A Design Method For Specifying Power Sources for Hybrid Power Systems

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Abstract

Many efforts have been made in recent years to address issues surrounding the use of fossil fuels for energy. However, it must be conceded that world's dependence on fossil fuels cannot cease overnight. In reality, the switch is expected to be a relatively slow migration of technologies over many decades. During this transition period the world will need bridging technologies to aid in the transition to alternate energy sources. One such technology, which shows much promise in boosting energy efficiency while reducing emissions and costs, is the adoption of hybrid power systems.

This thesis investigates the motives behind seeking alternate energy sources and discusses the future need to move away from fossil fuels and the likely role hybrid power systems will play in the future. A general outline of a hybrid power system is presented, and its key subsystems identified and discussed, paying attention to power generation, energy storage technologies and the performance of these systems.

A novel method of specifying the power sources in bespoke hybrid power systems are presented. A custom software tool aimed at evaluating how different hardware configurations and output duty cycles affect the performance of a hybrid power system is then presented and used in several case studies to investigate the effectiveness of the presented method in specifying power sources for a given application.

It was found that the hardware, output application and control strategy of a hybrid power system affects the overall performance of the system. Furthermore, if the output duty cycle of a hybrid power system is repetitive and predictable in nature, it was found that the hardware and control strategy of the system can be fine-tuned using simple techniques to optimise the overall system configuration and performance.

Dedicated to Nanda Meegahawatte, my father and friend.

Gone today but never forgotten and dearly missed.

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Glossary

Notation	Description
CHP	Combined Heat and Power
CI	Compression Ignition
CS	Control Strategy
DCCS	Duty Cycle Constrained Selection
DMU	Diesel Multiple Unit
EF	Electric Fraction
EMI	Electromagnetic Interference
Energy Vector	A means of transferring, in space and time, a quantity of energy
ESD	Energy Storage Device
HAM Triangle	A means of depicting the relationship between the Hardware, Application and Management of a hybrid system
HCCI	Homogeneous Charge Compression Ignition

Notation	Description
HDET	Hybrid Drivetrain Evaluation Tool
HPP	Hybrid Power Plant
HPS	Hybrid Power System
ICE	Internal combustion engine
Level of Hybridisation	Ratio between the output size of the primary power plant and secondary power plant of a hybrid power plant
LNG	Liquefied Natural Gas
LPG	Liquid Petroleum Gas
PEMFC	Proton Exchange Membrane Fuel Cell
Primary Power Plat	Power plant which produces power by means of converting the energy stored in a fuel
PV	Photovoltaic
Secondary Power Plant	An energy storage device capable of supplying and storing energy
SI	Spark Ignition
SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
SOH	State of Health
SUV	Sport Utility Vehicle

Notation	Description
Syngas/Synfuel	Referred to any type of artificially created hydrocarbon based fuel
Tertiary Power Plant	Similar to a secondary power plant however often have operating characteristics which are different from a primary and secondary power plant

Chapter 1

Introduction

1.1 Background

Arguably the biggest obstacle that humanity will face in the 21st century is the end of cheap and abundant energy.

Current world energy consumption is estimated to double that of 2005 by 2030 [1]. At present, the majority of the world's energy is obtained by burning fossil fuels such as oil, coal and gas [2]. The majority of these resources are consumed in the industrial, electricity generation and transportation sectors [3]. It is predicted that world oil production will peak sometime between now and 2040 [4]. This impending reduction in oil production will most likely see the cost of energy increase to unprecedented levels [5]. Greenhouse gas emissions from the use of fossil fuels since the industrial revolution have been linked to temperature rise and global climate change [6], furthermore, it is widely believed that if greenhouse gas emissions such as CO_2 are not reduced, the world's climate will be irrecoverably damaged leading to disastrous consequences for life on earth [7] [8]. Many efforts have been made in recent years to address these issues on both international and national fronts across many countries worldwide [9]. International emission regulations and legislation such as the Kyoto Protocol (Global), Emissions Trading Scheme (European Union) and Climate Change Levy (UK) have been designed to alleviate the dependence on fossil fuels, while allowing for progress and economic growth [10] [11].

In the transport sector, the most popular power generation technology is the Combustion Engine (covered in more detail in chapter 2, section 2.3.1). These devices commonly utilise fossil fuels to operate, and with the need for a reduction in world wide fossil fuel consumption and carbon emissions, there is a need for an alternative to this technology. At present the most promising alternative to fossil fuels in mobile applications, particularly in transport, is hydrogen [12] [13]. However, for hydrogen to replace fossil fuels, several significant technological challenges must be overcome (covered in more detail in chapter 2, section 2.2) [14].

In electricity production, there are initial signs of moving away from fossil fuel based generation technologies. These are mainly in the form of decarbonisation of electricity grids by using renewable energy sources [15] and various campaigns to lower energy consumption by means of more efficient electrical appliances and processing technologies [16]. Countries such as the United States, France and Japan have chosen to invest in nuclear power [2]; others such as China, Canada and Brazil have made use of their geographical locations and natural features by using hydro power [2]. Another noteworthy trend is the harnessing of wind energy, particularly in the USA; Germany and Spain [17]. Many advances have been made in current alternate energy production technologies, however there are many limitations and technological challenges to be overcome before they can compete with fossil fuel based energy production [18] [19] [20] [21] [22]. Furthermore, it is worth noting that currently all these alternate sources of energy amount to less than 15% of the global energy needs [2].

It must be conceded that the world's dependence on fossil fuels cannot cease in the short term. In reality, the switch is expected to be a relatively slow migration of technologies over many decades. During this transition period the world will need bridging technologies to aid in the transition, while avoiding economical and climatological problems [23]. One such technology that shows much promise in reducing costs and saving energy, thus indirectly reducing emissions and helping the environment, is the adoption of Hybrid Power Systems (HPS), covered in more detail in chapter 2 [24] [25]. At present, many advances have been made in the automotive industry towards hybrid road vehicles [26]. Furthermore, there are early signs of other industries such as the railways experimenting with hybrid power systems [27] [28].

1.2 Hybrid Drive Applications

Hybrid drivetrains first appeared in auto-mobiles at the turn of the 20th century. However, with the improvements in internal combustion engines over the years this technology was abandoned until the 1970's when oil shortages and environmental concerns helped hybrid vehicles make a comeback [29].

In recent years the adoption of this technology has been driven by the increasing cost of oil; global climate change from greenhouse gases; incentives of improved overall efficiency over traditional single source drivetrains and the potential for reduced emissions, especially in transport applications [30]. With this shift in motivation comes the need for a more detailed understanding of the behaviour of hybrid drivetrains, especially as they do not always out perform traditional single energy source drivetrains.

Currently a wide range of applications utilise hybrid power systems. Electricity grids that generate power from multiple sources such as coal, nuclear and renewable sources such as solar, wind and hydro can be considered as hybrid power systems [1] [10]. Industries that utilise commercial electricity grids but have the ability to generate electricity on their own via generators or from excess energy from industrial processes can also be considered as utilising hybrid power systems. In transport applications, the term is typically applied to drivetrains that consist of a primary power plant that consumes fuel to produce power, together with one or more energy storage devices that are used to supplement the primary power plant. Furthermore, the on-board energy storage is often used to capture the otherwise wasted kinetic energy of the vehicle when braking.

1.2.1 Aptitude

Any application that requires power can be serviced by a hybrid power system. However, the relative technological immaturity, and significant complexity over single source power systems make the impact of hybrid power systems not always apparent or clear [31] [32] [26] [33]. Studies have shown that drivetrain hybridisation does not always yield positive performance with respect to energy consumption [34]. Instead, performance largely depends on the duty cycle; energy source technologies; component sizing; system architecture and control strategy of the hybrid power system [35].

Generally the overall energy efficiency and potential [energy] savings from using a hybrid power system are heavily affected by the duty cycle of the intended application [36]. Applications that exhibit cyclic (positive and negative) power flow; uneven, difficult to predict and varying duty cycles benefit from drivetrain hybridisation, such as transport applications (e.g. automotive, railway) or electricity generation plants that can utilise multiple energy sources (e.g. wind-diesel generation).

1.3 Overview of the Research Problem

The performance of any system is fundamentally governed and limited by key decisions made during its design phase. In the case of a hybrid power system, these decisions relate to the relationship between its hardware; intended application and management as discussed in section 2.5.

Mainstream design methods of HPS consist primarily of iterative optimisation and modelling techniques. These often utilise highly detailed models of system components and application duty cycles and require highly complex simulations and models [37] (further details of these optimisation methods please refer to section 3.5 in chapter 3, and section 3.3 in chapter 4). While these approaches generally result in highly optimised design solutions, they are highly costly exercises due to the effort in accurate model development, and are generally more suited for large volume, highly lucrative markets such as the automotive sector.

Another common approach highlighted in the literature is the isolated optimisation of individual subsystems of a hybrid system. These often include the tuning of supervisory control strategy [38] [39], and addition of energy storage to traditional drivetrains [40]. Due to the simplicity of this approach, it is well suited in designing systems where development resources are limited. The main drawback of this approach is the difficulty in reaching a truly optimised solution, as the whole system behaviour cannot be taken into account. Another limitation of this approach is the difficulty in specifying the amount (capacity) of on-board energy storage in a HPS, due to the isolated nature of the system optimisation and design.

This thesis presents a method for **specifying power sources and control strategies to aid in the design process of a HPS that services applications for relatively well defined output duty cycles** to be used with the simple isolated design optimisation method described above. A key requirement for the method is the significant reduction for complex iterative computation, and the ability to make informed design decisions that aid in tuning a HPS to its intended application with very little in-depth system modelling.

1.3.1 Research Hypothesis & Objectives

The central hypothesis that is tested in this work is that the selection key components of a hybrid power system can be based on the application duty cycle the HPS must service. Furthermore, in instances where the application duty cycle takes on a relatively well definable and repetitive profile it is possible to use a simple method for the selection of key system components during the design of a hybrid power system. In order to test this hypothesis the following objects outlined in table 1.1 have been identified and discussed in the next section.

Objective	Description	Chapter
1	Literature review comprising of hybrid power systems (Chapter 2) and current design methods, with an emphasis on component sizing	3
2	Develop simulation methodology for the evaluation of component selection methods	4
3	Suitable case study identification	4
4	Develop suitable methodology for testing the thesis hypothesis	4
5	Test hypothesis using selected case studies	5, 6 & 7

Table 1.1: Outline of objectives to be addressed in the thesis

1.3.2 Research Methodology

Literature Review

To achieve the objectives set out in table 1.1 an in-depth understanding of hybrid power systems and their sub-components must be acquired. Furthermore, in order to ascertain the validity of the hypothesis to be tested in this thesis, a review of existing methods for hybrid system component sizing must be carried out.

The literature review for this thesis will be made up of material collected from the following sources conference proceedings, journal papers, books and key articles published on the internet and by government or research organisations. The search process will utilise search tools such as Google, Google Scholar and Web of Science and the main library at the University of Birmingham.

Simulation Methodology

In order to investigate how different hardware configurations affect a hybrid power system, it is necessary to have a means of evaluating the affects these have on a given system. The complex nature of HPS, and the significant time and cost associated with building test systems for evaluation purposes mean that experimentation using physical hardware will not be a practical option. Therefore, the most suitable method for investigation of these systems is via software based modelling and simulation.

To obtain a suitable simulation and modelling tool it, a review of existing modelling and simulation tools and methods will be carried out. This will likely be from existing simulation tools currently used at the University of Birmingham and those mentioned in the literature. Given the likely different application duty cycles being evaluated in the course of this thesis, a key requirement for a simulation tool must be its ability to accommodate a wide range of applications and configurations.

Case Study Identification & Selection

In order to test out the hypothesis outlined in section 1.3.1, suitable case studies must be identified and selected for in-depth analysis in this thesis. The identification of suitable applications is likely to be governed by the following factors:

- Suitability of application
- Suitability of duty cycle
- Availability of data for analysis

Method Development & Hypothesis Testing

In order to test the hypothesis presented in this thesis, a suitable method must be developed. It is envisaged this will be done by the analysis of the application duty cycles selected for use in the case studies. The method development process is likely to be a iterative process, consisting of the deconstruction of the application duty cycle into suitable parts which allows the extraction of key design parameters to be inferred.

The testing of the hypothesis will be done as individual case studies and presented as separate, self contained pieces of work as chapters in this thesis.

1.4 Overview of the Solution

The method is based on the premise that: *“the output duty cycle a hybrid power system is subjected to has the most significant impact on the overall system performance”* and via analysis of the intended application, and likely output duty cycle, it is possible to make decisions and specifications of the power sources of a HPS servicing the given application.

The power sources and control strategy selection is tackled by means of a four step feed-backward approach, where the output power cycle of the intended application is analysed to determine key energy and power requirements the HSP must meet. This is followed by further analysis, to determine the most suitable control strategy; energy component sizes and desired performance characteristics of the power plants. The solution steps can be summarised as follows:

Step One consists of obtaining the output duty cycle the HPS must service. This can be done either via system modelling and simulation or instrumentation of existing or similar systems.

Step Two consists of characterisation and analysis of the captured duty cycle. The step consists of extracting key energy, power and time dependant information from the application duty cycle to better understand the requirements the system components must meet.

Step Three tackles the hybrid system architecture and control strategy selection, by means of evaluating the intended performance and behaviour of the HPS. Taking into account original operational specifications, potential cost and complexity of the final system.

Step Four determines the sizing and evaluation of the power sources in the HPS.

1.5 Contributions to Knowledge

- The author first presents a broad overview of hybrid power systems. The various configurations and components are presented and discussed in detail. Finally, the author comments on the key features that contribute to the performance of hybrid energy systems and introduces the concept of the HAM (Hardware-Application-Management) triangle, a means of linking the different aspects that effect the performance of a hybrid system.

- Popular optimisation methodologies are reviewed with an emphasis on hybrid system design, performance and characterisation techniques are presented and discussed.

- The development of a method to aid in the sizing of power sources in a hybrid drivetrain is presented, particularly in selecting individual energy generation and storage device parameters, tuned to specific target applications. The effectiveness of the proposed method is then outlined by means of case studies.

1.6 Thesis Structure

The following outlines the contents of the chapters in this thesis:

Chapter 1 presents background for the work; the underlining motivation and gives a brief outline of the problem and proposed solution presented in this thesis.

Chapter 2 provides an overview of hybrid power systems and introduces the concept of the HAM triangle that represents key aspects that effect the performance of any hybrid power system.

Chapter 3 begins with a review of related power systems, followed by a discussion on design and development particularly looking at current methods adopted in the sizing of energy storage and power plants for hybrid power systems. The various simulation and optimisation techniques currently in use are also presented.

Chapter 4 introduces a method for power source sizing and evaluation for use in hybrid power systems, based on Duty Cycle Constrained Selection (DCCS). Next the modelling methodology and simulation tools used in this work are presented, concluding with a brief introduction to the case studies presented in the following chapters.

Chapter 5 presents a case study of a wind turbine coupled with an energy storage device to improve the electrical power generation response of a stand alone wind turbine using the DCCS method.

Chapter 6 presents a case study of a metro rail system powered by the national electricity grid and a wind farm, designed using the DCCS method.

Chapter 7 presents a case study of a fuel cell and battery hybrid railway vehicle based on a Class 150 Diesel Multiple Unit. Two methods for component sizing of the hybrid power system are explored and compared, while giving details of the overall performance, efficiency and fuel consumption of the vehicle.

Chapter 8 draws conclusions of the presented work and the key findings of the thesis. The strengths and limitations of the DCCS method is presented and the future direction of the research is discussed.

Chapter 2

Hybrid Power Systems

This chapter presents a broad overview of hybrid power systems. This is achieved by first reviewing the various sources of energy currently available, and presenting the concept of the ‘energy cycle’. The concept of an energy vector is presented giving examples of current and promising future technologies.

A generic topology of a hybrid power system is introduced, its individual subcomponents and their functions presented and then discussed. The basic system architectures of hybrid power systems are then introduced, and the advantages and disadvantages of the different configurations discussed. An introduction to hybrid power system control is presented, and the importance of effective control of these (hybrid) systems is discussed.

Finally, the key aspects that affect the performance of a hybrid power system are investigated, and the concept of the HAM triangle, which outlines the relationship between the **Hardware**, **Application** and **Management** of a hybrid power system is introduced.

2.1 The Energy Cycle

All systems require a source of power to operate. This power is generally produced by the conversion of stored energy (i.e. a fuel). Generally all types of available energy can be traced to two fundamental types. Namely, those obtained from atomic reactions (i.e. the sun) and those obtained from gravity (i.e. tidal). In the natural world these fundamental sources of energy are converted to many forms by natural phenomena and can be harnessed to produce useful power in many different applications (i.e. hydro-power generation).

This conversion process is commonly referred to as an ‘energy cycle’, and can be illustrated as shown in figure 2.1. Traditional power sources can be described as energy converters that produce power by converting the stored energy from a single source of energy for a given application, while a hybrid power source can be described as a power source that utilises two or more energy sources to produce power for a given application. Before any further discussion of hybrid power systems, the concept of an **Energy Vector** must be introduced.

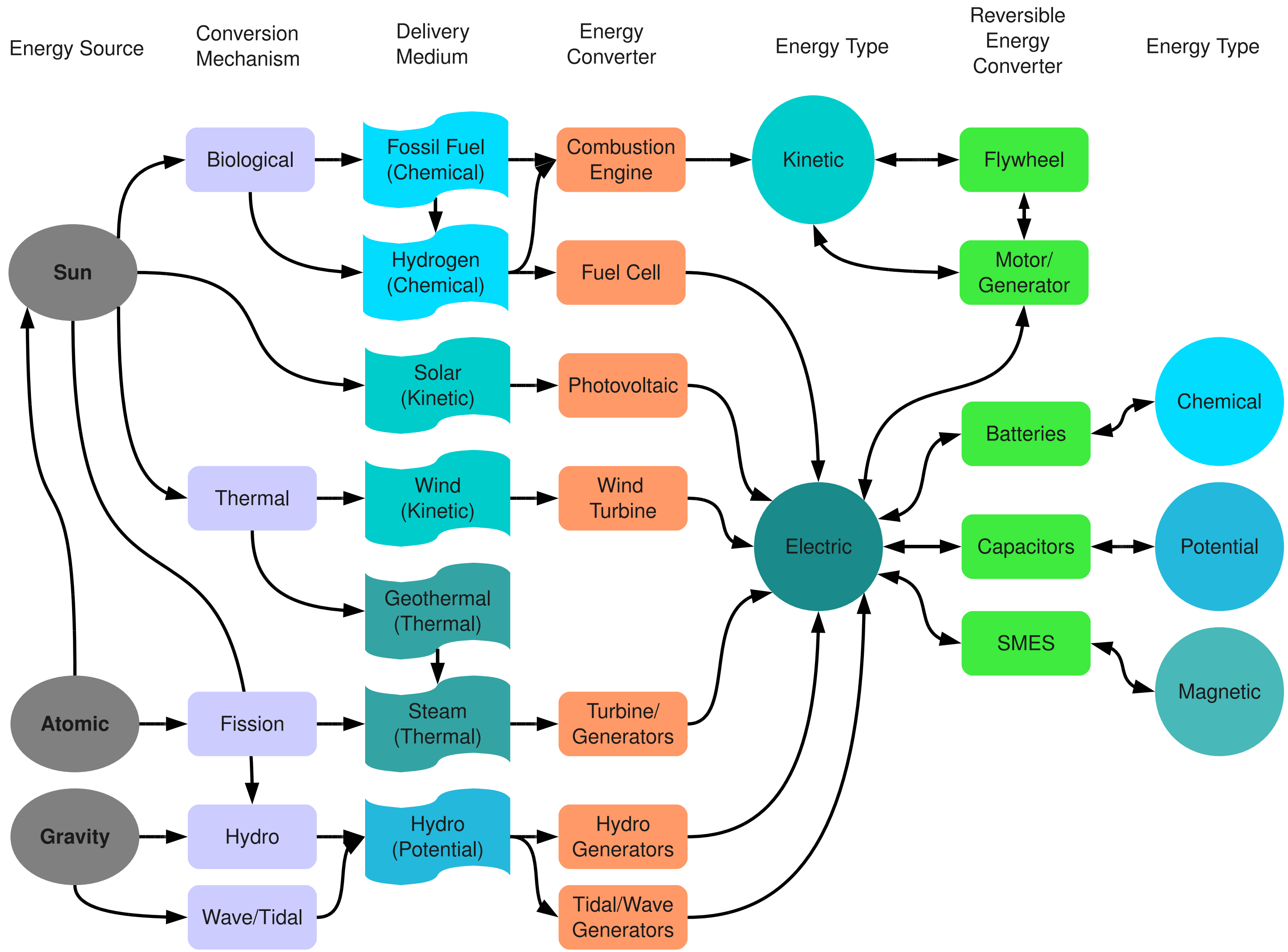


Figure 2.1: Energy Cycle Outline

2.2 Energy Vectors

In essence, an energy vector can be described as a means of transferring a quantity of energy, in space and time. Examples of vectors include fossil fuels; electricity; hydrogen and other synthetic fuels; heat exchange fluids; mechanical transmissions; oil-dynamic transmissions; pressure-dynamic transmissions and radiation [41]. The following sections present a discussion on fossil fuels and hydrogen in more detail, due to their relevance in current and future power systems.

2.2.1 Fossil Fuels

The most wide spread energy vectors in use at present are all derived from fossil fuels. These are generally hydrocarbon based fuels formed by natural phenomena over significantly long periods of time (typically millions of years), and refined to produce many types of solid, liquid and gaseous fuels such as coal, petroleum and methane.

It is worth noting these fuels are obtained by mining existing fuel deposits and therefore are a finite resource due to the significantly long time it takes to be produced. With the need to reduce global greenhouse gas emissions, the depletion of fossil fuel reserves, and the expected increase in cost of obtaining fossil fuels, there is general consensus that an alternative to fossil fuel based technologies must be sought for the future. Advances in alternate hydrocarbon based fuels such as synthetic or bio-fuels together with combustion engines that are capable of running on alternate fuel types have helped alleviate the dependence on fossil fuels. However, at present there is no viable contender to directly displace the combustion engine in most applications. Until such a day when a commercially viable alternate technology is developed to take the place of fossil fuel based power sources, the adoption of hybrid power sources has been widely recognised as a means to ease the impending energy shortage [42].

2.2.2 Hydrogen

Hydrogen is expected to play a large role in the future of the world's energy. To realise this goal of an energy economy that uses hydrogen as its base fuel, three main technological challenges must be overcome. First, the clean and efficient production of hydrogen; secondly, distribution and storage and finally, a means of utilising the hydrogen to produce power.

Hydrogen (H_2) can be produced from many different sources such as coal, natural gas, liquefied petroleum gas (LPG), propane, methane (CH_4), gasoline, light diesel, dry biomass, biomass derived liquid fuels (such as methanol, ethanol or biodiesel), as well as from water. There are many types of technologies adopted in hydrogen production. These include thermochemical; electrochemical; photobiological; and photoelectrochemical processors. Of these, steam reforming is the most widely used thermochemical process to produce hydrogen from raw materials such as natural gas, coal, methanol, ethanol, or even gasoline and comprises nearly 50% of the world's feedstock of hydrogen production [43]. This is largely attributed to it being the most energy efficient and large scale method of hydrogen production [44] [45].

Hydrogen has a higher energy density per unit mass compared with petroleum. However, its energy density per unit volume is significantly lower [46]. This low energy density per volume means the challenge of transportation and storage of hydrogen is considerably more complex when compared to petroleum. Therefore for the widespread adoption of hydrogen as an alternative to fossil fuels, an efficient, safe and cheap storage solution is required. At present the most widely adopted means of hydrogen storage is based on high pressure storage. However, to compete with current fossil fuel based fuels, a typical hydrogen fuel tank would need a volume increase of several orders of a magnitude over conventional fuel tanks. It is worth noting there are other competing storage technologies based on cryogenic; chemical and absorption of hydrogen in carbon nanotubes, however these technologies are still in relatively early development stages and have some technical hurdles to overcome before their widespread adoption.

The energy stored in hydrogen can be converted to useful power by means of combustion or via a chemical reaction to produce electricity. Please refer to sections 2.3.1 and 2.3.1 for further details.

2.3 Topology of a Hybrid Power System

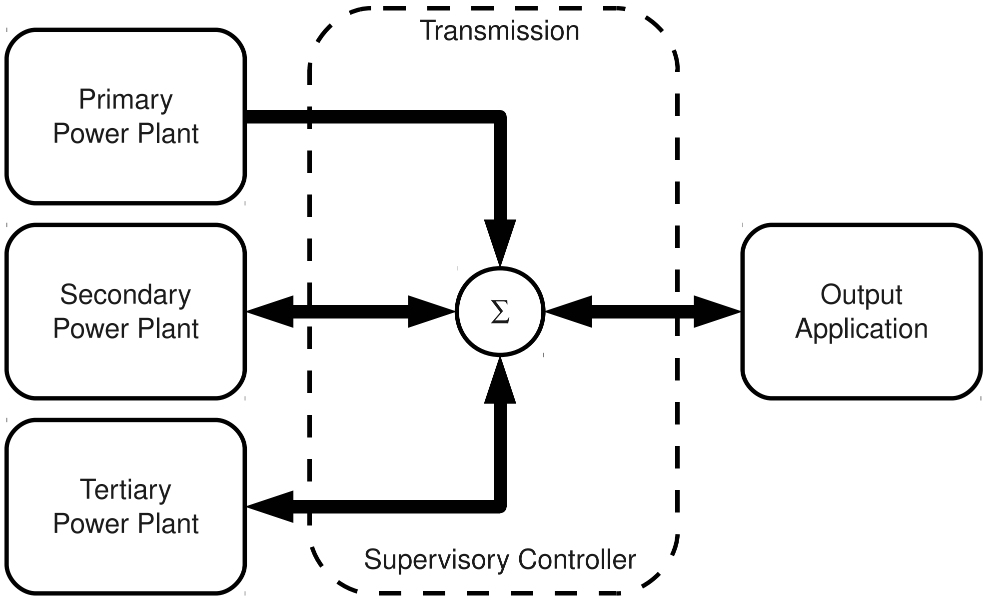


Figure 2.2: Block diagram outlining a typical topology of a hybrid drivetrain

As previously mentioned (section 2.1), a hybrid power system can be described as a power source that uses two or more sources of energy to produce power to its output application. Figure 2.2 presents a hybrid power system that is used as a template throughout this thesis. The system consists of three power sources (i.e. primary, secondary and tertiary power plants); a means of linking the outputs of the power sources together (i.e. transmission); a facility to allow the control of the individual components (i.e. supervisory controller) and a means of delivering power to the system's intended output application. The following sections provide a general overview of:

- Important primary, secondary and tertiary power plant technologies
- Electrical power conversion
- Popular transmission architectures
- Control strategies

It should be noted that throughout the course of this thesis the terms **Hybrid Power System** or HPS, **Hybrid Power Plant** or HPP are used to describe the power sources, supervisory controller and transmission of a hybrid power system, while the term **Hybrid Drivetrain** is used to refer to the whole hybrid system including the interface to an output application.

Furthermore, the following assumptions were made about the primary, secondary and tertiary power plants in the HPS: the primary power plant of a HPS is a power source capable of only sourcing power and cannot sink or absorb power from its output; the secondary power plant is an energy storage device, capable of both sourcing and sinking power; the tertiary power plant can only act as a sink of power, thus cannot supply power to its output. It should be noted that not all power plants in hybrid power systems suffer from these constraints; however these assumptions were deemed acceptable for the scope of this work.

2.3.1 Primary Power Plants

The primary power plant is the power plant that provides energy for the system. These utilise fuel to produce power and exhibit relatively uneven efficiency characteristics. An important feature of a primary power plant is that it is used to only produce power, and cannot absorb or sink a significant amount of power from its output.

There are many types of power sources that can be considered as primary power plants. These include nuclear power plants, combustion engines, fuel cells, wind turbines, tidal or wave power generators. The following sections provide brief reviews of three such devices, namely the combustion engine, fuel cell and wind turbine, as they are used in the case studies towards the end of this thesis.

The Combustion Engine

The most popular power generation technology in use today is the combustion engine. This can be described as a device that generates mechanical power, directly from the expenditure of chemical energy of fuel when combusted or burned. Engines that burn fuel in a combustion chamber that is an integral part of the engine are usually referred to as Internal Combustion Engines [47].

Internal Combustion Engines can be categorised by the method of initiating the combustion process in the engine, Spark Ignition (SI); Compression Ignition (CI) and Homogeneous Charge Compression Ignition (HCCI) and are summarised in table 2.1. SI and CI engines have had considerable improvements over the years [48] and boast long operating lifetimes; need little or no maintenance; are capable of withstanding harsh operating environments (e.g. extremely low temperatures); and are cheap to manufacture. This has allowed the ICE to be adopted in a wide range of applications and it is especially popular in land transport applications.

Type	Description
SI	Combustion is achieved with the aid of a spark plug, which ignites the air-fuel mixture within the pistons.
CI	The air-fuel mixture is compressed to such a high temperature and pressure that it spontaneously ignites [52].
HCCI	Works on similar principles as the CI engine with the exception that the fuel ignition occurs in multiple locations simultaneously within the combustion chamber, allowing relatively higher efficiencies over both SI and CI engines [51].

Table 2.1: Summary of different internal combustion engine types and modes of operation

The main drawbacks of these include overall efficiencies of less than 35% [35] and the requirement for complex carbon fuels such as fossil fuels to operate. Modern SI engines can utilise many types of fuels such as gasoline (petrol), LPG, Hydrogen [49] and different types of synthetic gasoline fuels. In the case of hydrogen fuels, hydrogen can be used as a direct replacement for petroleum as traditional internal combustion engines can run with few modifications on hydrogen. Another advantage of hydrogen fuelled ICE are the reduced CO_2 and other emissions [50]. However, this method of hydrogen utilisation is inefficient compared to hydrogen fuel cells, which are discussed in section 2.3.1. CI engines traditionally utilise heavier fuels such as diesel or synthetic/bio diesels and while there are no commercially available HCCI engines at present, developmental prototypes exist that run on a wide range of fuel types from gasoline to diesel [51].

Gas Turbines There are two basic configurations of gas turbines currently in use. Open-cycle type, where the working fluids gain their energy from the combustion of fuel within the engine, and close-cycle type, where the energy input is by heat transfer from an external source. Open-cycle engines are commonly used in propulsion applications due to the favourable power to weight ratio of these engines. Gas turbines are commonly used for stationary power generation as well as large scale transport applications (e.g. aircraft) or marine power plants.

Gas turbines traditionally run on natural gas or aircraft fuel. However, recent advances have seen these devices made compatible with a wide range of fuel types, ranging from various types of oils, including crudes (i.e. unrefined fossil fuels); off gasses or by-products of industrial processors; syngas and synfuels and bio-liquid fuels [53].

Fuel Cells

Fuel Cells are electrochemical energy conversion devices that produce electricity by means of a fuel (e.g. hydrogen) and oxygen. While all fuel cell systems operate using the same basic principle, they are usually categorised based on the electrolyte that is used. Currently there are six main types of fuel cell technologies in use worldwide as outlined in table 2.2.

From these the Proton Exchange Membrane fuel cell (PEMFC) architecture is widely considered to be the most suitable for transport applications. These were first developed in the 1960's, by General Electric for NASA on their first manned space vehicles. However, early versions of the PEMFC had a lifetime of only about 500 hours. The problem of water management in the electrolyte was judged too difficult to manage reliably, and the Alkaline fuel cell superseded PEMFC in these applications. Little or no development in PEMFC technology took place over the next few decades until the early 1990's, when a renewal of interest in the technology saw many improvements take place, mainly thanks to Ballard Power Systems (Canada) and the Los Alamos National Laboratory (USA) [54]. Over the past few decades the performance of these systems has seen a steady increase, with huge improvements to the output power and operating lifetimes [55].

Fuel cell type	Mobile ion	Operating temperature	Applications and notes
Alkaline (AFC)	OH^-	$50 \sim 200°C$	Used in space vehicles, e.g. Apollo shuttle
Proton exchange membrane (PEMFC)	H^+	$30 \sim 100°C$	Mobile applications, and for lower power CHP systems, e.g. automotive, railways
Direct methanol (DMFC)	H^+	$20 \sim 90°C$	Suitable for portable electronic systems of low power, running for long times, e.g. laptop computers
Phosphoric acid (PAFC)	H^+	$\sim 220°C$	Large numbers of 200-kW CHP systems in use, e.g. stationary power generation
Molten carbonate (MCFC)	CO_3^{2-}	$\sim 650°C$	Suitable for medium to large-scale CHP systems, up to MW capacity, e.g. stationary power generation
Solid oxide (SOFC)	O^{2-}	$500 \sim 1000°C$	Suitable for all sizes of CHP systems, 2 kW to multi-MW, e.g. stationary power generation, transport and military

Table 2.2: Fuel cell types and applications

For the practical operation of fuel cell systems, many more components and subsystems are required apart from the actual cells themselves. These include humidifiers, pumps, compressors, radiators and heat exchanges [56]. A typical PEMFC system is capable of converting the chemical energy in its fuel, to usable electrical energy at an efficiency of approximately 50% [54]. Furthermore, with additional heat exchangers the performance of these systems can be driven up to approximately 60% [57], a huge improvement of efficiency compared with a typical ICE, whose efficiency is no greater than 35% [35].

Wind

Throughout history the energy in wind has been harnessed for industrial processes as well as transportation. Modern wind turbines, a machine which essentially captures the energy in wind and converts it into electricity, have been steadily gaining popularity in generating electricity, and reduce the amount of fossil fuel used for electricity generation. These turbines range from relatively small devices, that output a few kilowatts, to several megawatts of power. These larger turbines are mainly used in large utility grids mostly in Europe and the United States.

All wind turbines work on the principle of capturing the energy contained in a gust of wind via a rotor (typically consisting of 2 or 3 blades), and converting it into kinetic energy by means of rotating a slow-speed shaft (up to 90rpm). The next step involves converting the slow-speed mechanical power into a high-speed mechanical power via a gearbox. This high-speed drive shaft is coupled with an AC generator to produce electricity. Depending on the turbine design, these systems include active yaw systems that ensure the turbine is always facing the right direction to harvest the maximum amount of wind energy. Often modern wind turbines have active pitch control on the rotor blades and braking systems to ensure the turbine rotor does not exceed its designed rotation

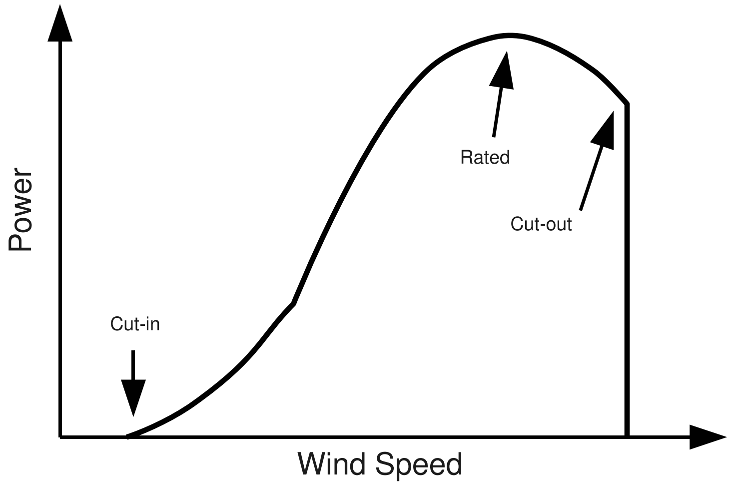


Figure 2.3: Typical wind turbine power curve

speeds in high wind conditions and to safeguard the system in case of failure [58].

Figure 2.3 shows a typical output power profile of a wind turbine with respect to wind speed. The turbine is only capable of generating its rated output power over a narrow wind speed range. Furthermore, the turbine cannot generate power when the wind speed is below (cut-in speed) or greater than (cut-out speed) a particular threshold, due to technical, design and safety limitations at higher speeds. The locations for wind energy harvesting are selected carefully to maximise the energy generation potential; however due to the unpredictable nature of wind power generation, for applications where continuous power is required, it is necessary to supplement wind power generation with other means of power generation. A typical example of this would be a wind turbine coupled with diesel-engine-generator to supply electricity to remote off-grid communities [59].

2.3.2 Secondary and Tertiary Power Plants

Secondary power plants in hybrid power systems are often an energy storage device, used to augment the performance of the primary power plant and absorb excess energy from the output application when required. Examples of these include chemical batteries and flywheels.

Generally a typical tertiary power plant can be considered as a device which has different operating characteristics, or is optimised for a different task than the primary and secondary power plants in a HPS. Examples of these include Ultra-Capacitors or even a resistor bank, used to dissipate excess energy in particular operating conditions.

Energy Storage Devices

A device which is capable of storing energy and producing it at a later time to perform a useful operation can be described as an energy storage device (ESD). There are many different ESD technologies available at present, and they can be broadly categorised by the physical principal they use to store energy. While a detailed review of all of these technologies is outside the scope of this work, the following sections provide a general overview of some key ESD technologies for hybrid power systems.

Chemical Batteries are devices that convert the chemical energy contained in their active materials directly into electrical energy by means of an electromechanical oxidation-reduction reaction [60]. For a number of battery technologies this process can be reversed and the battery energy replenished [61]. Today's battery technologies can be categorised into four types which are shown in figure 2.3 [60].

