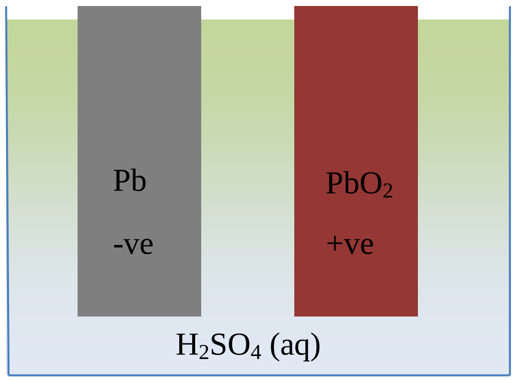
DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

Spring Semester 2015-16 (3.0 hours)

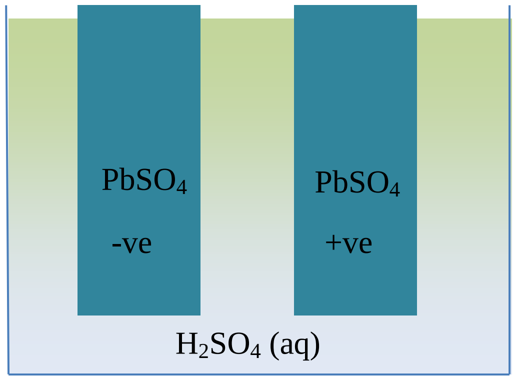
EEE6202 Energy Storage Management - ANSWERS

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



Charged PbA cell

(Electrode potential of 0.356V at -ve and 1.685V at +ve yields theoretical cell voltage of 2.041)



Discharged PbA cell

(4)

Cell chemistry is based around the reversible reactions below:

$$PbO_2 + Pb + 2H_2SO_4(aq) \xleftrightarrow{Charge/Discharge} 2PbSO_4 + 2H_2O$$

This may be split into the reaction at the positive electrode (Lead-dioxide)

$$PbO_2 + 3H^+ + HSO_4{}^- + 2e^- \xleftrightarrow{Charge/Discharge} PbSO_4 + 2H_2O$$

And the reaction at the negative electrode (Lead)

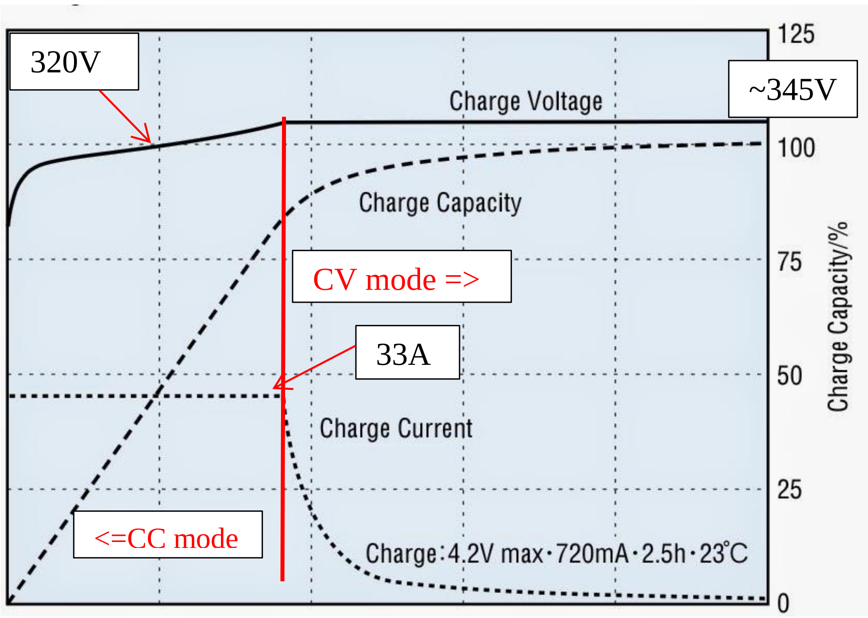
$$Pb + HSO_4{}^- \xleftrightarrow{Charge/Discharge} PbSO_4 + H^+ + 2e^-$$

(2)

