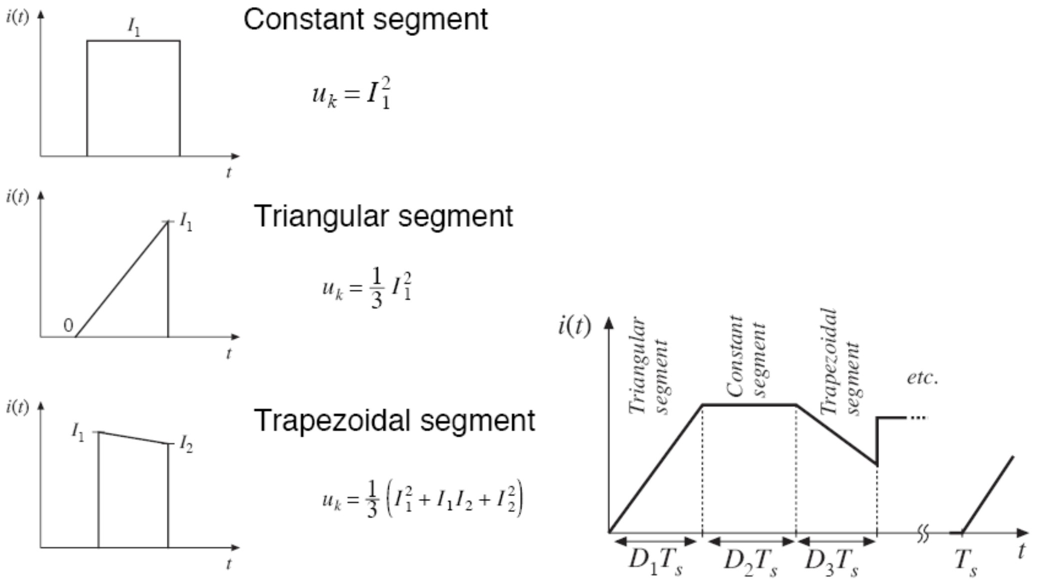
Power Electronics Section II Homework Problems
Step-up and Step-down Converters (non-isolated)



$$rms = \sqrt{\sum_{k=1}^{n} D_k u_k}$$

The duty cycle during DCM buck is given by $D = \sqrt{\frac{V_{LV}}{V_{HV}\left(V_{HV} - V_{LV}\right)} 2\,f\,L\,I_{LV}}$

The duty cycle during DCM boost is given by $D = \sqrt{\frac{\left(V_{HV} - V_{LV}\right)}{V_{LV}V_{HV}} 2\,f\,L\,I_{LV}}$ LV, HV = low, high voltage bus.

Problem 1

The Gen II Toyota Prius uses a 20 kW bidirectional converter to generate a 500 V dc link voltage from the 200 V NiMH battery. This higher voltage allows the efficiency, range, and emissions of the vehicle to be optimized. The bidirectional converter has an inductance of 435 uH and switches at 10 kHz. The filter capacitance on the battery is 283 μF.

The vehicle is operating in generating mode and the bi-directional converter is required to act as a buck at full power.

(i) Calculate the rms currents in the inductor and the output capacitor.

(ii) Calculate the switch and diode average and rms currents and the resulting conduction losses in (a) the IGBT with $V_{CE(knee)}$ = 2.5 V and R_{CE} = 0.01 Ω, and (b) the diode with $V_{F(knee)}$ = 1.5 V and R_{CE} = 0.005 Ω.

(iii) Calculate the rms current in input capacitor.

(iv) Calculate the peak-peak ac ripple voltage across the output capacitor.

(v) Calculate the following product, $L \cdot I_L$(rms) $\cdot I_L$(pk), in order to determine a relative sizing for the inductor.

[Ans. I_L(rms) = 100.3 A, I_{CLV}(rms) = 8 A, I_{QU}(rms) = 63.4 A, I_{QU}(dc) = 40 A, I_{DL}(rms) = 77.7 A, I_{DL}(dc) = 60 A,; P_Q = 140 W; P_D = 120 W; I_{CHV}(rms) = 49.2 A, Δ V_{CLV}(pk-pk) = 0.3 V, $L \cdot I_L$(rms) $\cdot I_L$(pk) = 4.97 HA^2]

Problem 2

The above vehicle is operating in generating mode.

(i) Determine the average battery current and power at the boundary current between CCM and DCM.

(ii) Calculate the rms currents in the inductor and the output capacitor.

(iii) Calculate the switch average and rms currents and the resulting conduction losses in (a) the IGBT with $V_{CE(knee)}$ = 2.5 V and R_{CE} = 0.01 Ω, and (b) the diode with $V_{F(knee)}$ = 1.5 V and R_{CE} = 0.005 Ω.

(iv) Calculate the rms current in input capacitor.

