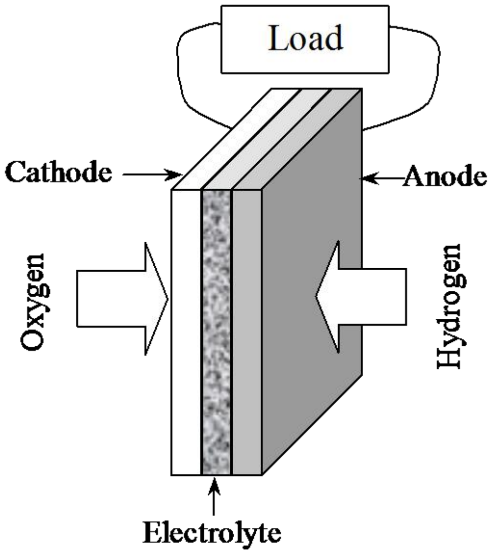
EEE6202 – summer 2015 - Answers

Question 1.

a. To produce a simple acid based fuel cell, 2 electrodes and an electrolyte are required. The electrodes are usually made flat, with a thin layer of electrolyte as shown in below. The structure of the electrode is porous, so that both the electrolyte from one side and the gas from the other can penetrate it. This is to give the maximum possible contact between the electrode, the electrolyte and the gas.



Basic cathode-electrolyte-anode construction of a fuel cell

To see how the reaction between hydrogen and oxygen produces an electric current, and where the electrons come from, let us consider the separate reactions taking place at each electrode

At the anode of an **acid electrolyte** fuel cell the hydrogen gas ionises, releasing electrons and creating H^+ ions (or protons).

$$2H_2 \rightarrow 4H^+ + 4e^- \tag{1.2}$$

This reaction releases energy. At the cathode, oxygen reacts with electrons taken from the electrode, and H^+ ions from the electrolyte, to form water:

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \tag{1.3}$$

Clearly, for both these reactions to proceed continuously, electron produced at the anode must pass through an electrical circuit to the cathode. Also, H^+ ions must pass through the electrolyte. An acid is a fluid with free H^+ ions, and so serves this purpose very well. Certain polymer can also be made to contain mobile H^+ ions. These materials are referred to as “proton exchange membranes”, because an H^+ ion is also a proton.

b. Consider the basic reaction for the hydrogen/oxygen fuel cell:

$$2H_2 + O_2 \rightarrow 2H_2O$$

This is equivalent to:

$$H_2 + 0.5\ O_2 \rightarrow H_2O$$

The product is one mole of H_2O, and the inputs are one mole of H_2 and a half mole of O_2. Thus

$$\Delta g_f = g_f \text{ of products} - \sum g_f \text{ of reactants}$$

Hence we have

$$\Delta \bar{g}_f = \left(\bar{g}_f\right)_{H2O} - \left(\bar{g}_f\right)_{H2} - 0.5\left(\bar{g}_f\right)_{O2}$$

Now we can say that:

Electrical work done = *charge* x *voltage* = *-2FE* (Joules)

$$E = -\Delta \bar{g}_f / 2F$$

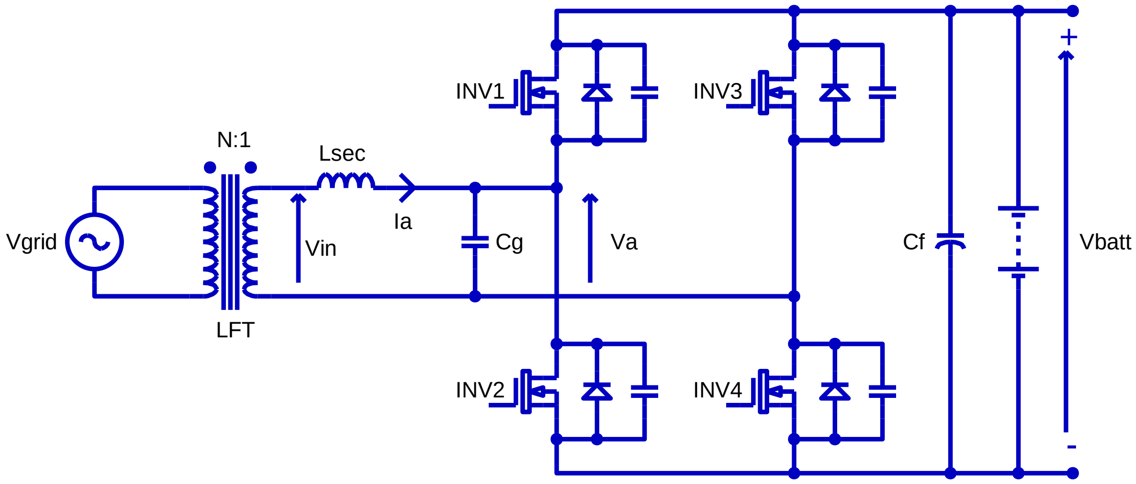
$$E = -\Delta \bar{g}_f / 2F = 237200/(2 \times 96485) = 1.23\ (V)$$

To power a 5V cell phone would require a minimum of 5/1.23 = 4 fuel cells connected in series to reach the correct voltage. HOWEVER, given that the fuel cells have internal resistance and lose voltage dependant on a number of different phenomena, I would assume at least 5 connected in series.

