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DC-DC Converter Basics

ABSTRACT

A DC-to-DC converter is a device that accepts a DC input voltage and produces a DC output voltage. Typically the output produced is at a different voltage level than the input. In addition, DC-to-DC converters are used to provide noise isolation, power bus regulation, etc. This is a summary of some of the popular DC-to-DC converter topolopgies:

1. BUCK CONVERTER STEP-DOWN CONVERTER

In this circuit the transistor turning ON will put voltage Vin on one end of the inductor. This voltage will tend to cause the inductor current to rise. When the transistor is OFF, the current will continue flowing through the inductor but now flowing through the diode. We initially assume that the current through the inductor does not reach zero, thus the voltage at Vx will now be only the voltage across the conducting diode during the full OFF time. The average voltage at Vx will depend on the average ON time of the transistor provided the inductor current is continuous.

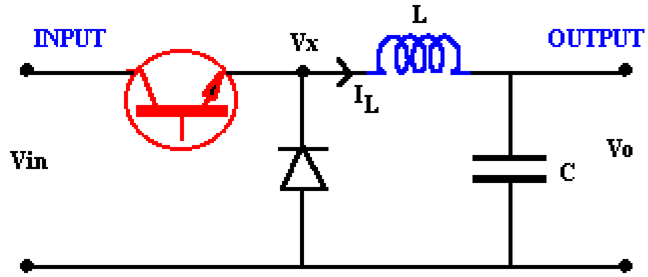

Fig. 1: Buck Converter

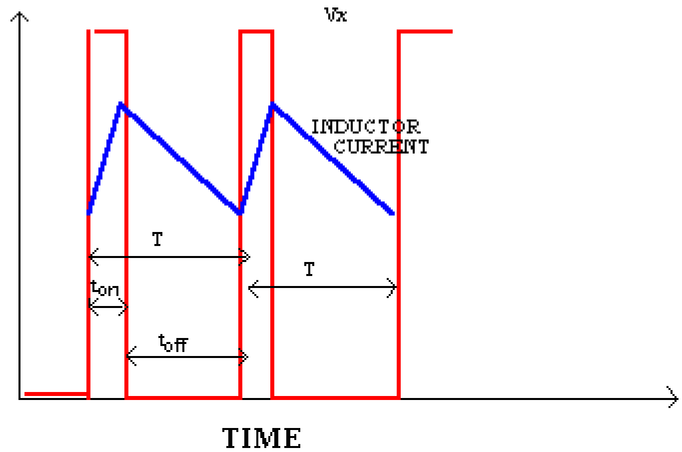

Fig. 2: Voltage and current changes

To analyse the voltages of this circuit let us consider the changes in the inductor current over one cycle. From the relation

$$V_x - V_o = L\frac{di}{dt}$$

the change of current satisfies

$$di = \int_{ON} \left(V_x - V_o\right)dt + \int_{OFF} \left(V_x - V_o\right)dt$$

For steady state operation the current at the start and end of a period T will not change. To get a simple relation between voltages we assume no voltage drop across transistor or diode while ON and a perfect switch change. Thus during the ON time $V_x = V_{in}$ and in the OFF $V_x = 0$. Thus

$$0 = di = \int_0^{t_{on}} (Vin - Vo)dt + \int_{t_{on}}^{t_{on}+t_{off}} (-Vo)dt$$

which simplifies to

$$(Vin - Vo)t_{on} - Vo\ t_{off} = 0$$

or

$$\frac{Vo}{Vin} = \frac{t_{on}}{T}$$

and defining "duty ratio" as

$$D = \frac{t_{on}}{T}$$

the voltage relationship becomes Vo=D Vin Since the circuit is lossless and the input and output powers must match on the average $V_o * I_o = V_{in} * I_{in}$. Thus the average input and output current must satisfy $I_{in} = D\ I_o$ These relations are based on the assumption that the inductor current does not reach zero.

