DR. ÖZGÜR ÜSTÜN 12 . 11 . 2013

INDUSTRIAL APPLICATIONS OF POWER ELECTRONICS

2013 – 2014 FALL

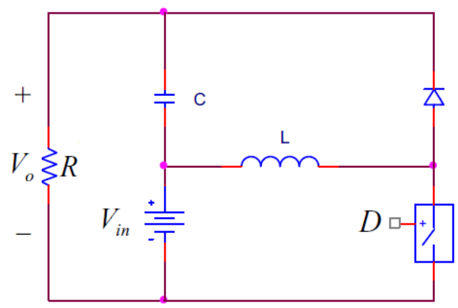
MIDTERM EXAM

QUESTIONS

1. Some concepts which are related with DC-DC power converters are given. Briefly explain;
   a) *"duty cycle", "switching frequency", "output voltage ripple" and "inductor volt-second balance".*
   b) *"continuous (CCM)", "boundary (BCM)" and "discontinuous (DCM)" conduction modes. What are the characteristic properties of these modes? Sketch three identical current waveforms for every mode. How do load resistor (R), inductor (L) and switching frequency (f_s) values affect the operation modes?*
2. What is a magnetically coupled DC-DC power converter? What are the main advantages and disadvantages of using transformers in power converters? Sketch the circuit schema of the "flyback" and "forward" converters. Explain the main differences between these two converters?
3. Propose a suitable power converter for given applications and explain why.
   a) *12V to 24V battery charger with isolation.*
   b) *Low ripple input current MPPT converter for PV modules.*
   c) *200V to 5V LED driver with constant output current.*
   d) *12V to -5V converter for analog IC power supplies.*
   e) *Power Factor Correction converter with continuous input current.*
4. A CCM buck converter is suitable for "constant output current" battery charger applications. Design a 36V to 24V battery charger with constant 9A output current. Battery voltage varies 20V to 28V between empty and charged states. Inductor and switching frequency values are given L = 200µH and f_s = 100kHz.
   a) *Calculate output power (P_o), average input current (I_d) and duty cycle (D) for empty and charged conditions.*
   b) *Calculate peak-to-peak inductor current ripple (Δi_L) for empty and charged conditions.*
   c) *Plot the input current waveforms for empty and charged conditions.*
   d) *For the worst case, plot the capacitor current and calculate the required capacitor value to obtain $\Delta v_o = 0.25V$.*
5. An electronic device with 15V / 7A ratings is supplied by a 12V battery through a DCM buck-boost converter. Switching frequency of the converter is given as 20kHz.
   a) *Calculate the critical inductor value (L_{crit}) for this converter?*
   b) *Select $L = 0.75 * L_{crit}$ and calculate D, Δ_1 and Δ_2 values.*
   c) *Plot the inductor current and inductor voltage waveforms, calculate maximum inductor current value.*
   d) *Plot the capacitor current and calculate the required capacitor value to obtain $\Delta v_o/V_o = 1\%$.*
6. A different DC-DC power converter is given at the figure. Assume CCM;

   DT_s : main switch ON – diode OFF

   $D'T_s$: main switch OFF – diode ON

   a) *Sketch two sub-circuits for DT_s and $D'T_s$ time intervals and find inductor voltage values for these sub-circuits.*
   b) *Apply inductor volt-second balance and calculate the voltage conversion ratio of the converter. Which type of a converter is this?*
   c) *What is the average value of inductor current? Find an expression for peak-to-peak inductor current ripple, maximum and minimum values of inductor current.*

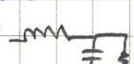
GOOD LUCK !

IAPE 2013-2014 MIDTERM (12.11.2013)

(3) Suitable converters for given applications;

a. Electrical isolation is needed, isolated converters can increase or decrease input voltages. "Forward" or "Flyback"

b. Low ripple input current means continuous input current. Since Boost Converter has inductor at input side, at CCM operation input current will be continous. "Boost"

c. Buck converter type output filters () are suitable for constant output current applications. But for given application, input to output ratio ($^{200}/_{5}$) is very high, therefore transformer must be utilized in the converter. "Forward" or "Flyback"

d. Negative output voltage is needed. "Buck-Boost"

e. Input current programming is needed and "inductor input" converters are suitable for this applications. "Boost"

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(4) $V_d = 36V$ $\quad V_o = 20V \sim 28V$ (20V ↑ empty, 28V ↑ charged) $\quad I_o = 9A$ (constant) $\quad L = 200\mu H$ $\quad f_s = 100kHz$.

