Data Provided: None

The University Of Sheffield.

DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

Spring Semester 2015-16 (3.0 hours)

EEE6202 Energy Storage Management

Answer **FOUR** questions. **No marks will be awarded for solutions to a fifth question.** Solutions will be considered in the order that they are presented in the answer book. Trial answers will be ignored if they are clearly crossed out. **The numbers given after each section of a question indicate the relative weighting of that section.**

1. **a.** Explain with the aid of suitable diagrams and chemical reaction equations, the basic composition and discharge process of a lead-acid cell from 100% State-of-Charge (SoC) until fully discharged. State any assumptions made. **(10)**

b. A 320V nominal, 66Ah $LiFePO_4$ battery pack is charged using a CC-CV method from 0% SoC with an initial Constant Current at the 0.5C rate.

i) Sketch the current, voltage and SoC curves over the full duration of charging. Indicate the CC and CV regions on the sketch including any known operating points. **(6)**

ii) The battery pack is constructed from identical 33Ah, 3.34V nominal cells with a manufacturer-specified float-charge voltage of 3.6V. A passive balancing method can be applied during charging of the pack using any configuration of eight identical 20Ω chassis resistors. What configuration of cells and resistors yields the minimum balanced power loss of the pack and what current does each cell charge with in this configuration at the CC/CV cross-over point, assuming that the charger still supplies current at the 0.5C rate of the pack during CC mode? **(3)**

iii) What is the maximum dissipated power for the selected configuration? **(1)**

2. **a.** With the aid of a suitable diagram, detail the key components required in a high-voltage multi-cell battery pack. **(6)**

b. **i)** Describe with the aid of a circuit diagram and component descriptions, the 2nd-order equivalent circuit model introduced by J. Randles for modelling the State-of-Charge (SoC) and State-of-Health (SoH) of a lead-acid cell. Self-discharge mechanisms should be included. **(7)**

ii) Derive the 2nd-order state-variable equations for Randles' equivalent circuit for a lead-acid cell including self-discharge characteristic. **(3)**

c. Figure 1 shows a Nyquist diagram of the impedance of two different batteries modelled by a 2nd-order transfer function. Identify and estimate two values of the resistive parameters for each battery.

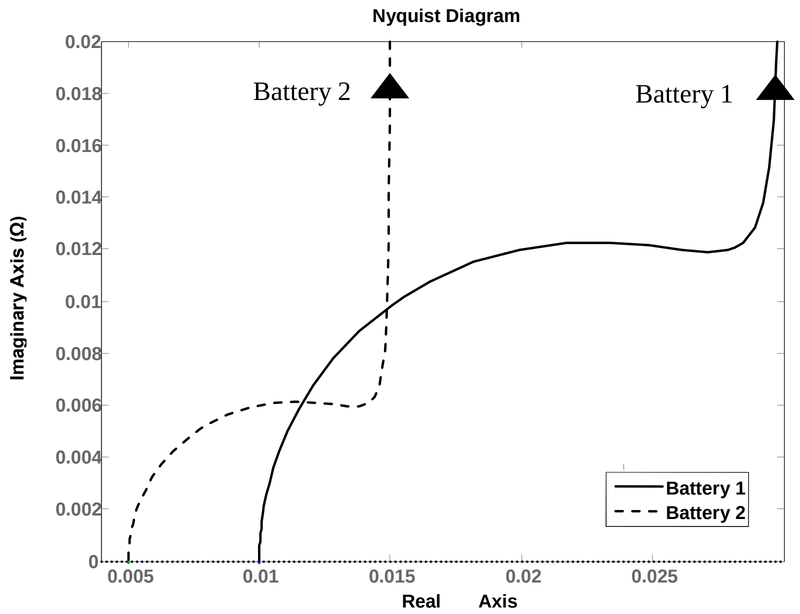

Figure 1. Nyquist impedance plots of two batteries **(4)**

3. **a.** Explain with the aid of a suitable diagram, the operation of a basic fuel cell constructed with an alkaline electrolyte. Your explanation should include the anode and cathode reaction equations. **(10)**

b. Using the information in Table 1, calculate the open circuit potential and maximum thermodynamic efficiency of a hydrogen fuel cell operating at 200^{o}C.

A Higher Heating Value HHV = −285.84kJ/mole may be assumed.