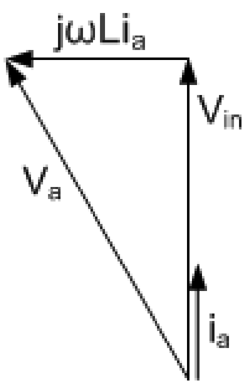
c. PAFC's operate at >200^{o}C and are more usually suitable for large high power generation installations. The high temperature operation does not make this a suitable technology for operation within a small portable piece of equipment

Question 2.

a. Considering a grid-tied system operating at 50Hz, four switching devices are configured as a PWM-controlled H-Bridge, the centre-points of which are coupled to a 50Hz isolation transformer. The Energy Storage System is connected across the H-bridge DC rails in parallel with a suitably sized DC-link capacitor to filter out both the high frequency switching harmonics and the second harmonic resulting from use of the single-phase utility. The leakage inductance of the transformer is responsible for facilitating the power transfer and power factor control between the H-bridge and the grid (phasor diagram). Through use of a PWM scheme in combination with a current-control loop, the direction of power flow can be controlled to allow charging or discharging of the battery from or to the grid. Considering the desire for operation as close to unity power factor as is possible, the phasor diagram describes the effect that the leakage inductance (referred to the secondary winding) has on the system, where Vin is the voltage across the secondary winding of the LFT (with leakage inductance Lsec), Ia is the current flowing through this secondary leakage inductance and Va is the voltage applied to the H-bridge before rectification. A small filtering capacitor is used on the secondary windings of the transformer to filter the high frequency PWM from the 50Hz mains?



Grid-tied bidirectional four-switch-converter topology



$$Va = \sqrt{V_{in}{}^2 + (\omega L_{sec} I_a)^2}$$

$$\sqrt{2} * Va \leq V_{max} \text{ and } I_a = \frac{P_{out}}{V_{in}}$$

$$\therefore L_{sec} \leq \frac{V_{in}}{P_{out}\omega}\sqrt{\frac{V_{Batt}{}^2}{2} - V_{in}{}^2}$$

Phasor diagram and governing equations of converter

Assuming ideal switches/diodes and all power losses are contained within the transformer: Considering zero power transfer (Ia = 0), the minimum battery voltage must be satisfied from maximum grid therefore Va = Vin = VBattmin/sqrt(2) = 79.34V. A transformer turns ratio of 253/79.34 = **3.19:1** is chosen.

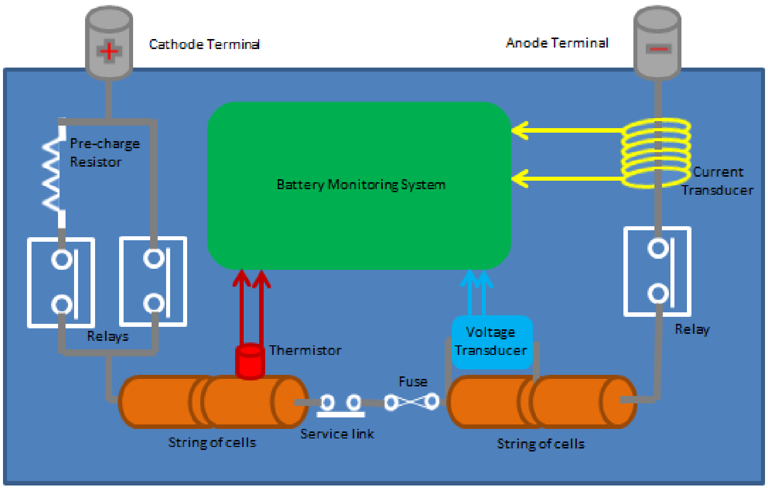
The maximum leakage inductance must be calculated from the equation above to ensure the required power transfer (3.6kW output). Maximum power occurs at CC-CV threshold so Vbatt = 191.4, and the worst case scenario here is at minimum Vgrid, so Vinmin = 207/3.19 = 64.89V. Lsec = 6.8mH. But grid-side leakage was requested, so Lpri = Lsec * N^2 = 69.2mH.

b. Each module has a series –parallel combination of four cells with 66Ah capacity each when new. Therefore each new module has a terminal voltage of 5V discharged and 8.4V on float charge with full capacity of 66Ah. Pack is therefore 240V discharged and 403.2V on float charge with full capacity of 66Ah when new. Capacity of ESS when installed is therefore 52.8Ah (80% SoH).

The fully charged ESS has 52.8Ah capacity. At 8A discharge, total operating time can be 6hrs and 36 minutes allowing for operation until 06:41. Assuming PV supplies 6A from sunrise at 06:30, Battery only has to supply 2A from 06:30. This means 11 minutes at 8A is not used of the total capacity leaving 1.46667Ah available from 06:30. At 2A, this gives an operating time of the battery until full discharge of 44 minutes. So lighting only available until 07:14 since PV cannot supply all of the current required.