a. $P_o = V_o \cdot I_o$

empty → $P_o = 20 \cdot 9 = 180W$

charged → $P_o = 28 \cdot 9 = 252W$

$I_d = \frac{P_o}{V_d}$

empty → $I_d = {}^{180}/_{36} = 5A$

charged → $I_d = {}^{252}/_{36} = 7A.$

$D = V_o/V_d$

empty → $D = {}^{20}/_{36} = 0,555$

charged → $D = {}^{28}/_{36} = 0,777.$

b. for $D \cdot T_s$ interval $v_L = V_d - V_o$ slope $= \frac{V_d - V_o}{L}$

$$\Delta i_L = \frac{(V_d - V_o)}{L} \cdot D \cdot T_s$$

empty $\rightarrow \frac{(36-20)}{200\mu} \cdot 0{,}555 \cdot \frac{1}{100k} = 0{,}444\ A.$

charged $\rightarrow \frac{(36-28)}{200\mu} \cdot 0{,}777 \cdot \frac{1}{100k} = 0{,}311\ A.$

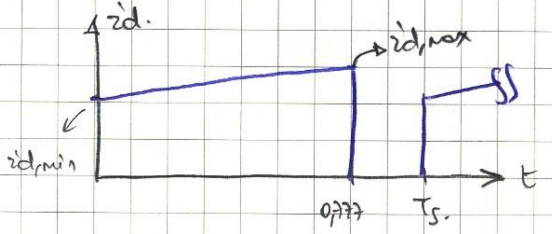
c. Input current is same as increasing part of the inductor current.

empty $\rightarrow$

$i_{d,max} = I_o + \frac{\Delta i_L}{2} = 9{,}222\ A.$

$i_{d,min} = I_o - \frac{\Delta i_L}{2} = 8{,}778 A.$

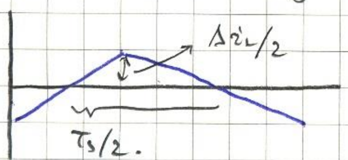
charged $\rightarrow$



$i_{d,max} = I_o + \frac{\Delta i_L}{2} = 9{,}155 A$

$i_{d,min} = I_o - \frac{\Delta i_L}{2} = 8{,}845 A.$

d. $i_C = i_L - i_o$ for all time intervals



$$\Delta Q = \frac{\Delta i_L \cdot T_s \cdot 1}{2 \cdot 2 \cdot 2} = C \cdot \Delta v_o$$

$$C = \frac{\Delta i_L \cdot T_s}{8 \cdot \Delta v_o}$$

empty $\rightarrow$ 0,444A $\rightarrow$ worst case

charged $\rightarrow$ 0,311 A.

$\Delta v_o \rightarrow$ constant

$$C = \frac{0{,}444}{8 \cdot 100000 \cdot 0{,}25} = 2{,}22\ \mu F$$

GIPTA

(5) Electronic device → 15V @ 7A → $R = 15/7 = 2,143\ \Omega$

$V_d = 12V$ $V_o = 15V$ (negative) DCM operation $f_s = 20kHz$

a • To find L_{crit}, converter must be assumed as BCM.

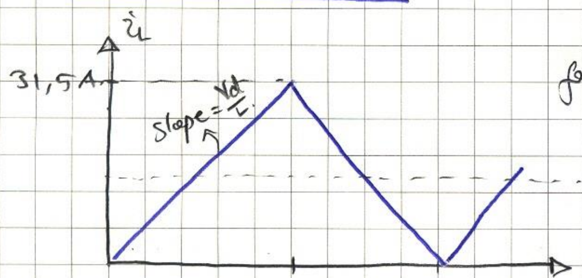
$$\frac{V_o}{V_d} = \frac{15}{12} = \frac{D}{1-D} \Rightarrow D = 5/9$$

for Buck-Boost Converter $\langle i_L \rangle_{T_s} = I_L = I_o + I_d = 7 + \frac{15 \cdot 7}{12} = 15,75A$

by formula

$$L_{crit} = \frac{R(1-D)^2}{2 f_s} = \frac{15}{7} \cdot \left(\frac{4}{9}\right)^2 \cdot \frac{1}{40k} = 10,58\ \mu H$$

by waveform



for BCM $\Delta i_L = I_{L,max} = 2 \cdot I_L = 31,5A$

slope for $DT_s = \frac{V_d}{L}$ $\Delta i_L = \frac{V_d}{L} \cdot D \cdot T_s \Rightarrow 31,5 = \frac{12}{L} \cdot \frac{5}{9} \cdot \frac{1}{20000}$

$L_{crit} = 10,58\ \mu H$

b • $L = L_{crit} \cdot 0,75 = 7,94\ \mu H$ $L < L_{crit} \Rightarrow$ DCM operation.

