Class notes : APE

DC-DC CONVERTER Lect:3 (Boost Converter)

The Circuit configuration of step up (boost) converter is shown in Fig.1. This converter is use to increase the DC voltage level. In this project two boost converters are used.

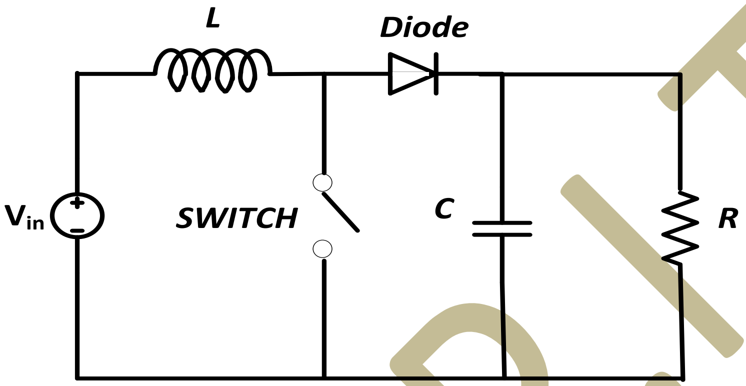


Fig.1 Circuit diagram of Boost converter

Basic principle of operation:

Similar to buck converter, this converter also operates in two modes.

Mode 1: when switch is ‘ON’. Inductor starts to store energy and hence current rises through inductor. Load is short circuited through switch and thus output voltage reaches to zero.

Voltage across inductor:

$$V_L = V_{in}$$

Now inductor voltage during DTs interval:

$$L\frac{I_{\max} - I_{\min}}{DT_s - 0} = V_{in}$$

$$\Delta I_L = \frac{V_{in}}{L} DT_s \qquad (1)$$

Inductor current increase linearly during this period.

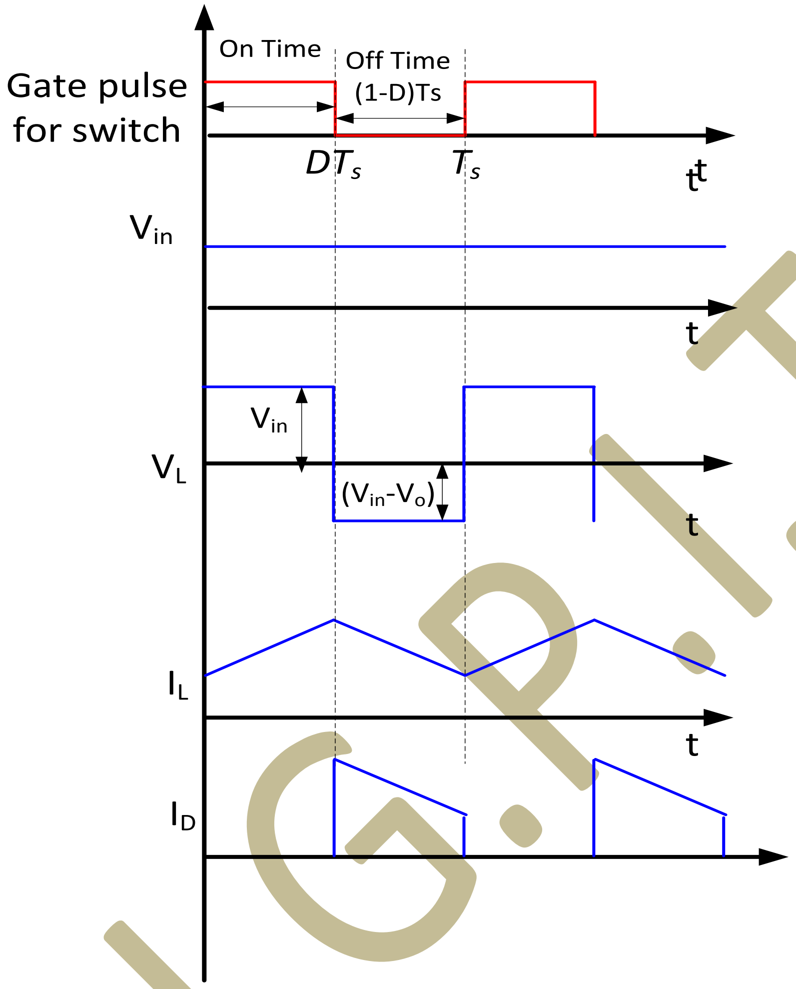


Fig. 2 Boost converter: switching pulses, voltage and current waveforms

Mode 2: when switch is ‘OFF’. During this interval, inductor current cannot die down instantaneously. Inductor starts to discharge and hence change its polarity. As the polarity of induce emf is reversed and diode is forward biased. Now, inductor voltage

$$V_L = V_{in} - V_0$$

So similar to above analysis, inductor current during (1-D)Ts interval:

$$\Delta I_L = \frac{V_{in} - V_0}{L}(1-D)T_s \tag{2}$$

During a steady state both (1) and (2) must be equal and hence equating:

$$\Delta I_L = \frac{V_{in} - V_0}{L}(1-D)T_s = \frac{V_{in}}{L} DT_s$$

$$V_0 = \frac{V_{in}}{1-D}$$

(Considering the system to be loss less, the output voltage can be derived as:

$$V_o = \frac{T_s}{T_{OFF}} V_{in} = \frac{T_s}{T_s - T_{in}} V_{in} = \frac{1}{1-d} V_{in} \tag{3}$$

And hence

$$V_{in} = (1-d)V_o \tag{4}$$

Design of Boost Converter (Selection of 'L' and 'C')

The relationship between the input voltage Vin and the output voltage Vo.

In case of Boost converter, when switch is **ON**, Voltage across inductor:

$$V_L = V_{in}$$

Now inductor voltage during DTs interval:

$$L\frac{I_{\max} - I_{\min}}{DT_s - 0} = V_{in}$$

$$\Delta I_L = \frac{V_{in}}{L} DT_s \tag{1}$$

When switch is **OFF**, inductor voltage

$$V_L = V_{in} - V_0$$

So similar to above analysis, inductor current during (1-D)Ts interval:

$$\Delta I_L = \frac{V_{in} - V_0}{L}(1-D)T_s \tag{2}$$

During a steady state both (1) and (2) must be equal and hence equating:

$$\Delta I_L = \frac{V_{in} - V_0}{L}(1-D)T_s = \frac{V_{in}}{L} DT_s$$

$$V_0 = \frac{V_{in}}{1-D}$$

The ripple content in the inductor current waveform and ripple content in the output voltage.

