Technische Universität Graz

AVL List GmbH Graz

Sheng YU

Development of Energy Management for a Fuel Cell Electric Vehicle

Master Thesis

Graz University of Technology

Faculty of Mechanical Engineering and Economic Sciences

Institute of Automotive Engineering

Supervisor:

Associate Prof. Dr. Mario Hirz, Institute of Automotive Engineering

Industry Supervisor:

Markus Kogler, AVL List GmbH, Powertrain Controls

Blocked until March 2024

Graz March 2019

Acknowledgement

Along with the finalization of this thesis, my internship in AVL List as well as study at Graz University of Technology (TUG) come to the end. Such an interesting and unforgettable experience makes my abroad learning life valuable and meaningful. This master thesis cannot be completed without help and support from my professors, colleagues, friends and families. Here I would like to show my sincere appreciation to all of them.

I am particularly grateful to Prof. Mario Hirz for being my supervisor in TUG. From the beginning of my study in Graz, he provided many useful suggestions for my study as well as life in Graz in very detail. As for my thesis, Prof. Hirz gave me very professional advices, showed me useful literatures and discussed and organized my working plan with my tutor in AVL. Moreover, using his precious time, Prof. Hirz revised my thesis with patience and high-level professionalism.

Many thanks to department manager Patrick Teufelberger in AVL for giving me the chance to do my thesis in AVL, communicating with Prof. Hirz to organize the work plan, making me stay on schedule and giving me suggestions after each two-week reporting.

I should also give a big thanks to my supervisor in AVL List, Markus Kogler, who continuously guided and supported my work with infinite patience from basic knowledge to top-level structure, answering my basic questions and correcting my working direction. Moreover, he introduced many colleagues to me who gave me inspiration about problems we faced, shared with me available resources in company that supported my work. I must admit, this work would not be finished without the support of Markus.

I also would like to express my gratitude to Stefan Trojer, who is my associate supervisor in AVL with rich experience of fuel cell research. From the very beginning of this work, Stefan helped me to solve many office stuff and computer things, told me lots of basic knowledge about my work field and plenty of useful materials to get me on track as soon as possible.

Thanks to my girlfriend LUO Wenjun, she always companied with me during my study in Graz, and encouraged me in my thesis. She provided many useful suggestions, modified my grammar and spelling mistakes. She deserves my appreciation and love.

Finally, tons of thanks to those colleagues in AVL and friends who answered my questions and supported my work. They are really important for my work and all their kindness will best kept in my mind forever.

Sheng YU

February 2019, Graz

Statutory Declaration

Ich erkläre an Eides statt, dass ich die vorliegende Arbeit selbstständig verfasst, andere als die angegebenen Quellen/Hilfsmittel nicht benutzt, und die den benutzten Quellen wörtlich und inhaltlich entnommenen Stellen als solche kenntlich gemacht habe.

Graz, am ……………………………………………………………………………….

(Unterschrift)

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and I have explicitly marked all material, which has been quoted either literally or by content from used sources.

………………………….. …………………………………………………………

(Date) (Signature)

Abstract

Fuel cell electric vehicles are becoming more and more important all over the world, and the topology with ‘fuel cell + battery’ is a current research trend, which can reduce power requirement of the fuel cell. And as one of most important parts of vehicle control unit (VCU), the energy management strategy plays the role of distributing power between fuel cell system and battery. Therefore, a control strategy that can reduce hydrogen consumption and meet dynamic requirement at the same time is of great significance for VCU development. It is also the main target of this master thesis.

To achieve the research goal, a fuel cell system with 55 kW maximum net power and a 9.9 kWh battery are used. Efficiency map of fuel cell system is established firstly. Then two concepts of control strategy have been developed based on the principle of logic threshold and global optimization strategy, and implemented in Simulink. Through simulation of Graz and Frankfurt to Vienna driving cycle, concepts of energy management strategies have been verified.

Thresholds of strategies have been optimized then, for the final target reducing hydrogen consumption. Results show that energy control strategies in this thesis have led to a significant improvement of fuel economy. More significantly, this research can provide reference to development of real vehicle control unit of fuel cell electric vehicles.

Key words: FCEV, EMS, Logic threshold, Global optimization, Modeling and simulation

Kurzfassung

Brennstoffzellen-Elektrofahrzeuge werden auf der ganzen Welt immer wichtiger, und die Topologie mit "Brennstoffzelle + Batterie" ist ein aktueller Forschungstrend, der den Energiebedarf der Brennstoffzelle reduzieren kann. Als eine wichtige Komponente des Fahrzeugsteuergeräts (VCU) spielt die Energiemanagementstrategie die Rolle der Verteilung von Energie zwischen Brennstoffzellensystem und Batterie. Daher ist eine Steuerungsstrategie, die den Wasserstoffverbrauch reduzieren und gleichzeitig die dynamischen Anforderungen erfüllen kann, von großer Bedeutung für die VCU-Entwicklung. Es ist auch das Hauptziel dieser Masterarbeit.

Um das Forschungsziel zu erreichen, wird ein Brennstoffzellensystem mit 55 kW Maximalleistung und 9,9 kWh Batterie verwendet. Zunächst wird die Effizienzkarte des Brennstoffzellensystems erstellt. Anschließend werden zwei Konzepte der Steuerungsstrategie basierend auf dem Prinzip der Logikschwelle und der globalen Optimierungsstrategie entwickelt und in Simulink implementiert. Durch Simulation der Fahrzyklen von Graz und Frankfurt nach Wien wurden die Konzepte für Energiemanagementstrategien verifiziert.

Die Schwellenwerte der Strategien wurden dann für das Endziel optimiert, den Wasserstoffverbrauch zu reduzieren. Die Ergebnisse zeigen, dass die Strategien zur Energiesteuerung in dieser Arbeit eine deutliche Verbesserung des Kraftstoffverbrauchs bewirken. Wichtiger ist, dass diese Forschungsergebnisse die Entwicklung einer realen Fahrzeugsteuereinheit von Brennstoffzellen Elektrofahrzeugen unterstützen können.

Schlüsselwörter:
FCEV, EMS, Logikschwelle, Globale Optimierung, Modellierung und Simulation

Contents

Abbreviations

FCHEV – Fuel Cell Hybrid Electric Vehicle

EMS – Energy Management Strategy

EMCU – Energy Management Control Unit

EV – Electric Vehicle

HEV – Hybrid Electric Vehicle

FCEV – Fuel Cell Electric Vehicle

SoC – State of Charge

ICE – Internal Combustion Engine

VCU – Vehicle Control Unit

PHHV – Parallel Hydraulic Hybrid Vehicle

BoP – Balance of Plant

MEA – Membrane electrode assembly

FCS – Fuel Cell System

PTC – Positive Temperature Coefficient

HHV – High Heating Value

LHV – Low Heating Value

SU – Startup

SD – Shutdown

FCCU – Fuel Cell Control Unit

Symbols

Parameters und constants

P_{el}	Electric stack power	kW
$P_{H_2\_LHV}$	Hydrogen chemical power with low heating value	kW
P_{therm_LHV}	Hydrogen thermal power with low heating value	kW
N	Number of fuel cell unit	-
I	Current	A
λ	Air stoichiometric ratio	-
U_{Avg_Cell}	Average voltage of fuel cell unit	**V**
η_{el}	Electric efficiency of stack	-
η_{FCS}	Efficiency of fuel cell system	-
P_{net}	Net power of fuel cell system	kW
ΔH	Hydrogen enthalpy	kJ/g
P_{Aux}	BoP components power consumption	kW
m_{H_2}	Hydrogen mass flow	g/s
P_{FCS}	Power of fuel cell system (equals P_{net})	kW
P_{FCS_Idle}	Idle power of fuel cell system	kW
P_{FCS_EffLo}	Low efficiency power of fuel cell system	kW
P_{FCS_EffMax}	Maximum efficiency power of fuel cell system	kW
P_{FCS_EffHi}	High efficiency power of fuel cell system	kW
P_{FCS_Max}	Maximum power of fuel cell system	kW
SoC_{Act}	Actual state of charge of battery	%
SoC_{Min}	Minimum state of charge of battery	%
SoC_{Lo}	Low state of charge of battery	%
SoC_{Mid}	Medium state of charge of battery	%
SoC_{Hi}	High state of charge of battery	%
SoC_{Max}	Maximum state of charge of battery	%
P_{Dmd}	Demand power	kW
$V_{Vehicle}$	Actual velocity of vehicle	km/h
P_{Bat}	Battery power	kW

Δ	Best efficient charging power of battery	kW
ε	Best efficient discharging power of battery	kW
P_{Recup}	Recuperation power	kW
$CBat$	Energy capacity of battery	kWh
α	Efficient range adjustable left coefficient	-
β	Efficient range adjustable right coefficient	-
γ	Hysteresis value for fuel cell system states changing	%

1 Introduction

1.1 Background

1.1.1 Status and trends of fuel cell electric vehicles

According to statistics, oil consumption of global transportation accounted for 61% of global oil consumption, and it will go up to 62% in 2020 [1]. People around the world all concern that environment will be harmed by automotive industry, and people will rely on the less and less oil resource seriously. So it became the focus of different countries to develop vehicles, which can reduce energy consumption, as well as decrease the exhaust emissions. From the sustainable development point of view, fossil fuel has been used in more than 97% of transportation, however, the storage of it on earth is limited. For this reason, we need to understand alternative ways of getting resource and ways of vehicle driving, to solve the issue of sustainable development of transportation. There are three categories of energy on earth: fossil fuel that is unrenewable resource, renewable resources that include wind energy, solar energy and water energy as well. Comparing to traditional vehicles, fossil fuel is still the main energy of hybrid vehicle, so hybrid vehicles do not belong to sustainable development transportation. Pure electrical vehicles, which belong to new energy vehicles, have advantages such as zero (local) emissions, simple structure, multi-energy selection and high efficiency. The main energy of fuel cell electrical vehicles is hydrogen, which can be gained from renewable energy. That is to say, it can be supplied sustainably. Thus this could be a feasible way to achieve sustainable transportation.

Because of shortage of energy and stress of environment pollution, electrical vehicles have been become the new focus of many automotive manufacturers all over the world. These companies invest lots of money and formulate strategies to accelerate processes to promote the development of electrical vehicles. Currently, there are three kinds of electrical vehicles, which includes electrical vehicles (EV), hybrid electrical vehicles (HEV) and fuel cell electric vehicles (FCEV). Electric vehicles are only powered by battery, and used in the early research. But the development has been limited for reason that the energy density of battery is much lower than of liquid fuel, which means it needs large battery systems to drive a car for longer driving ranges. But this situation will be much better if traditional battery is replaced by fuel cell. Fuel cell electrical vehicles with high energy storage capacity and zero local emissions are considered as an promising transportation technology with advanced prospect in the future.

Currently, companies in many countries have started to develop FCEV, such as Europe, America and Japan, they invested much money and resources. And many automotive brands including GM, Mercedes Benz and Toyota, have successfully developed FCEV. These cars have been driven on public streets and their performances have shown convincing characteristics. One famous example is the Mirai from Toyota [2]. Mirai can run 500 km without charging and re-fueling. In the future we can see that FCEV will become more and more popular and companies will invest more and more money in FCEV research and development.

In order to have a general understanding of the state of art of fuel cell vehicle, some market-available cars related will be introduced here, details about which are shown in Table 1.

Table 1 Market-available fuel cell vehicles technology reviews

	Powertrain configuration	**E-motor maximum power (kW)**	**Battery capacity (kWh)**	**Fuel cell stack output power (kW)**	**Driving range_NEDC (km)**	**Price (Euro)(could be different due to time and countries)**
Hyundai NEXO [3]	Combined hybrid (depending on driving mode)	120	1	95	756	69.000
Toyota Mirai [4]	Series	113	1.6	114	550	70.000
Honda Clarity Fuel Cell [5]	Parallel	100	33	100	650	30.000
Mercedes-Benz GLC F-cell [6]	Combined hybrid (depending on driving mode)	155	13.5	75	478	49.000

…

1.1.2 Basic principles of hydrogen fuel cells

Hydrogen fuel cell is one power generation unit, which directly transfers electrochemical reaction to electric energy. Theoretically, hydrogen fuel cell has 100% thermal efficiency, with high fuel economy. However, limited by current technologies, and consideration of the system energy consumption, the total transfer efficiency of current different fuel cells is between 45% and 60%.

Fuel cell is an energy transfer device, which transfers the chemical energy stored in fuel and oxidant to electric energy based on electrochemical principles. So, the process is actually a redox reaction. Fuel cell mainly consists of four parts: anode, cathode, electrolyte, and external load. Hydrogen and oxygen will go into the anode and cathode of fuel cell separately.At the anode side of an acid electrolyte, hydrogen gas ionizes, releasing electrons and creating H+ ions.

$$2H_2 \rightarrow 4H+ + 4e-$$

Electrons released at anode go through external circuit to cathode side and react with oxygen and H+ ions from the electrolyte. Finally, water is formed.

$$O2 + 4e- + 4H+ \rightarrow 2H_2O$$

For the reactions in both anode and cathode to react continuously, electrons produced at the anode have to go through an external electrical circuit to the cathode. Also, H+ ions must pass through the electrolyte, and it can fluid to cathode side freely in an acid.

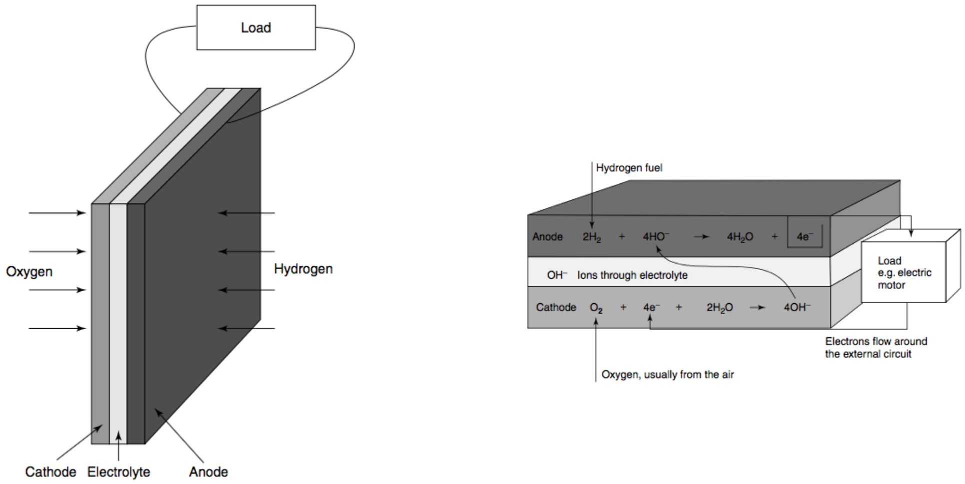


Figure 1 **Operating principle of fuel cell unit [2]**

To increase the contact area among hydrogen, anode, cathode, and the electrolyte, the anode and cathode are usually made flat and porous, so that the reaction gases can pass through and the reaction product can exhaust easily. The function of electrolyte is to deliver H+ ions and separate hydrogen and oxygen.