Question 3.

a. The required terminal voltage can be constructed from a network of cells, strings or modules Per-unit measuring devices such as thermistors, current transducers (CTs) and voltage transducers (VTs) are included to implement safety-critical control of the various relays necessary for isolation and pre-charge, whilst capturing time-domain data of the battery's operation allowing SoC and SoH monitoring via computations carried out and recorded in the BMS. In terms of EVs, the BMS can also communicate with charging infrastructure by means of an external communication databus. For high voltage packs a suitably robust case and durable tracking label are required.



Generic components of a battery pack

b. **Monitoring:** BMS collects and stores all useful data measured in the pack e.g. voltages, currents, temperatures and calculates State-of-Function (State-of-Charge and State-of-Health)

Protection: The BMS keeps the battery operating in its Safe Operating Area. Prevents under-voltage (discharge) over-voltage (charge), over-current (charge/discharge, over-temperature (at all times

Load management: Connection of pack with EVSE may require initial charging (pre-charge) of the DC-link capacitance of a load. To limit in-rush current the BMS operates relays and resistor networks. The BMS also determines whether re-gen is possible/allowable to avoid overcharging.

Computation: Considering the available data stored by the BMS, it should be possible to calculate important operational limits and indicators of SoC and SoH:

a. Total number of cycles and time/usage between charges
b. Total usage time since fitted to the EV (Age of pack in hours)
c. Energy delivered since last charge (kWh)
d. Total energy provided since first fitted to EV (kWh)
e. Maximum charging/discharging current allowable (temperature dependant)

f. Charge delivered or stored, usually the net current integrated over time (Coulomb counting)
g. Internal impedance of cells

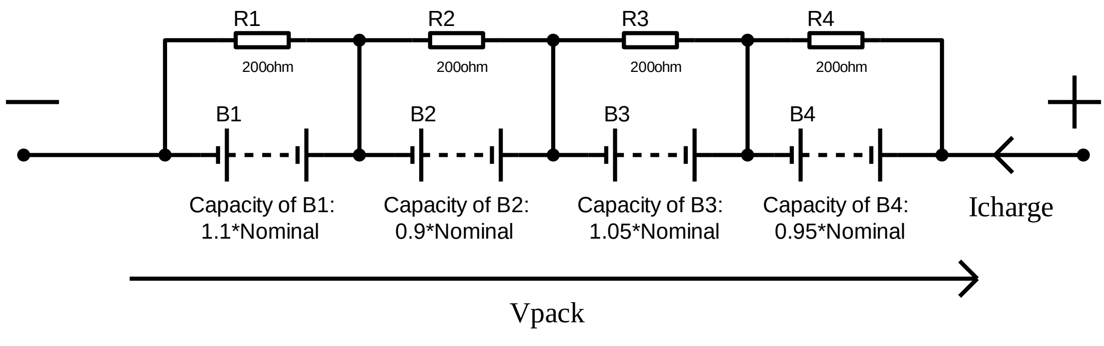
Communication: Smart battery packs can communicate with EVSE or external data-logger:

a. Through directly wired link (RS-232)
b. Serial communications via CAN-bus (automotive)
c. Via wireless comms (Bluetooth, Wi-Fi)
d. Power-line communication (serial data multiplexed onto DC-bus of vehicle)

Optimisation: Whilst the BMS could be taught to optimise the charging/discharging strategies and develop more accurate SoF estimation techniques over time, optimisation is usually focussed on actively ensuring that each cell of the pack is kept at the same voltage or SoC. This can be done through charge-balancing of the packs

c. **Assumption: In steady state the Open-Circuit Voltage of each battery is assumed to have a linear correlation to the available capacity above 20-30% SoC – 100V initial pack voltage is above 30% SoC if 320V is nominal pack voltage. Since the proportions of capacity add to 4, the average voltage of a module would be 25V and each module can be calculated according to the capacity ratio:**

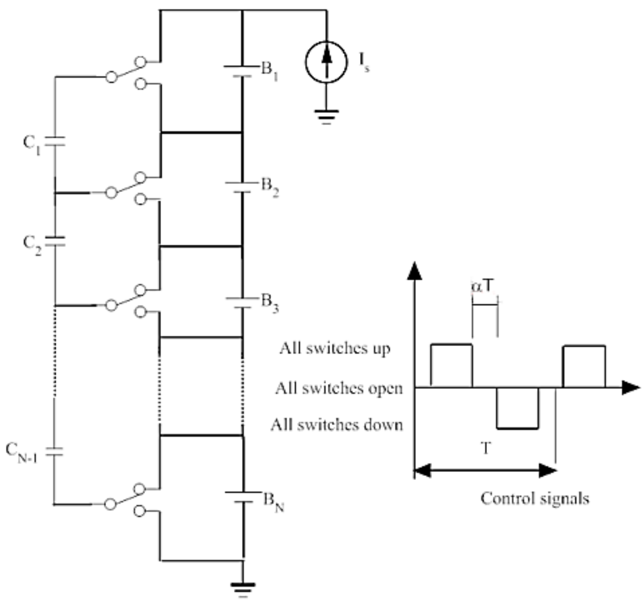
V_{B1ini} = 27.5V	V_{B2ini} = 22.5V	V_{B3ini} = 26.25V	V_{B4ini} = 23.75V
I_{R1} = 137.5mA	I_{R2} = 112.5mA	I_{R3} = 131.3mA	I_{R4} = 118.8mA
P_{R1} ~ 3.78W	P_{R2} ~ 2.53W	P_{R3} ~ 3.45W	P_{R4} ~ 2.82W



