Paper Number(s): **E3.14**

IMPERIAL COLLEGE OF SCIENCE, TECHNOLOGY AND MEDICINE
UNIVERSITY OF LONDON

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING
EXAMINATIONS 2000

EEE PART III/IV: M.Eng., B.Eng. and ACGI

POWER ELECTRONICS AND MACHINES

Wednesday, May 3 2000, 10:00 am

There are SIX questions on this paper.

Answer FOUR questions.

All questions carry equal marks.

Time allowed: 3:00 hours

Corrected Copy

Q. 5

Examiners: Dr T.C. Green, Dr J.C. Vickery

1) (a) Uninterruptable power supplies, UPS are installed by electricity consumers to overcome power quality problems. Discuss the range of problems that a UPS can solve and state any limitations that the design of the UPS may place on its effectiveness.

[8 marks]

(b) Some power quality problems are caused by the operation of diode rectifiers. Explain how the problems arise.

[4 marks]

(c) Describe the operation of an alternative to a simple diode rectifier that is able to avoid power quality problems. What other advantages and disadvantages does the circuit have.

[8 marks]

2) (a) Describe, with the aid of diagrams, the main differences between a mosfet designed for a power application and a general-purpose mosfet.

[6 marks]

(b) What is the main difficulty in designing a mosfet for voltages of 1000 V or more? Describe the device developed from the mosfet that is better suited to high voltage use.

[6 marks]

(c) Figure 1 shows a mosfet used to switch an inductive load (which may be considered as a constant current load). It is shown with and without a turn-off snubber. Given the following data, calculate the turn-off power loss in the transistor in each circuit and the loss in the resistor of the snubber.

[8 marks]

Switching Frequency, f_s = 15 kHz
Supply Voltage, V_S = 300 V
Load Current, I_L = 20 A
Snubber capacitor, C_S = 2 nF

Drain current fall-time, t_{fi} = 50 ns
Drain-source voltage rise time without snubber, t_{rv} = 5 ns

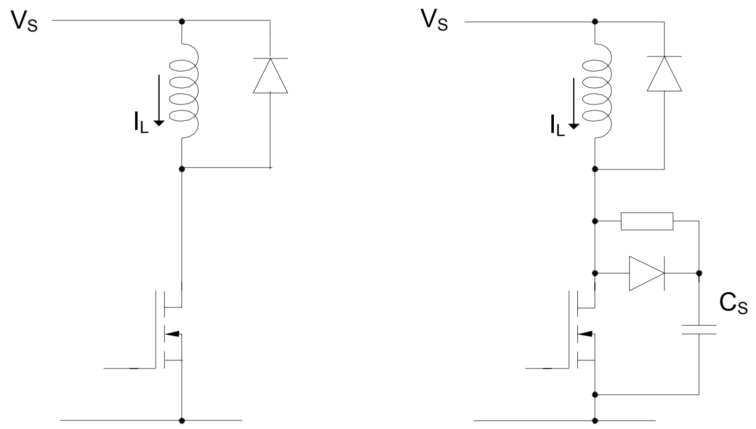


Figure 1 An inductive load switched by a MOSFET alone and by a MOSFET with a snubber.

3) (a) Sketch the inverter circuit required to convert DC to three-phase AC and describe the way in which the switching of the power semiconductors is modulated to set the voltage magnitude and frequency of the AC. What is the relationship between the DC voltage and the maximum amplitude of the AC?

[7 marks]

(b) A DC/three-phase converter is connected as shown in figure 2 to a 415 V(line), 50 Hz three-phase system via a set of inductors of 4 mH each. Calculate the inverter voltage (magnitude and phase) necessary to supply 35 kW from the inverter to the three-phase system at unity displacement factor. Calculate the voltage required to draw 35 kW from the three-phase system into the inverter.

[6 marks]

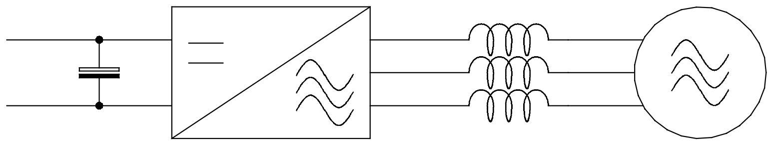


Figure 2 A DC/three-phase converter and three-phase supply system.

(c) Describe, with the aid of a diagram, how an inverter would be used to operate an induction machine with controlled slip.

[7 marks]

4) (a) Compare and contrast the Cúk and Flyback switch mode power supplies, SMPS.

[5 marks]

(b) Derive the relationship between input and output voltage for the Cúk SMPS.

[5 marks]

(c) A power supply is to be designed that is subject to size constraints and voltage ripple tolerance. The outline specification is for conversion of +15V to -5V at an output current of 2A. Calculate the current flowing in the inductor of the flyback SMPS and in both inductors of the Cúk SMPS.

[5 marks]

(d) Given the constraint that the LI^2 of the inductors is limited to 1×10^{-3} HA^2 for the flyback and 0.5×10^{-3} HA^2 for each inductor in the Cúk, calculate the value of the inductors. Calculate the peak-to-peak ripple current flowing in the input of each SMPS and the peak-to-peak output voltage ripple if the output capacitor has an effective series resistance of 40 mΩ and the switching frequency is 40 kHz.

[5 marks]

5) (a) Figure 3 shows two designs of isolated flyback switch-mode power supplies, smps. Discuss the issues relevant to choosing between the two designs.