Battery Type	Description	Typical Applications
Primary	Single use, non-rechargeable energy devices. The advantages of these devices are that they are convenient; simple and easy to use; require little or no maintenance; possesses a good shelf life; have a reasonably high energy and power density; are reliable and relatively cheap to produce.	Popular source of power in a wide range of Applications, ranging from portable electric and electronic equipment to computers and watches.
Secondary	Rechargeable batteries	Consumer electronic devices such as laptops, remote controls and toys; automobiles to provide power for starting ICE's to providing tractive power.
Reserve	Used to deliver high power for relatively short periods of time after activation; constructed to withstand deterioration in storage; exhibit very low self-discharge prior to use; usually contain highly active materials to obtain the required high energy, high power and/or low-temperature performance	Missiles, torpedoes and other weapon systems.
Advanced	Exhibit improved or advanced rechargeable characteristics such as increased energy and power densities, long life, low cost and need little or no maintenance and high levels of safety. These systems have emerged due to the ever increasing need for high performance energy storage devices.	Electric vehicles, electric-utility storage, portable electronics and renewable energy storage from wind and solar generators.

Table 2.3: Chemical Battery Types

Super-Capacitors are devices that utilise a large surface area between the conductive materials to store energy in an electric field.

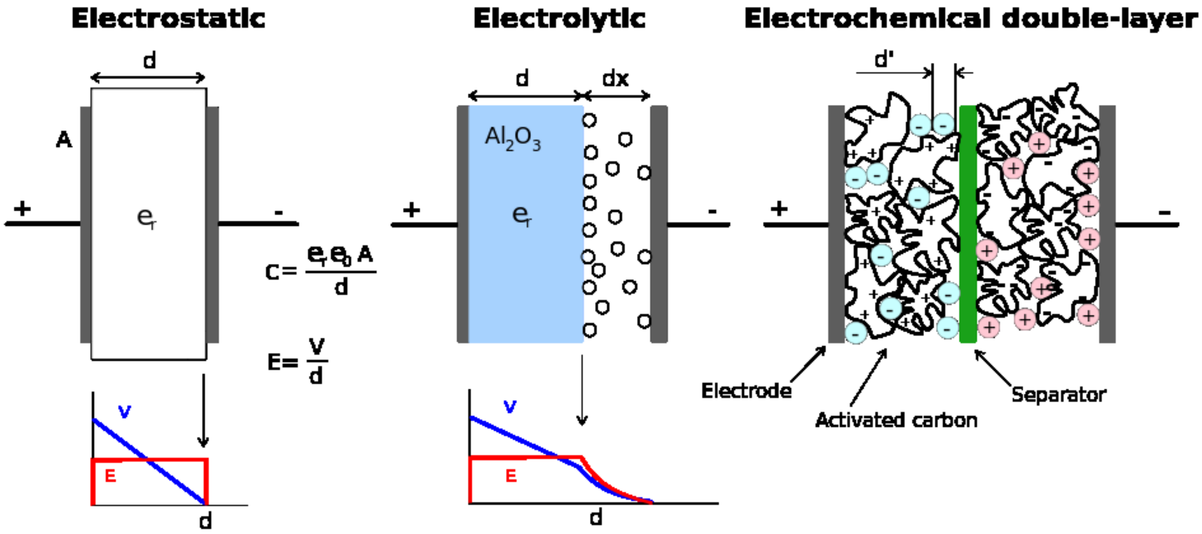


Figure 2.4: Capacitor Construction

Traditional electrostatic or electrolytic capacitors have utilised thin metal strips separated by a dielectric film to achieve high capacitances (figure 2.4) [62]. However, the capacitance achievable by these architectures, falls short for high energy applications such as hybrid traction. The electric double-layer capacitors; also known as the ultra-capacitors or super-capacitors, have seen much development in recent years due to their significantly higher power densities and lifetimes. These devices utilise carbon foil electrodes, that are impregnated with conductive electrolyte; positive and negative foils with this carbon mesh, have an electronic barrier or separator that is porous to ions between them (figure 2.4). This architecture allows ultra-capacitors to exhibit energy and power densities significantly higher than their more traditional counterparts, thus making them viable candidates as energy storage devices in hybrid traction applications [23].

Flywheels are arguably one of the oldest methods of energy storage available and have been in use in one form or another for millennia, with the earliest known use dating back to potters wheels and in ancient Egyptian drilling devices [63]. The basic principle of a flywheel is the storage of energy as kinetic energy in a rotating mass.

The potential for high rates of energy input and release; increased reliability due to advances in composite materials; highly efficient bearings that have reduced frictional losses, and allow very high rotational speeds; advanced electric and mechanical interfaces that enable the stored energy to be recovered, and utilised have meant flywheels are likely to play a significant role in HPS. However, with the relatively high internal mechanical stresses high end flywheel systems generate; inherent gyroscopic effects; the potentially dangerous consequences of mechanical failure, especially in traction applications, great care must be taken when utilising flywheels [23].

Superconducting Magnetic Energy Storage or SMES, utilises a magnetic field to directly store electrical energy. These devices utilise an electromagnet made from superconducting wire to maintain the magnetic field with virtually no losses. Furthermore, as these devices directly store electrical energy (i.e. there is no conversion to another type of energy as in chemical batteries, ultra capacitors or flywheel systems) these devices have the potential of delivering very high storage efficiencies.

At present the main limiting factor of this technology for use in traction applications is the cryogenic temperature that existing superconductors operate at. While many advancements have been made with the development of high temperature superconducting materials that operate at temperatures above $150K$, the overall cost of these systems has so far inhibited their widespread use [64]. It can be assumed once room temperature superconducting materials become available, this technology will be a significant contender as secondary power plants in hybrid power systems.

Resistive Power Dissipation

An important component which is utilised extensively in this thesis as a tertiary power plant, is a **resistive power dissipation device**, also referred to as **rheostatic braking** systems in electric traction applications. The basic principal of operation is based on converting electrical energy into heat via a large resistor. This device is used in the case studies as a means of dissipating excess energy in a hybrid power system during particular operating conditions.

2.3.3 Electrical Power Conversion

At this point it is a good time to expand on the concept of 'electrical power conversion' a little further. As previously covered in section 2.1, energy types (i.e. kinetic, potential, etc.) can be converted from one type to another (figure 2.1). In the case of electrical energy conversion devices, there are two fundamental devices with special relevance to HPS. These are electrical machines and electronic drives and will be discussed further in the following sections.

Electrical Machines

An electrical machine or motor is a device that converts electrical energy into kinetic energy via the interaction of opposing magnetic fields. Furthermore, these devices can also be used to convert kinetic energy to electrical energy. Currently there are many different machine architectures in use; however, they all consist of the same general

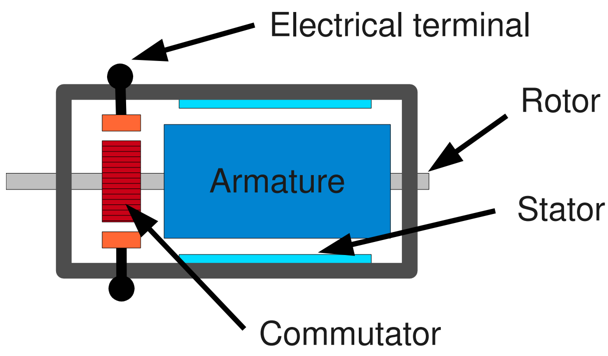


Figure 2.5: Topology of an electrical machine

components outlined in figure 2.5. The following sections present a general overview of the different types of popular electric machines.

DC Machines have two sets of windings, one in the rotor and the other in the stator. The winding in the rotor is called the armature winding, while the stator windings are also referred to as field windings. The correct switching phases of the magnetic fields induced in the armature windings are maintained by a set of mechanical components called commutators and brushes (figure 2.5).

Depending on the number of supply sources and the connection between the armature and stator windings, these machines can be subdivided into the following types:

- Separately Excited DC Machines
- The DC Shunt Machines
- Series DC Machines

The advantages of DC machines are mainly the ease of control, due to a linear relationship between torque and input power and established manufacturing technologies. The main drawbacks include the high maintenance cost due to brush and commutator wear; low maximum speed; power to weight ratio; limited efficiencies; high Electromagnetic Interference (EMI) due to the commutator [52].

AC Machines can be described as DC machines in which the armature circuit is located in the stationary piece of the structure. The most significant impact of this being the elimination of the commutator and brushes found in DC machines. These machines utilise AC sources (single or multiphase) to operate, and can be found in low power applications such as mains powered wall clocks and timers to large turbine electricity generators and locomotives. AC machines can be further divided into two broad types, based on the type of rotor design [52]:

- Synchronous Machines
- Asynchronous Machines (also known as Induction Machines)

Permanent Magnet Machines are motors that use permanent magnets instead of field coils to generate magnetic flux. Similar to AC machines, these can be further subcategorised as:

- Synchronous Type
- Asynchronous Type

Switched Reluctance Machines are doubly salient, singly excited reluctance machines with independent phase windings on the stator. The stator and rotor are made of magnetic steel laminations. The rotor has no windings or magnets.

These devices have unique features that make them strong competitors to AC and DC motors in various adjustable speed applications. The main advantages include simple and low cost construction due to its simple rotor design; simpler power electronics due to the lack of bidirectional currents and ON/OFF nature of the control pulses; torque-speed characteristics that can be tailored to the application requirement during design; high starting torque without high inrush current problems due to high self-inductance; high torque/inertia ratio with low rotor inertia; can achieve very high rotation speeds and their ability to operate in spite of stator phase failures due to independent phase control.

The main disadvantages of these machines are acoustic noise and high torque ripple and complex power converter architectures for reliable operation.

Electronic Drives

An electronic drive can be described as a device capable of converting electrical energy from one voltage and frequency to another. These devices are widely in use in any application that utilises electrical energy to operate (i.e. electrical machines, AC-DC power conversion) and generally comprise of the following subsystems:

- Command interface
- Control electronics and processor
- Power switching elements

The command interface is the way the drive communicates with the outside world, and often consists of digital and analogue input/output interfaces, and in recent years has included popular network protocol interfaces [65]. Advanced drives that are used in industrial applications, especially for controlling complex AC machines, which require variable speed operation often utilise microprocessor based internal control electronics. Finally the power switching is carried out by power switching devices, capable of withstanding high voltages and currents.

While it is not in the scope of this thesis to provide detailed explanations of the operating principals of these devices, it is suffice to state that these devices play a vital role in the effective operation of any electrical system, and their operating characteristics must be taken into account to predict the operation of these systems.

2.3.4 Popular Transmission Architectures

The transmission or architecture of a hybrid power system can be described by how the individual power plants are connected together to deliver power to the output application. Currently there are many types of hybrid power system architectures in use [23]. These transmissions vary from one another based on the different power plants utilised and how they are connected and interact with one another to deliver power to the output of the system. It should be noted that each architecture has its own advantages and weaknesses and is largely dependent on its individual power plant technologies and output applications. These different architectures can be grouped into the following three broad categories, which are discussed in further detail in the following sections:

- Series hybrids
- Parallel hybrids
- Series-Parallel hybrids

Series Hybrid

Generally this architecture is most suited for applications that require electrical output power, and/or utilise electrical power sources, such as electricity grids or large traction applications like heavy duty trucks, buses and locomotives, as these are much less sensitive to the added weight of the motor-generators, and benefit from the increased

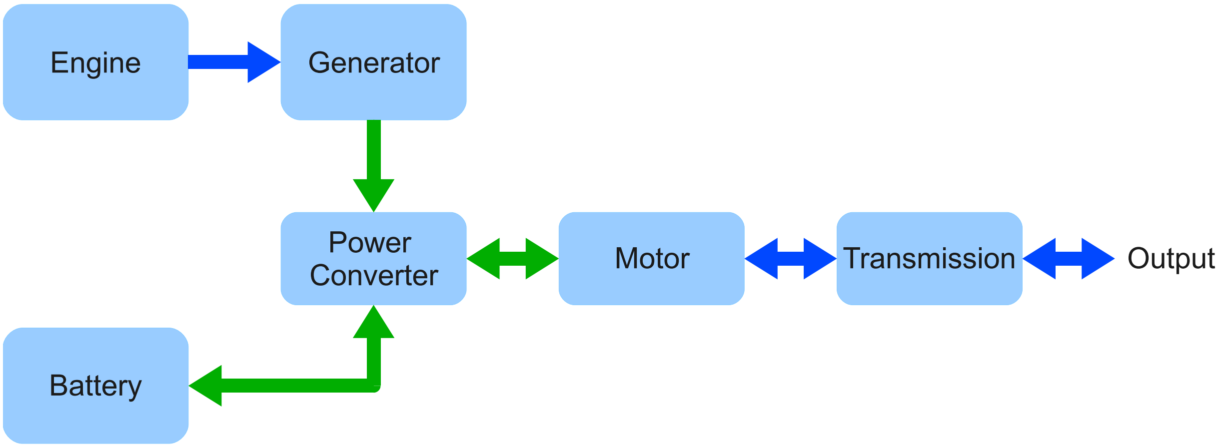


Figure 2.6: Block diagram of a Series Hybrid Architecture

efficiency of large power converters used to convert kinetic energy from the ICE to electrical energy. Generally this architecture is most suited for applications that require electrical output power, and/or utilise electrical power sources, such as electricity grids or large traction applications like heavy duty trucks, buses and locomotives, as these are much less sensitive to the added weight of the motor-generators, and benefit from the increased efficiency of large power converters used to convert kinetic energy from the ICE to electrical energy.

A good example of a series hybrid drivetrain (figure 2.6) is an electric vehicle powered by multiple electric power sources (e.g. ICE-generator and battery pack). The benefits of this architecture include a simplified drivetrain due to the reduction of mechanical transmission components such as clutches throughout the mechanical link, and the flexibility for locating the engine-generator sets away from the mechanical transmission [66]. For applications that utilise ICEs, the flexibility that is gained by the separation of engine speed and vehicle speed, allows for more flexible control strategies to be implemented, and the potential for a higher overall system efficiency to be achieved.

However, this configuration suffers a double conversion penalty in mechanical output applications (such as automotive), due to the two-stage conversion process when

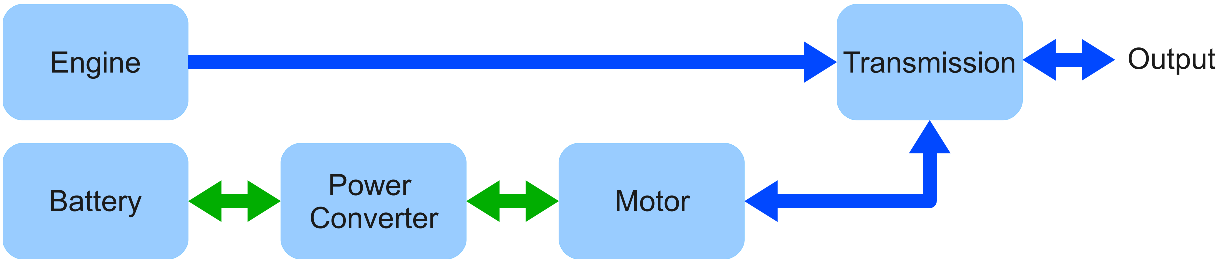


Figure 2.7: Block diagram of a Parallel Hybrid Architecture

powered by an internal combustion engine, or other mechanical energy generation processes (i.e. the conversion of chemical energy to thermal energy to kinetic energy to electrical energy to kinetic energy).

Parallel Hybrid

This architecture can be described as the implementation of multiple, unrelated power plants to a single output application (figure 2.7). These sources are directly coupled in parallel before or after a mechanical transmission, often used in transport applications, which require the output energy in the form of kinetic energy.

This configuration allows a vehicle to be propelled with any combination of the available power plants, and exhibits lower losses compared to a series configuration, when utilising power plants that produce power as kinetic energy, such as combustion engines in relatively low power applications. Another advantage of this approach is that it provides higher reliability from complete propulsion system failure, due to the separation of the different power plants.

However, the inherent linking of the primary power plant, typically an internal combustion engine, to the vehicle speed can lead to lower efficiencies and limits the flexibility in suitable supervisory control strategies of the overall system [31].

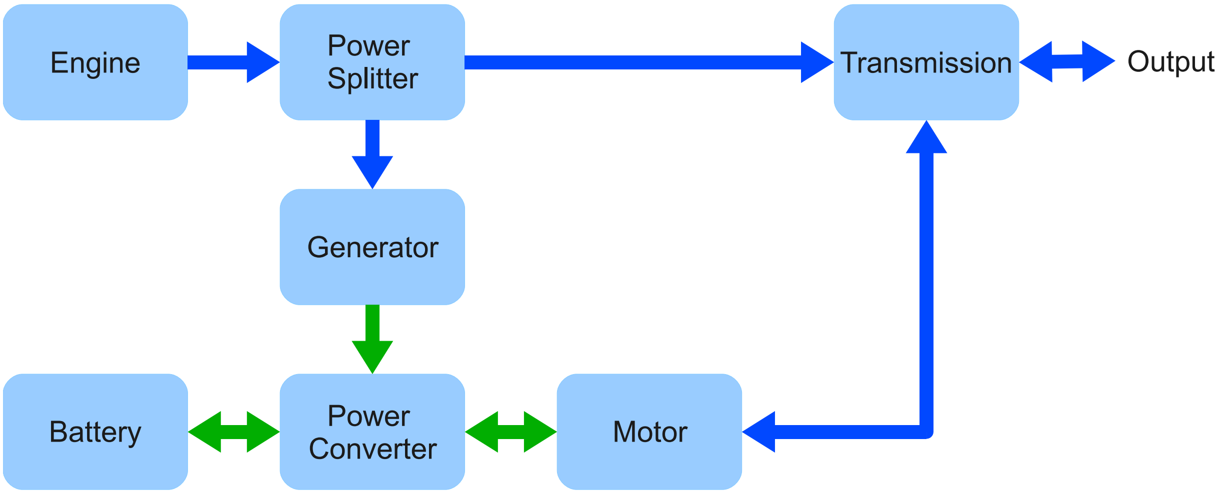


Figure 2.8: Block diagram of a Series-Parallel Hybrid Architecture

Series-Parallel Hybrid

A combination of the above mentioned series and parallel hybrid architectures, the series-parallel configuration (figure 2.8) allows the best attributes of the series and parallel architectures to be combined.

In an automotive application, it can be considered to be a parallel hybrid system with the energy sources linked electrically, thus allowing series hybrid operating characteristics for particular control strategies (e.g. charge the energy storage device from the internal combustion engine). The major limitation of this configuration is the increased complexity and cost of the overall system [23].

2.3.5 Control Strategies

The most important aspect of any system is the effective control of its sub-components. This is more so important in a complex system, such as a hybrid power system. There are two fundamental types of control objectives to be fulfilled in the operation of these systems:

1. The effective control of the output of the hybrid power system.

2. The control of the individual power plants of the system, as to ensure continuous; uninterrupted; problem free; operation of the hybrid power system. This type of control is often referred to as ‘supervisory control’.

Output Control

This type of control relates to the performance of the hybrid power plant with respect to the outside world or intended application. The operational requirements of this form of control are usually highly dependant on the duty cycle of the intended application, and decisions made at the design stage of a hybrid drivetrain.

To understand the control objectives of this type of control it is necessary to identify the typical applications a hybrid power plant is suited for. Section 1.2 expands upon this concept further and provides examples and outlines the typical requirements of a hybrid drivetrain.

Supervisory Control

This applies to the management of the individual power plants and transmission of a hybrid power system. The objectives of a hybrid supervisory controller can be listed as the follows:

- Ensure individual power plants operate at their optimum levels
- Manage State Of Charge (SOC) of energy storage devices to provide desired operating goals (e.g. charge sustaining)
- Manage State Of Health (SOH) of individual power plants to provide a long operating lifetime

- Ensure the hybrid power plant operates within safe physical design limits for example temperature

At present there are many different types of supervisory control strategies being explored for use in hybrid power plants. These range from Rule Based strategies that utilise deterministic or fuzzy methods for system control to optimisation based strategies where the optimum control solution is derived from the information of a duty cycle that has already taken place [38]. The following section provides a brief overview of popular techniques used to formulate HPS control strategies.

Selection and Design

In the selection and operation of the supervisory control strategy and output control strategy in a HPS, there are many approaches to control strategy selection and design. From these by far the most prevalent are rule based control strategies. These methods utilise a set of conditional-action rules: when the conditions are matched by a predefined state, the actions are performed, and have been widely adopted in artificial intelligence and expert systems [67]. The key advantages of this approach include relatively low computational overhead, and the ability to implement with little knowledge of the intended application. These have seen wide adoption in supervisory control strategies and can be further divided as deterministic and fuzzy logic types.

Deterministic In this method, intuition and human experiences are used to form rules, that are used to govern the behaviour of the hybrid system. These are often aimed at maintaining measurable physical properties, such as battery state of charge; vehicle speed; fuel economy of an internal combustion engine. The main disadvantage of this method is that the efficiency of the whole drivetrain is not taken into account. Examples of popular deterministic rule based control strategies are outlined in table 2.4.

Fuzzy logic control can be considered to be made up of multiple rule based deterministic control loops; each optimised with an individual goal in mind. Fuzzy logic controllers are specially suitable for multi-domain, non-linear and time varying applications [68]. The advantages of this approach are primarily the robustness, due to their tolerance to imprecise measurements, and flexibility gained by fuzzy rules being easily tuned if necessary [69]. This method can be further classed as Conventional, Adaptive and Predictive and are described further in table 2.5.

From the literature, a few other noteworthy approaches to the control of HPS can be obtained:

Equivalent fuel consumption minimisation was introduced by Paganelli, Guerra et al [76] [77] [78]. In this method, equivalent fuel consumption is defined as the extra fuel consumption that is required for the battery recharge in the near future. Thus the fuel economy of the total system can be obtained, by using the fuel consumption of the internal combustion engine and the equivalent fuel consumption. The control of the hybrid drivetrain is then based on the objective of minimising the combined fuel consumption [79]. The main drawback of this approach is that charge sustaining of storage devices is not directly addressed.

Robust control consists of the simplification of the control to a linear time-invariant system. Pisu et al [80] have approached this problem by means of realising an output feedback controller, that minimises fuel consumption with respect to a family of possible torque/power input profiles.

Optimal predictive control was introduced by Salman et al [81], where a cost function

Name	Description
Threshold based	A very simple control strategy. Typically in this case a particular physical parameter such as the SOC of the battery is monitored by the supervisory controller, if its value drops below a predefined threshold the charge is topped up using the available energy source [69].
Power follower	Uses the primary power plant to provide motive power. When additional power is required during the operation, it is obtained by the secondary energy devices. The SOC of the on-board energy storage is maintained by a set of predefined rules based on engine power; battery SOC; vehicle speed. At present this is the dominant control strategy adopted by commercial hybrid automobiles, such as the Toyota Prius and Honda Insight [70].
Modified power follower	Based on the 'Power follower' strategy. Improves the control, by utilising a cost function based on energy usage and vehicle emissions [71]. Technically superior to the original (power follower), in practice this method significantly increases the implementation complexity.
State machine	Utilises a simplified set of valid states a HPS can occupy. The transition between these modes are decided based on the driver demand; vehicle operating condition; system or a sub-system fault conditions [72]. This approach ensures safe and robust operation of a HPS. However, it lacks the ability of optimising performance of a system to particular needs, such as fuel economy or emissions.

Table 2.4: Examples of Deterministic Rule Based Control Strategies

Name	Description
Conventional	Traditionally made up of several rule based deterministic control loops. Each designed to achieve a specific and more importantly different objective. Limitations of this approach is the difficulty in designing static rules, that ensure the overall optimum operation of highly dynamic, and contradicting goals such as optimum energy efficiency and performance [73].
Adaptive	A variation on the conventional type. The impact of the fuzzy rules are allowed to be tuned by means of a cost function. This allows the overall performance of the control strategy to be customised, with specific objectives and applications in mind [74].
Predictive	Can be thought of as the natural progression of adaptive fuzzy logic. In this variation the cost function, or parameter weightings are tuned dynamically based on a predicted, or anticipated duty cycle of the system. In hybrid vehicle applications this prediction can take the form of acquiring knowledge of typical route traffic; urban driving cycles; geographical information such as hills via an on board GPS; traffic update systems, and optimise the controller behaviour for optimum performance [74] [75].

Table 2.5: Examples of Fuzzy Logic Based Control Strategies

representing the equivalent fuel consumption over a preview or look ahead window is used, to find a real-time predictive optimal control solution. It was proposed that the information for the look ahead window would be obtained by means described in the 'predictive fuzzy logic' method outlined previously.

It should be noted that there is no single winner from all the methods outlined above when designing a control strategy for a HPS. Instead the drivetrain architecture, performance, intended application and motivation for drivetrain hybridisation must be all considered, to help choose the most appropriate method for the task at hand.

2.4 Key Performance Indicators

The performance of a system can be described as the amount of useful work accomplished by the system with respect to the resources used. With traditional single [energy] source drivetrains, this is often a linear relationship between installed power and availability of fuel (i.e. size of fuel tank). However, when considering hybrid power systems this relationship becomes significantly more complex due to the time and state dependant nature of its sub-components (e.g. the available total power can vary significantly based on the stored energy in the on-board energy storage devices).

Therefore, not only is it important to quantify what is meant by the 'performance' of a hybrid power system, it is also important to understand what affects the performance of such a system in order to improve its performance. The following sections explain the term 'performance' with respect to HPS, and discusses how the performance and sizing of the installed power plants affect the performance of these systems.

2.4.1 Performance

Performance is a highly subjective parameter and a system can be considered to have different 'performances' based on its intended application. It is difficult or unfair to class the 'performance' of a system without considering the intended application of a given system. In an automotive example, the performance of a vehicle is measured using a combination of the vehicle's acceleration; top-speed; range; fuel economy; driving style; installed power and intended use or driving duty cycle. While the achievable top-speed and acceleration is important for a sports car; fuel economy, passenger comfort and space is more important for a family saloon.

Accurately quantifying or measuring the 'performance' of a HPS becomes more challenging, due to the need to measure and predict characteristics of the drivetrain that are affected by time and state dependant parameters, such as the State Of Charge (SOC); State Of Health (SOH) of energy storage devices; size and utilisation of individual power plants; operating efficiencies of sub-systems and efficiency of the system as a whole.

For the scope of this work, it is assumed that the performance of a HPS relates to its ability to function uninterrupted, for the duration of its application duty cycle (i.e. not break down or need unplanned maintenance or assistance).

2.4.2 Level of Hybridisation

The ratio between the output size of the primary power plant and secondary power plant of a hybrid power plant is often referred to as the level of hybridisation. In the case of ICE or other kinetic primary power plants and electrical secondary power plant based hybrid systems, this ratio is often referred to as the Electric Fraction (EF). This metric is generally used to describe the operating behaviour of a hybrid power system, and helps identify a particular system's applicability to a particular output application or duty cycle.

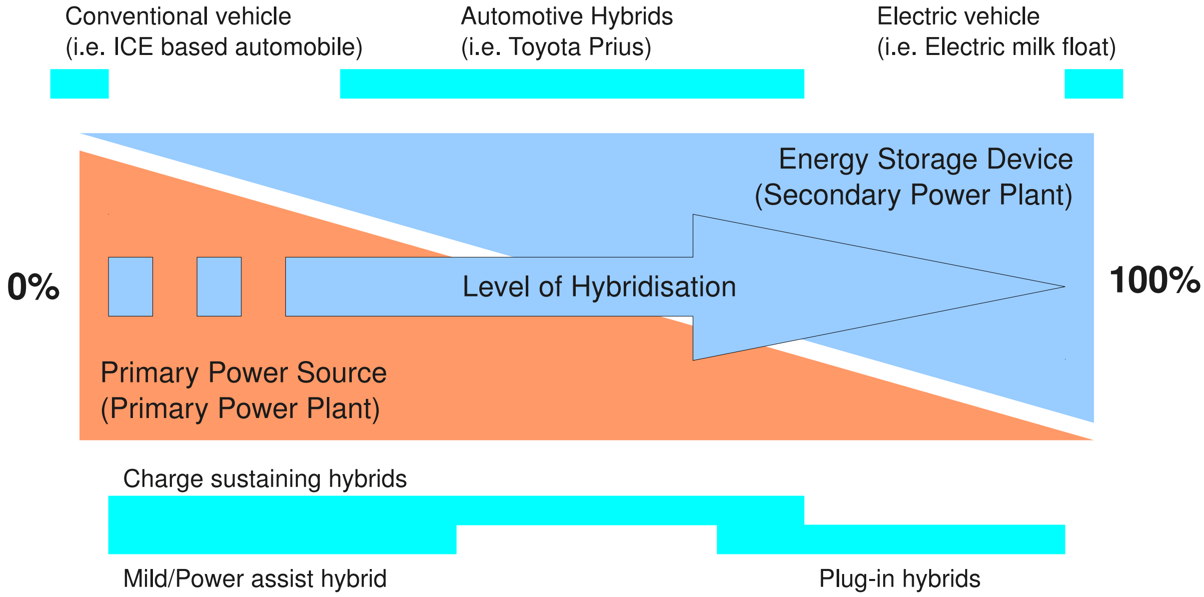


Figure 2.9: Diagram that depicts the level of hybridisation of a hybrid drivetrain based on the ratio between the primary and secondary energy sources

Figure 2.9 illustrates how the level of hybridisation varies with respect to a hybrid power system's power plants. At one extreme lies vehicles that rely solely on a single, non-replenishable (during operation) power source for generating power; these usually have little or no on-board energy storage. A good example of such a system is a standard ICE based automobile. The other extreme is a system that uses a large energy storage device for power, which must be replenished (or charged) off line [23]. A good example of such a system is an electric milk-float.

When a combination of the two (primary and secondary power plants) make up the total installed power, it is considered to utilise a hybrid power system. Based on the ratio of primary to secondary (typically electric) energy a hybrid power plant can be further classed as a **charge sustaining hybrid** or **plug-in hybrid**. The former must ensure the on-board energy storage devices are never completely depleted via a supervisory control strategy (covered in section 2.3.5 in more detail), while the latter relies on the user topping up on-board energy storage devices regularly to ensure optimum operation of the overall system.

If the electric fraction or secondary power plant size is a small fraction of the installed overall power, the drivetrain is commonly described to be a **mild hybrid** or **power assist hybrid**, as the effect of having on-board energy storage plays a relatively small role in the overall operation of the vehicle.

Systems whose energy storage devices make up a significant proportion of the available power in the drivetrain are often referred to as **power hybrids**. These configurations are often not capable of being operated purely by the primary power plant and often require both the primary and secondary power plants to operate simultaneously to reach maximum output power and/or performance [82].

2.5 HAM Triangle

There are many different factors that contribute towards the efficient operation and performance of a HPS. These range from physical parameters, that relate to the power plants and drivetrain design, to the intended application, and duty cycle the hybrid power plant is subjected to over its operating lifetime. These can be broadly categorised as, a hybrid system's **Hardware**, intended **Application** and operational **Management** and can be illustrated as shown in figure 2.10. The relationship between these three properties can be summarised as follows:

Hardware: relates to the physical make up of a hybrid drivetrain and includes the individual power plants and their underlining technologies together with the drivetrain architecture.

Application: corresponds to the duty cycle the hybrid drivetrain is subjected to as part of its normal operation. These typically vary from application to application.

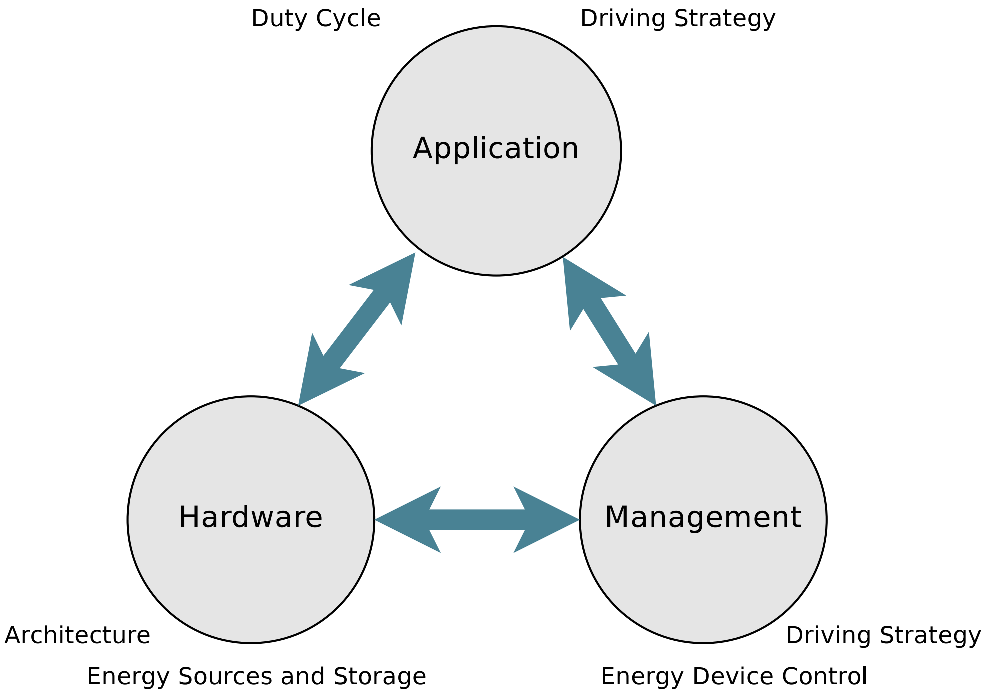


Figure 2.10: HAM Triangle used to describe the relationship between the different aspects that effect the efficiency and performance of a hybrid power plant

Management: of the hybrid drivetrain, corresponds to the supervisory control strategy implemented to ensure the correct operation of the hybrid power plant, and the output control strategy or driving strategy (in transport applications) adopted.

To achieve high performance, reliability and efficient operation of a hybrid drivetrain all three of these aspects must be considered during the design of any hybrid power system.

2.6 Summary

A broad review of the various sources of energy currently available and the concept of the 'energy cycle' was presented. The concept of an energy vector were presented with a discussion on the most popular current and likely future technologies.

A generic topology of a hybrid power system was then introduced, with a discussion of its individual subcomponents and functions. Next, hybrid power system transmissions or architectures were introduced, and the advantages and disadvantages of the different configurations discussed. An introduction to hybrid power system control was presented, and the importance of effective control of hybrid systems was discussed.

Finally the key aspects that affect the performance of a hybrid power system were investigated, and the concept of the HAM triangle, which outlines the relationship between the hardware, application and management of a hybrid power system was introduced.

Chapter 3

Design of Hybrid Power Systems

This chapter investigates the task of ‘hybrid power system design’. This is done by first reviewing different types of hybrid power systems and identifying the key differences and features in them. Next the concept of ‘design & development’ is introduced, giving a background on the different types of design methods currently used and commenting on the importance of standards, motives behind design processes and introduces the role and importance of systems engineering in the design of complex systems.

Next a review of the literature in hybrid power system design is provided and popular simulation and modelling tools and techniques are described and discussed. This review is concluded with a discussion of popular optimisation techniques used in the design and development of HPS.

3.1 Review of Related Systems

There are many systems that can be described as utilising a hybrid power source to operate. The in-depth classification and reviewing of each and every one of these do not fall into the scope of this work. Instead, brief descriptions of three types of systems that commonly utilise multiple energy sources to operate are presented. In each case the system's hardware layout is described, history and applications presented; concluding with key functional and operational challenges. The aim is to provide the reader with an overview of the diversity of HPS and help identify the differences in these systems.

The power systems discussed below have been categorised by the primary type of energy the intended application requires. Namely, kinetic, electrical and combined energy. It should be noted that all of the described systems have common characteristics and can be classed as hybrid power systems. For the scope of this thesis and the work presented within, only a subset of these systems (e.g. electrical and traction applications) that produce a single output energy type, and conform to the topology described in section 2.3 are considered as a HPS.

3.1.1 Kinetic

The best example of a hybrid power source that is required to deliver power as kinetic energy is in traction applications. In recent years the adoption of hybrid drivetrains in the automotive industry has increased significantly. These systems generally consist of an ICE and chemical battery or flywheel based energy storage device, and make use of hybrid architectures based on series-parallel systems.

Key requirements for these HPS include the need to be mobile, provide high power for brief periods of time (i.e. during vehicle acceleration), have a high reliability, while being cheap to manufacture and maintain. Furthermore, the highly varied nature of automotive duty cycles have made the design of these systems very complex.

3.1.2 Electrical

By far the best and biggest example of a hybrid power system that produces electrical energy as an output, is a national electricity grid or 'National Grid'. These systems can be described as having a series-hybrid architecture, and are generally made up of many 'electricity generators' or sources and a means of delivering the generated electricity to consumers. Furthermore, until very recently there has been little utilisation of any significant amount of energy storage in these systems.

Traditionally these systems have consisted of generators that can be controlled to produce the required level of output power proportional to the instantaneous demand in electricity, by maintaining a predefined voltage and frequency (230VAC @ 50Hz in the UK) within acceptable limits. However, as more generators powered by renewable sources of energy have been introduced to the grid, the control and maintenance of voltage and frequency stability have become more complex, due to the unpredictable generation characteristics exhibited by wind, wave and solar generators.