The sulphuric acid solution in a lead-acid cell will naturally dissociate into positive hydrogen ions (H^+) and negative hydrogen-sulfate ions (HSO_4^-). Consequently, the atoms in the metal plates will try to form ionic bonds once they have dissociated on contact with the acid solution. When a lead-acid cell is discharged, the dissociated lead on the surface of the negative plate (anode) will combine with the HSO_4^- ions in the electrolyte, forming plated lead-sulfate on the anode whilst releasing H^+ ions 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 free H^+ and HSO_4^- ions in the electrolyte as well as the dissociated lead-dioxide on the surface of the positive plate to form plated lead-sulfate on the cathode whilst releasing water molecules into the solution diluting the acidic solution. Eventually, both plates become fully plated so that the free H^+ and HSO_4^- 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.

(4)

b. i) At 0.5C, charge current is 33A.
Nominal voltage ~320V



Charging of a typical lead-acid battery

(6)

ii) 320/3.34 = 96 cells in series (but each cell 33Ah so must be a parallel string so 192).

96*3.6V = 345.6V peak pack voltage @ CC/CV boundary.

8 resistors allow 8 strings of 12 cells, 6 strings of 16 cells, 4 strings of 24 cells or 2 strings of 48 cells. (Could have 2 parallel resistors on 4 strings or 2, 3 or 4 parallel resistors on 2 strings, but these decrease the resistance hence increase current hence decrease cell charging current)

$I_{res} = V_{string}/R$ so minimum dissipation current @ CC/CV boundary is for smallest string (using 8 resistors, 1 per 12 cells)

I_{res} = 12 * 3.6 / 20 = 2.16A

So current available to charge = 0.5C-rate – 2.16A, BUT 2 parallel strings so each cell charged by ~15.42A (0.47C-rate of cell) **(3)**

iii) Power dissipated = 345.6^2 / 8R = 746.5W **(1)**

2. **a.** The required terminal voltage can be constructed from a network of cells, strings or modules with the necessary interconnections and terminals.

Per-unit measuring devices such as thermistors, current transducers (CTs) and voltage transducers (VTs) are included to implement safety-critical control.

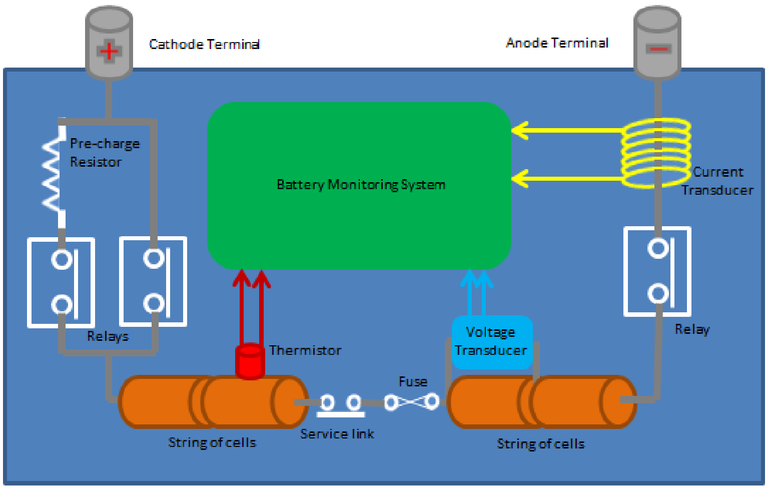
Various relays necessary for isolation and pre-charge

BMS necessary to capture time-domain data of the battery's operation allowing SoC and SoH monitoring via computations carried out and recorded.

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.

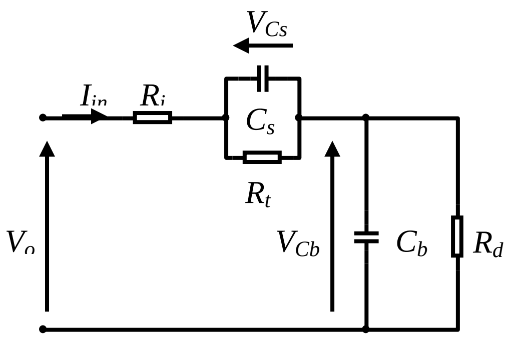
(3)



Generic components of a battery pack

(3)

b. i)