The ripple content can be obtained from ON or OFF both the intervals by utilizing equation:

$$V_L = L\frac{di}{dt}$$

For ON interval dt=DTs, current changing from I_{min} to I_{max} and consider as ΔI

So,

$$L\frac{I_{\max} - I_{\min}}{DT_s - 0} = V_{in} \text{ and hence } \Delta I_L = \frac{V_{in}}{L} DT_s$$

$$L = \frac{V_{in}}{\Delta I_L} DT_s \tag{3}$$

For capacitor

$$i_c = c\frac{dv}{dt}$$

so, for the on duration $c = i_c \frac{DT_s}{\Delta V_0}$ and hence $c = I_0 \frac{DT_s}{\Delta V_0}$

So capacitor can be designed using following formula:

$$c = \frac{V_0}{R}\frac{DT_s}{\Delta V_0} \tag{4}$$

– Prepared By: Dr. Shaikh Mo Suhel (PhD, M.Tech, GATE, B.E Electrical)
Associate Professor & Head of Electrical Department

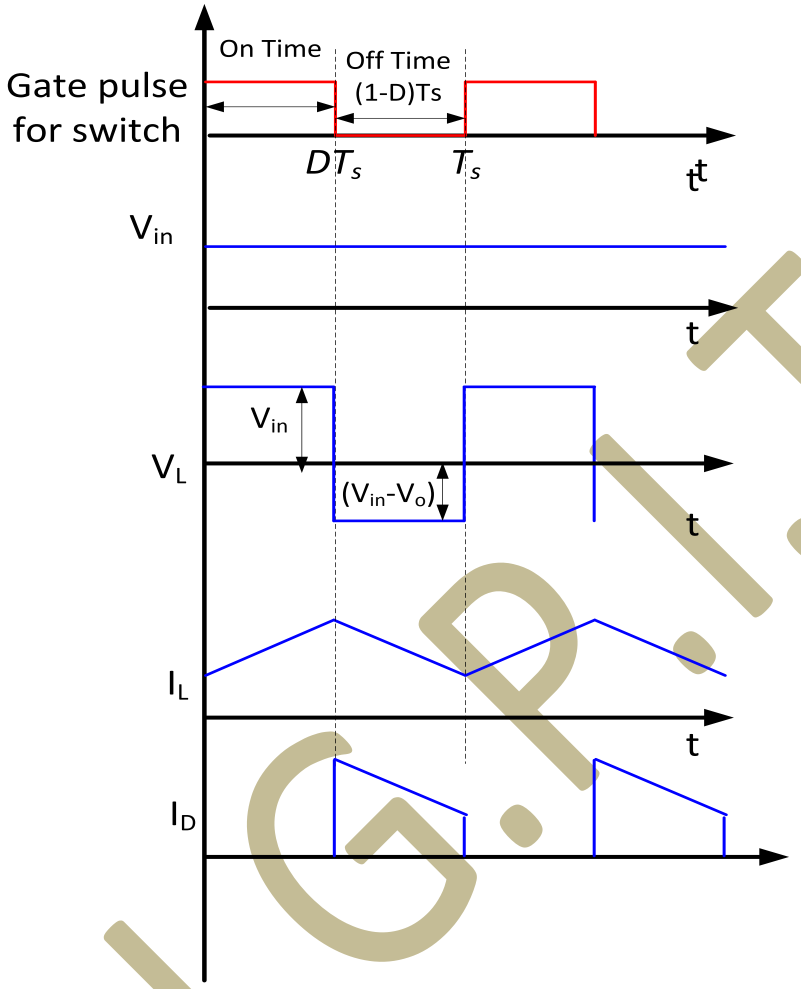


Fig.10 Boost Converter waveforms [2]

Example: Determine the inductor size (*L*) and capacitor size (*C*) for continuous conduction operation mode of the converter that limits the inductor current ripple to 20% and the capacitor voltage ripple content to 4%:

$V_0 = 36$ V and R_0=10 ohm so $I_{0\ avg}$=36/10=3.6 Amp.

Inductor current (input current)=3.6/(1-D)=3.6/(1-0.66)=10.58Amp

Now ΔI_L=10.58*0.2=2.11 Amp (20% is given)

From equation (3):

$$L=\frac{V_{in}}{\Delta I_L}DT_s=\frac{12}{2.16}0.66\times\frac{1}{120000}=30.58uH$$

Similarly, from equation (4):

$$c=\frac{V_0}{R}\frac{DT_s}{\Delta V_0}=\frac{36}{10}\frac{0.667}{1.44\times120000}=13.87\text{uF}$$

Determine the boundary load value of *Ro*

Avg. value of Load current

$$I_{o\ avg}=\frac{V_{0\ avg}}{R}$$

Input and output current relation is:

$$I_{s\ avg}=\frac{I_{0\ avg}}{(1-D)}$$

So,

$$I_{s\ avg}=\frac{V_{0\ avg}}{R(1-D)}=\frac{V_{in}}{R(1-D)^2}$$

Now this average input source current should greater than the half of the ripple value to operate converter in continuous mode, So,

$$I_{s\ avg}=\frac{V_{in}}{R(1-D)^2}\geq\frac{\Delta I_L}{2}$$

$$\frac{V_{in}}{R(1-D)^2}\geq\frac{V_{in}}{2L}DT_s$$

$$R\leq\frac{2L}{(1-D)^2DT_s}$$

This is the critical values of Resistance for boundary condition.

– Prepared By: Dr. Shaikh Mo Suhel (PhD, M.Tech, GATE, B.E Electrical)
Associate Professor & Head of Electrical Department

DC-DC CONVERTER Lect:4 (Buck-boost Converter)

The Circuit configuration of buck-boost converter is shown in Fig.1. The output voltage of the buck-boost converter can be either higher or lower than the input voltage.

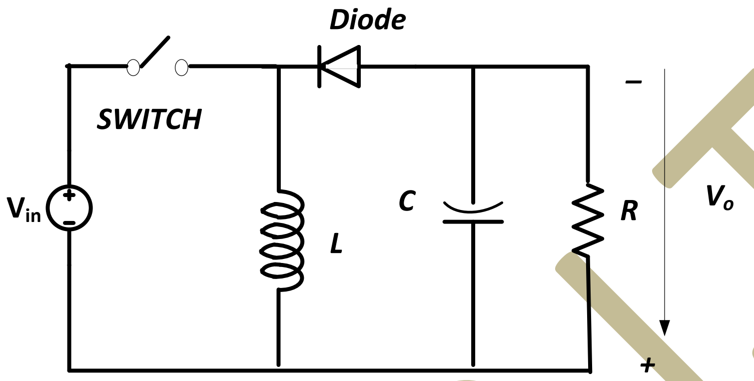


Fig.1 Circuit diagram of Buck-boost converter

Basic principle of operation:

Mode 1: when switch is ‘ON’. Inductor starts to store energy and hence current rises through inductor. Voltage across inductor:

$$V_L = V_{in}$$

Now inductor voltage during DTs interval:

$$L\frac{I_{\max} - I_{\min}}{DT_s - 0} = V_{in}$$

$$\Delta I_L = \frac{V_{in}}{L} DT_s \tag{1}$$

The rate of change of inductor current is a constant, indicating a linearly increasing inductor current. The capacitor is large enough to maintain constant output voltage.