[4 marks]

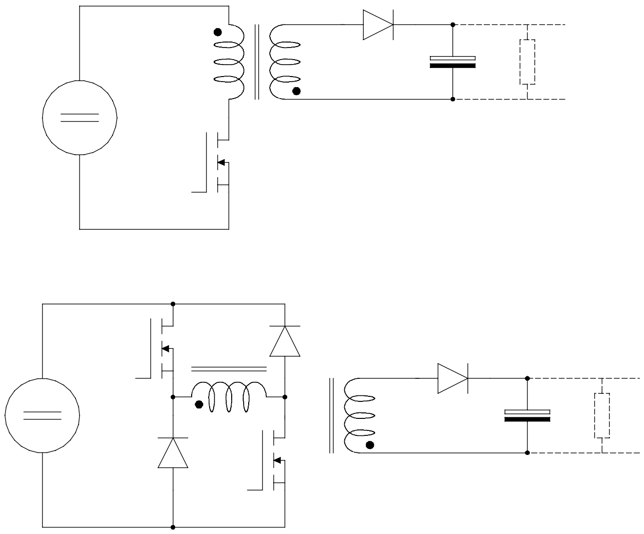


Figure 3 Isolated Flyback SMPS

(b) Figure 4 shows two isolated buck converters (also known as the push-pull and forward converters). Discuss the issues relevant to choosing between the designs.

[4 marks]

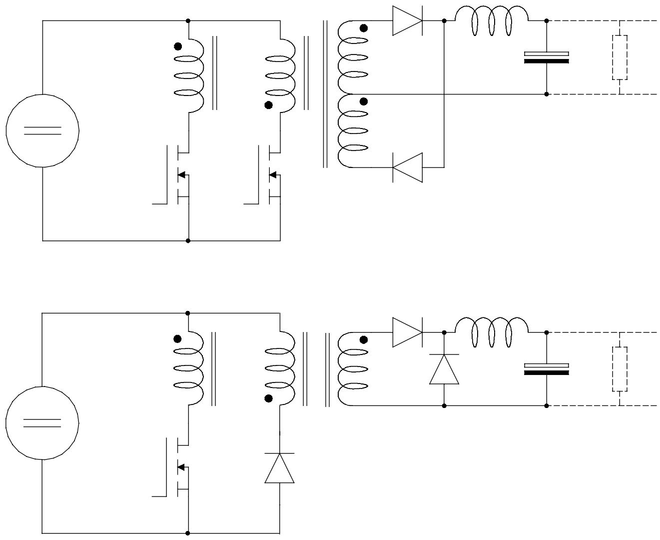


Figure 4 Isolated Buck SMPS

(c) A power supply is to be designed using the two-transistor flyback circuit. The requirement is for 15 V output from an input voltage of 340 V.

(i) Choose a transformer ratio such that the voltage induced across the primary when the transistors are off is 225 V.

[3 marks]

Continued overleaf.

(ii) Assuming that the converter is in discontinuous mode find an expression for the input power in terms of duty-cycle, inductance and frequency.

[3 marks]

(iii)Find the duty cycle that keeps the circuit in discontinuous mode in terms of the turns ratio and the input and output voltages. Calculate the critical value of duty cycle for this design.

[3 marks]

(iv) Choose a value of primary inductance to ensure that the circuit can convert 30 W and remain in discontinuous mode for a switching frequency of 50 kHz.

[3 marks]

6) (a) Describe the operation of a brushless dc motor. Provide block diagrams of the systems and a sketch of the power converter circuit.

[7 marks]

(b) Compare the power converter circuit to the power converter circuit required for a traditional (brushed) dc motor to be operated in forward and reverse rotation with breaking and accelerating torque.

[4 marks]

(c) Justify the shape of the torque-speed diagram in figure 4 with respect to a dc machine. Calculate the principal points on the diagram for a system with the following properties:

DC input voltage 100 V
Armature resistance 0.5 Ω
Field flux at maximum field current 18 mWb
Armature constant 12.5 $V.s.rad^{-1}.Wb^{-1}$ (or $N.m.A^{-1}.Wb^{-1}$)
Rated armature current 8 A

[5 marks]

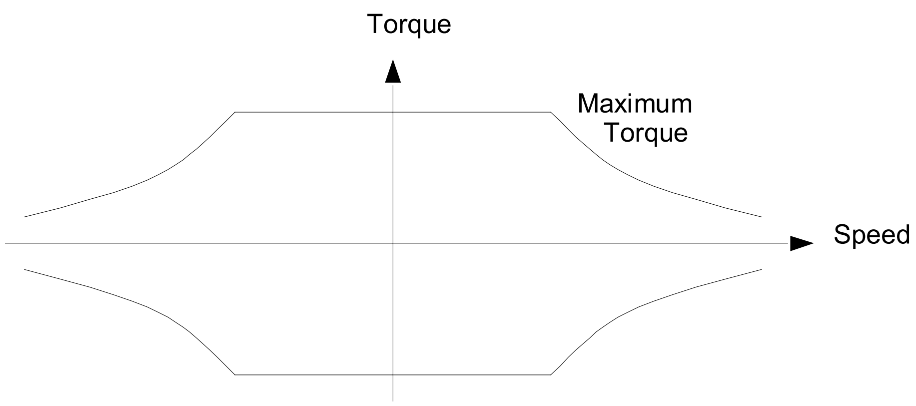


Figure 4 A typical torque speed diagram of an electrical drive system

(d) Summarise the relative merits of brushed and brushless dc drive system.