1.1 Transition between continuous and discontinuous

When the current in the inductor L remains always positive then either the transistor T1 or the diode D1 must be conducting. For continuous conduction the voltage V_x is either V_{in} or 0. If the inductor current ever goes to zero then the output voltage will not be forced to either of these conditions. At this transition point the current just reaches zero as seen in Figure 3. During the ON time V_{in}-V_{out} is across the inductor thus

$$I_L(peak) = (Vin - Vout) \cdot \frac{t_{ON}}{L} \qquad (1)$$

The average current which must match the output current satisfies

$$I_L(average\ at\ transition) = \frac{I_L(peak)}{2} = (Vin - Vout)\frac{dT}{2L} = Iout(transition) \qquad (2)$$

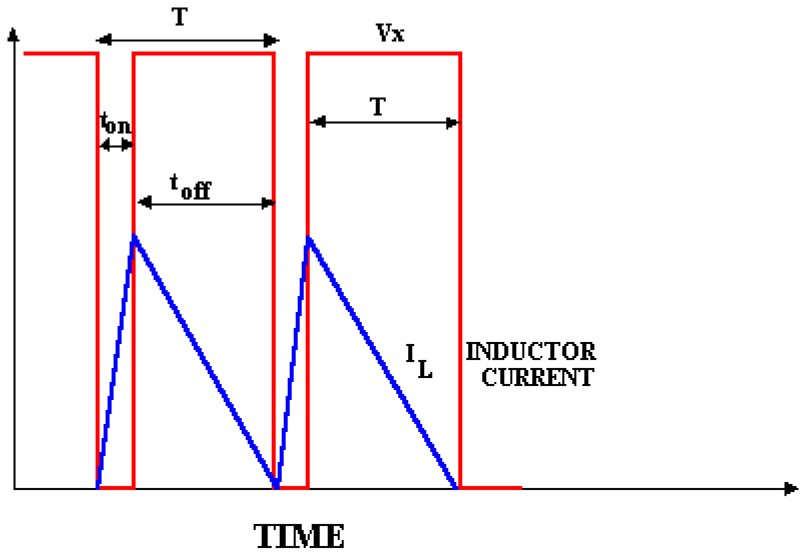

Fig. 3: Buck Converter at Boundary

If the input voltage is constant the output current at the transition point satisfies

$$Iout(transition) = Vin\frac{(1-d)d}{2L}T \tag{3}$$

1.2 Voltage Ratio of Buck Converter (Discontinuous Mode)

As for the continuous conduction analysis we use the fact that the integral of voltage across the inductor is zero over a cycle of switching T. The transistor OFF time is now divided into segments of diode conduction d_dT and zero conduction d_oT. The inductor average voltage thus gives

$$(V_{in} - V_o)\, DT + (-V_o)\, \delta_d T = 0 \tag{4}$$

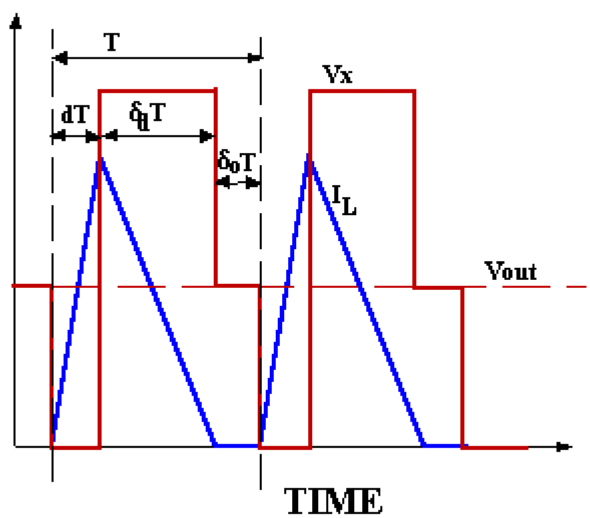

Fig. 4: Buck Converter - Discontinuous Conduction

$$\therefore \frac{Vout}{Vin} = \frac{d}{d + \delta_d} \tag{5}$$

for the case $d + \delta_d < 1$. To resolve the value of δ_d consider the output current which is half the peak when averaged over the conduction times $d + \delta_d$