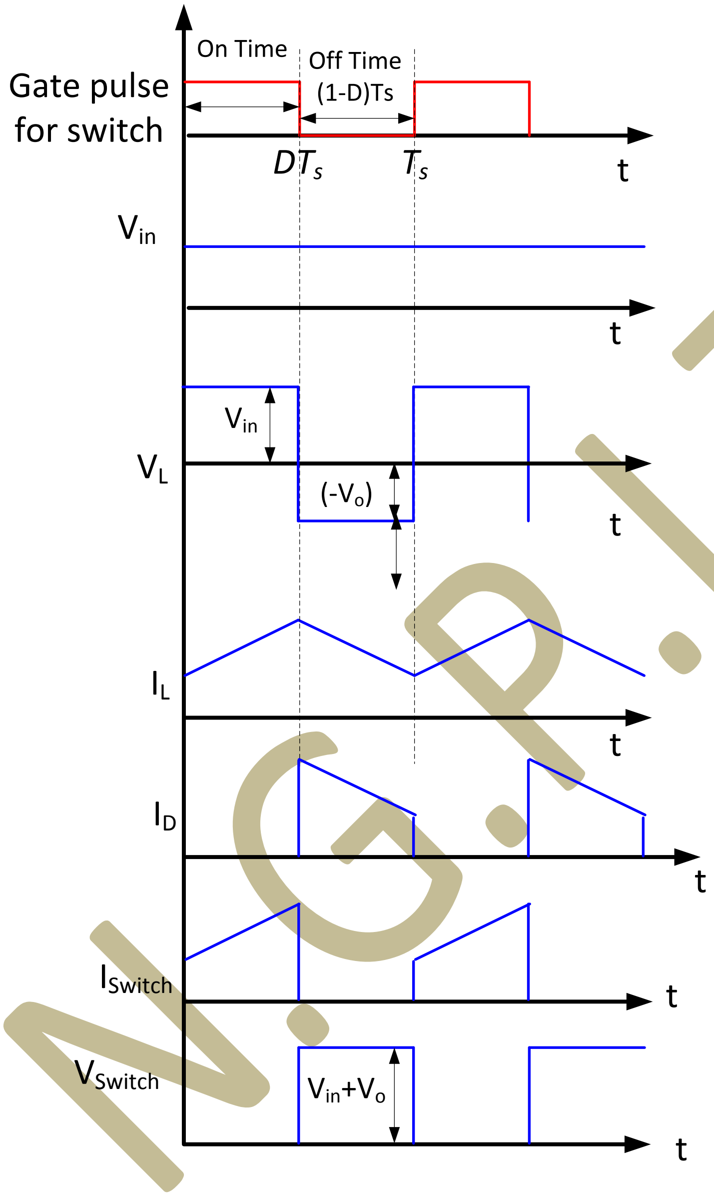


Fig. 2 Buck-boost converter: switching pulses, voltage and current waveforms

Mode 2: when switch is ‘OFF’. During this interval, inductor current cannot die down instantaneously. Inductor starts to discharge and hence change its polarity. As the polarity of induce emf is reversed and diode is forward biased. Now, inductor voltage

$$V_L = V_0$$

So similar to above analysis, inductor current during (1-D)Ts interval:

$$\Delta I_L = \frac{V_0}{L}(1-D)T_s \qquad (2)$$

During a steady state both (1) and (2) must be equal and hence equating:

$$\Delta I_L = \frac{V_0}{L}(1-D)T_s = \frac{V_{in}}{L}DT_s$$

$$V_0 = -V_{in}\frac{D}{1-D}$$

Equation shows that the output voltage has opposite polarity from the source voltage. Output voltage magnitude of the buck-boost converter can be less than that of the source or greater than the source, depending on the duty ratio of the switch. If D > 0.5, the output voltage is larger than the input; and if D < 0.5, the output is smaller than the input. Therefore, this circuit combines the capabilities of the buck and boost converters. Polarity reversal on the output may be a disadvantage in some applications

Compare buck, boost and buck-boost converter with reference to technical parameters.

Topology selection criterion:

Criterion	Buck	Boost	Buck-Boost
Switch (Voltage)	V_{in}	V_o	$(V_{in}+V_o)$
Switch (Current)	Io	I_{in}	$(I_{in}+I_o)$
Switch (I_{rms})	$\sqrt{D}\ Io$	$\sqrt{D}\ I_{in}$	$\sqrt{D}\ (I_{in}+I_o)$
Switch (I_{avg})	$D\ Io$	$D\ I_{in}$	$D(I_{in}+I_o)$
Diode (I_{avg})	$(1-D)\ Io$	$(1-D)\ I_{in}$	$(1-D)\ (I_{in}+I_o)$
I_L	Io	I_{in}	$(I_{in}+I_o)$
Effect of L on C	Significant	Little	Little
Pulsating Current	input	output	both

DC-DC CONVERTER Lect:6

Forward Converter:

The forward converter, shown in Fig. 1, is another magnetically coupled dc-dc converter. The switching period is Ts, the switch is closed for time DTs and open for (1 - D)Ts. Steady-state operation is assumed for the analysis of the circuit, μ_r= finite (magnetizing current is finite), and the current in inductance L is assumed to be continuous.

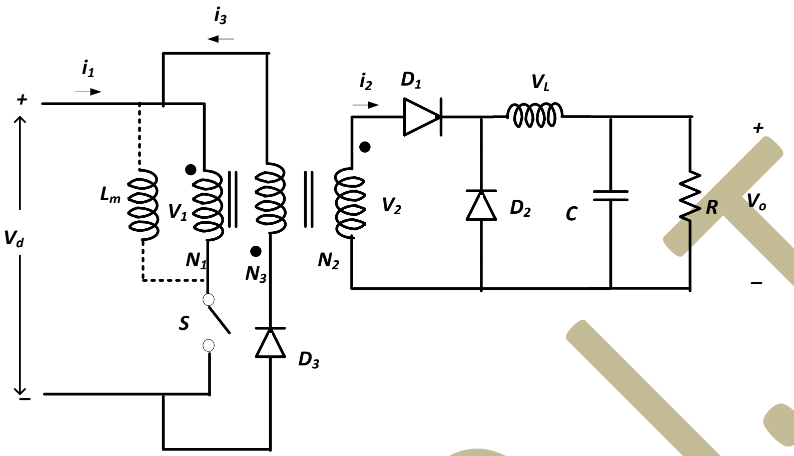
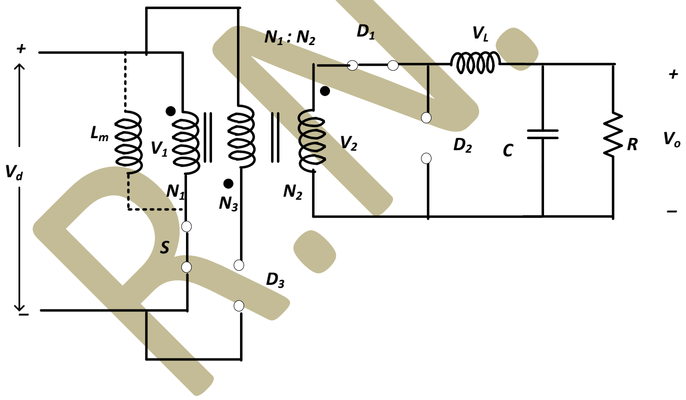


Fig.1 Forward Converter

Principle of operation:

The converter operates at high frequency and avoids the core saturation. This circuit is operates in two modes of operation.