by formula

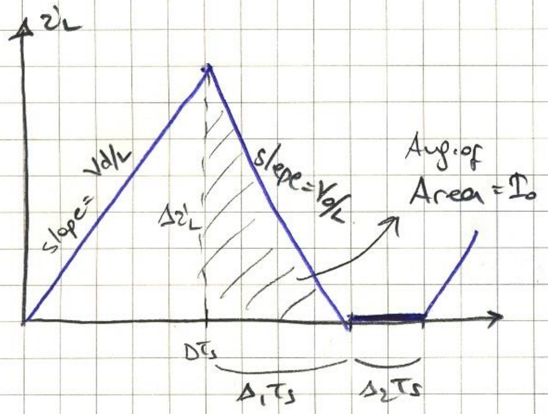
$$K = \frac{2 L f_s}{R} = \frac{2 \cdot 7,94\mu \cdot 20000}{15/7} = 0,1482$$

$\Delta_2 = 1 - D - \Delta_1 = 0,134$

$$D = \frac{V_o \cdot \sqrt{K}}{V_d} = \frac{15 \sqrt{0,1482}}{12} = 0,481$$ $\Delta_1 = \sqrt{K} = 0,385$

GIPTA

by waveform



$$\Delta i_L = \frac{V_d}{L} \cdot DT_s = \frac{V_o}{L} \Delta_1 T_s$$

$$\text{Area} = \frac{\Delta i_L \cdot \Delta_1 T_s}{2}$$

$$\text{Average of Area} = \frac{\Delta i_L \cdot \Delta_1}{2} = 7$$

$$7 = \frac{V_o}{L} \cdot \Delta_1 \cdot T_s \cdot \frac{\Delta_1}{2} =$$

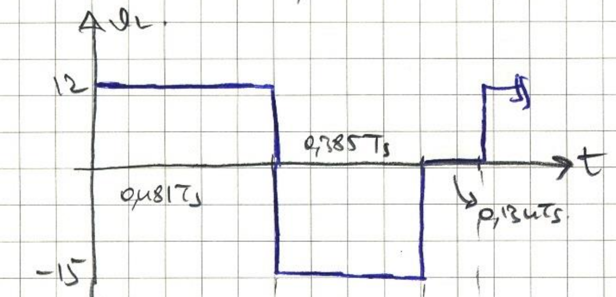
$$\Delta_1 = \sqrt{\frac{7 \cdot 2 \cdot 7{,}94\mu}{15 \cdot 1/20000}} = 0{,}385$$

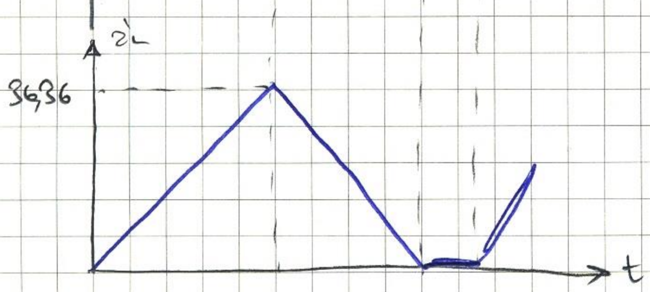
$$\frac{\Delta i_L \cdot \Delta_1}{2} = 7 \Rightarrow \Delta i_L = \frac{2 \cdot 7}{\Delta_1} = \frac{14}{0{,}385} = 36{,}36\,A.$$

$$\Delta i_L = \frac{V_d}{L} DT_s \Rightarrow D = \frac{\Delta i_L \cdot L}{V_d \cdot T_s} = \frac{36{,}36 \cdot 7{,}94\mu}{12 \cdot 1/20000} = 0{,}481$$

$$\Delta_2 = 1 - D - \Delta_1 = 0{,}134.$$

C. From the previous part, $\Delta i_L = i_{L,max} = 36{,}36\,A$



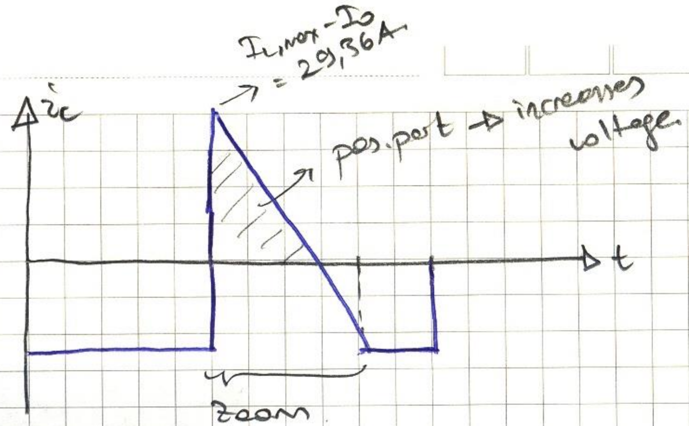


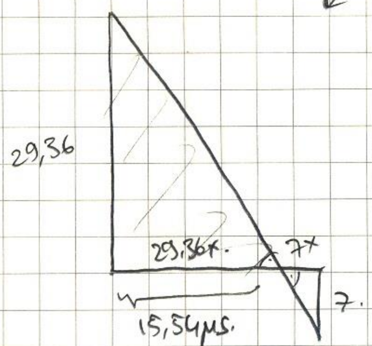
d.