It is worth noting, currently most electricity grids consist of very little or no energy storage devices; instead they can be described as hybrid systems that consist of multiple primary power plants (referring back to the HPS topology presented in section 2.3).

3.1.3 Combined

Another noteworthy system type that may be described as hybrid power systems are those whose output applications require two or more forms of energy. These systems generally utilise one or more types of input power sources, and sometimes have on-board energy storage capabilities. Two examples of these are Combined Heat and

Power (CHP) systems and Energy Hubs.

A CHP or co-generation plant is a device that usually utilises a single source of energy to produce electricity and heat for a particular application. These are generally used in industrial or commercial applications where electricity and heat is required. These systems have seen many advances in recent years due to their ability to achieve very high overall efficiencies over more traditional parallel approaches to electricity and heat generation systems.

Widely believed to be the future evolution of power distribution networks (i.e. gas, electricity grids), energy hubs utilise multiple energy vectors such as gas, electricity and heat to produce the desired output, which often consists of multiple energy types.

3.2 Design & Development

The design and development process of any product or system consists of many phases. These can be loosely described as initial concept development; system-level design; detailed design; testing and refinement; and production (figure 3.1). This process is a interdisciplinary activity requiring input from marketing, engineering and manufacturing disciplines to achieve high quality results [83].

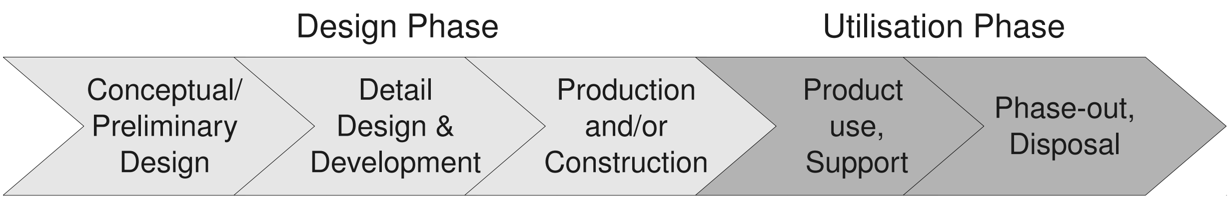


Figure 3.1: Product Life Cycle

The in-depth discussion of the whole design and development process is beyond the scope of this thesis, however it is important to appreciate some of the basic motives and processors related to system design and development. This section outlines the motives behind the design and development of a system and provides a very brief overview of popular design approaches used to engineer complex systems.

3.2.1 Motives

Apart from the obvious objective of designing a product that meets the design specification from a functionality viewpoint, there are other more subtle design decisions and considerations which must be managed and met during the design process of a system. The following outlines some of the most important ones, providing examples and discussing the potential adverse effects of ignoring them during the design phase.

Technical Standards: These are predefined specifications or requirements a product or system must meet. These often relate to emissions (EMC, particulates, greenhouse gasses); safety and reliability or usability of a product and sometimes must be met in order for items to be sold in particular countries (e.g. CE marking for European countries). Therefore for the successful introduction of any product, appropriate standards must be identified and adhered to, to ensure the success of the product.

Cost: Possibly one of the most important aspects of any product is its cost and this generally includes research; design and development; manufacturing and profitability of product. In the scope of engineering, cost is a key metric in design and selection of technologies, and often requires designers to make difficult decisions between cost and features of a product.

Maintenance & Reliability: Somewhat connected to the previously mentioned 'cost' category, is the effort put into maintaining a particular reliability and maintainability of a given product, during the design and development phase. The reliability generally relates to the specification of a system to operate problem-free and failure-free for a particular period of time, while the maintainability of a product relates to the difficulty or ease of repairing once the inevitable failure of components occurs.

Traditionally the aspect of maintainability of a product has been of less importance at the design stage, particularly as the costs associated with the repair and maintenance are largely encountered by the end users rather than manufacturers. However, with the introduction of various recycling legislations such as the EU directive 2002/96/EC also known as WEEE (Waste Electrical and Electronic Equipment) [84] and the move towards 'Design-Build-Maintenance' (DBM) contracts for complex products such as in railways, considering the complete life cycle of a product during the design and development phase has become more important.

3.2.2 Formal Methods

There are many formal design approaches and methods in existence. While all of them in essence achieve the same end result, i.e. the transformation of a product concept to an actual product, the individual approaches and routes they adopt can be very different. This section provides a brief outline of a few popular design methods in use at present.

Co-Design is a design philosophy which can be described as incorporating multiple perspectives and ideals during the design process of a product or system. This methodology has recently been adopted in the design of hardware and software embedded systems such as mobile phones [85].

C-K Theory is a method used in design and reasoning of design, introduced by A. Hatchuel and B. Weil [86]. The approach models the dynamics of design as a joint expansion of a space of **C**oncepts and **K**nowledge. The theory is often utilised to increase innovation during the design phase and shows promise in the fields of engineering and industrial design.

TRIZ was originally proposed by G. Altshuller et al. in 1946, and was based on the realisation that contradictions can be methodically resolved through the application of innovative solutions [87]. Over time TRIZ has evolved into a formalised process for creative problem solving, where a problem is solved by the application of a series of inventive principles; over the years this method has been adopted in a wide range of range of industries and disciplines from finance to engineering.

Design for X consists of a large subset of design practices, aimed at optimising a system or product's design to a particular task or objective. The 'X' can be replaced with a number of adjectives such as reliability; robustness; serviceability; environmental impact; or manufacturability [83].

3.2.3 Systems Engineering

The systems engineering approach is another noteworthy approach towards the design and development of products/systems. This approach is a high-level process methodology towards the design of systems, and can be described as "a technologically based interdisciplinary process to bring systems, products and structures into being". It is widely adopted in the design and development of complex systems across many industries (e.g. railways, automotive) and often makes use of some of the formal design methods described in the previous section.

Although the principals and objectives of systems engineering are reasonably well defined, the implementation can vary significantly in practice. As a result several frameworks have been developed over the years to improve communication and understanding of the systems engineering process, together with process models such as the

Waterfall; Spiral and Vee process models. The detailed investigation of systems engineering process is outside the scope of this thesis; however for further information on systems engineering and its application please refer to the work titled *Systems Engineering and Analysis* by B.S. Blanchard & W.J. Fabrycky [88].

3.3 HPS Design Methods Review

This section presents a review of the literature related to the design and development of hybrid power system hardware and control strategies. There are numerous techniques and approaches adopted in the design of HPS. These are typically based on quantitative and qualitative approaches to design, and generally fall into the following broad categories: **optimised trial and error** and **constraint based design optimisation**. It should be noted that this is by no means an exhaustive review of the work carried out in this area of research. Instead the following provides a overview of popular methods and approaches being used to tackle the challenges in designing and optimising hybrid power systems.

3.3.1 Optimised Trial and Error

This is an approach where multiple system configurations are evaluated to determine the most suitable configuration. Often these methods utilise popular optimisation techniques, discussed in section 3.5, to reduce design iterations and reach a suitable configuration. These methods generally utilise vast amounts of computing power to reach an optimal design solution, by evaluating many suboptimal solutions [89].

A. Kleimaier et al. [90] presents a method for designing and controlling a parallel hybrid vehicle using optimal control theory. The method utilises an off-line tool to simulate and analyse a powertrain's optimised behaviour and optimises the system operation strategy, control variables and fuel consumption via a trial and error method. Finally design data for vehicle components are extracted from the min/max values of vehicle component characteristics such as engine and motor speeds, power outputs and gear ratios.

B.A. Kalan et al. [40] outlines the development of a parallel hybrid vehicle comprising of an ICE; battery pack and super-capacitors. The system was based on a modified 'Holdern Commodore' a saloon car manufactured by 'GM Holdern Ltd'. A noteworthy point from this work was the capacity selection of the on-board energy storage devices and supervisory control strategy was done based on available hardware, rather than using a clear design approach.

Z. Rahman et al. [91] presents an approach in system design of a series hybrid heavy-duty transit bus. The paper describes a design process and validation exercise using a custom software tool named V-ELPH (developed in-house at the Texas A&M University). A noteworthy observation from this work was that the energy storage capacity was selected purely based on its ability to propel the vehicle in an all electric mode and not taking into account driving duty cycle or control strategy.

Ryan R. Rowe et al. [92] documented the process of converting a '2000 Chevrolet Suburban' Sport Utility Vehicle (SUV) to a parallel-hybrid vehicle. In this work, much like in many other 'conversion' projects, the power plant capacities were arbitrarily chosen based on cost or component availability rather than being optimised to maximise the vehicle performance.

Hongxing Yang et al. [93] presents a methodology for sizing system components of a hybrid solar-wind power generation system, based on recursive modelling of system components to generate various system configuration response plots for particular operating regimes (e.g. 24 hours or 12 hours of storage). It is worth noting, that like many model based selection techniques, this method involves a significant amount of system modelling and simulation.

M. Muselli et al. presented work looking at the design and sizing of engine-generator, battery pack and PV system for a hybrid-photovoltaic power generator system and supplied a case study of the system operating in Corsica (an island in the Mediterranean Sea). The method involved recursive simulation of various system configurations, taking into account total system cost and historical solar irradiation data to determine the most suitable configuration.

3.3.2 Constraint Based Design Optimisation

This utilises optimisation techniques to maximise or minimise a pre-determined criteria to reach an optimum design. Often these methods require detailed component and system models; utilise a vast amount of computing power; suffer from reaching local minima or maxima instead of global optimum solutions [37].

Mehrdad Ehsani et al. [94] describes work aimed at developing system design philosophies of electric hybrid vehicle propulsion systems, at the Department of Electrical Engineering at Texas A&M University. The process consists of first identifying system design constrains such as vehicle rated velocity; specified time to attain said velocity; maximum speed; acceptable maximum mass and physical dimensions together with powertrain specific variables as gear ratios; motor specifications; architectures and primary power plant technologies and characteristics. Next, characteristics of the load such as rolling resistance; aerodynamic drag; climbing resistance are quantified. Finally, based on commercially available hardware and design requirements, the vehicle drivetrain components and subsystems were selected.

Ryan Fellini et al. [95] outlines an optimisation method that starts by applying constraints to the design environment by specifying key performance requirements of the vehicle in question (similar to the previous method). Then uses popular optimisation methods (discussed further in section 3.5), together with leading software simulation tools, namely ADVISOR and TDES (reviewed in more detail in section 3.4) to compute an optimal system specification.

D. Assanis et al. [89] also presents an optimisation approach for hybrid electric propulsion systems similar to the ones described above, using ADVISOR and TDES with high resolution engine map models to find the most suitable engine size, battery pack and motor combination for minimum fuel consumption.

T. Markel et al. [96] addressed the task of energy storage device selection from a different angle. In their work looking at the design of a plug-in hybrid electric vehicle, they approached the task from a life-cycle/endurance and cost point of view. The capacity and technology (e.g. NiMH, Li-Ion or Lead-Acid) were selected based on each technology's discharge cycle rating and minimum required energy storage capacity to meet the vehicle's desired range (as this was to be a plug-in hybrid vehicle). In other work [97] [98] the component sizing and control strategy selection were carried out with the aid of custom optimisation tools and the ADVISOR vehicle simulator.

In another paper titled *Energy Storage System Requirements for Hybrid Fuel Cell Vehicles* [99] expanded on previous work exploring how fuel cell and battery choices can impact on efficiency, cost, vehicle mass and volume using the ADVISOR vehicle simulator.

Magnus Korpaas et al. [100] tackles the challenge of sizing energy storage devices for a wind power generator using a dynamic programming algorithm and spot pricing of electricity.

Tomas Markvart's work outlined in the paper titled *Sizing of Hybrid Photovoltaic-Wind Energy Systems* [101] refers to a simple method based combining meteorological data for solar and wind power for sizing system components. The solution utilises a simple graphical form using the photovoltaic (PV) and wind components as coordinates in a Cartesian plane and deduction to determine appropriate system characteristics.

3.4 Simulation Tools

From the literature review on design and development of HPS, it can be concluded that modelling and simulation play important roles in this process. This section provides a basic overview of popular simulation and design tools used in the design and development of hybrid drivetrains. Due to the relative maturity of hybrid drivetrains in the automotive sector, most of the following have origins or are mainly used in the automotive industry; however it should be noted that these tools can be adapted to be used in a wide range of applications.

3.4.1 ADVISOR

Development of the Advanced Vehicle Simulator (ADVISOR) was first started in 1994 at the National Renewable Energy Laboratory (NREL) and uses the MATLAB/Simulink modelling environment. It was developed for the US Department of Energy (DOE) as an analysis tool to assist in the development of hybrid electric vehicle technologies in conjunction with Ford, General Motors and Daimler-Chrysler. Its primary role is to highlight the system-level interactions of hybrid and electric vehicle components and their impacts on the vehicle performance and fuel economy [97].

3.4.2 V-ELPH

The V-ELPH application is a successor to the Electrically Peaking Hybrid (ELPH) application originally developed by Dr Mark Ehsani and others at the Applied Power Electronics Centre at the department of Electrical Engineering at Texas A&M University during the latter half of the 1990's. It is system level simulation and analysis package written using the MATLAB/Simulink modelling environment and is aimed at studying energy efficiency, fuel economy, vehicular emissions together with vehicle lifetime costs and control strategies of hybrid drivetrains [102].

3.4.3 SIMPLEV

SIMPle Electric Vehicle (SIMPLEV) simulator was originally developed during the development of the Simplified Federal Urban Driving Schedule (SFUDS) battery test cycle in conjunction with the DOE's Idaho National Laboratory (USA) in the early 1990's. The application is a DOS based application written using the BASIC programming language [103]. It is capable of simulating a wide range of vehicle architectures ranging in size from small purpose-built vehicles (e.g. golf carts) to railway locomotives and provides second-by-second predictions of powertrain component performance parameters over any user specified driving cycle in the time or displacement domain.

3.4.4 MARVEL

Developed by the Argonne National Laboratory (ANL) under a research and development programme funded by the DOE in the USA, MARVEL is a software package which was originally written in PL/I language and later converted to FORTRAN in the early 1990's. The application can identify the optimal combination of battery and ICE characteristics for different vehicle types and performance requirements based on life-cycle cost or fuel efficiency using component models and user selectable control strategies [104].

3.4.5 WARPSTAR

WARPSTAR (WARwick Powertrain Simulation Tool for ARchitectures) is a flexible powertrain simulation tool developed using MATLAB/Simulink modelling environment by the University of Warwick. This tool has been developed in collaboration with approx 50 partner companies over a period of time and brings together all currently known hybrid powertrain architectures, as well as conventional and pure electric vehicle powertrain architectures. The tool has been designed for use in a whole spectrum of vehicle types from passenger cars to heavy duty applications and uses models based on real components to ensure results are relevant in the real world [105].

3.4.6 Hybrid2

Developed by the University of Massachusetts and NREL in 1994 and was written using Microsoft™VisualBasic©. The application contains a library of component models which include wind and solar generators; ICE-generators and batteries. Apart from the usual energy related modelling capabilities, the tool is also capable of optimisation of system components and performing economic analysis of configurations [106].

3.4.7 Custom Simulators

Apart from the above examples, there are a multitude of simulation and modelling tools in existence around the world. These range from highly complex research tools to relatively simple applications designed for specific applications and purposes. The following sections outline two such tools which have been developed at the Centre for Rail Research and Education at the University of Birmingham, specifically for use in the railway industry.

MTS

The Muti-Train Simulator (MTS) was developed by Dr. Colin Goodman and others from the Traction Research Group of the University of Birmingham and its origins date back to the 1970's. The first version of the application was written in Fortran programming language, and has been ported to a number of programming languages over the years, while the most recent version utilises object oriented C++. The tool was primarily developed for the modelling of DC railway networks and over the years has been used by numerous companies such as British Rail, GEC and Hawker-Siddeley for both research and study contracts, while customised versions have been sold to clients such as LUL, BR, GEC, MTRC (Hong Kong), Atkins and Anasaldo [107].

STS

Developed by Dr Stuart Hillmansen at the University of Birmingham during the mid part of 2000's, the Single Train Simulator (STS) is a branch of the MTS tool described above. The tool was developed using the MATLAB/Simulink modelling environment and was developed specifically for evaluating energy and power consumption of electric and self-powered (e.g. diesel multiple units) railway vehicles [108] [109] [35].

3.5 Popular Optimisation Techniques

The task of optimisation can be described as the tuning of a system's parameters to maximise a particular output or goal. Within the domain of HPS, optimisation is generally encountered during the initial phase of design and development. The final optimisation result greatly contributes to the overall operation and efficiency of the final system. This section outlines the most popular optimisation techniques in use today, and discusses the advantages and disadvantages of each method.

3.5.1 Global Optimisation

There are several methods available to achieve optimised performance based on global optimal operating points. In general this approach is not directly applicable in the control of real-time systems. However, these techniques have been utilised with much success in the design and optimisation of HPS and as a tool for optimising advanced control strategies [110]. Programming approaches that can benefit from this type of optimisation in the scope of supervisory control are outlined below.

Linear programming is one such method. It can be defined as the exercise of maximising or minimising a linear function that is subject to linear constraints [111]. Tate and Boyd's [112] work in which they tackle the problem of maximising fuel efficiency as a non-linear convex optimisation problem can be used as an example of how this method can be applied to energy management in hybrid vehicles. The main limitation of this approach is the difficulty in applying it to a more sophisticated drivetrain.

Optimal control theory is to determine the control signals to a system that will cause a process to satisfy the physical constraints, and at the same time minimise or maximise some performance criterion [113]. An example of this approach is the energy management of a parallel hybrid drivetrain by Delpar et al [114]. The analytical nature of this approach makes it superior to others; however the variations that exist in hybrid drivetrains means it is not always applicable.

Dynamic programming is a strong contender for use in the optimal control of hybrid drivetrain applications. In this method a problem is divided into stages with a decision required at each *stage*; each of the stages has a number of valid *states* associated with it. A decision at one *stage* transforms one state into a *state* in the next stage. It should be noted that the decision for choosing the next state is *not* based on previous states or decisions, however the final stage must be solvable by itself [115]. An practical example of this method is the control strategy optimisation carried out by Len at al [116] of the power management of a hybrid electric truck.

Stochastic dynamic programming can be considered a subset of the above mentioned general dynamic programming methodology. In this case, if the decision making involved in choosing the next state in the controller is based on a probability function, this method is considered to be stochastic dynamic programming [115]. The complexity and relatively high computational overhead required for dynamic programming based solutions are regarded as the main drawbacks of this approach.

In the case of hybrid drivetrain design at present there is no single method or practice adopted. Instead, current design processors consist of many tools and methodologies, tailored for particular applications and goals. The following presents the most popular methods available to date and outlines the benefits and potential shortcomings of the various approaches. Due to the complex nature of the optimisation and design task at hand, all design tools rely on some form of simulation or modelling process to compute optimum design characteristics. In the automotive sector simulation software such as ADVISOR are commonplace while many other energy simulation and optimisation tools exist, tailored for particular applications [37].

The most straightforward approach to HPS design is using mathematical models to evaluate design criteria and constraints in an iterative process, where each possible configuration and system architecture is considered, until the most suitable configuration is obtained. In practice this approach is rather impractical due to the significant computational power and time required to perform such a task.

An improvement on this method is utilising optimisation algorithms such as gradient based optimisation algorithms, such as Sequential Quadratic Programming (SQP) to reduce the possible configurations and the number of overall iterations to compute a solution. However, the success of this approach relies heavily on the quality of gradient information used and the results are often multi-modal and impractical due to shortcomings or limitations of input models and data [89].

A further evolution of the above approach is the use of meta-models; namely simpler models derived from more complicated ones. The use of simpler models allow the computational cost and time to be eased, and a range of optimisation techniques and algorithms can be used to determine solutions [37]. Table 3.1 [37] gives a rough overview of the most popular algorithms in use at present in HPS design & optimisation.

3.6 Summary

Different types of hybrid power systems were reviewed, identifying key differences and features exhibited in the most popular types of HPS. Next the concept of 'design & development' was introduced, with backgrounds on the different types of design methods in use. The importance of standards and motives behind design processes was also discussed. The concept of systems engineering in the design of complex systems was introduced.

A review of the literature in hybrid power system design was provided, exploring

Algorithm	Advantages	Disadvantages
SQP	Best general purpose code. Very efficient on smooth problems	Requires accurate derivatives. Only finds local solutions
Trajectory	Deals with small scale noise more effectively	Requires derivatives. Slow convergence towards solution
Complex	Derivative free. Better chance of getting through local solutions and large noise	Starting points must be feasible. Stochastic in nature. Slow convergence towards solution.
DIRECT	Derivative free. Searches both locally and globally. No starting point or control parameters needed.	Lack of formal convergence criteria. Suitable for small number of variables.
SMO	Can be efficient. Can smooth out data. Provides insight to problem.	Often fails with multimodal problems. Suitable only for small number of design variables.

Table 3.1: Optimisation algorithms under study

current approaches in the specification of power sources and control strategies. Finally, popular simulation and modelling tools and techniques were described and discussed, concluding with a discussion of popular optimisation techniques used in the design and development of HPS.

Chapter 4

A Method for Power Source Sizing and Evaluation

The design of hybrid power systems as discussed in chapter 3, often involves highly complex design methods which are very labour intensive and time consuming exercises. Furthermore, these can be somewhat over complicated and unnecessary, in applications where the intended output duty cycle takes on a predictive, repetitive and quantifiable pattern, such as railway traction or some industrial processes.

This chapter introduces a method to aid in the selection of power sources and control strategies during the design phase of a hybrid power system. The aim of this method is the simplification of the design process for HPS that service relatively well defined duty cycles. The advantages of this approach over the popular methods in use are the significant reduction of complex iterative computation techniques, and the ability to make informed design decisions that aid in tuning a particular HPS to a given application.

This is followed by the introduction to a modelling methodology and application framework, which is used throughout this thesis to help quantify and evaluate the challenges faced in the design and optimisation of hybrid power systems. The simulation tools and models, which were developed as part of this work are explained in detail, and a simulation model of a hybrid power system is presented.

4.1 Approach Outline

The **Duty Cycle Constrained Selection** (DCCS) method is a qualitative approach to aid in the design of a hybrid power system, and is based on the premise that: *"the output duty cycle a hybrid power system is subjected to has the most significant impact on the overall system performance"*. By careful analysis of the intended application, and likely output duty cycle, it is possible to make decisions and specifications of the power sources of a HPS servicing the given application. This approach to HPS design can in some instances reduce or even eliminate the need for complex component modelling and computation intensive optimisation techniques (see chapter 7 for a comparison between a duty cycle driven optimisation design method and a trial and error based design method). The DCCS approach tackles the design problem of a hybrid drivetrain by dividing it into two fundamental steps:

- Output performance characterisation
- Hybrid power plant specification

In the first step the desired properties of the final drivetrain are evaluated. For an application in traction, this would relate to the vehicle acceleration and deceleration requirements; resistance to motion; route characteristics such as gradient and surface condition; other desirable vehicle characteristics such as top speed, mass and the proposed operating duty cycle. This first design step has many aspects in common with traditional single-source drivetrain design and is not within the scope of this work. It is suffice to say, the output performance characterisation of any application should be

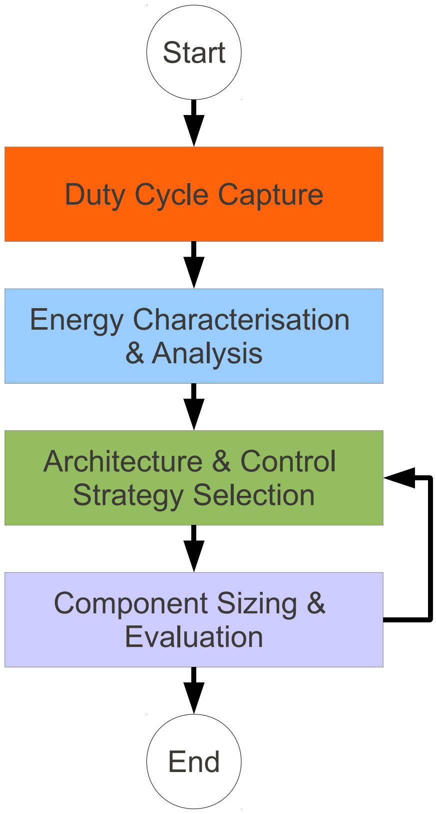


Figure 4.1: Generic block diagram outlining the DCCS method

done using the standard design methods in use, for further information on standard design practices please refer to section 3.3.

Once these operational specifications have been defined, the component specification and selection is tackled by means of a feed-backward approach, where the output power cycle of the intended application is analysed to determine key energy and power requirements the HSP must meet. This is followed by further analysis, to determine the most suitable control strategy; energy component sizes and desired performance characteristics of the power plants. The novel method proposed in this thesis is illustrated in figure 4.1, which shows a system block diagram of the DCCS method and the following sections expand the method in more detail.

4.1.1 Duty Cycle Capture

For the accuracy and effectiveness of this method as a design tool, the following fundamental requirements must be met, as the results of the method rely heavily on the load cycle of the target application:

1. The application must consist of a definable duty cycle. In other words, the output application and actual duty cycle must be made available to the designer to utilise this method. Furthermore, use of 'idealised' or heavily simplified output duty cycles will result in poorly matched results from this method.

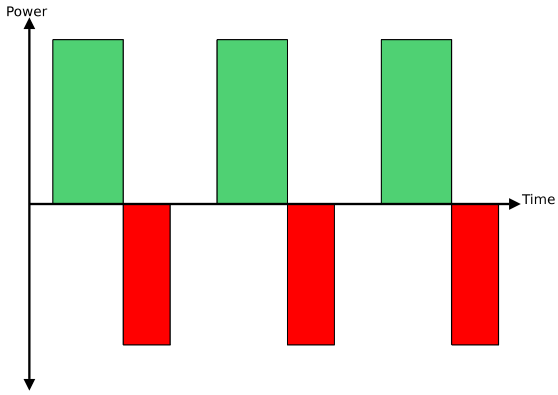
2. The duty cycle must be repeatable and ideally repetitive in nature. In other words, in order to utilise this method, the application duty cycle must be fixed or have a relatively low statistical variation over its operating life cycle. A good example of a suitable duty cycle would be a railway vehicle servicing a predetermined route, day in and day out. Furthermore, a poor or inappropriate duty cycle would be a typical automotive duty cycle where each journey can vary significantly from one another.

This information can be obtained either via simulation [117] (section 4.2), or instrumentation of an existing system. Figure 4.2(a) illustrates a generic power load cycle that the method uses as input data.

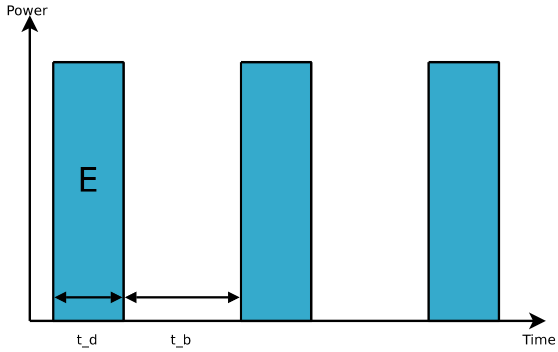
4.1.2 Energy Characterisation and Analysis

At the heart of the DCCS method lies the analysis of key output characteristics the hybrid power system must meet. In this step, these characteristics are extracted by means of the following key metrics:

- Positive/negative power flow to HPS:



(a) Generic Power Cycle



(b) Generic Powering/Regenerative Power Cycle

Figure 4.2: Power Cycle Profile

  - Energy content in sustained events
  - Duration of events
  - Delay between events

- Proportion of time the maximum power is required over the duty cycle
- Most common output power demand over the duty cycle

Powering and Regeneration Event Analysis

In this step, the positive and negative (regenerative) power events in an output duty cycle are separated and analysed separately. The duration (t_d), separation (t_b) and energy content (E) of each continuous event in each profile is obtained as shown in figure 4.2(b). Analysis of this information helps gain an insight into the frequency, and duration of the most common energy demands the HPS face, thus giving an invaluable insight into the nature of the applications duty cycle.

Maximum Sustained Power

A key feature of a HPS is its ability to supply an output power that is higher than its individual energy sources (separately). Analysis of the maximum sustained power provides an insight into the potential of downsizing the often costly, and more complex primary power plant, compared with a traditional single-source drivetrain. As the availability of combined power is directly proportional to the energy in on-board ESD, the sizing of the primary power plant must be done as to ensure adequate performance is maintainable.

Analysis of the positive power cycle derived above, allows the designer to gain an insight into the characteristics of the output power profile and determine the **proportion of time the maximum installed power is required** and the **most common power demand** for the duty cycle. These metrics can provide a good insight into any powering patterns, the applicability of any primary power plant downsizing and the sustained, continuous combined maximum power (P_{max}) requirement for the HPS.

4.1.3 Architecture and Control Strategy Selection

For this step, the characteristics obtained from the above step, together with the initial duty cycle, are used to make key design decisions related to the HPS architecture and supervisory control strategy.

Architecture

The first decision is the overall type of hybrid to be implemented; charge sustaining or plug-in hybrid. This dictates the underlining objective of the control strategy to be implemented and aids in determining the energy storage device to be used and its capacity. Decisions based on system architecture are often governed by the intended application and the desired output type (e.g. kinetic or electrical energy). However, analysis of the output power profiles can help tune the hybridability or energy mix ratio (equation 4.1) for the HPS.

$$\gamma_{mix} = \frac{E_s}{E_{pwr}} \tag{4.1}$$

Where γ_{mix} is the energy mix ratio, E_{pwr} is the average output energy of a powering event and E_s is the permissible average energy to be extracted from the energy storage device (equation 4.2).

$$E_s = \mu_{inout} \cdot E_{regen} \tag{4.2}$$

Where μ_{inout} is the energy storage device storage-recovery efficiency and E_{regen} is the average energy from negative (regenerative) power events. It should be noted for $\gamma_{mix} \longrightarrow 0$ values are most suitable for mild, load levelling or plug-in hybrids, while $\gamma_{mix} \longrightarrow 1 \gg$ values indicate a system that is suitable for the downsizing of the primary energy source.

Losses & Limitations

As with all practical systems there are losses associated that reduce the efficiency of any system from its theoretical limits. Some of these are attributed to frictional losses in various mechanical components such as clutches and gear boxes, while others are due to design decisions and practical limitations of a given technology.

In the example of a traction application, some of a vehicle's kinetic energy can be recovered via regenerative braking when decelerating. However, it should be noted that at very low and high speeds the amount of recoverable energy is limited, due to physical limitations in electric machines and drives.

Another requirement often encountered in traction applications is the need for a pre-

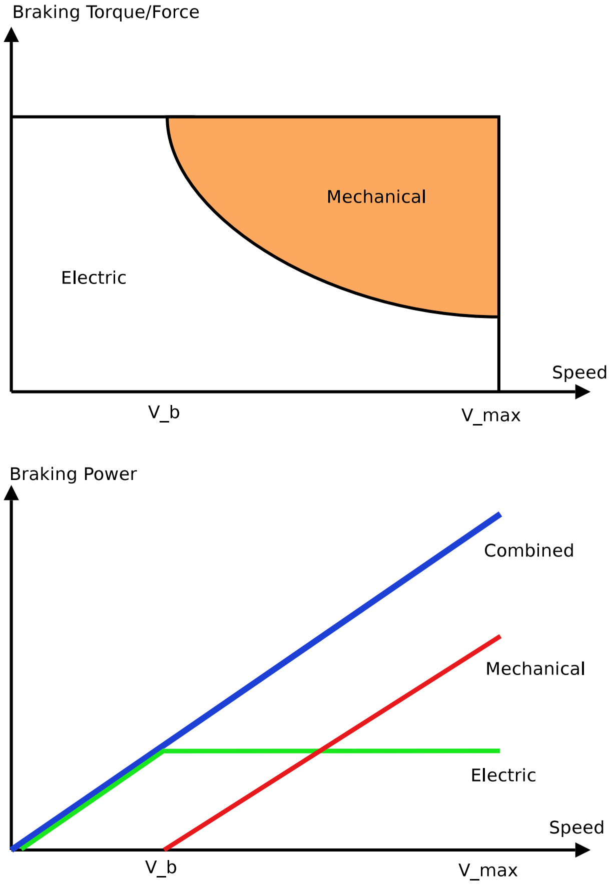


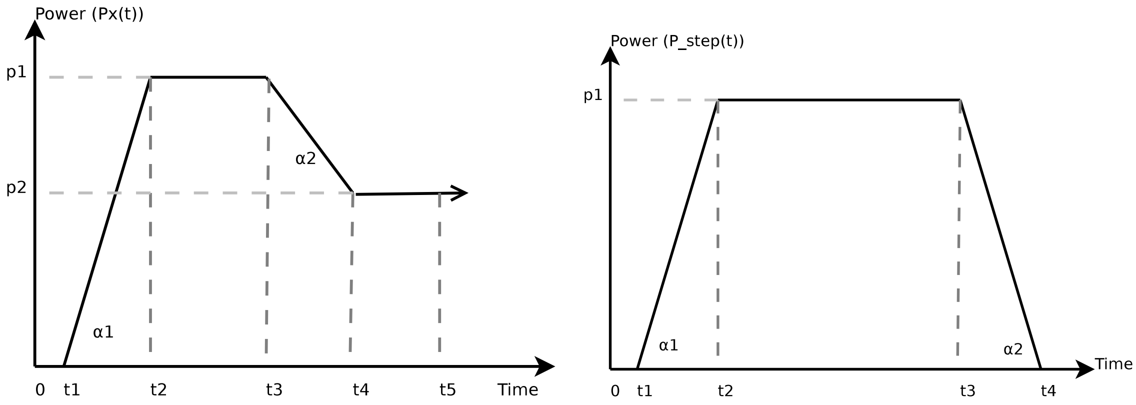
Figure 4.3: Braking effort and braking power profile of a railway vehicle which utilises both electric and friction braking

dictable deceleration characteristic for a vehicle. This is often achieved by providing a vehicle with the ability to generate a uniform braking effort, irrespective of the speed it is travelling. In vehicles powered by a HPS the energy split of electrical (regenerative) vs mechanical (friction) braking can be outlined as in figure 4.3. Not all the kinetic energy of a vehicle can be recovered via regeneration, especially at high speeds as the negative torque generated by a typical electric machine is often below the required deceleration requirement. Therefore some energy will be lost when aggressive deceleration is performed, and it is important to take into consideration this characteristic, especially when specifying electric machines for hybrid or electric applications where regeneration is desirable.

Control Strategy

It is possible to determine key characteristics of a suitable control strategy from the information obtained from the previous steps. This is achieved by defining a generic response $P_x(t)$ (figure 4.4(a), equation 4.3) for the primary and secondary power plants and tuning these responses to provide a step response $P_{step}(t)$ (figure 4.4(b), equation 4.4) of the hybrid drivetrain output power with similar characteristics to the average response outlined in the previous sections.

$$P_x(t) = \begin{cases} 0 & 0 \leq t < t_1 \\ \frac{p_1}{t_2 - t_1} t - \frac{p_1 t_1}{t_2 - t_1} & t_1 \leq t < t_2 \\ p_1 & t_2 \leq t < t_3 \\ \frac{p_2 - p_1}{t_4 - t_3} t + \frac{p_2 t_3 - p_1 t_4}{t_3 - t_4} & t_3 \leq t < t_4 \\ p_2 & t_3 \leq t < t_5 \\ 0 & t_5 \leq t < \infty \end{cases} \tag{4.3}$$



(a) Generic Power Response (b) Power Step Response

Figure 4.4: Generic Power Profiles

$$P_{step}(t) = \begin{cases} 0 & 0 \leq t < t_1 \\ \frac{p_1}{t_1} t & t_1 \leq t < t_2 \\ p_1 & t_2 \leq t < t_3 \\ \frac{p_1}{t_3 - t_4} t - \frac{p_1 t_4}{t_3 - t_4} & t_3 \leq t < t_4 \\ 0 & t_4 \leq t < \infty \end{cases} \tag{4.4}$$

Where p_1 and p_2 are power demands and t_1,t_2,t_3,t_4 and t_5 are the times (relative to zero) at which particular events are triggered. Any successful hybrid drivetrain control strategy must therefore meet the requirements outlined in equations 4.5 and 4.6. Where the output response of the primary and secondary energy devices are $P_p(t)$ and $P_s(t)$ for a step response $P_{step}(t)$.

$$P_{step}(t) = P_p(t) + P_s(t) \tag{4.5}$$

$$\int_0^\infty P_{step}(t) \cdot dt = \int_0^\infty P_p(t) \cdot dt + \int_0^\infty P_s(t) \cdot dt \tag{4.6}$$

$$E_{step} = E_p + E_s \tag{4.7}$$

For charge sustaining, simple mild hybrids $E_s = E_s^{'}$ (from equation 4.2), while for charge sustaining hybrids that use the primary power plant to top up the energy storage device, $E_s > E_s^{'}$. However;

$$\Delta E_s = E_s - E_s^{'}$$

$$\Delta E_s \leq \int_0^{t^{'}} P_p(t) \cdot dt$$

Where, $t^{'} = t_{b(p)} - t_{d(s)}$. Given $t_{b(p)}$ is the average delay between powering events and $t_{d(s)}$ is the average duration of a regenerative power event. Finally for events where;

$$\Delta E_s > \int_0^{t^{'}} P_p(t) \cdot dt$$

the drivetrain must be a plug-in hybrid.

