ET4119 Electronic Power Conversion 2012/2013
Solutions 25 January 2013

1. In the circuit shown above, the diodes and the current source may be considered ideal. The following is given:

V_s=230V
L_s=5mH
I_d=10A
f=50Hz

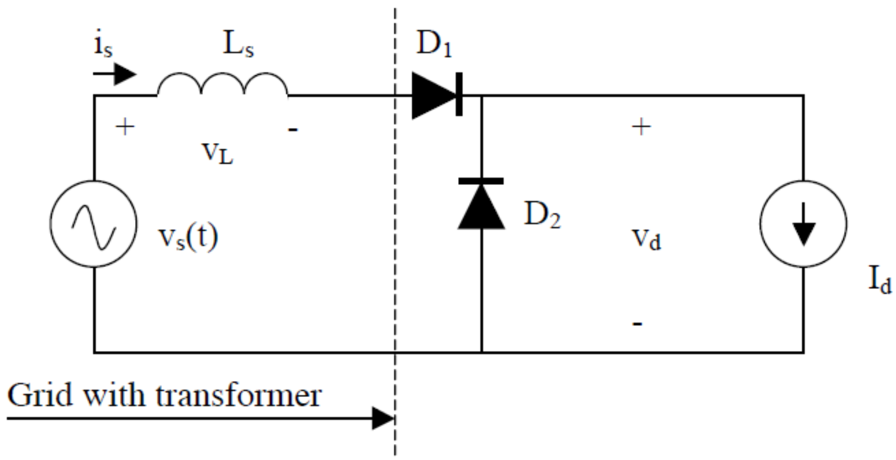
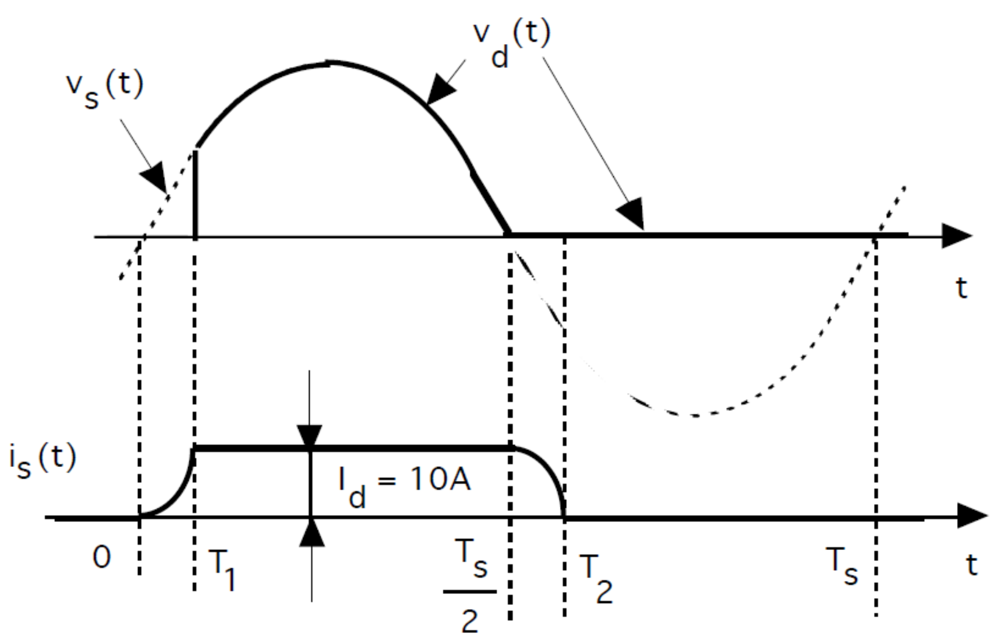


Figure 1 a. rectifier circuit b. input voltage waveform

1.1



1.2 For $v_s(t) < 0$, D1 is off and D2 conducts. Inductor current equals zero. As $v_s(t)$ crosses zero going positive, it takes a finite time for the current $i_s(t)$ to build up to 10 A.

During this buildup time T1, D2 remains in conduction which keeps $v_d(t) = 0$, ie. creates a voltage notch.
As $v_s(t)$ crosses zero going negative, $v_d(t)$ will equal zero as diode D2 turns on, so there will be no voltage notch. The average value of the the voltage waveform shown above with the voltage notch caused by Ls is smaller than the Ls = 0 waveform.