Randles' 2nd order equivalent circuit with self-discharge **(3.5)**

R_d represents the self-discharge resistance

C_b is still considered the main charge store

The voltage across C_b is again considered to be a suitable indicator of SoC

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 **(3.5)** 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

R_t and C_s describe transient effects resulting from shifting ion concentrations and plate current densities.

ii)

$$\dot{V}_{C_b} = \frac{I_{in}R_d - V_{C_b}}{C_b R_d}$$

$$\dot{V}_{C_s} = \frac{I_{in}R_t - V_{C_s}}{C_s R_t}$$

$$V_o = V_{C_s} + V_{C_b} + I_{in}R_i$$

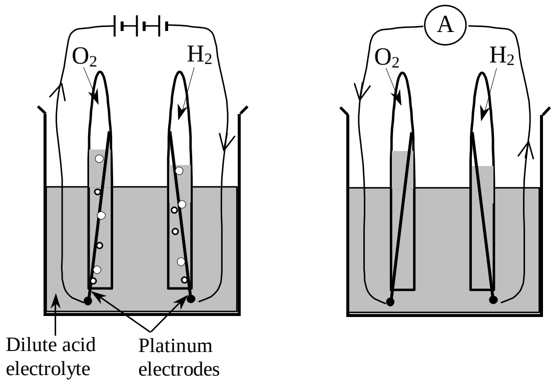
(3)

c. A value for R_i may be approximated when the imaginary impedance is zero. Investigation of the Nyquist plots shows that the value of R_t may be approximated from the real impedance where the Nyquist imaginary term tends to infinity being the sum of R_i and R_t, yielding another fast identification of model parameters (assuming ideal model conditions).

Batt1: Ri = 10mΩ, Rt = 20mΩ

Batt2: Ri = 5mΩ, Rt = 10mΩ **(4)**

3. a. The basic operation of the hydrogen fuel cell is very simple. In Fig. 2(a), water is being electrolysed into hydrogen and oxygen by passing an electric current through it whilst in Fig. 2(b) the power supply has been replaced with an Ammeter, and a small current is flowing. **The electrolysis is being reversed — the hydrogen and oxygen are recombining, and an electric current is being produced.**



(a) Electrolysis of water (b) Reverse process of electrolysis

Principle of operation of hydrogen fuel cells **(1)**

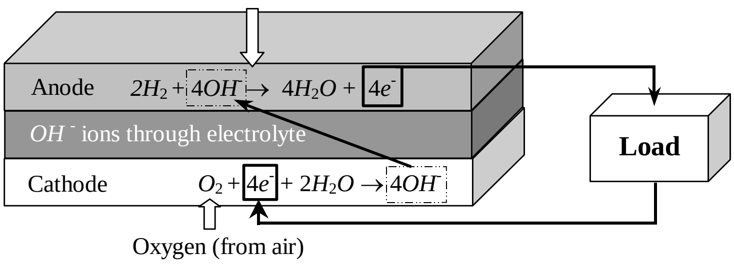
This reverse process can be explained by the fact that the hydrogen is being "burnt" or combusted in the simple overall chemical reaction (same as for acid):

$$2H_2 + O_2 \rightarrow 2H_2O$$ **(1)**

However, instead of heat energy being generated, electrical energy is produced. The experiment in Fig. 2(b) makes a reasonable demonstration of the basic principle of the fuel cell, but the current produced is very small. The main reasons for the small current are:

- The low "contact area" between the gas, the electrode and electrolyte
- The large distance between the electrodes — the electrolyte resists the flow of current

To overcome these problems the electrodes are usually made **flat**, with a **thin layer of electrolyte** as shown in Fig. 3. 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**. **(4)**



Alkaline electrolyte fuel-cell

The reactions at each electrode are different. In an alkali the hydroxyl (OH-) ions are available and mobile. At the anode these react with hydrogen, releasing energy and electrons, and producing water:

$$2H_2 + 4HO^- \rightarrow 4H_2O + 4e^-$$

At the cathode oxygen reacts with electrons taken from the electrode, and water in the electrolyte, forming new OH- ions:

$$O_2 + 4e^- + 2H_2O \rightarrow 4OH^-$$

For these reactions to proceed continuously the OH- ions **must be able to pass through the electrolyte**, and there **must be an electrical circuit for the electrons to go from the anode to the cathode.** Also comparing the electrode equations, we see that, as with the acid electrolyte, twice as much hydrogen is needed as oxygen. This is shown in Fig. 2. It should be noted that although water is consumed at the cathode, it is created twice as fast at the anode. **(4)**