[4 marks]

Answers and Marking Schedule *Paper 3.14 2000*

4 answers from 6 questions required.

1) Uninterruptable power supplies, UPS are installed by electricity consumers to overcome power quality problems. Discuss the range of problems that a UPS can solve and state any limitations that the design of the UPS may place on its effectiveness.

[8 marks]

The prime problem that a UPS will overcome is a power outage, i.e., a loss of supply for a matter of minutes. During the supply loss the UPS will supply loads by taking energy from a local store (battery) or a local generator or both. An off-line UPS is only active during a power outage and is bypassed by a switch when the utility company supply is available.

An on-line UPS is active at all times. It rectifies the utility company supply and re-inverts it to AC to supply the load. It is able to provide continuity of supply through even very short interruptions to the supply. It is also able to:

- *Correct voltage sag and swell*
- *Correct frequency drift*
- *Correct distorted voltage wave-shape*
- *Suppress voltage dips and spikes*
- *Filter hf noise*

If the on-line UPS internal rectifier is a sine-wave current design the UPS will draw sine-wave current from the utility supply even if the loads are distorting (diode rectifiers).

Some power quality problems are caused by the operation of diode rectifiers. Explain how the problems arise.

[4 marks]

The typical single-phase diode rectifier has a large "reservoir" capacitor on the DC side. The diodes are reverse biased and non-conducting until the instantaneous AC voltage exceeds the DC voltage. The capacitor then charges rapidly with a current drawn from the AC side that is limited only by the wiring inductance and resistance. The conduction period is brief. The AC side current waveform is composed of brief, large amplitude current pulses aligned to the positive and negative peaks of the voltage waveform. This waveform is rich in harmonics; the harmonic amplitudes are large compared to the 50 Hz component.

The power distribution network is badly affected by these current harmonics. Harmonic voltage drops occur in the supply impedances which are observed as "flat top" voltage waveforms supplied to other customers. Because all the rectifiers in a system operate synchronously the harmonics from all source are additive.

Customers suffer reduced voltage magnitudes and harmonic excitation of transformers and motors. Utility companies suffer (lossy) harmonic excitation of transformers and extra loss in supply cables from the flow of harmonic current.

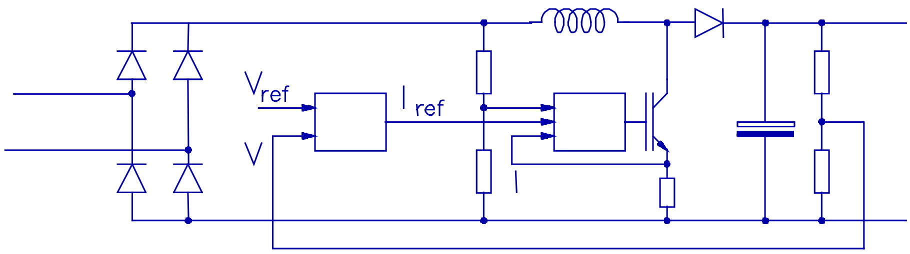
Describe the operation of an alternative to a simple diode rectifier that is able to avoid power quality problems. What other advantages and disadvantages does the circuit have.

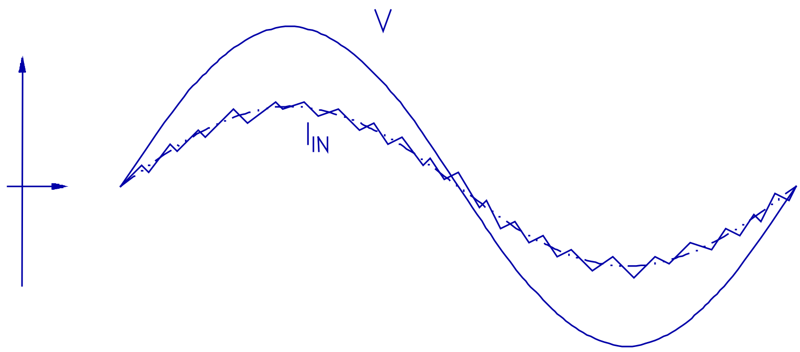
[8 marks]

A boost type SMPS can be arranged to draw a controlled current from a varying voltage. A diode bridge is used to rectify the AC voltage and a control loop set to force the current to be a full wave rectified sinewave also (a simple sinewave will be drawn from the AC supply). The magnitude of the sinewave is set by a second controller according to the error between the DC output voltage and its reference value.

Because the circuit is under closed loop control the output voltage can reject output current disturbance and changes in input voltage magnitude. The current control can easily be amended to provide current limiting to prevent large fault currents.

The circuit suffers a twice line-frequency output voltage ripple because of the inherent pulsation of a single phase power source. Although the circuit can be controlled to avoid low frequency current harmonics there are emission of high frequency current multiples of the switching frequency.





2) Describe, with the aid of diagrams, the main differences between a power MOSFET and a signal MOSFET.

> *The signal MOSFET has a lateral structure in which both the on-state channel and the off-state depletion region develop horizontally between the source and drain diffusions. A deep depletion region for high voltage must also mean a long, high-resistance channel.*
>
> *The power MOSFET uses a double diffused vertical structure which allows the depletion region to build up in the drain region and not in the channel. This allows the channel to be kept short. Thus voltage rating can be large (circa 500V) without excessive RDS(on). Channel width is made large by parallel operation of thousands of tessellated cells.*

[6 marks]

What is the main difficulty in designing a MOSFET for voltages of 1000V or more? Describe the development of the MOSFET that would be used instead.