Mode 1: when switch ‘S’ is close ($0 < t < t_{on}$):



- All dot become positive

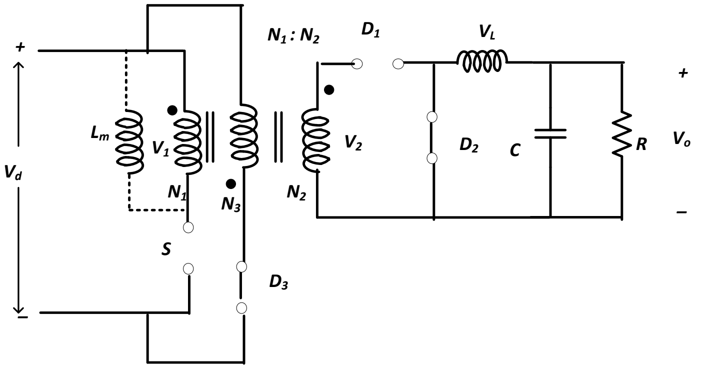
Diode D1 is forward bias and Diode D_3 and D_2 are reversed biased. I_m increase linearly and i_1 also increases linearly. Voltage induce in tertiary winding $V_d \frac{N_3}{N_1}$

Volt appear across D_3 is $V_d\left(1+\frac{N_3}{N_1}\right)$

Volt appear across D_2 is $V_d \frac{N_2}{N_1}$

– Prepared By: Dr. Shaikh Mo Suhel (PhD, M.Tech, GATE, B.E Electrical)
Associate Professor & Head of Electrical Department

Mode 2: when switch 'S' is Open ($t_{on} < t < T_s$):



D3 start conducting because $\frac{d\phi}{dt}$ is negative. all '•' become negative.

Voltage across primary winding

$V_1 = -{}^{N_1}\!/_{N_3} V_d$ and $i_3 = i_m {}^{N_1}\!/_{N_3}$

Forward converter preferably operates in discontinuous mode (i.e., flux in the core should be zero, completely reset the core)

$$\uparrow d\phi = \frac{V_d DT}{N_1}$$

At, t=tm (=time when flux reaches zero see Fig.2)

$\downarrow d\phi = \frac{V_d}{N_3} t_m$; increment and decrement of the flux should remain same so, $t_m = \frac{N_3}{N_1} DT$

For discontinuous mode: $t_m < (1-D)T$

D must be limited to $D_{\max}$ such that

$$t_m = (1-D)T$$

$\frac{N_3}{N_1} DT = (1-D)T$ and hence $\frac{N_3}{N_1} D_{\max} T = (1-D_{\max})T$

$D_{\max} = \frac{1}{1 + {}^{N_3}\!/_{N_1}}$ $D_{\max} = \frac{1}{2} if \; N_3 = N_1$

If D>0.5 in above case, then im will not become zero, core will saturate. So we should keep D<0.5.

– Prepared By: Dr. Shaikh Mo Suhel (PhD, M.Tech, GATE, B.E Electrical)
Associate Professor & Head of Electrical Department

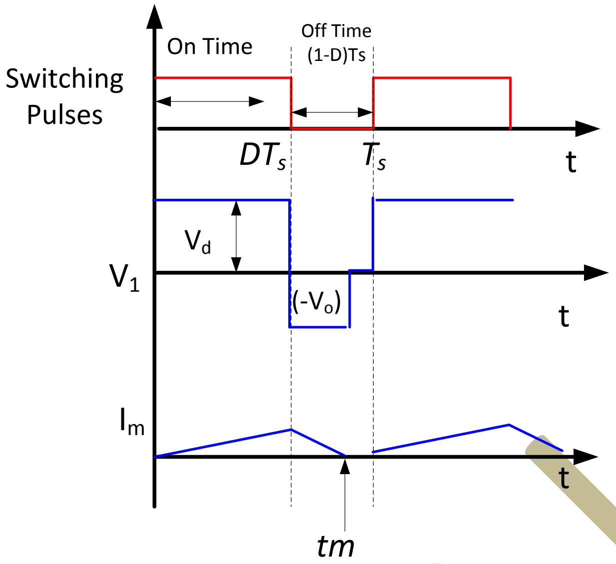


Fig.2 Magnetizing current and voltage across the primary

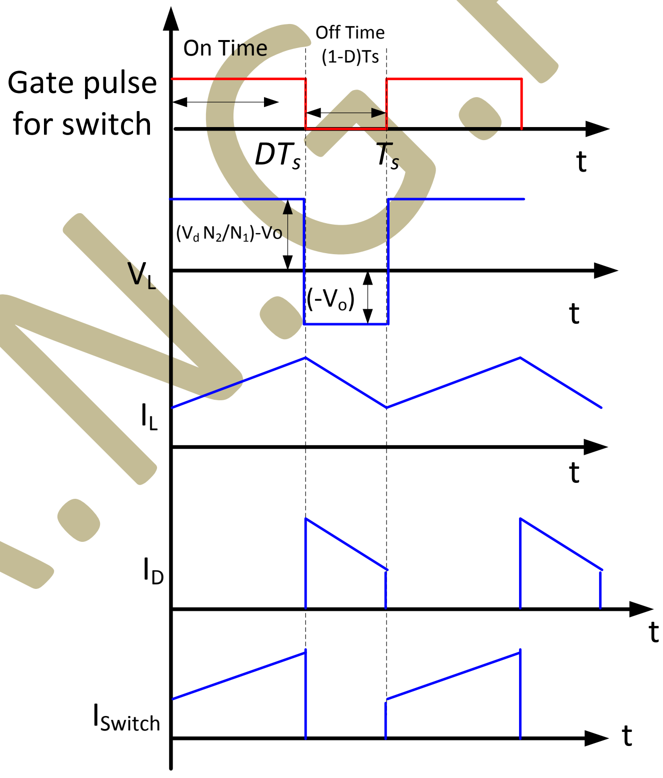


Fig. 3 Forward converter waveforms

– Prepared By: Dr. Shaikh Mo Suhel (PhD, M.Tech, GATE, B.E Electrical)
Associate Professor & Head of Electrical Department

DC-DC CONVERTER Lect:7

Push-Pull Converter:

Fly back and forward converter opertes in 1^{st} quadrant and discontinuous mode only. The circuit configuration of Push-pull converter is shown in Fig. 1. Anti-parallel diode shown dotted are needed to provide a path for the current due to leakage flux of the transformer. Here bidirectional core excitation, so core utilization is improved. The switching pulses are deveoped such that:

For t=0 to t=DT/2 ; T_1 is on and T_2 is off

For t=DT/2 to T/2; T_1 and T_2 both are off (Δ interval)

For t=T/2 to t=(1+D)T/2; T_1 is off and T_2 is on

For t=(1+D)T/2 to T ; T_1 and T_2 both are off (Δ interval)