Gibbs free energy of formation for water as a function of reaction temperature		
Form of H_2O	Temperature ^{0}C	$\Delta\bar{g}_f$ (kJ/mole)
Liquid	25	-237.2
Liquid	80	-228.2
Gas	80	-226.1
Gas	100	-225.2
Gas	200	-220.4
Gas	400	-210.3
Gas	600	-199.6
Gas	800	-188.6
Gas	1000	-177.4

Table 1 **(6)**

c. Using suitable diagrams, explain the differences in the operational voltage (as a function of current density) of a hydrogen fuel cell when operated at 40^{o}C and 800^{o}C. Be sure to describe any important phenomena in your explanation. **(4)**

4. **a.** With the help of a suitable diagram describe the operation of a Pumped Hydroelectric Energy Storage (PHES) system. Include the energy equation in your description. **(6)**

b. Calculate the energy stored (in GWh) for each of the four PHES systems detailed in Table 2.

PHES Station	Average Head height Δh (m)	Volume of water (m^3)
Ffestiniog (Wales)	310	1.7million
Cruachan (Scotland)	350	11.3million
Foyers (Scotland)	175	13.6million
Dinorwig (Wales)	520	6.7million

Table 2 – PHES head height and volume **(5)**

c. The measured average energy storage for each of the four sites presented in Table 2 is given in Table 3. The Dinorwig PHES has a mass flow rate of ~$390m^3s^{-1}$ of water through its 6 turbine generators. Calculate the instantaneous power (in GW) that Dinorwig is theoretically capable of providing and explain the reasons for any differences between your answers and the measured values. You may assume the density of water to be 1000 kgm^{-3}.

PHES Station	Power (GW)	Energy Stored (GWh)
Ffestiniog (Wales)	0.36	1.3
Cruachan (Scotland)	0.40	10
Foyers (Scotland)	0.30	6.3
Dinorwig (Wales)	1.80	9.1

Table 3 – PHES measured average energy storage

(3)

d. Calculate the volume of air required to store 9.1GWh of energy if a Compressed Air Energy Storage (CAES) system was used to increase the pressure inside a vessel of constant volume, containing a constant mass of air from atmospheric (0.1Mpa) to 7Mpa.

How does this compare to the energy stored by Dinorwig PHES? **(3)**

e. By comparing the differences between diabatic and adiabatic CAES systems, which technology would be preferable for an industrial-scale energy storage system to be built in a very cold country? **(3)**

5. **a.** With the aid of diagrams and an equivalent circuit, describe the structure and charging process of a symmetrical Supercapacitor. In particular describe the difference between Supercapacitor, capacitor and battery operation. **(7)**

b. **i)** Why are Supercapacitors used for peak-power buffering in Electric Vehicles (EVs)?

ii) With the aid of a suitable diagram, describe where Supercapacitors may be used in an EV drivetrain. **(4)**

c. An Electric Vehicle has a 400V traction battery and a 12V Supercapacitor bank. A buck-boost converter is to be developed to couple the two systems to allow peak power buffering.

i) With the aid of a circuit diagram and current waveform, derive the DC-DC transfer function of a non-isolated buck-boost converter in terms of the traction battery voltage, Supercapacitor voltage, and duty ratio δ. You may assume continuous current operation. **(6)**

ii) Considering the voltage levels given above, calculate the duty ratio required and describe why a transformer would be necessary for this application. **(3)**

6. **a.** With the aid of a suitable diagram, describe the mechanical components and operation of a Flywheel which can be used in an Energy Storage System that is designed for maximum efficiency at high rotational speeds. **(6)**

b. A 20kW flywheel is to be used in a large vehicle that requires sustained peak power for 5 minutes. Using the data given in Tables 4 and 5, how many times faster must a constant thickness disc flywheel made from Kevlar rotate, compared to a constant stress disc made of cast-iron?

You may assume a safety factor of 0.2 and also assume that each flywheel has a thickness that is 20% of its diameter. **(8)**

Flywheel Shape	K
Constant stress disk	0.931
Constant thickness disc	0.606
Thin rim	0.500
Constant stress bar	0.500
Rod or circular brush	0.333
Flat pierced disc	0.305

Table 4 – Flywheel Shape Factor, K

Flywheel material	Specific strength (kJ/kg)	Density (kg/m^3)
Cast iron	19	7,300
Kevlar	1,700	1,000

Table 5 – Flywheel Material Specific Strengths and densities

c. Describe the three key services that distributed Energy Storage Systems can offer to support the National Grid. **(6)**

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