> *At 1000V or more the drain region must be so deep and so lightly doped (to support the off-state depletion region) that the drift resistance of this region in the on-state is the most significant contribution to RDS(on). Thus the on-state voltage drop and on-state power loss become unacceptable as the off-state voltage rating is increased.*
>
> *To reduce on-state voltage, conductivity modulation of the drain drift region is used. A heavily doped layer (of the opposite type of semiconductor) is inserted at the drain to inject minority carries. This is now a hybrid bipolar/field effect device known as an Insulated Gate Bipolar Transistor*

[6 marks]

Figure 1 shows a MOSFET used to switch an inductive load (represented here as a constant current source). It is shown with and without a turn-off snubber. Given the following data, calculate the turn-off power loss in the transistor in each circuit and the loss in the resistor of the snubber.

Switching Frequency, f_S = 15kHz
Supply Voltage, V_S = 300V
Load Current, I_L = 20A
Snubber capacitor, C_S = 2nF

Drain-source voltage rise time without snubber, t_{tv} = 5ns
Drain current fall-time, t_{fi} = 50ns

No Snubber Case.
During voltage rise:

$$E_{rv} = \int^{t_{rv}} v.I.dt$$

$$= \int^{t_{rv}} V\frac{t}{t_{rv}}.I.dt$$

$$= \left[VI \cdot \frac{t_{rv}}{2}\right]$$

$$= 300 \cdot 20 \cdot \frac{5 \cdot 10^{-9}}{2}$$

$$= 15 \cdot 10^{-6}\,\mathrm{J}$$

During Current Fall:

$$E_{fi} = \int^{t_{fi}} V.i.dt$$

$$= \int^{t_{fi}} V \cdot I \cdot \left(1 - \frac{t}{t_{fi}}\right) \cdot dt$$

$$= \left[VI \cdot \left(t_{fi} - \frac{t_{fi}}{2}\right)\right]$$

$$= 300 \cdot 20 \cdot \frac{50 \cdot 10^{-9}}{2}$$

$$= 150 \cdot 10^{-6}\,\mathrm{J}$$

Total Transistor Power Loss Without Snubber:

$$P_{ws} = f_S\left(E_{rv} + E_{fi}\right)$$

$$= 15 \cdot 10^3\left(15 \cdot 10^{-6} + 150 \cdot 10^{-6}\right)$$

$$= 2.475\,\mathrm{W}$$

With Snubber: the drain current falls as I(1-t/tfi) so capacitor current rises at I.t/t_{fi}
Check state of snubber capacitor at end of t_{fi}

$$V = \frac{1}{C}\int^{t_{fi}} I\frac{t}{t_{fi}}dt$$

$$= \frac{I \cdot t_{fi}}{2C}$$

$$= \frac{20 \cdot 50 \cdot 10^{-9}}{2 \cdot 2 \cdot 10^{-9}}$$

$$= 250\,\mathrm{V}$$

So the capacitor continues to charge after the end of t_{fi}
During $t_{fi,}$ the energy loss is:

$$E_{fi} = \int^{t_{fi}} v.i.dt$$

$$= \int^{t_{fi}} \frac{I}{C} \cdot \frac{t^2}{2t_{fi}} \cdot I \cdot \left(1 - \frac{t}{t_{fi}}\right) \cdot dt$$

$$= \left[\frac{I^2}{C} \cdot \left(\frac{t_{fi}^2}{6} - \frac{t_{fi}^2}{8}\right)\right]$$

$$= \frac{20^2}{2 \cdot 10^{-9}} \cdot \frac{\left(50 \cdot 10^{-9}\right)^2}{24}$$

$$= 20.8 \cdot 10^{-6}\,\text{J}$$

When the drain current has reached zero the snubber continues to charge but at constant current but there is no loss in the transistor because the drain current is zero.

The energy stored in the snubber capacitor is lost in the resistor at transistor turn-on.

$$E_R = \tfrac{1}{2} C \cdot V^2$$

$$= \tfrac{1}{2} \cdot 2 \cdot 10^{-9} \cdot 300^2$$

$$= 90 \cdot 10^{-6}\ \text{J}$$

Transistor Power Loss With Snubber:

$$P_{ws} = f_S E_{fi}$$

$$= 15 \cdot 10^3 \cdot 20.8 \cdot 10^{-6}$$

$$= 0.312\ \text{W}$$

Power Loss in Snubber:

$$P_{ws} = f_S E_r$$

$$= 15 \cdot 10^3 \cdot 90 \cdot 10^{-6}$$

$$= 1.35\,\text{W}$$

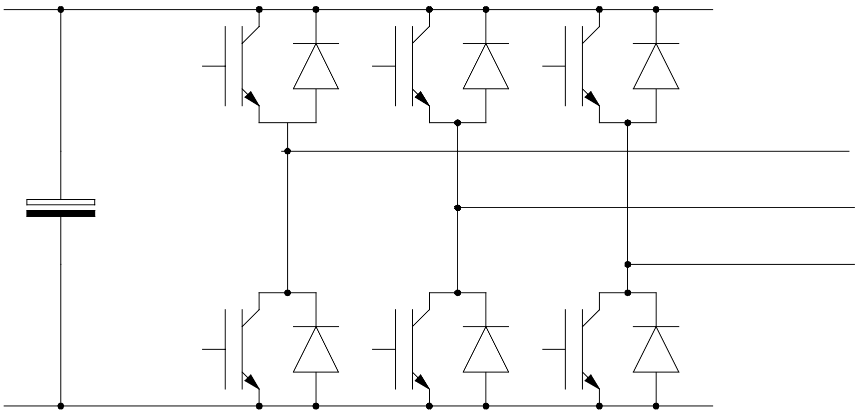
[8 marks]

3) Sketch the inverter circuit required to convert DC to three-phase AC and describe the way in which the switching of the power semiconductors is modulated to set the voltage magnitude and frequency of the AC. What is the relationship between the DC voltage and the maximum amplitude of the AC?