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 H2O, and the inputs are one mole of H2 and a half mole of O2. Thus

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

Hence we have

$$\Delta \bar{g}_f = (\bar{g}_f)_{H2O} - (\bar{g}_f)_{H2} - 0.5(\bar{g}_f)_{O2}$$ **(2)**

Now we can say that:

$$\textit{Electrical work done = charge x voltage = -2FE (Joules)}$$

$$E = -\Delta \bar{g}_f / 2F$$ **(1)**

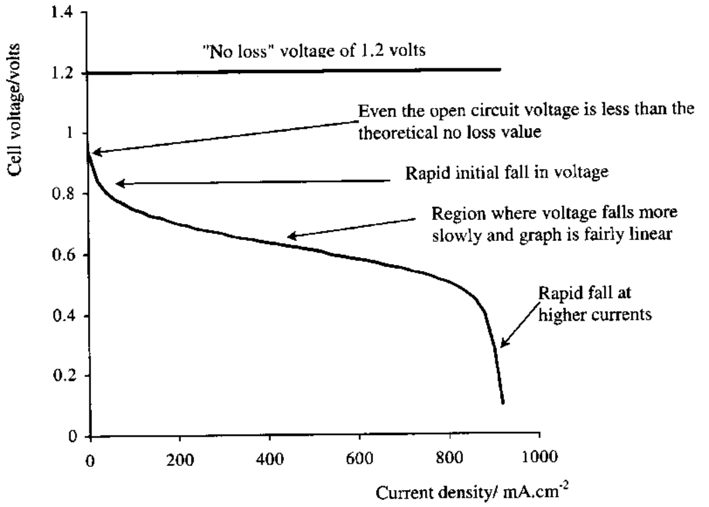
$$E = -\Delta \bar{g}_f / 2F = 220400/(2 \times 96485) = 1.14\ (V)$$ **(1)**

$$\textit{Maximum Efficiency possible } \eta = \frac{\Delta \bar{g}_f}{\Delta \bar{h}_f} \times 100\%$$ **(1)**

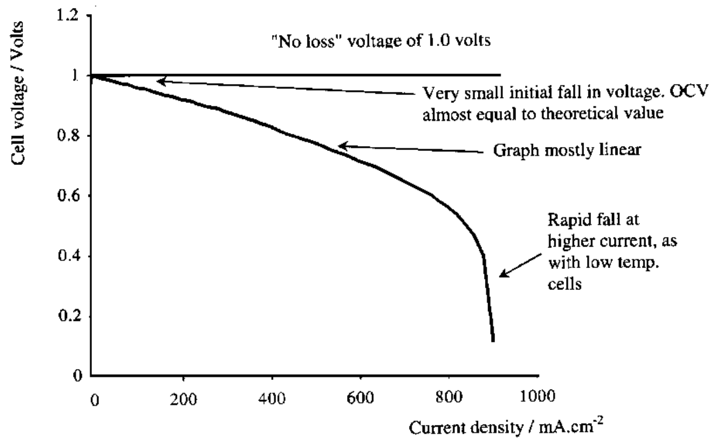
$$\eta = \frac{-220400}{-285840} * 100 = 77.1\%$$ **(1)**

c. A hydrogen fuel cell has a typical "no loss" value of about 1.2 volts for a cell operating below 100 ^{0}C. However, when in operation, it is found that the voltage is often considerably less than this as shown below.

