input voltage, capacitance, resistance, switching frequency and duty ratio were kept the same. The turns ratio was made to be 5. The output voltage was then around 500V. The output was a constant voltage which shows that the flyback converter works effectively producing a constant step up voltage.

Conclusion

DC/DC converters are cheap and simple to make and design therefore they are widely used in applications that require compact devices. The buck-boost converter is mainly used where the characteristics of both the buck and boost are required. This can be applications that need some form of power regulation or voltage regulation. As the buck-boost converter can step up and step down a voltage, it can control the voltage output of a device. A common application for buck-boost converters is battery regulation. When a battery has full charge, the particular device may not need its full voltage capacity therefore the converter can step down the voltage before it is inputted into the device. As the battery begins to lose its charge over its lifetime, the converter can then begin to step up its voltage to meet the devices requirements.

The flyback converter is able to increase the efficiency of a buck-boost converter with a few simple modifications. The flyback converter is a popular device due to its simplicity and ability to provide more than one output with the use of a busbar. The flyback converter only requires one switch compared to other isolated converters and does not require an inductor filter. However, in many cases an inductor filter will be embedded into the circuit to reduce voltage ripples. The flyback is prone to high voltage and current ripples however these can be filtered out by adding more components. The extra components however increase the cost and complexity of the circuit. Designers will often make a trade-off between these when choosing the flyback converter in applications. This trade-off often leads to the flyback converter being used in low power applications rather than high power.

Overall the flyback converter is an effective SMPS which can achieve high efficiency and reliability through correct design. This makes it a widely used device in the industry for low power applications.

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