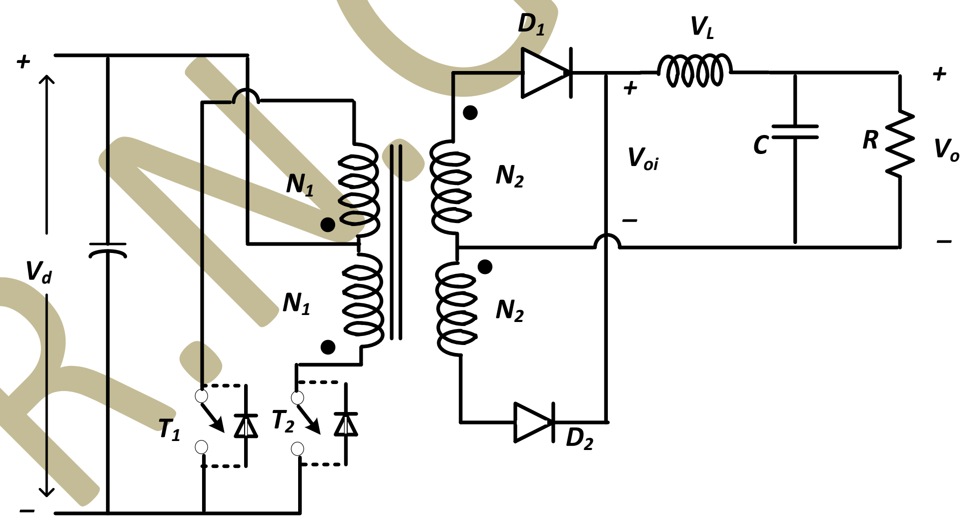
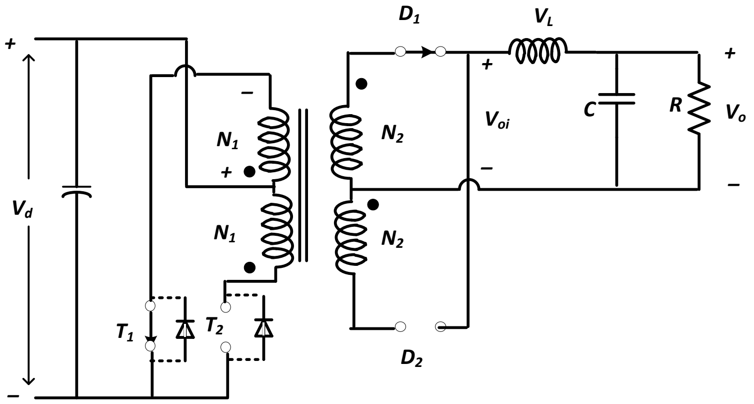


Fig.1 Push-pull Converter

Principle of operation:

When switch ‘T_1’ is ‘ON’ (0 < t < DT/2) and T2 is ‘OFF’:



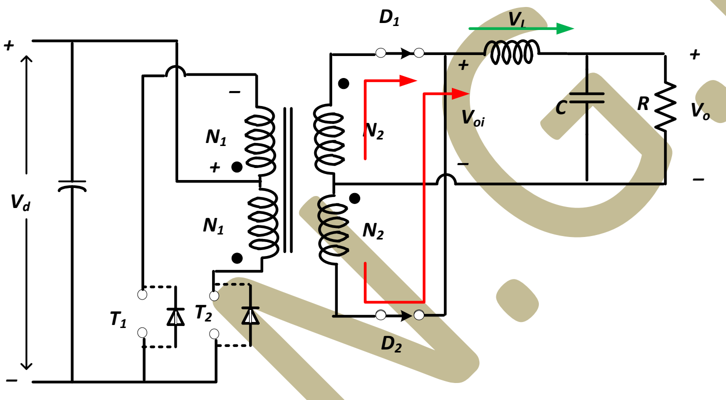
All dot become positive, Primary winding is excited with polarity as shown. Diode D_1 is forward biased. Voltage across inductor is :

$$V_L = \frac{N_2}{N_1} V_d - V_o \qquad (1)$$

Voltage across the switch (T_2) $=> V_{T2} = 2V_d$

Voltage across the diode (D_2) $=> V_{D2} = 2V_d \frac{N_2}{N_1}$

When both the switches are off (Δ interval):



Energy stored in the inductor causes the current to flow in the secondary winding through both the diodes. $i_{D1} = i_{D2} = -\frac{1}{2} i_L$

Voltage across secondary winding

$$V_L = -V_O$$

When switch 'T_2' is 'ON' ($T/2 < t < (1+D)T/2$) and T_1 is 'OFF':

Here core excitation is reverse. All dot become negative. Diode D_2 is forward biased. All other states such as Voltage across the inductor, output voltage etc. remains same such as when T_1 is ON and T_2 is off.

When both the switches are off (Δ interval):

Similar state as discussed earlier.

Now, for the inductor case volt-sec balance:

$$\left(\frac{N_2}{N_1}V_d - V_o\right)\frac{1}{2}t_{on} = V_o\left(T-\frac{1}{2}DT\right) \qquad => \qquad \frac{V_o}{V_d} = 2\frac{N_2}{N_1}D$$

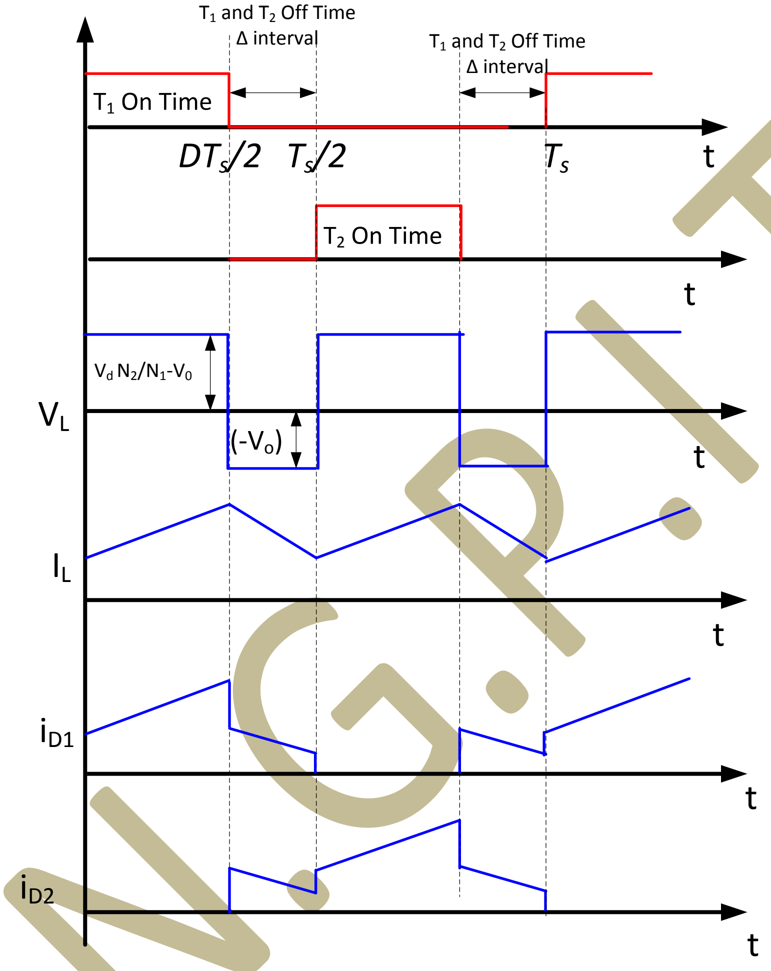


Fig. 2 Push-Pull converter waveforms

Limitations: Required identical turns (N_1=N_2) to symmetrical flux distribution

Small blinking time (must) to avoid turning both the switch on simultaneously.

