EE 3-21

Solutions:

1. This question relates to the design of an instrument for measuring bio-potentials from neurons in the brain.

a) Explain why a potential of 70mV can exists across the cell membrane of a neuron when it is at rest.

- Bookwork.
- Explanation of ionic imbalance between the cell membrane of the neuron [1]
- Identification of contributions of sodium and potassium ions [1]
- Saying that this is evaluated using the Nernst potential equation [1]

b) Figure 1.1 shows an AC coupled bio-potential amplifier for measuring neural activity from the brain. The electrodes used have a capacitance CE=60uF and Vsig and Vos denote the measured bio-potential and common mode offset.

i) Give one advantage and one disadvantage of using AC rather than DC coupled bio-potential amplifiers for this application

- Advantage: Remove common mode offset thus allowing large gain in front end. [1]
- Disadvantage: Reduction of input impedance causing potential attenuation of the signal. [1]

ii) C1 and R1 are used to AC couple the input signal to the amplifier. C1 is chosen to be 100pF. Explain why 100pF is a suitable value.

- 100pf is suitable because it is very small relative to the electrode capacitance CE and thus will cause minimum attenuation at the input of the measurement system, that is the capacitor C1. [1]

iii) Derive the input voltage to the amplifier Vin, and show that it is high pass function stating the equation of the cut off frequency stating any assumptions made. To aid you calculations you may use just one branch of the differential input for your analysis.

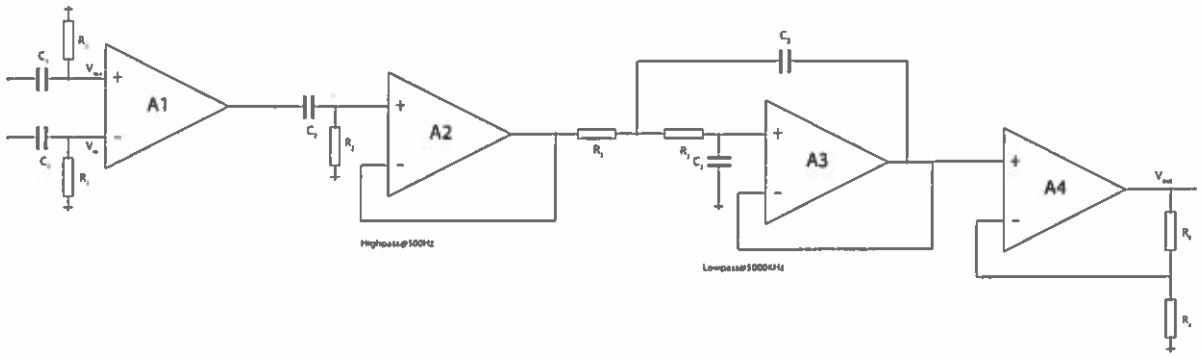
- Assuming C1<<CE we can derive: $V_{in} = (V_{sig} + V_{os}).SR_1C_1/(SR_1C_1 + 1)$ [1]
- $f_c = 1/2\pi R_1C_1$ [1]
- Note: You will loose 1 point if you don't state the assumption.

iv) Calculate a suitable value for R1 to give you a high pass cut off at 10 Hz.

- $R_1 = 1/2\pi C_1 f_c = 1/2\pi(100p)(10) = 159M\Omega$ [1]

c) The Bio-potential amplifier in Figure 1.1 is used as part of a monitoring system to detect the action potential signal shown in Figure 1.2. The gain of the Bio-potential amplifier is set to A=1000. The output of the Bio-potential amplifier is band-pass filtered between 0.3KHz and 5KHz with a 20db/decade high-pass followed 40db/decade low-pass filter. A final gain stage is added to maximize the dynamic range between +3V to -3V.

i) Sketch the full schematic of this monitoring system, indicating suitable resistor values for you filters. You may assume all capacitors are, C=100pF for your filters.



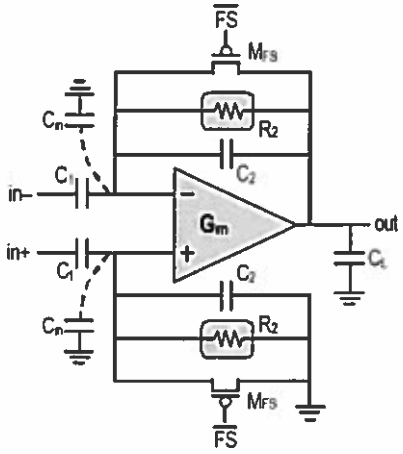
- Schematic shown above for complete system (student needs to identify first order high pass and second order low pass (using a sallen key))[4]
- High pass value $R_2=1/2\pi C_2 f_c = 1/2\pi(100p)(300Hz)=5.3M\Omega$ [0.5]
- Low pass value $R_3=1/2\pi C_3 f_c = 1/2\pi(100p)(5000Hz)=318K\Omega$ [0.5]

ii) Choose suitable gains and resistor values to ensure that the action potential shown in Figure 1.1 is utilizes the maximum dynamic range.