1.1.3 Energy management of fuel cell electrical vehicles

Nowadays, the cost of FCEV is still so high and its related technologies are imperfect, so using battery or super capacitor as assistant power working with fuel cell has become a new research direction. Different power resources are used in hybrid propulsion systems, thus the propulsion systems are various, due to the diversity of combinations of fuel cell, super capacitor, battery and DC-DC converter. Energy management includes the control strategies based on various propulsion system structures. Different systems need different control methods as well as principles of design. Targets are also different, e.g. to reduce the hydrogen consumption, to assure performance of vehicle, and to keep the state of charge (SOC) of battery within a certain level.

Currently, there are mainly two hybrid driving structure of the fuel cell electrical vehicles. One is fuel cell + battery. Another is fuel cell + (battery) + capacitor.

Figure 2 demonstrates powertrain structure of first hybrid fuel cell electrical vehicle, which is fuel cell plus battery. When FCEV are developed, some special requirements of fuel cell itself should be taken into consideration. For instance, when the fuel cell is started, compressor needs to charge, fuel cell stacks should be warmed up, and hydrogen and oxygen need to be humidified. Meanwhile, braking energy should be reused. So the structure of battery and fuel cell working together can meet such requirements mentioned above. This kind of structure can decrease system requirements of the fuel cell power and dynamic characteristics, and reduce the costs of fuel cell system. On the other side, such a structure increases the weight, volume and complexity of driving system; especially the development of vehicle controller for controlling working status of two power resources is more complex.

For the time being, fuel cell has an increasingly higher energy density, and battery provides power as an assistant power resource, when the vehicle starts, speeds up, climbs, and the demand power changes dynamically. In addition, it works as storage system for energy recuperation during braking. This structure is also what is discussed more detailed in this thesis.

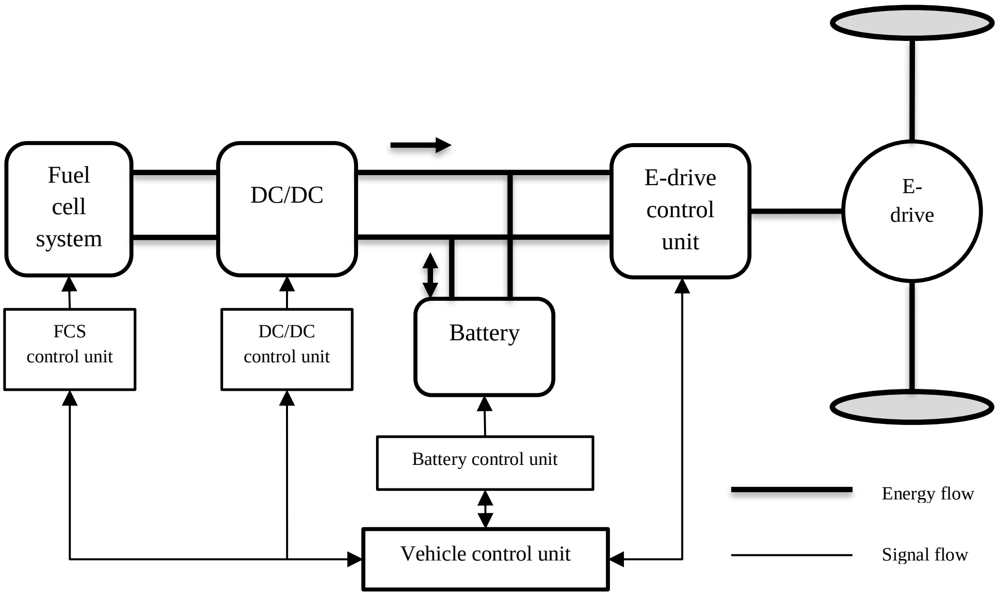


Figure 2 Propulsion system of fuel cell + battery

Apart from the structure of fuel cell plus battery, there are also two structures, which are fuel cell plus capacitor and fuel cell plus battery plus capacitor. That is to say, there are two or three power resources in the hybrid electrical vehicle. Figure 3 shows one general structure of it.

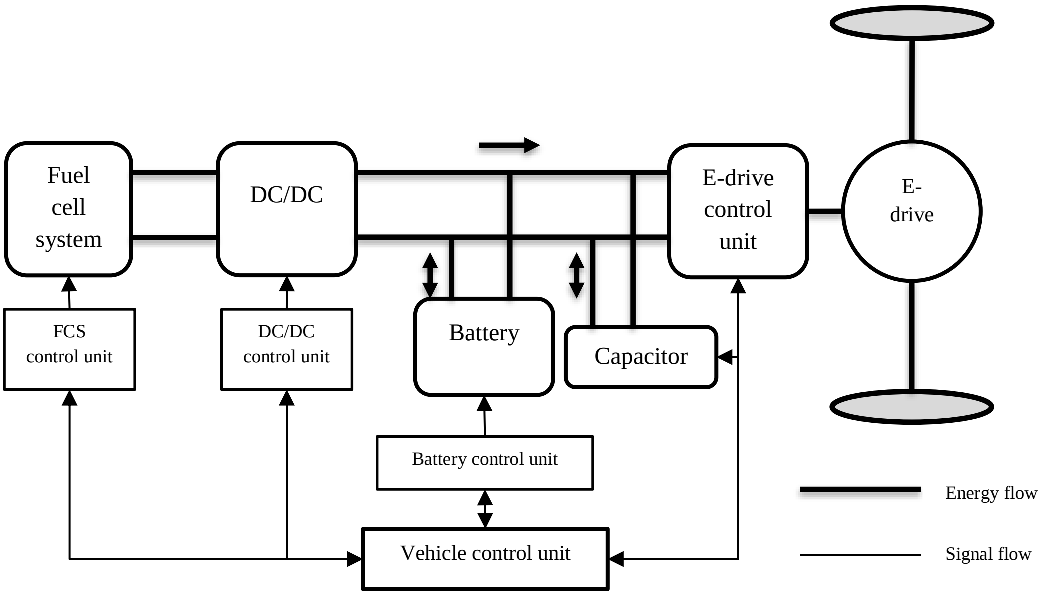


Figure 3 Propulsion system of fuel cell + battery + capacitor

1.2 Objective

The main target of this master thesis is to develop energy control strategies to reduce the hydrogen consumption of the fuel cell system.

To achieve this target, three steps should be accomplished. The first step is evaluating the fuel cell system, which is the base of following work. Actually, control strategies are developed fully based on it. Secondly, strategies based on rules are developed, which are the most important part of the present work; these strategies define the distributions of power during FCEV working. The last part is to optimize strategies developed in part two. Main method is defining important parameters, which could have impact on the fuel consumption result, and then using different ways to optimize these parameters, finally getting a reduced hydrogen consumption.

1.3 Literature review

The energy resource of traditional hybrid vehicle concludes internal combustion engine (ICE) and battery, and the key of such kind of hybrid technology development is the development of vehicle control unit (VCU) for managing multi energy resources. Main function of VCU is to control the vehicle energy management and propulsion system. Algorithm achieving the vehicle energy management and propulsion system controlling is called control strategy. Control strategy and relative controller are core of parts of vehicle controlling. For ICE and battery hybrid vehicle, ICE, e-drive, converter, battery, clutch and gearbox are concluded into one propulsion system, which is a nonlinear dynamic system integrated with mechanical, electromechanical, chemical and thermodynamic systems. The complexity of VCU very depends on these system parameters and configuration, uncertainty of vehicle driving conditions as well. Consequently, control strategy of hybrid vehicles is an issue of how to handle the decision of complex questions and deal with one nonlinear time-varying system.

For fuel cell hybrid electric vehicle (FCHEV), it is a must to coordinate different energy resources to make it work properly, no matter the topology of vehicle is fuel cell + battery or fuel cell + battery + super capacitor. Therefore, energy management strategies used in ICE and battery hybrid vehicle can be applied in FCHEV in general, which achieve the power distribution among multi energy resources.

So, four strategies about the energy management of hybrid vehicle will be introduced generally in this section. Target is to summarize these presented control strategies and to give short words to each of them to analyze the advantages and disadvantages.

The first is logic threshold based control strategy. One set of parameters limiting engine working areas are pre-fixed by experienced experts, and based on that, working models of hybrid power systems are judged and selected. [7] introduced such kind of energy control strategy based on the logic threshold methodology for Parallel Hydraulic Hybrid Vehicles (PHHV). The energy distribution of the PHHV can be controlled in real-time and the operation modes of the PHHV can be changed dynamically by means of this energy control strategy. An energy management strategy combining a logic threshold approach and an instantaneous optimization algorithm is developed for the investigated PHEV in paper [8], whose objective is to achieve acceptable vehicle performance and drivability requirements while simultaneously maximizing engine fuel economy and maintaining the battery state of charge (SOC) in its rational operation range at all times. [9] also designed an improved logic threshold approach of energy management for a power-split HEV assisted by an integrated starter generator. These publications focus on the logic threshold control strategy, whose algorithm is relatively simple and easy to implement. Moreover, comparing with offline optimization results, this control strategy can optimize parameters sets at the beginning, then get shifting rules more economic and more reasonable.

Instantaneous optimization strategy is the second one. This control strategy is based on one theory called equivalent fuel consumption. That is to say, in a certain transient working condition, working rang of e-drive can be confirmed firstly, after that, relevant operation point of ICE is calculated. Then based on the calculation of actual fuel consumption of ICE and equivalent fuel consumption of e-drive, the best combination of ICE and e-drive operation points is selected to define the final operation points. [10] presents an instantaneous optimization algorithm based on the knowledge of the efficiency maps of ICE and the generator for the energy management system in hybrid electric vehicles. Within this work, engine operating points are determined by assessing not only the efficiency map of the engine but also the efficiency map of the generator and the charge/discharge efficiency of the battery pack in order to maximize the efficiency of the energy delivered from the hybrid energy source to the drive system. Based on logic threshold control strategy, one instantaneous optimization algorithm is used to improve the equivalent fuel consumption in [11]. However, loads of floating point operation is needed during instantaneous optimization strategy, which means it is hard to implement to real vehicle. At the same time, the calculation of equivalent fuel consumption is very dependent on the accuracy of charge and discharge efficiency of battery, optimization results are consequently hard to be sufficiently accurate.

The next approach is a global optimization strategy, which is a kind of energy management strategy based on the best optimization approach and best control theory. Generally, target is to get the lowest fuel consumption in a certain driving cycle, and main algorithms are simulated annealing method [12] and dynamic programming. [13] presents one global optimization based on simulated annealing, meanwhile, criteria of method choosing are resource required, algorithm complexity as well as CPU time versus problem size. [14] demonstrates that a global optimization algorithm, based on the Bellman principle, was used to generate the most efficient operating conditions for a parallel pre-transmission hybrid and a specific driving cycle, to optimize the energy flow. From [15], it is known that though global optimization control strategy belongs to offline optimization, which means strategy cannot be applied in real-time. Parameters of control rules can be corrected based on results from global optimization. So how to implement global optimization and how to use its results are becoming the research hotspot of hybrid energy management.

The last strategy that should be mentioned is intelligent control strategy, which uses fuzzy logic or neural networks to decide working mode and torque distribution of hybrid energy system; this is also a kind of mathematic optimization approach based on logic threshold strategy. The underlying theme of the fuzzy rules is to optimize the operational efficiency of all components, considered as one system, and potential fuel economy improvement is shown by using fuzzy logic, relative to other controllers, which maximizes only the efficiency of the engine [16]. Hybrid electric vehicles, using neural networks, are tested in [17], and the driving range of the vehicle increases by 8.9%. [18] discusses intelligent control using both methods, fuzzy logic and neural networks. And presents controller using intelligent algorithm can adapt to different drivers and driving cycles. Nowadays, fuzzy control based on fuzzy logic has strong robustness and good real-time performance, it is therefore the main research direction of energy management strategy.

1.4 The main contents of the thesis

The main contents of this thesis are divided into the following parts.

In chapter 1, background and objectives of this research are addressed. Then different study approaches and directions of energy management strategy of hybrid electric vehicle are summarized.

In chapter 2, the internal situation of Fuel Cell System (FCS) is analyzed. It is focussed on Balance of Plant (BoP) of FCS, and particularly the startup and shutdown processes are discussed. Consequently, two models to describe startup and shutdown processes respectively are built in this section.

In chapter 3, based on efficiency map of FCS from chapter 2, two energy management strategies are developed. Development of control strategies are discussed in very detail here, then models based on strategy concept are created in Simulink. After that, analysis of simulation results and discussion about it are presented.

In chapter 4, three sets of parameters involved in strategies in chapter 3 are optimized and discussed.

In chapter 5, future work and conclusion of this work are summarized.

2 Fuel cell system analysis

Chemical energy is transferred to electric energy in fuel cell stack, which is combined with hundreds of fuel cell units for the automobile. The voltage of signal cell is less than 1 V, and consequently, voltage needed in vehicle is increased by stacking many cells in series [19]. However, fuel cell stack cannot work alone, it must be integrated with other auxiliary components, such as compressor and cooling pump. Figure 4 shows a general structure of a complete fuel cell system. Usually there are four sub-systems to assemble one FCS: hydrogen supplement to stack anode system, controlled by U_1; oxygen or air supply to stack cathode system, usually using compressor flow air, and controlled by U_2; cooling system with de-ionized water, a pump could be used here, and temperature of coolant controlled by U_3; hydrogen and air flow humidifying system using de-ionized water, humidity controlled by U_4. Moreover, U_6 controls the traction e-drive, and the energy management control strategy for FCHEV is implemented in U_5, which is also the main task of this paper.

A high pressure (from atm to 3 bar) of oxygen is important to increase the reaction rate, thus, fuel cell efficiency as well as power density. Therefore, a compressor driven by a motor is needed to compress air to certain pressure level. Temperature will increase simultaneously while air pressure raising, so air cooling system is needed to cool down reaction air before going into stack. And in case of dehydration of membrane, air with vapor will leave stack after reaction, a humidifier is used to add vapor into air flow. And for the sustainable recycle of water in whole system, a water separator is needed. On the side of anode, hydrogen in the tank, existing as gas or liquid, goes into the anode of stack, whose flow rate is controlled by a valve. In every fuel cell unit of stack, hydrogen meet oxygen and react to produce electric energy from chemical reaction. As stack only maintains under condition with temperature below 100 °C, heating from reaction will be taken away from stack by the de-ionized water coolant, then, coolant with heating will pass through a radiator or heat exchanger to remove system heating.