[7 marks]

The DC to three-phase inverter consists of 6 semiconductor switches arranged in series pairs. The mid-point of each pair can connected to the +ve or –ve rail of the DC supply. Anti-parallel diodes are necessary to provide a current path for inductive loads when the current direction is opposite to the normal conduction of the switch. The switches of each pair are turned on and off in anti-phase with a short dead-time in between. The duty cycle can be sinusoidal modulated by taking the switching instances from comparison of a high frequency triangle wave carrier and a sinusoidal modulating wave. The three-phases would share the same carrier wave but would use modulating waves phase displaced by 120°.

Each phase voltage is limited to $\pm V_{DC}/2$



A DC/three-phase converter is connected as shown in figure 2 to a 415 V(line), 50 Hz three-phase system via a set of inductors of 4 mH each. Calculate the inverter voltage (magnitude and phase) necessary to supply 35 kW from the inverter to the three-phase system at unity displacement factor. Calculate the voltage required to draw 35 kW from the three-phase system into the inverter.

[6 marks]

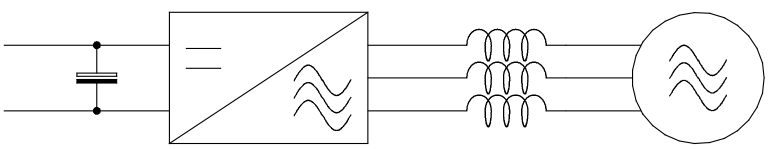


Figure 2 A DC/three-phase converter and three-phase supply system.

The line currents required for 35 kW are:

$$I_L = \frac{P}{\sqrt{3}V_L} = \frac{35 \times 10^3}{\sqrt{3} \times 415} = 48.69\ A$$

The inductive voltage drop is:

$$V_X = j\omega L I_L = 2\pi \times 50 \times 4 \times 10^{-3} \times 48.69 = 61.19V$$

The phase voltage is:

$$V_P = \frac{V_L}{\sqrt{3}} = 240V$$

For delivery of power to the three-phase system the inductive voltage drop must lead by 90°

$$\overline{V_{inv}} = \overline{V}_L + \overline{V}_X = 240 + j61.19 = 247.7\langle 14.3^0$$

For extraction of power from the three-phase system the inductive voltage drop must lag by 90°

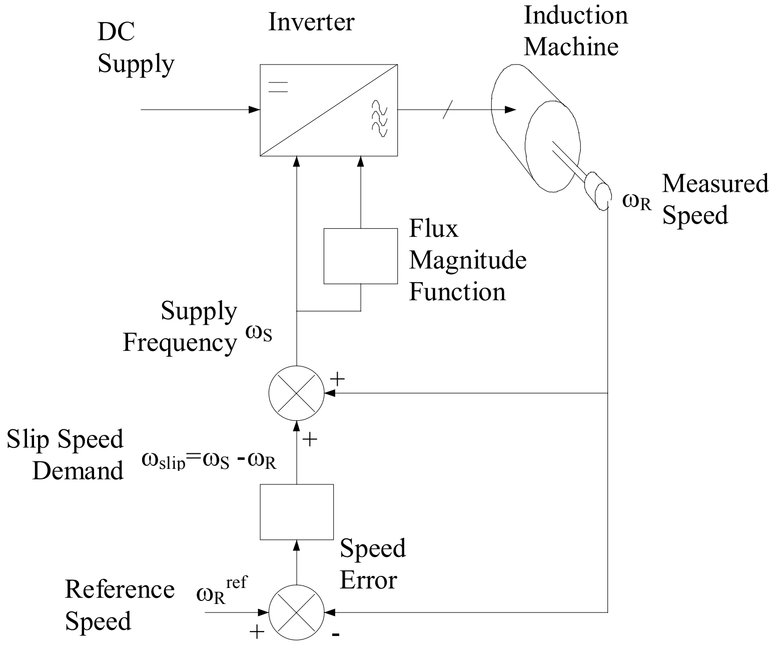
$$\overline{V_{inv}} = \overline{V}_L + \overline{V}_X = 240 - j61.19 = 247.7\langle -14.3^0$$

Describe, with the aid of a diagram, how an inverter would be used to operate an induction machine with controlled slip.

[7 marks]

Slip compensated speed control relies on the fact that the torque produced by an induction machine is approximately linearly proportional to the slip speed provide the slip speed is not greater than about 5% of base speed. The slip speed is defined as the difference between the rotational speed of the flux wave (synchronous speed) and the rotational speed of the rotor. The speed error is processed by a standard linear controller (PI etc.) and the output interpreted as a slip speed demand. This is imposed by adding the measured rotational speed to the slip speed to form the synchronous speed to be synthesised by the inverter. The voltage magnitude to be synthesised by the inverter is set so as to maintain the flux-linkage magnitude constant . Most commonly this is approximated as varying the applied voltage in proportion to the frequency and at low frequency, where the stator resistance voltage drop dominates, adding a voltage boost.