1.3 During time interval T1

$$v_L = L_s \frac{di_L}{dt} \; ; \int_0^{I_d} di_L = I_d = \frac{1}{\omega L_s} \int_0^{\omega T_1} \sqrt{2} V_s \sin(\omega t) d(\omega t)$$

$$\omega L_s I_d = \sqrt{2}\, V_s \{1 - \cos(\omega T_1)\}$$

$$V_d = \frac{1}{2\pi} \int_{\omega T_1}^{\pi} \sqrt{2} V_s \sin(\omega t) d(\omega t)$$

2. A 1 kW, 48V output step-down converter is to be evaluated. Consider all the components to be ideal. The output capacitor C is so large that the output voltage can be considered to be constant. The input voltage is 100V, and the switching frequency is 80 kHz.

2.1 The first step is to calculate the critical inductance for the converter to operate in the Continuous Conduction Mode. Once that is done it will be obvious that in 2.1 the converter works in CCM and in 2.2 in DCM.

$$1\text{kW} = (48\text{V})I_o \ ;\ I_o = 20.83\text{ A} \ ;\ D = \frac{48}{100} = 0.48 \ ;\ \text{switch on-time} = \frac{0.48}{8\text{x}10^4} = 6\text{x}10^{-6}\text{ se}$$

$$\Delta i_L = \frac{(100\text{V} - 48\text{V})(6\text{x}10^{-6}\text{ sec})}{4\text{x}10^{-5}\text{ H}} = 7.8\text{ A}$$

$$I_{L,peak} = 20.83 + 3.9 = 24.73\text{ A};$$

$$I_{L,rms} = \sqrt{I_o^2 + <(I_{L,ripple})^2>} \ ;\ <(I_{L,ripple})^2> = \frac{(3.9)^2}{3} = 5.07\text{ A}^2$$

$$I_{L,rms} = \sqrt{(20.83)^2 + 5.07} = 20.95\text{ A}$$

2.2 The same procedure as in 2.1, the current waveform is different since the converter works in DCM.

2.3 Cost ~ $L*I_{L,peak}*I_{L,rms}$ for both inductors. The cost ratio can then be calculated using the results from 2.1 and 2.2.

3. Design a full bridge converter to operate in continuous conduction mode (CCM) for the following specifications:

$360V < V_{in} < 400V$ (nominal 400V)

$200W < P_o < 500W$ (nominal 500W)

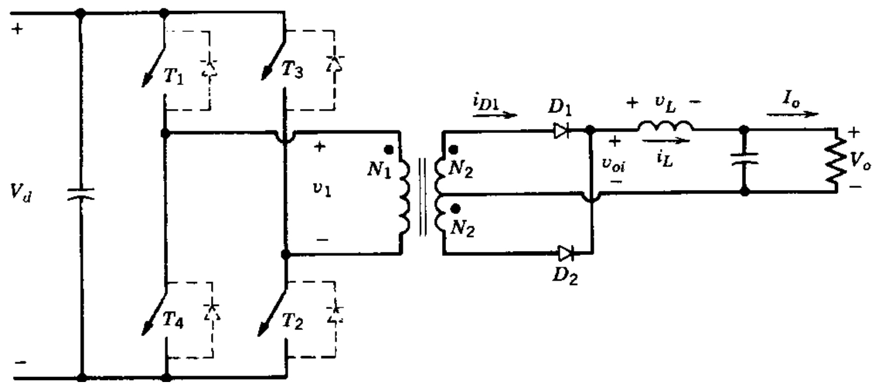
$V_o = 54V$

f=100kHz

$\Delta i_{Lp\_p} < 20\%$ of nominal load current

$\Delta v_{Op\_p} < 20mV$

$L_M \sim 4mH$



Solution: The solution below is generalised for the situation that output diodes are not ideal which means they have certain voltage drop U_D. In the exam question the diodes are assumed to be ideal so you can replace U_D with 0.

First we should define the transformer turns ratio. Again this is done at minimum input voltage, maximum output voltage and maximum selected duty ratio.

$$\frac{N_2}{N_1} = n = \frac{U_{\mathrm{o,max}} + U_{\mathrm{D}}}{D_{\mathrm{f\text{-}max}} U_{\mathrm{in,min}}} \approx \underline{0.36}\,.$$

The nominal operating point may now be defined as

$$D_{\mathrm{f\text{-}nom}} = \frac{U_{\mathrm{D}} + U_{\mathrm{o,nom}}}{n U_{\mathrm{in,nom}}} = 0.389$$

$$D_{nom} = 2D_{\mathrm{f\text{-}nom}} = 0.778$$

$$I_o = \frac{P_{onom}}{U_{onom}} = \frac{500\ \mathrm{W}}{54\ \mathrm{V}} \approx 9.26\ \mathrm{A}$$