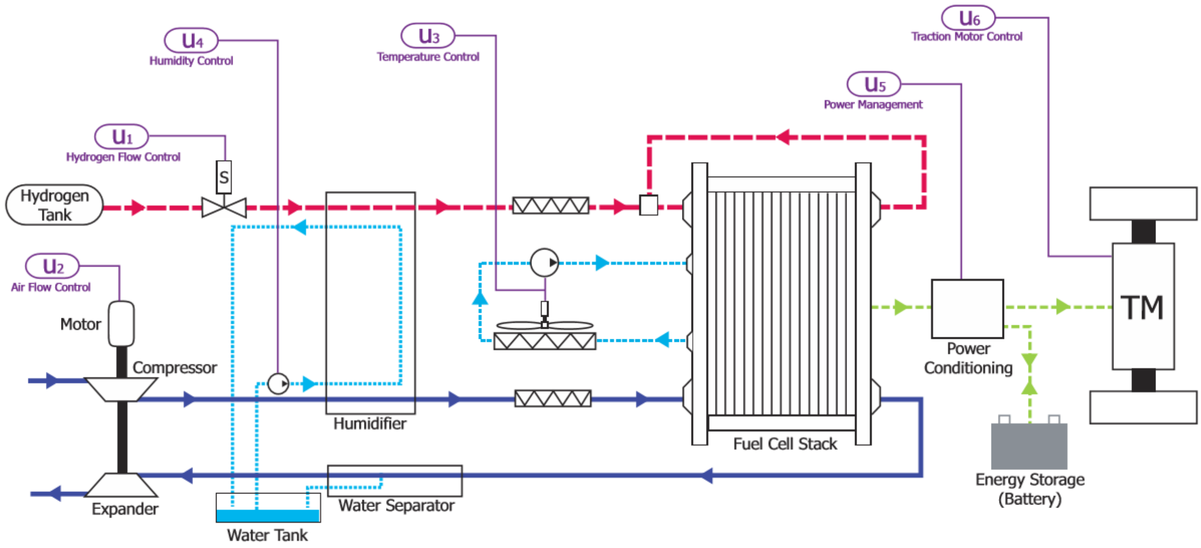


Figure 4 Automotive fuel cell propulsion system [20]

Except definition of startup and shutdown processes, details of FCS internal working processes will not be discussed in this work, it should be only focus on things about energy consumption and management.

2.1 Balance of Plant

In order to get FCS dynamic behavior and auxiliary components power consumption, current from 0A to 380A has been simulated in a provided FCS ‘black box’ model. The FCS Model was built for the project for performing model-in-the-loop test. This Model was built according to the actual FCS mechanization/Layout. Esch component Insider (compressor, cooling system...) are Part of AVL s generic FCS library and is based on differential equations picturing the physical behavior. The ‘black box’ model has four inputs (current, PTC heater switch, FC pressure and air stoichiometric ratio) and two categories of outputs (BoP (balance of plant) power consumption and efficiency), shown in Figure 5.

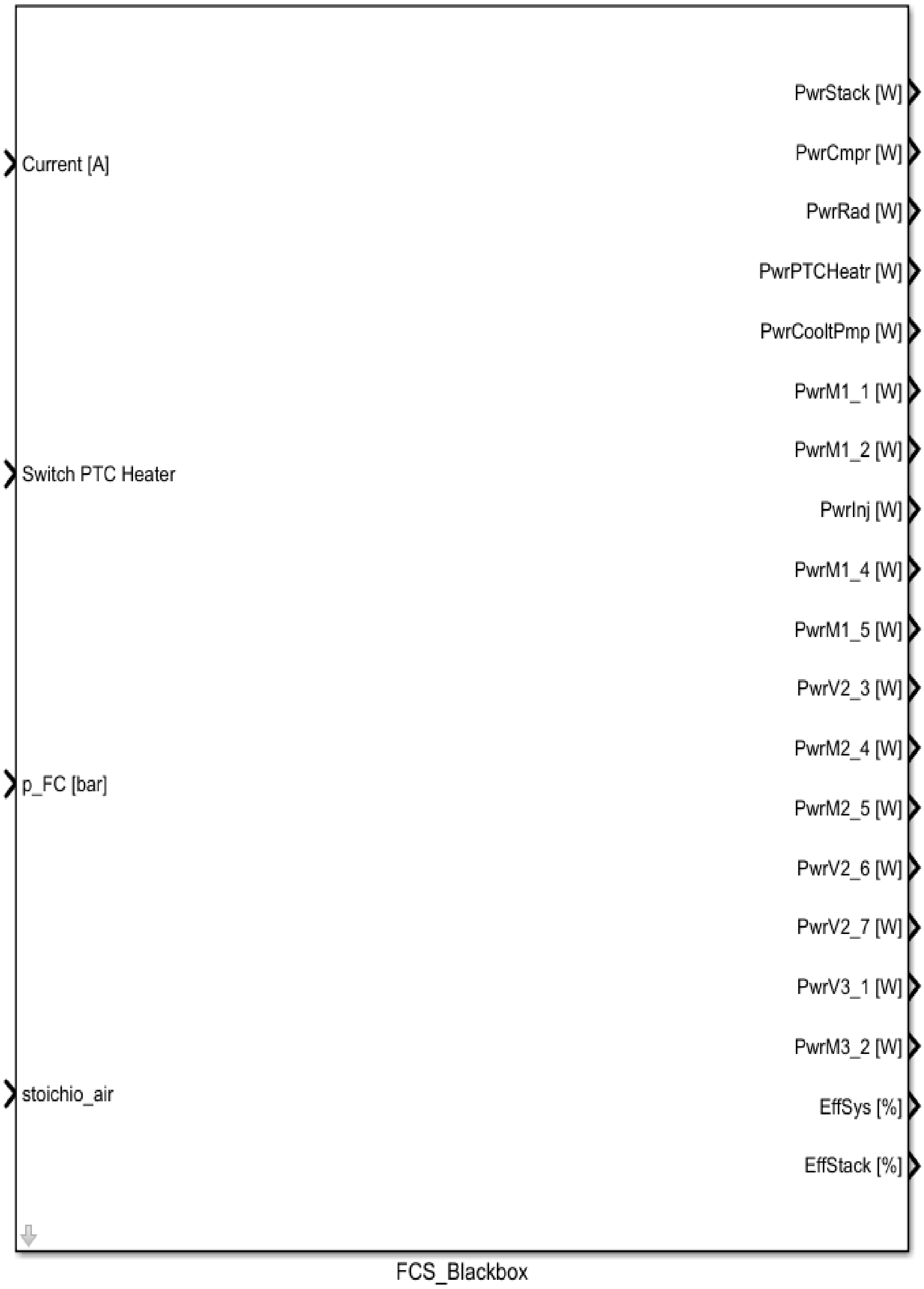


Figure 5 FCS Blackbox simulation model

FCS blank box used in this work, like mentioned above, has four input parameters, including current, switch of PCT heater, fuel cell reaction pressure and air stoichiometric ratio. After getting demand power from range externder energy management control unit, demand power has been transferred into current, the relationship between power and current is dependant on fuel cell system characteristic and the corresponding data coming from system itself is used here. The reason that relationship of power and current is non-liner is the voltage loss when current increasing [21].

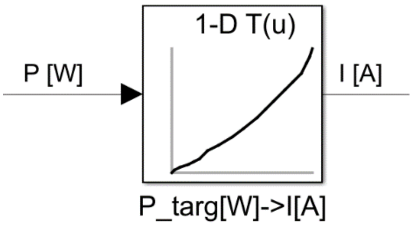


Figure 6 **Power to current Look-up table in Simulink**

Getting demand power order from VCU, through look-up table, Figure 6, and relationship between power and current is shown in Figure 7.

In our case, switch PTC (Positive Temperature Coefficient) heater is always off because low temperature condition is not considered here.

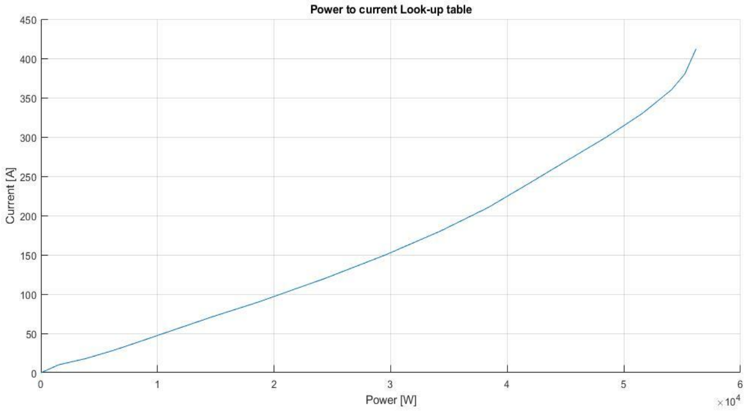


Figure 7 **Curve of Power to Current**

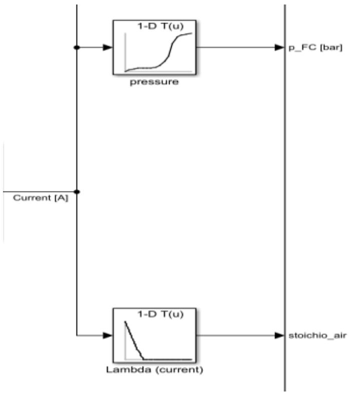


Figure 8 **Current to Pressure and λ Look-up table in Simulink**

Similarly with transfer of power to current, inputs of pressure and stoichiometric ratio of air (λ) are applied through look-up table in Simulink, Figure 8, and corresponding data shown in Figure 9 and Figure 10.

The pressure map was the result of an optimization regarding the FCS efficiency with AVL CAMEO, by considering the Stack and compressor efficiency maps.

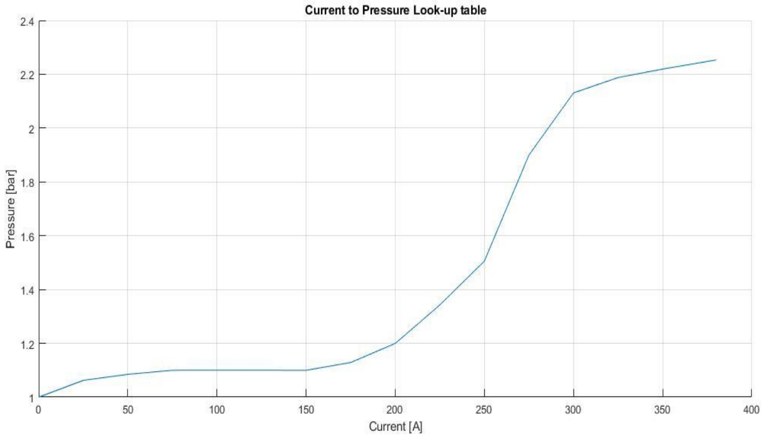


Figure 9 Curve of Pressure over Current

The map for the Lambda (air stoichiometry) was given by the stack supplier.

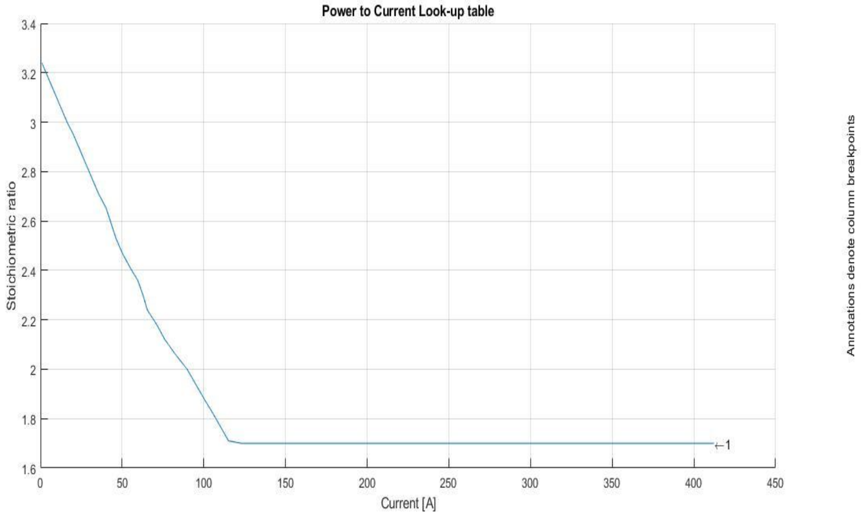


Figure 10 Curve of Lambda over Current

Once four inputs go into FCS black box, BoP components power consumption get demonstrated in Figure 11. One significant fact is that power consumption of compressor accounts for a large part in BoP components power consumption, while cooling and radiator power consumption only accounts for a small proportion of that.