Technology

Based on the requirements that have been specified so far, the design process must identify the technologies to be used as the primary and secondary energy components. This decision must take into account the desired power gradients ($\frac{dp}{dt}$) from the primary and secondary devices; cyclic loading and applicability of the chosen technology; acceptable weight and volume of power plants; maintenance and service life of system components. These parameters are most relevant for the secondary power plant or energy storage devices.

4.1.4 Component Sizing and Evaluation

The final step in this method is the specification of the remaining aspects and components of the hybrid drivetrain.

Primary Power Plant

The most appropriate maximum sustained primary source power ($P_{p,max}$) is affected by the fundamental hybrid architecture (plug-in hybrid, etc.), and control strategy in place. For designs that utilise no primary downsizing it is safe to assume that $P_{p,max} = P_{max}$; however for drivetrains that benefit from the primary energy source downsizing this relationship becomes more complicated (see equation 4.8)

$$P_{p,max} = P_{max} - P_{s,max} \tag{4.8}$$

Where $P_{s,max}$ is the maximum sustained power available from the secondary source (i.e. storage device). The exact value of this can be obtained by trial and error as choosing a value too small could lead to poor performance of the hybrid drivetrain.

Secondary Power Plant

This is typically an energy storage device. The capacity (C_{ESD}) of the energy storage device is determined by using equation 4.9.

$$C_{ESD} = \frac{\Delta E}{\Delta SOC} \cdot f_f \tag{4.9}$$

Where ΔE is the mean energy extracted from the storage device in the duty cycle, ΔSOC is the maximum acceptable SOC swing for the energy storage device (this is determined from the operational characteristics of the chosen storage technology) and

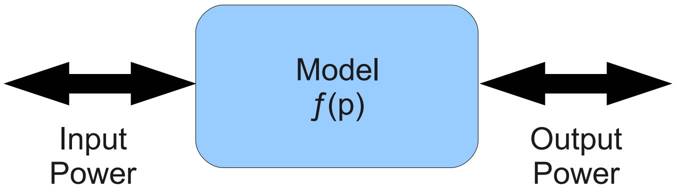
f_f is a unit-less coefficient used to fine tune the capacity value. This is necessary as, while the raw method provides a 'minimum' ESD capacity value, it is important to evaluate the effect of tuning the capacity to identify if a slightly larger or smaller value may yield a significant improvement in overall system performance. Furthermore, it should be noted that this value can be determined by further simulation of the hybrid energy drive (section 4.2). For an example of this please refer to the case study in chapter 5.

Tertiary Power Plant

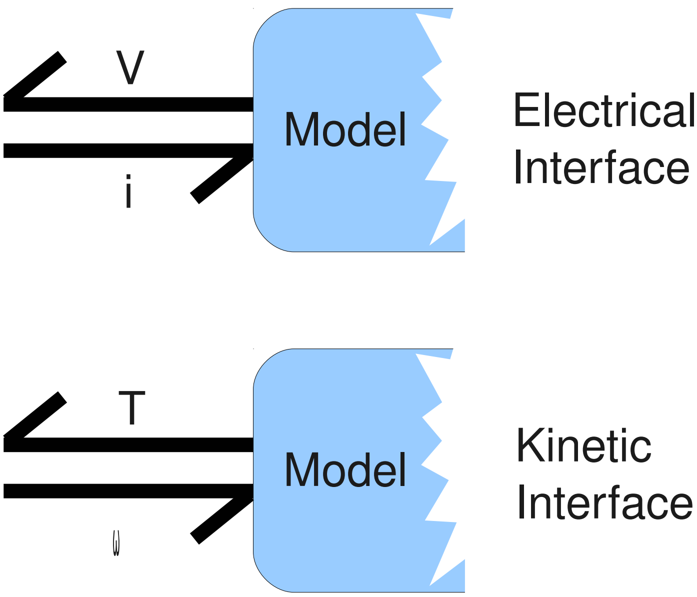
In the scope of this work the tertiary power plant has been assumed to be a resistor bank, used to dissipate excess energy in the HPS. Therefore it is necessary to understand the energy dissipation requirements of the application duty cycle to choose a suitable size for the braking resistors in a highly optimised system.

4.2 Modelling Methodology

In order to understand how different hardware configurations; component technologies; output applications; control strategies; affect a given HPS, it is necessary to have a means of evaluating the affects these have on a given system. The complex nature of HPS, and the significant time and cost associated with building test systems for evaluation purposes mean that experimentation using physical hardware was not a practical option. Therefore, it was decided that the evaluation of different hybrid drivetrains would be done via software based device modelling and simulation.



(a) Generic Power Model Block Showing Input and Output Power Flow



(b) Illusration of an Electrical and Mechanical (Kinetic) Power Model Interface

Figure 4.5: Power Flow Model Blocks

4.2.1 Power Flow Modelling

For this purpose a highly flexible simulation tool was developed using Microsoft® C#, which allowed the author to evaluate the impact different parameters have on the performance of a given HPS. The fundamental basis of the evaluation tool is the modelling of power flowing through a given system. Figure 4.5(a) illustrates a generic 'power model block' and outlines the input/output power flow in the model. The behaviour of the output power can be described by equation 4.10. Where P_{output} is the output power, P_{input} is the input power and $f(p)$ is the transfer function of the model.

$$P_{output} = f(P_{input}) \tag{4.10}$$

In any system that involves the transfer of power, the physical properties of the power are dependent on the type of energy being transferred. Using an electric machine as an example, the total electrical energy delivered to the device is a product of the current and voltage supplied to the input, while the total kinetic energy obtained by the device is a product of the torque and angular velocity of the rotator. The modelling method described above utilises kinetic and electrical energy based power model interfaces, as illustrated in figure 4.5(b). Furthermore the relationship between these system parameters can be outlined using equation 4.11. Where P is power, T is torque, ω is angular velocity, I is current and V is voltage. These two types of interfaces were chosen due to their relevance in hybrid power systems and particularly in the case studies discussed in section 4.4.

$$P = T\omega = IV \tag{4.11}$$

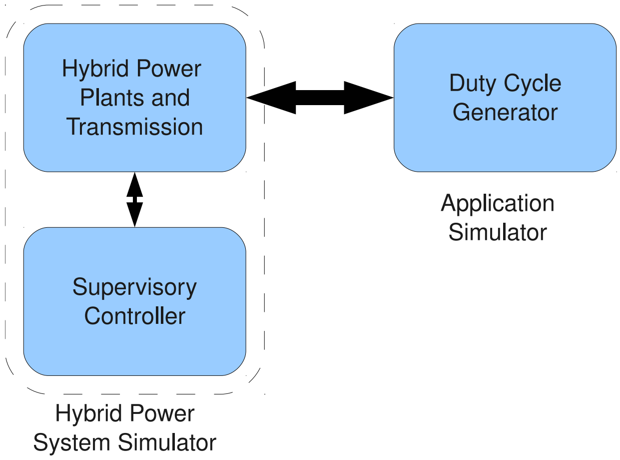


Figure 4.6: Block Diagram of The Hybrid Drivetrain Evaluation Tool

4.2.2 Simulation Tool

Using the fundamental building blocks described in the previous section, the 'Hybrid Drivetrain Evaluation Tool' or HDET outlined in figure 4.6 was developed. The inner-workings of the 'Hybrid Power System Simulator' are covered in more detail in section 4.3.

The 'Duty Cycle Generator' block consists of a simulator tailored to the application being considered (e.g. railway vehicle), and varies from application to application. An example of such a 'duty cycle generator' block can be found in section 7.2. To evaluate HPS performance using real world datasets, a 'Static Power Profiler' (SPP) block was created. This provided a means of interfacing a pre-determined static power vs time profile with a dynamic model of a HPS. The model/simulator takes an input data file with specific time and power datum, and generates a dynamic power demand for the simulated HPS. For an example of when the SPP is utilised please refer to chapter 5.

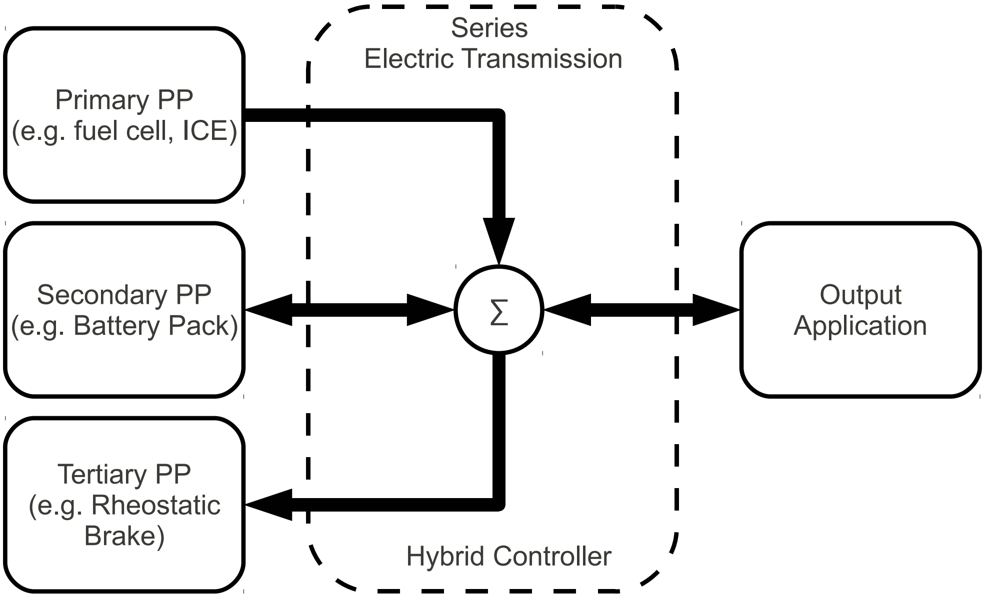


Figure 4.7: Block Diagram of The Hybrid Power System Simulator

4.3 Hybrid Power System Simulator

As all of the case studies (covered in chapters 5, 6 and 7) consisting of electrical energy based power plants, it was decided to base the Hybrid Power System Simulator (HPSS) on a series-hybrid system architecture discussed in chapter 2, and consists of the following models:

- Primary Power Plant Model (e.g. fuel cell stack, internal combustion engine)
- Secondary Power Plant Model (e.g. battery pack)
- Tertiary Power Plant Model (e.g. Rheostatic brake)
- Hybrid Controller Model (i.e. the overall control of the individual energy components and the practical implementation of the supervisory control strategy is handled by this model)

The total power output from the HPS can be represented by equation 4.12. Where $P_{total}(t)$ is the total power output of the hybrid power system, and $P_{Primary}(t)$, $P_{Secondary}(t)$

and $P_{Tertiary}(t)$ are the power output from primary, secondary and tertiary power plants respectively. It should be noted that these values are dependant on the individual models' internal parameters and vary with the state of each model over the course of the simulation.

$$P_{total}(t) = P_{Primary}(t) + P_{Secondary}(t) + P_{Tertiary}(t) \tag{4.12}$$

The following sections outline the various subsystem models and components developed for the HPSS and used in this thesis. It should be noted that the behaviour of the various device models such as primary power plants (e.g. fuel cell stack) and secondary power plants (e.g. battery packs), power converters and motors are all modelled in the power domain and make use of efficiency maps obtained from existing literature. For further information on the tool please refer to appendix B.

4.3.1 Power Converter

The power converter model is a rudimentary power flow model of a dc/dc or dc/ac converter. The model utilises a typically representative efficiency map (figure 4.8) of a power converter to determine its output power given a specific input power value.

4.3.2 Fuel Cell Stack

For the use in the case study discussed in chapter 7, a PEMFC was modelled. In order to operate a fuel cell system at a high efficiency, the fuel flowing into the stack must change in-line with the output power of the fuel cell stack. This is primarily due to the relationship between stack power and the fuel flowing through the cells at any given moment. However, in practice the response of a fuel cell system is constrained by the response times of the external pumps, compressors and control loops that govern

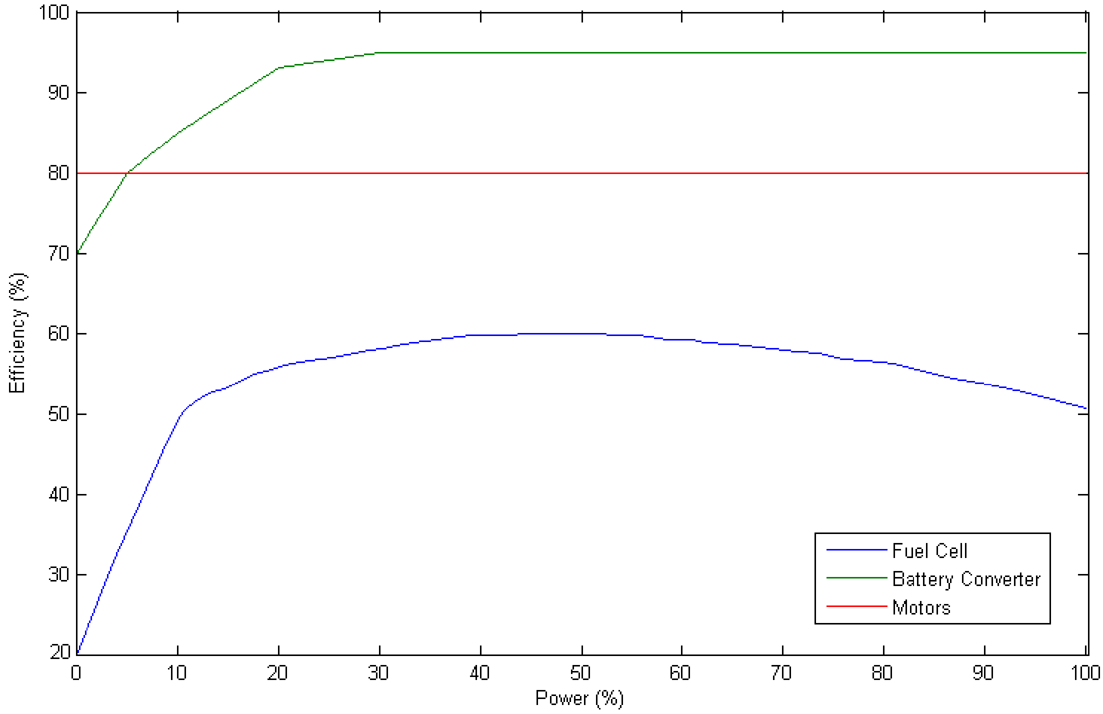


Figure 4.8: Normalised Output Power vs. Efficiency

Fuel Cell Type	Proton Exchange Membrane
Voltage at P_{max} ($V_{P_{max}}$)	$0.41\ V$
Current density at P_{max} ($i_{P_{max}}$)	$1.49\ Acm^{-2}$
Number of cells in stack (n_{cells})	800
H_2 and O_2 utilisation ratios (U_{H_2}, U_{O_2})	1.0
Mola mass of H_2 (M_H)	$1.00794\ gmol^{-1}$
Mola mass of O_2 (M_O)	$15.0004\ gmol^{-1}$

Table 4.1: Fuel Cell Model Configuration

the operation of the overall system [118]. Therefore the accurate dynamic modelling (electrical) of a fuel cell system can be complex.

The in-depth modelling of a fuel cell system is beyond the scope of this work. Instead, a static model of a PEMFC was developed, with the properties outlined in table 4.1 from the literature [118] [57]. To improve the dynamic response of the model, the following assumptions and constrains were enforced on the model:

- The rated model output power relates to the output power at the DC link (in a series-hybrid architecture) or transmission of the HPS (thus encompassing the dc/dc converter, fuel cell stack and all its sub systems).
- The output power of the overall fuel cell model cannot be altered instantaneously. Instead, an increase or decrease in output power is limited by a predetermined rate of change ($\frac{dp}{dt}$) and cannot exceed a predetermined output power.
- In all cases the time taken for the fuel cell system to reach its maximum output power is $30s$.
- The above mentioned maximum power of the fuel cell stack is obtained by varying the active area of the cells within the stack, and calculated with the aid of equation 4.13.
- The fuel cell stack output power is determined by a power-efficiency curve [57] (figure 4.8).
- A voltage-current density curve (figure 4.9) is used to determine the cell output voltage.
- The fuel consumption (F_{H_2}), in this case H_2 is obtained with the aid of equations 4.14 and 4.15 [119].

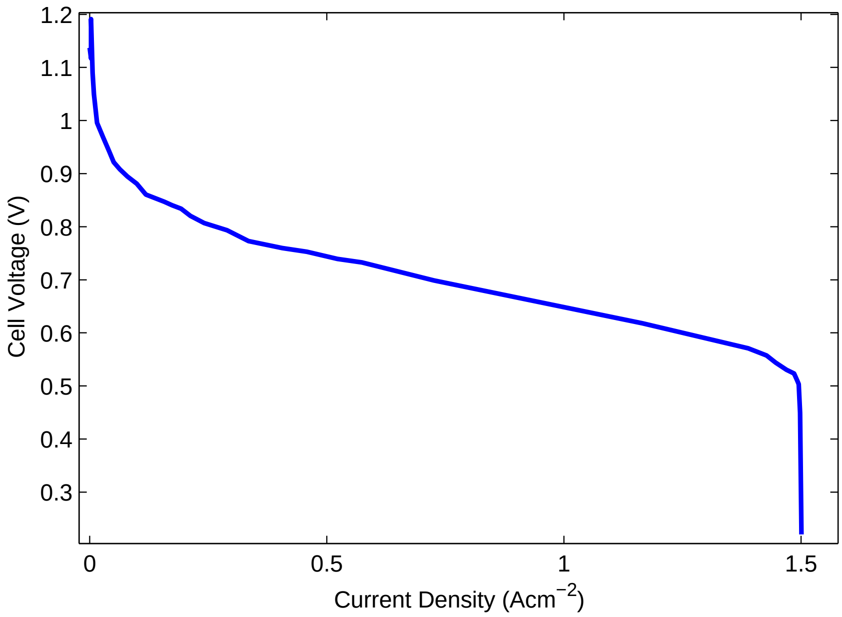


Figure 4.9: Fuel Cell Voltage vs. Current Density

$$ActiveArea = \frac{P_{max}}{n_{cells} V_{P_{max}} i_{P_{max}}} \tag{4.13}$$

$$q_{H_2} = M_{H_2} \frac{nI_{FC}}{2F}, q_{O_2} = M_{O_2} \frac{nI_{FC}}{4F} \tag{4.14}$$

$$F_{H_2} = \frac{n_{cells}}{U_{H_2}} \int q_{H_2} \cdot dt, F_{O_2} = \frac{n_{cells}}{U_{O_2}} \int q_{O_2} \cdot dt \tag{4.15}$$

Where q_{H_2} is the hydrogen consumption rate, M_{H_2} and M_{O_2} is the molar mass of hydrogen and oxygen dioxide, n is number of atoms, I_{FC} is the current flowing through the stack, F is Faraday's constant $(96,450\ Cmol^{-1})$, F_{H_2} and F_{O_2} is the total hydrogen and oxygen consumed, n_{cells} is the total number of cells in the stack, U_{H_2} and U_{O_2} are the utilisation ratios of hydrogen and oxygen dioxide.

Type	NiCd
Specific Energy	$55.0\ Whkg^{-1}$
Specific Power	$120.0\ Wkg^{-1}$
Pack OC Voltage	$300\ V$
Capacity per Pack	$100\ Ah$
Initial SOC	55%
SOC_{Min}	20%
SOC_{Max}	80%
SOC_{Topup}	30%

Table 4.2: Battery Model Configuration

4.3.3 National Grid

The case study presented in chapter 6, involves a HPS that is connected to a national electricity network also referred to as a 'National Grid'. Therefore a national grid model based on the power converter model described in section 4.3.1 was developed. It should be noted that unlike the original power converter model, the national grid mode was assumed to have an efficiency of 100%, thus not taking into account any losses at the point of delivery to the external power network.

4.3.4 Battery Pack

For use in the case studies presented in this thesis, particularly in chapter 7, a battery model based on a $300V$, $100Ah$ NiCd battery pack was developed. The properties of the simulated battery pack are represented in table 4.2 and have been sourced from the literature [120]. For the purpose of this work the following assumptions and constrains are applied to the operation of the battery pack:

- The model output relates to the output power at the DC link or transmission of the HPS.
- The output power of the overall system cannot be altered instantaneously. Instead

	Providing Power (discharging)	Accepting Power (charging)
Positive Gradient (MWs^{-1})	1.0	1.0
Negative Gradient (MWs^{-1})	1.0	1.0
Maximum Power (kW)	500.0	500.0

Table 4.3: Battery Power Limits

an increase or decrease in output power is limited by a predetermined rate of change and power (table 4.3).

- The SOC of the battery pack is calculated with the aid of equation 4.18.
- The efficiency of the battery pack is effected by the efficiency-power response curve of the dc/dc converter (figure 4.8).

$$P_{battery} = \frac{P_{out}}{\mu_{\Delta t}} \tag{4.16}$$

$$\Delta SOC = \frac{\Delta E_{\Delta t}}{E_{total}} = \frac{P_{battery}\Delta t}{VC} \tag{4.17}$$

$$SOC = SOC_{initial} + \int \Delta SOC \cdot dt \tag{4.18}$$

Where, ΔSOC is the change in SOC, $\Delta E_{\Delta t}$ is change in energy in unit time Δt, E_{total} is total energy capacity of battery, $P_{battery}$ is power flow, Δt is unit time step, V is voltage of the pack and C is the combined capacity (Ah) of the battery packs, P_{out} is output power of complete battery system (including power converters), $\mu_{\Delta t}$ is efficiency.

Type	Electric Brake
Maximum Acceptable Power	$500.0kW$

Table 4.4: Electric Brake Model Configuration

4.3.5 Rheostatic Brake

As previously mentioned in section 2.3.2, the tertiary power plant in all the HPS referred to in this thesis consists of a resistive power dissipation device (i.e. rheostatic brake). The main reason for selecting this type of device is to allow a sink for excess power during the simulation and evaluation of a particular HPS configuration. An example of such a situation is dissipating regenerative braking energy when the energy storage devices of HPS cannot accept the energy due to over charging as shown in chapter 7. Furthermore, to simplify the modelling and system specifications of the HPS investigated in this work, the rheostatic brake model was developed with the following assumptions and constrains:

- The brake can accept any power demand up to a predetermined limit (table 4.4)
- It can dissipate the accepted power with no performance limitations for any period of time (i.e. performance of brakes do not degrade with prolonged use)

4.3.6 Hybrid Controller

The dynamic behaviour of the simulated HPS is achieved by means of power flow modelling of the subsystems outlined above. The output of these subsystems is managed using a 'hybrid controller' which utilises predefined supervisory control strategies to supply power to the output application of the HPS.

There are many different approaches to supervisory control in HPS, for a more in-depth review of the different types and approaches please refer to the work by Farzad

Rajaei Salmasi [38] where a broad overview of control strategies for hybrid electric vehicles is presented. The following rule-based control strategies were used as part of the HPS supervisory control system in the case studies presented in this thesis. These are mainly based on very popular control strategies presented in the literature on control of hybrid power systems.

LL-CS: Is a **L**oad **L**evelling **C**ontrol **S**trategy based on a simple rule based system, where output power is provided by the primary power plant, while the secondary power plant is used to supplement the peak power demand and absorb braking energy.

TC-CS: Is a **T**rickle **C**harge **C**ontrol **S**trategy, the secondary power plant provides the output power, while absorbing the braking energy and relies on a rule based decision making process similar to the LL-CS. In this the primary power plant operates at its highest efficiency point when the hybrid power plant is providing power (e.g. in a traction application when accelerating, maintaining vehicle speed or stationary e.g, idling). When absorbing power (e.g. in a traction application when deceleration is taking place) the primary power plant is switched off.

MLL-CS: Is a **M**odified **L**oad **L**evelling **C**ontrol **S**trategy. Very similar in nature to the LL-SC, the main difference being that output power is initially sourced solely from the secondary power plant for a pre-set time (T_{delay}) before the primary power plant is activated.

PS-CS: Is a **P**eak **S**having **C**ontrol **S**trategy. Its operation is based on using the primary power plant to supply power up to a predetermined threshold, once the power demand exceeds the pre-set threshold the secondary power plant is used to provide the excess power.

LSPP-CS: Is a **L**imited **S**econdary **P**ower **P**lant **C**ontrol **S**trategy. In this type of control strategy, the primary power plant is disabled and the hybrid power system uses the energy stored in the secondary power plant to deliver power to the output application. In the event of depleting the energy reserve in the energy storage device the system output is disabled until the storage device energy has been replenished.

It is assumed that in most instances the secondary power plant will be some form of ESD(Energy Storage Device). Furthermore, it should be noted the above control strategies are only used while the ESD state of charge remains within its safe operating limits (SOC_{Min} and SOC_{Max}) outlined in table 4.2. Should the state of charge drop below a pre-set threshold (SOC_{Topup}), the controller will attempt to top-up the ESD via the primary power plant with a charging power equal to the ESD capacity (e.g. 30kW power charge for a battery pack of 30kWh capacity). In this mode of operation the output power is sourced from the primary power plant. Once the ESD reaches a state of charge of 50% the selected control strategy operation resumes. Likewise, in the event of the ESD reaching the upper limit of the allowed state of charge (SOC_{max}), the controller will switch the primary power plant completely off, and output power will be drawn from the ESD, until the ESD state of charge reaches 50%, at which point the selected control strategy operation will resume. In any of the above cases if the ESD is not capable of absorbing the required energy the excess energy will be diverted to the tertiary power plant; typically a resistive load as described in section 4.3.5.

4.4 Introduction to Case Studies

The following sections provide a brief overview of the three case studies presented in chapters 5, 6 and 7 of this thesis, where the power source sizing and evaluation method described in section 4.1 is used to determine the characteristics of the power sources and controls strategies of HPS.

It should be noted that there are many different applications which are suitable as case studies for use in this thesis. The following specific applications outlined below were selected, due to a combination of them meeting the previously stated prerequisites for the DCCS method (section 4.1.1) and the availability of suitable datasets to carry out the necessary analysis. Finally, it is worth pointing out that the case studies have been presented as self contained pieces of work, presenting a brief outline of the target application, application of the design method and followed by a discussion of results and key findings and conclusions.

4.4.1 Hybrid-Power Generation System

In this chapter a hybrid power system that comprises of a wind turbine and an energy storage device to generate a fixed, continuous output power. The main aim is to reduce the discontinuous and often uneven nature of generated power from a typical wind turbine. While the selected application and analysis work maybe simplistic in nature, it provides a good and simple opportunity to present the application of the DCCS method.

4.4.2 Hybrid-Power and a Commuter Rail Network

The case study investigates the effects of powering a commuter railway network via a hybrid power system consisting of a wind farm, energy storage device and the national electricity grid. While this case study can be described as a progression of the previous case study, it is intended to increase the complexity in the analysis performed of the output power profile of the HPS during the application of the DCCS method.

4.4.3 Fuel Cell Hybrid Railway Vehicle

The final case study presented in this thesis and the most in-depth, is based on the design and evaluation of a fuel cell-battery hybrid railway vehicle based on a Class 150 Diesel Multiple Unit. In this case study two methods for component sizing of the hybrid power system are investigated side by side, while giving details of the overall performance, efficiency and fuel consumption of the vehicle.

Furthermore it should be noted that some of this work and analysis was presented at the Eleventh Grove Fuel Cell Symposium 2009 and has been accepted for publication in the Journal of Power Sources [121].

4.5 Summary

A method to aid in the selection of power sources and control strategies during the design phase of a HPS was presented, giving details of the individual steps that make up the method. Namely duty cycle capture; energy characterisation and analysis; architecture and control strategy selection; component sizing and evaluation.

Next a modelling methodology and application framework, which is used in the case studies presented in this thesis to help quantify and evaluate the challenges faced in the design and optimisation of hybrid power systems was presented. The simulation tools and models which were developed as part of this work were explained in detail, and a simulation model of a hybrid power system was presented. Finally a brief overview of the next three chapters (5, 6 and 7) was presented commenting on the rationale behind the selection of the case studies.

Chapter 5

Case Study : Hybrid-Wind Power Generation System

Wind powered electricity generation has grown significantly in recent years. In the UK this trend has been driven by government and European targets [10] [11] together with the increasing environmental concerns that traditional fossil fuel based generation technologies pose [6].

One of the biggest challenges in generating power from renewable sources such as wind compared with traditional power plants, is the generated power is largely dependant on the resource (i.e. wind, tides, sun) rather than the power demand at a given moment. This mismatch between generation and demand leads to the possibility that power generation may not always occur during required periods (i.e. solar power generation is lowest during the winter months when electricity demand is at its highest levels) [122]. Therefore investment in excess generation capacity is required, to ensure power network performance for periods when the power from renewable sources falls short of demand.

Another drawback of the discontinuous and unpredictable nature of wind based electricity generation is, as the proportion of installed wind power in an electricity grid increases, the potential for complications posed by the generation-demand mismatch must be addressed. Furthermore as micro level electricity generation becomes more popular via more affordable domestic wind turbines and photovoltaic technologies; the practice of selling excess power to national electricity grids via feed-in tariffs becomes more widespread, the difficulty in maintaining grid performance will increase further [123].

In recent years much debate has taken place on the effects of energy storage in wind power generation. The motivation behind this trend includes the stabilisation of network voltage and frequency and load regulation (reactive, active power component smoothing) [124] [125]; energy arbitrage in short-term energy markets [126]; aid in continuous power generation in locations with turbulent or highly intermittent wind resources; increasing efficiency and performance of wind diesel generation systems [127]; alternatives to grid reinforcement in remote generation sites and smoothing variations in power production in intermittent generation resources [128]. Furthermore, there are many storage technologies being developed to cater for hybrid-wind applications which include pumped-hydro, molten salt batteries, compressed air storage [129], flywheel storage [130], superconducting magnetic energy storage [131] and super-capacitor [132] and biomass [133] based storage technologies.

In this chapter the power generation data of an existing wind turbine is used, to gain an understanding of the generation characteristics and performance specifications for an energy storage device, used to reduce the discontinuous nature of a typical wind turbine generator. Finally a suitable hybrid system and control strategy is proposed with the aid of the DCCS design method, and its performance evaluated via the Hybrid Drivetrain Evaluation Tool outlined in chapter 4.

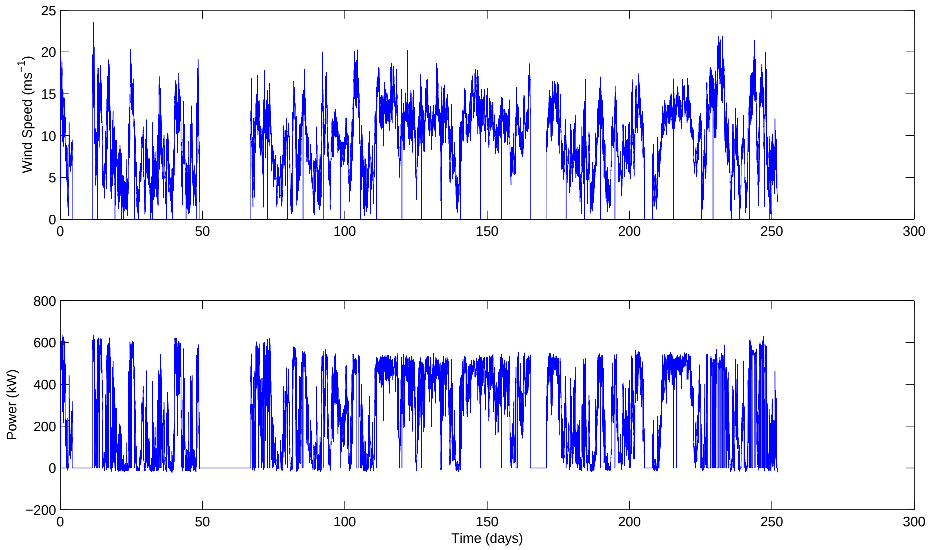
Rotor diameter	44.0 m
Rotor speed	18rpm / 27rpm
Rotor concept	3 blades without coning, tilt=$4°$, upwind
Power regulation	Stall regulation, tip angle=$0°$
Electrical power	Nominal 600/120kW
Hub height	40m
Tower	39.375m, conical tubular steel towers

Table 5.1: Technical specifications of BONUS 600kW Mk IV Wind Turbine

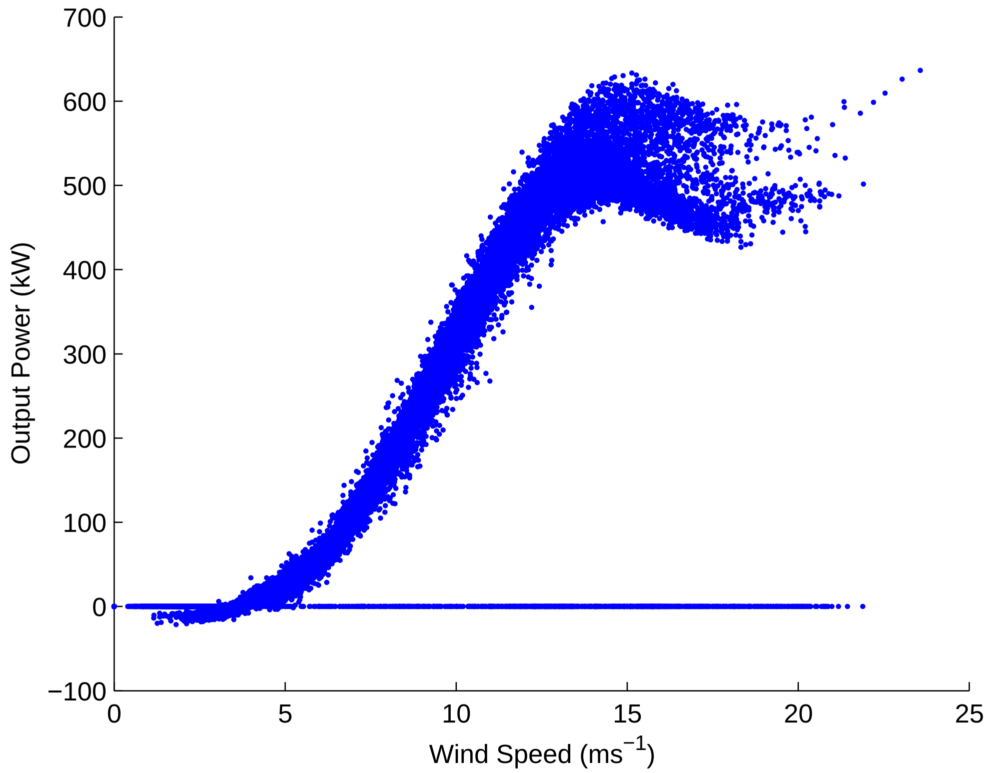
5.1 Wind Power Generation

For the scope of this work power data (figure 5.1) generated by a BONUS $600kW$ wind turbine installed at Modi in Crete [134] was used. The data corresponds to a period starting from the 26^{th} of December for 251 days (approximately 8 months). The periods of zero wind speed and turbine output power correspond to periods when the turbine was out of service, due to either harsh wind conditions or equipment failure. As these discrepancies are typical with this method of energy generation these 'down time' periods have been included in the study to obtain the most realistic generation duty-cycle from wind energy.

Analysis of the generation profile in figure 5.1(a) provides the turbine characteristic outlined in figure 5.1(b). Inspection of the response curve shows that there is significant variation at high wind speeds between generated power. This is likely due to the power data being averaged values over 10 minute periods of time. Furthermore, at lower wind speeds the turbines are seen to actually consume energy.