If a fuel cell is operated at higher temperatures, the shape of the voltage vs. current density graph changes. The reversible "no loss" voltage falls as temperature increases. However, the difference between the actual operating voltage and the "no loss" value usually becomes less. In particular the initial fall in voltage as current is drawn from the cell is markedly less. **(4)**



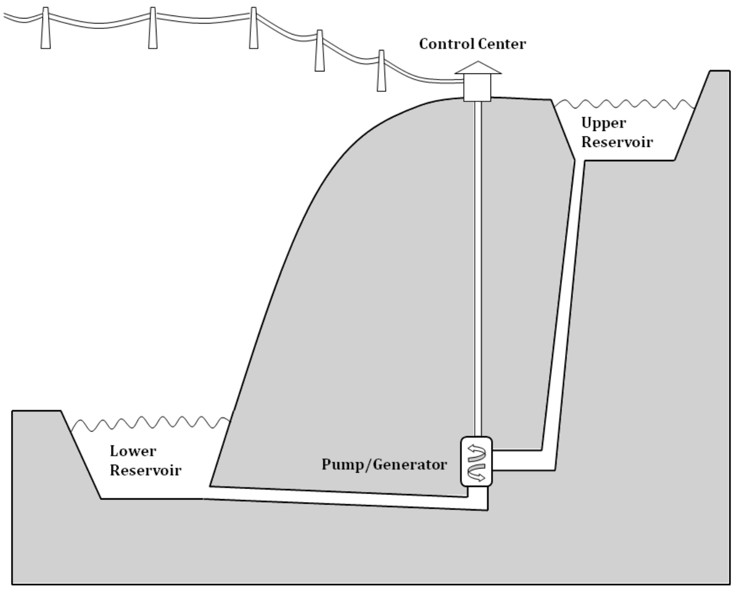
Hydrogen fuel cell operating at 40°C



Hydrogen fuel cell operating at 800°C

4. **a.** PHES works by pumping water from a low altitude reservoir up-hill to a high altitude reservoir during periods of low electrical usage (i.e. off-peak when electrical prices are at a lowest). When the electrical demand increases significantly (peak times when the price of electricity increases), the water stored in the higher reservoir is allowed to freefall through tunnels containing electrical turbine generators, thereby generating electricity as shown in below. In essence PHES utilises gravitational potential energy:

$$P.E = mg\Delta h \text{ (J)}$$ **(4)**



Typical PHES system **(2)**

b. Energy stored = $P.E = mg\Delta h$ in **Joules** so divide by 3600 seconds in an hour to get Wh, then scale accordingly ($1m^3$ = 1000kg):

PHES Station	Head height Δh (m)	Volume of water (m^3)	Energy Stored (GWh)
Ffestiniog (Wales)	310	1.7million	~1.43
Cruachan (Scotland)	350	11.3million	~10.77
Foyers (Scotland)	175	13.6million	~6.48
Dinorwig (Wales)	520	6.7million	~9.48

(5)

c. Dinorwig PHS is capable of a mass flow rate of ~$390m^3s^{-1}$ (~$390000kgs^{-1}$) of water through its 6 turbine generators. Considering that the definition of a Watt of power is 1 Joule per second then it is also apparent that the maximum theoretical power due to work done of Dinorwig's 6 turbines is:

Power (W) = $390{,}000 \text{ kgs}^{-1} * 9.8 \text{ ms}^{-2} * 520\text{m} = 1.99\text{e}9 \text{ kgm}^2\text{s}^{-3} = 1.99\text{GW}$ **(2)**

Compared to measured results, this value is somewhat higher than expected (1.80GW), however as the turbines have a round-trip inefficiency associated with the transfer from Potential Energy -> Kinetic Energy -> Electrical Energy, it can be estimated from these figures that the turbines operate at 87% efficiency.

(1)

d. If a CAES system was to attempt to store 9.1GWh of energy by increasing the pressure of a vessel of constant volume and mass of air from atmospheric pressure (0.1Mpa) to 7Mpa, the required volume of stored air would be:

$$E = P_B V_B ln\frac{P_A}{P_B} \therefore V_B = \frac{E}{P_B ln\frac{P_A}{P_B}} = \frac{-3.276e13}{7e6 * ln\frac{0.1e6}{7e6}} = \sim 1.1 million\, m^3$$