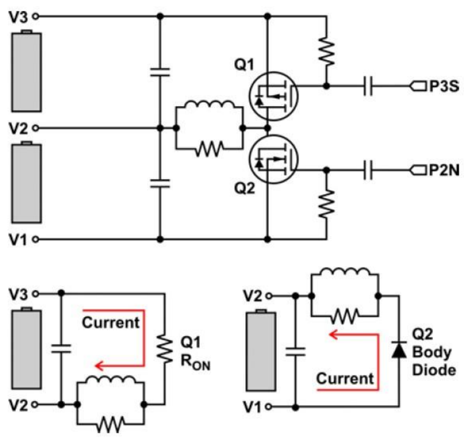
Assuming that the pack remains balanced during full CC-CV charging: The maximum power dissipation will initially occur during the CV mode as the controller switches from CC to CV (when float-charge voltage is maximum). At 100V per module this will dissipate 4 x 50W = 200W. However, as the pack current demand decays in CV mode, the charger must provide > 0.5A else the balance resistors will begin to rob current from the modules if CV mode is continued.

Switches may be added in series with the resistors to control the speed of balancing and amount of power dissipated, thereby reducing pack heating.

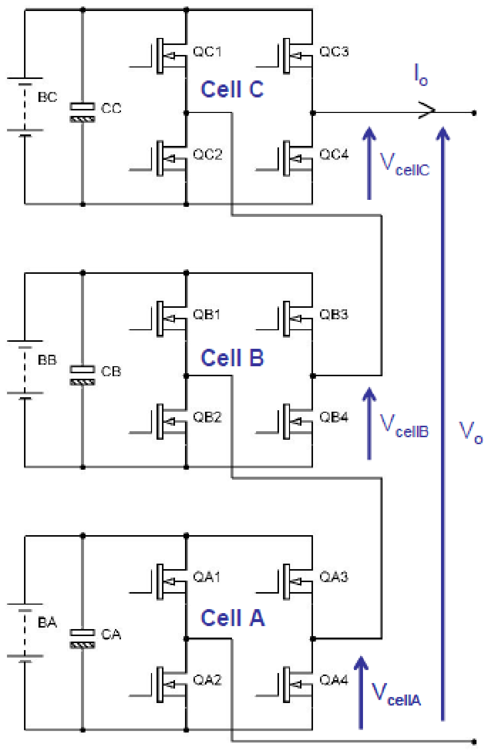
d. **Switched capacitor balancing:** Considering the loss mechanisms of the passive balancing techniques, by replacing the resistors with an energy storage device (e.g. a capacitor in this case) overcharged cells can be used to charge the capacitor which can then be switched across a weaker cell, allowing discharge of the capacitor's stored energy. For simple operation (see Fig), all switches are operated in unison, and equalised cell voltages are possible, albeit with a slow equalisation speed and extra cost since each DPST switch (with off position) would have to be constructed from two semiconductor switches that do not have an intrinsic body diode. For "smarter" equalisation schemes, the switches can be operated individually if individual cells/strings can be monitored for ideal voltage (similar to the switched resistor method above).



Switched inductor balancing: In order to increase equalisation speed, the active capacitors could be replaced by a switched inductor/inductors/transformers scheme, where the rate of change of equalisation current is governed by the magnitude of the inductance used. This can however, lead to high current stresses in the switching devices. A switched inductors balancing scheme is shown below for a two-cell system. The system can be cascaded for more batteries, each pair requiring two switches (with intrinsic body diode), an inductor and a damping resistor, thereby increasing complexity and cost. The switches are generally operated with 50% duty cycle, where half a cycle of operation is shown below.

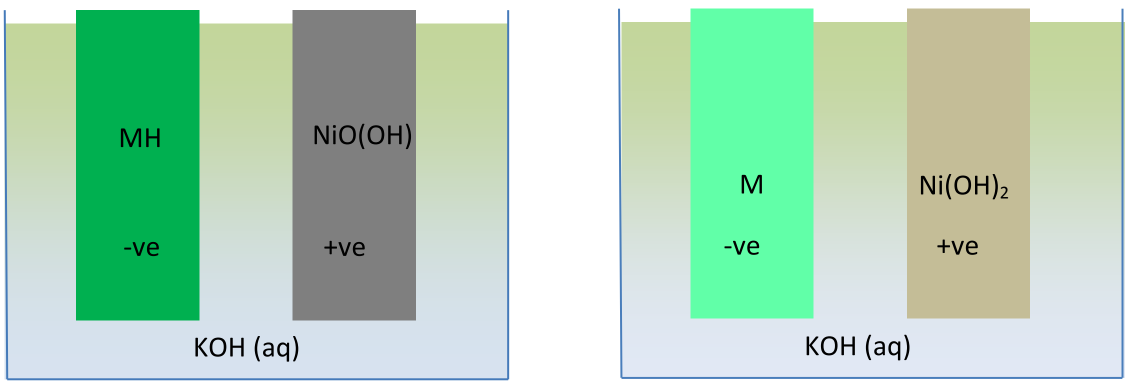


Switching converter balancing: At the most complicated (and expensive) end of the scale for balancing systems, full-bridge converter modules can be implemented per cell/string allowing fully controlled bidirectional equalisation for high equalisation speed and vastly improved accuracy and thermal control:



Question 4.

a. Assuming that the insulating separator of the cell is neglected, a NiMH cell can be considered to comprise two parallel plates dipped into an alkaline electrolyte as shown below:



Charged NiMH cell Discharged NiMH cell

Cell chemistry is based around the reversible reactions below:

$$NiO(OH) + MH \xleftrightarrow{Charge/Discharge} Ni(OH)_2 + M$$

This may be split into the reaction at the positive electrode (Nickel Hydroxide)

$$NiO(OH) + H_2O + e^- \xleftrightarrow{Charge/Discharge} Ni(OH)_2 + OH^-$$

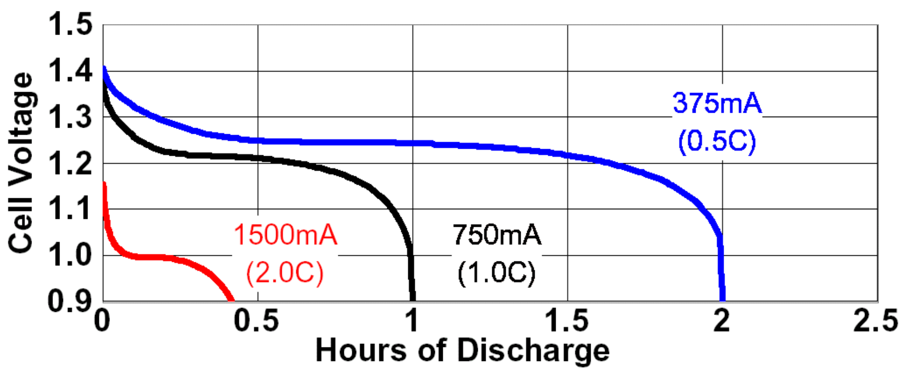
And the reaction at the negative electrode (Metal)

$$MH + OH^- \xleftrightarrow{Charge/Discharge} M + H_2O + e^-$$

The alkaline solution in a NiMH cell will naturally dissociate into positive potassium ions (K^+) and negative hydroxyl ions (OH^-). Consequently, the atoms in the metal plates will try to form ionic bonds once they have dissociated on contact with the alkaline solution. When a NiMH cell is discharged, the dissociated metal-hydride on the surface of the negative plate (anode) will combine with the hydroxyl ions in the electrolyte, forming plated metal on the anode whilst releasing water molecules (H_20) into the electrolyte and making free electrons available for conduction. When a load is applied to the terminals, these electrons flow to the positive electrode (cathode), where they combine with water molecules in the electrolyte and the dissociated nickel-oxide hydroxide on the surface of the positive plate to form plated nickelous-hydroxide on the cathode whilst releasing negative hydroxyl ions into the solution for recombination with the metal-hydride on the anode etc, etc. Eventually, both plates become fully plated so that the hydroxyl ions in the electrolyte cannot access material to combine with. Usually the discharge process is stopped before full plating can occur as irreversible damage can occur.
Note that the potassium ions dissociated in the alkaline play no part in the chemical reaction, and so the alkaline electrolyte serves only as a transport mechanism for the hydroxyl ions.

b. Cell voltage starts at ~1.4V, decaying to nominal 1.2V/1.25V until deep discharge cut off at 0.9V/1.0V

At 0.5C, discharge time is 2 hours.



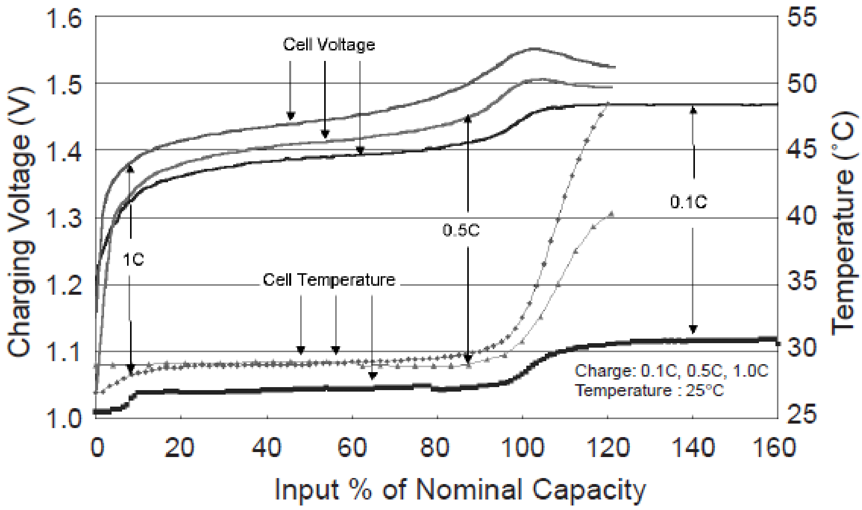
Discharging of a typical AA format NiMH cell at 21°C