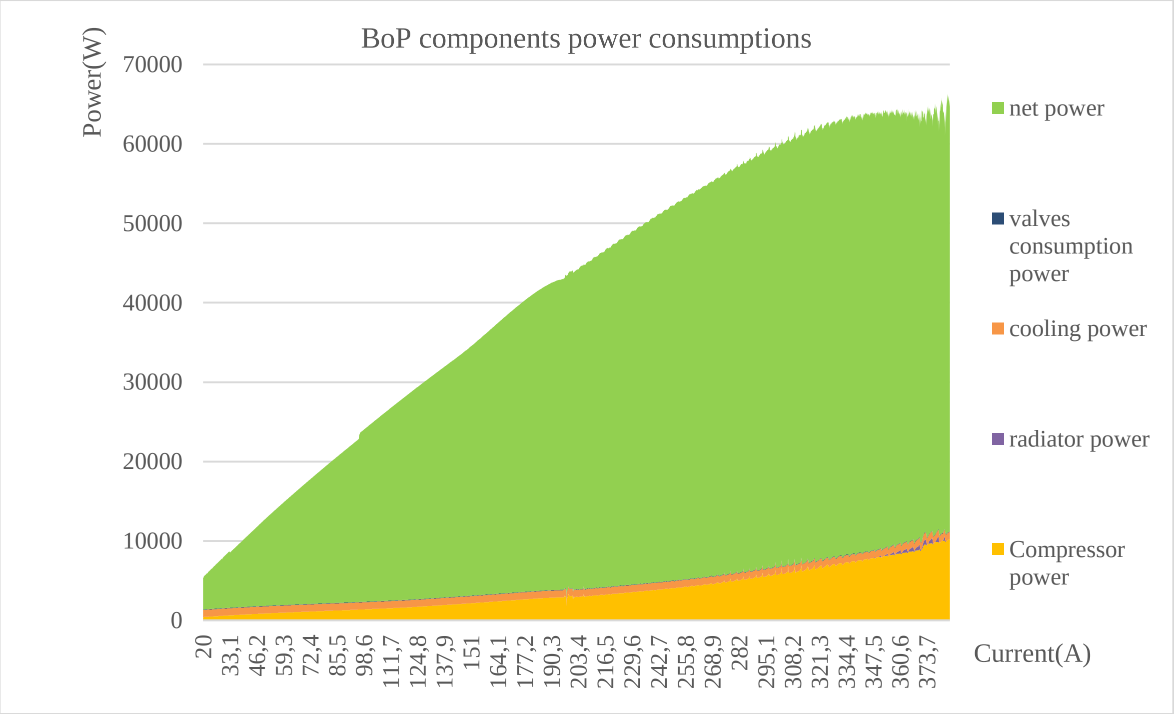


Figure 11 **BoP components power consumption over current**

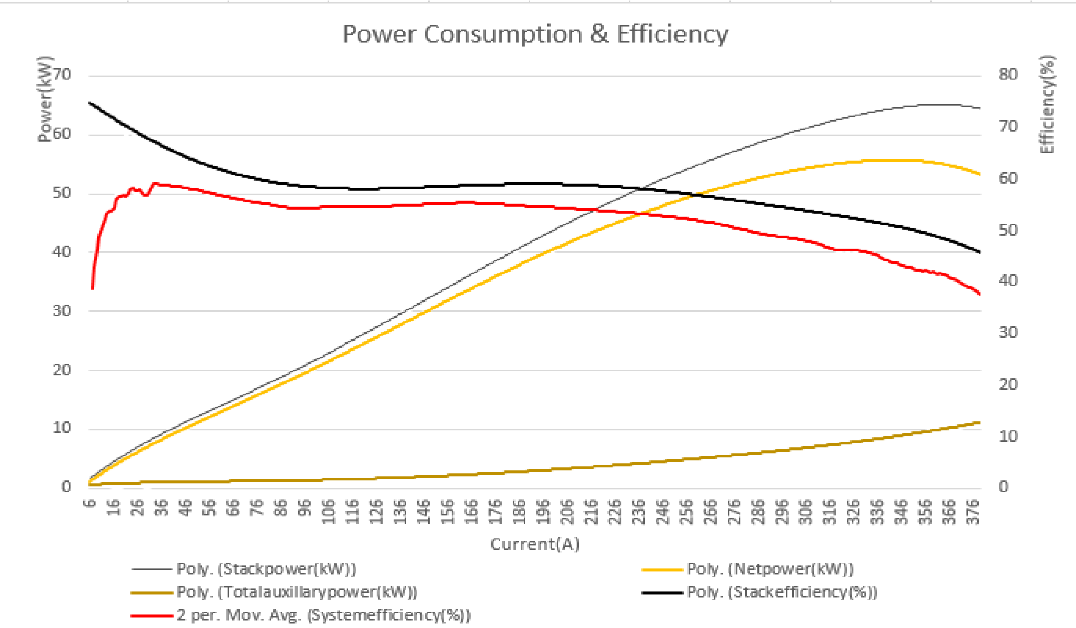


Figure 12 **Power consumption and efficiency**

Changings of stack power, net power and total auxiliary power consumption (grey, orange and brown line respectively) are also clearly shown in Figure 12. Electrical stack power is calculated by:

$$\begin{cases} P_{el} = P_{H_2\_LHV} - P_{therm\_LHV} \\ P_{H_2\_LHV} = 1.235 * N * I * \lambda \\ P_{therm\_LHV} = \left(1.253 - U_{Avg\_Cell}\right) * N * I \end{cases} \qquad [2.1]$$

Hydrogen with specific energy density (HHV: high heating value or LHV: low heating value, the choose between both is depandand on the state of water in the product of combustion.In our case, LHV is chosen due to heat of vaporization not be used in this case [22]) transfers to chemical energy $P_{H_2\_LHV}$ with heating loss, which is expressed by P_{therm_LHV}. Residual power output is called electrical stack power P_{el}. N in equation [2.1] is the number of fuel cell units, and U_{Avg_Cell} is the average voltage of all fuel cell units. To calculate $P_{H_2\_LHV}$ and P_{therm_LHV} based on HLV, voltage equivalent 1.253 needs to be replaced with 1.481 V. Certainly, these calculations are implemented in FCS black box model.

Electric efficiency and fuel cell system efficiency are illustrated in Figure 12, black and red line respectively. And they are generally calculated by:

$$\begin{cases} \eta_{el} = P_{el}/P_{H_2\_LHV} \\ \eta_{FCS} = P_{net}/P_{el} \end{cases} \qquad [2.2]$$

2.2 Startup and Shutdown

Lifecycle of proton exchange membrane fuel cell (PEMFC) is a significant factor that will influence its industrialization. There are several reasons that may lead the stack degradation. For instance, the reaction impurity can influence the voltage of fuel cell unit [23]. And the operation temperature also influences the current density, and resistance of MEA (Membrane electrode assembly) [24]. Start-up and shut-down cycle also can demand the FCS, such as deactivation of fuel supplement system and water management system.

Although, foundamental action to change this situation, to reduce stack degredation and prolong lifecycle, is the improvement of stack material, it is useful to implement proper control strategy under the precondition of no great technical breakthrough of stack material [25]. The start-up and shut-down processes play an important role in the PEMFC lifecycle control. Because a high potential will be fromed in cathode due to existence of the interface of cathode (oxigen) and anode (hydrogen) during start-up and shut-down [26][27].

Various publications have discussed the control strategies and degredation mechanisms of start-up and shut-down process. A specific strat-up and shut-down process have been designed by Kim [28] and Shen [29], aiming to get influence about the PEMFC stack degredation when humidification in cathode. And results show that durability of stack will be longer if start-up and shut-down process have been operated in a lower humidity. Literature [30] researched influence on carbon carrier by different operation condition, such as air humidity, temperature and oxygen concentration, and it shows that air humidity and operating temperature have great influence on the corrosion of carbon carrier. [31] also studied the effects of operating conditions on the stack degredation after frenquently startup and shutdown, and these operating conditions eventually influence the degredation speed more or less. These operating conditions includes humidity in cathode, dummy load, supply order of reacting gas, etc. The effect of hydrogen purging in anode on stack degradation also was discussed in [32].

Startup (SU) and shutdown (SD), therefore, have significant influence on stack degradation, and proper operations of that can effectively avoid it. Based on the previous literature review,, processes of SU and SD have been discussed in this work. The present thesis introduces one model to describe them, moreover, this model is changeable for future research.

Startup and shutdown processes are implemented in fuel cell system. From the point of view of the system level, FCS gets signals of startup and shutdown from energy management control unit, based on control strategy, then the processes of startup and shutdown run inside of FCS. After specific time, FCS will provide power normally.

In the processes of startup and shutdown, the operating time of each process is dependent on the control strategy and power needed will provided by battery.

General process of startup and shutdown are shown in Figure 13 and Figure 14, based on which, BoP components' switch time and power have been defined with one possibility, shown in Figure 15 and Figure 16, startup and shutdown process respectively.