Which is significantly less volume of air stored than Dinorwig requires of water (6.7million m^3) for 9.1GWh storage. Note negative sign as work is being done on the air by the system. **(3)**

e. The system operates by operation of electric motors (loading the grid during off-peak times) to compress air at atmospheric pressures (~1 bar or 100kPa at sea level) to pressures exceeding 70bar (7MPa). The pressurisation of air from atmospheric pressure to 70MPa can heat the gas/air significantly, and so multistage compressors use inter- and after-coolers to regulate the temperature by dissipation. This loss of thermal energy must be accounted for when the process is reversed and the gas or air is expanded. Either the high-pressure gas is heated by mixing with natural fuel in combustors (i.e. burnt) or the exhaust from a combustion gas turbine recuperator must be used for heating of the gas/air. The expanding air drives electrical turbine generators during peak loading times of the grid, allowing stabilisation and energy balancing. This process is called Diabatic CAES and results in low round-trip efficiencies of less than 50%; however Diabatic technology is well-proven with high reliability plants that are capable of starting without extraneous power.

For large-scale applications the heat energy associated with compressing the gas/air must be conserved since dissipating the heat lowers the energy efficiency of the storage system. In this case thermal storage is necessary so that the thermal energy removed from the compressed gas can be used during expansion, avoiding the need for extra thermal input (at cost and inefficiency). This process is called Adiabatic CAES and the theoretical efficiency of adiabatic storage approaches 100% with perfect insulation, but in practice round trip efficiency is expected to be 70%. The captured heat can be stored in a solid such as concrete or stone, or more likely in a fluid such as hot oil (up to 300 °C) or molten salt solutions (600 °C).

So in a very cold country where thermal storage would be even more difficult, tried and proved Diabatic systems would be preferable. **(3)**

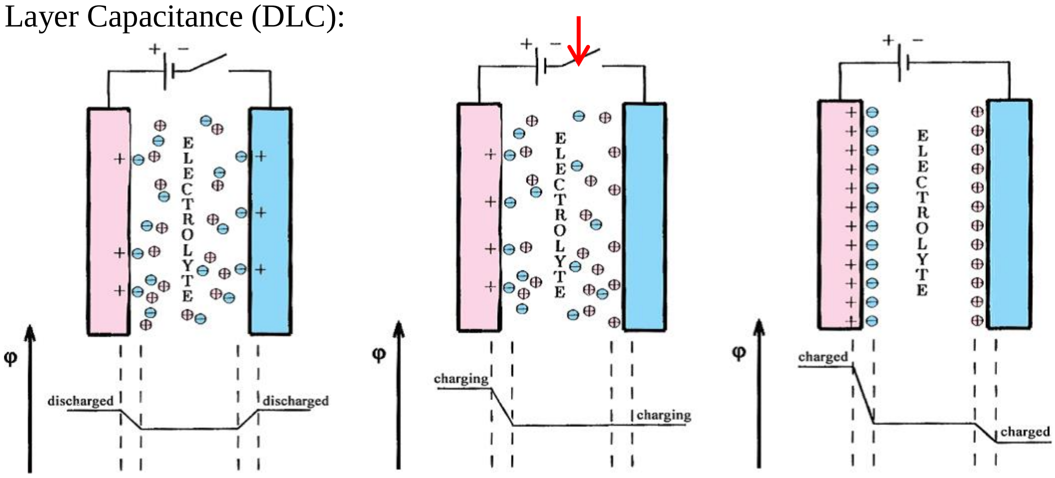
5. **a.** **Supercapacitors differ from regular capacitors in that they have a very high capacitance** due to their electrode/dielectric construction.

They can therefore **store a large amount of energy considering their size**.

They are technically an electrochemical device, consisting traditionally of **two high-surface-area carbon electrodes immersed in an aqueous or non-aqueous electrolyte**.

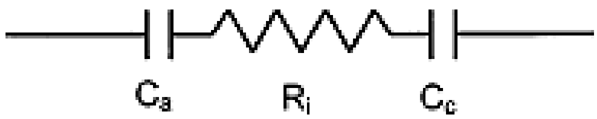
However, **unlike a battery** where the migration of electrons and hydroxyl ions across the electrolyte is due to the electrochemical reaction with the electrode material during charge/discharge, a **Supercapacitor stores energy by the formation of electrical double layers** (EDLs) at the electrode/electrolyte interface similar to traditional electrolytic capacitors used in electronics. **(4)**

The charging process of a Supercapacitor through formation of the Double-Layer Capacitance (DLC):



(2)