$$Iout = \frac{I_L(peak)}{2} d + \delta_d \tag{6}$$

Considering the change of current during the diode conduction time

$$I_L(peak) = \frac{V_0(\delta_d T)}{L} \tag{7}$$

Thus from (6) and (7) we can get

$$I_{out} = \frac{V_0 \delta_d T \cdot (d + \delta_d)}{2L} \tag{8}$$

using the relationship in (5)

$$Iout = \frac{Vin\, d\ \delta_d T}{2L} \tag{9}$$

and solving for the diode conduction

$$\delta_d = \frac{2L\ Iout}{Vin\, d\ T} \tag{10}$$

The output voltage is thus given as

$$\frac{Vout}{Vin} = \frac{d^2}{d^2 + (\frac{2L\ Iout}{Vin\ T})} \tag{11}$$

defining k* = $2L/(V_{in}\ T)$, we can see the effect of discontinuous current on the voltage ratio of the converter.

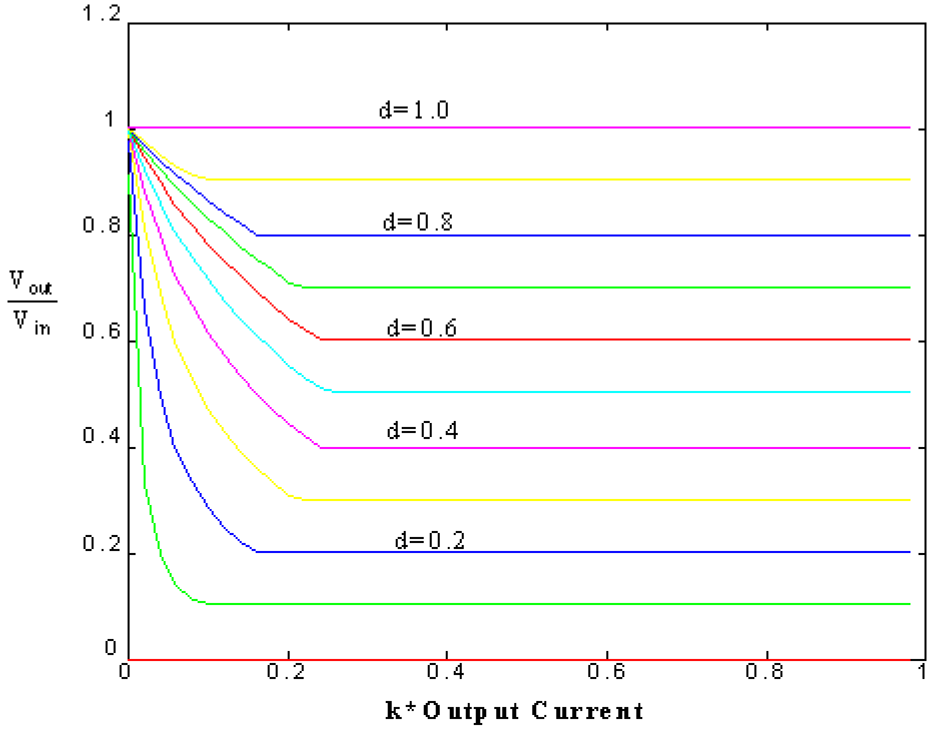

Fig. 5: Output Voltage vs Current

As seen in the figure, once the output current is high enough, the voltage ratio depends only on the duty ratio "d". At low currents the discontinuous operation tends to increase the output voltage of the converter towards V_{in}.