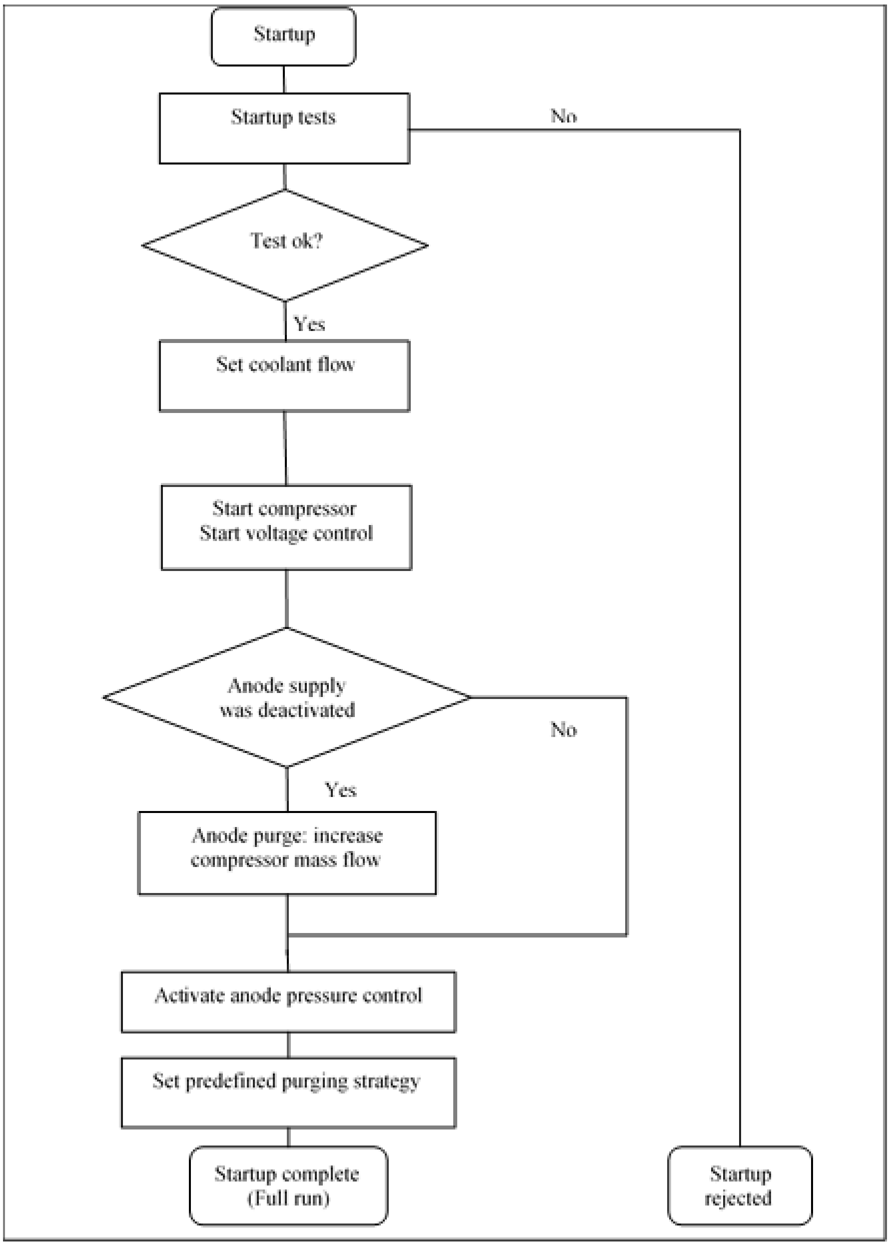


Figure 13 **Startup process**

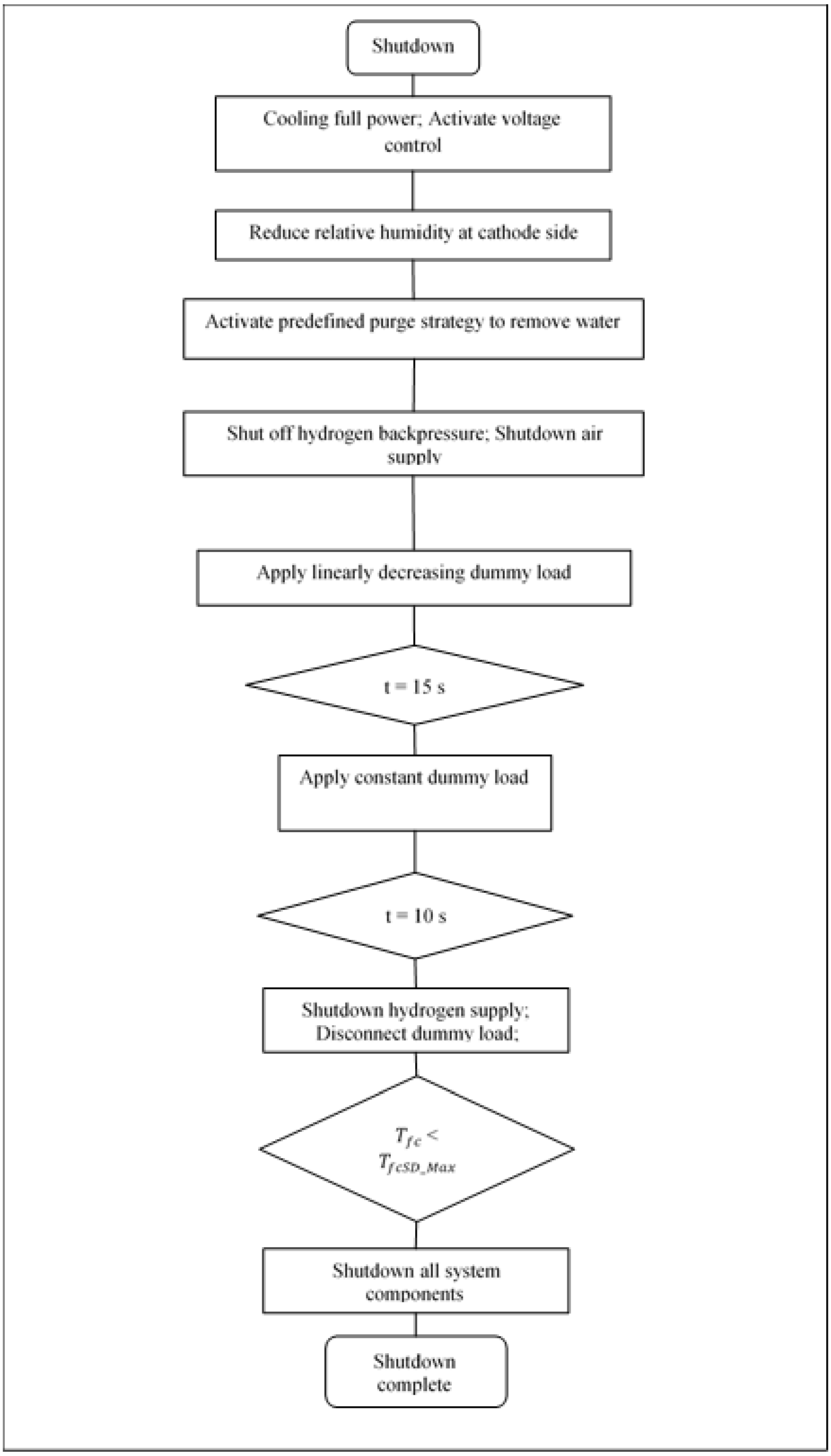


Figure 14 **Shutdown process**

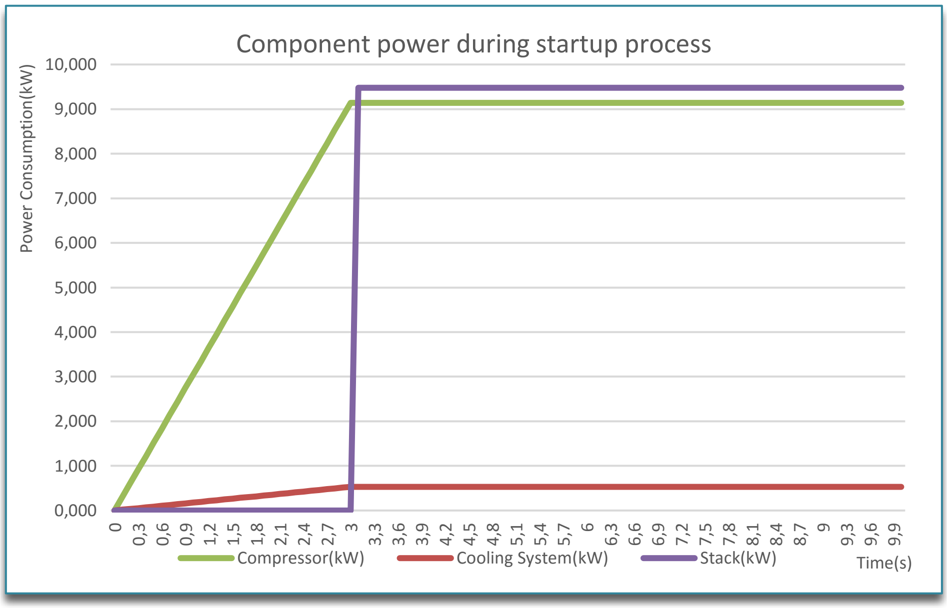


Figure 15 BoP components and stack power during startup process

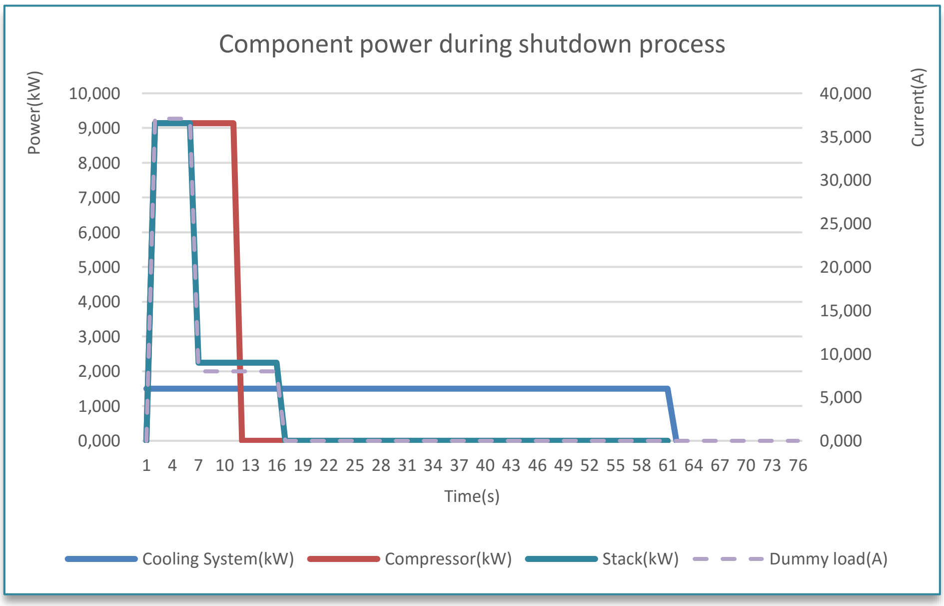


Figure 16 BoP components and stack power during shutdown process

From the point of view of system level, the total operating time and power delivery of each process are important to FCS controlling, which could influence the dynamic response and efficiency of FCS. The initial setup for startup and shutdown is the considering of stack degradation and power consumption. In the startup process, predefined purging strategy on anode is the main action to avoid stack degradation, due to oxygen-hydrogen interface in anode, which will form high potential in anode, and eventually stack degradation. In the shutdown process, the changing of air humidity [30], and dummy load (to consume residual potential in stack) will have effect on reducing stack degradation. Moreover, rules of status changing of FCS are also defined as Figure 17, getting FCS status, based on demand power from driver. VCU sends start or shutdown request to FCCU (fuel cell control unit), then FCCU execute orders from VCU.

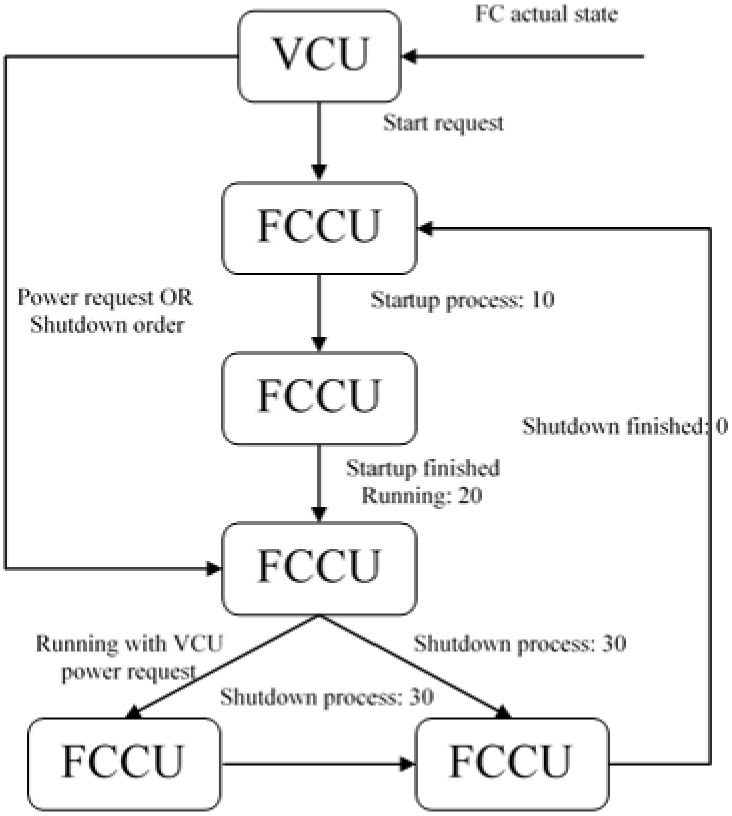


Figure 17 **Rules of status changing of FCS**

2.3 Conclusions of section

In this section, general knowledge about the FCS and its SD/SU is introduced.

a. Efficiency map of FCS is the most important output, which is the foundation of EMS discussed in next chapter;
b. The reason of stack degradation has been discussed, and based on publications, effects on stack degradation have been taken into consideration of startup and shutdown model crating.
c. SU/SD process has been defined and also implemented in Simulink model, based on which, status changing rules are developed.

3 Control strategies of energy management

Two energy resources consisting of fuel cell system and battery increase the complexity of driving system design. However, there is also more flexibility and freedom to optimize the structure. In the process of energy system design, energy management strategy (EMS) is significant in development, which is also one of main functions of the vehicle control unit.

Comparing to traditional ICE and battery hybrid vehicle, the most different point of fuel cell electric vehicles is zero emission. So, the only purpose of EMS is to increase the efficiency and fuel economy maximally and extend lifecycle of fuel cell stack, under the premise of components of driving system working normally and responding quickly. In this work, design of EMS focuses on vehicle control strategy. That includes consideration of fuel cell system and battery as sub-component assembled, involving their output characteristics. Particularly, the distribution of power and braking recuperation have been considered as a part of control strategy.

From literature review in chapter one, it is known that instantaneous optimization strategy and global optimization strategy are two approaches in the EMS development. However, due to computation complexity and hardness of driving cycle prediction, they are not easy to use in development of powertrain systems for actual cars. Consequently, energy management strategies based on logic threshold have been developed in this work. Then control models based on control concepts are created in Matlab/Simulink and results of simulation are proved to discuss the presented ideas and approaches.

3.1 Simulation model overview

In order to get a general understanding about this work, the structure of simulation model created in Matlab/Simulink, Figure 18, will be introduced here firstly, before go into details about specific energy management strategies.

There are four main parts from top structure. The first one is driving cycle choosing module, which includes different driving cycles, such as ENDC, Graz, Frankfurt to Vienna, etc. This module will provide dynamic demand power and velocity to next module, energy management control unit (EMCU), detail will be discussed in 3.2.5. In EMCU, power distribution strategy will handle how to distribute power between FCS and battery, then give power order to FCS and battery. FCS module, which was introduced in the previous chapter 2, will handle the request power and states from EMCU, and give feedback to EMCU. After getting demand power from driving cycle choosing module and actual power from FCS, battery module will provide residual power, the actual state of charge (SOC) will also send to EMCU.

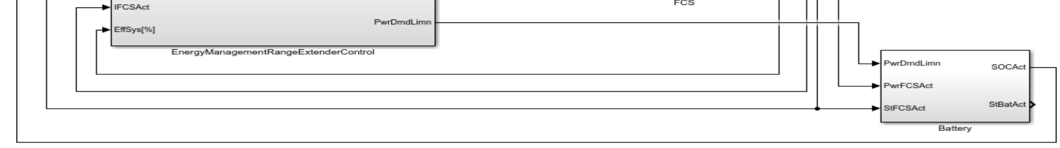


Figure 18 **Overview of simulation model**

3.2 Control strategies concept

3.2.1 Foundation and basic strategy of EMS

The target of the present investigations on EMS of FCEV is to reduce hydrogen consumption, and as the main energy resource, efficiency map of FCS is considered the foundation of building concept of EMS. In this work, the maximum power of FCS is 55kW. After simulation FCS blank box model in chapter 2 with current 0 – 380A, the efficiency map of FCS is shown in (curve is fitted).

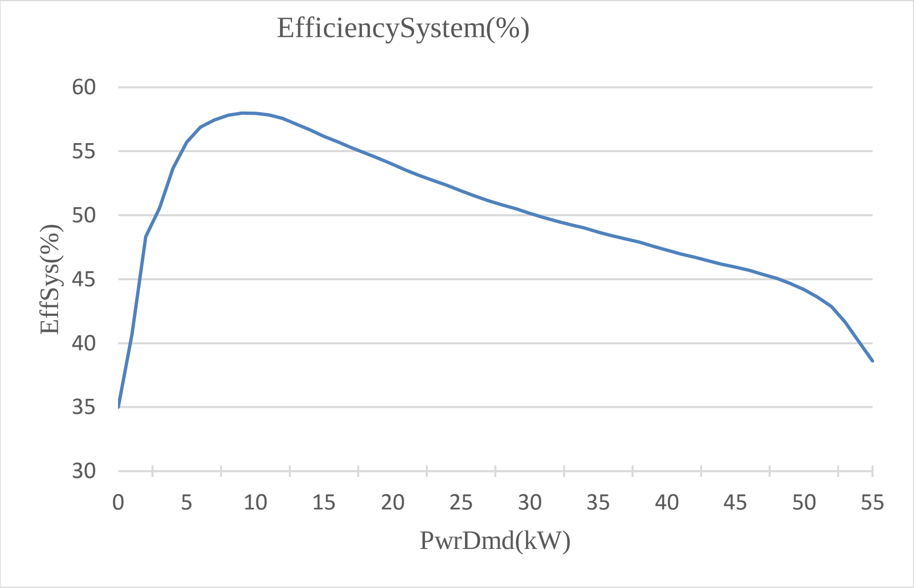


Figure 19 Efficiency map of FCS

The efficiency of FCS can be calculated as:

$$\eta_{\mathrm{FCS}} = \frac{P_{FC\_Stack} - P_{Aux}}{m_{H_2} * \Delta H} * 100\% \qquad [3.1]$$

In this equation, P_{FC_Stack} is total power from fuel cell stack, P_{Aux} is power consumed by auxiliary components; and m_{H_2} is hydrogen mass flow in g/s, ΔH is hydrogen enthalpy with value of 120kJ/g.

The efficiency of FCS is very low if net power is low, theoretically, efficiency could be zero if net power is 0 kW. In this situation, fuel cell should be shutdown status or idle, which just offers energy to auxiliary components, without net power outputting. Therefore, a minimum threshold P_{FCS_Idle} is defined, and with the maximum working threshold P_{FCS_Max}, the working range of FCS has been defined. Apart from this, the maximum efficiency point is fixed, which is P_{FCS_EffMax}. And an efficient range from P_{FCS_EffLo} to P_{FCS_EffHi}, which mean the efficiency of output power lower and higher than maximum efficient point respectively, has been defined too. These five important operation points are demonstrated in Figure 20.

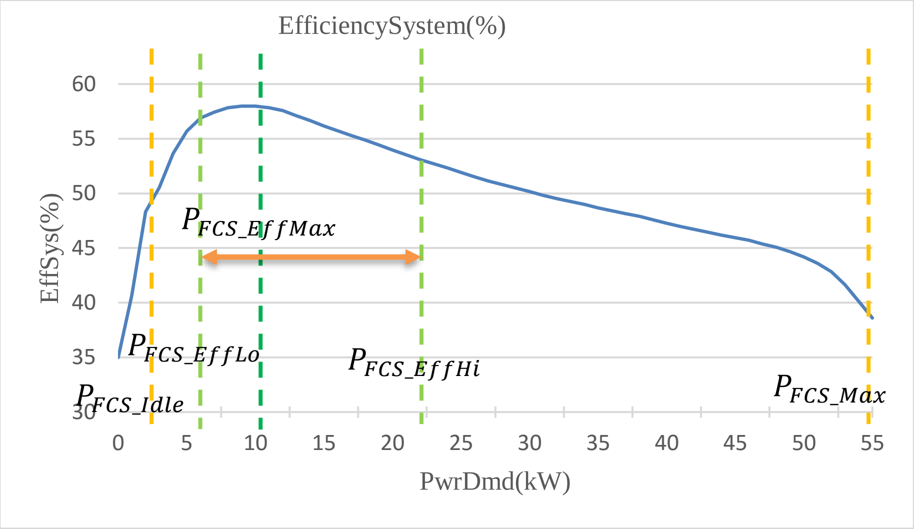


Figure 20 Operation points of FCS

On the other hand, one battery with 9.9kW is used in this work, thus the efficiency map of the battery is shown in Table 2. From previous engineering experience, different battery working range is defined [33]. Deep discharge of battery should be avoided in order to protect battery; and on the other hand, in case of recuperation, energy can be absorbed by battery when vehicle is braking, battery should have enough capacity to charge. Consequently, the first one is normal working range with state of charge (SoC) from 10% to 90%. Then a high efficiency range is also defined from SoC 50% to 70%, in which battery has a relatively high efficiency for charging and discharging. Lastly, SoC with value of 30% means battery has a lower energy. All these battery SoC limitations are defined for the later concept developing of EMS, and will be changed for strategy optimization discussed in chapter 4.