- From figure 1.2 student needs to realize that the 100uV DC is rejected and thus the maximum AC signal passing through is 150uV ptp or 100uV 0top. Realising this the maximum possible gain of the system is 3.3V/100uV=33000. [2]
- Total gain of the system 33000=A1xA2xA3xA4=1000x1x1xA4, thus gain of final stage A4=33[1]
- Thus gain of last stage A4=1+R5/R4=33, therefore R5/R4=32. So we can choose R5=64K and R4=2K. [1]

d) **The bio-potential amplifier shown in Figure 1.1 is to be modified to allow a fully integrated implementation in CMOS for recording from a micro-needle array. The requirements are the gain of the modified amplifier is set by a ratio of capacitors and the output and input common mode voltages at DC are the same. Sketch the schematic of the modified bio-potential amplifier.**

- Bookwork.
- Sketch of the Harrison amplifier.[2]

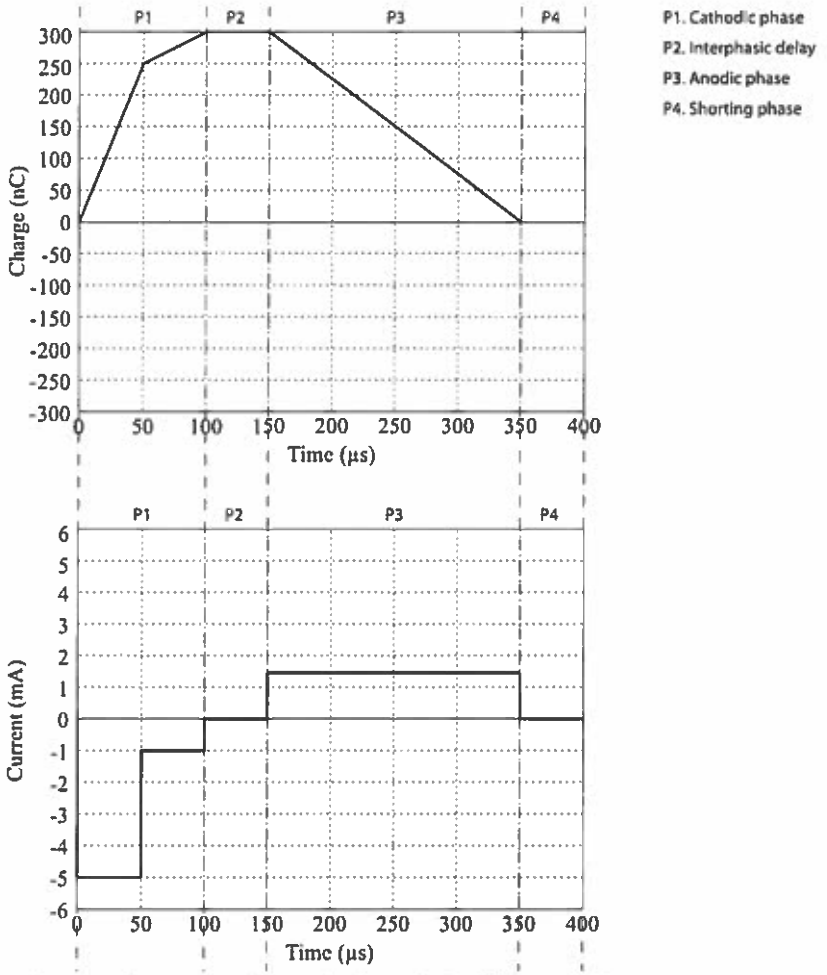


2 This question relates to the design of an electrical stimulation circuit for a spinal cord implant for pain relief.

a)Given the stimulus is a current-mode, charge-balanced, asymmetric biphasic waveform with the timing of the different phases being 2:1:4:1 (cathodic:interphasic:anodic:shorting), sketch and complete the charge delivery profile shown in Figure 2.1 (this shows the profile for only the first 100μs). Annotate the different phases.