– Prepared By: Dr. Shaikh Mo Suhel (PhD, M.Tech, GATE, B.E Electrical)
Associate Professor & Head of Electrical Department

DC-DC CONVERTER Lect:8

Half-bridge Converter:

The circuit configuration of half-bridge converter is shown in Fig. 1. The operation of half-bridge converter is similar to push-pull converter. Anti-parallel diodes shown dotted are needed to provide a path for the current due to leakage flux of the transformer. Here bidirectional core excitation, so core utilization is improved. The switching pulses are developed such that:

For t=0 to t=DT/2 ; T_1 is on and T_2 is off

For t=DT/2 to T/2; T_1 and T_2 both are off (Δ interval)

For t=T/2 to t=(1+D)T/2; T_1 is off and T_2 is on

For t=(1+D)T/2 to T ; T_1 and T_2 both are off (Δ interval)

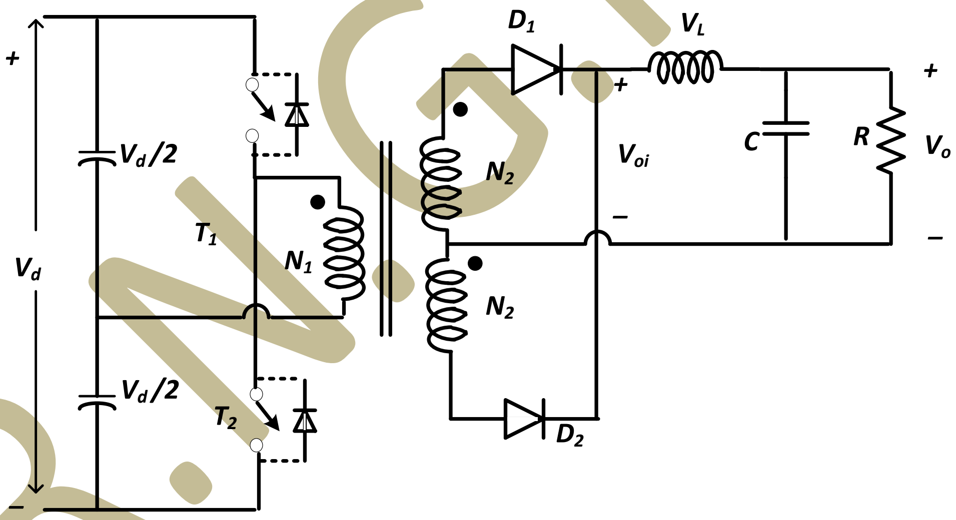
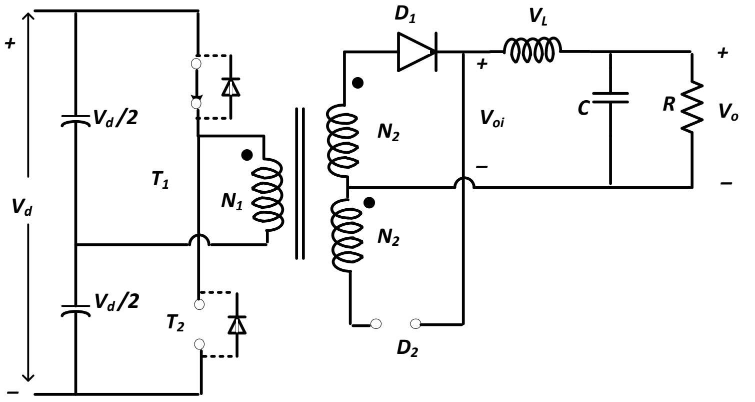


Fig.1 Half-bridge DC-DC Converter

Principle of operation:

When switch ‘T1’ is ‘ON’ (0 < t < DT/2) and T2 is ‘OFF’:



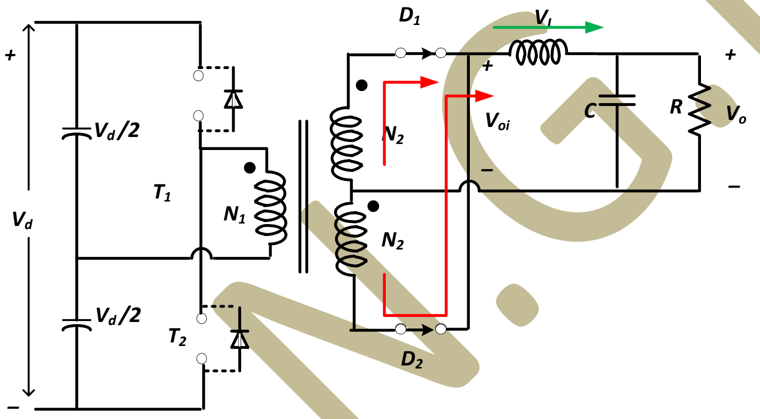
All dot become positive, Primary winding is excited with polarity as shown. Diode D_1 is forward biased. Voltage across inductor is

$$V_L = \frac{N_2}{N_1}\frac{V_d}{2} - V_o \qquad (1)$$

Voltage across the switch (T_2) => $V_{T2} = V_d$

Voltage across the diode (D_2) => $V_{D2} = V_d \dfrac{N_2}{N_1}$

When both the switches are off (Δ interval):



Energy stored in the inductor causes the current to flow in the secondary winding through both the diodes. $i_{D1} = i_{D2} = -\frac{1}{2} i_L$

Voltage across secondary winding

$$V_L = -V_O$$

When switch 'T$_2$' is 'ON' (T/2 < t < (1+D)T/2) and T$_1$ is 'OFF':

Here core excitation is reverse. All dot become negative. Diode D_2 is forward biased. All other states such as Voltage across the inductor, output voltage etc. remains same such as when T_1 is ON and T_2 is off.

When both the switches are off (Δ interval):

Similar state as discussed earlier.

Now, for the inductor case volt-sec balance:

$$\left(\frac{N_2}{N_1}\frac{V_d}{2}-V_o\right)DT-V_o\left(\frac{1}{2}-DT\right)=0 \qquad => \qquad \frac{V_o}{V_d}=\frac{N_2}{N_1}D$$

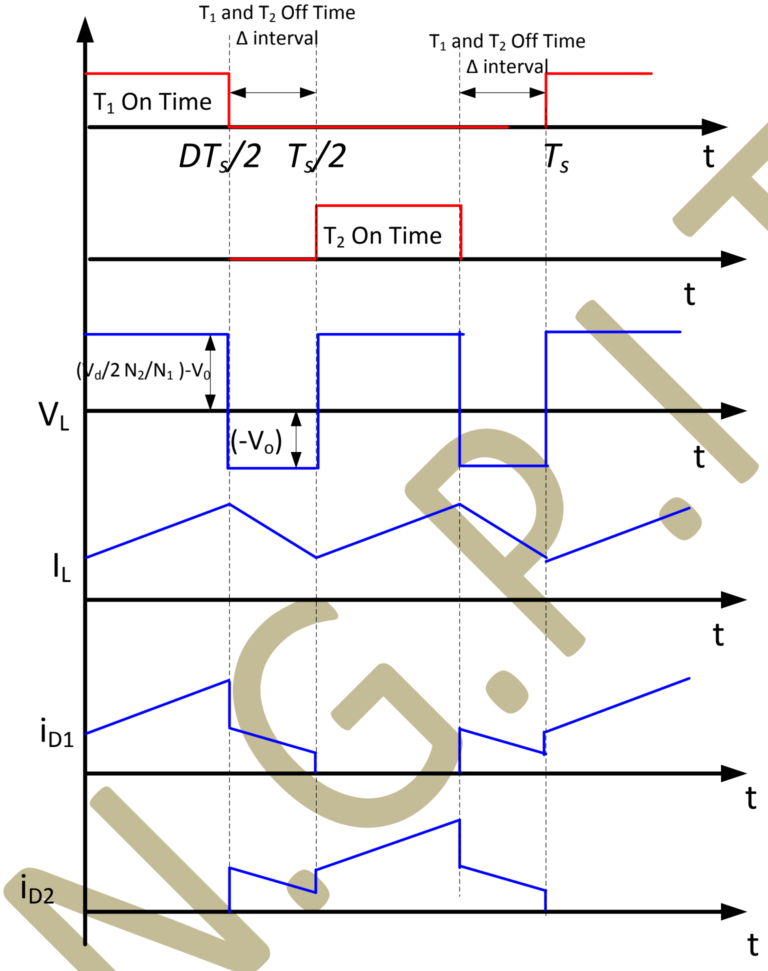


Fig. 2 Half-Bridge converter waveforms

Limitations: Required identical turns (N_1=N_2) to symmetrical flux distribution

Small blinking time (must) to avoid turning both the switch on simultaneously

Full-bridge Converter:

The circuit configuration of ful-bridge converter is shown in Fig. 1. The operation of full-bridge converter is similar to push-pull converter. Anti-parallel diodes shown dotted are needed to provide a path for the current due to leakage flux of the transformer. Here bidirectional core excitation, so core utilization is improved.