Slip Compensated
Speed Control



4) Compare and contrast the Cúk and Flyback switch mode power supplies, SMPS.

Both provide a reverse polarity output voltage that can be greater or less than the magnitude of the input voltage according to the relation $\frac{V_O}{V_I} = \frac{-\delta}{1-\delta}$*.in continuous operation.*

The Cúk converter has an extra inductor and an extra capacitor. The advantage these bring is that both the input and output currents flow in inductors and thus if the inductor currents are maintained in continuous conduction then the input and output currents can be designed to have vary low ripple values. For EMC compliance and low output voltage ripple the Cúk converter has advantages. The flyback converter is a lower cost circuit.

[5 marks]

Derive the relationship between input and output voltage for the Cúk SMPS.

We assume that the capacitors are sufficiently large such that the voltages across them do not change significantly during a switching cycle. We further assume that the inductors are in continuous conduction and that resistive and semiconductor voltage drops are negligible. The rise and fall of current in the inductors can be found and the assumption of steady-state applied.

$$\Delta i_1(on) = \frac{V_I}{L_1} \cdot \frac{\delta}{f} \qquad \Delta i_1(off) = \frac{V_I - V_{C1}}{L_1} \cdot \frac{1-\delta}{f}$$

$$\Delta i_1(on) + \Delta i_1(off) = 0$$

$$\frac{V_{C1}}{V_I} = \frac{1}{1-\delta}$$

$$\Delta i_2(on) = \frac{V_O + V_{C1}}{L_2} \cdot \frac{\delta}{f} \qquad \Delta i_2(off) = \frac{V_O}{L_2} \cdot \frac{1-\delta}{f}$$

$$\Delta i_2(on) + \Delta i_2(off) = 0$$

$$\frac{V_O}{V_{C1}} = -\delta$$

$$\frac{V_O}{V_I} = \frac{-\delta}{1-\delta}$$

[5 marks]

A power supply is to be designed that is subject to size constraints and voltage ripple tolerance. The outline specification is for conversion of +15V to -5V at an output current of 2A.

Calculate the current flowing in the inductor of the flyback SMPS and both inductors of the Cúk SMPS.

Flyback

$$I_O = I_D(average) = I_L(1-\delta)$$

$$\delta = \frac{V_O}{V_O - V_I} = \frac{-5}{-5-15} = 25\%$$

$$I_L = \frac{2}{(1-0.25)} = 2.67\,A$$

Cuk

$$I_{L2} = I_O = 2\,A$$

$$V_I I_{L1} = -V_O I_{L2}$$

$$I_{L1} = -I_{L2}\frac{V_O}{V_I} = \frac{-2\times -5}{15} = 0.667\,A$$

[5 marks]

Given the constraint that the LI^2 of the inductors is limited to 10^{-3} HA^2 for the flyback and $0.5\text{x}10^{-3}$ for each inductor in the Cúk, calculate the value of the inductors. Calculate the peak-to-peak ripple current flowing in the input of each SMPS and the peak-to-peak output voltage ripple if the output capacitor as an effective series resistance of 40mΩ and the switching frequency is 40 kHz.

Flyback

$$L = \frac{10^{-3}}{2.67^2} = 0.14\,\text{mH}$$

$$\Delta i_L = \frac{V_I}{L}\cdot\frac{\delta}{f} = \frac{15\times 0.25}{0.14\times 10^{-3}\times 40\times 10^3} = 0.67\,A$$

$$I_I(ptp) = \hat{i}_L = I_L + \Delta i_L = 2.67 + 0.67 = 3.33\,A$$

$$V_O(ptp) = \hat{i}_L R_{ESR} = 3.33\times 0.04 = 133\,\text{mV}$$

Cuk

$$L_1 = \frac{0.5\times 10^{-3}}{0.667^2} = 1.125\,\text{mH}$$

$$L_2 = \frac{0.5\times 10^{-3}}{2^2} = 0.125\,\text{mH}$$

$$I_I(ptp) = \Delta i_{L1} = \frac{V_I}{L_1}\cdot\frac{\delta}{f} = \frac{15\times 0.25}{1.125\times 10^{-3}\times 40\times 10^3} = 0.083\,A$$

$$\Delta i_{L2} = \frac{V_O}{L_2}\cdot\frac{1-\delta}{f} = \frac{5\times(1-0.25)}{0.125\times 10^{-3}\times 40\times 10^3} = 0.75\,A$$

$$V_O(ptp) = \Delta i_2 R_{ESR} = 0.375\times 0.04 = 30\,\text{mV}$$

[5 marks]

5) Figure 3 shows two designs of isolated flyback switch-mode power supplies, SMPS. Discuss the issues relevant to choosing between the two designs.

[4 marks]