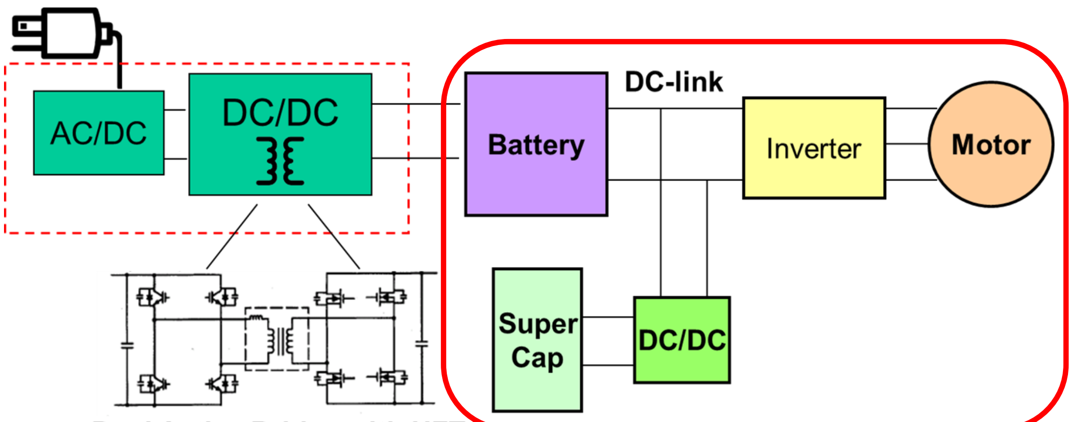
Considering the Double Layer Capacitance formed at each electrode and taking into account the resistance (terminals and electrolyte) encountered by electrons when flowing into/from the Supercapacitor, an equivalent circuit is much simpler than that encountered for electrochemical batteries:



(1)

b. Supercapacitors fill the gap between traditional capacitors used in electronics and low-voltage batteries, because of their nearly unlimited **cycle stability** as well as extremely **high power capability**. Very **high currents can be sourced/sinked** due to the low operating voltage of the Supercapacitor. A pack of suitably-connected Supercapacitors is more than capable of sinking/sourcing hundreds of amps for **fast transients**. **(2)**

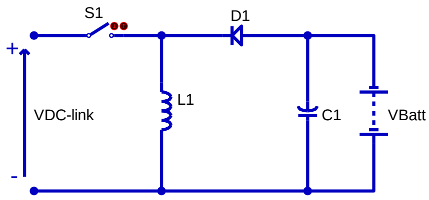
For this reason, they are often used as a peak-power buffer in a DC system or regenerative braking system in an EV, **dealing with excessive transient demands so that more transient-sensitive parts of the DC system (a Li-ion battery, for example) are protected.** **(1)**

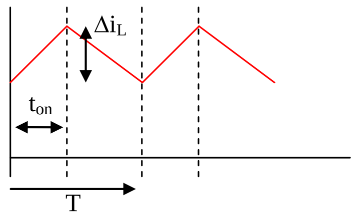


Dual Active Bridge with HFT

(1)

c. i) Note polarity of battery and filter capacitor:





$$\Delta i_L = \frac{V_{DC-link}}{L_1}.t_{on} \quad \Delta i_L = -\frac{V_{Batt}}{L_1}\left(T - t_{on}\right)$$ **(5)**

$$\frac{V_{Batt}}{V_{DC-link}} = -\frac{\delta}{1-\delta} \qquad (V_{Batt} = -ve)$$ **(1)**

ii) $$\delta = \frac{V_{Batt}}{V_{Batt} - V_{DC-link}} \qquad (V_{Batt} = -ve)$$

δ = 0.029 or 2.9% so regulation very difficult. Transformer turns ratio allows wider regulation. Transformer also includes isolation advantage. **(3)**

6. **a.** Typically, a flywheel is used as part of an energy storage system with a **motor spinning the flywheel to a high speed** storing energy in terms of kinetic energy. The motor is often disengaged using an electromagnetic clutch and the momentum of the flywheel keeps it spinning,

A generator can then be used to extract energy from the flywheel when it is required.