2. BOOST CONVERTER STEP-UP CONVERTER

The schematic in Fig. 6 shows the basic boost converter. This circuit is used when a higher output voltage than input is required.

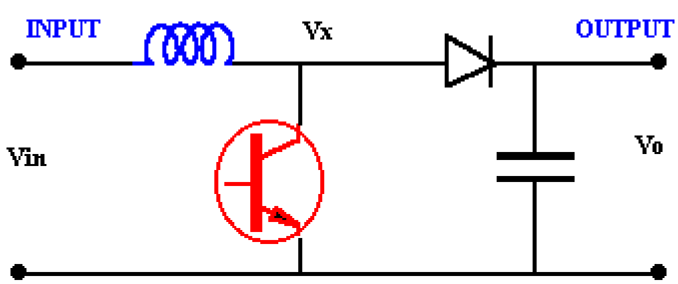

Fig. 6: Boost Converter Circuit

While the transistor is ON $V_x = V_{in}$, and the OFF state the inductor current flows through the diode giving $V_x = V_o$. For this analysis it is assumed that the inductor current always remains flowing (continuous conduction). The voltage across the inductor is shown in Fig. 7 and the average must be zero for the average current to remain in steady state

$$Vin\, t_{on} + (Vin - Vo)t_{off} = 0$$

This can be rearranged as

$$\frac{Vo}{Vin} = \frac{T}{t_{off}} = \frac{1}{(1-D)}$$

and for a lossless circuit the power balance ensures

$$\frac{Io}{Iin} = (1-D)$$

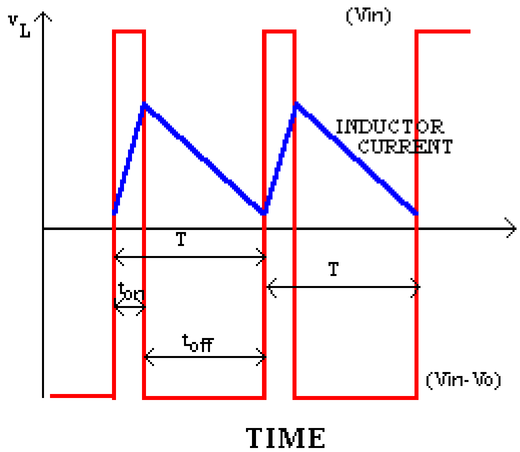

Fig. 7: Voltage and current waveforms (Boost Converter)

Since the duty ratio "D" is between 0 and 1 the output voltage must always be higher than the input voltage in magnitude. The negative sign indicates a reversal of sense of the output voltage.

3. BUCK-BOOST CONVERTER

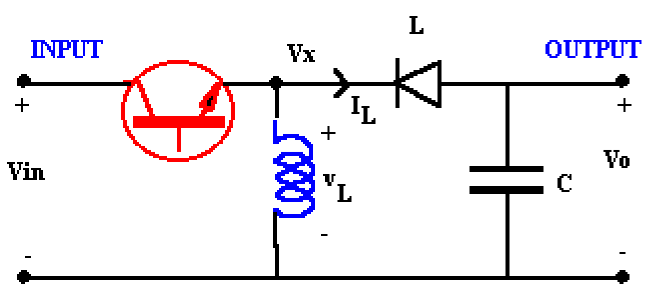

Fig. 8: schematic for buck-boost converter

With continuous conduction for the Buck-Boost converter $V_x = V_{in}$ when the transistor is ON and $V_x = V_o$ when the transistor is OFF. For zero net current change over a period the average voltage across the inductor is zero