[Ans. I_B(dc) = 13.8 A, P_B = 2.76 kW, I_L(rms) = 16 A, I_{CLV}(rms) = 8 A, I_{QU}(rms) = 10.1 A, I_{QU}(avg) = 5.5 A, I_{DL}(rms) = 12.4 A, I_{DL}(dc) = 8.3 A, P_Q = 14.8 W; P_D = 13.2 W; I_{CHV}(rms) = 8.5 A]

Summer 2011

Problem 3

The above vehicle is operating in generating mode and the bi-directional converter is required to act as a buck converter.

At 2 kW, or 10 % of rated load:

(i) Is the converter operating in CCM or DCM?

(ii) Calculate the rms currents in the inductor and the output capacitor.

(iii) Calculate the switch average and rms currents and the resulting conduction losses in (a) the IGBT with $V_{CE(knee)} = 2.5$ V and $R_{CE} = 0.01\ \Omega$, and (b) the diode with $V_{F(knee)} = 1.5$ V and $R_{CE} = 0.005\ \Omega$.

(iv) Calculate the rms current in input capacitor.

[Ans. DCM, I_L(rms) = 12.54 A, I_{CLV}(rms) = 7.57 A, I_{QU}(rms) = 7.92 A, I_{QU}(dc) = 4.0 A, I_{DL}(rms) = 9.71 A, I_{DL}(dc) = 6.0 A, P_Q = 10.1 W; P_D = 9.5 W; I_{CHV}(rms) = 6.84 A]

Summer 2008

Problem 4

The Lexus RX400h hybrid vehicle uses a bidirectional converter to generate a 650 V dc link voltage from the 288 V NiMH battery. The bidirectional converter has an inductance of 245 uH and switches at 10 kHz.

The vehicle is operating in generating mode and the bi-directional converter is required to act as a buck at full power.

(i) Calculate the rms currents in the inductor and the low-voltage output capacitor.

(ii) Calculate the switch and diode average and rms currents and the resulting conduction losses in (a) the IGBT with $V_{CE(knee)} = 2.5$ V and $R_{CE} = 0.01\ \Omega$, and (b) the diode with $V_{F(knee)} = 1.5$ V and $R_{CE} = 0.005\ \Omega$.

(iii) Calculate the rms current in high-voltage input capacitor.

(iv) Calculate the following product, $L \cdot I_L(\text{rms}) \cdot I_L(\text{pk})$, in order to determine a relative sizing for the inductor.

[Ans. I_L(rms) = 105.9 A, I_{CLV}(rms) = 18.9 A, I_{QU}(rms) = 70.5 A, I_{QU}(dc) = 46.2 A, I_{DL}(rms) = 79 A, I_{DL}(dc) = 58 A,; P_Q = 165 W; P_D = 118 W; I_{CHV}(rms) = 53.3 A, $L \cdot I_L(\text{rms}) \cdot I_L(\text{pk}) = 3.55\ \text{HA}^2$]

Summer 2006

Problem 5

In many applications, the standard silicon diode can have excessive power loss compared to replacing the diode with another MOSFET. The switching on and off of the upper and lower MOSFET switches are then synchronized, hence the name, the **synchronous** buck or boost.

Design a Voltage Regulator Module (VRM) for local power regulation of a microprocessor on a mobile phone. The VRM is powered from a 3.3 V lithium ion battery and uses a synchronous buck converter. The microprocessor specifications call for a 1 V supply with a +/- 1 % allowable fluctuation while consuming 50 mA. The switching frequency is 1 MHz. Neglect the parasitic effects of the controlled MOSFETs.

(i) Sketch the synchronous buck converter.

(ii) Choose an inductor that limits the current ripple to +/- 10 %.

(iii) Choose a capacitor to limit the voltage ripple to +/ 1 %.

(iv) Calculate the total conduction losses in the upper and lower MOSFET switches for $R_{DS(ON)} = 0.5\ \Omega$.

(v) Calculate the increase in conduction losses if the lower MOSFET is replaced by a Schottky diode with a characteristic forward voltage knee of 0.4 V and a slope of 0.1 Ω.

[Ans. 69.6 uH, 62.5 nF, 1.3 mW, losses increase to about 14 mW]

Summer 2009

Problem 6

The Gen II Toyota Prius uses a 20 kW bidirectional converter to generate a 500 V dc link voltage from the 200 V NiMH battery. This higher voltage allows the efficiency, range, and emissions of the vehicle to be optimized. The bidirectional converter has an inductance of 435 uH and switches at 10 kHz. The filter capacitance on the battery is 283 μF.

The vehicle is operating in **motoring** mode and the bi-directional converter is required to act as a **boost** at full power.

(i) Calculate the rms currents in the inductor and the output capacitor.

(ii) Calculate the switch and diode average and rms currents and the resulting conduction losses in (a) the IGBT with $V_{CE(knee)} = 2.5$ V and $R_{CE} = 0.01\ \Omega$, and (b) the diode with $V_{F(knee)} = 1.5$ V and $R_{CE} = 0.005\ \Omega$.