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<u>The inductor value</u> L would be selected to give the associated inductor-current peak-to-peak ripple Δi_{L-pp} as defined above: $\Delta i_{L-pp} = 0.2 \cdot I_o = 0.2 \times 9.3\ \mathrm{A} \approx 1.85\ \mathrm{A}$. We consider again all the limiting operational points (input voltage limits and output voltage limits) and form a design table. The table is presented in a separate excel-file and not displayed here.

$$\Delta i_{L,pp,on} = \frac{u_{\mathrm{L,on}} DT_s}{L} \rightarrow \underline{L} = \frac{(nU_{\mathrm{in}} - U_{\mathrm{D}} - U_{\mathrm{o}})DT_s}{\Delta i_{\mathrm{L,pp,on}}} \approx \underline{190\ \mu\mathrm{H}}\,.$$

<u>The capacitor value</u> C would be selected in this example to limit the associated output-voltage peak-to-peak ripple to 20 mV. In the practical applications, the equivalent series resistance (ESR) will typically define the size of the output capacitor due to the defined ripple voltage and the power losses it would cause. When the peak-to-peak ripple is only associated to the charge/discharge of the output capacitor, then the peak-to-peak ripple voltage $u_{\mathrm{o,pp}}$ may be defined for a CCM buck converter as using the positive change of charge

$$\Delta u_{\mathrm{o,pp}} = \frac{T_{\mathrm{s}} \Delta i_{\mathrm{L,pp}}}{8C} \text{ giving } \underline{C} \geq \frac{T_{\mathrm{s}} \Delta i_{\mathrm{L,pp}}}{8 \Delta u_{\mathrm{o,pp}}} \approx \underline{120\ \mu\mathrm{F}}.$$

This equation can be derived on the basis of the capacitor current waveform. Its dependence on the operating point and duty cycle is included within the inductor peak-to-peak current.

