PE10

DC-DC CONVERTERS.

The dc-dc converters are widely used in regulated switch-mode dc power supplies and in dc motor drive applications. The input is unregulated dc voltage, which is obtained by rectifying the line voltage, and therefore it will fluctuate due to changes in the line-voltage magnitude.

1. Non-switching dc-dc converter (dc choppers)
2. switching dc-dc converters
   - Step-down (buck) converter
   - Step-up (boost) converter
   - Step-down/step-up (buck-boost) converter
   - Cúk converter
   - Full-bridge converter

Of these five converters, only the step down and step up are basic converter topologies. Both the buck-boost and Cúk converters are combinations of the two basic topologies. The full-bridge converter is derived from the step-down converter.

CONTROL OF dc-dc CONVERTERS

In a dc-dc converter with a given input voltage, the average value of output is controlled by changing the switch on and off durations.

Here there are two methods

1. Keeping the switching frequency constant

This method is name as Pulse-width Modulation technique. With a constant $T_p = t_{ON} + t_{OFF}$, the switch duty ratio $D = \lambda$, which is defined as the ratio of the on duration to the switching time period, is varied.

2. Keeping the pulse width constant.
The switching frequency is varied and this method is named as Frequency Modulation Technique. Variation in the switching frequency makes it difficult to filter the ripple components in the output and input waveforms of the converter.

In PWM technique, the frequency of repetitive waveform with a constant peak, which is shown to be a saw-tooth, establishes the switching frequency. This frequency is kept constant and chosen to be in a few kilohertz to a few hundered kilohertz.

The control voltage is obtained by amplifying the error or difference of the actual output voltage and its desired value.

$$\lambda = D = \frac{T_{ON}}{T}$$

T_{ON} = ton duration
T = period time of switching

$$f = \frac{1}{T}$$ switching frequency.

Compulsory Conditions

1 - The V_L voltage must change its polarity with switching

2 - The balance $V_L \times t$ = Volt×second must be provided

For Buck Converter

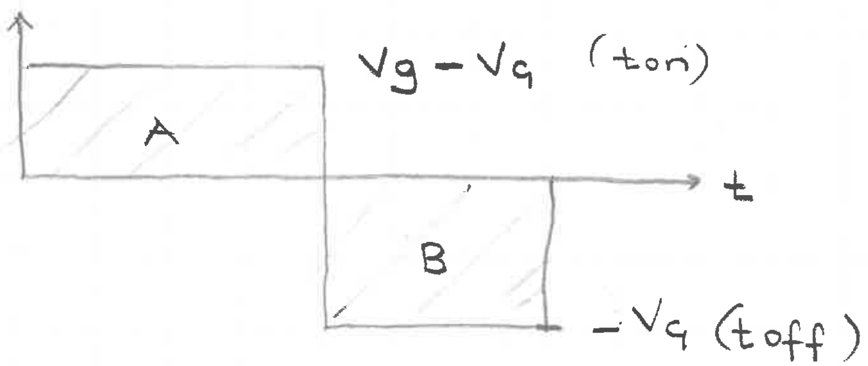
$$V_L + V_q - V_g = 0$$
$$V_L = V_g - V_q$$

for on-state

$$V_L = -V_q$$

for off-state.

For polarity change $V_g > V_q$



The calculation based on voltage×time balance

$$(V_g - V_q) \cdot t_{on} = V_q \cdot \underbrace{t_{off}}_{T_s - t_{on}} \Rightarrow \frac{V_q}{V_g} = \frac{t_{on}}{T_s} = D = \eta$$

$$i_L = i_c + i_q$$

If $i_L > i_q$ C is charge-state

$i_L < i_q$ C is discharge-state

Basic Specifications of DC-DC CONVERTERS.

- The control is linear.
- The output value is varied as average value.
- There are ripples both input and output side.
- Forced-commutation is needed
- They are high frequency circuits.
- Usually for lower power levels and high frequencies MOSFET, for the power and frequency values above middle level ones, IGBT is prefered.

STRUCTURES OF DC CHOPPERS.

FOR A QUADRANT DC Chopper

Resistive load

I_a = output current = U_a / R i = lower case for instant value

$i_a = i_T = i_d$ i_d = Dc supply current.