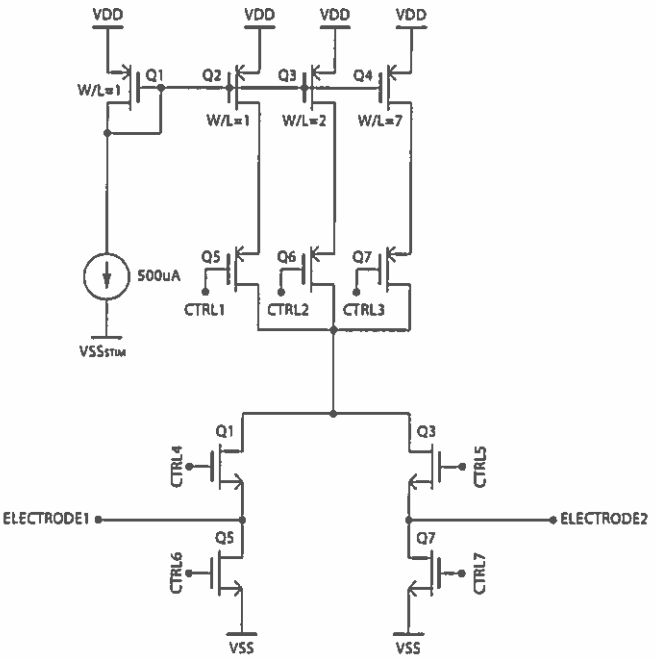
b) Sketch the corresponding current waveform to the charge delivery profile you completed in your answer to part (a).

(a, b) see below:



Marking (a) [1 mark each for correctly marking phases 2-4 + 1 mark for correctly annotating phases]
Marking (b) [1 mark for each phase (1/2 for each correct time and magnitude)]

(c) Design the stimulator circuit to generate the appropriate current pulses required for bipolar electrodes given a 500μA current source, labeling the different control signals required.



Marking (c) [2 marks for current mirror, 1 marks for H-bridge, 1 mark for control signals]

(d) Design a state machine to generate the appropriate control signals for the circuit you provided in your answer to (d).

Can use a 3-bit counter to count from 0-7, with clock frequency = 20kHz (=1/50us).

Define control signals based on control signals X2, X1, X0 (from counter).

Truth table:

X2:X1:X0	000	001	010	011	100	101	110	111
CTRL1				X	X	X	X	
CTRL2	X	X		X	X	X	X	
CTRL3	X							
CTRL4	X	X						
CTRL5				X	X	X	X	
CTRL6				X	X	X	X	X
CTRL7	X	X						X

CATHODIC = !X2.!X1.!X0
ANODIC = !X2.X1.X2 + X2.!(X1.X0)
SHORTING = X2.X1.X0

CTRL1 = ANODIC
CTRL2 = CATHODIC + ANODIC
CTRL3 = !X2.!X1.!X0
CTRL4 = CATHODIC
CTRL5 = ANODIC
CTRL6 = ANODIC + SHORTING
CTRL7 = CATHODIC + SHORTING

Marking (d) [1 mark for counter (or serial shift register), ½ mark for clock, 1 mark for truth table, 1 ½ marks for Boolean expressions]

(e) Compare monopolar and bipolar electrode configurations describing one benefit of each configuration.

Benefit of bipolar stimulation: Better selectivity, as electric field is more targeted between electrodes.
Benefit of monopolar stimulation: Better energy efficiency because reduced shunting current

Marking (e) [1 mark for each benefit]

(f) Explain how the electrode material may influence the design.

The electrode material may influence the design as the maximum current magnitude (and charge density) is material specific. This means some materials may be able to conduct more current than others per unit area. In practice this will define the minimum required area for a given charge delivery.

Marking (f) [1 mark for current density, 1 mark for electrode size]

3. This question relates to the design of chemical sensor instrumentation.

a) Explain the principles of cyclic voltammetry using illustrations where necessary. [4]

- Bookwork.
- Explanation of Cyclic voltammetry [2]
- Diagram of input and output waveforms [2]

b) Figure 1.1 shows an Ion-Sensitive Field Effect Transistor. The threshold voltage of the device is modulated be a pH dependent potential described by:

$$V_{chem} = \gamma + 2.3\alpha U_t pH$$

i. Why is this sensor well suited for applications such as DNA sequencing ? [2]

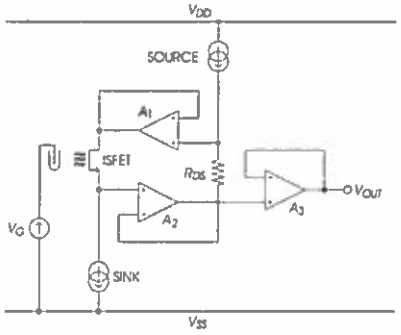
- Any of the following two:
- Scales with Moores law so we can build large arrays reducing cost of sequencing.
- Allows label free detection without the use of bulky optics.
- Allows integration with instrumentation on a single chip to increase limit of detection.