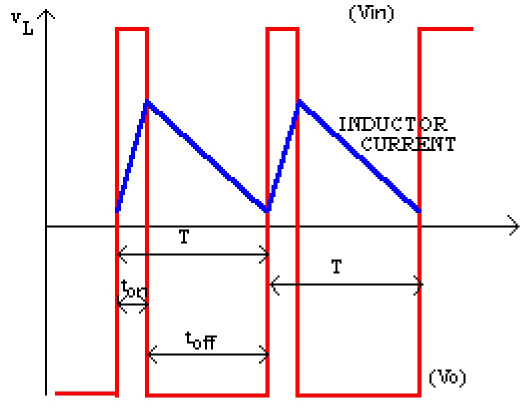

Fig. 9: Waveforms for buck-boost converter

$$Vin\,t_{ON} + Vo\,t_{OFF} = 0$$

which gives the voltage ratio

$$\frac{Vo}{Vin} = -\frac{D}{(1-D)}$$

and the corresponding current

$$\frac{Io}{Iin} = -\frac{(1-D)}{D}$$

Since the duty ratio "D" is between 0 and 1 the output voltage can vary between lower or higher than the input voltage in magnitude. The negative sign indicates a reversal of sense of the output voltage.

4. CONVERTER COMPARISON

The voltage ratios achievable by the DC-DC converters is summarised in Fig. 10. Notice that only the buck converter shows a linear relationship between the control (duty ratio) and output voltage. The buck-boost can reduce or increase the voltage ratio with unit gain for a duty ratio of 50%.

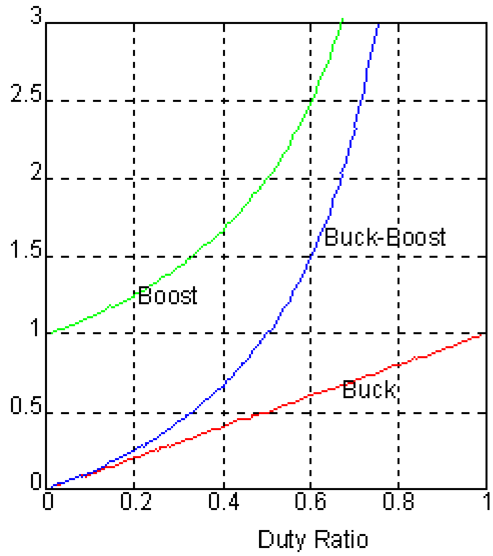

Fig. 10: Comparison of Voltage ratio

4. CUK CONVERTER

The buck, boost and buck-boost converters all transferred energy between input and output using the inductor, analysis is based of voltage balance across the inductor. The CUK converter uses capacitive energy transfer and analysis is based on current balance of the capacitor. The circuit in Fig. 11 is derived from DUALITY principle on the buck-boost converter.

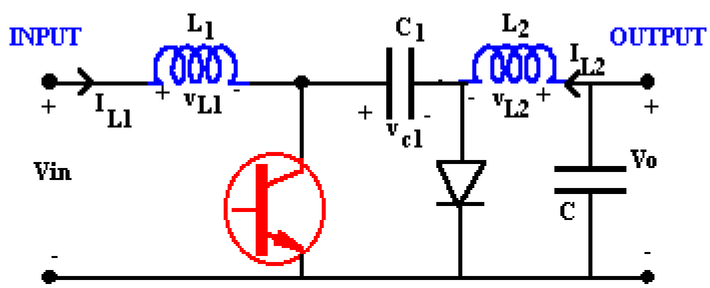

Fig. 11: CUK Converter

If we assume that the current through the inductors is essentially ripple free we can examine the charge balance for the capacitor C1. For the transistor ON the circuit becomes

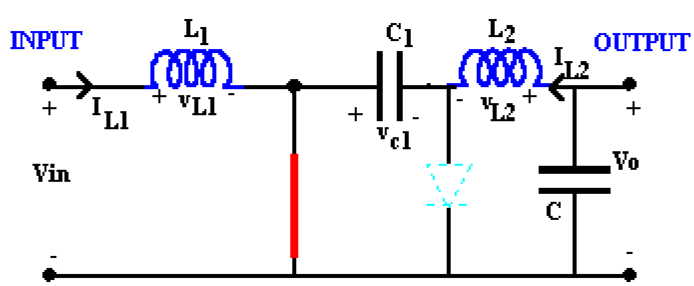

Fig. 12: CUK "ON-STATE"

and the current in C1 is I_{L1}. When the transistor is OFF, the diode conducts and the current in C1 becomes I_{L2}.