$i_D = 0$ i_D = Diode current

$$U_a = \frac{1}{T_p}\int_0^{T_i} U_d \cdot dt = \frac{T_i}{T_p} \cdot U_d = \lambda \cdot U_d = D \cdot U_d$$

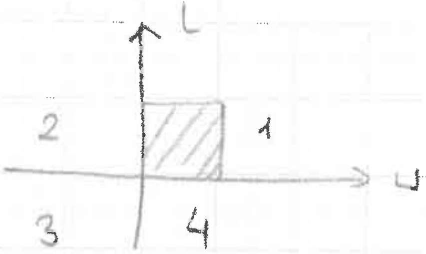
$$0 \leq D = \lambda < 1 \qquad 0 \leq U_a \leq U_d$$

Inductive Load

$i_a = i_T + i_D$

$I_T = \lambda \cdot I_a$

$I_D = (1 - \lambda) I_a$



The aim of using diode is to protect the circuit elemen from excessive back-emf due to inductor.
Output voltage is uni-directional and positive.

TWO QUADRANT DC CHOPPER

$$U_a = \frac{1}{T_p}\left[\int_0^{T_i} U_d \cdot dt + \int_{T_i}^{T_p} -U_d \cdot dt\right]$$

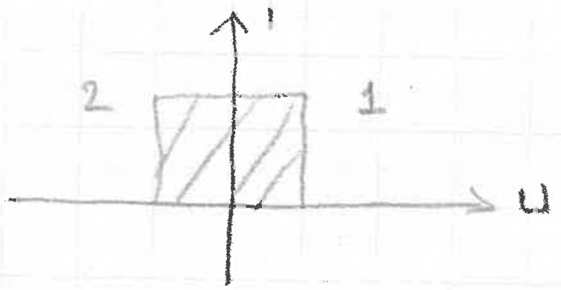
$$U_a = \frac{1}{T_p} U_d \left[T_i - (T_p - T_i)\right]$$

$$U_a = \frac{1}{T_p}(2T_i - T_p)\, U_d = (2\lambda - 1)\cdot U_d$$

$$U_a = (2\lambda - 1)\cdot U_d$$

$$0 \leq \lambda \leq 1$$

$$-U_d \leq U_a \leq U_d$$



for $\lambda < \frac{1}{2}$, $U_a < 0$
negative operation mod

for $\lambda > \frac{1}{2}$, $U_a > 0$
positive operation mode

for $\lambda = \frac{1}{2}$ $U_a = 0$
for $\lambda = 1$ $U_g = U_a$

The energy flow is from supply to load when the transistor is on-state. But it is from the load to the supply when the diode is on-state.

STEP-DOWN (BUCK) CONVERTER.

As the name implies, a step-down converter produces a lower average output voltage than the dc input voltage. Its main application is in regulated dc power supplies and dc motor speed control.

During the interval when the switch is on, the diode becomes reverse biased and the input provides energy to the load as well as to the inductor.

During the interval when the switch off, the inductor current flows, transferring some of its stored energy to the load.

When the switch is on-state, the current flowing in inductor increases linearly. For off-state, that current decreases linearly.

Inductor and capacitor constitutes a low-pass filter for ripples on output voltage.

If the current of inductor is bigger than the desired value of output current, the capacitor is charged with this excessive current. However, the output current is the lack of desired value, the capacitor supplies to output current.

$$V_a = \frac{1}{T_p}\int_0^{T_s} V_g(t)\cdot dt = \frac{1}{T_p}\left(\int_0^{t_{on}} V_g\cdot dt + \int_{t_{on}}^{T_s} 0\cdot dt\right) = \frac{t_{on}}{T_p} = D\cdot V_g = \alpha\cdot V_g$$

V_a = output voltage $\qquad$ V_g = Input voltage

STEP UP (BOOST) CONVERTER

Its main application is in regulated dc power supplies and the regenerative braking of dc motors. As the name implies, the output voltage is always greater than the input voltage.

When the switch is on, the input supplies energy to the inductor. When the switch is off, the output stage receives energy from inductor as well as from the input. So output voltage is bigger than input voltage

The inductor current increases and decreases linearly The diode is on-state due to the voltage of inductor when the power switch is off

$V_g \cdot t_{ON} + V_L \cdot t_{off} = 0$ by dividing to T_p

$V_g \cdot t_{ON} + (V_g - V_q)\, t_{off} = 0$ → $V_o = V_q$

$$\frac{V_q}{V_g} = \frac{1}{1-\lambda} \rightarrow D$$

All the current for the load is supplied by capacitor when the power switch is off-state. When the switch is on-state, the capacitor is charged.