ii. What is the maximum sensitivity achievable using this sensor ? [2]

- For maximum sensitivity a=1 therefore:
- $\frac{\partial Vchem}{\partial pH} = 2.3aU_t = 59mV/pH$

iii. Sketch the schematic of a circuit used to instrument to this sensor and describe it's operation. [4]

- Bookwork.
- Identification and explanation that a constant charge method is required and explanation of the operation [2]
- Schematic [2]



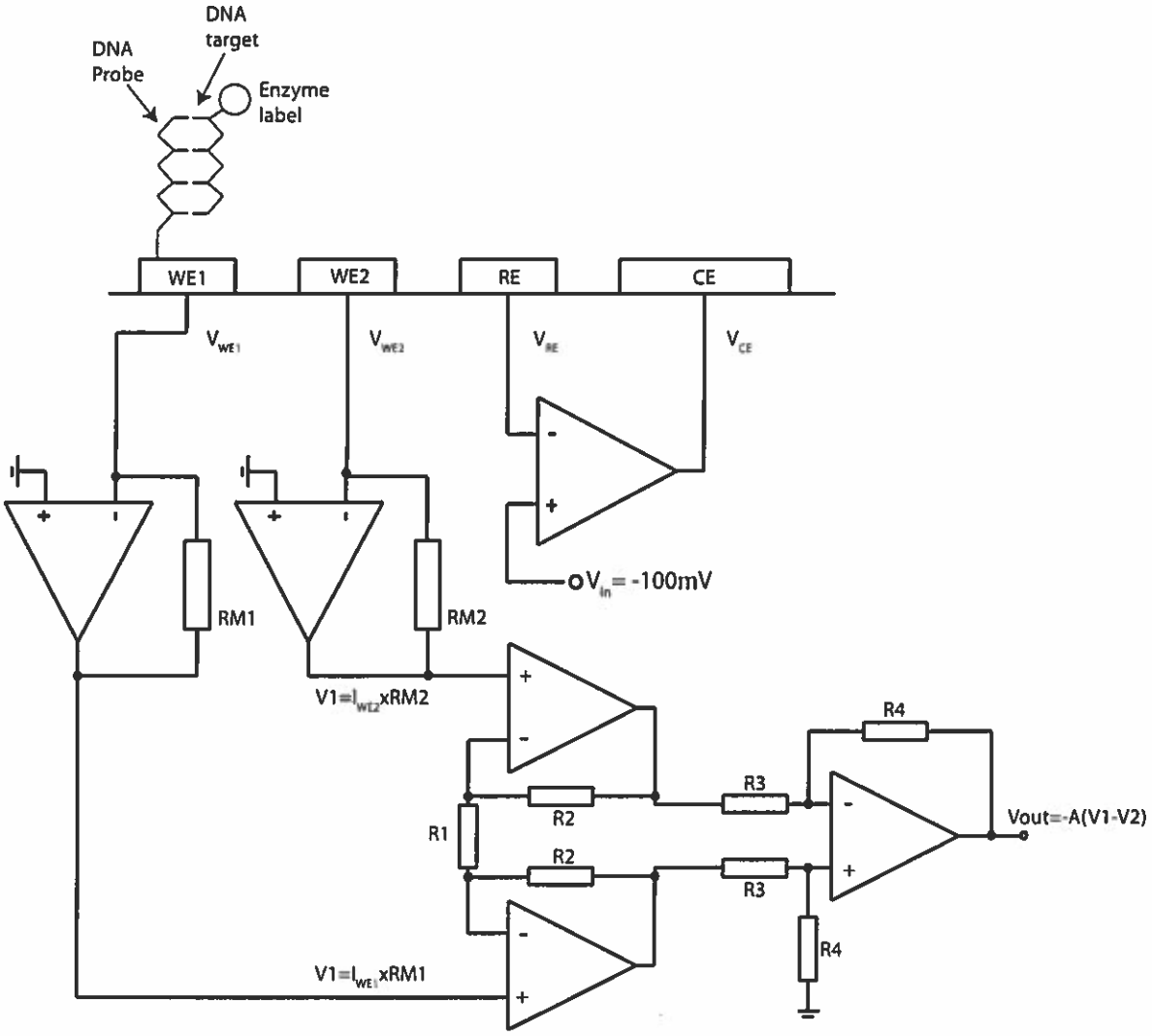
- Circuit diagram of an ISFET source-and-drain follower circuit

c) Figure 1.2 shows an amperometric sensor used for the detection of DNA hybridization. The sensor works on the principle of a redox reaction confirming hybridization on WE1 at a cell potential of V_{cell}=100mV. An additional electrode, WE2 is added for sensor drift compensation. It is desirable that the output of any instrumentation system use the difference between the hybridization reaction and drift to confirm a reaction.

i. Design instrumentation to interface to this sensor which provides the cell bias, V_{cell} and a suitable readout which can utilize the second electrode, WE2 to increase the signal-to-noise ratio at the output. You are required to show all your schematics and label voltages where necessary. [6]

- New application of theory. Student needs to identify he can use the standard instrumentation taught and take a differential measurement using a simple difference amplifier.