(a) Wind Speed and Output Power over a 8 month period



(b) Wind Turbine Output Characteristics

Figure 5.1: Data from a BONUS 600kW Wind Turbine

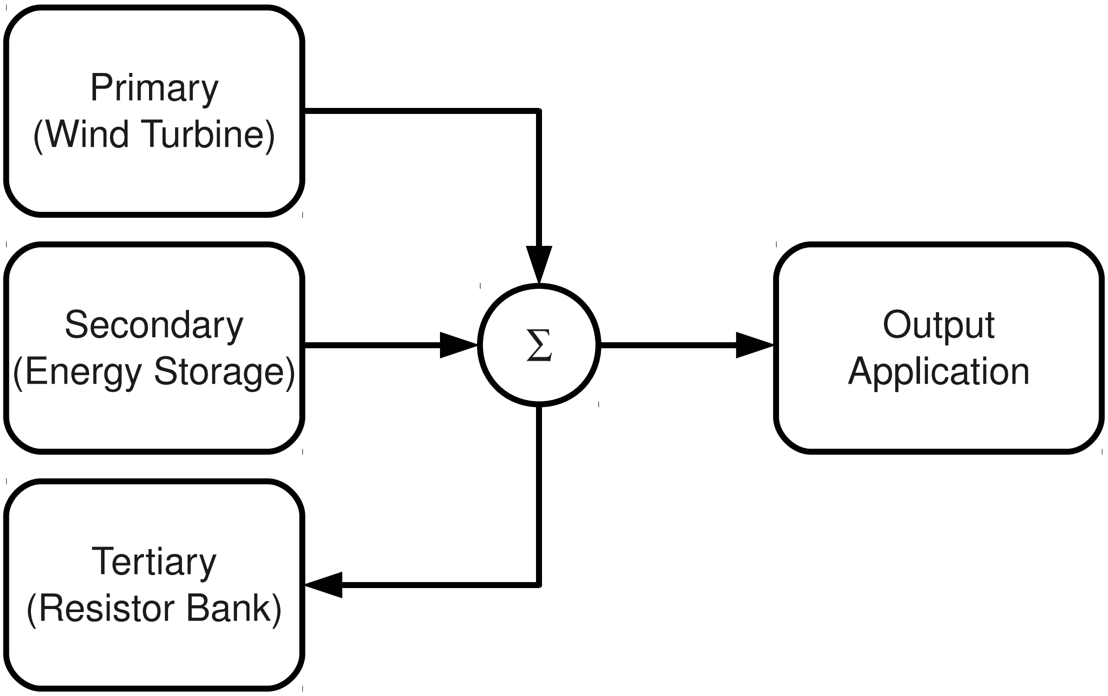


Figure 5.2: Proposed Hybrid Wind Power Plant

5.2 Hybrid Power System Design

$$P_{Hybrid} = P_{ESD}(t) + P_{Res}(t) = 230kW - P_{Wind}(t) \quad (5.1)$$

The objective of this work is the design of a HPS capable of smoothing the discrete and unpredictable nature of wind power generation by integrating a wind turbine with energy storage to produce a hybrid power plant with the topology outlined in figure 5.2. With the aid of equation 5.2, the relationship between the various components of the proposed hybrid wind power plant can be evaluated.

$$P_{Out}(t) = P_{Wind}(t) + P_{ESD}(t) + P_{Res}(t) \quad (5.2)$$

Where $P_{Wind}(t)$ is the output power of the wind turbine, $P_{ESD}(t)$ is the output power of the energy storage device, $P_{Res}(t)$ is the power component flowing into the resistor bank used to dissipate any excess energy in the system and $P_{Out}(t)$ is the output power of the whole system. There are many choices when it comes to the selection of the desired output characteristic of the wind turbine; as this case study is meant to be a simple introduction to the design method presented in this thesis (chapter 4), the target value of P_{Out} was selected to be a constant, equal to the mean output power of the wind turbine (equation 5.3).

$$P_{Out}(t) \equiv Ave(P_{Wind}) \approx 230\ kW \tag{5.3}$$

5.2.1 Duty Cycle Capture

With the aid of equations 5.2 & 5.3 the output response of the secondary and tertiary power plants of the hybrid system can be obtained (equation 5.1). In figure 5.3; the 'Green' trace represents the power which must be sourced by the energy storage device (secondary power plant) of the hybrid system when the generated wind power is insufficient to deliver the target $230\ kW$ of output power. Similarly the 'Red' trace represents the excess power generated by the wind turbine which must be absorbed by the Secondary and Tertiary Power Plants of the hybrid system.

5.2.2 Energy Characterisation and Analysis

The proposed target power demand response in figure 5.3 can be used to generate the discharge/charge event plots shown in figure 5.4. Analysis of these plots helps determine the following patterns in power and energy content of the target power demand:

- In the discharge events the majority of the power is either very low or centred around $230\ kW$ while the majority of charging events fall between $250\ kW$ and $300\ kW$ (figure 5.5(a)).

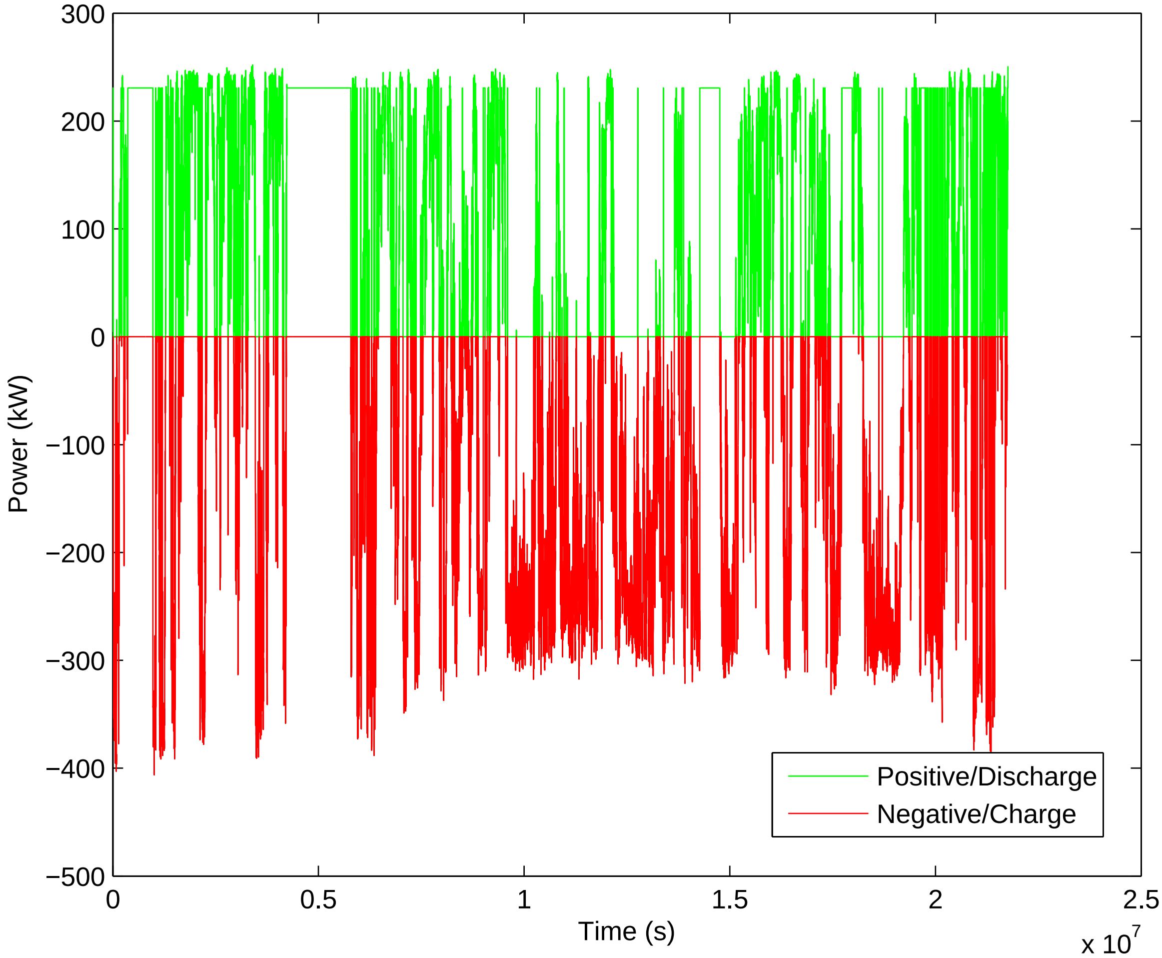


Figure 5.3: Secondary and Tertiary Power Plant Target Response Profile

- The majority of discharge events deliver no more than $4\ MWh$ of energy per event while the majority of charge events carry no more than $6\ MWh$ of energy (figure 5.5(b)).
- Analysis of the time between charge/discharge cycles reveals that for the discharge events the recovery period between events is no greater than 6 hours on average while for charge events this value is generally less than 8 hours (figure 5.5(c)).

5.2.3 Architecture and Control Strategy Selection

Given the large, cyclic duty cycle the energy storage device would be subjected to; high storage capacities; little or no need for mobility in the intended application, pumped-hydro or a compressed air based energy storage technology would be most suited for this type of system.

Due to the discrete nature of the output power from the primary power plant (wind turbine); the desired output characteristics of the complete HPS (i.e. constant power output), a very simple control strategy where the excess power from the primary power plant is used to charge the energy storage device would be most suitable. When the power exceeds the power the energy storage device can absorb, it can be either dissipated by the tertiary power plant (i.e. resistor bank) or exported to the electricity grid by increasing the power output of the system, above its nominal $230\ kW$. It should be noted that this second option is likely to carry a reasonable financial burden, due to potential contractual obligations of the wind power source, and more importantly upgrades to the infrastructure to allow the delivery of higher power to the output of the system.

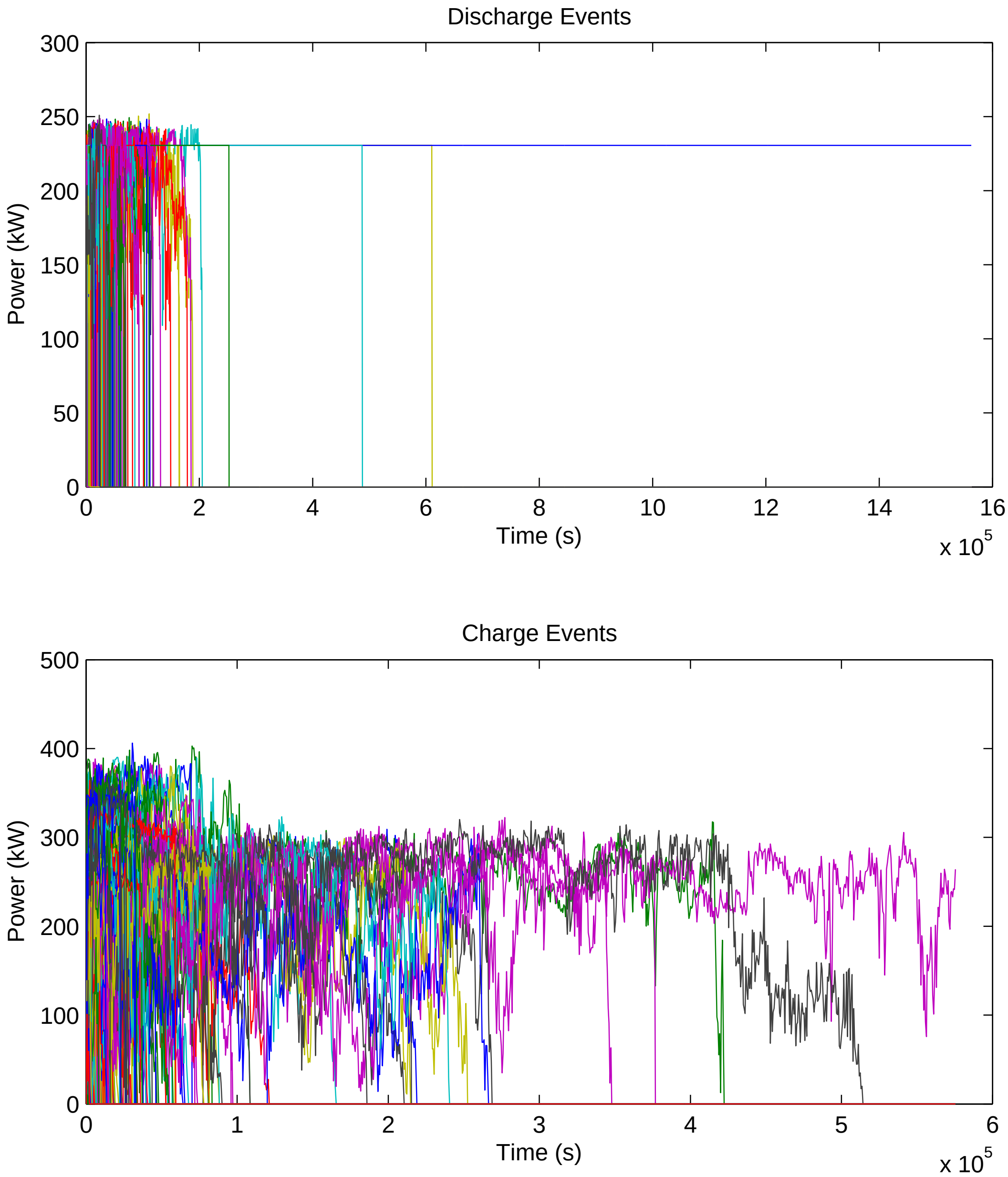
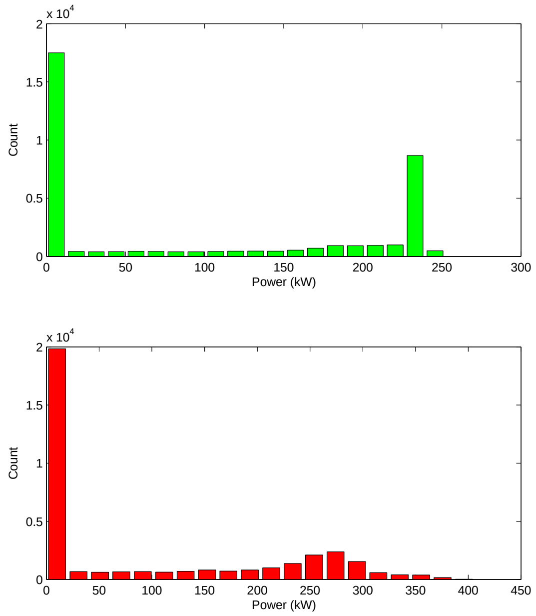
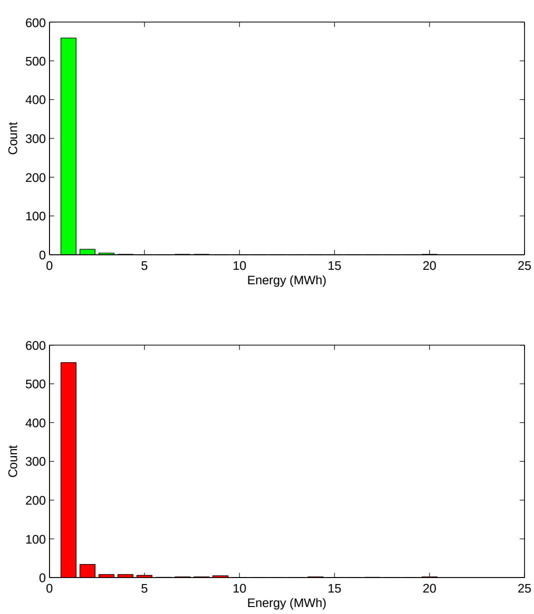


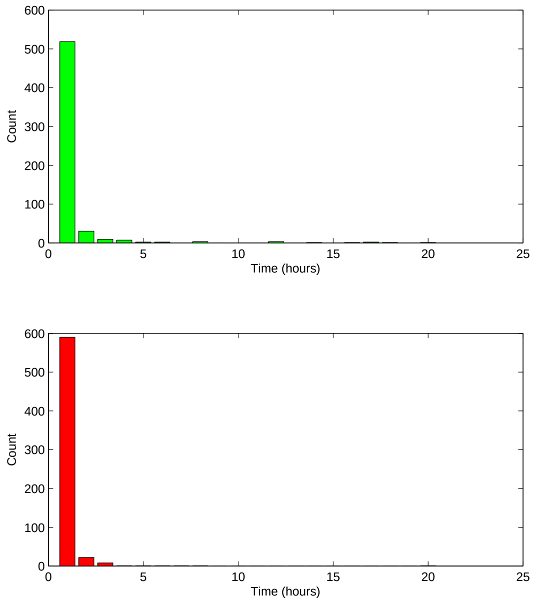
Figure 5.4: Charge/Discharge events, extracted from the ESD power duty cycle



(a) Output Power



(b) Energy Content



(c) Recovery Time

Figure 5.5: Histograms of ESD Charge(green)/Discharge(red) Event Characteristics

Target Storage Capacity	7.5	MWh
Working SOC Range	80.0	%
Power Source Max (discharge)	≈230.0	kW
Power Sink Max (charge)	≈400.0	kW

Table 5.2: Summary of Secondary Power Plant (Energy Storage Device) Specifications

5.2.4 Component Sizing and Evaluation

From section 5.2.2 the average energy stored per charge event is found to be no greater than $6\ MWh$. Based on an acceptable SOC swing of 80% of the total storage capacity, the energy storage capacity for the proposed system can be calculated with the aid of equation 4.9 as $7.5M\ Wh$ using a f_f coefficient of 1.0. Furthermore, from the output power histogram in figures 5.5(a) the maximum source power of the storage system must be no less than $230\ kW$, while the sink power or power during charging must be able to reach a minimum of $375\ kW$.

5.3 Discussion and Analysis

Using HDET (section 4.2.2) and the NiCd battery pack (section 4.3.4) as the ESD in the system, the proposed HPS (figure 5.2) was modelled. The results from the DCCS method are outlined in table 5.3. Analysis of the storage device's SOC shows it is saturated on a number of occasions, when the generated wind energy is significantly greater than the available storage capacity (figure 5.7).

Figure 5.6 provides a means of evaluating the effects of varying the installed ESD capacity on the unrecoverable/lost energy of the system due to insufficient energy storage. The recommended minimum energy storage capacity calculated from the DCCO method is $7.5\ MWh$, this results in $363.11\ MWh$ of energy being unrecoverable via the system's ESD. Increasing the ESD capacity by 167%, to $20.0\ MWh$ allows the reduction

ESD Capacity	7.5	MWh
Starting SOC	50.0	%
Final SOC	10	%
Acceptable SOC swing	80.0	%
Max. Power Source (discharge)	230.0	kW
Max. Power Sink (charge)	-375.0	kW
Total Generated Wind Energy	1385.55	MWh
Unrecoverable Wind Energy ($7.5MWh$)	363.11	MWh
Unrecoverable Wind Energy ($20.0MWh$)	237.92	MWh

Table 5.3: Results Summary For the Proposed Hybrid Wind Power System Using 7.5MWh/20MWh of Energy Storage

of unrecoverable energy by 34%, to $237.92\ MWh$. Therefore it is recommended that a energy storage device capacity of approximately $20.0\ MWh$ would be more suitable for the HPS.

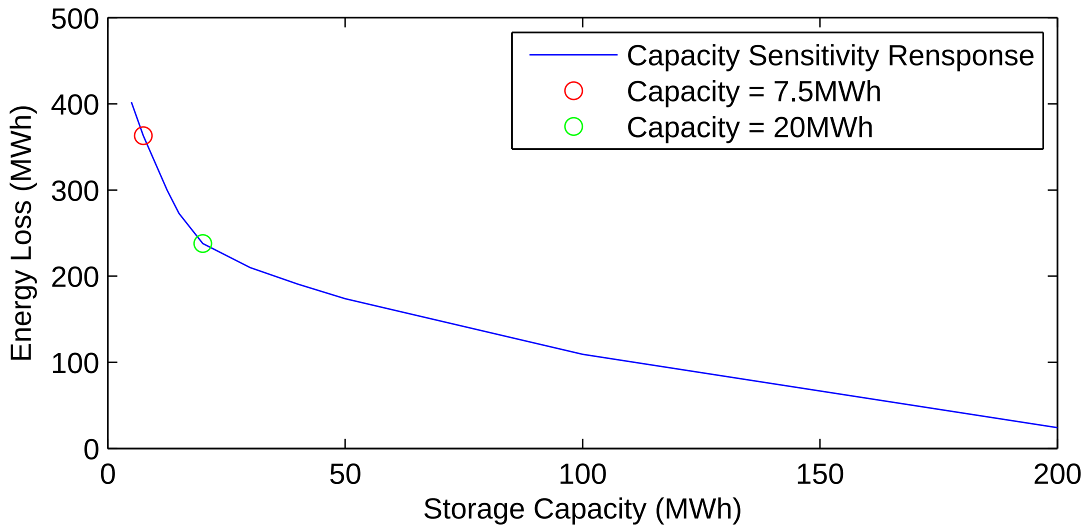


Figure 5.6: Unrecoverable/Lost Wind Energy VS Energy Storage Device Capacity

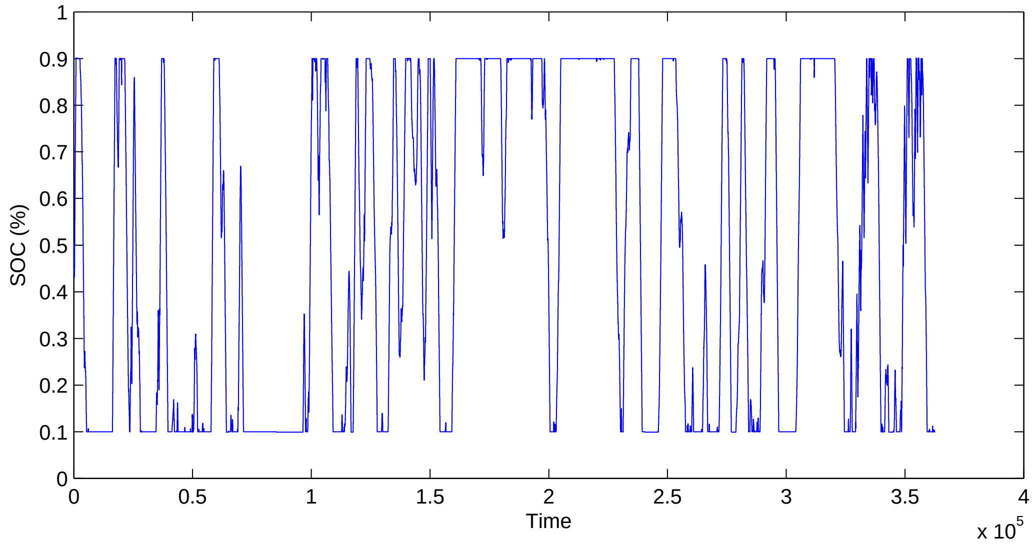


Figure 5.7: 7.5MWh Energy Storage Device SOC Plot

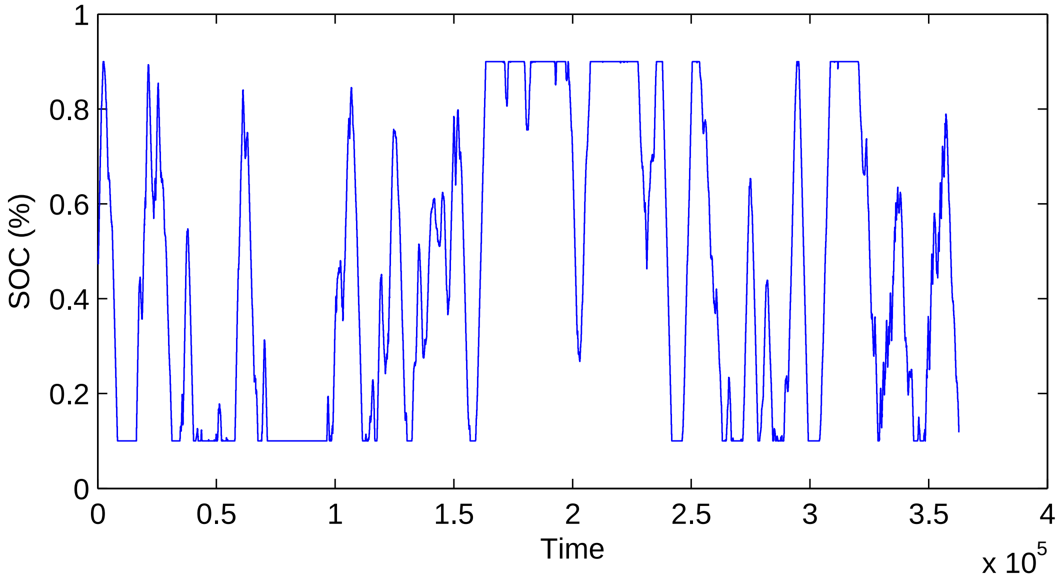


Figure 5.8: 20MWh Energy Storage Device SOC Plot

5.4 Conclusions

Introduction of energy storage to a wind turbine based power generation system can improve the discontinuous and somewhat unpredictable nature of wind power generation. However, the effectiveness of the introduced energy storage is highly dependant on the availability of the wind energy and installed capacity of energy storage.

The design process of a hybrid power system that comprises of a wind turbine and energy storage device, using the DCCS method (presented in chapter 4) was presented. It was found the minimum acceptable storage capacity of the ESD should be $7.5\ MWh$. If the system's ESD was based on a NiCd battery pack (section 4.3.4), increasing this figure to $20.0\ MWh$ would allow a 34.5% increase in energy saving over the $7.5\ MWh$ configuration.

Given the operating duty cycle and high storage capacity, a storage technology which is deployable on a large scale and has proven reliability and availability is required. Subjected to geographical constraints, technologies such as pumped hydro or compressed air based systems maybe suitable. In the case of offshore wind power generation, the prospects of pumped-hydro based energy storage can be particularly attractive for mountainous coast lines, especially when considering the reduced infrastructure cost of a lower rated connection to the national grid.

5.5 Critical Review of Method

A key characteristic of the application duty cycle presented in this chapter is its simplistic nature. The most significant work encountered in the application of the DCCS method to the case study involved steps 2 and 3 of the method, namely the Energy Characterisation & Analysis and Architecture & Control Strategy Selection steps.

The duty cycle's uneven distribution of energy production over the sampled duration contributed to the relatively non-linearity relationship between unrecoverable energy vs energy storage device capacity outlined in figure 5.6. A noteworthy point, which outlines a key strength of this approach was its ability to extract key requirements for ESD technologies servicing the given application.

Chapter 6

Case Study : Integration of Hybrid Electric Power to Commuter Rail Network

As emphasis on adopting environmentally friendly technologies increases and urban populations choose public transport over personal transport solutions, the need for a sustainable, environmentally friendly and reliable transport infrastructure is greater than ever before. From an environmental point of view, commuter railways at peak periods out perform most modes of transport [135]. However, with increasing competition from automotive manufacturers [26], and more efficient transport technologies of the future, the railways must seek means of innovating further to maintain their competitive edge and dominance as the affordable, green mode of transport for the masses [136].

Drivetrain hybridisation is the obvious path to follow for future diesel rolling stock. However, highly efficient electric railway networks must explore means of improving efficiency and embracing new technologies in today's ever competitive, and increasingly environmentally friendly transport sectors. Currently the most popular means of energy

Net consumed	65.83	GWh/year
	180.15	MWh/day
Mean power	7.50	MW
Maximum mean power	15.35	MW
Minimum mean power	798.00	kW

Table 6.1: Summary of commuter rail power network energy usage statistics

saving adopted by electrified railway networks is the recovery of kinetic energy via regenerative braking, and using the recovered energy to power near by vehicles on the network.

In this chapter the effects of introducing a wind farm, and additional energy storage to an urban commuter rail network is explored using the DCCS method (chapter 4). The performance of the proposed HPS is evaluated via the HDET outlined in section 4.2. The objective of the study is the reduction in overall power sourced from the national electricity grid; peak power shaving to reduce cost and utilisation of renewable energy to power the network.

6.1 Power Consumption of a Commuter Rail Network

Figures 6.2, 6.3 and 6.4 outline the average energy usage statistics for an urban commuter railway network situated in the north west of England, from 1^{st} July 2007 to 30^{th} June 2009 in half hourly increments [137]. There is a notable pattern to the demand profile of the network, with clear peaks that correspond to weekday commuter rush hour periods (morning and evening), and a general consistent usage pattern over the weekends (Figure 6.3).

The energy usage characteristics for the network are summarised in table 6.1. It should be noted that all power values correspond to the average power over a 30 minute period, derived from the energy statistics in figures 6.3 and 6.4. The energy to power

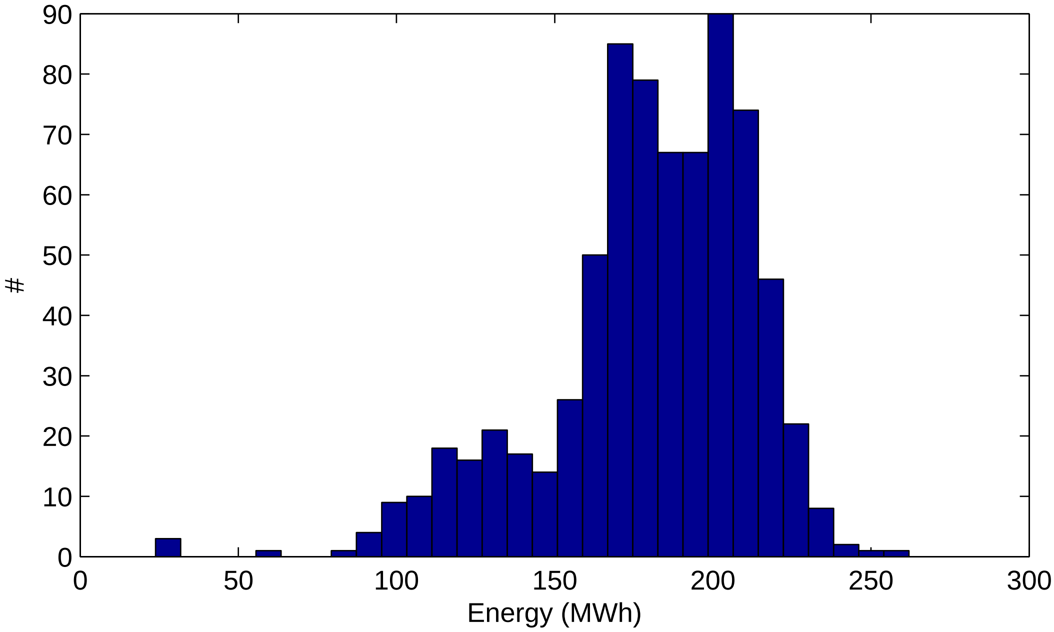


Figure 6.1: Histogram of Daily Energy Consumption for Commuter Rail Network

conversion was done using equation 6.2. Where, E_i is mean energy, $P(t)$ is power, P_i is mean power and ΔT is unit time step of 30 minutes.

$$E_i = \int_{t_1}^{t_1+\Delta T} P(t) \cdot dt \tag{6.1}$$

$$P_i = \frac{E_i}{\Delta T} \tag{6.2}$$

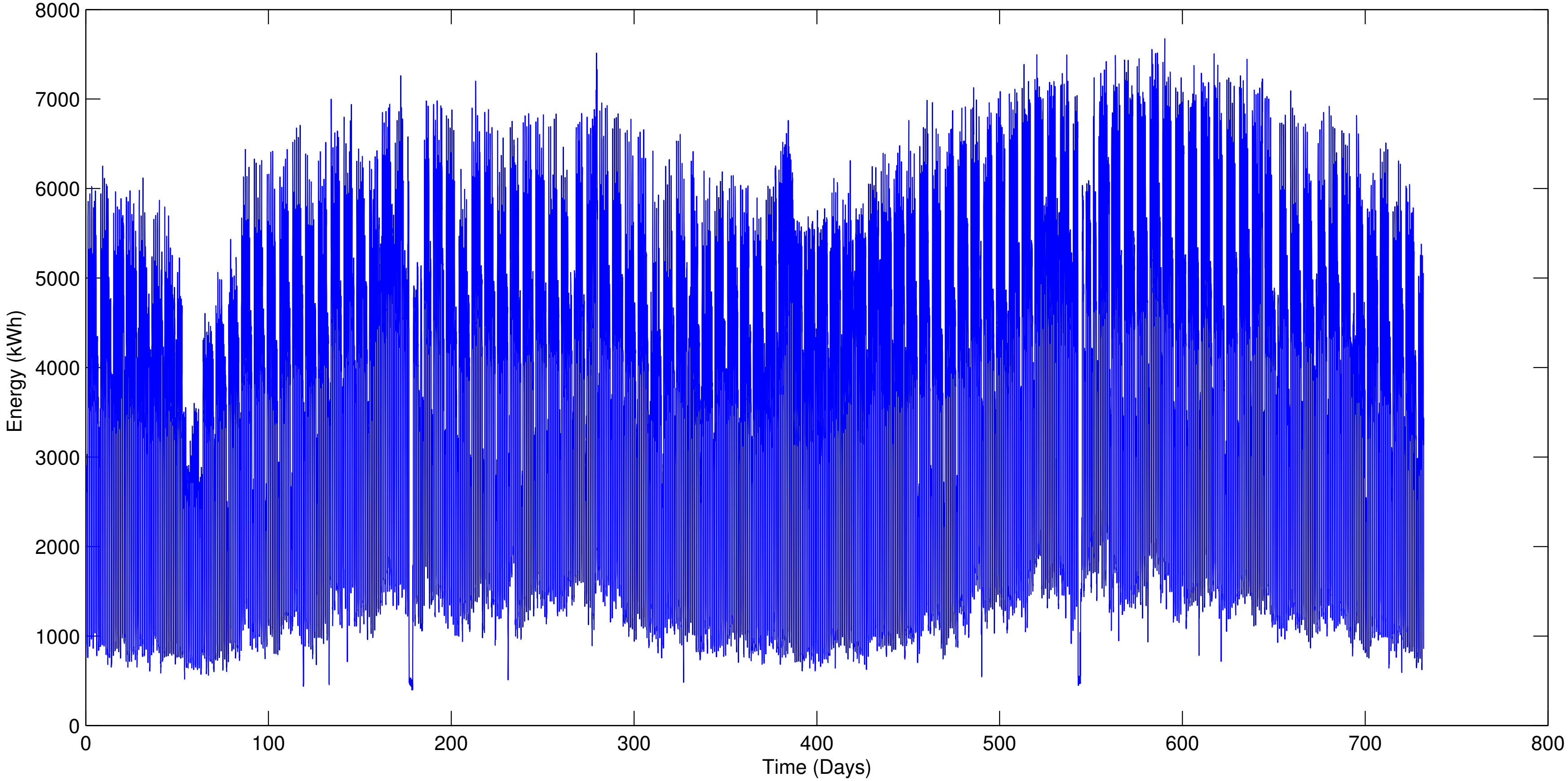


Figure 6.2: Energy Consumption Characteristics for Commuter Rail Network

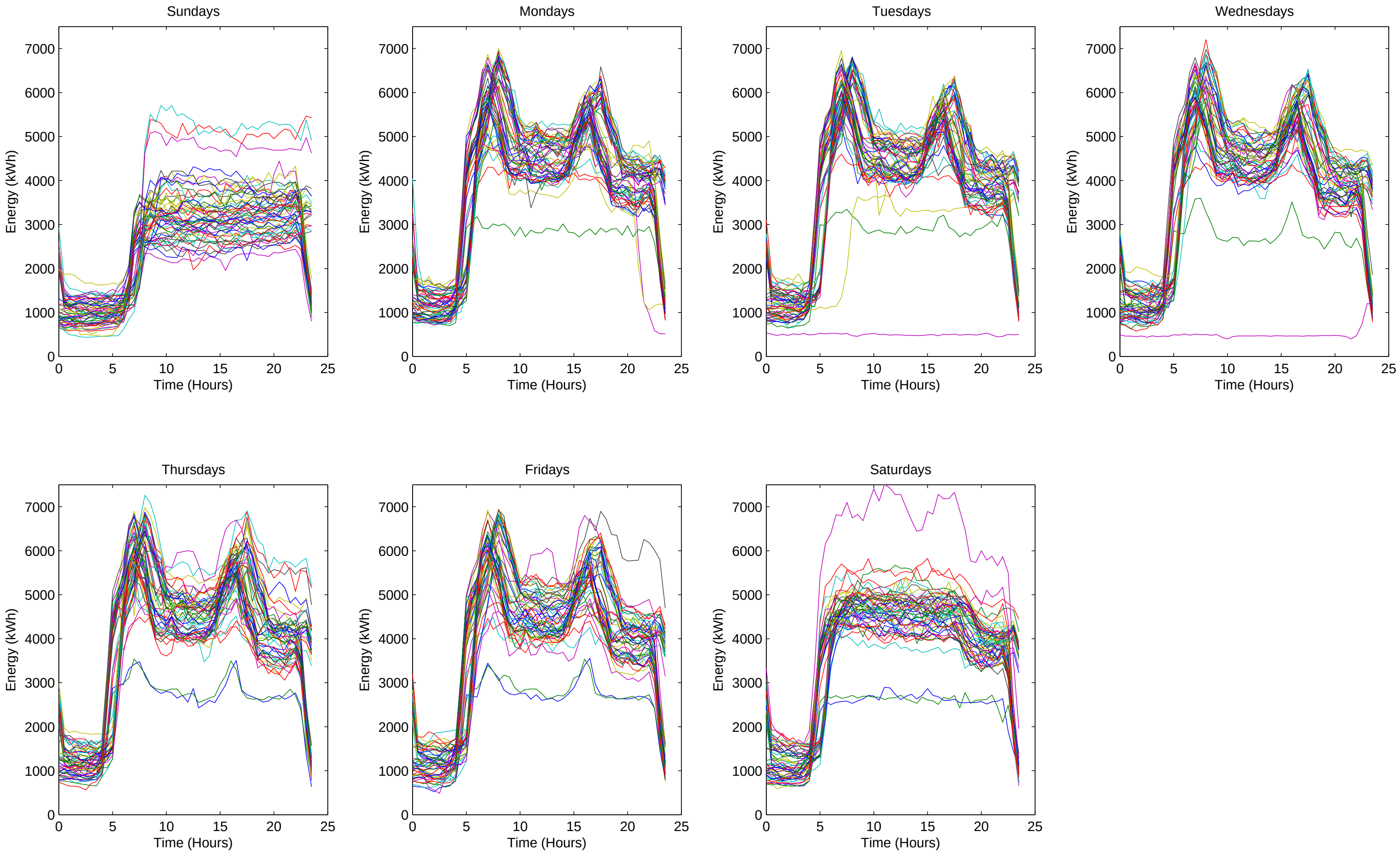


Figure 6.3: Energy Usage by Day of the Week

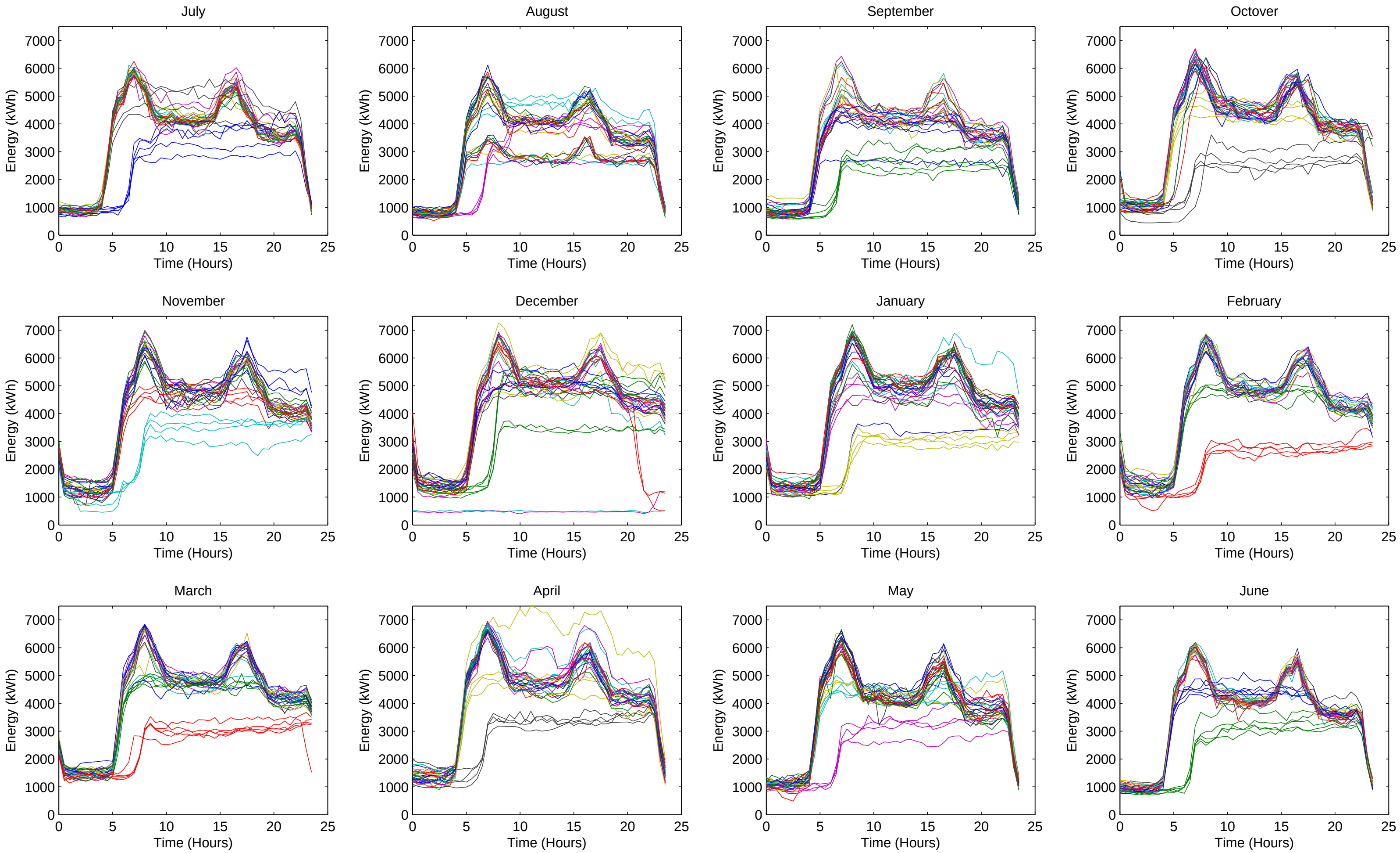


Figure 6.4: Energy Usage by Month (July 2007 - June 2009)

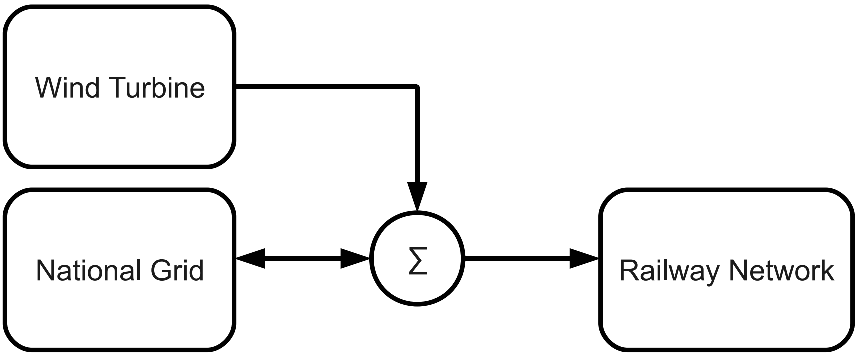


Figure 6.5: Proposed Power Delivery Setup

6.2 Utilisation of Wind Power in a Commuter Rail Power Network

Figure 6.5 outlines the proposed electrical power delivery setup for introducing wind power to the railway network. In this configuration the power generated by the wind turbine will be used to power the railway network, while any short fall in power will be supplied by the national electricity grid.