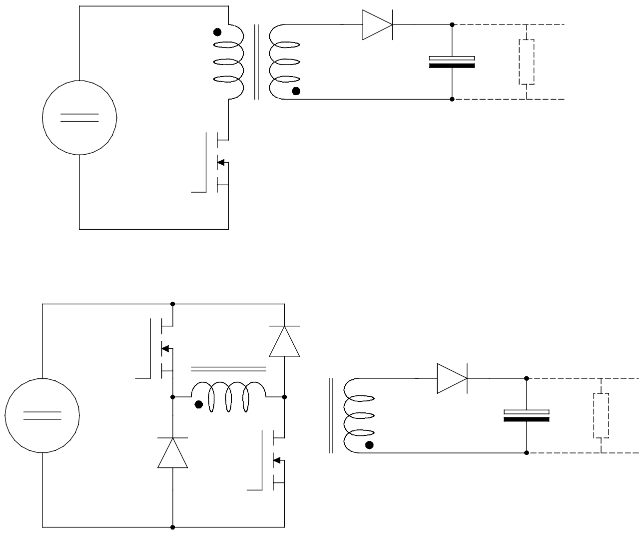


Figure 3 Isolated Flyback SMPS

Both circuits produce and output of $\frac{V_o}{V_i} = \frac{N_S}{N_P} \cdot \frac{-\delta}{1-\delta}$ *and so are applied in similar circumstances. The difference lies in the way in which stored energy in the leakage field of the primary winding is released. In the single transistor circuit, the only current path available to release energy when the transistor is off is for primary current to charge the drain-source capacitance of the MOSFEt to above the idealised value (the input voltage plus the referred secondary voltage). This requires MOSFEt voltage ratings that could be several times the input voltage and dependent on the coupling factor of the transformer and the maximum primary current.*

The two transistor circuit allows the primary leakage energy to return to the supply when the transistor switch off by providing a path for primary current through the two primary side diodes. The mosfets need only be rated for the input voltage and do not need to block either the referred secondary voltage or trapped energy over-voltage. The choice is between two mosfets at low and well determined voltage or one at a considerably higher and parasitic dependent voltage. In determining the cost advantage of the mosfet choices the non-ground-referenced gate drive of the upper transistor in the two-transistor circuit is significant.

Figure 4 shows two isolated buck converters (also known as the push-pull and forward converters). Discuss the issues relevant to choosing between the designs.

[4 marks]

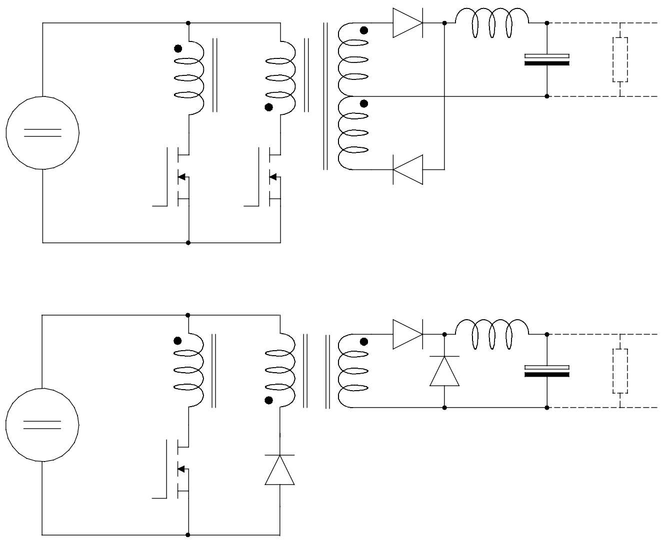


Figure 4 Isolated Buck SMPS

Both circuits produce an output voltage according to $\frac{V_o}{V_i} = \frac{N_s}{N_p} \cdot \delta$ *but for the two transistor circuit* δ *is the sum of the duty-cycles of the transistors.*

The two-transistor (push-pull) circuit uses one transistor to magnetise the transformer core in a positive sense and one to magnetise the core in a negative sense. Thus, the flux can be designed to swing between the saturation flux density in the positive sense to the saturation flux density in the negative sense. The single transistor circuit magnetises the core in a positive sense with the transistor and at turn-off the magnetising current (and hence flux) discharges through the primary side diode. The flux density can be designed to swing between zero and the saturation flux density.

Thus for a given core cross-section, the two transistor circuit can achieve twice the flux swing and therefore use a lower frequency or a higher voltage. Alternatively, for a given voltage and frequency a smaller core can be used.

To allow for de-magnetisation δ *must not exceed ½ in the single transistor circuit.*

A power supply is to be designed using the two-transistor flyback circuit. The requirement is for 15 V output from an input voltage of 340 V. Choose a transformer ratio such that the voltage induced across the primary when the transistors are off is 225 V.

[3 marks]

$$\frac{V_P}{N_P} = \frac{V_S}{N_S} \quad k = \frac{N_P}{N_S} = \frac{V_P}{V_S} = \frac{225}{15} = 15$$

Assuming that the converter is in discontinuous mode find an expression for the input power in terms of duty-cycle, inductance and frequency.

[3 marks]

Input power can be found from the average input current. The input current is a saw-tooth wave.

$$\frac{di_P}{dt} = \frac{V_I}{L_P} \qquad \hat{i}_P = \frac{V_I}{L_P} \cdot \frac{\delta}{f} \qquad I_P = \tfrac{1}{2} f \, \hat{i}_P \frac{\delta}{f} = \tfrac{1}{2} \frac{V_I}{L_P} \cdot \frac{\delta^2}{f}$$

$$P_I = V_I I_P = \tfrac{1}{2} \frac{V_I^{\,2}}{L_P} \cdot \frac{\delta^2}{f}$$

Find the duty cycle that keeps the circuit discontinuous in terms of the turns ratio and the input and output voltages. Calculate the critical value for this design.

[3 marks]

To ensure discontinuous operation, the duty-cycle must be short enough to allow discharge of the flux.

$$\Delta\phi(on) = \frac{V_I}{N_P} \cdot \frac{\delta}{f} \qquad \Delta\phi(off) = -\frac{V_O}{N_S} \cdot t_{diode}$$

$$t_{diode} = \frac{N_S}{V_O} \cdot \frac{V_I}{N_P} \cdot \frac{\delta}{f}$$

$$t_{diode} < \frac{1-\delta}{f}$$

$$\delta < \frac{1}{\left(1 + \frac{V_I N_S}{V_O N_P}\right)}$$

$$\delta < \frac{1}{1 + \frac{340}{15 * 15}} = 39.8\%$$

Choose a value of primary inductance to ensure that the circuit can converter 30 W and remain in discontinuous mode for a switching frequency of 50 kHz.