Table 2 Efficiency of Battery

Efficiency(%)	SoC(%)										
Power(kW)	0	10	20	30	40	50	60	70	80	90	100
-90	90.96	93.11	93.45	94.05	94.51	94.60	94.56	94.59	94.96	95.03	95.17
-80	91.81	93.79	94.10	94.44	95.06	95.14	95.11	95.14	95.47	95.54	95.66
-70	92.69	94.48	94.76	95.25	95.53	95.70	95.67	95.70	95.99	96.05	96.16
-60	93.61	95.20	95.45	95.68	96.21	96.27	96.24	96.27	96.53	96.58	96.68
-50	94.57	95.94	96.15	96.52	96.80	96.85	96.83	96.85	97.07	97.12	97.20
-40	95.56	96.70	96.87	97.18	97.41	97.45	97.43	97.45	97.53	97.65	97.73
-30	96.60	97.48	97.62	97.65	98.03	98.05	98.05	98.06	98.20	98.23	98.28
-20	97.68	98.30	98.39	98.55	98.67	98.69	98.63	98.69	98.74	98.81	98.84
-10	98.81	99.13	99.19	99.26	99.33	99.34	99.33	99.34	99.39	99.40	99.41
0	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
10	98.75	99.08	99.14	99.24	99.32	99.34	99.35	99.35	99.38	99.40	99.42
20	97.46	98.15	98.27	98.46	98.62	98.68	98.70	98.70	98.75	98.78	98.84
30	96.13	97.19	97.39	97.67	97.92	98.00	98.03	98.03	98.12	98.16	98.25
40	94.77	95.22	96.48	96.87	97.20	97.12	97.36	97.36	97.47	97.54	97.65
50	93.36	95.23	95.56	96.06	96.48	96.62	96.67	96.67	96.82	96.85	97.05
60	91.91	94.21	94.52	95.23	95.74	95.92	95.98	95.98	96.15	96.25	96.44
70	90.41	93.17	93.66	94.38	94.99	95.20	95.27	95.28	95.48	95.60	95.81
80	88.84	92.11	92.98	93.52	94.23	94.47	94.56	94.56	94.80	94.94	95.18
90	87.21	91.01	91.67	92.64	93.46	93.73	93.83	93.83	94.11	94.26	94.55

Before going into the development of EMS, a basic traditional strategy demonstrated in Figure 21, for comparison should be addressed in advance. It is one kind of simple and traditional control strategy, which is divided into five areas.

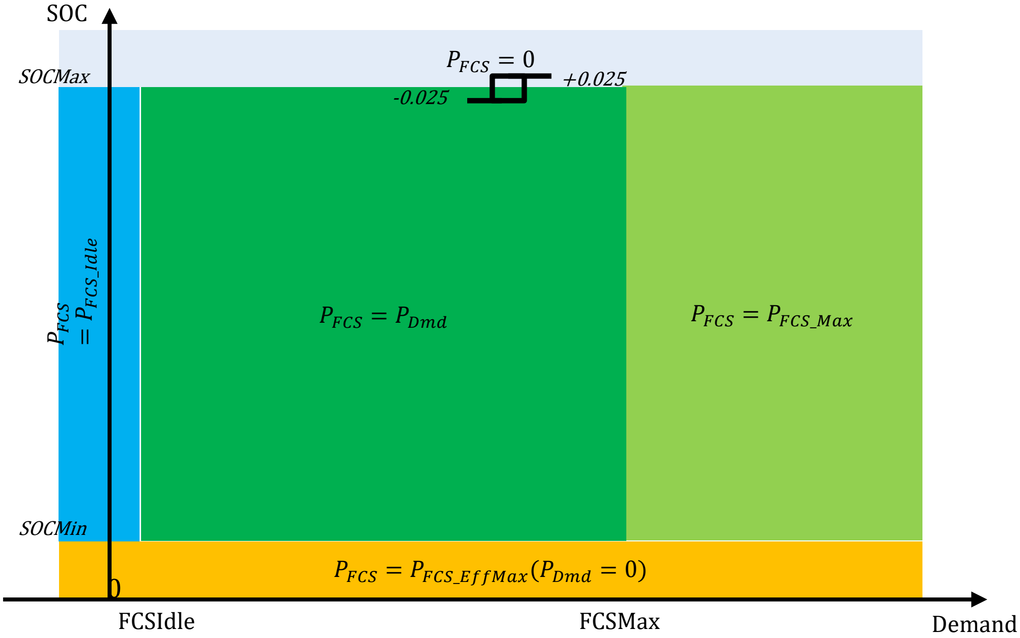


Figure 21 Basic strategy for comparison

a. If actual battery SoC is less than minimum limitation, $SoC_{Act} \leq SoC_{Min}$,

$$P_{FCS} = P_{FCS\_Max} \qquad [3.2]$$

In this special condition, battery has a low SoC, which cannot supply enough energy to e-drive. So message showing vehicle does not have ability to drive should be sent to driver, and demand power will be limited in 0 kW, $P_{Dmd} = 0$. Vehicle should wait for period to let FCS working in maximum power until battery SoC exceeding minimum limitation.

b. If actual battery SoC is beyond maximum limitation, $SoC_{Act} > SoC_{Max}$,

$$P_{FCS} = 0 \qquad [3.3]$$

In order to let battery have capacity to absorb energy from vehicle braking, FCS should be shut down when actual SoC of battery reaches the maximum limitation. But in case of frequently shutdown and startup of FCS, which could hurt system itself severely, hysteresis of FCS states changing is applied here. In another word, FCS will be shut down when $SoC_{Act} = SoC_{Max} +$ 2.5%, and startup again when actual SoC decreases to below SoC_{Max} minus 2.5 percent.

c. In the normal working range, $SoC_{Min} < SoC_{Act} \leq SoC_{Max}$,

$$P_{FCS} = \begin{cases} P_{FCS\_Idle}\ (P_{Dmd} \leq\ P_{FCS\_Idle}) \\ P_{Dmd}\ (P_{FCS\_Idle}\ <\ P_{Dmd} \leq\ P_{FCS\_Max}) \\ P_{FCS\_Max}\ (P_{Dmd} >\ P_{FCS\_Max}) \end{cases} \quad [3.4]$$

This basic strategy for comparison is kind of load following strategy, power of FCS will dynamically change based on demand power, and if FCS cannot response as quick as demand power, battery will cover the rest of demand power.

3.2.2 FixedPoint strategy

The first EMS is called FixedPoint strategy in which the battery plays an important role to cover the rest of demand power.FCS works with three fixed operation points, which are idle operation point, maximum efficiency operation point and maximum power operation point. Based on the concept, rules are created and demonstrated in Figure 22.

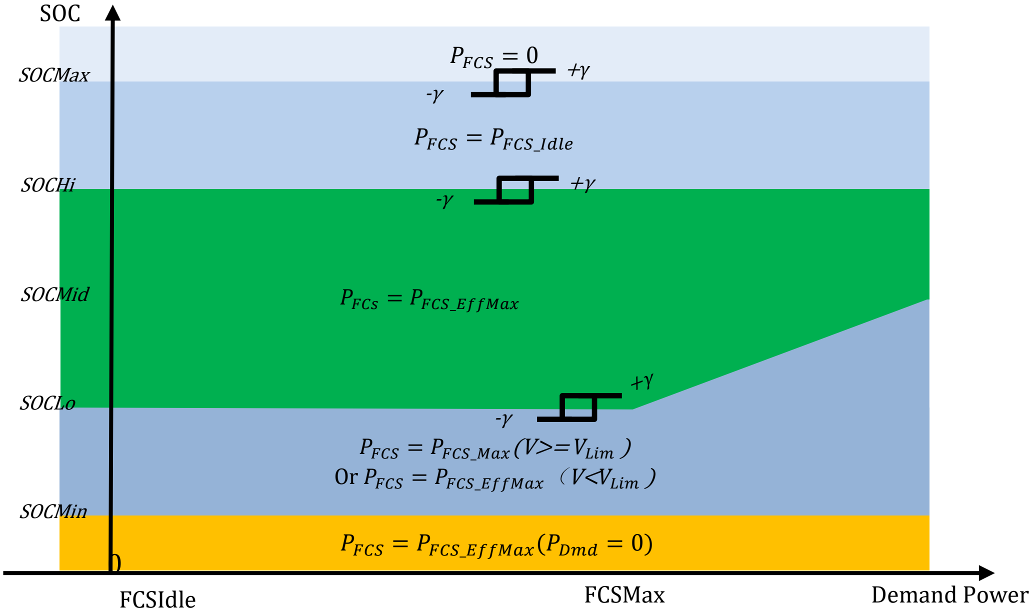


Figure 22 FixedPoint Strategy

a. When actual SoC of battery is below minimum SoC, $SoC_{Act} \leq SoC_{Min}$,

$$P_{FCS} = P_{FCS\_Max} \qquad [3.5]$$

In this case, control rule is same with the basic strategy, priority is battery charging and demand power limited.

b. If the actual SoC is, $SoC_{Min} < SoC_{Act} \leq SoC_{Lo}$,

$$P_{FCS} = \begin{cases} P_{FCS\_EffMax}\ (V_{Vehicle} < V_{Lim}) \\ P_{FCS\_Max}\ (V_{Vehicle} \geq V_{Lim}) \end{cases} \qquad [3.6]$$

As the speed of system cooling is dependent on velocity of vehicle, velocity or demand power should be taken into consideration when FCS operation points change. And slash shown in Figure 22 is considered of SoC range and demand power range. In this SoC range (from minimum SoC to low SoC) if demand power is more than the maximum power of FCS, net power of FCS should be adapted with demand power. And these rules are implemented in Simulink model.

c. When $SoC_{Lo} < SoC_{Act} \leq SoC_{Hi}$,

$$P_{FCS} = P_{FCS\_EffMax} \qquad [3.7]$$

As the target of EMS of FCS is to reduce hydrogen consumption as far as possible, FCS should work as the maximum efficiency as much time as possible. In this FixedPoint strategy, FCS works with maximum efficiency in this SoC range except other two operation points, idle and maximum power operation points.

d. When $SoC_{Hi} < SoC_{Act} \leq SoC_{Max}$,

$$P_{FCS} = P_{FCS\_Idle} \qquad [3.8]$$

When SoC of battery increases until this range, operation point of FCS will change to idle operation point. Within this SoC range and FCS working with idle operation point, battery has a high level of SoC to cover most of demand power, and meanwhile it has space to absorb energy from vehicle braking.

e. When $SoC_{Max} < SoC_{Act}$,

$$P_{FCS} = 0 \qquad [3.9]$$

FCS will be shut down if SoC reaching maximum level to leave room for recuperation energy.

In the present system, FCS will produce power based on EMS signal, but it is known that FCS does not have quick dynamic response due to its characteristic [34], comparing to internal combustion engine, so the role of battery is to absorb or supply residual power to e-drive. The power from or to battery can be expressed by:

$$\mathrm{P_{Bat}} = \mathrm{P_{FCS}} - \mathrm{P_{Dmd}} \qquad [3.10]$$

If result of $\mathrm{P_{Bat}}$ is positive, which means battery is charging, on the contrary, if negative, means battery is discharging.

In addition, ‘Hard change’ of operation points should be avoided during driving. ‘Hard change’ means changing the operation points or power of FCS dramatically, for instance, from 3 kW to 25 kW in one second. On the one hand, due to a slower power output [35], FCS cannot provide much power as required, on the other hand, frequent dramatic load change may affect the working situation of compressor, furtherly the efficiency of FCS. So in this following strategy, power changing rate is limited within 10 kW per second, which also can be calibrated in the future.

Similar with basic strategy, hysteresis of FCS status changing is implemented in FixedPoint strategy, in order to avoid frequently operation points changing.

FCS will operate within three fixed operation points. On the one hand, such fixed point strategy can reduce dynamic fluctuation of FCS, battery will cover the residual power. On the other hand, FCS can work at the maximum efficient power if demand power is around the similar power.

3.2.3 LoadFollowing strategy

If demand power or driving cycle is steady, FixedPoint strategy can achieve an ideal hydrogen consumption, as FCS works with maximum efficiency operation point most time. However, reality is not like that. Real driving cycle has bigger demand on power range and is more dynamic, so the second EMS called LoadFollowing strategy is developed. Load following means in this control strategy FCS will almost follow the demand power, and battery will cover the peak power. Thena comparison will be done in the later chapter.

The target of LoadFollowing strategy is to keep battery SoC within a certain range, in which battery has higher efficiency to charge or discharge. At the same time, FCS will work more dynamically than the behavior in FixedPoint strategy.

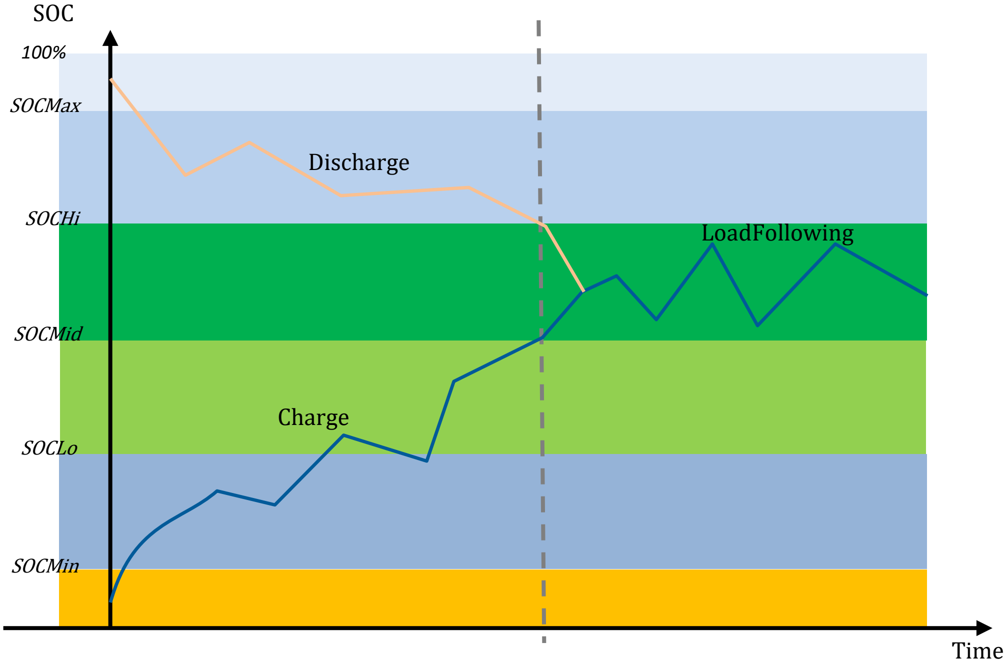
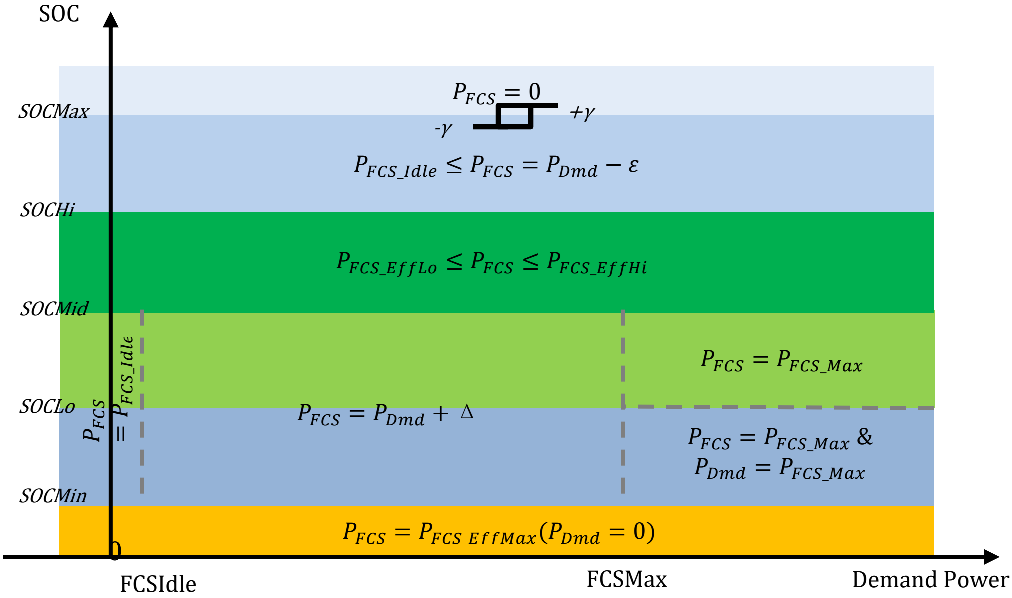