(iii) Calculate the rms current in input capacitor.

(iv) Calculate the peak-peak ac ripple voltage across the output capacitor.

(v) Calculate the following product, $L \cdot I_L(\text{rms}) \cdot I_L(\text{pk})$, in order to determine a relative sizing for the inductor.

[Ans. I_L(rms) = 100.3 A, I_{CLV}(rms) = 8 A, I_{DU}(rms) = 63.4 A, I_{DU}(dc) = 40 A, I_{QL}(rms) = 77.7 A, I_{QL}(dc) = 60 A; P_Q = 210 W; P_D = 80 W; I_{CHV}(rms) = 49.2 A, ΔV_{CLV}(pk-pk) = 1.2 V, $L \cdot I_L(\text{rms}) \cdot I_L(\text{pk}) = 4.97\ \text{HA}^2$]

Problem 7

The above vehicle is operating in motoring mode. The voltage on the dc link reduces proportionately with the motor power. Thus, the dc link voltage drops to 350 V at 10 kW. For this condition

(i) Calculate the rms currents in the inductor and the output capacitor.

(ii) Calculate the switch and diode average and rms currents and the resulting conduction losses in (a) the IGBT with $V_{CE(knee)}$ = 2.5 V and R_{CE} = 0.01 Ω, and (b) the diode with $V_{F(knee)}$ = 1.5 V and R_{CE} = 0.005 Ω.

(iii) Calculate the rms current in input capacitor.

[Ans.]

Problem 8

A fuelcell vehicle features two interleaved 30 kW boost converters to provide a total output power of 60 kW. The converters are interleaved in order to reduce the ripple current coming from the source. The vehicle generates a 400 V dc link voltage when the fuel cell drops to 160 V at full power. Each converter has an inductance of 45 µH and switches at 16 kHz.

(i) Determine the rms and peak currents currents in each phase inductor.

(ii) Calculate the following product, $L \cdot I_L$(rms) $\cdot$ I_L(pk) x 2, in order to determine a relative combined sizing for the two inductors.

(iii) Calculate peak-peak and rms values of the ripple current from the fuelcell input capacitor. Use the following formulae for the input peak-peak ripple current.

$$0 \le D \le 0.5 \quad \Delta I_{I(p-p)} = \frac{V_{LV}}{f\,L}\frac{(1-2D)}{(1-D)}D$$

$$0.5 \le D \le 1.0 \quad \Delta I_{I(p-p)} = \frac{V_{LV}}{f\,L}(2D-1)$$

(iv) Calculate peak-peak and rms values of the ripple current from the fuelcell input capacitor if the phases are **not interleaved** but switched together in phase.

(v) Determine the peak and rms inductor current and the product, $L \cdot I_L$(rms) $\cdot$ I_L(pk), if a **bulked up single phase** is used to achieve the same input current ripple as the interleaved converter.

[Ans. I_{L1}(rms) = I_{L2}(rms) = 203.7 A, I_{L1}(pk) = I_{L2}(pk) = 266.7 A, $L \cdot I_L$(rms) $\cdot$ I_L(pk) x 2= 4.89 HA^2, Δ I_{CFC}(pk-pk) = 44.4 A, I_{CFC}(rms) = 12.8 A, Δ I_{CFC}(pk-pk) =266.6 A, I_{CFC}(rms) = 77 A; I_L(rms) = 400.2 A, I_L(pk) = 422.2 A, $L \cdot I_L$(rms) $\cdot$ I_L(pk) = 22.8 HA^2]

Problem 9

A fuelcell vehicle features two interleaved 30 kW boost converters to provide a total output power of 60 kW. The converters are interleaved in order to reduce the ripple current coming from the source. Each converter has an inductance of 45 µH and switches at 16 kHz.

At lower power levels only one phase of the interleaved converter is required to operate. The other phase is disabled. The vehicle generates a 400 V dc link voltage when the fuel cell drops to 200 V at 5 kW. For this condition:

(i) Is the converter operating in CCM or DCM?

(ii) Determine the peak and rms currents in the inductor and the rms current in the fuelcell input capacitor.

(iii) Sketch to rough scale the inductor current.

(iv) Calculate the switch average and rms currents and the resulting conduction losses in (a) the IGBT with $V_{CE(knee)}$ = 2.5 V and R_{CE} = 0.01 Ω, and (b) the diode with $V_{F(knee)}$ = 1.5 V and R_{CE} = 0.005 Ω.

(v) Calculate the rms current in input capacitor.

[Ans. DCM, I_L(pk) = 83.3 A, I_L(rms) = 37.3 A, I_{CLV}(rms) = 27.7 A, I_{QL}(rms) = 26.3 A, I_{QL}(dc) = 12.5 A, I_{DU}(rms) = 26.3 A, I_{DL}(dc) = 12.5 A, P_Q = 38.2 W; P_D = 22.2 W; I_{CHV}(rms) = 23.1 A]