- Schematic of Potentiostat for correct polarity [2]
- Schematic of transimpedance amplifier with differential readout [4]
- Loose 1 point for incorrect biasing voltages.
- A potential solution:



ii. **Explain why the counter electrode, CE, is larger than the working electrode, WE1.** [2]

- Counter electrode has to source double the current to accommodate two working electrodes, therefore it needs to have double the area.

4. This question relates to the design of a system for neonatal electroencephalography (EEG) monitoring. The monitor has 3 electrodes, one on either side of the head recorded independently with a reference connected to the ear of the baby. The signal is primarily contaminated with heart rate (ECG, 120 beats per minute) and breathing signals (respiration, 30-50 breaths per minute).

a) Given the EEG bandwidth of interest is stated as 2-40Hz, without any pre-processing ranges from +/- 100µV and requires a minimum resolution of 1µV.
   i. What would be the required ADC resolution and sampling rate (assuming Nyquist sampling)?

If BW=40Hz, Nyquist criterion states we sample at least twice this. So sample at 100Sample/s. If input range is +/-100uV and minimum resolution is 1uv, then DR=(100-(-100))/1=200. ADC resolution = log(200)/log(2) = 7.64, therefore need 8-bit. [1 mark for resolution, 1 mark for sampling rate]

   ii. What data rate would be required to transmit the raw data (eg. wirelessly)

Datarate = 2 (channels) x 8-bit x 100S/s = 1,600 bit per sec = 1.6kbps. [1 mark for resolution x sampling rate, 1 mark for identifying there are 2 channels]

b) If the raw data is to be transmitted, encoded using Hamming (7,4) determine the following:
   i. The required data-rate.

If encoded using Hamming (7,4) – then for each 4 bits, we need to transmit 7 bits. Therefore transmitted datarate = 7/4 * 1.6kbps = 2.8kbps [1 mark]

   ii. Encode the 8-bit word "183" (decimal value) using Hamming (7,4).

(183)10=(10110111)2. To transmit this need 2x 4-bit words (1011 and 0111) (each encoded to 7-bits) so total of 14-bit. [1 mark]
So ab1c011 de0f111, where a-f are the Hamming parity check bits.
So for 1st word: a= (parity for bit 1, 2 and 4) = 0, b=(parity for bits 1, 3 and 4) = 1, c= (parity for bits 2, 3 and 4) = 0 [1 mark]
2nd word: d= (parity for bit 1, 2 and 4) = 0, e=(parity for bits 1, 3 and 4) = 0, f= (parity for bits 2, 3 and 4) = 1 [1 mark]
So encoded bit sequence is: 0110011 0001111

iii) Describe how Hamming (7,4) provides error checking and/or error detection.

Hamming codes are a family of linear error-correcting codes. They can detect up to two-bit errors or correct one-bit errors without detection of uncorrected errors. By contrast, the simple parity code cannot correct errors, and can detect only an odd number of bits in error. Hamming codes are perfect codes, that is, they achieve the highest possible rate for codes with their block length and minimum distance 3. [1 mark for saying they can both detect + correct, 1 mark for specific numbers]

c) To maximize data transmission bandwidth and extract useful features from the data, the ECG and respiration need to be removed.
   i. Suggest two methods for removal of the ECG and respiration signals.

Since the ECG and respiration are 2Hz (120 beats per minute / 60) and 0.5-0.83Hz (30-50 beats / 60) it would be possible to use a high order high-pass filter [1 mark] or Independent Component Analysis (ICA) [1 mark]

   ii. State one challenge of each method. [2]