Figure 23 SoC keeping of LoadFollowing Strategy

In this strategy, SoC of battery will change like Figure 23. There are three situations that could happen in battery about the SoC. Firstly, SoC below target range, left blue line, FCS will provide power to e-drive. Meanwhile, charge battery in order to increase SoC; relatively, SoC over target range, pink line, FCS and battery will meet demand power at the same time, which means battery SoC will reduce until reaching target range. Thirdly, when SoC is in target range, right blue line, from middle SoC to high SoC, battery will be charged or discharged to keep SoC staying within target SoC range.



ε: Best efficiency discharge power of battery
Δ: Best efficiency charge power of battery

Figure 24 Rules of LoadFollowing Strategy

Based on goal of strategy discussed above, a series of rules shown in Figure 24 are defined to achieve this target.

a. When $SoC_{Act} \leq SoC_{Min}$,

$$P_{FCS} = P_{FCS\_Max} \qquad [3.11]$$

Demand power is limited to zero, and FCS works with maximum power to charge battery.

b. When $SoC_{Min} < SoC_{Act} \leq SoC_{Mid}$,

$$P_{FCS} = \begin{cases} P_{FCS\_Idle}\ (P_{Dmd} \leq P_{FCS_{Idle}}) \\ P_{Dmd} + \Delta\ (P_{FCS_{Idle}} < P_{Dmd} \leq P_{FCS_{Max}}) \\ P_{FCS\_Max}\ (P_{Dmd} > P_{FCS_{Max}}) \end{cases} \qquad [3.12]$$

In real driving situation, there could be many braking actions, especially in city driving cycle, which means the demand power will have many changes between negative and positive value. And if FCS shutdowns once demand power is negative and is started up once demand power is positive, FCS itself could be hurt frequently, which is not good for FCS life cycle. Moreover, actual SoC of battery is relative low, need to be charged. Based on such considerations, FCS works with idle operation point if demand power is less than FCS idle, including negative demand power (vehicle braking). Delta shown in Figure 24 is the best efficiency charging power of battery, when demand power is between FCS idle to maximum power, battery will be charged with Delta.

There is a special condition. Demand power will be limited to FCS maximum power when actual SoC is less than SoC_{Lo}. It will make sure that SoC will not decrease till minimum level again.

c. When $SoC_{Mid} < SoC_{Act} \leq SoC_{Hi}$,

$$P_{FCS} = \begin{cases} P_{FCS\_Idle}\ (P_{Dmd} \leq P_{FCS_{Idle}}) \\ P_{Dmd} + \Delta\ (P_{FCS_{Idle}} < P_{Dmd} \leq P_{FCS_{Max}}) \\ P_{FCS\_Max}\ (P_{Dmd} > P_{FCS_{Max}}) \end{cases} \qquad [3.13]$$

Target in this SoC range is to keep SoC staying in, and FCS will work in the most efficient range, from low efficiency point to high efficiency point. Hydrogen consumption will be reduced if FCS works in this range as far as possible due to relative highest efficiency.

d. When $SoC_{Hi} < SoC_{Act} \leq SoC_{Max}$,

$$P_{FCS} = P_{Dmd} - \varepsilon\ (\geq P_{FCS_{Idle}}) \qquad [3.14]$$

Epsilon shown in Figure 24 is the best efficient discharging power of battery. As SoC is in high level, battery discharges until SoC go down to target range.

e. When $SoC_{Act} > SoC_{Max}$,

$$P_{FCS} = 0 \qquad [3.14]$$

FCS will be shut down in this case, and the hysteresis of status changing of FCS is also applied here.

3.2.4 Equivalent hydrogen consumption calculation

FCS provides energy to e-drive for driving. At the same time, battery is charged or discharged when start up and shutdown of the FCS because of energy demand of the auxiliary components. So, for comparability of the total energy balance, electric energy in battery should be calculated into an equivalent hydrogen consumption. Actually, the concept or procedure calculated equivalent hydrogen consumption for charging battery by FCS can be used in other cases, or at least provide a general idea for thinking the energy transferring of battery.

Basic concept is shown in Figure 25. At one time step *t*, demand power of vehicle is satisfied by electric energy from battery and hydrogen chemical energy from FCS. In order to keep SoC of battery within an optimal range, battery need to be charged using energy from FCS in the future in a certain efficiency (EffFCS in figure 25) (recuperation energy should be subtracted from battery energy). As battery charging is done in the future, and FCS working operation point charging battery is unknown, the efficiency of battery charging as well as FCS are also unknown, we take an average efficiency of FCS (EffFCSAv in figure 25) into calculation (efficiency of battery charging not considered).

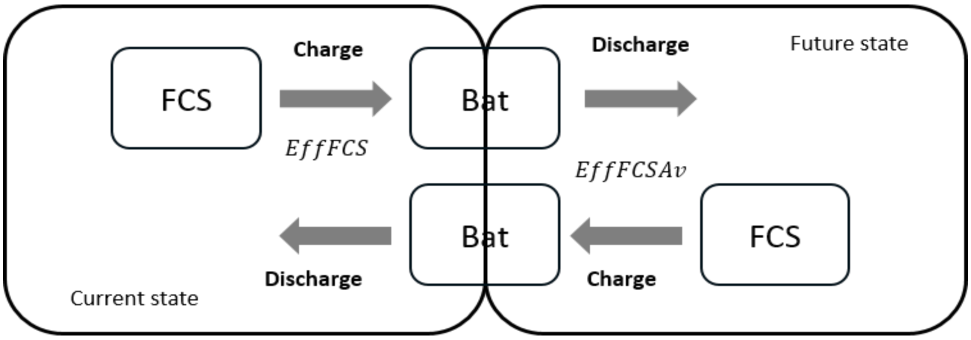


Figure 25 Concept of equivalent hydrogen consumption calculation

The equivalent hydrogen consumption of battery is calculated by:

$$EquivH_2CnsBat = \int_0^T \frac{CBat * \left(SOC_{present} - SOC_{laststep}\right) / t_{step} - Pwr_{Recup}}{Eff * H_2LHV} \; (kg) \tag{3.15}$$

$$SOC_{present} - SOC_{laststep} > 0,\ charge\!: Eff = EffFCS;$$

$$SOC_{present} - SOC_{laststep} < 0,\ discharge\!: Eff = EffFCSAvg.$$

CBat is the capacity of battery, which is 9.9 kW, H_2LHV is the lower heating value of hydrogen, being 241.83 kJ mol^{-1}, and Pwr_{Recup} is recuperation energy of vehicle braking. When battery is charging, using current FCS efficiency, otherwise, when discharging, using average FCS efficiency. In real driving cycle, results calculated by [3.15] may not be very accurate, however, for EMS development, it could provide reference when model simulation.

After getting battery equivalent hydrogen consumption, total system equivalent hydrogen consumption can be calculated using equation [3.16], and more useful value, equivalent hydrogen consumption per 100 km can also be calculated with [3.17]. $EquivH_2CnsPer100km$ is an important value, which can used for evaluation of the EMS.

$$EquivH_2Cns = ActH_2CnsFCS - EquivH_2CnsBat \; (kg) \tag{3.16}$$

$$EquivH_2CnsPer100km = EquivH_2Cns/Distance \; (kg/100km) \tag{3.17}$$

3.2.5 Implementation of control strategies

After finalization of the control strategies concept development, the equivalent hydrogen consumption, status of startup and shutdown control design and three control strategies have been implemented in EMCU module, demonstrated in Figure 26.

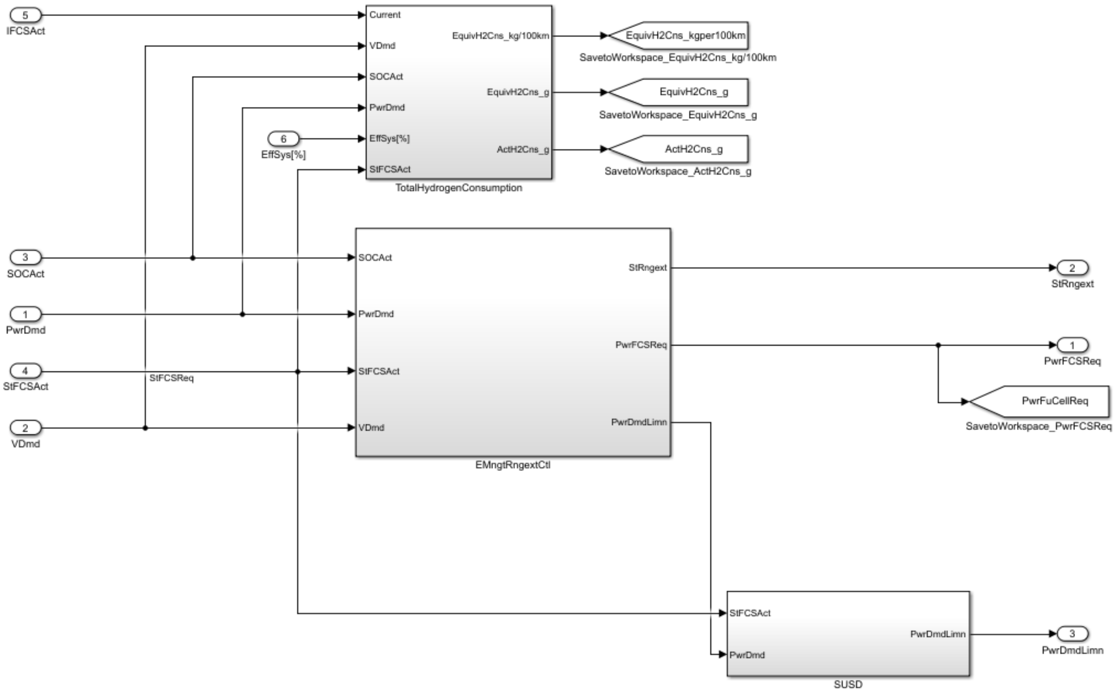


Figure 26 Module of energy management range extender control

There are three main modules in EMCU. The first one, Figure 27, is the calculation module of equivalent hydrogen consumption. After getting signals of actual current of FCS, demand vehicle, actual battery SoC, demand power, actual efficiency of FCS and actual state of FCS, concept of equivalent hydrogen consumption calculation is implemented here. Equation 3.15 is implemented in this module. Totally there

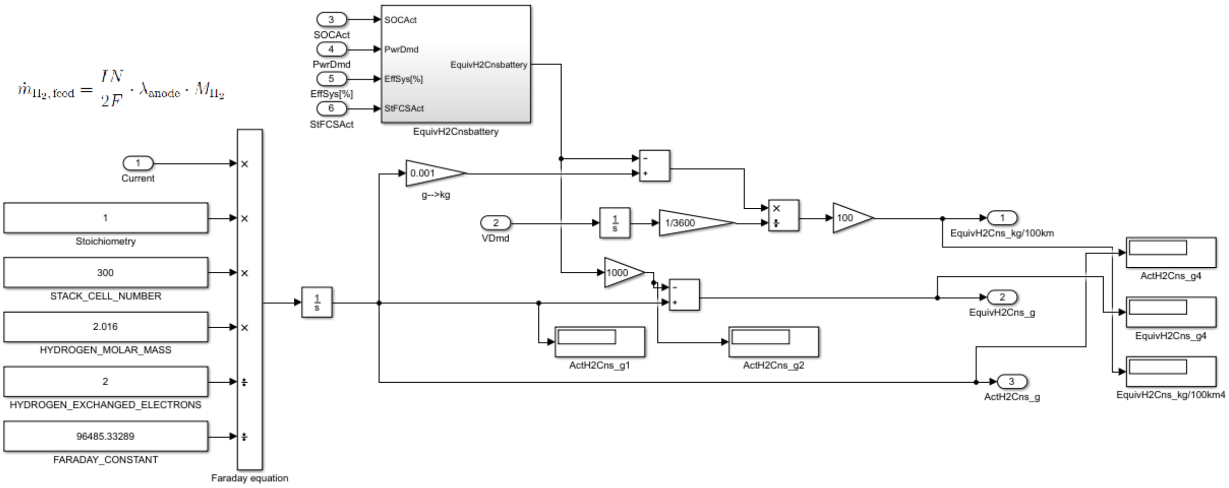


Figure 27 Module of equivalent hydrogen consumption calculation

are three outputs will show calculation results, they are equivalent hydrogen consumption per 100 km, total equivalent hydrogen consumption and total actual hydrogen consumption.

The second module in EMCU is the implementation of three energy management strategies, shown in Figure 28. The strategy mode is selected manually at the beginning of simulation. Based on concepts discussed before, four inputs, which are actual battery SoC, demand power, actual state of FCS and demand velocity, are needed. Finally three outputs, request FCS power, request FCS state and request battery power, are generated.