A wind farm with twelve, $600\ kW$ turbines (based on the turbine characteristics and output data outlined in chapter 5, section 5.1), with a total peak output power of $7.2\ MW$ was used in this work. The figure of $7.2\ MW$ was chosen to match the mean power consumption of the railway network, which was found to be $\approx\ 7.5\ MW$ (table 6.1). Table 6.2 provides a summary of the resulting power consumption of the railway network with wind power. Comparison of the total energy consumption characteristics presented in tables 6.1 and 6.2 shows a reduction in mean power of nearly 37%; overall energy consumption of the railway network can be reduced by up to 32% and produces nearly $3\ GWh$ of excess energy annually that could be injected to the national grid.

Net consumed energy by system	44.43	GWh/year
	121.54	MWh/day
Net generated energy by system	2.91	GWh/year
Mean power	4.73	MW
Maximum mean power	15.04	MW
Minimum mean power	-6.51	kW

Table 6.2: energy usage statistics for commuter rail power network with 7.2MW of wind power

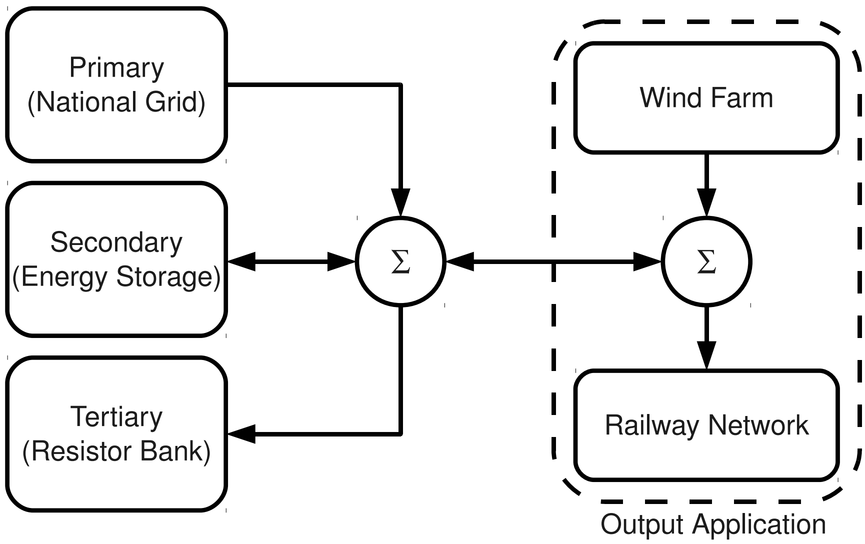


Figure 6.6: Proposed Power Delivery Setup With Energy Storage

6.3 Hybrid Power System Design

To evaluate the effects of introducing energy storage to the railway power network, and compare the advantages/disadvantages with a purely national grid powered system, the HPS configuration outlined in figure 6.6 is used. It is assumed that the wind farm is directly connected to the railway network power system, while the national grid acts purely as a power source. Finally the energy storage devices will be able to source and sink power. The combination of the national grid supply and energy storage device can be considered as a HPS. The operating characteristics or behaviour of the HPS can be represented by equation 6.3.

$$P_{hybrid}(t) = P_{wind}(t) - P_{rail}(t) \quad (6.3)$$

$$P_{hybrid}(t) = P_{ng}(t) + P_{esd}(t) + P_{res}(t) \quad (6.4)$$

Where $P_{wind}(t)$ is the power generated by the wind turbines, $P_{rail}(t)$ is the power consumed by the railway network, $P_{hybrid}(t)$ is the combined output/input power of the hybrid power system, $P_{ng}(t)$ is the power sourced from the national grid and $P_{esd}(t)$ is the power from the energy storage device and $P_{res}(t)$ is the dissipated/lost power via resistor banks.

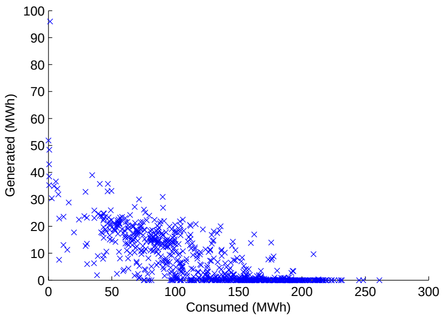
6.3.1 Duty Cycle Capture

Figure 6.7 provides an outline and analysis of the duty cycle the HPS must meet to service the railway network with $7.2\ MW$ of wind power. The power profile was obtained with the aid of equation 6.3 above.

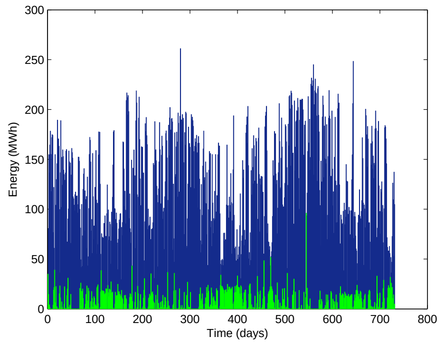
6.3.2 Energy Characterisation and Analysis

Analysis of the HPS duty cycle or combined wind and railway network power characteristics presented in figure(s) 6.7 show:

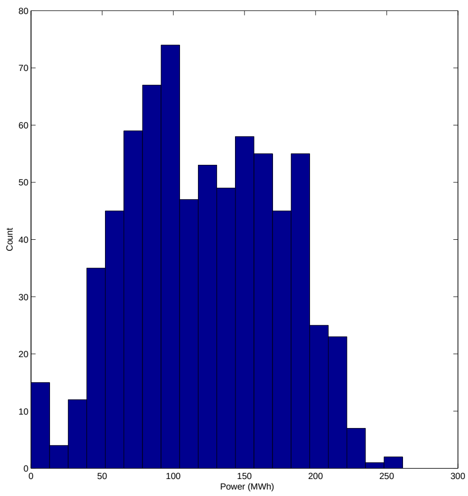
- In the case of consumed power:
  - The mean daily consumed energy is approximately $120\ MWh$.
  - In practise the daily consumption values are reasonably well distributed between $50\ MWh$ and $200\ MWh$ (figure 6.7(c)).
- In the case of generated power:



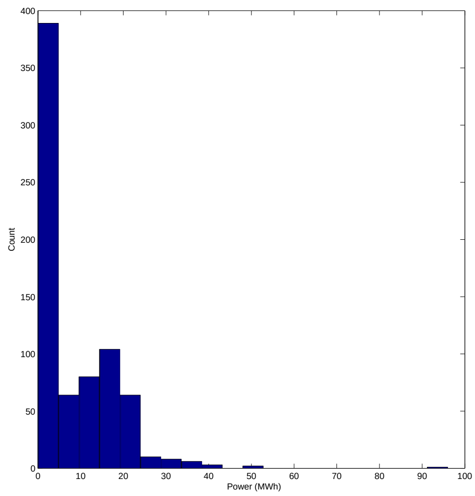
(a) Daily energy consumption/generation tally



(b) Daily Consumed vs Generated Energy



(c) Daily Consumed Energy



(d) Daily Generated Energy

Figure 6.7: Daily energy usage characteristics of a commuter rail network with 7.2MW of wind power

  - The mean daily generated power is approximately $8\ MWh$.
  - A significant proportion of days consist of very low levels of overall generated energy under $5\ MWh$ (figure 6.7(d)).
  - Considering the days where the above value is exceeded, the power generated is more than $10\ MWh$ but no greater than $25\ MWh$.

- The energy characteristics hint at the potential to store up to $25\ MWh$ of the excess generated wind power, and use it to reduce the $50\ MWh$ to $200\ MWh$ of peak power supplied by the national grid daily.

- There are relatively well defined, repeatable load peaks that occur twice a day on weekdays, that relate to the morning and evening rush hours; each day consists of up to 5 hours of lower power consumption, no more than $4\ MW$ when the railway network is closed during the night (figure 6.3).

6.3.3 Architecture and Control Strategy Selection

Given the pure electrical nature of the system the most suitable HPS architecture is undoubtedly a series architecture. Given the nature of the application, there are two main scenarios that can justify the implementation of energy storage on the power network, namely:

- Reduction in overall energy consumption
- Peak power shaving to minimise energy costs at peak hours

In the case of the latter (peak power shaving), it is difficult to gauge the implications and benefits of displacing power consumption peaks to off peak times, as the pricing structures and general energy markets that effect this type of application are complex.

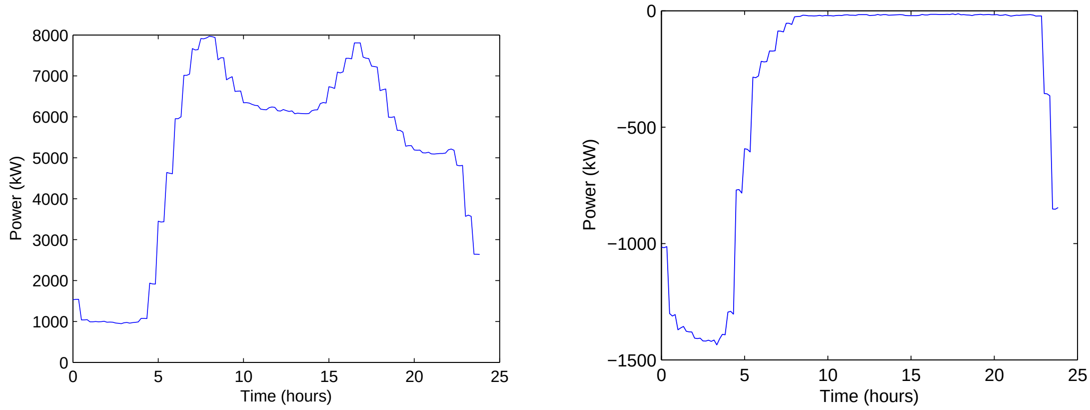
Therefore, this case study will focus on the potential for an overall reduction in energy consumption by the introduction of energy storage to the power network.

Analysis of the daily consumption characteristics in figures 6.7(c) and 6.2, and the generated surplus wind energy shown in figure 6.7(d) hints at the potential of using energy storage to reduce the daily energy consumption rather than anything more long term (i.e. over months, seasons or years). Given the relatively large difference between surplus wind energy, and consumed energy (typically a ratio of 1:15) a control strategy designed to store the excess wind energy, and reduce peak power loads was chosen.

At this point it is worth noting that some key characteristics of a suitable energy storage device technology have been outlined from the analysis so far. These can be summarised as:

- Given the energy storage device charge-discharge cycle will be approximately 1 day, an energy storage technology with a relatively small self discharge characteristic is highly desirable.
- The static nature of the storage application, makes the energy density (weight and volume) of the chosen storage technology of less importance.
- The high power and large amounts of energy stored, hint at the need for a storage technology capable of delivering very high power with a long life cycle.
- Low maintenance technology is always desirable, however a storage technology that requires a moderate level of maintenance or supervision is acceptable for this application.

Examples of energy storage devices which meet the above requirements are Sodium-sulfur or Sodium-Metal-Chloride batteries; pumped-hydro or compressed air storage.



(a) Consumption (b) Generation

Figure 6.8: Normalised Daily Consumption/Generation of a $7.2MW$ Wind Farm

6.3.4 Component Sizing and Evaluation

On average a significant proportion of excess wind energy is generated during the night and early morning (figure 6.8(b)); typically for the first 8 hours of each day, which corresponds to the time the overall network power demand is at its lowest. Assuming the excess wind energy is stored during the early hours of the day, and used during the peak hours until depleted, the system must have a minimum storage capacity of approximately $8\ MWh$. If the storage device has a working SOC range of 60%, the total capacity of the storage device must be a minimum of $13.3\ MWh$ (from equation 4.9).

Using HDET (section 4.2.2) and the NiCd battery pack (section 4.3.4) as the ESD in the system, the proposed HPS (figure 6.6) was simulated. The simulation showed with a ESD capacity of $13.3\ MWh$, $43.61\ MW/year$ will be sourced from the national grid, while nearly $1.8\ MWh$ of excess wind energy would be lost annually due to the SOC of the battery packs being too high to accept additional energy during days with high wind generation.

In order to accommodate these high generation time periods, an investigation of system performance with different ESD capacities was done to investigate the benefit

ESD Capacity (MWh)	NG Sourced (GWh/year)	Excess (GWh/year)
1.00	44.3000	2.740
3.33	44.1572	2.514
6.66	43.9597	2.214
13.32	**43.6093**	**1.779**
26.64	43.1209	1.204
39.96	42.8341	0.864
53.28	42.6580	0.658
66.60	42.5332	0.511
79.92	42.4378	0.398
93.24	42.3670	0.315
120.00	42.2707	0.202

Table 6.3: National-Grid energy supply Statistics of a commuter rail power network with 7.2MW of wind power and energy storage

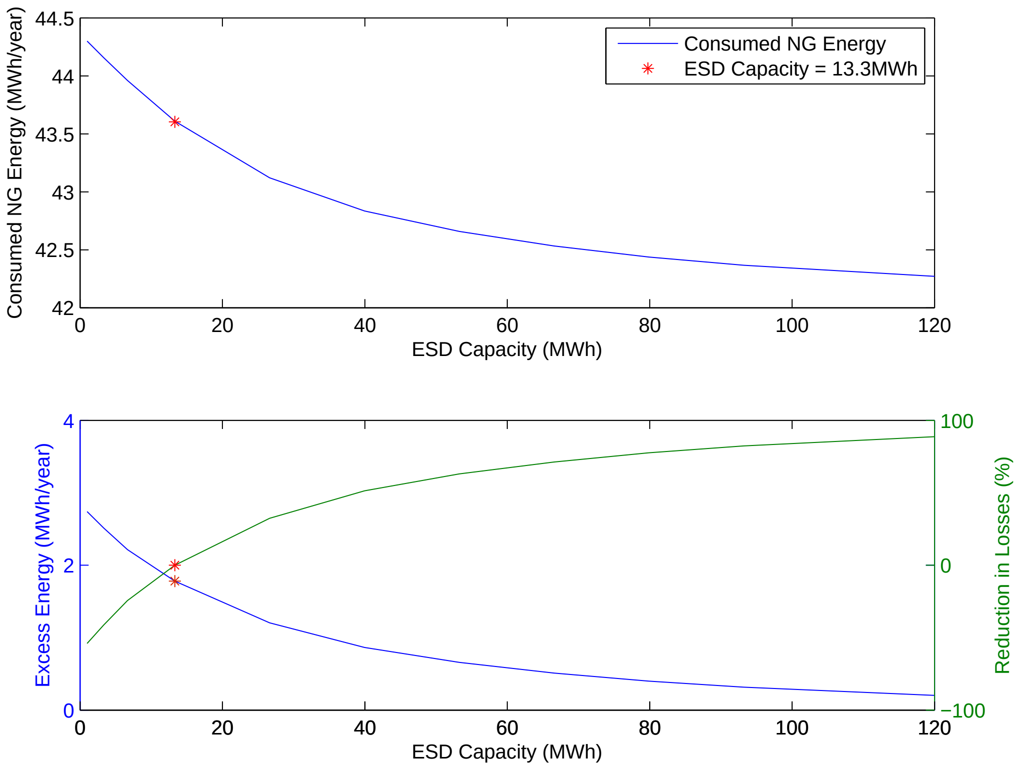


Figure 6.9: Excess Wind Energy VS Energy Storage Device Capacity

of a different ESD capacity. The results from these configurations are summarised in table 6.3, while figure 6.9 illustrates the effects of varying ESD capacity on excess energy.

6.4 Conclusions

By introducing wind power to the selected railway power network, the total energy sourced from the national grid was reduced by 32.5%, and nearly $3\ GWh/year$ of excess wind energy was generated. Introducing $13.3\ MWh$ of energy storage to the system, reduced the energy sourced by the national grid by a further 1.2%, while reducing the exported energy by up to 39%.

The introduction of wind and energy storage to the energy mix of the power network reduces the mean power drawn by the national grid by up to 37%. However, the maximum sustained power demand may not be affected significantly as peak wind power and peak network power consumption is unlikely to overlap a great deal on average.

From figure 6.9 it can be concluded that a vast amount of energy storage is required to make a significant reduction in the sourced energy from the national grid. In practise the procurement, installation and maintenance of such an energy storage infrastructure is likely to not be cost effective. Therefore injecting the excess energy to the national grid instead of storing and using at a later time is likely to be the most prudent option.

6.5 Critical Review of Method

The case study presented in this chapter introduces the application of the DCCS method to a complex application duty cycle. This provided an opportunity to carry out a more in-depth analysis in the steps 1, 2 & 3 of the method. The analysis involved a significant amount of attention to the duty cycle and logical objectives of the supervisory control strategy of a hybrid power system servicing the application duty cycle. Possibly the most noteworthy aspect of the method in the case study was its ability to identifying key characteristics of the duty cycle and provide a better understanding of the different strategical options available to the designer of such a system.

Chapter 7

Case Study : Fuel Cell Hybrid Railway Vehicle

Railway transport is arguably one of the least environmentally damaging forms of transport [138]. Current widely deployed electrification means that the majority of passenger kilometres generate zero emissions at the point of use. Railways also share in the CO_2 benefits that occur through the increasing de-carbonisation of grid electricity, however the extremities of most railway networks contain lightly loaded routes which are uneconomic to electrify [139]. The vehicles which operate on these routes are currently diesel powered, and therefore are exposed to future fuel supply issues and uncertain future costs. In the short to medium term these vehicles could be replaced or re-engineered to utilise hybrid propulsion systems; with a view to eventually replace the diesel prime mover with a fuel cell when the economic and reliability case can be made.

These devices produce nearly zero emissions at the point of use. Today, much research is taking place into investigating the use of fuel cells in transport applications such as automobiles, buses, locomotives, ships, submarines and they are available in output power from a few kilowatts to several thousand. In the market it is possible to find many different types of fuel cells, but for transportation needs the most popular is the Proton Exchange Membrane (PEM) based technology. PEM fuel cells offer a valid alternative to internal combustion engines for transportation vehicles [140] and in the literature it is possible to find some analysis of fuel cell locomotives in applications such as tunnelling, mining [141] and hybrid shunt locomotives [142]. Thanks to this precedent analysis [143] [144], there exists a suitable background to develop the investigation.

Due to fuel cells running on hydrogen as opposed to fossil fuels such as coal, petroleum, and natural gas they have the potential of being a carbon neutral source of energy. At present the challenge is the efficient extraction and delivery of Hydrogen. There are many technologies available to obtain Hydrogen of which the most popular is steam reforming of natural gas. Currently this is the most energy-efficient and large scale method of hydrogen production available [43] [145] [45], however in this process CO_2 is produced:

$$CH_4 + 2H_2O + Energy \longrightarrow 4H_2 + CO_2 \tag{7.1}$$

The simplest carbon neutral method of obtaining H_2 is by electrolysis of water:

$$H_2O + Energy \longrightarrow H_2 + \frac{1}{2}O_2 \tag{7.2}$$

If the electrical energy for this process is obtained from renewable sources (i.e. hydro-power, solar energy or wind energy) it is possible to produce hydrogen with no impact on green house gases [146].

In this chapter the effects of a hybrid power propulsion drive on a commuter rail vehicle are investigated. First the modelling methodology of a railway vehicle is introduced and a railway vehicle simulator presented. The simulator output is validated and the output compared with a railway vehicle powered by a pure diesel, diesel-hybrid or fuel cell system. The design of a hybrid power system, using a simple Trail and Error (section 3.3) is presented and finally compared with the DCCS design method (chapter 4), and their performance evaluated via the Hybrid Drivetrain Evaluation Tool outlined in section 4.2. Finally, the fuel (H_2) requirements are compared with typical diesel and hybrid diesel powered vehicles with the aim of understanding the potential energy and CO_2 savings gained from such a vehicle.

It should be noted that the first half of this analysis work, related to the trial and error method, was presented at the Eleventh Grove Fuel Cell Symposium 2009 and has been published in the Journal of Power Sources [121].

7.1 Vehicle and Journey Details

All results outlined in this chapter are centred around a Class 150 Diesel Multiple Unit (DMU) railway vehicle running along a segment of the Birmingham Snow Hill Line in the United Kingdom between Stratford-Upon-Avon and Birmingham Moore Street Station. It should be noted the journey stopping-cycles are idealised, and in practice there are likely to be unforeseen delays (i.e. stops) encountered by the vehicle, such as the request station stops mentioned in section 7.3. Details of the selected journey and vehicle are given in tables 7.1, 7.2 and figures 7.1(a), 7.1(b).

7.2 Railway Vehicle Simulation

The forces that govern the behaviour of a railway vehicle are shown in figure 7.2. The vehicle response is achieved by solving the equation of motion for a railway vehicle [147] by using Lomonossoff's equation (equation 7.3).

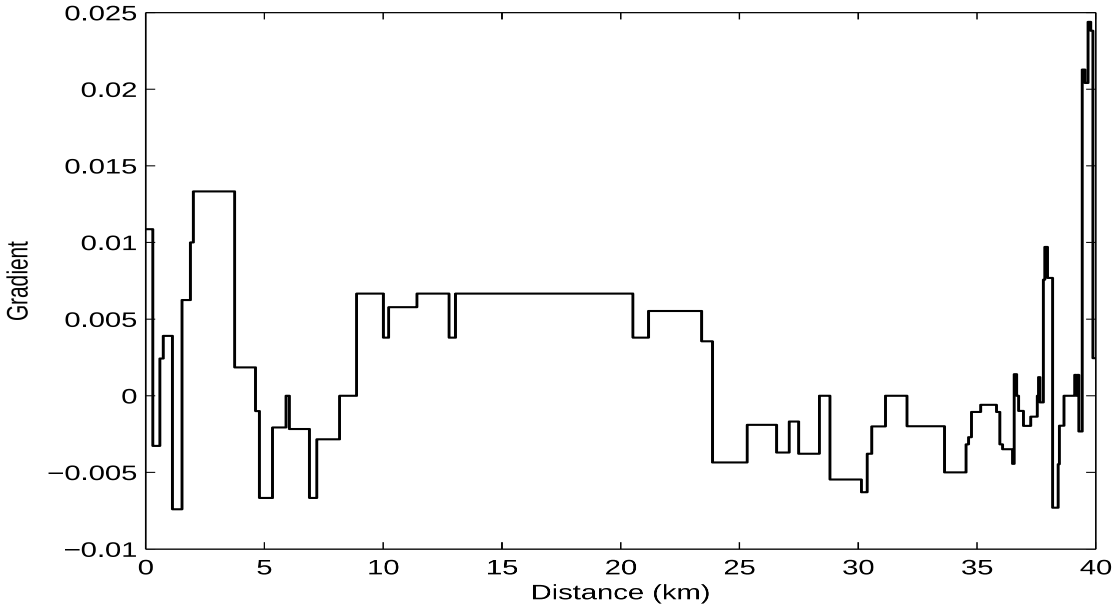
$$M_e \frac{d^2 s}{dt^2} = F - R_{total} - Mg \sin \alpha \tag{7.3}$$

Start Location	Stratford-Upon-Avon Station
End Location	Stratford-Upon-Avon Station (via Birmingham Moore Street Station)
Stations	34
Station List	Stratford-Upon-Avon, Wilmcote, Wootton Wawen, Henley in Arden, Danzey, Wood End, The Lakes, Earlswood, Wythall, Whitlocks End, Shirley, Yardley Wood, Hall Green, Spring Road, Tyseley, Small Heath, Bordesley, Birmingham Moore Street (and back)
Journey Length	78.58 km

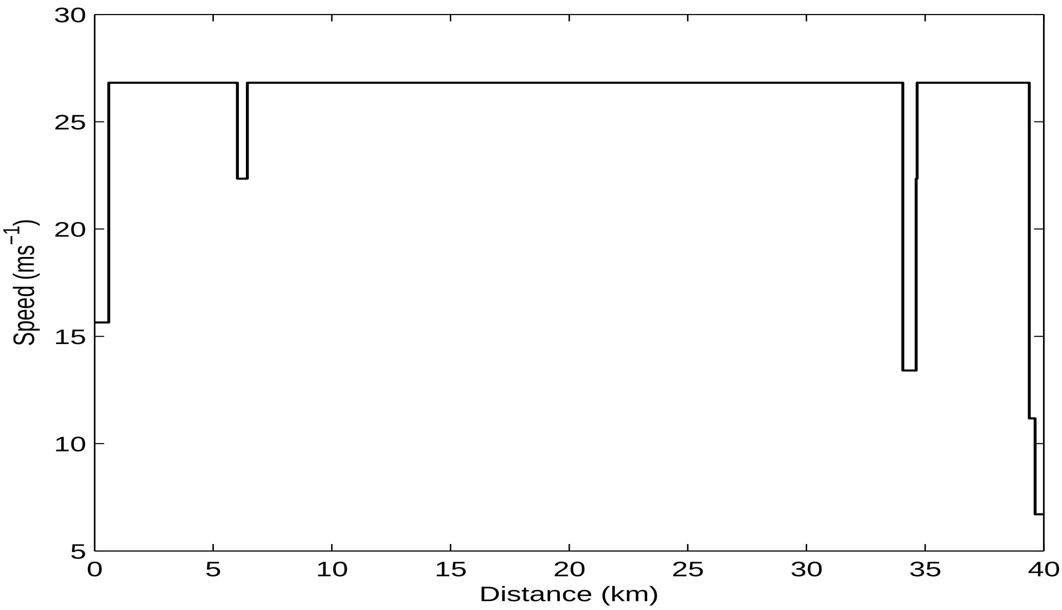
Table 7.1: Journey Details (Stratford-Upon-Avon to Birmingham Moore Street)

Railway Vehicle	British Rail, Class 150 DMU
Mass	$76.5 \times 10^3\ kg$
Number of Seats	124
Speed (Max)	$33.5\ ms^{-1}$ ($\approx 75\ mph$)
Tractive Effort (Max)	$\approx 40.0\ kN$
Tractive Power (Max; at wheels)	$374\ kN$
Base speed	$8ms^{-1}$ ($\approx 18\ mph$)
Percentage of powered axles	50%
Acceleration mass co-efficient (λ)	0.08
Davis equation coefficients	A = $2.09 \times 10^3\ N$ B = $9.83\ Nm^{-1}s$ C = $6.51\ Nm^{-2}s^2$ D = $0.00\ kg^{-1}$

Table 7.2: Vehicle Characteristics for a Class 150 DMU



(a) Gradient vs displacement



(b) Line speed vs displacement plot

Figure 7.1: Details of simulated route between Stratford-Upon-Avon to Birmingham Moore Street

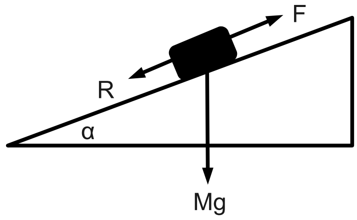


Figure 7.2: Forces acting upon a typical railway vehicle

Where, M is the total mass of the vehicle, M_e is the inertial mass of the vehicle, g is the gravitational acceleration, R_{total} is the resistance to motion the vehicle experiences while moving along the track, $\sin\alpha$ is gradient of the track and F is the total tractive effort produced at the powered wheels of the vehicle and s is vehicle displacement. The term R_{total} (resistance to motion) is the sum of mechanical friction, aerodynamic drag and frictional losses due to the vehicle interacting with the running rails. Furthermore with help from the Davis Equation the total resistance to motion ($R_{total} + Mg\sin\alpha$) can be expressed empirically as:

$$R_{total} = (A + B\frac{ds}{dt})M + C(\frac{ds}{dt})^2 + Mg\alpha + \frac{DMg}{r}$$

Where $\frac{ds}{dt}$ is the velocity of the vehicle, r is the track radius, α is the gradient angle of the track ($\sin\alpha \approx \alpha,$ where, $\alpha \to 0$) and A, B, C and D are constants. Therefore, from the above the vehicle response can be calculated for a given track and vehicle characteristic by the following equation:

$$TE = M_e\frac{d^2s}{dt^2} + [(A + B\frac{ds}{dt})M + C(\frac{ds}{dt})^2 + Mg\alpha + \frac{DMg}{r}] \quad (7.4)$$

Where TE is the tractive effort delivered by the traction packages, A, B, C and D can be determined by vehicle characteristic data obtained by run down tests or by the use of the methods proposed by Armstrong and Swift for UK rolling stock [148].

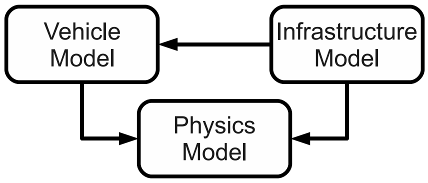


Figure 7.3: Flow Diagram of Railway Vehicle Simulator

7.2.1 Simulator Topology

A railway vehicle simulator (RVS) was developed to investigate the effects different components have on the performance and behaviour of hybrid railway vehicles. The simulator consists of the following primary components (figure 7.3):

- Infrastructure Model
- Vehicle Model
- Physics Model

7.2.2 Infrastructure Model

Provides all spacial and temperal information about a simulated railway journey. This includes the characteristics of the track, signalling information such as line speeds and station stops based on the location along the track. This information is obtained by providing the model with datasets outlined below.

Gradient profile - this relates to the vertical gradient of the railway track as the vehicles travel along. Each datum is made up of two components: location and gradient. The location is a distance in kilometres, where 'zero' represents the start of the simulated journey. The gradient is the ratio of the vertical displacement against the horizontal displacement of the track.

$$Gradient = \frac{VerticalDisplacement}{HorizontalDisplacement}$$

where, $Gradient > 0$, when vehicle moves up hill, $Gradient < 0$ when vehicle moves down hill and $Gradient = 0$ when moving along a flat piece of track.

Curvature profile - this relates to the horizontal curvature of the railway line as the vehicle moves along the track. Each datum is made up of three components: start location, end location and curvature. The start/stop location as mentioned above is a value in kilometres from the start of the proposed simulation data set. The curvature is the radius (in metres) of the given track segment.

Line speeds - this relates to the maximum speed the vehicle should reach on any given piece of railway line. The data is represented by a start location, stop location and line speed for the given track segment.

Station locations - this represent the location of stations along the simulated journey. Each datum is made up of two components: location of the station in kilometres from beginning of the simulated journey and the station name.

7.2.3 Vehicle Model

The purpose of the Vehicle Model is to control the behaviour of the vehicle as it moves along the track. This is achieved by adjusting the output tractive effort of the traction packages by changing the throttle. The control of the throttle is based on the location, infrastructure and signalling information provided by the Infrastructure Model. The Vehicle Model can be separated into the following sub systems:

Throttle - this relates to the output tractive effort of the vehicle as a percentage of the maximum achievable tractive effort. Its value can lie between -100% and $+100\%$, where negative values represent the braking effort.

Driving Strategy Evaluator - sets out to simulate the behaviour of a train driver, by controlling the above outlined throttle. Using a combination of comparing the current line speed, next line speed limit and the distance to the next station the DSE (Driving strategy evaluator) determines the target velocity of the vehicle (see figure 7.4).

Once the target velocity has been worked out the vehicle target throttle value is selected based on the vehicles acceleration/deceleration limits and control style. At present the DSE has three control styles available to it.

- Notched control - use of a finite number of preset throttle points (e.g. 10%, 20%, 30%)
- PID control - a proportional-integral-derivative controller [149] with user selectable gains
- Hybrid control - a combination of notched and PID control. In this control method the throttle demand is set to preset notch values if the vehicle speed is not within a preset limit of the target vehicle speed. Once the vehicle speed is within the target threshold the control is switched to PID mode

7.2.4 Physics Model

The actual vehicle response is calculated by the Physics Model. With the aid of equation 7.4 the acceleration of the vehicle is calculated. Furthermore the vehicle speed and displacement values are calculated by using the standard equations of motion below.

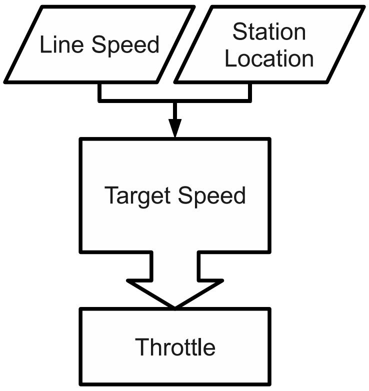


Figure 7.4: Driving Strategy Evaluator Function Block

$$F_{total} = ma \tag{7.5}$$

$$v = u + a\Delta t \tag{7.6}$$

$$s = u\Delta t + \frac{1}{2}a(\Delta t)^2 \tag{7.7}$$

where F_{total} is the sum of forces acting upon the vehicle, m is mass, a is acceleration ($\frac{d^2s}{dt^2}$) , u is the original speed of the vehicle ($\frac{ds}{dt}$), v is the new speed of the vehicle, s is displacement and Δt is the simulation time step. It should be noted that the vehicle acceleration (a) is a dynamic value that depends on the vehicle position, speed and tractive effort. However, for the purpose of the simulation, this is assumed to be static for very small time steps (typically $\ll 1s$).