c. 1) **Full-charge detection by temperature**

The cell or battery pack will be fitted with a low-cost thermistor with a cut-off temperature of ~50°C. As the NiMH approaches full SoC, the internal temperature of the cell being monitored increases. However, since the thermistor is usually affixed to the skin of the sealed cell, the core of the spiral-wound cell could be many degrees hotter than the temperature measured by the thermistor and so the thermal delay results in overcharge. With more modern/expensive equipment, a microprocessor can be used to evaluate the rate of change of temperature of the outside of the cell as a more effective indication of a fully charged battery.

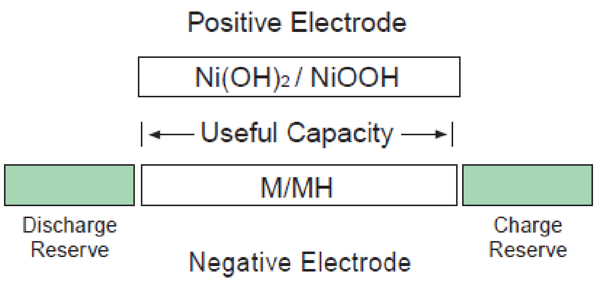
2) **Full-charge detection by voltage signature (Negative Delta Voltage – NDV)**

In this case more advanced chargers will monitor time and cell voltage and cease charging when a defined voltage signature is recorded – usually a voltage drop (NDV) occurring when the cell is fully charged by a constant current. This method is more accurate than temperature measurements but does require a certain value of charge rate so that a large enough NDV can be measured.



Constant current charging for a NiMH battery at varying C-rates

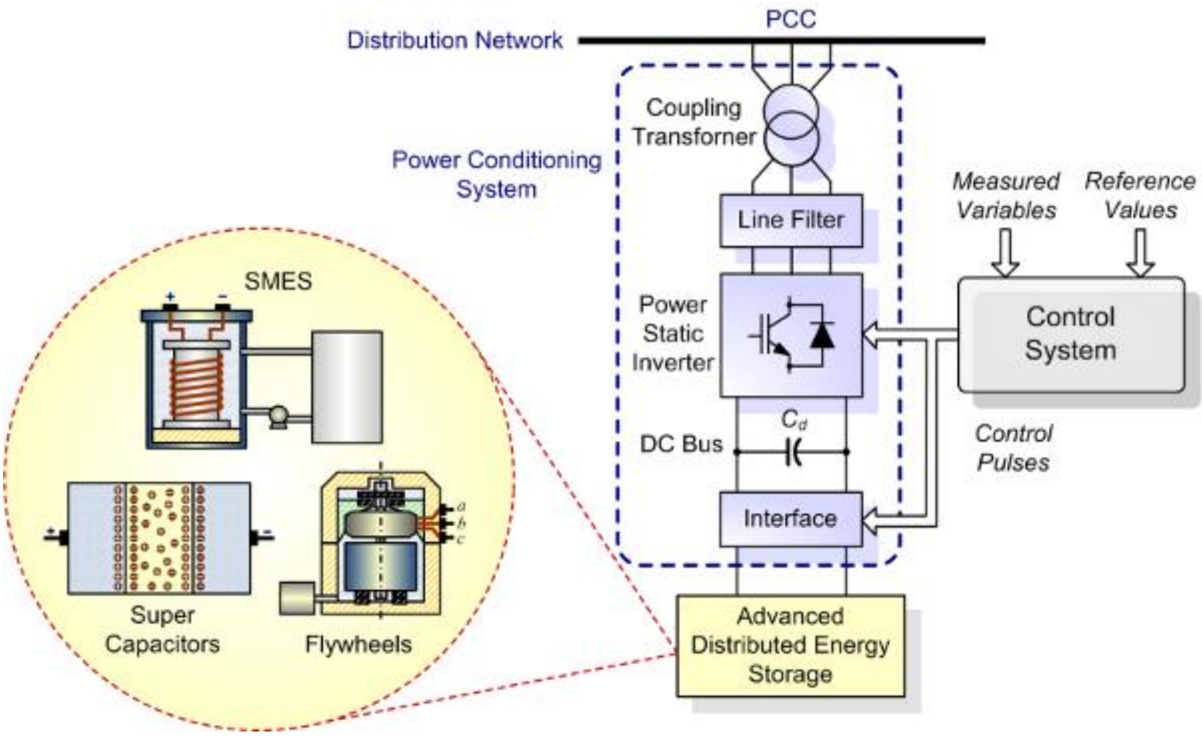
d. Redundant active material is usually added to the negative electrode so that the positive electrode reaches full charge first, releasing oxygen gas (O_2) that can be quickly re-absorbed by the extra protective material in the negative electrode. Conversely the negative electrode does not reach full charge and hydrogen is not released. This prevents gassing but generates heat and pressure until venting occurs.