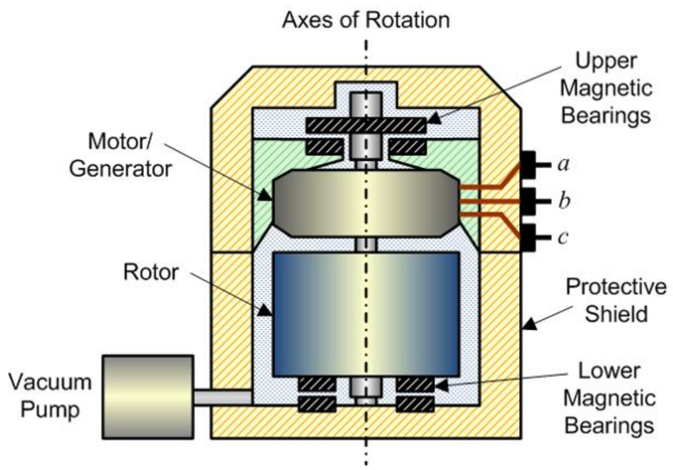
The flywheel is usually sited **within an evacuated container to reduce loss due to air friction and windage issues when the flywheel is rotating at high speed**. This is only usually a problem with modern high speed systems where turbulence around the rotor / flywheel causes significant drag on the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

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.**

Additionally, **to reduce losses in bearings, the flywheel usually has lossless magnetic suspension bearings**.

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.

(3.5)



(2.5)

b. 20kW over 5 minutes = 1.67kWh = 6MJ of storage required **(1)**

To store the equivalent energy in a constant stress disc flywheel made of cast-iron with safety factor s = 0.2, K = 0.931 and specific strength S_s = 19kJ/kg:

$$E_{mmax} = (1 - 0.2^2) * 0.931 * 19kJ/kg = 16.98kJ/kg$$

Therefore a cast-iron mass of 353.4kg or 0.048m^3 would be required to store 6MJ (ρ = 7300kgm^{-3}).

If a disc thickness of 20% of the diameter is assumed, the radius required would be 33.68cm (13.47cm thickness).

Considering that the energy stored in a solid cylinder flywheel (disc) is given by:

$$E = \frac{1}{4}mr^2\omega^2$$

The rotational speed can be calculated:

$$\omega = \sqrt{\frac{4E}{mr^2}} = \sqrt{\frac{4 * 6e^6}{353.4 * 0.3368^2}} = 773.7.1\, rad/s \; \equiv 7387rpm$$ **(3)**

To store the equivalent energy in a constant thickness disc flywheel made from kevlar with safety factor s = 0.2, K = 0.606 and specific strength S_s = 1700kJ/kg:

$$E_{mmax} = (1 - 0.2^2) * 0.606 * 1700kJ/kg = 988.99kJ/kg$$

Therefore a mass of 6.07kg or 0.00607m^3 would be required to store 6MJ

(ρ = 1000kgm^{-3}).

If a disc thickness of 20% of the diameter is assumed, the radius required would be 16.9cm (6.76cm thickness).

The rotational speed can be calculated:

$$\omega = \sqrt{\frac{4E}{mr^2}} = \sqrt{\frac{4 * 6e^6}{6.07 * 0.1676^2}} = 11{,}864\, rad/s \; \equiv 113{,}294\, rpm$$ **(3)**

Therefore a Kevlar constant thickness disc must rotate ~15.3 times faster than constant stress cast-iron flywheel. **(1)**

Note: Due to a typo in the notes, some students used the inertia equation for a thin-walled cylinder flywheel, and so $E = \frac{1}{2}mr^2\omega^2$, and therefore the speeds are 5224rpm and 80,111rpm respectively. The ratio is still the same and these answers were treated as valid.

c. Peak Power Buffering: Time-shifting of energy demand to average out the total demand on the grid and avoid sudden generation/load requirements **(2)**

Firm Frequency Response: Aim to keep the grid frequency as close to 50Hz as possible. NGC pays providers if they can help to manage all credible circumstances that might result in frequency variations by ensuring sufficient generation and/or demand is available within a window of time during the day. **(2)**

Fast Reserve: Manage a greater-than-forecast demand on the grid (Or during unforeseen generation unavailability). NGC pays providers that can deliver increased generation or reduced demand. **(2)**

CG/DAS