BUCK - BOOST CONVERTER

The main application of buck-boost converter is in regulated dc power supplies. Sometimes Negative-polarity output may be desired with respect to the common terminal of the input voltage. Or sometimes the output voltage is desired to be either higher or lower than input voltage

A buck-boost converter can be obtained by cascade connection of step-up and step-down converters.

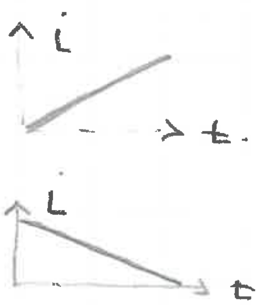
*
$$\frac{V_a}{V_g} = -D \cdot \frac{1}{1-D} = \lambda \cdot \frac{-1}{1-\lambda} \quad \text{or} \quad = \frac{-D}{1-D}.$$

The Output-to-input voltage conversion ratio is the product of the conversion ratios of two converters (assuming that switches in both converters have the same duty ratio).

When the the switched is closed, the input provides energy to the inductor and diode is reverse biased. When the switch is open, the energy stored in inductor is transferred to the output. No energy is supplied by the input during this interval.

$V_L = L \cdot \frac{di}{dt}$ for the increasing slope V_L is +

for the decreasing slope V_L is −



For that converter,

* V_a is reversed polarity of V_g

When the switch is on, Load is supplied with the current of capasitor. When the switch is off, the capasitor is charged with the current of inductor

CURRENTS IN DC/DC CONVERTERS

For Buck Converter

$U_q = U_g \cdot D$ For power balance $I_g = I_q \cdot D$

as opposite to the voltage.

From the circuit

$I_L = I_q$

$I_T = D \cdot I_L = T_{on} \cdot I_L$ $\quad I_D = (1-D) \cdot I_L = T_{off} \cdot I_L$

from Kirchhoff law

$-I_T - I_D + I_L \Rightarrow \quad I_L = I_T + I_D$

For Boost Converter

$U_q = U_g \cdot \frac{1}{1-D}$ For power balance $I_g = I_q \cdot \frac{1}{1-D}$

as opposite to the voltage.

From the circuit;

$I_L = I_g$

From Kirchhoff law

$-I_L + I_T + I_D \Rightarrow \quad I_L = I_T + I_D$.

For Buck and Boost Converter

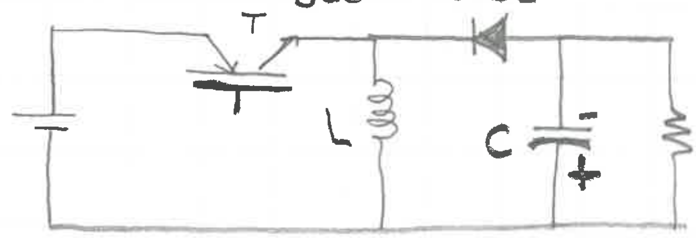
$U_q = U_g \cdot \frac{D}{1-D}$ For power balance $I_g = I_q \cdot \frac{D}{1-D}$

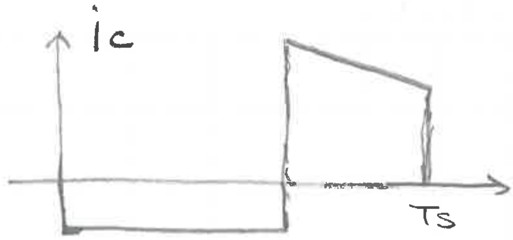
as opposite to the voltage.