Oxidation prevention in a NiMH cell

Question 5.

a. When a flywheel and motor / generator set is utilised as part of an energy storage system, the electronic drive of the motor generator shares a common dc link with a static inverter which forms a grid interface to the utility grid, via a suitable filter to remove high frequency harmonic interference, and a matching transformer. A control loop built around the system ensures transfer of energy into and out of the utility grid and from / to the flywheel storage system as required.



Typical energy storage system

This flywheel based storage system is typical of electrical energy storage systems of various scales. For a battery based system, the 'advanced distributed energy storage' and 'interface' blocks in the above diagram can be replaced by a suitable battery bank and power electronic interface to the dc link, if required

b. The container also acts as a safety containment system is case of catastrophic failure of the flywheel. The lightweight composites utilised in high speed flywheels tend to fail catastrophically and delaminate. This leads to all of the stored energy being released at one time. Containment is necessary to prevent damage to surrounds if failure should occur.

c. A flywheel is usually sited within an evacuated container to reduce loss due to air friction and windage issues when the flywheel is rotating at high speed. This is only usually a problem with modern high speed systems where turbulence around the rotor / flywheel causes significant drag on the system and therefore causes the flywheel to slow down loosing energy.

d. The maximum specific energy is given by

$$E_{mmax} = K\frac{\sigma_{max}}{\rho}$$

Where the specific strength is taken as

$$Specific\ strength = \frac{\sigma_{max}}{\rho}$$

Therefore, for a constant stress disk of Kevlar,

$$E_{mmax} = 0.931\ x\ 1700 = 1582.7\ kJ/kg$$

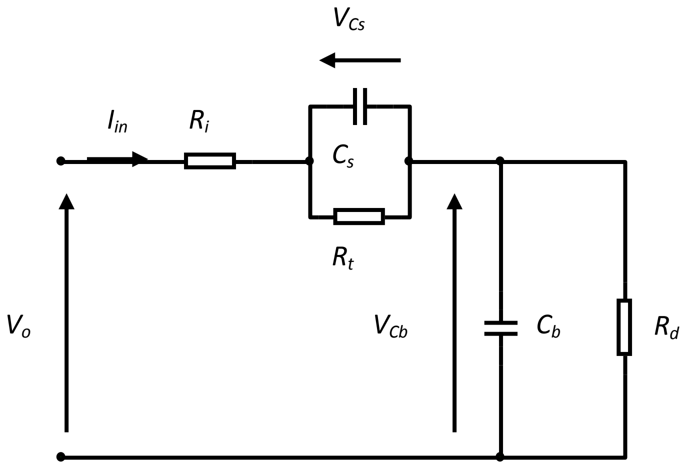
And for a carbon steel thin rim flywheel,

$$E_{mmax} = 0.5\ x\ 44 = 22\ kJ/kg$$

Therefore there is a theoretical maximum ratio of 1582.7/22 = **71.94 : 1**

Question 6.

a. R_d represents the self-discharge resistance (approximately 5kΩ), C_b is still considered the main charge store (equivalent to 101500F for a fully charged, healthy 12V 45Ah nominal battery). The voltage across C_b is again considered to be a suitable indicator of SoC, whilst the SoH is inferred by observing a significant change in C_b over time due to ageing effects such as active mass degradation and crystallisation of the active mass which will effectively reduce the surface area of the parallel plates/grids. R_i models the resistance of the battery's terminals and inter-cell connections (between 5-100mΩ), whilst R_t (10-500mΩ) and C_s (1000-20000F) describe transient effects resulting from shifting ion concentrations and plate current densities.



b. At 10A discharge over 1600s, each pulse removes 4.4444444Ah from the battery. If the battery is 43Ah (minimum) this would require 9.675 pulses. 0.675 of a pulse equates to 3Ah. The final pulse stops after 490 seconds = 1.361111Ah, so there must be 10 or more pulses. At the maximum capacity (47Ah) would need 10.575 pulses, so there cannot be more than 11 pulses. 10 pulses removes 44.4444444Ahr without residual so there must be 11 pulses initiated = 44.44444444+1.361111111 = 45.8Ah.

c. The voltage across the charge store 'C_b' at time $t2$ if charged with a time-varying current $Iin(t)$ from time $t1$ and initial voltage condition V_{Cb1} can be found from (8.3):

$$V_{Cb2} = V_{Cb1} + \frac{1}{C_b} * \int_{t1}^{t2} I_{in}(t) * dt \quad (V) \tag{8.3)}$$

However, it was previously defined that the capacity of an electrochemical device is given by:

$$Capacity = \frac{1}{3600} * \int_{0}^{Charge-end} I_{in}(t) * dt \quad (Ah) \tag{8.4)}$$

By substituting the total capacity measured from the pulsed-discharge over the full discharge duration and taking the linear OCV-SoC approximation to account for the change in V_{Cb}, the value of C_b is shown to be:

$$C_b = \frac{dAh * 3600}{dV} \tag{8.5}$$

Each pulse removes ~9.66% SoC considering part b above. Therefore after 10 pulses there is 3.4% or 1.56Ah remaining.