$DT_s \rightarrow i_C = -I_o$

$\Delta_1 T_s \rightarrow i_C = i_L - i_o$

$\Delta_2 T_s \rightarrow i_C = -I_o.$





$$\Delta_1 T_s = 29{,}36x + 7x = 36{,}36x = \frac{0{,}385}{20000} = 19{,}25\,\mu s.$$

$36{,}36x \qquad 19{,}25\,\mu s$

$29{,}36x \qquad ? \Rightarrow 15{,}54\,\mu s.$

$$\Delta Q = \frac{29{,}36 \cdot 15{,}54\mu}{2} = C \cdot \Delta v_o \qquad \Delta v_o = 1\% \cdot V_o = 0{,}15\,V.$$

$$C = \frac{29{,}36 \cdot 15{,}54\mu}{2 \cdot 0{,}15} = 1{,}52\,mF$$

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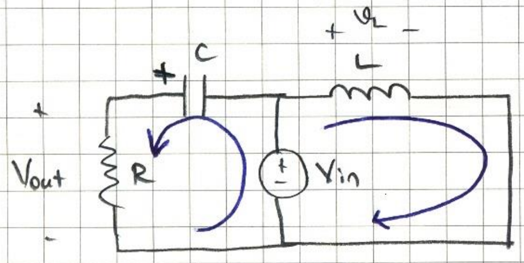
(6) Assume CCM;

a.

DT_s time interval (main switch ON / diode OFF)

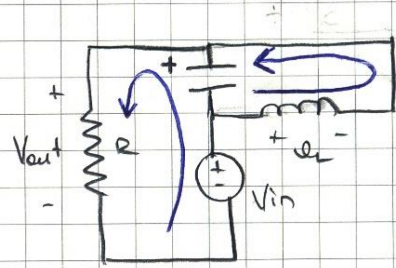


$v_L = V_{in}.$

inductor is charged via input voltage.

capacitor current is equal to output current.

$D'T_s$ time interval (main switch OFF / diode ON)



$v_L = V_{in} - V_{out}$

inductor is being discharged

capacitor current is equal to difference between inductor current and output current.

b. IVSB $\Rightarrow$ $v_{L,DT_s} \cdot DT_s + v_{L,D'T_s} \cdot D'T_s = 0.$

$v_{L,DT_s} \to V_{in}$, $v_{L,D'T_s} \to (V_{in} - V_{out})$

$$V_{in} \cdot D + (V_{in} - V_{out})(1-D) = 0$$

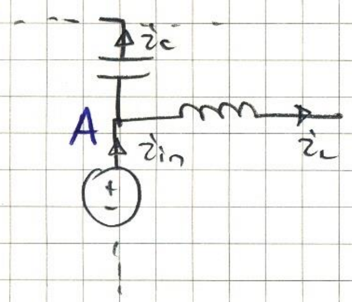
$$V_{in} \cdot D + V_{in} - V_{in} \cdot D - V_{out} + V_{out} \cdot D = 0$$

$$V_{in} = V_{out}(1-D)$$

$$\boxed{\frac{V_{out}}{V_{in}} = \frac{1}{(1-D)}}$$

This converter is a "Boost" type converter!

c.



for Node A $\quad i_{in} = i_L + i_C$

(averaging)

$$\langle i_{in} \rangle = \langle i_L \rangle + \langle i_C \rangle \quad (\langle i_C \rangle \to 0)$$

$$\boxed{I_{in} = I_L}$$

peak-to-peak inductor current ripple Δi_L.

$DT_s \longrightarrow$ slope $= V_{in}/L$

$D'T_s \longrightarrow$ slope $= (V_{out} - V_{in})/L$

$$\boxed{\Delta i_L = \frac{V_{in}}{L} \cdot DT_s = \frac{V_{out} - V_{in}}{L} \cdot (1-D) \cdot T_s.}$$

$$i_{L,max} = I_L + \frac{\Delta i_L}{2} = I_{in} + \frac{V_{in}}{2L} DT_s$$

$$i_{L,min} = I_L - \frac{\Delta i_L}{2} = I_{in} - \frac{V_{in}}{2L} DT_s.$$