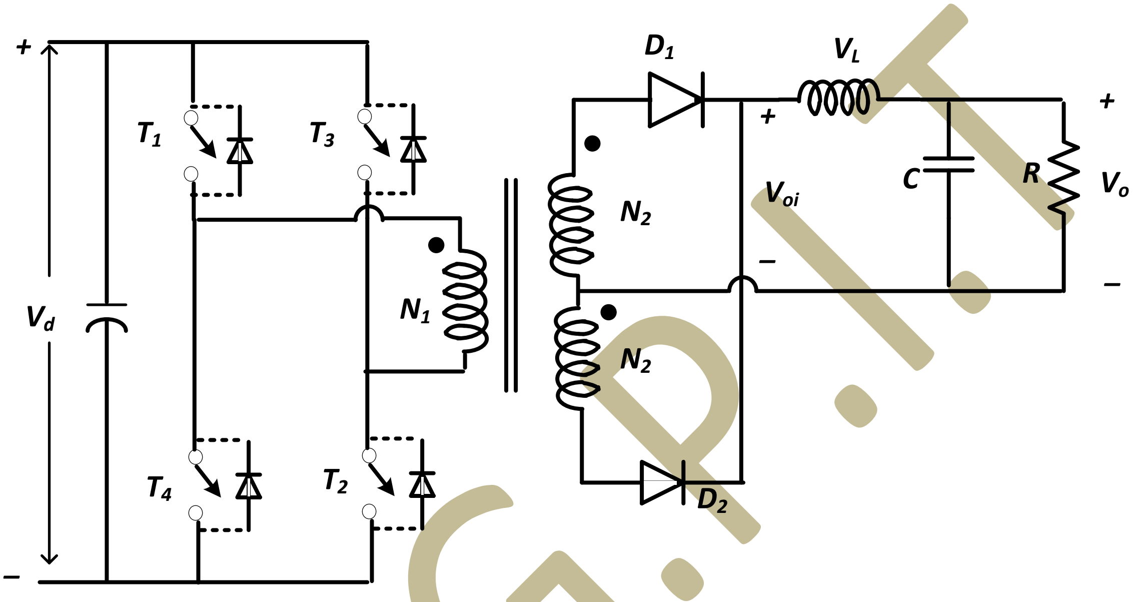
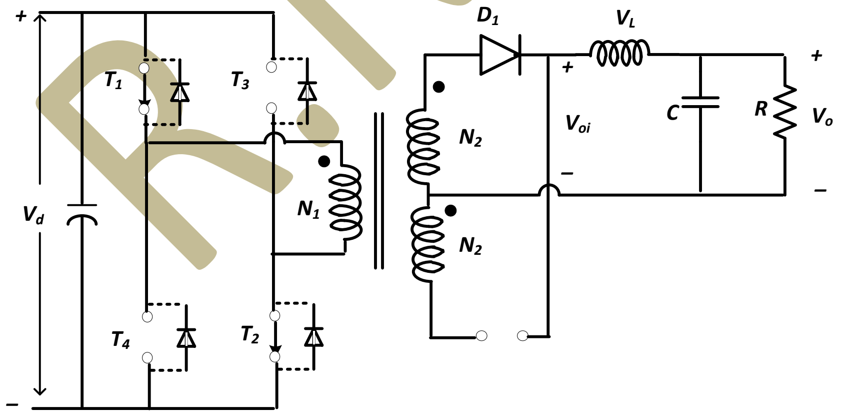


Fig.1 Full-bridge DC-DC Converter

Principle of operation:

When both the switch ‘T1’ and ‘T2’ are ‘ON’ ($0 < t < DT/2$) :



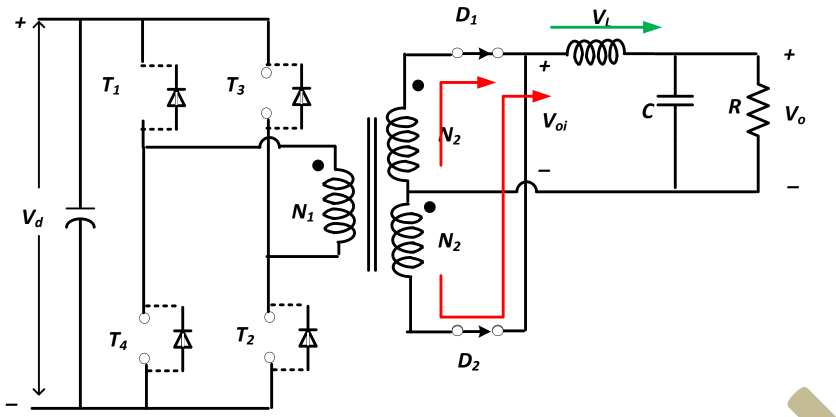
All dot become positive, Primary winding is excited with polarity as shown. Diode D_1 is forward biased. Voltage across inductor is

$$V_{oi} = \frac{N_2}{N_1} V_d$$

$$V_L = \frac{N_2}{N_1} V_d - V_o \qquad (1)$$

Voltage across the switch (T_3 and T_4) $\Rightarrow V_{T3} = V_{T4} = V_d$

When all four switches are off (Δ interval):



Energy stored in the inductor causes the current to flow in the secondary winding through both the diodes. $i_{D1} = i_{D2} = -\frac{1}{2} i_L$

Voltage across secondary winding

$$V_{oi} = 0$$

$$V_L = -V_O$$

When switch ‘T$_3$’ and ‘T$_4$’ are ‘ON’ (T/2 < t < (1+D)T/2):

Here core excitation is reverse. All dot become negative. Diode D$_2$ is forward biased. All other states such as Voltage across the inductor, output voltage etc. remains same such as when T$_1$ is ON and T$_2$ is off.

When both the switches are off (Δ interval):

Similar state as discussed earlier.