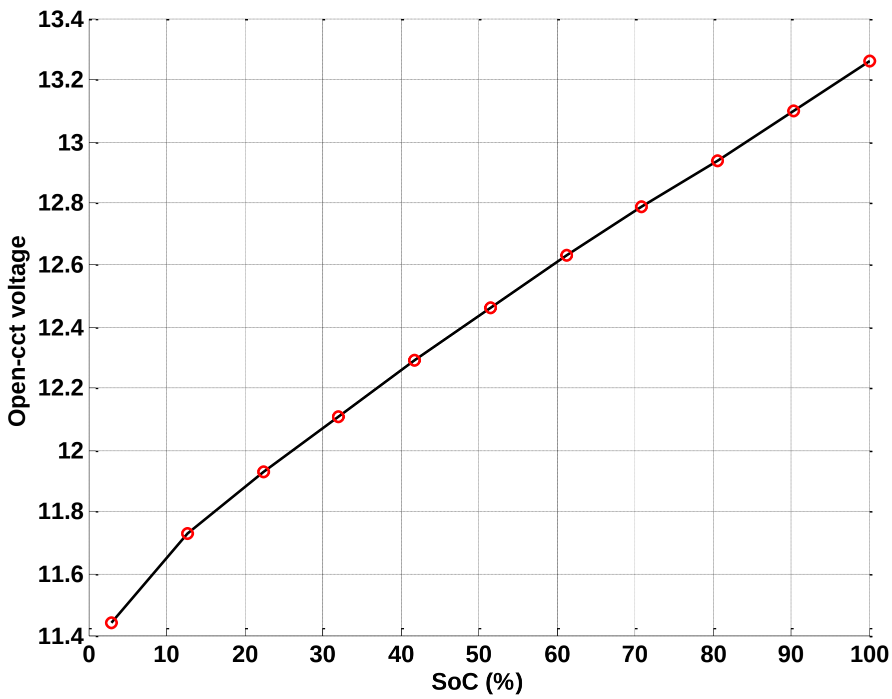
Each voltage in the table represents a 9.66% discharge with starting point (100% at 13.26V). Considering a line of best fit passing through point 2 and point 8:

dV = (12.94 - 11.93) = 1.01,

dSoC = (80.68 – 22.72) = 57.96,

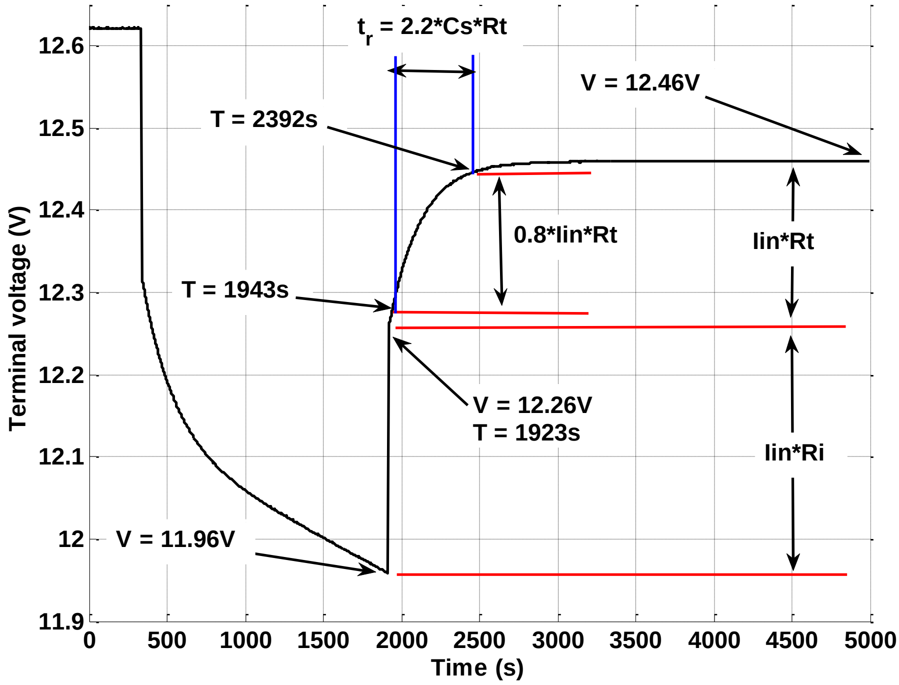
therefore dAh = 0.5796 * 46 = 26.662Ah

so Cb = (26.662 * 3600)/1.01 ~ 95032F.



d. Considering exponential rise times and RC networks with 10A discharge current as below:

i. Ri = 30mΩ
ii. Rt = 20mΩ
iii. Voltage 0.67*Iin*Rt = 12.394 so estimate T ~ 2151s, therefore tau ~ 230s
iv. Cs ~ 10205F (Actually 10000 from Simulink model)



t_r = 2.2*Cs*Rt
V = 12.46V
T = 2392s
0.8*Iin*Rt
Iin*Rt
T = 1943s
V = 12.26V
T = 1923s
Iin*Ri
V = 11.96V
Terminal voltage (V)
12.6
12.5
12.4
12.3
12.2
12.1
12
11.9
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (s)