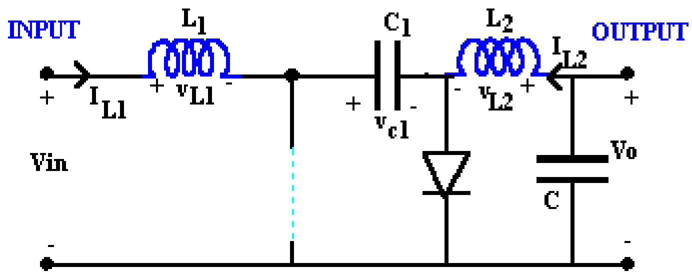

Fig. 13: CUK "OFF-STATE"

Since the steady state assumes no net capacitor voltage rise ,the net current is zero

$$I_{L1} t_{ON} + (-I_{L2}) t_{OFF} = 0$$

which implies

$$\frac{I_{L2}}{I_{L1}} = \frac{(1-D)}{D}$$

The inductor currents match the input and output currents, thus using the power conservation rule

$$\frac{Vo}{Vin} = -\frac{D}{(1-D)}$$

Thus the voltage ratio is the same as the buck-boost converter. The advantage of the CUK converter is that the input and output inductors create a smooth current at both sides of the converter while the buck, boost and buck-boost have at least one side with pulsed current.

4. Isolated DC-DC Converters

In many DC-DC applications, multiple outputs are required and output isolation may need to be implemented depending on the application. In addition, input to output isolation may be required to meet saftey standards and / or provide impedance matching.

The above discussed DC-DC topologies can be adapted to provide isolation between input and output.

4.1 Flyback Converter

The flyback converter can be developed as an extension of the Buck-Boost converter. Fig 14a shows tha basic converter; Fig 14b replaces the inductor by a transformer. The buck-boost converter works by storing energy in the inductor during the ON phase and releasing it to the output during the OFF phase. With the transformer the energy storage is in the magnetisation of the transformer core. To increase the stored energy a gapped core is often used.

In Fig 14c the isolated output is clarified by removal of the common reference of the input and output circuits.

