The University Of Sheffield.

Electronic & Electrical Engineering.

EEE6202 ENERGY STORAGE MANAGEMENT

Credits: 15

Course Description including Aims

1. To introduce fuel cell systems as a clean and efficient alternative energy source.
2. To provide a basic understanding of the principles of operation and characteristics of fuel cell systems.
3. To discuss recent development and applications of fuel cell technology.
4. To introduce battery energy storage systems and Supercapacitor storage
5. To provide basic understanding of the operation and characteristics of different battery chemistries and how Supercapacitors differ from batteries
6. To introduce single phase interfaces for bidirectional energy storage
7. To introduce mechanical energy storage in terms of flywheels / compressed air.

Outline Syllabus

Fuel cell systems: Principles of operation, different fuel cell structures, open circuit voltage and efficiency, fuel cell irreversibilities, operational characteristics, electrical dynamic behaviours, recent development and applications in electric and hybrid vehicles and energy storage. **Battery / Supercapacitor Energy storage:** Principles of primary / secondary cell operation, different battery chemistries used in energy storage in electric vehicles / hybrid electric vehicles (EV / HEVs) and in energy storage systems (ESS). Comparison of batteries and Supercapacitors. Charging of batteries / ESS interfaces at single phase for distributed energy storage. Wireless charging for vehicles. Vehicle to grid (V2G). **Mechanical Energy storage:** Principles of mechanical energy storage, flywheels / compressed air. Mechanics of energy storage, precession torques and counter-rotating systems for vehicles. Examples of energy storage.

Time Allocation

36 lectures plus 12 hours of additional support material.

Recommended Previous Courses

None.

Assessment

3-hour examination, answer 4 questions from 6.

Recommended Books

Books to be recommended in the course

Objectives

By the end of the module a successful student will be able to

1. Describe the principles of operation, basic characteristics and recent developments of different forms of fuel cell systems.
2. Use appropriate techniques for modeling fuel cell behavior.
3. Discuss the potentials and limitations of fuel cell systems as static and mobile electric energy sources.
4. Explain the principles of battery and Supercapacitor operation.
5. Construct a basic model of a battery system.
6. Discuss distributed ESS interface operation at single phase level.
7. Describe the principles, advantages and disadvantages of V2G systems at domestic level.
8. Describe the principles of mechanical energy storage, including flywheels and compressed air systems.

Detailed Syllabus

This syllabus is meant to add detail to the contents of the course, and not necessarily be representative of the lecture number. The material will be taught over 36 lectures.

Fuel cell systems:

Introduction to fuel cell technology and different types of fuel cell. Basic principles of hydrogen fuel cells, reaction rate, cell interconnection – the bipolar plate, fuel cell types, ancillary components of a fuel cell system, advantages and disadvantages of fuel cell technologies.

- Efficiency and open-circuit voltage, energy and EMF of the hydrogen fuel cell, efficiency and efficiency limits, efficiency and fuel cell voltage, the effect of pressure and gas concentration. **(3 lectures)**
- Operational voltage of fuel cell, fuel cell irreversibilities – causes of voltage drop, activation losses, fuel crossover and internal currents, ohmic losses, mass transport or concentration losses, combined effect, dynamic electrical behaviour of fuel cell. **(3 lectures)**
- Fuel cell applications in electric and hybrid vehicles, voltage regulation, energy storage buffer, fuel cell power-train configurations, discussion on state-of-art development and the impacts on global energy supply and environment. **(2 lectures)**

Battery and Supercapacitor Systems:

- Introduction to battery technologies, different battery chemistries, energy densities / power densities of different batteries. Difference between electrochemical energy storage and electrical energy storage in supercapacitors. Flow batteries. **(3 lectures)**
- Performance characteristics of battery technologies, Definition and measurement of state of charge / state of health. Thermal effects on battery performance. Dynamic charge acceptance. **(3 lectures)**
- Different modeling methodologies for batteries, equivalent circuits, electrochemical models, **(2 lectures)**
- Measurement of internal impedance of cells, electrochemical impedance spectroscopy, PRBS estimates. **(3 lectures)**
- Charging requirements and charger topologies. **(3 lectures)**
- Battery pack assembly / disassembly and pack safety **(3 lectures)**
- Differences between static and mobile energy storage requirements. Second life usage of EV batteries. **(2 lectures)**

- V2G operation, effects on grid operation and long term impact on battery lifetime. **(2 lectures)**

Mechanical Energy Storage Systems:

- Introduction to mechanical energy storage systems, compressed air / flywheels. **(3 lectures)**
- Mechanics of energy storage including flywheel procession torques. Containment of flywheels and compressed gas / safety. **(2 lectures)**