7.3 Simulator Validation

Figure 7.5 is the vehicle speed vs displacement plot of a class 150 travelling along half of the selected route. The three plots represent the practically measured results

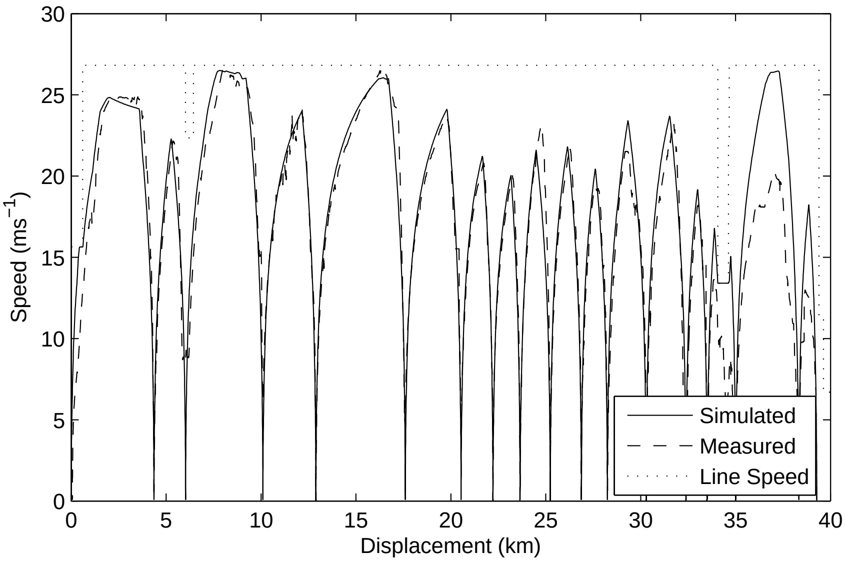


Figure 7.5: Vehicle speed, line speed vs displacement (Stratford-Upon-Avon to Birmingham Moore Street)

(dashed line) obtained via a handheld gps receiver placed in the vehicle, simulated data (solid line) and line speed (dotted line). It should be noted that the measured journey differs slightly from the journey described in section 7.1, due to the vehicle not stopping at all the stations. This is due to some stations along the route being request stops. It should be noted that the mass of the vehicle has been assumed to be constant for each propulsion system type, and therefore the required power and performance of each vehicle type are similar. It is estimated that the different mass of each propulsion system would have negligible effect on the total vehicle mass, and therefore is an important, but second-order effect. This issue would merit further investigation in more in depth analyses.

	DMU	Hybrid-DMU	Pure Fuel Cell
Fuel Consumption (ℓ)	102.0	82.0	$38.0\ kg(H_2)$
Journey Duration (s)	5711.0	5711.0	6275.1
Powering Energy (kWh)	294.4	294.4	355.0
Braking Energy (kWh)	124.8	124.8	96.6

Table 7.3: DMU, Hybrid-DMU and Pure Fuell Cell Vehicle Results

7.4 DMU and Fuel Cell Analysis

A vehicle powered by a $500\ kW$ diesel engine for primary motive power was simulated [35]. The engines of the vehicle are operated along the traditional propeller curve, and gave a total fuel consumption of 102 litres (table 7.3). If the CO_2 emissions for a diesel vehicle are $2.73\ kg\ell^{-1}$ [150] the total CO_2 produced is $278.5\ kg$.

A vehicle based on the diesel vehicle described above, with an additional battery pack was also simulated. The vehicle is operated in electric only mode, i.e. with the diesel engines turned off until the power demanded reaches a level where the engine can operate efficiently. At higher speeds the vehicle operates with both electrical and diesel power, with the operation of the engine being constrained around its optimum operating point. The vehicle captures the kinetic energy and stores it in the battery under braking. The total fuel consumption for this vehicle and journey was 82 litres (table 7.3), with the state of charge at the end of the journey within 2% of the starting state of charge. This relates to $224\ kg$ of CO_2 for the journey.

A fuel cell vehicle with a $470\ kW$ stack was used to provide motive power for the vehicle. The fuel cell only vehicle was found to take approximately 10 min longer (table 7.3) than the diesel vehicle to complete the given journey. This is primarily due to the reduced rate of change of power ($\frac{dp}{dt}$) in the fuel cell stack compared to the modelled diesel vehicle. The lower acceleration caused by the reduced rate of change of power prevents the vehicle from reaching the target line speed for a significant proportion of the journey therefore reduces the available energy to be recovered via regenerative braking. The total hydrogen consumption obtained by the simulation provides a means of benchmarking any fuel cell hybrid vehicle configurations to determine any energy savings.

7.5 Hybrid Power System Topology

The total power output from the proposed hybrid power system can be obtained from equation 4.12, and consists of the following models (figure 7.6):

- Fuel Cell Stack (section 4.3.2)
- Battery Pack (section 4.3.4)
- Rheostatic Brake (section 4.3.5)
- Hybrid Controller (section 4.3.6)

To determine the best hardware configuration and supervisory control strategy of the fuel cell and battery pack, to achieve the best possible performance for a HPS, two methods where chosen in the design of the HPS system. The first was based on a simple trial and error method, which consists of evaluating different component sizes and control strategies to obtain a suitable configuration. The second was the DCCS method outlined in chapter 4.

7.6 Trial and Error Method

The five fuel cell stack configurations listed in table 7.4 were evaluated with five battery packs; with capacities ranging from $100Ah$ to $500Ah$ in $100Ah$ steps. The resulting

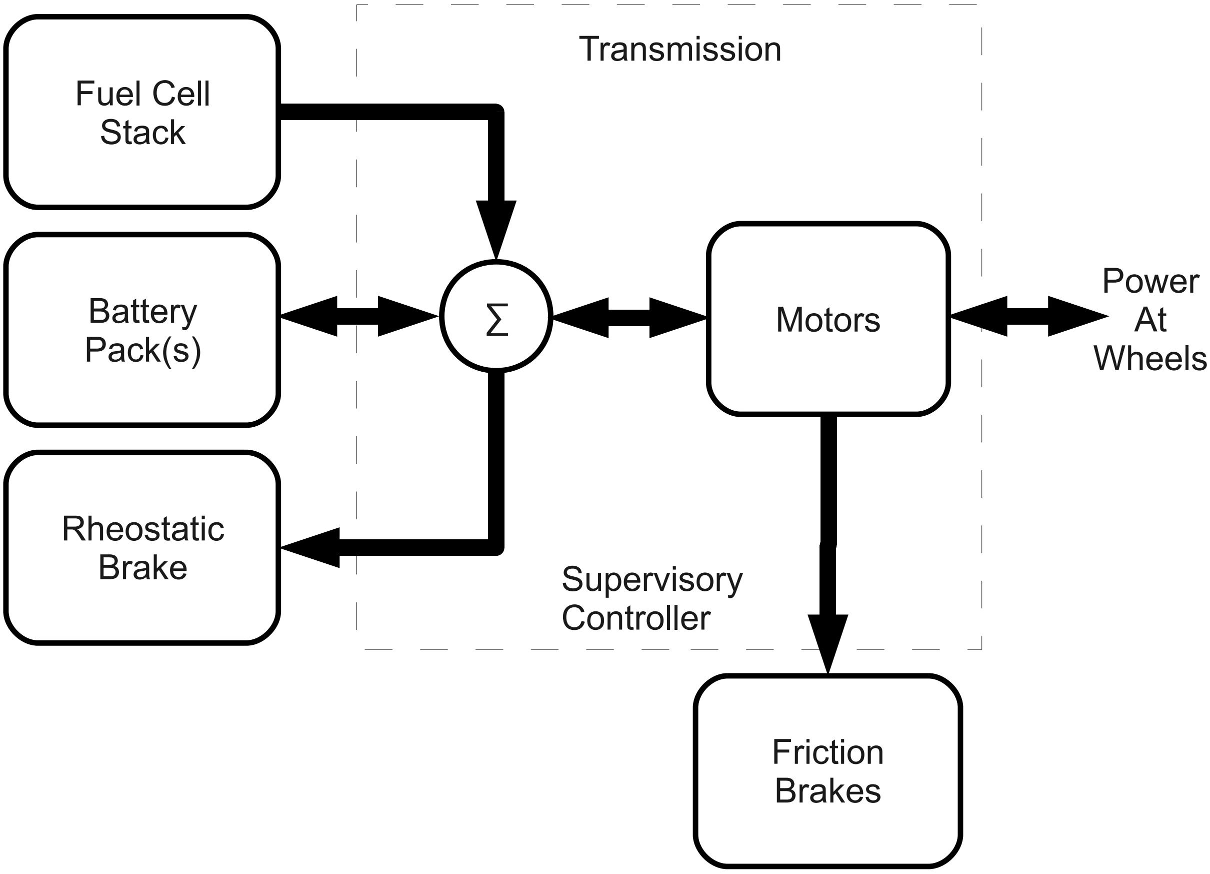


Figure 7.6: Proposed Drivetrain for the Fuel Cell Hybrid Railway Vehicle

FC ID	Power Max (kWh)	Positive Gradient (kWs^{-1})	Negative Gradient (kWs^{-1})
1	470	15.7	50.0
2	570	19.0	50.0
3	670	22.3	50.0
4	770	25.7	50.0
5	870	29.0	50.0

Table 7.4: Fuel Cell Power Limits

25 HPS combinations were evaluated using the HDEL (section 4.2) using the railway vehicle simulator outlined in section 7.2 to create the output duty cycle of the vehicles. The Load-Levelling (LL-CS) and Trickle-Charge (TC-CS) control strategies outlined in section 4.3.6 were evaluated with each hybrid power plant configuration.

7.6.1 Load Levelling Control Strategy

All simulation runs start with a battery SOC of 50% as shown by figure 7.7. The final SOC is found to vary significantly, while the mean SOC over the journey ranges from 31% to 62%; a variation of over 30%. The highlighted SOC profiles correspond to the three main modes the hybrid controller operates in:

A - shows a configuration that requires the controller to intervene due to the battery SOC reaching the upper allowed limit (SOC_{max}).

B - is when intervention is required due to battery SOC reaching critically low (SOC_{topup}) levels.

C - outlines a profile the selected control strategy is utilised for the duration of the journey with no intervention.

In a charge sustaining hybrid power plant for stable, sustainable operation the mean SOC must ideally be close to the initial value. Very small SOC swings often correspond to a battery pack which is over sized; adding unnecessary weight and cost to the system. While large SOC swings, particularly ones that reach the permitted upper or lower limits correspond to a battery pack that is too small for the hybrid configuration. Furthermore in these configurations the adopted control strategy becomes ineffective as the supervisory controller must intervene when the storage device SOC is outside the safe operating limits.

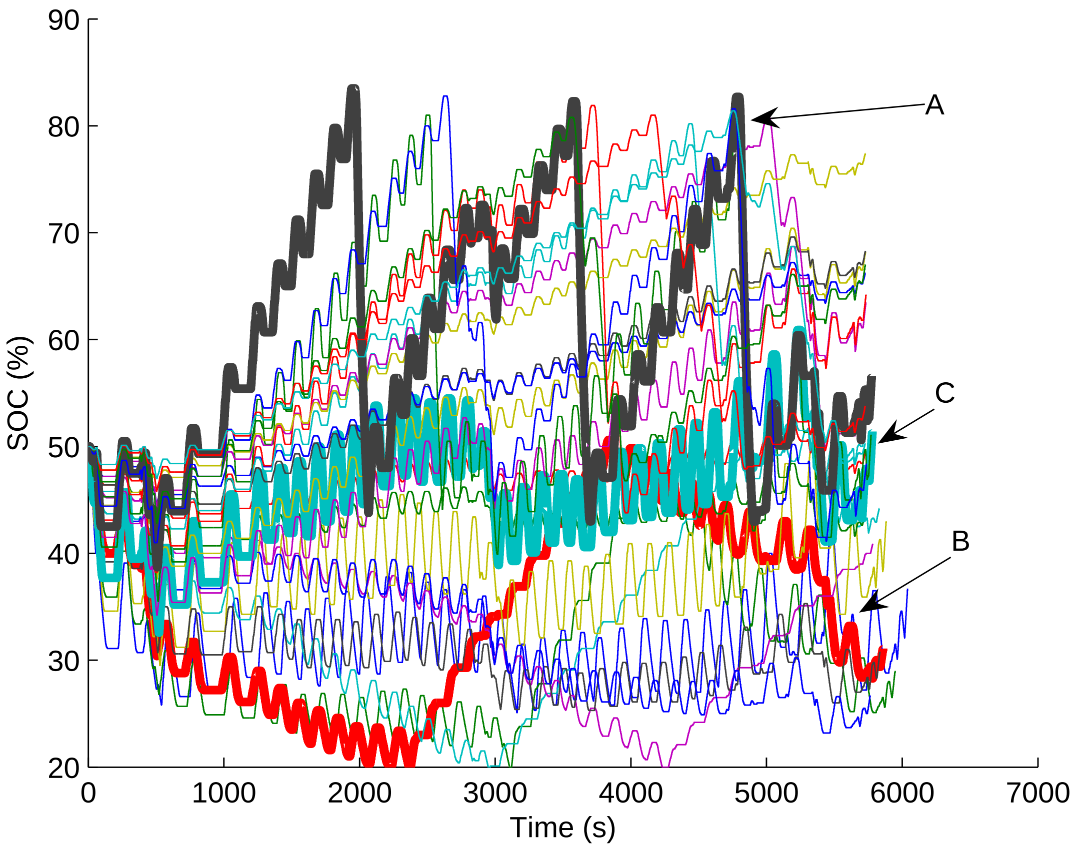


Figure 7.7: Battery State of Charge vs Time plot for different configurations using the Load Levelling Control Strategy

It can be deduced that with this control strategy for configurations which utilise smaller fuel cell stacks the battery often needs a top-up charge, while for the configurations with larger fuel cell stacks the battery has a tendency of being over charged and requires continuous discharging to remain within operating limits as shown by figure 7.8(e). The selected control strategy plays the most significant role for configurations that utilise a fuel cell stack of $570\ kW$ and $670\ kW$ irrespective of battery pack capacity.

A significant proportion of energy is lost via rheostatic braking instead of being captured by the battery pack in configurations with the smallest battery pack capacities as illustrated by figure 7.8(c). This is mostly due to the smaller packs not being able to absorb large amounts of energy in the relatively short period of time the vehicle spends decelerating. Somewhat counter-intuitively high amounts of energy are lost for configurations that use the smallest fuel cell stack ($470\ kWh$). This is due to the hybrid controller spending a significant proportion of time topping up the battery charge due to the battery SOC dropping below the lowest permissible limit (figure 7.8(e)). During this charging period hybrid operation is suspended, therefore braking energy must be dissipated via the rheostatic brake.

Finally the total journey duration does not change significantly over the different configurations (by approximately 5 min) while the overall hydrogen consumption varies between $24.5\ kg$ and $33.5\ kg$ for the different configurations; a variation of $9\ kg$.

(a) Mean State of Charge (%)

FC ID	Pack Count x1	x2	x3	x4	x5
1	31.862	31.143	34.781	35.521	34.117
2	38.083	**30.950**	33.011	43.847	47.188
3	45.766	49.326	53.431	55.683	55.555
4	54.289	57.994	57.683	60.673	61.276
5	59.585	58.122	59.801	60.288	**62.133**

(b) Hydrogen consumption (kg)

FC ID	Pack Count x1	x2	x3	x4	x5
1	**33.597**	32.629	31.47	32.134	31.105
2	30.201	29.343	28.173	27.328	27.324
3	28.643	27.826	27.646	27.643	27.643
4	27.358	26.866	25.851	25.518	27.946
5	26.889	26.106	26.259	25.143	**24.593**

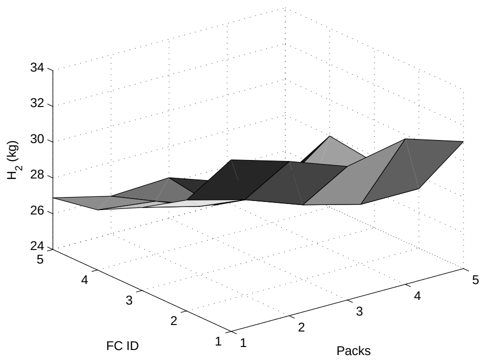
(c) Total journey duration (seconds)

FC ID	Pack Count x1	x2	x3	x4	x5
1	**6040.0**	5948.3	5859.4	5831.2	5783.6
2	5882.1	5835.5	5765.3	5729.3	5729.2
3	5780.1	5733.5	5729.5	5729.2	5729.2
4	5771.1	5734.1	5729.3	5729.1	5729.2
5	5774.6	5736.1	5729.4	**5729.0**	**5729.0**

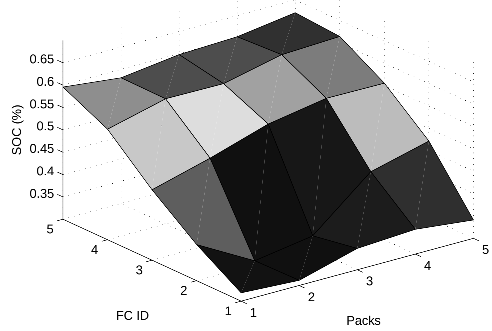
(d) Total rheostatic braking energy (kWh)

FC ID	Pack Count x1	x2	x3	x4	x5
1	0.06	1.37	1.91	2.52	1.67
2	0.06	0.05	0.07	0.09	0.09
3	0.06	0.07	0.08	0.08	0.08
4	2.59	0.08	0.12	0.14	0.08
5	3.76	0.14	0.11	0.15	0.16

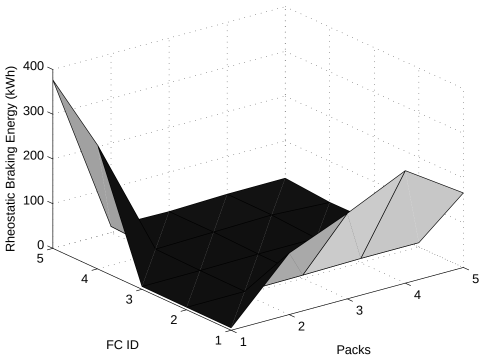
Table 7.5: Fuel Cell Hybrid Results for Load Levelling Control Strategy



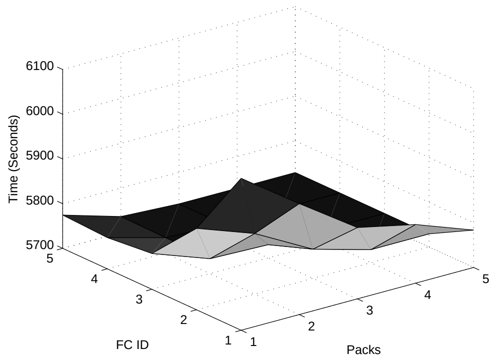
(a) Hydrogen Consumption Results



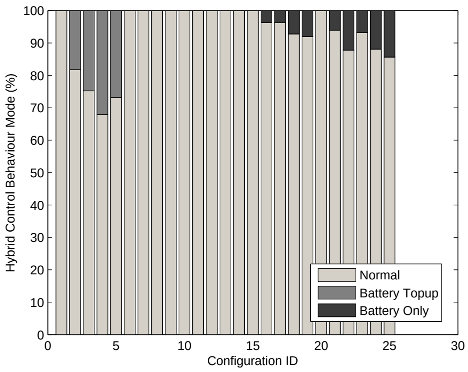
(b) Mean Battery SOC



(c) Rheostatic Braking Energy



(d) Journey Duration



(e) Hybrid Controller Status Plot

Figure 7.8: Fuel Cell Hybrid Results for Load Levelling Control Strategy

7.6.2 Trickle Charge Control Strategy

The battery SOC was prone to drift significantly outside the safe operating levels (figure 7.9(e)), due to the large proportion of time the hybrid control strategy operation is suspended, due to the SOC reaching its limits and the supervisory controller intervening. As with the load levelling control strategy a significant amount of energy is lost for the smallest battery pack and smallest fuel cell stack power configurations (figure 7.9(c)), the cause for these results are similar in nature to the previous results.

The variation in overall journey duration is approximately 4 min (figure 7.9(d)). This is most likely due to the significant intervention by the hybrid controller to maintain the battery SOC, especially with configurations that utilise larger battery packs and/or fuel cell stacks. There is a $5\ kg$ difference in hydrogen consumption between the best and worst fuel economies, however the relatively low variation is likely due to the control strategy not being used for large portions of the journey in many of the configurations.

7.6.3 Discussion

Analysis of the above results show the most suitable configuration to be a $670\ kW$ fuel cell stack with $60\ kWh$ to $90\ kWh$ of energy storage utilising a load levelling control strategy. This provides a hydrogen consumption of $27\ kg$ for the simulated journey. This figure translates into approximately $148.5\ kg$ of CO_2. It should be noted that this figure will be higher in practice as the conversion figure does not take into account indirect CO_2 contributors in the conversion process such as electricity; currently obtained by mostly fossil fuel powered power plants.

Compared with a pure fuel cell vehicle a hybridised fuel cell vehicle provides nearly a 30% reduction in fuel and emissions while not significantly effecting the overall journey duration (increase of less than 2%). Compared with a pure diesel vehicle; fuel cell hybrid

(a) Mean State of Charge (%)

		Pack Count				
		x1	x2	x3	x4	x5
FC ID	1	34.211	34.435	41.079	40.802	39.517
	2	52.379	49.684	**26.202**	47.665	50.604
	3	54.241	56.596	57.666	59.16	58.93
	4	61.504	62.19	61.992	61.676	63.179
	5	62.26	63.025	62.814	**63.633**	62.844

(b) Hydrogen consumption (kg)

		Pack Count				
		x1	x2	x3	x4	x5
FC ID	1	29.087	31.23	28.11	27.642	27.645
	2	28.645	28.719	28.307	27.059	**27.040**
	3	28.852	28.291	27.216	28.194	27.443
	4	30.092	30.152	27.436	28.358	26.388
	5	**32.033**	30.807	28.787	27.805	28.991

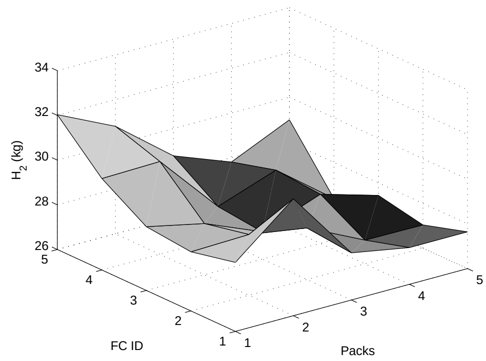
(c) Total journey duration (seconds)

		Pack Count				
		x1	x2	x3	x4	x5
FC ID	1	**5971.8**	5914.6	5814.4	5796.7	5795.7
	2	5810.4	5785.1	5747.0	5729.4	**5729.3**
	3	5800.3	5736.8	5729.6	**5729.3**	**5729.3**
	4	5854.4	5738.0	5729.4	**5729.3**	**5729.3**
	5	5895.4	5739.0	**5729.3**	**5729.3**	**5729.3**

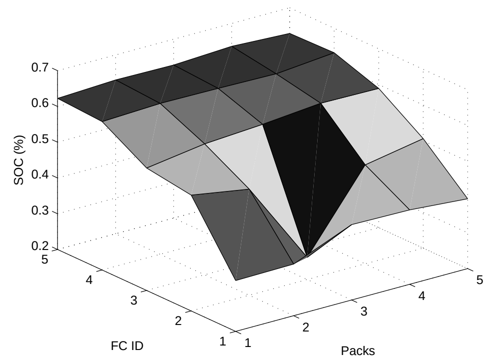
(d) Total rheostatic braking energy (kWh)

		Pack Count				
		x1	x2	x3	x4	x5
FC ID	1	1.238	2.442	2.315	2.787	3.217
	2	2.986	1.523	0.994	0.753	0.747
	3	4.252	0.697	0.766	0.767	0.765
	4	6.264	0.762	0.779	0.784	0.799
	5	8.261	0.833	0.824	0.835	0.879

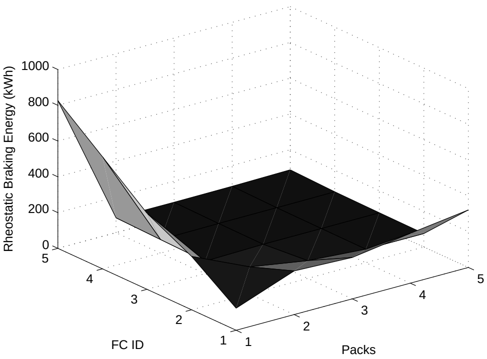
Table 7.6: Fuel Cell Hybrid Results for Trickle Charge Control Strategy



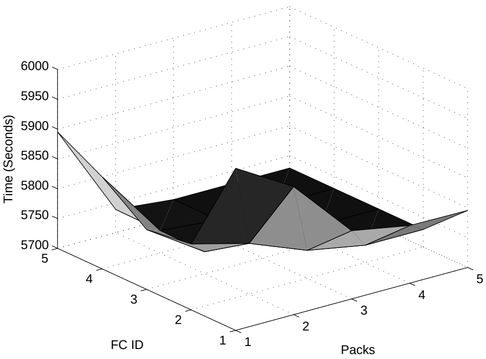
(a) Hydrogen Consumption Results



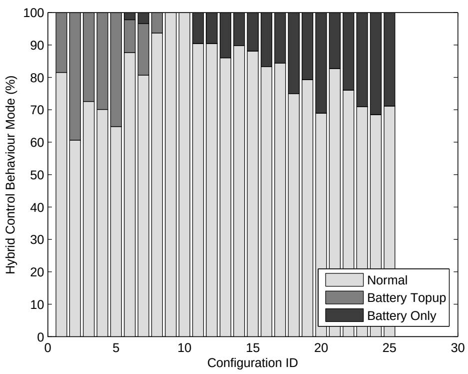
(b) Mean Battery SOC



(c) Rheostatic Braking Energy



(d) Journey Duration



(e) Hybrid Controller Status Plot

Figure 7.9: Fuel Cell Hybrid Results for Trickle Charge Control Strategy

vehicles have the potential of reducing CO_2 emissions by up to 45%, however analysis of the two control strategies presented in this work show that the optimum performance of a hybrid drivetrain is significantly affected by the adopted hybrid control strategy.

7.7 Duty Cycle Constrained Selection Method

The implementation of the method outlined in section 4.1, in which the analysis of an application duty cycle is used to determine key parameters, and characteristics of a HPS is presented in the following sections.

7.7.1 Duty Cycle Capture

The power cycle shown in figure 7.10 was obtained from the railway vehicle simulator (section 7.2). As with the previous method an assumption was made that the electrical to mechanical energy conversion process has an overall efficiency of 80% (i.e. to produce the 374kW of power at the wheels of the vehicle an electrical power of 468kW is required). This efficiency value takes into account any losses in the drivetrain due to the vehicle traction motors, transmission, gear boxes, etc.

7.7.2 Energy Characterisation and Analysis

Results from the energy characterisation and analysis of the power cycle obtained by the railway vehicle simulator are outlined in figures 7.11 and 7.12. The relationship between the duration (t_d); event separation (t_b) or delay between events; and energy content (E) of each powering/regenerative event is illustrated in figures 7.13(a) and 7.13(b). Analysis of the ‘powering’ data provide the following key characteristics:

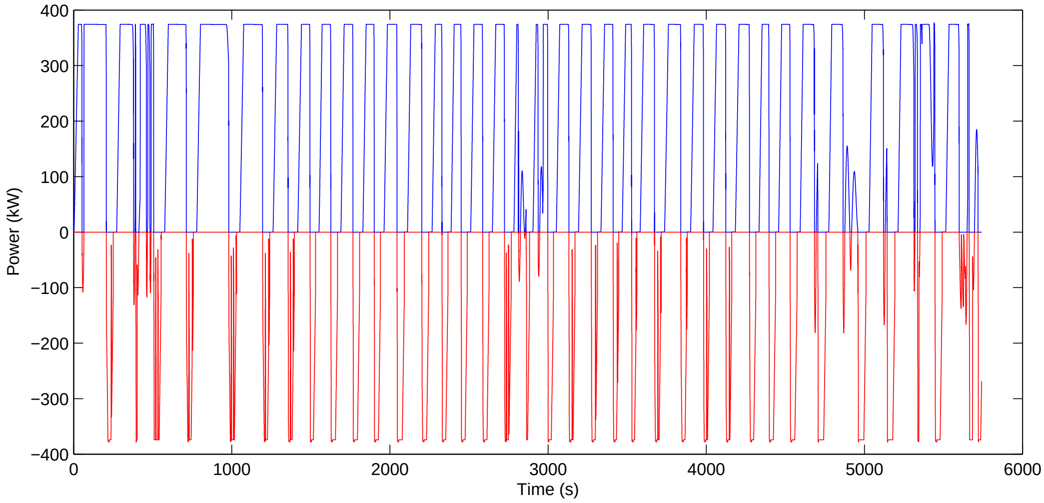


Figure 7.10: Power Cycle At Wheels

- A significant proportion of powering events have an energy content between $5kWh$–$10kWh$
- these events last on average between $40s - 80s$
- An average delay between events are between $80s - 100s$
- The maximum sustained power demand can be determined to be $467.5kW$ ($374kW$ at the wheels) with a duty cycle of approximately 62% (figure 7.14)

Analysis of the 'regenerative' data (figure 7.13(b)) provide the following key characteristics:

- Average energy content of regenerative events are between $2.5kWh - 3.5kWh$
- On average events last between $35s - 50s$
- Delay between regenerative events are $95s - 110s$

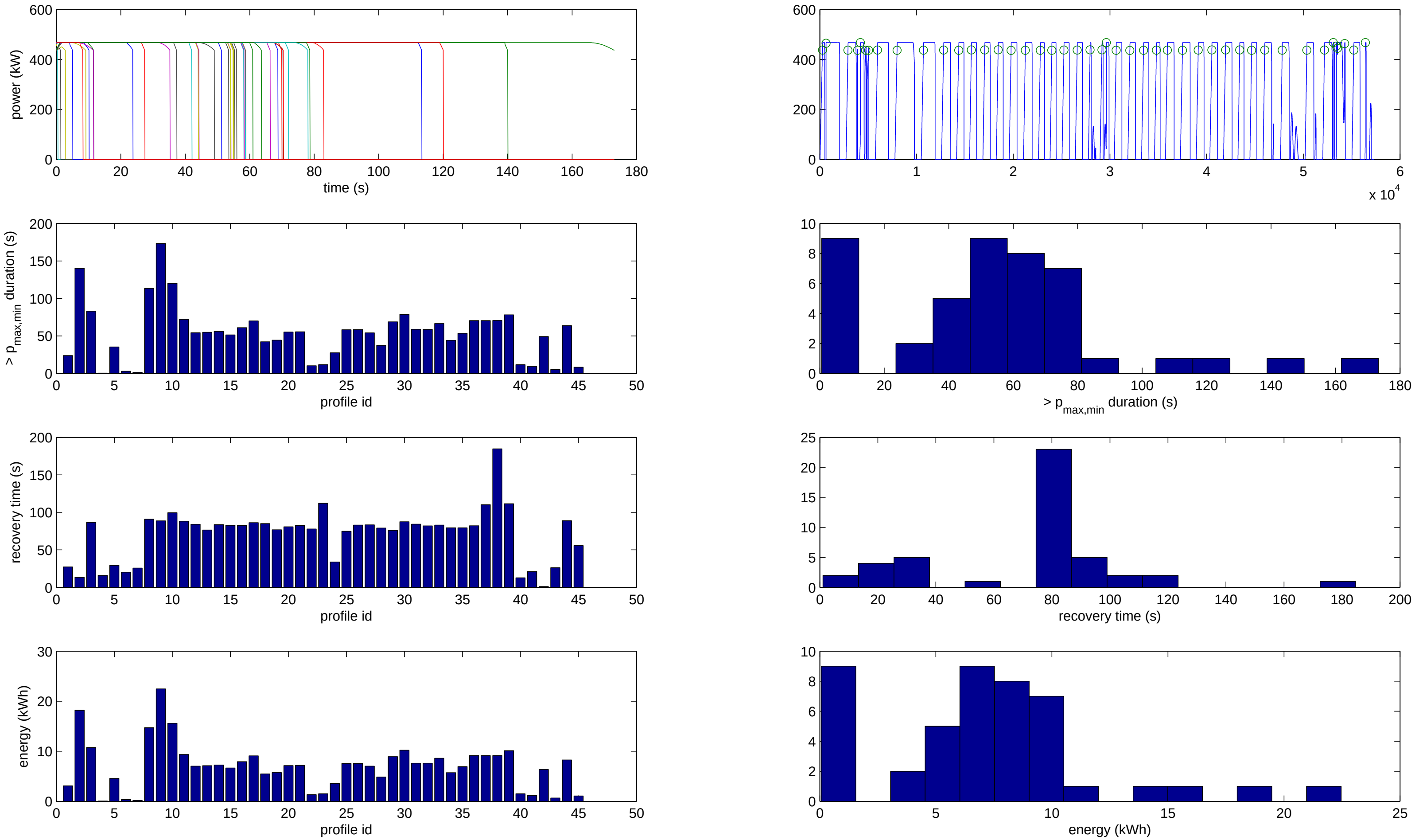


Figure 7.11: Powering analysis breakdown

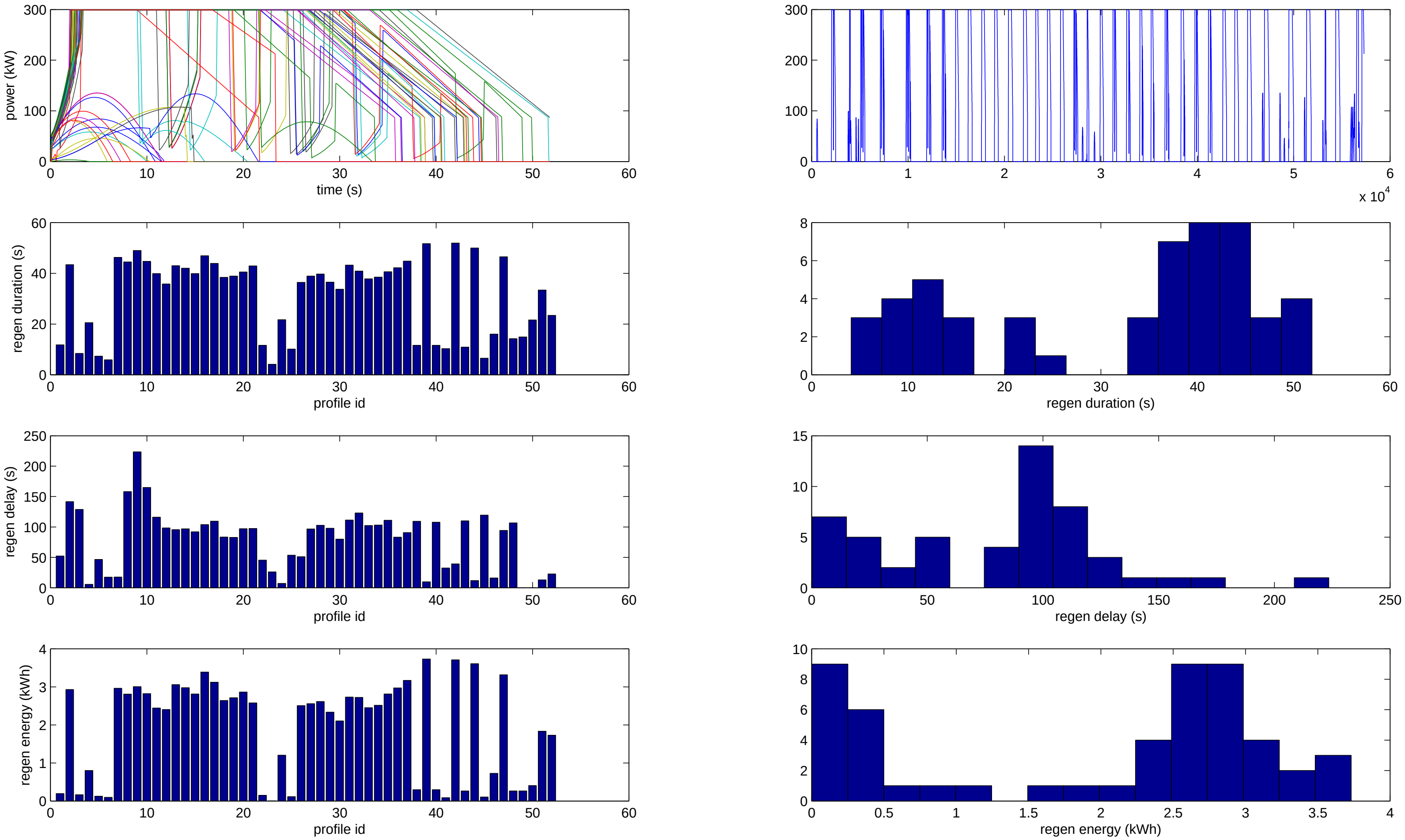


Figure 7.12: Regenerative analysis breakdown

	Power Gradient (kWs^{-1})		Power (kW)		Duration (s)				
	$\frac{dp^+}{dt}$	$\frac{dp^-}{dt}$	p_1	p_2	t_1	$t_2 - t_1$	$t_3 - t_2$	$t_4 - t_3$	t_5
Primary	20.0	$> p_1$	468	468	0	0	0	60	-
Secondary	$> p_1$	$> p_1$	468	0	0	60	540	0	600

Table 7.7: Primary and Secondary Energy Device Characteristics

7.7.3 Architecture and Control Strategy Selection

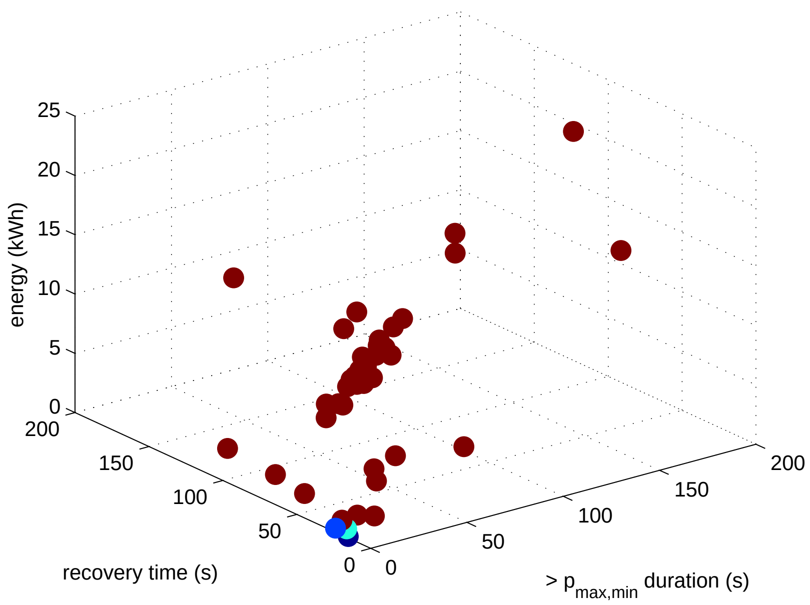
As the hybrid drivetrain is to be based on a fuel cell hybrid vehicle, a series hybrid all-electric architecture is the most appropriate.