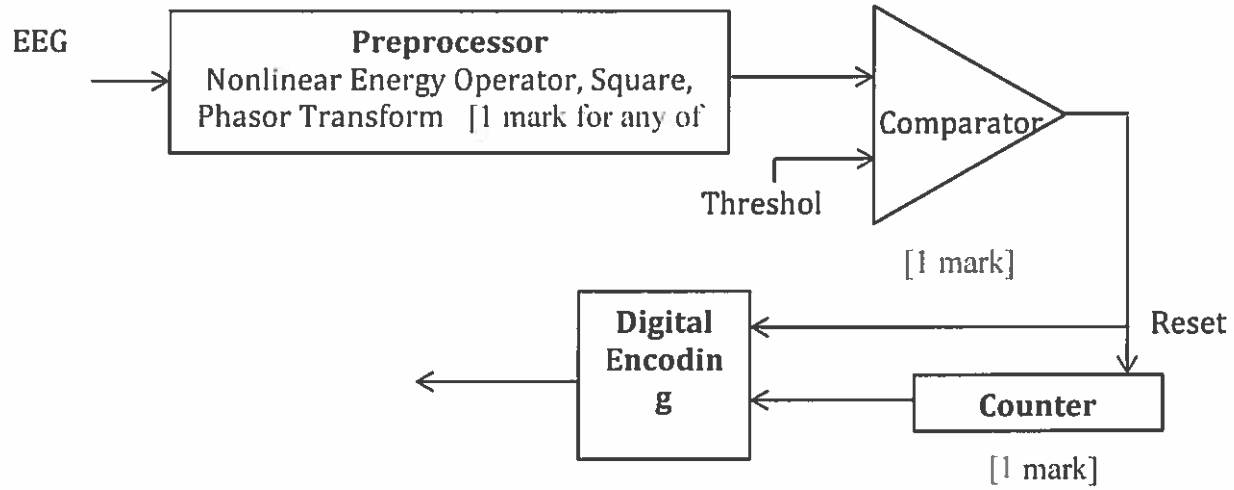
High-pass challenge is the potential cross-over with the EEG bandwidth and the high order needed. Possible alternatives are to elude to the fact that this will cause a time delay in the recording. [1 mark] Challenges with ICA include the assumption that the signals are independent, complexity of implementation in real-time and that there is only one channel of data. ICA typically requires multiple observations. [1 mark for any of these]

d) **The typical signals during normal sleep/wake cycling are show in Figure 4.1. The duration of the sleep-wake cycle gives some indication of the development of the brain and can detect abnormalities. A system is required that will detect the types of activity depicted in Figure 1(sleep-wake discharges). These burst-quiet periods range from 3-20 seconds.** ***(Note: you can assume the ECG and respiratory artifacts have already been removed).***

Draw a block diagram for a system that would detect this type of activity and classify it. The system is required to output an indicator of the burst activity and the quiet period (0 for quiet, and 1 for bursting). It also needs to follow this with the duration in seconds of this activity. Estimate what would be the maximum new data rate?

A system that can detect this activity is the same as a spike detector, use of a signal enhancement, followed by a threshold detector, with a counter to determine the time period between bursts and their durations.

System Diagram

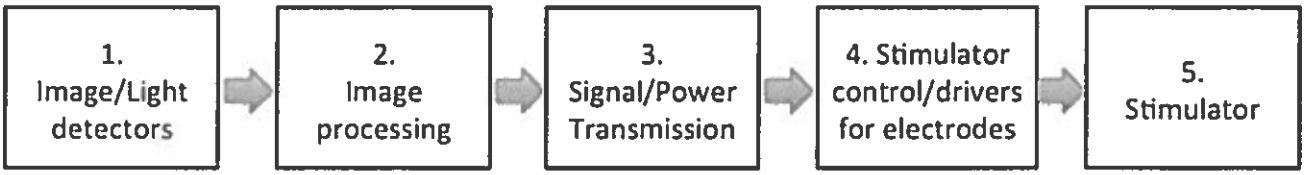


The astute will realise the bursting activity will cause multiple threshold crossings in one period of bursting. To overcome this they could insert an envelope detector prior to the comparator. The alternative is to realise that the minimum period of bursting is 3 seconds (stated in question). As such a system that tries to monitor when bursting stops (using some memory) or a secondary counter to measure the 3 second period and then wait for a decrease in activity over a certain period. [2 marks for any attempt at these]
The new data rate would be 1 bit for burst/quiet plus 6 bits for the counter output. As this would be over a period of minimum 3 seconds, then the estimate would be 7 bits in 3 seconds or 2.33 bits/second. [1 mark]

5. This question concerns a retinal prosthesis for the restoring vision.

a) Sketch a system block diagram of a retinal prosthesis that would help a blind person to potentially recognise large objects around him. Clearly label each block and briefly explain the role of each of them.