- Reading Week and Contingency **(2 lectures)**

UK-SPEC/IET Learning Outcomes

Outcome Code	Supporting Statement
SM1p	The basic principles of operation and characteristics of hydrogen fuel cell systems are introduced. Furthermore, electrical and mechanical energy storage systems and their main components are also introduced, and their main advantages/disadvantages are discussed. The ability to exploit these ideas is tested in the exam.
SM2p	The mathematical tools required for the determination of the performance of the fuel cells and energy storage systems are addressed and their application is demonstrated through examples. The ability to exploit these ideas is tested in the exam.
SM3p	Chemical reactions of varying fuel cells and battery chemistries are studied and contrasted for use in electric vehicles and static energy storage systems. Appreciation of mechanical systems and moments of inertia is given in discussion of mechanical energy storage systems. The ability to exploit these ideas is tested in the exam.
SM1m	Discussion of the development of energy storage systems throughout history and their development towards grid-connected “smart” solutions is discussed in detail. Descriptions of such systems in the context of efficiency, cost, geography and socio-economic impact would be expected in an exam.
SM2m	The importance of simulation in assessing the performance of battery packs is high-lighted and Matlab/Simulink is described for the development of a model for examples of energy storage systems. The ability to derive and exploit these models is tested in the exam.
SM3m	Chemical reactions of varying fuel cells and battery chemistries are studied and contrasted for use in electric vehicles and static energy storage systems. Appreciation of mechanical systems and moments of inertia is given in discussion of mechanical energy storage systems. The ability to contrast and exploit these technologies is tested in the exam.
SM4m	Developments in fuel cell technologies and battery energy storage systems are updated as required and presented/discussed. The ability to contrast and exploit these technologies is tested in the exam
SM5m	The importance of simulation in assessing the performance of battery packs is described in detail using 1st-, 2nd- and multi-order equivalent circuit models that may be manipulated mathematically or in Matlab/Simulink for State-of-Function analysis. The ability to derive and manipulate these models is tested in the exam.
SM6m	The development of energy storage systems in the context of efficiency, cost, geography and socio-economic impact is considered to enable future optimised

grid-connected “smart” solutions. The need for societal appreciation of energy usage is discussed during the lectures. Evaluation of the best system for a given climate/topography would be expected in an exam.

SM1fl Discussion of the development of energy storage systems throughout history and their development towards grid-connected smart solutions is discussed in detail. Descriptions of such systems in the context of efficiency, cost, geography and socio-economic impact would be expected in an exam.

SM2fl Developments in fuel cell technologies and battery energy storage systems are updated as required and presented/discussed. The ability to contrast and exploit these technologies is tested in the exam

EA1p The application of electric circuit laws for development of equivalent circuit models for battery storage systems is discussed in detail and tested for in the exam.

EA2p Loss mechanisms in various energy storage systems are discussed and analytical equations describing these losses are derived and incorporated into the modelling process. Appreciation and calculation of these losses is expected in the exam.

EA3p Application of iterative computational methods such as coulomb-counting is discussed, in order to predict State-of-Function of a battery and optimise the charging/discharging of an EV or decide when a battery should be replaced ahead of malfunction. Appreciation of these techniques is tested in the exam.

EA4p Discussion of observer based systems allows an appreciation of the need to “close the loop” in any engineering system, and predict the outcome of an energy storage system in response to a given situation of inputs. Appreciation of the measurement of safety critical system parameters and their manipulation in a closed loop observer is expected in an exam.

EA1m The application of electric circuit laws for development of equivalent circuit models for battery storage systems is discussed in detail and techniques that allow parameter estimation of equivalent circuit elements for State-of-Health estimation are introduced and tested for in the exam.

EA2m Loss mechanisms in various energy storage systems are discussed and analytical equations describing these losses are derived and incorporated into the modelling process. Appreciation and calculation of these losses is expected in the exam.

EA3m Application of alternative iterative computational methods such as coulomb-counting and Pseudo Random Binary Sequence methods is discussed, in order to predict State-of-Function of a battery and optimise the charging/discharging of an EV or decide when a battery should be replaced ahead of malfunction. Appreciation of these techniques is tested in the exam.

EA4m Discussion of observer based systems allows an appreciation of the need to “close the loop” in any engineering system, and predict the outcome of an energy storage system in response to a given situation of inputs. Appreciation of the measurement of safety critical system parameters and their manipulation in a closed loop observer is expected in an exam.

EA5m Two-terminal ‘Black Box’ modelling of unknown systems is introduced using simple 1st-order equivalent circuit models and extended to 2nd-order models when simulation results show significant discrepancies between predicted and real-world solutions. The application of such techniques to variants of electrochemical storage systems is demonstrated and tested for in the exam.