From equations 4.1 and 4.2, given an average storage device efficiency (μ_{inout}) of approximately 53% for the NiCd battery packs (Appendix C); $E_s = 124.8\ kWh$; and $E_{pwr} = 294.8\ kWh$, yields an energy mix ratio (γ_{mix}) of 0.22. Therefore it is safe to conclude the most suitable charge sustaining hybrid drivetrain architecture would be a series mild hybrid architecture.

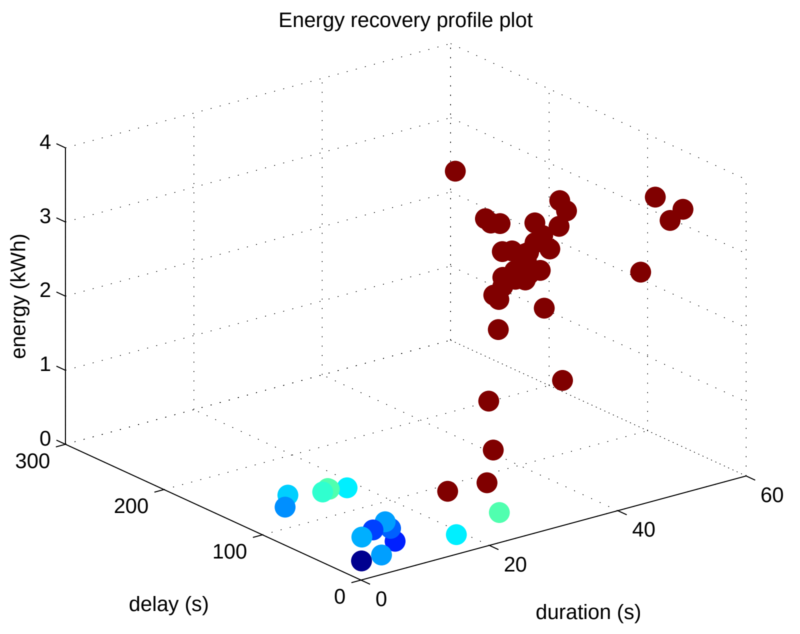
Due to the relatively slow response of a typical fuel cell system, any adopted control strategy must perform two key tasks:

- Load levelling using the on-board storage device
- Charge sustaining of on-board storage device

With this requirement in mind, the performance characteristics for the primary and secondary (storage) devices are presented in table 7.7. Therefore a modified load levelling control strategy (section 4.3.6) with a primary turn on delay (t_{delay}) of $15s$ was chosen.



(a) Energy(E) vs Duration(t_d) vs Recovery (t_b) for Powering Power



(b) Energy(E) vs Duration(t_d) vs Recovery (t_b) for Regenerative Power

Figure 7.13: Powering/regenerative analysis

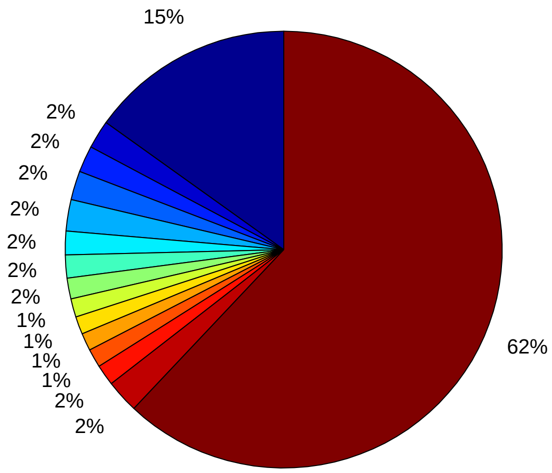


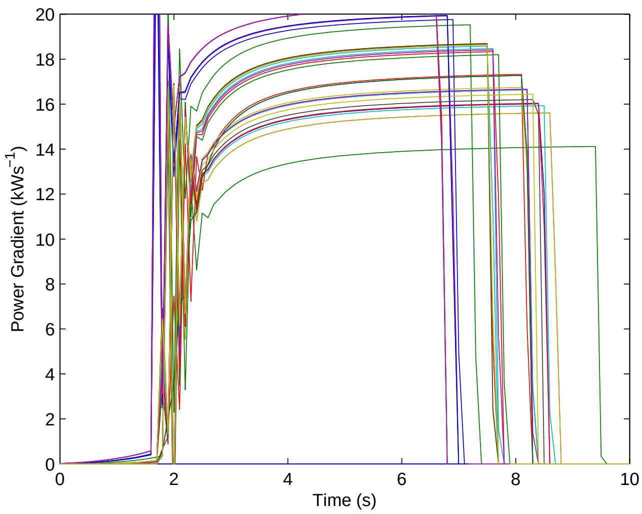
Figure 7.14: Duty cycle analysis

7.7.4 Component sizing and Evaluation

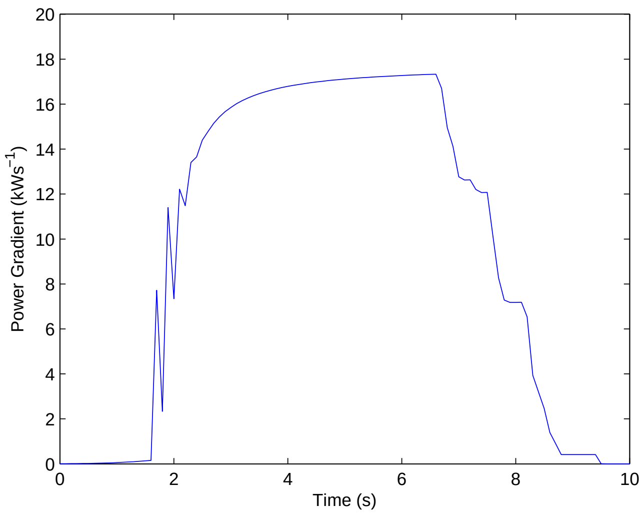
Due to the high proportion of time the vehicle requires maximum output power, the primary energy source (fuel cell) should ideally operate at maximum efficiency, to minimise the overall fuel consumption. For the modelled fuel cell stack, this figure is approximately at 47.5% of full output power, therefore a $985\ kW$ fuel cell stack was selected.

During a typical powering event, the rate of change of power is between $10\ kWs^{-1}$ and $20\ kWs^{-1}$ (figure 7.15(a)). Therefore if the primary energy source (fuel cell) was tuned to meet this requirement it would be possible to maintain the overall performance of the vehicle in the event of loss/failure of the on-board energy storage devices. Therefore a primary fuel cell of $985\ kW$ with a power gradient of $20\ kWs^{-1}$ was selected.

From figure 7.12 the average regenerative energy per event can be determined to be no more than $4\ kWh$, while the highest value is no more than $5\ kWh$. In practice the energy absorbed by the energy storage devices will be less than this value therefore a single battery pack of $100\ Ah$ ($30\ kWh$) would be sufficient for this HPS.



(a) Composite



(b) Mean

Figure 7.15: Rate of change of traction power per event

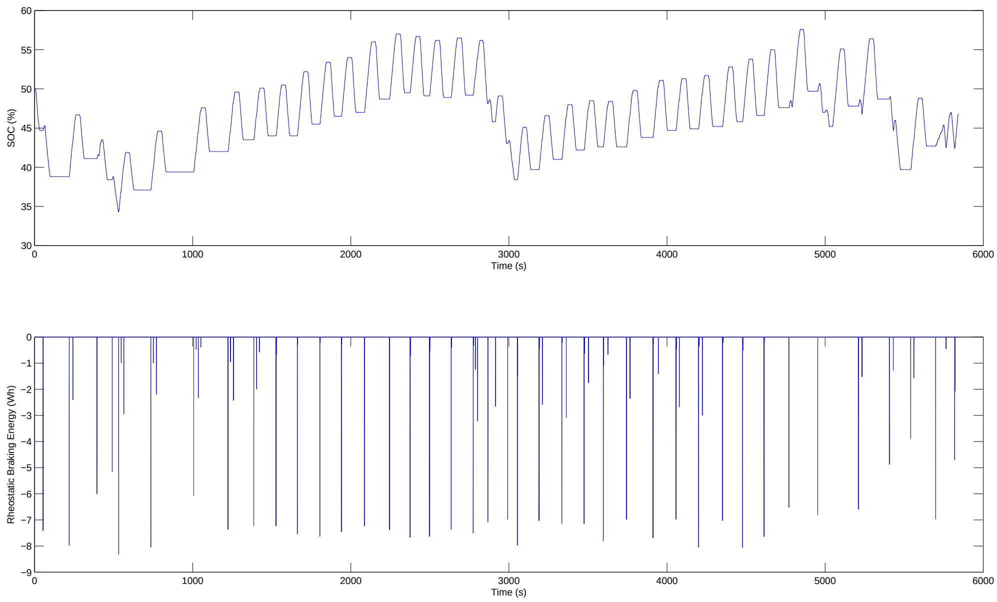


Figure 7.16: Results of hybrid drivetrain simulation

Hydrogen Consumption (kg)	26.70
Journey time (s)	5841.70
Average SOC (%)	46.00
ΔSOC (%)	-3.00
Rheostatic Braking Energy (kWh)	0.49

Figure 7.17: Results of hybrid drivetrain simulation

7.7.5 Discussion

The results from the chosen configuration with the tuned charge sustaining control strategy (section 4.3.6) are outlined in table 7.17 and figure 7.16. Analysis of the results show that the charge of the energy storage device is stable and little energy is lost to the rheostatic braking.

Power Plant Type	CO_2 Emissions Total (kg)	Grams per seat km	kg per vehicle km
Diesel	278.5	27.9	3.54
Diesel Hybrid	224.0	22.4	2.85
Fuel Cell	209.0	20.9	2.69
FC Hybrid	148.5	14.8	1.88

Table 7.8: Comparison of CO_2 emissions by primary power plant type

7.8 Conclusions

The relationship between H_2 generation and CO_2 emissions varies significantly and is largely based on the method the hydrogen is produced. Currently steam reforming of natural gas comprises almost 50% of the world's hydrogen generation. If hydrogen is obtained by means of steam reforming approximately $5.5\ kg$ of CO_2 is generated for every $1\ kg$ of H_2 [43]. Based on this assumption, the CO_2 emissions for a hybrid railway vehicle utilising a fuel cell as its primary power plant has the potential of significantly reducing the CO_2 emissions a conventional diesel railway vehicle produces (table 7.8).

The two design methods provided HPS configurations that exhibited similar fuel consumption and performance characteristics. However, the DCCS method provided a means of greatly simplifying the design process, while reducing the number of iterations required to reach a final solution.

7.9 Critical Review of Method

Like in the previous case study presented in chapter 6 the application duty cycle was significantly complex to provide an opportunity to explore the application of each step of the DCCS method. The inherent repetitive and repeatable nature of railway duty cycles meant that the case study was ideally suited for the method. Furthermore, the alternate design method based on the trial and error selection of the system components provided a good basis to compare the complexity and effort involved in the application of the different methods to the case study.

Chapter 8

Conclusions and Future Work

This chapter begins with a summary of the three case studies presented in chapters 5, 6 and 7. This is followed by a review of the key findings presented in this thesis and the strengths of the DCCS method.

Next a discussion of the likely limitations of this approach and its short comings when applied to real world applications is presented. Finally, the likely future research path to further develop this method is outlined, giving details of the key areas of further work and practical validation of both the simulation framework and method.

8.1 Conclusions

This thesis presents a method for use in designing hybrid power systems, particularly for aiding with making decisions related to energy storage device sizing, power plant technology and control strategy selection. The method was applied to three distinct case studies with varying levels of complexity from a simple hybrid-wind power generation system to a fuel cell hybrid railway vehicle.

8.1.1 Analysis of DCCS Method in Case Studies

Case Study 1

The first of the case studies (Chapter 5) applied the DCCS method to a hybrid power system comprising of a $600\ kW$ wind turbine coupled with an energy storage device. The objective of the system was to improve the discontinuous nature of power generation via wind power by ensuring the hybrid power system produced an output power equal to the average power generated by the wind turbine.

An example application with a relatively simple output duty cycle was chosen to highlight the application of the **Energy Characterisation and Analysis** and **Architecture and Control Strategy Selection** steps of the DCCS method. Thus outlining the application of the initial steps related to generating a suitable output duty cycle and the deconstruction of the output duty cycle for analysis.

Case Study 2

The next case study (Chapter 6) expanded upon the previous work and introduced a more complex output duty cycle for the hybrid power system to service. The case study was selected to mainly highlight the first **Duty Cycle Capture** step and help outline the complexities associated with interpretation of the application duty cycle. Furthermore, the relatively open ended design decisions related to the overall operation of the hybrid power system's control strategy was introduced. Particularly when deciding the cycle time frame of the energy storage devices such as storing energy over hours, days, months or seasons.

Case Study 3

The final of case study (Chapter 7) provided a complete analysis of the DCCS method using a complex application duty cycle related to the railway vehicle servicing a commuter route and provides an opportunity to apply the four primary steps that make up the DCCS method in detail.

Furthermore a complete modelling of a railway vehicle was presented and results compared with a trial and error design method comprising of several rule based control strategies. Part of this work, was presented at the Eleventh Grove Fuel Cell Symposium 2009 and has been published in the Journal of Power Sources [121].

8.1.2 Key Findings

Drivetrain hybridisation offers a real solution for improving the efficiency of power systems servicing dynamic duty cycles. The advantages over traditional single source power systems are generally related to a hybrid power system's ability to be optimised to meet the different types of output duty cycles encountered in a typical application. For example super capacitors can be used to service high transient power demands; chemical batteries can provide medium power and store energy; while traditional fuel based power sources can be optimised to provide the average power and overall energy for a given application duty cycle.

To gain a high performance from a hybrid power system, three fundamental aspects of the given system must be considered during the design phase. These can be broadly described as the **Hardware**, intended **Application** and operational **Management** of the system components. To achieve high performance, reliability and efficient operation of a hybrid drivetrain all three of these aspects should be considered during the design of any hybrid power system.

At present there are two fundamental types of hybrid power systems in active development and deployment. These are systems that are mass produced in significantly large numbers for a specific application, and bespoke systems often optimised for a particular task. In practice these systems are very similar physically, however the available resources and design approaches vary significantly. For example in the automotive industry, vast amounts of resources are spent optimising system performance, while stand alone diesel-hybrid generators are produced with significantly lower research and development budgets.

The method presented in this thesis is aimed at the second type described above, the key advantage of this approach over other available methods, is the significant reduction for complex iterative computation, and the ability to make informed design decisions that aid in tuning a HPS to its intended application with very little in-depth system modelling.

8.1.3 Strengths

Possibly the most significant advantage of the DCCS approach presented in this thesis is its ability to provide an insight into key characteristics of a given application duty cycle and translate these attributes into energy and power requirements. The approach facilitates the selection of ESD technologies based on the likely duty cycle a given application will exert on its power source. Therefore this approach is particularly helpful given that current ESD technologies have highly variable operating characteristics such as energy/power densities; cycle lifetimes; environmental robustness and maintenance requirements; and more importantly cost.

Furthermore, when comparing the other popular design methods utilised in power source sizing and control strategy selection of HPS, the DCCS method involves significantly less modelling and computation. This is an important point to consider given the application space the method is intended for, i.e. bespoke or devices with relatively small production quantities with modest research and development budgets.

Finally, it is worth mentioning this method is ideally suited for use by systems design engineers, at feasibility or relatively early stages of design and development of a given hybrid system.

8.1.4 Limitations

As the DCCS method uses only the duty cycle of a given application as its input dataset, the resulting system configuration is highly tuned to a given input dataset. Therefore unrepresentative input datasets will often provide misleading or mismatched results from the method.

Furthermore, duty cycles which exhibit highly asymmetric or uneven positive/negative power events will result in poor results, as the method relies on the input duty cycle to be repeatable and repetitive. A typical example of such an ‘asymmetric’ duty cycle could be a railway vehicle servicing a long mountainous route, where a high amount of power is required during the ascent and a disproportional amount of regenerative braking energy is encountered during the descent. Therefore, for such an example the installed ESD of the hybrid system would be considerably larger than necessary to absorb the regenerative braking which occurs during a selected phase of the overall journey.

Finally, the success of the approach is highly dependant on the interpretation and analysis of the input duty cycles, therefore implementation by inexperienced users could lead to poor results.

8.2 Future Work

The following sections provide the author's views on suitable follow on work to further refine and improve the DCCS method, with the objective of developing an automated tool to perform the analysis. The key follow on research areas can be summarised as the characterisation of *typical application duty cycles* and *supervisory control strategies*.

The first of these would involve an investigation into typical duty cycles currently serviced by single source power systems, followed by the identification of attributes which lend themselves to benefit from being serviced by HPS. Together with the classification of common characteristics in different duty cycles. Investigation of this nature is currently being carried out by a number of groups including ones at the Universities of Birmingham and Warwick looking into railway and automobile duty cycles and their effects on energy efficiency and emissions. By compiling an extensive set of typical duty cycles and their key characteristics it will help identify duty cycles which would benefit from the DCCS method and help better understand the limitations of the method.

The other key area worth further study is the investigation into supervisory control strategies currently being considered for HPS. The ideal outcome of the investigation would be a comparison table of control strategies with respect to their duty cycles. This would aid in the selection of a suitable supervisory control strategy based on a given application duty cycle. Early stages of this research is underway at the University of Birmingham while much work is currently underway around the world looking at developing suitable supervisory control strategies for HPS.

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Appendix A

Duty Cycle Generator

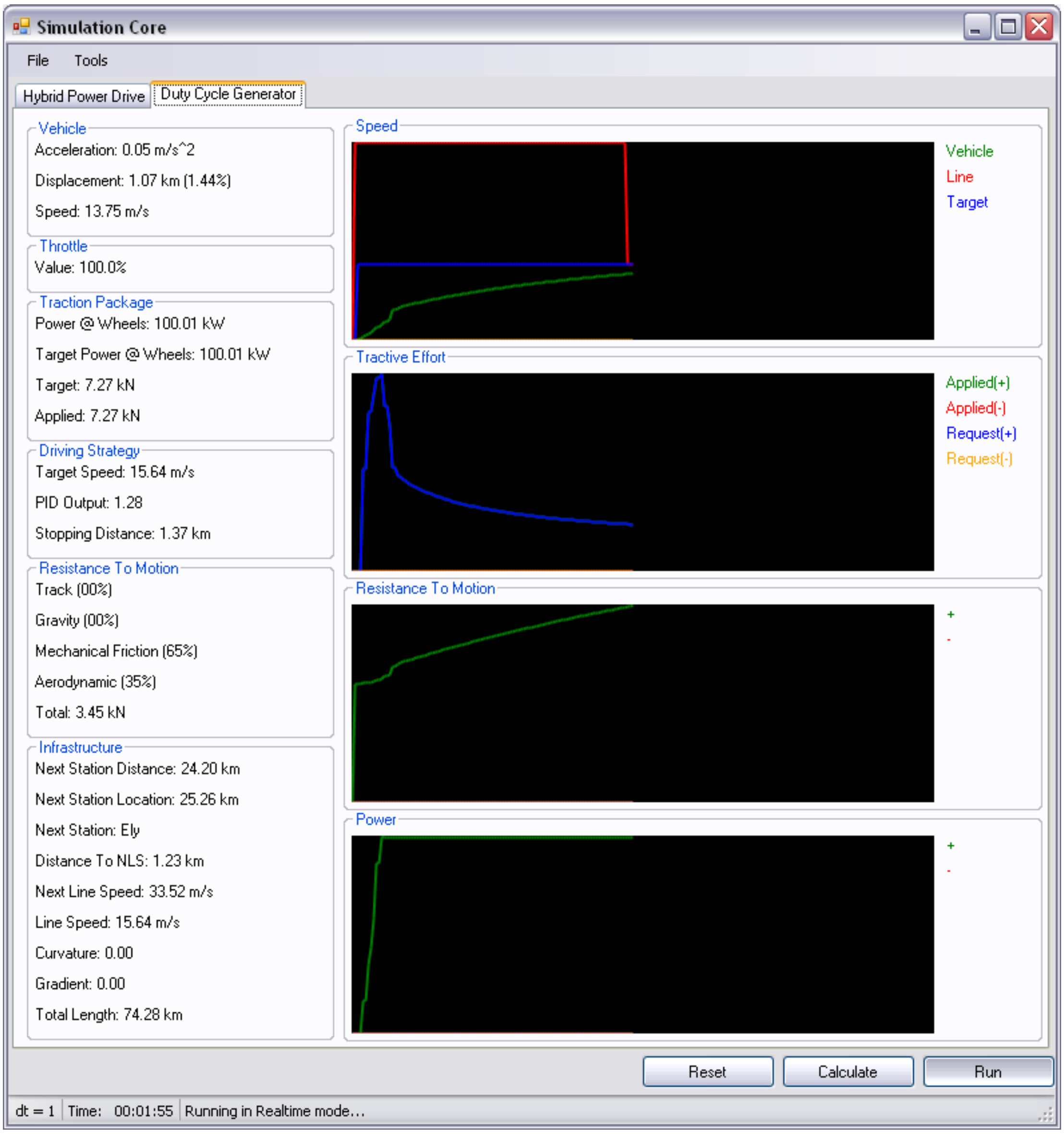

Figure A.1: Screenshot of the Railway Vehicle Simulator

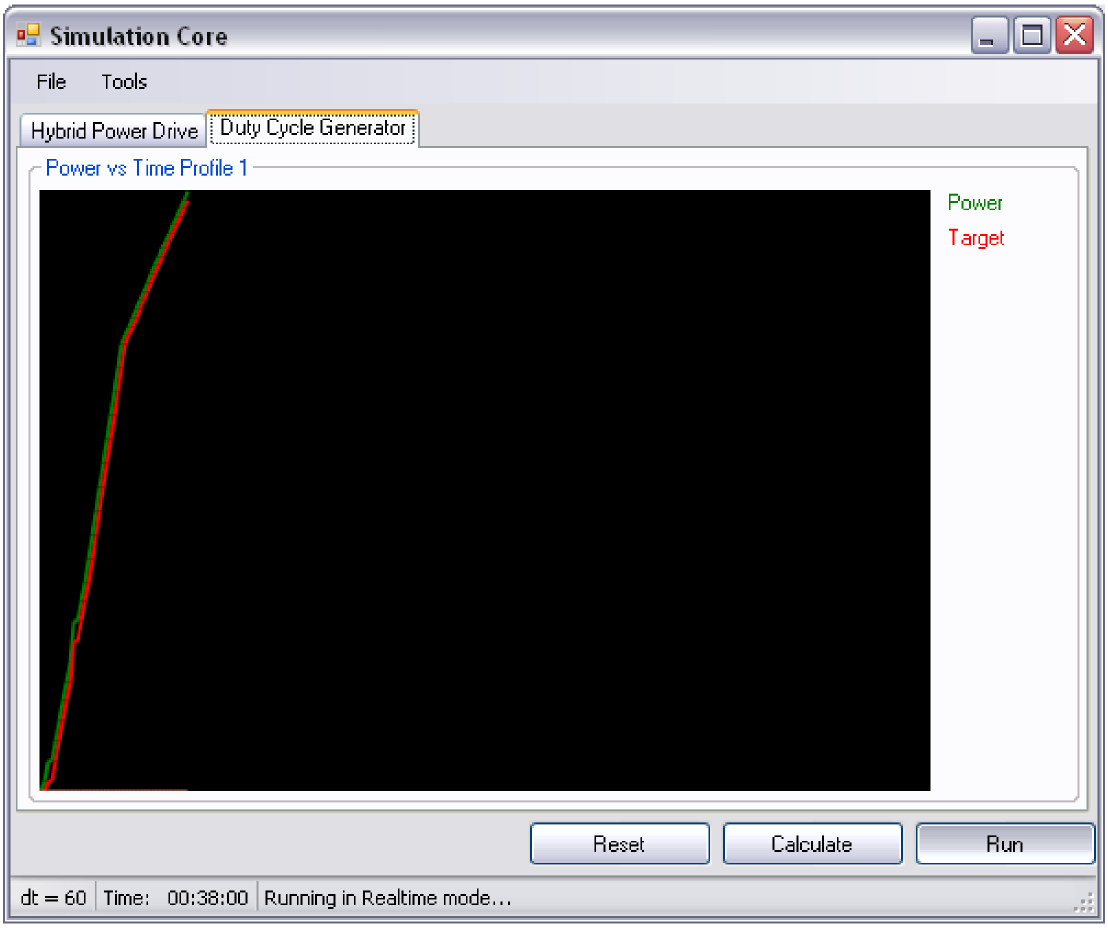

Figure A.2: Screenshot of the static power profiler (SPP)

Appendix B

Hybrid Power System Simulator

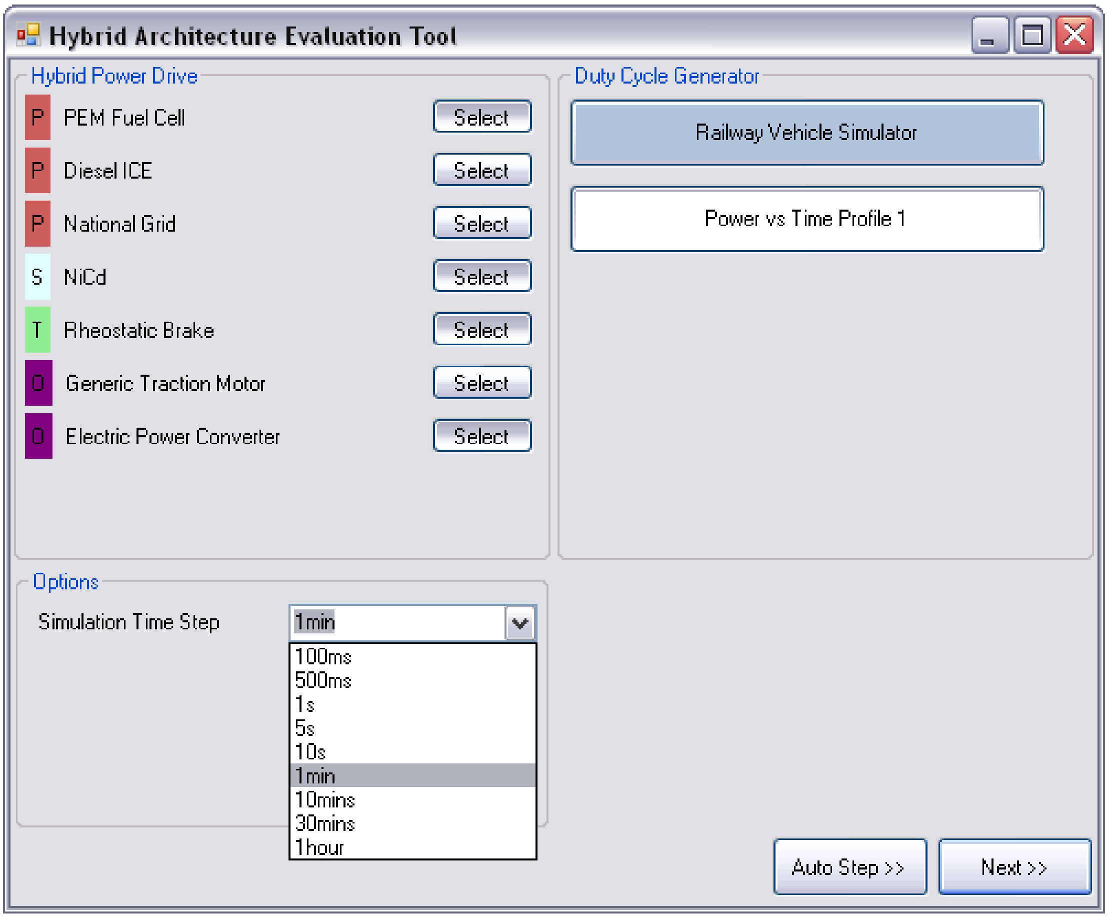

Figure B.1: Screenshot of model selection screen of the Hybrid Evaluation Tool

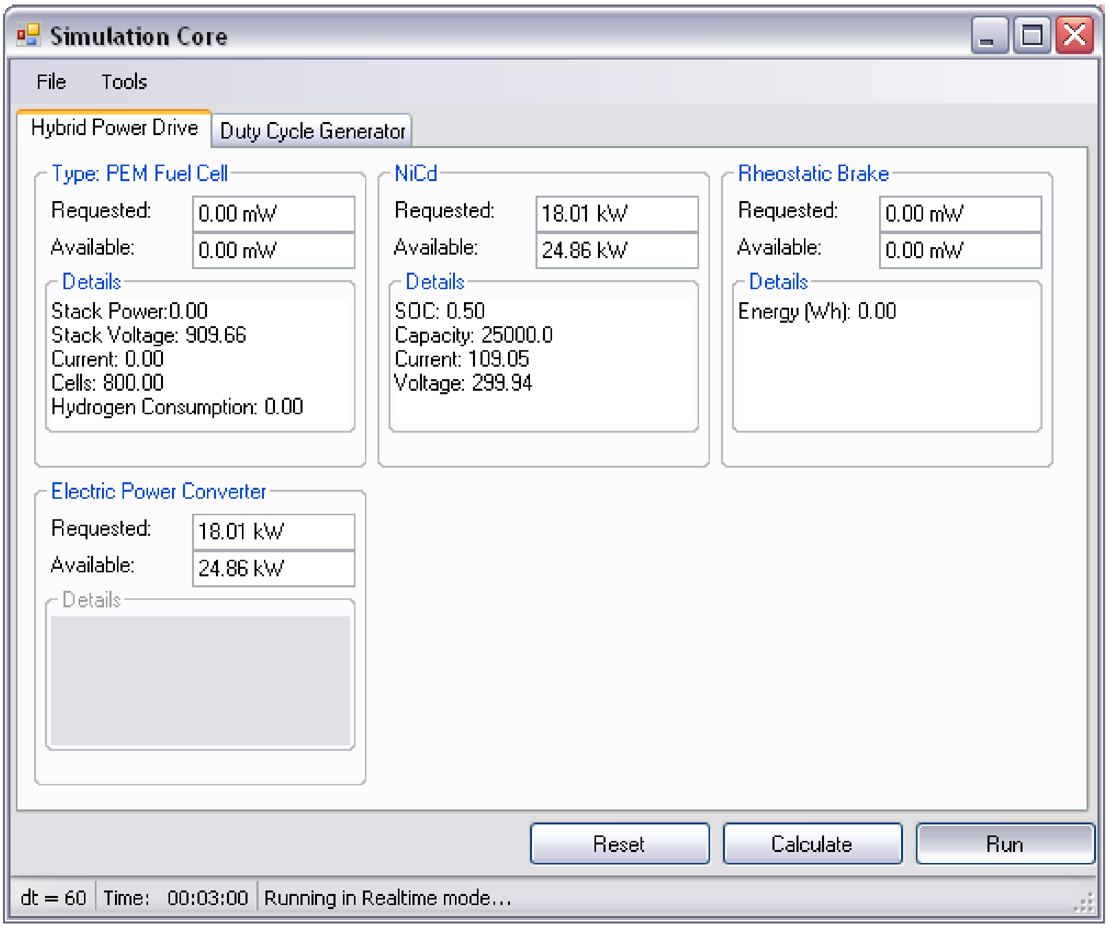

Figure B.2: Screenshot of the Hybrid Power System simulator

Appendix C

NiCd Battery Pack Storage Efficiency Evaluation

In this section the storage efficiency parameter, μ_{inout} (section 4.1.3) of the NiCd battery pack modelled in section 4.3.4 is investigated. A single $30\ kWh$ battery pack is subjected to multiple charge-discharge cycles (with varying values), where its SOC is increased from 25% to 75% then discharged to 25%. Please refer to figure C.1 for an example.

The total energy consumed to increase the SOC, and energy extracted during the discharging of the pack is then calculated, based on standard charge/discharge rates used in chemical battery evaluation tests. The results of these experiments are outlined in table C.1. By taking an average value of these efficiency parameters the overall storage efficiency for the NiCd battery pack model (μ_{inout}) was found to be 53%.

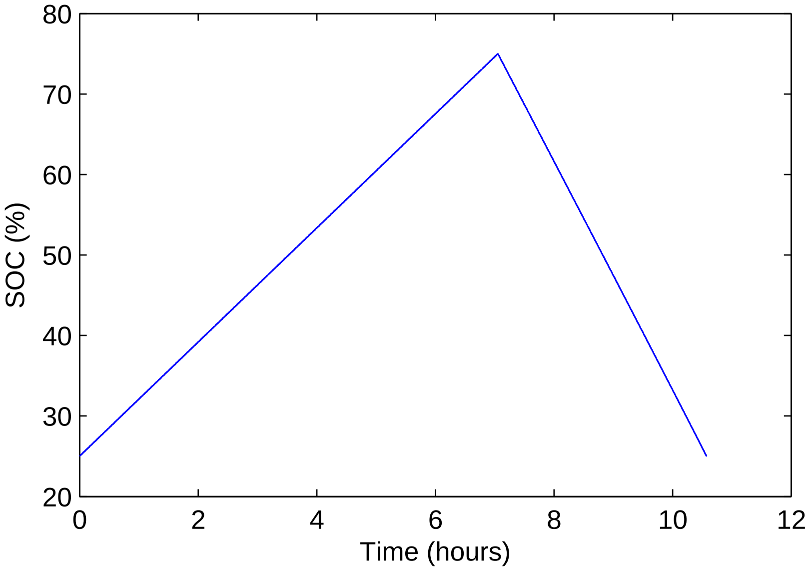

Figure C.1: SOC profile for a 30 kWh battery pack with a charge/discharge rate of 1/10C (3kW)

Discharge / Charge Rate (kW)	Stored Energy (kWh)	Extracted Energy (kWh)	Efficiency (%)
1/10 C	21.17	10.56	49.88
1/4 C	20.80	10.65	51.06
1/2 C	20.19	10.76	53.28
1 C	19.13	10.93	57.14
2 C	18.40	10.29	55.92
5 C	17.71	9.04	51.06

Table C.1: Results of NiCd battery pack storage efficiency investigation

Appendix D

Publications

- Danushka Meegahawatte, Stuart Hillmansen, Clive Roberts, Marco Falco, Andrew McGordon, Paul Jennings, Analysis of a fuel cell hybrid commuter railway vehicle, Journal of Power Sources, Volume 195, Issue 23, Selected Papers from the, Eleventh Grove Fuel Cell Symposium London, United Kingdom and Selected Papers from E-Mrs Spring Meeting 2009, Strasbourg, France, 1 December 2010, Pages 7829-7837, ISSN 0378-7753, DOI: 10.1016/j.jpowsour.2010.02.025.
- Lu, S.; Meegahawatte, D. H.; Guo, S.; Hillmansen, S.; Roberts, C.; Goodman, C. J.; , ”Analysis of energy storage devices in hybrid railway vehicles,” Railway Engineering - Challenges for Railway Transportation in Information Age, 2008. ICRE 2008. International Conference on , vol., no., pp.1-6, 25-28 March 2008.