(a) A system block diagram:



1. Image acquisition device: converts light into electrical signal (phototransduction). Could be photodiode arrays or a camera which would additionally convert the output into digital signals.
2. Image processing device: takes the output of the (1) and processes it according to some retinomorphic algorithm to calculate the stimulation patterns.
3. Signal Transmission from (1) and (2) – normally outside the eye to (4) and (5) which are normally inside the eye. Data and power telemetry circuits on the transmitter and receiver side. Could be separated into 3a (external) and 3b (internal, implanted) part.
4. Stimulator Electronics: signal controllers and stimulation electrode current drivers.
5. Stimulator: the cable and electrodes

[2 marks for the system block diagram + 1 mark for each description 1.-5. = 7 marks]

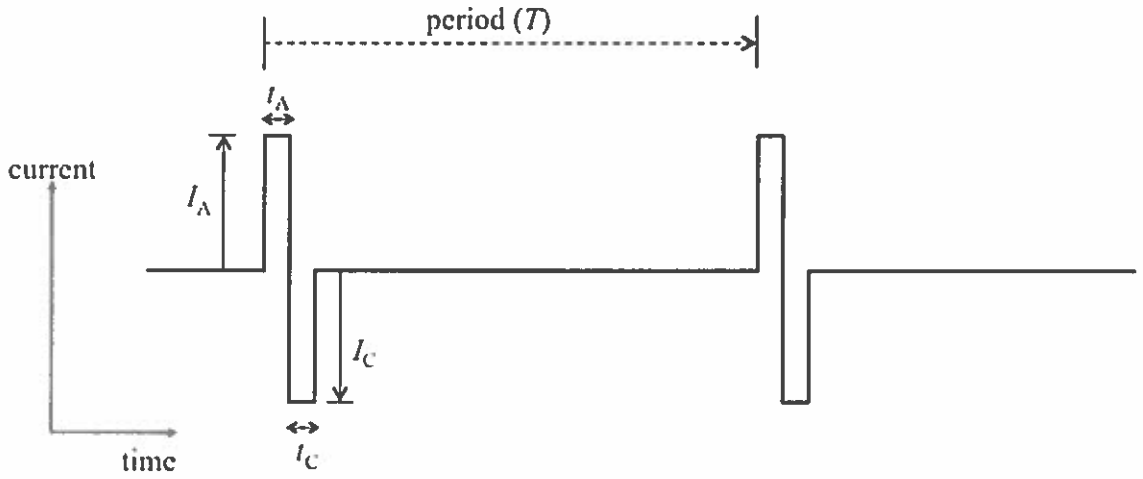
b) If the target visual acuity and equivalent frame rate are 25 x 25 pixels at 20 frames per second and given that targeted neurons require minimum Qmin=50nC for stimulation,

i. Define the key specifications for the stimulator (the current magnitude and pulse width for each phase, and the period/repetition rate). Assume biphasic, symmetric stimulation pulses (where the minimum interphase delay is negligible) and that no more than one row of stimulation electrodes (25 in total) can be simultaneously on.

For 25 arrays of electrodes and 20FPS = 500 stimulation cycles per second => 2ms cycle. For a biphasic, symmetric stim. maximum stimulation time is Tstim = 1ms, giving a minimum current of Istim_min=Qmin/Tstim_max = 50nC/1ms = 50μA.
The stimulation waveform parameters are:
$I_{anodic} = I_A = 50\mu A$, $t_{anodic} = t_A = 1ms$,
$I_{cathodic} = I_C = -50\mu A$, $t_{cathodic} = t_C = 1ms$,
period T = 50ms, i.e repetition frequency f=20Hz (every 50ms).

ii. Sketch the stimulation waveform at a single electrode and clearly label all relevant parameters.

Stimulation waveform diagram:



[1mark for correct I_A and t_A, 1 mark for I_C and t_C and 1 mark for the period T, + 2 marks for the stimulation waveform diagram = 5 points]

c) If the maximum allowable charge density for a Pt electrode is qm=150μC/cm^2,

i. What is the electrode minimum area required and calculate the diameter D of the electrode? You may assume the electrodes are flat and circular.

Area = $I_A * t_A / q_m$ = 50nC / 1.5μC/mm^2 = 0.033mm^2 [1 mark]
Area = $\pi * D^2/4$ => D = 206μm [1mark]

ii. What is the minimum size of the electrode array if the minimum spacing between adjacent electrodes is d=94μm?

Array edge length = 25*(D+d) = 25*300μm = 7.5mm.
Array size: 7.5 x 7.5 mm^2 [1mark]
Total: 3 marks

d) If the electrode-tissue impedance is R=10kΩ□calculate the average power dissipation at the load impedance for a single electrode and for the whole stimulation array.