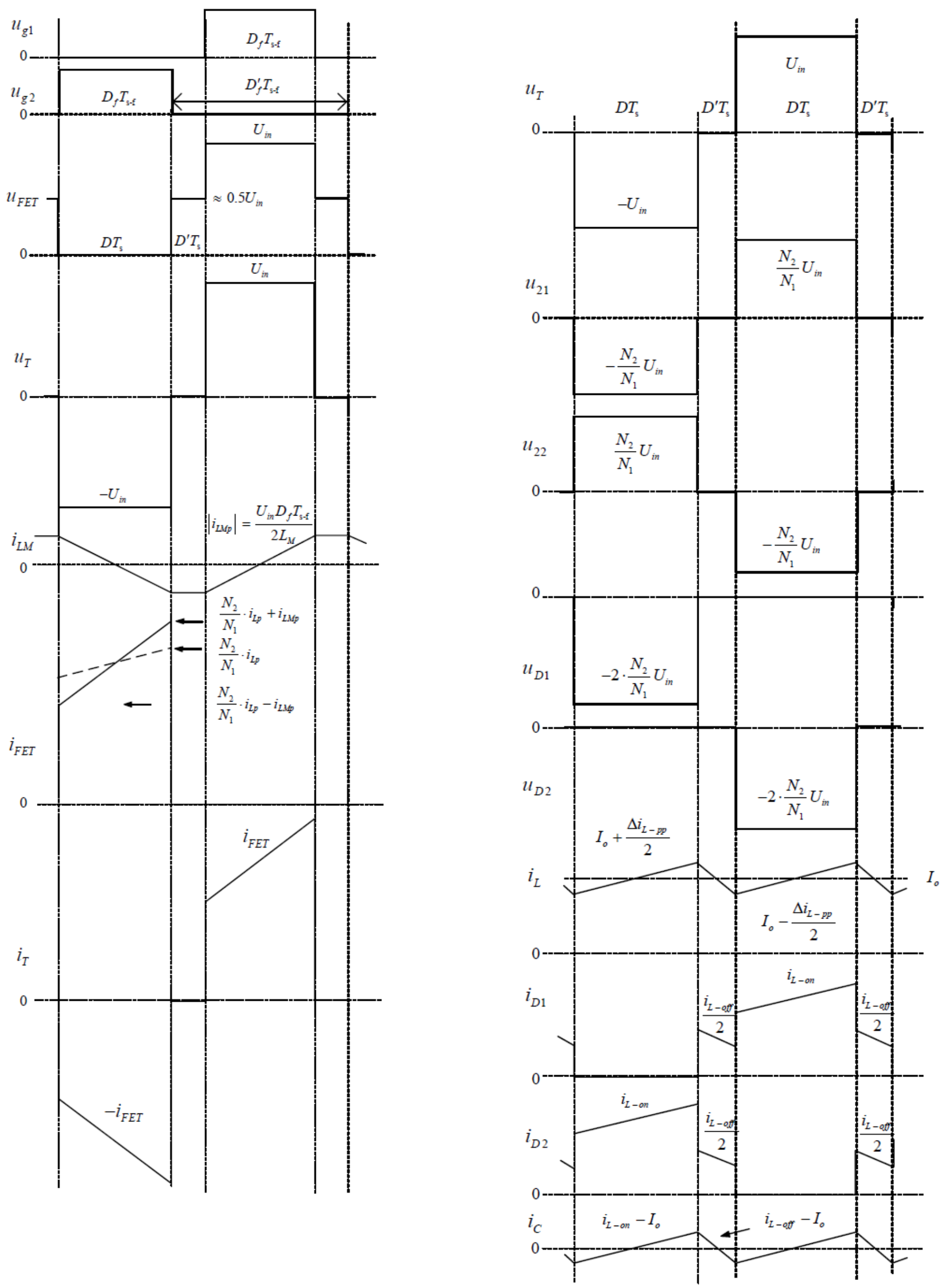
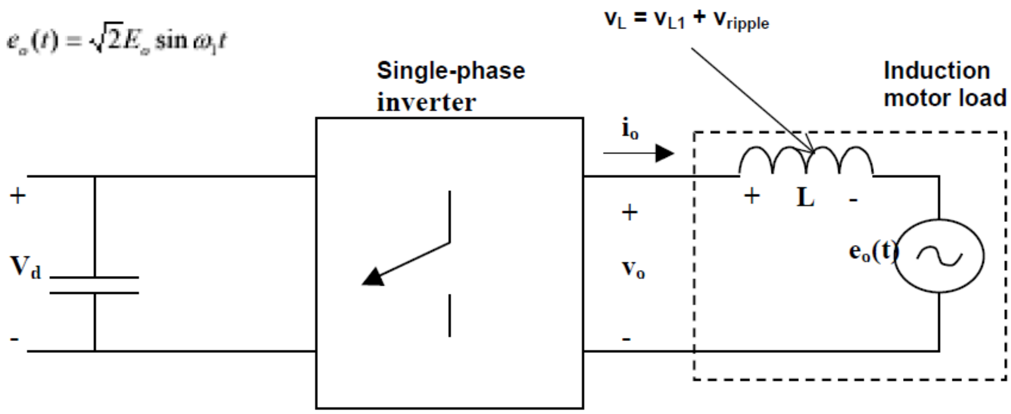


Fig.2. a) Primary waveforms b) Secondary waveforms

4. The problem with ripple in the output current from a single-phase full bridge inverter is to be studied. The first harmonic of the output voltage is given by V_{o1}=220V at f = 47 Hz. The load is given in the figure as L = 100 mH in series with an ideal voltage source $e_o(t)$. The converter works in square wave mode.



4.1

$$V_{o1,\,ph} = \frac{4}{\pi} V_d \,; \quad \text{Eq. (8-36) in text. } V_{o1,\,ph} = \sqrt{2}\ V_{o1} \,;\ V_{o1} = 220V$$

$$V_d = \frac{\pi}{4}\sqrt{2}\ V_{o1} = \frac{\pi}{4}\sqrt{2}\ (220) = 244V$$

4.2

Ripple current is as shown in Fig. 8-19a.

$$2\, I_{ripple,peak} = \frac{1}{\omega L}\int_0^{\pi}\{V_d - \sqrt{2}\ V_{o1}\sin(\omega t)\}\ d(\omega t) = \frac{1}{\omega L}\{\pi V_d - 2\sqrt{2}\ V_{o1})$$

$$I_{ripple,peak} = \frac{1}{2\omega L} V_d \{\pi - \frac{8}{\pi}\} \,;$$

$$\text{Put in numbers: } = \frac{1}{(2)(2\pi)(47)(0.1)}\ \{\pi - \frac{8}{\pi}\}\ (244) = 2.46\ A$$

4.3 Advantages: simple control, low switching losses (the switching frequency is fundamental frequency)

Disadvantages: high current ripple, the output voltage cannot be controlled

4.4 Modifications: e.g. voltage cancellation modulation scheme