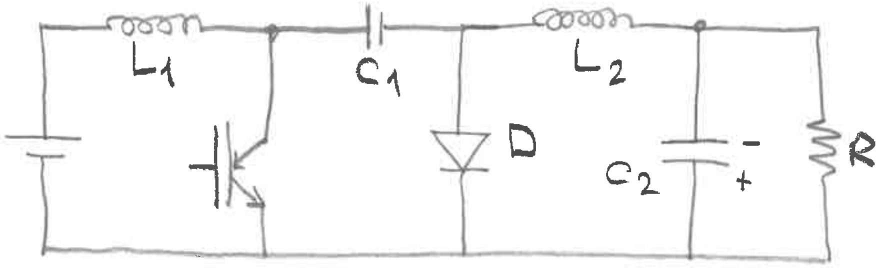
$I_g = I_T$ $\quad I_D = I_q$

$-I_T + I_g - I_q = 0 \Rightarrow \quad I_L = I_g + I_q$

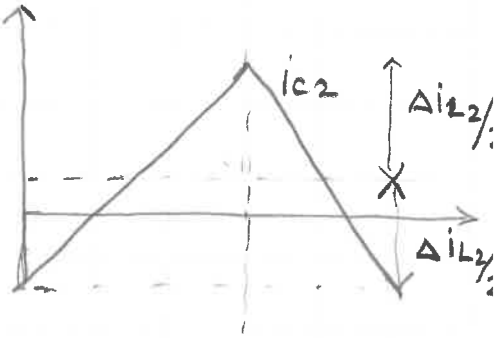
Buck-boost







CUK

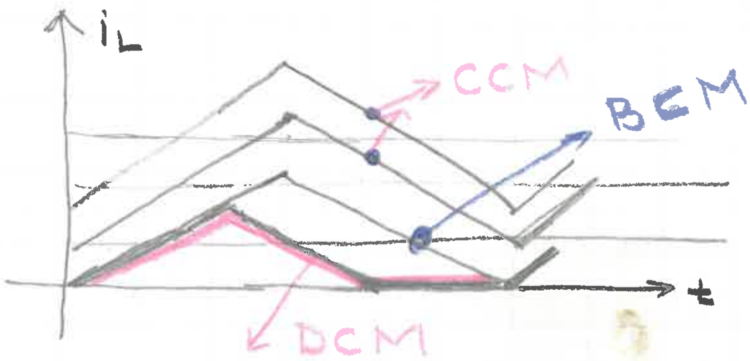


CONTROL OF DC/DC CONVERTERS.

Dc-Dc converters are operated in two different mode based on current of inductor.

1. Continous Current Mode (CCM)
2. Discontinuous Current Mode (DCM).

This mode is determined according to parameters of circuit/topology. If the $I_{L min} > 0$, this means that the converter operates in CCM mode.



BCM: Boundary Current Mode
I_L starts from zero point in BCM.

If the L value of circuit > L critic ⇒ CCM

If the L value of circuit < L critic ⇒ DCM

If $I_{L\,av} = \frac{I_{L\,peak}}{2} = \frac{V_a}{R} \Rightarrow i_{L\,peak\ to\ peak} = \frac{2 V_a}{R} = \Delta i_L$

For Buck Converter

$$V_g - V_a = L \cdot \frac{di}{dt} = L \cdot \frac{\frac{2 V_a}{R}}{D \cdot T} \quad \text{for on-state}$$

($D \cdot T \rightarrow T_{on}$)

$$V_a = L \cdot \frac{\frac{2 V_a}{R}}{(1-D)T} = V_L = L \cdot \frac{di}{dt} \quad \text{for off-state}$$

Anyone can be followed to obtain L_{critic}.

$$L_{critic} = \frac{(1-D) \cdot R \cdot T}{2} \qquad \frac{V_a}{V_g} = D$$

For Boost Converter

$$\frac{V_a}{V_g} = \frac{1}{1-D}$$

$$V_g = V_L = L \cdot \frac{di}{dt} \quad \text{for on-state}$$

$$V_a - V_g = V_L = L \cdot \frac{di}{dt} \quad \text{for off-state}$$

With a similar approach,

$$L_{critic} = \frac{D \cdot (1-D)^2 \cdot R \cdot T}{2}$$

Ex. For a boost converter, dc supply is 12 V and the desired output is 30V. Switching frequency is 25 kHz and load value is 50Ω. a) Find the D duty ratio b) For CCM, find the L_{critic} value

a) $$\frac{V_a}{V_g} = \frac{1}{1-D} = \frac{30}{12} = \frac{1}{1-D} \Rightarrow D = 0,6$$

b) $$L_{critic} = \frac{0,6\,(1-0,6)^2 \cdot 50}{2 \cdot 25.000} = 96\,\mu H$$

Any mode can be chosen based on conditions.
In DCM peak value of current is higher than the one in CCM. So, Dimensions of devices increase.
In CCM there is some energy left to provide energy for next cycle
In DCM, switching losses is lower since the inductance current starts with zero point.

Dimensions	CCM	DCM.
	Lower Ipeak and Vpeak values for switch stress which means less expensive switches	Higher Ipeak, Vpeak to stress switches which means more costly switches.
Efficiency	Higher efficiency	Lower efficiency
Zout values	Lower	Higher.