Average power dissipation for a single electrode:
$P_1 = R * I^2 * t_{active} * \Gamma$ = 10 kΩ * (50 μA)^2 * 0.002 s * 20 Hz = 1 μW
($t_{active} = t_A + t_C$ = 2 ms, $\Gamma = 1/T$ = 20 Hz in this case)
[1 mark for correct t_{active} + 1 mark for correct P_1]

For 25 electrodes which are simultaneously active $P_{stimulator}$ = 25 μW. [1 mark]
Total: 3 marks

e) What is the electrode voltage needed to drive each electrode if a design requirement is that the minimum stimulation strength is at least two times Qmin (i.e. 100nC)? [2]

For 100nC, from (b): I_{stim} = 100μA. [1 mark]
Now $V = I_{stim} * R_{load}$ = 100 μA * 10 kΩ = 1V . [1 mark]
Total: 2 marks

For (c), (d) and (e) some fraction of marks can be given in each case when a correct formula was used to solve the problem.

6. This question concerns power supplies for body worn and implanted medical electronics.

a) The link efficiency of a wireless power transfer system is given in Equation (1):

$$\eta_{link} = \frac{k^2 Q_{TX} Q_{RX}}{\left(1+\sqrt{1+k^2 Q_{TX} Q_{RX}}\right)^2} \quad (1)$$

where k is the coupling factor and Q_{TX} and Q_{RX} are the Q-factors of the transmit and receive coils respectively.

i) What do k and Q_{RX}/Q_{TX} physically represent? Give a formula for each.

[4]

|book work and prior general knowledge of EEE|

k is the coupling factor and is the fraction of flux produced by the primary that links with the secondary

[1]

Hence is can be written as:

$$k = \frac{\Phi_{12}}{\Phi_1} \text{ or } k = \frac{M_{12}}{\sqrt{L_1 L_2}}$$

[1]

Q is the quality factor of the coils. This is physically a measure of the energy stored in the resonator, divided by the energy dissipated per cycle

[1]

For an inductor it is written as:

$$Q = \frac{\omega L}{R}$$

[1]

ii) In the design of a wireless power transfer system, what factors have a strong influence on the coupling factor, k?

[2]

|Basic Understanding|

Coupling factor is influenced by the coil geometry (shape and size of the coils) and the distance between them, as well as the materials that the flux must pass through (i.e. air or a ferro magnetic material)

[2]

iii) What factors have a strong influence on the Q-factor of the coils?

[2]

Q-factor is largely influenced by the frequency of operation, coil core material and conductor material.

[2]

The skin depth in a conductor is given in equation (2):

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \quad (2)$$

where □ is the material resistivity, □ is the frequency of operation and □ is the magnetic permeability.

iv) By considering only equations (1) and the coil Q-factor (using equation (2)), what frequency should an inductive wireless power system be operated at to ensure maximum link efficiency?

[3]

[Algebraic manipulation]
Because the Q-factor is proportional to L/R, but the skin depth, which is proportional to resistsnce, is proportional to 1/sqrt( ), the Q-factor is proportional to sqrt( ). This suggests that, as we want to maximise Q, we should operate the system at the maximum possible frequency, i.e. tending to infinity.

[3]

v) What important effect was not taken into account in part iv) and how would this change your choice of frequency for maximum link efficiency?

[2]

[Understanding]
The Q-factors of the coils will not increase indefinitely as the frequency increases. This is because at some point (when the driving frequency causes the wavelength to be around 1/10 the coil length) the coils will start to radiate energy into the far field, dropping the Q factor.

b) Motion-driven energy harvesting devices have been used on body-worn electronics applications, with the Seiko kinetic watch probably being the best known.

i) Explain the principle of operation of an inertial energy harvester.

[3]

[Bookwork]
A proof mass is suspended on a spring suspension. When the frame of the device experiences acceleration, the mass moves relative to the frame. The relative motion is used to do work against a transduction mechanism, which can be implemented via several mechanism, the most common being piezoelectric, electrostatic and electromagnetic.

[3]

ii) What, fundamentally, limits the output power of such devices?

[2]

[Interpretation]
The power output of these devices depends on the proof mass, the distance the mass can move through, and the driving frequency and displacement. The driving motion is not changeable by the engineer, so the limit is simply how large the device can be and what material the proof mass can be made of.

[2]

iii) Explain why a simple passive full-wave diode rectifier is a poor choice for using as an interface circuit to an electromagnetic harvester

[2]

[Interpretation]

In order to extract power from a sinusoidal motion, a sinusoidal component force, in phase, at the same frequency is required (only in-phase signals at the same frequency can result in conversion of active power, e.g. voltage and current or force and velocity). This means that a sinusoidal current should be drawn from the transducer in phase with the sinusoidal emf. A passive rectifier does not draw a sinusoidal current and thus draws reactive power due to the harmonics, which causes loss and leads to inefficiency.

[2]