[3 marks]

A value of δ of 35% is chosen to provide a safety margin.

$$L_P = \tfrac{1}{2} \frac{V_I^{\,2}}{P_I} \frac{\delta^2}{f} = \frac{0.5 \times 340^2 \times 0.35^2}{30 \times 50 \times 10^3} = 4.72\ \text{mH}$$

6) Describe the operation of a brushless DC motor. Provide block diagrams of the systems and a sketch of the power converter circuit.

[7 marks]

Brushless machine has a permanent magnet rotor and a wound stator. The stator is typically windings which have trapezoidal back-emf. The stator is fed with regulated current. The polarity of current in each winding is set according to the whether the winding is in the north or south pole field of the rotor. Consequently, as the rotor rotates the polarities of the stator currents are changed in synchronism. This requires measurement of the absolute rotor position. The amplitude of the stator current can be set to control the torque developed. The power converter is a voltage source device with current feedback.

Diagrams as in notes.

Compare the power converter circuit to the power converter circuit required for a traditional (brushed) DC motor to be operated in forward and reverse rotation with breaking and accelerating torque.

[4 marks]

Diagram of 4-transistor (4 quadrant) chopper required. A typical brushless-dc drive will have 6 transistors compared with 4 for the brushed design. The extra cost, not least of the extra high-side driver is a disadvantage but it is only a 50% increase in semiconductor numbers for the advantage of now brush gear. Both circuits would normally be used in current feedback control. The brushless form requires 3 current sensors compared to one in the brushed form.

Justify the shape of the torque speed diagram in figure 4 with respect to a DC machine. Calculate the principal points on the diagram for a system with the following properties:

DC input voltage 100 V
Armature resistance 0.5 Ω
Field flux at maximum field current 18 mWb
Armature constant 12.5 $V.s.rad^{-1}.Wb^{-1}$ (or $N.m.A^{-1}.Wb^{-1}$)
Rated armature current 8 A

[5 marks]

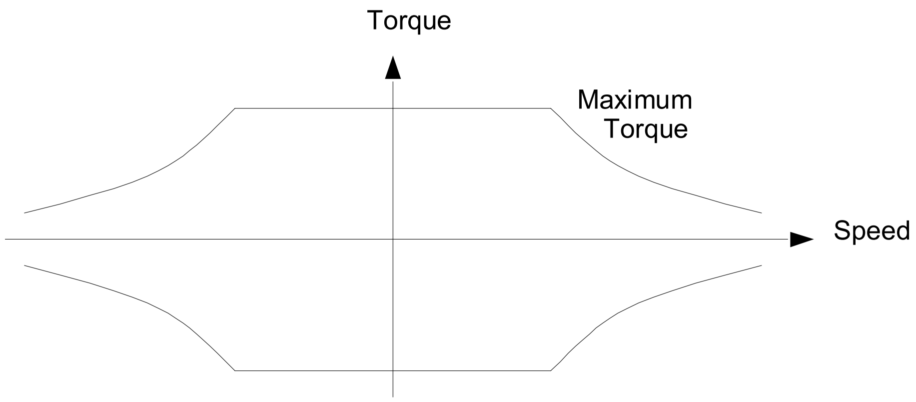


Figure 4 A typical torque speed diagram of an electrical drive system

Torque is proportional to current and flux. Under constant flux conditions the maximum torque achieved is limited by the current rating of the machine and is independent of speed (or direction). By reversing the current, reverse torque can be achieved.

$$T_{\max} = I_{\max}\phi_{\max}k_a = 8\times 0.018\times 12.5 = 1.8\ \text{Nm}$$

As speed increases, the back EMF of the machine increases. Eventually a point is reached where the back EMF is equal to the maximum available supply voltage and it is no longer possible to maintain the desired current flow. Beyond this point the field current is reduced to reduce the flux. The fall in flux reduces the back EMF and allows current control to be maintained but causes a reduction in available torque. Flux is decreased in inverse proportion to the speed so as to maintain the back EMF constant. Therefore the torque available becomes inversely proportional to speed.

The maximum speed at which maximum torque is available is:

$$\omega_{base} = \frac{V_{\max}}{\phi_{\max}k_a} = \frac{100}{0.018\times 12.5} = 444\ \text{rad/s}\ \text{ or } 4244\ \text{rpm}$$

more accurately:

$$\omega_{base} = \frac{V_{\max} - I_{\max}R_a}{\phi_{\max}k_a} = \frac{100 - 0.5 * 8}{0.018\times 12.5} = 426\ \text{rad/s}\ \text{ or } 4074\ \text{rpm}$$

The same speeds can be achieved in reverse.

Summarise the relative merits of brushed and brushless DC drive system.

[4 marks]

Brushless form:

- *does not require regular maintenance*
- *does not have arcing and EMC problems of commutation*
- *does not have field current power loss*
- *requires 6 transistors, position sensor and current sensor*

Brushed form:

- *can be operated with single transistor chopper if only positive speed and torque required.*
- *can be operated open loop (in terms of speed, current or both) in undemanding applications*
- *brush gear requires significant extra volume in small machines.*