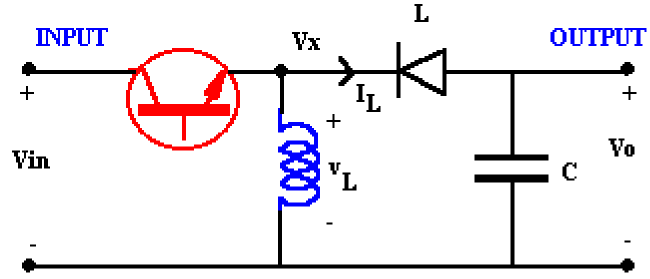

Fig. 14(a): Buck-Boost Converter

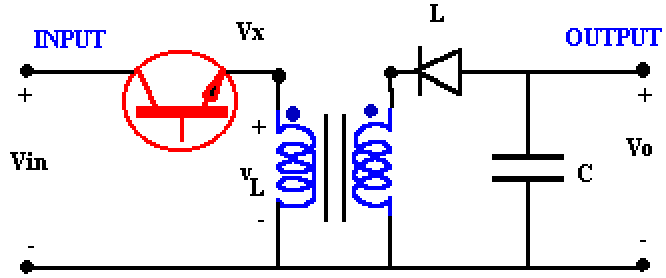

Fig. 14(b): Replacing inductor by transformer

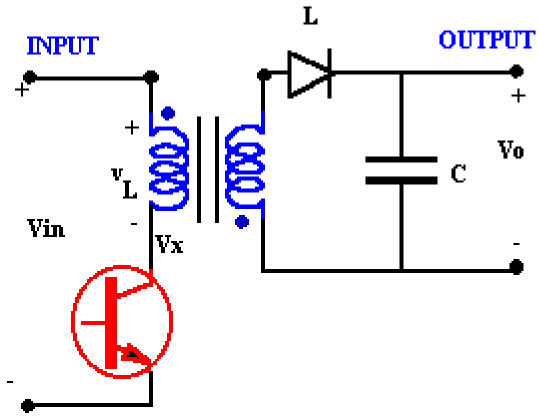

Fig. 14(c): Flyback converter re-configured

4.2 Forward Converter

The concept behind the foward converter is that of the ideal transformer converting the input AC voltage to an isolated secondary output voltage. For the circuit in Fig. 15, when the transistor is ON, Vin appears across the primary and then generates

$$Vx = \frac{N_1}{N_2} Vin$$

The diode D1 on the secondary ensures that only positive voltages are applied to the output circuit while D2 provides a circulating path for inductor current if the transformer voltage is zero or negative.

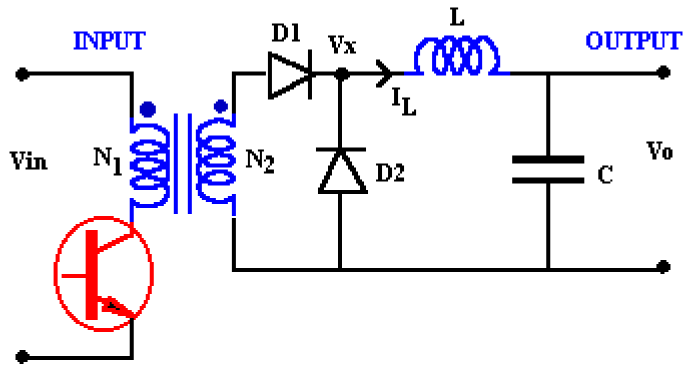

Fig. 15: Forward Converter

The problem with the operation of the circuit in Fig 15 is that only positive voltage is applied across the core, thus flux can only increase with the application of the supply. The flux will increase until the core saturates when the magnetising current increases significantly and circuit failure occurs. The transformer can only sustain operation when there is no significant DC component to the input voltage. While the switch is ON there is positive voltage across the core and the flux increases. When the switch turns OFF we need to supply negative voltage to rset the core flux. The circuit in Fig. 16 shows a tertiary winding with a diode connection to permit reverse current. Note that the "dot" convention for the tertiary winding is opposite those of the other windings. When the switch turns OFF current was flowing in a "dot" terminal. The core inductance act to continue current in a dotted terminal, thus

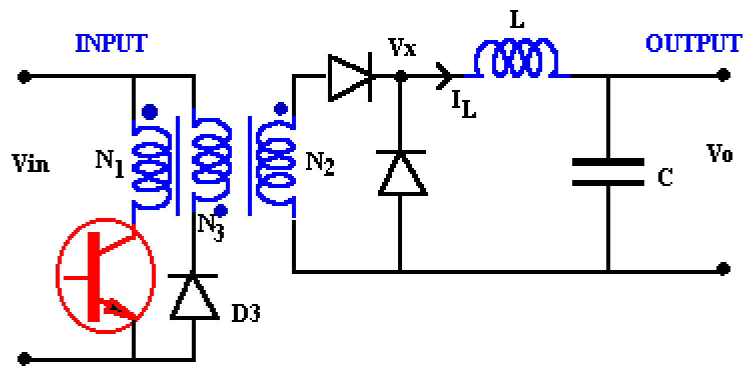

Fig. 16: Forward converter with tertiary winding

For further reading:

[1] "Power Electronics: Converters, Applications and Design", Mohan, Undeland and Robbins, Wiley, 1989.

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