Now, for the inductor case volt-sec balance:

$$\left(\frac{N_2}{N_1}V_d - V_o\right)DT - V_o\left(\frac{1}{2} - DT\right) = 0 \qquad => \qquad \frac{V_o}{V_d} = 2\frac{N_2}{N_1}D$$

For the same input and output voltage: $\left(\frac{N_2}{N_1}\right)_{Half-Bridge} = 2\left(\frac{N_2}{N_1}\right)_{full-Bridge}$

Neglecting magnetizing current: $\left(I_{switch}\right)_{Half-Bridge} = 2\left(I_{switch}\right)_{full-Bridge}$

Therefore, large power rating it is advantageous to use full-bridge converter

– Prepared By: Dr. Shaikh Mo Suhel (PhD, M.Tech, GATE, B.E Electrical)
Associate Professor & Head of Electrical Department

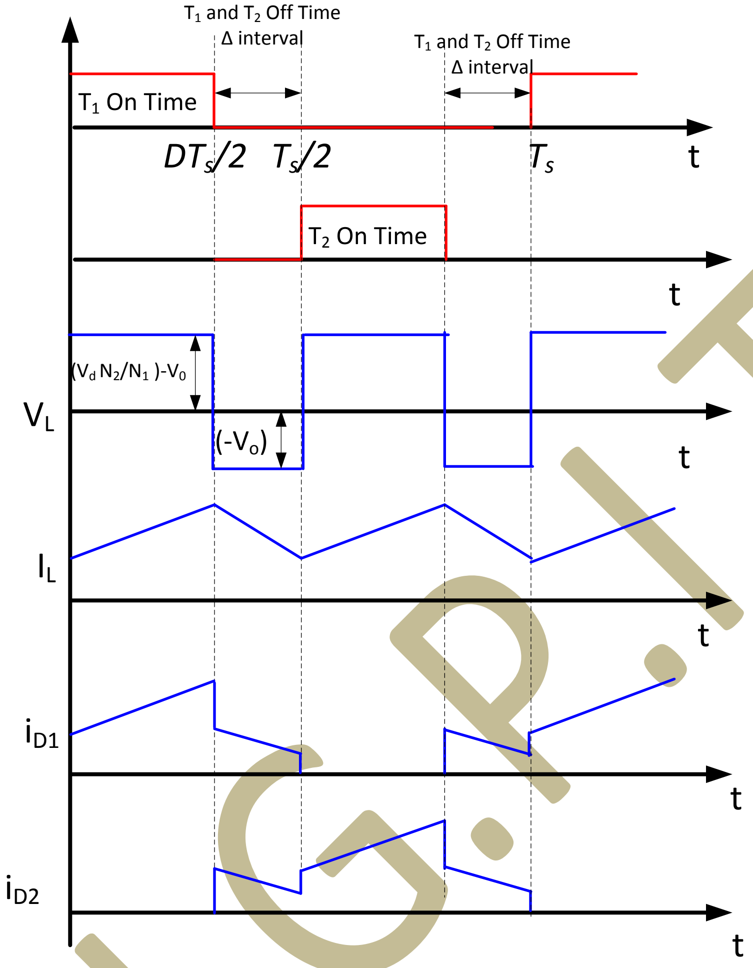


Fig. 2 Full-Bridge converter waveforms

Resonant Converter Lect

Class-E Resonant Converter:

The circuit configuration of Class-E resonant converter is shown in Fig. 1. This circuit consist only one switch and hence low switching losses and high efficiency can be achieved.

- Very popular in low power application (High frequency electronic lamp ballast)
- Normally used for fixed output voltage

- Output voltage can be varied by varying switching frequency

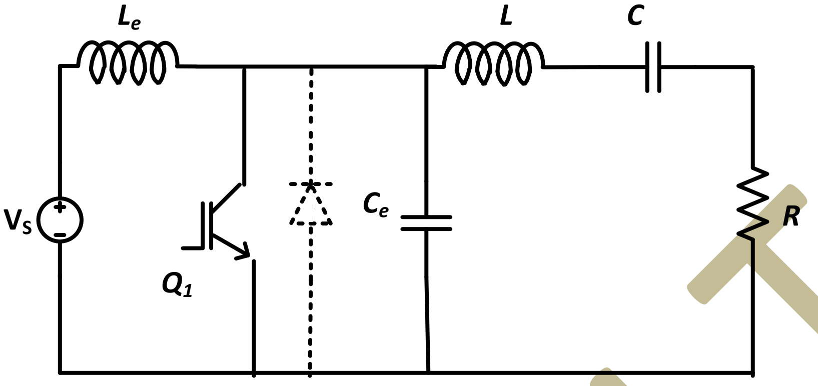
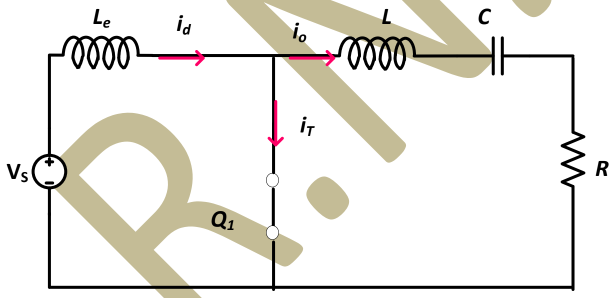


Fig.1 Class-E Resonant Inverter

Principle of operation:

When switch ‘Q1’ is ‘ON’:

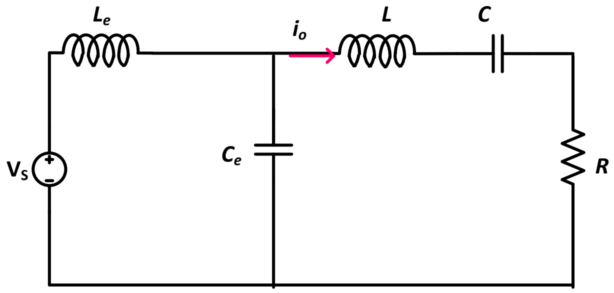
- Input inductor is sufficiently large, hence input to the converter is a dc current source I_d.
- $i_T = i_d + i_o$
- i_o is almost sinusoidal, the value of L & C are chosen to have a high quality factor Q≥7 and low damping ration δ≤0.07.



- when switch is turned off, because of capacitor Ce voltage across the switch builds up slowly. This aloowing zero-voltage turn-off of the switch.

When switch ‘Q1’ is ‘OFF’:

- $i_c = i_d + i_o$ builds voltage slowly reaches its peak and evantually comeback to zero. at which instant the switch is turned back ‘ON’



- When switch voltage falls to zero $i_c = c_e \frac{dV_T}{dt}$ thus switch voltage tends to be negative. To limit this voltage antiparallel diode is connected.

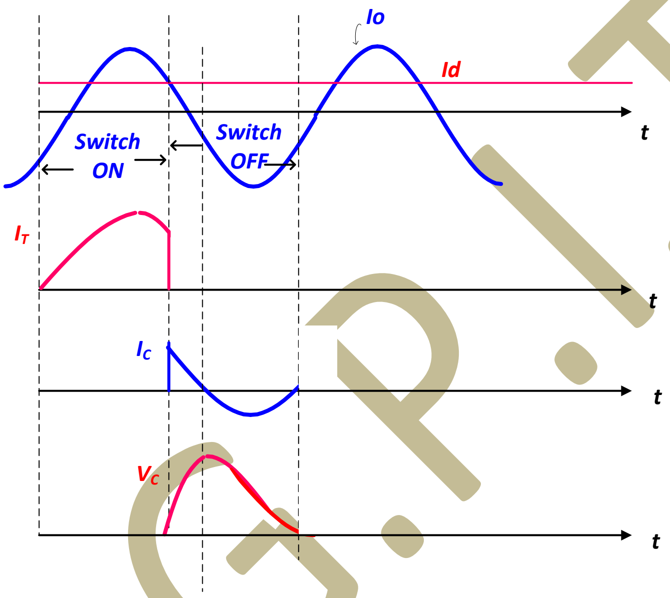


Fig. 2 Waveforms Resonant Converter

- Switching frequency is slightly higher than the resonant frequency.
- Increase in fs, io and vo decreases