EA6m Extraction of equivalent circuit parameters from measured data through use of circuit time constants, Bode plots and Nyquist diagrams is discussed to derive and manipulate equivalent circuit models to be used in observer-based prediction algorithms. The ability to extract equivalent component values from such diagrams is tested for in the exam.

D1p The development of energy storage systems in the context of efficiency, cost, geography and socio-economic impact is considered to enable future optimised grid-connected “smart” solutions. The need for societal appreciation of energy usage from mobile phones to EVs to smart cities is discussed during the lectures. Evaluation of the most optimum system for a given climate/topography/economy would be expected in an exam.

D3p Electrochemical energy storage systems can be unpredictable since there is no definite method of measuring the energy stored at any moment in time in an unknown system. Observer based predictor-corrector methods are introduced to enable some boundaries to be placed on the systems. The effect of parameter tolerances and fuel-cell/battery voltage swing is demonstrated. Best-guess initial approach to develop the necessary power electronics required for power transfer is described and developed to optimise efficiency. Input-output characteristics would be given in an exam and the necessary constraints/design decisions to be imposed would be expected.

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EP1p Development of an energy storage system from theoretical concept design equations to evaluation of losses, manufacturing constraints, testing of single cells, multi-cell packaging and control/safety constraints is discussed and considered in the context of the location of the system and its users. Appreciation of each stage of development would be expected in the exam.

EP2p Discussion of the properties of different chemistries/materials for electrochemical and mechanical energy storage systems is supported by worked examples comparing the relevant efficiencies, cost, safety and environmental factors. Similar comparisons would be expected in an exam for a given system specification.

EP4p Whilst the course is self-contained, every diagram/data table is referenced to its original author/text so that students may use manufacturer’s handbooks for various chemistries and understand charge/discharge graphs and parameter tables for safe operation. Relevant electronic information sources are detailed for a broader appreciation of the many chemistries that cannot be discussed in the time available. The ability to extract relevant system data from a manufacturer's specification is tested for in the exam.

EP6p Fundamental grid code requirements and industry standard practices are introduced. Health and safety constraints are discussed where relevant and tested for in the exam.

EP7p Quality issues during manufacture of energy storage systems are discussed and contrasted for different chemistries/mechanical systems. Discussion of developing trends arising from historical safety-critical quality issues identifies possible future technologies for development. Appreciation of the need for safe, repeatable use technology is tested for in the exam for given use scenarios.

EP8p Electrochemical energy storage systems can be unpredictable since there is no definite method of measuring the energy stored at any moment in time in an unknown system. Observer based predictor-corrector methods are introduced to enable some boundaries to be placed on the systems. The effect of parameter tolerances and fuel-cell/battery voltage swing is demonstrated. Best-guess initial approach to develop the necessary power electronics required for power transfer is described and developed to optimise efficiency. Input-output characteristics would be given in an exam and the necessary constraints/design decisions to be imposed would be expected.

EP1m Development of an energy storage system from theoretical concept design equations to evaluation of losses, manufacturing constraints, testing of single cells, multi-cell packaging and control/safety constraints is discussed and considered in the context of the location of the system and its users. Appreciation of each stage of development would be expected in the exam.

EP2m Discussion of the properties of different chemistries/materials for electrochemical and mechanical energy storage systems is supported by worked examples comparing the relevant efficiencies, cost, safety and environmental factors. Similar comparisons would be expected in an exam for a given system specification.

EP4m Whilst the course is self-contained, every diagram/data table is referenced to its original author/text so that students may use manufacturer's handbooks for various chemistries and understand charge/discharge graphs and parameter tables for safe operation. Relevant electronic information sources are detailed for a broader appreciation of the many chemistries that cannot be discussed in the time available. The ability to extract relevant system data from a manufacturer's specification is tested for in the exam.

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	approach to develop the necessary power electronics required for power transfer is described and developed to optimise efficiency. Input-output characteristics would be given in an exam and the necessary constraints/design decisions to be imposed would be expected.
EP1fl	Discussion of the properties of different chemistriesmaterials for electrochemical and mechanical energy storage systems is supported by worked examples comparing the relevant efficiencies, cost, safety and environmental factors. Similar comparisons would be expected in an exam for a given system specification.
ET2fl	Awareness that engineers need to take account of the commercial and social contexts in which they operate for energy systems
ET4fl	Awareness that Energy storage should promote sustainable development and ability to apply quantitative techniques where appropriate.
ET5fl	Awareness of relevant regulatory requirements governing engineering activities in the context of energy storage systems
ET6p	Knowledge and understanding of risk issues with batteries and fuel cells, including health & safety, environmental and commercial risk, and of risk assessment and risk management techniques.
ET4m	Awareness that Energy storage should promote sustainable development and ability to apply quantitative techniques where appropriate.