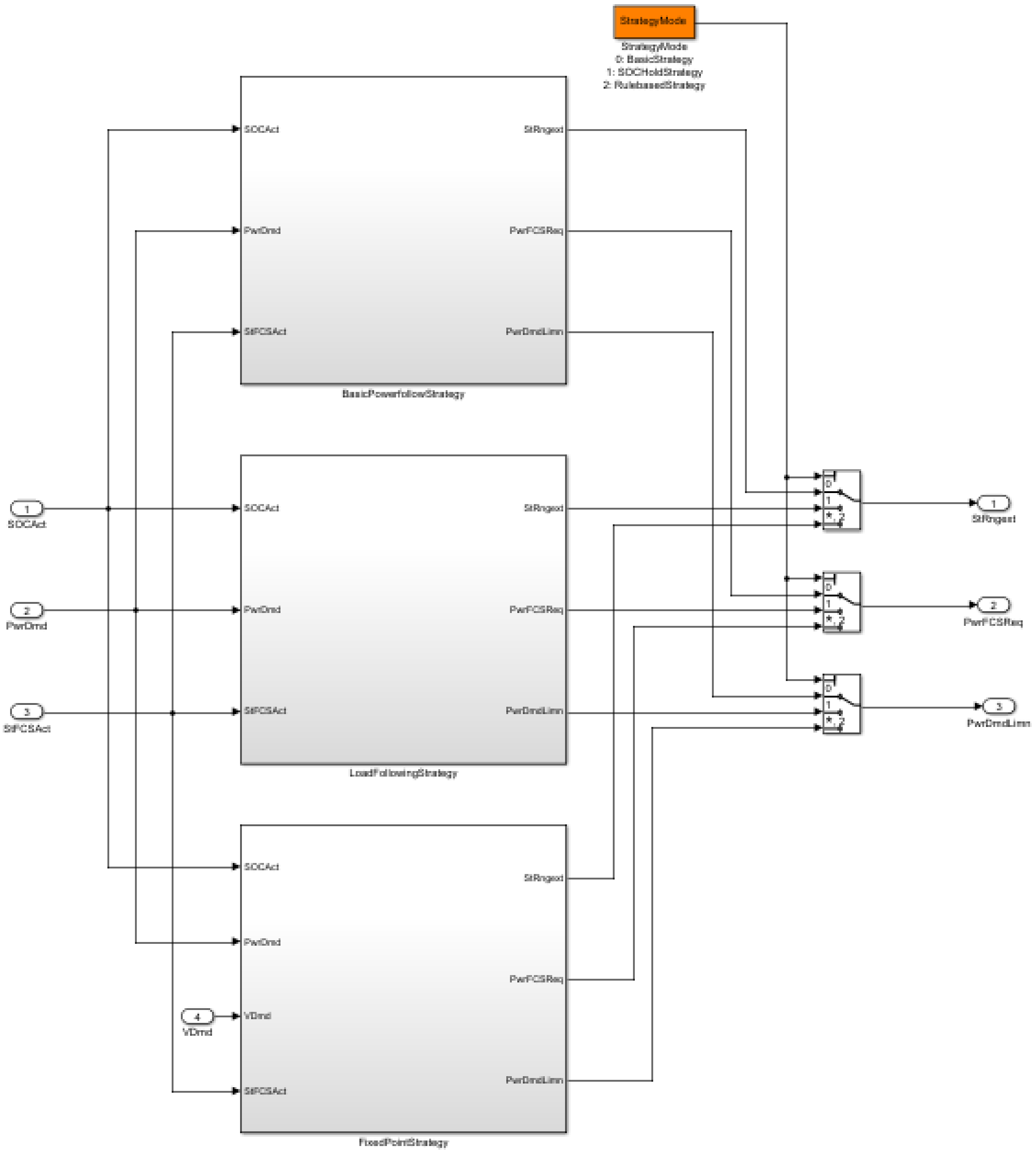


Figure 28 Three EMS in simulation model

The third one module is startup and shutdown module. Control strategies about startup and shutdown introduced in chapter 2.2 is implemented here. In this module, power delivery concerning startup and shutdown will be considered, then final signal of request battery power is generated.

3.3 Simulation results

3.3.1 Initial parameters setting

Based on concepts of EMS introduced in previous chapter, three strategies, including basic strategy for comparison, have been implemented in model built in Simulink. Graz driving cycle, corresponding city center driving cycle, and Frankfurt to Vienna (FraVie) driving cycle, corresponding highway driving cycle, are simulated and tested in model. Before simulation and testing, parameters in EMS should be defined first. Table 3 demonstrates each threshold that werde choosen in EMS.

Table 3 Initial Parameters

P_{FCS_Idle}	3 kW
P_{FCS_EffLo}	4 kW
P_{FCS_EffMax}	9 kW
P_{FCS_EffHi}	20 kW
P_{FCS_Max}	55 kW
SoC_{Min}	10%
SoC_{Lo}	30%
SoC_{Mid}	50%
SoC_{Hi}	70%
SoC_{Max}	90%
V_{Lim}	30km/h
γ	2.5%

3.3.2 Simulation results of two strategies

3.3.2.1 Graz driving cycle

Graz driving cycle shown in Figure 29 has a great fluctuating demand power with positive and negative value, and peak power is not so high, near 70 kW. Graz driving cycle has been chosen due to that it is close to real city center driving condition, and can check the practicability of EMS at the extreme.

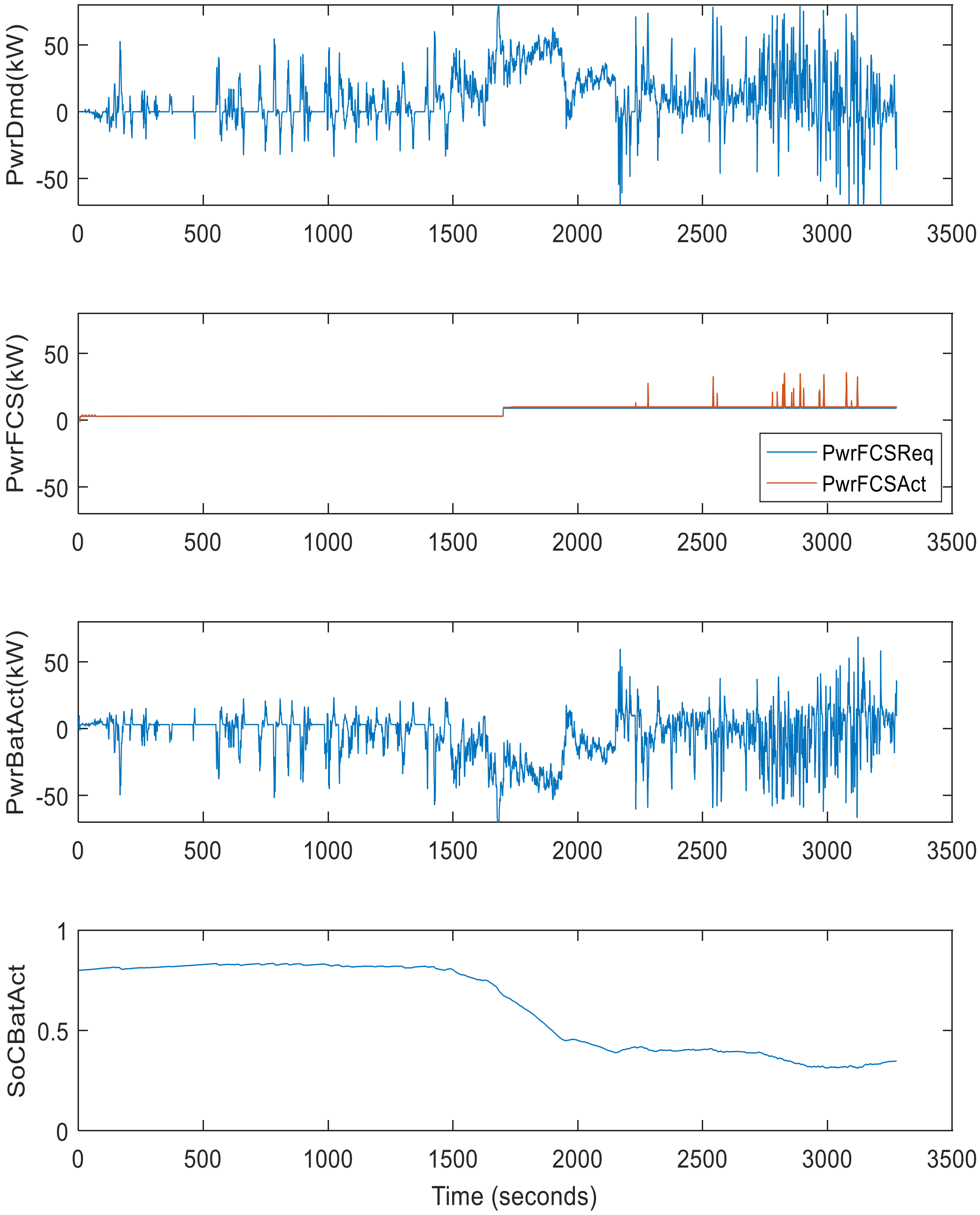


Figure 29 Graz driving cycle with initial SoC 80% in FixedPoint

The x-axis in Figure 29 is simulation time, which is from 0 to 3277 second in Graz driving cycle in FixedPoint strategy. The first diagram is the curve of demand power. Demand power of it is from -70kW to 70kW roughly. There are many stops in the first half part of driving cycle, from around 1600s, demand power increases, and stays in a high level. Within the latter half, demand power changes dramatically from minimum to maximum power. The second diagram is the actual power of FCS. Its behavior changes according to established EMS. In the first half part, FCS works with idle operation point due to high level battery SoC, when SoC begin to decrease around 1500s, FCS changes to maximum efficiency point, in the last half part, FCS occasionally works in maximum power point due to the temporary peak power. The third diagram demonstrates performance of battery. Based on the design of strategy concept, battery will cover the residual power automatically. So similar with changing of demand power, the first half part before 1500s, battery discharges almost time, then response dramatically within the latter half part. The last diagram is the SoC changing of battery. It is shown that SoC begins with 80%, and keep steady before 1500s because of low level demand power and power supply from FCS, so no energy consumption in battery. SoC decreases from 1500s due to the increasing of demand power, finally stay around 40%.

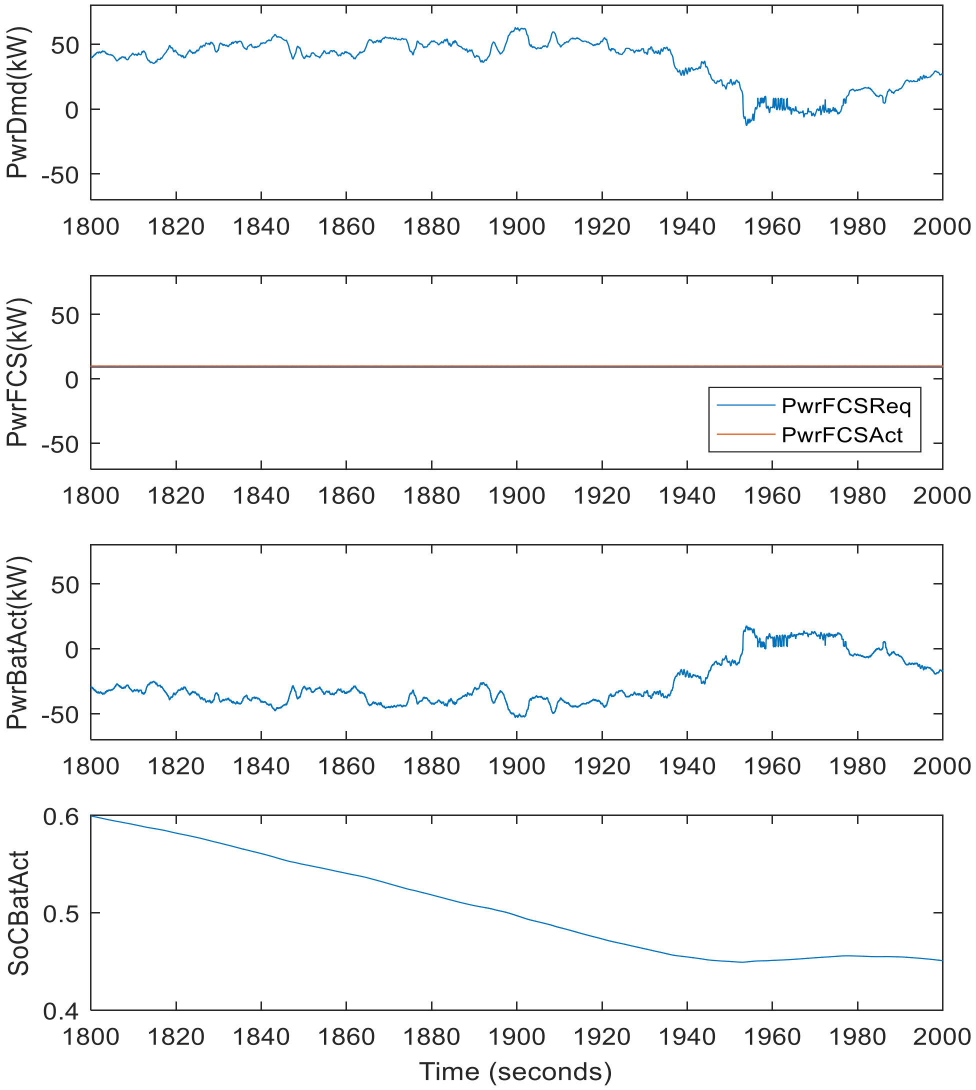


Figure 30 Graz driving cycle with initial SoC 80% in FixedPoint (1800-2000s)

From Figure 29, it is shown tht FCS performs as desired, working with two fixed operation points and occasional fluctuations, reason for which is operation point would like to jump from P_{FCS_EffMax} to P_{FCS_Max} in short time period. Meanwhile, battery as an energy buffer covers the residual dynamic response, the actual power of it changes along with demand power, and SoC varies based on strategy rules defined before.

Figure 30 exemplary demonstrates the performance of FCS and battery from 1800 to 2000 seconds.. Demand power stay at high level most time, around 50 kW, a short low power period appears from 1940s. In this 200s time period, FCS words in maximum efficiency power point solidly. Battery provides residual power and dynamically responses following the demand power. Due to discharging in this period, SoC of battery goes down from 60% to 45%.

Advantage of FixedPoint strategy is that FCS works with three operation points most of the time, less dynamic fluctuations appear. Additionally, if driving cycle is ideal, with appropriate demand power, FCS will work with maximum efficient operation point more time. However, FCS may work in maximum power operation point, relative lower efficiency more often, if average value of demand power of driving cycle is higher. It means that in this case total efficiency is lower and hydrogen consumption is higher. The fact can be also proved when using FraVie (highway) driving cycle to simulate – see discussion in the subsequent section.

At the same time, LoadFollowing strategy has also been implemented. Figure 31 shows performance of FCS and battery, particularly, Figure 32 tells more details about it.

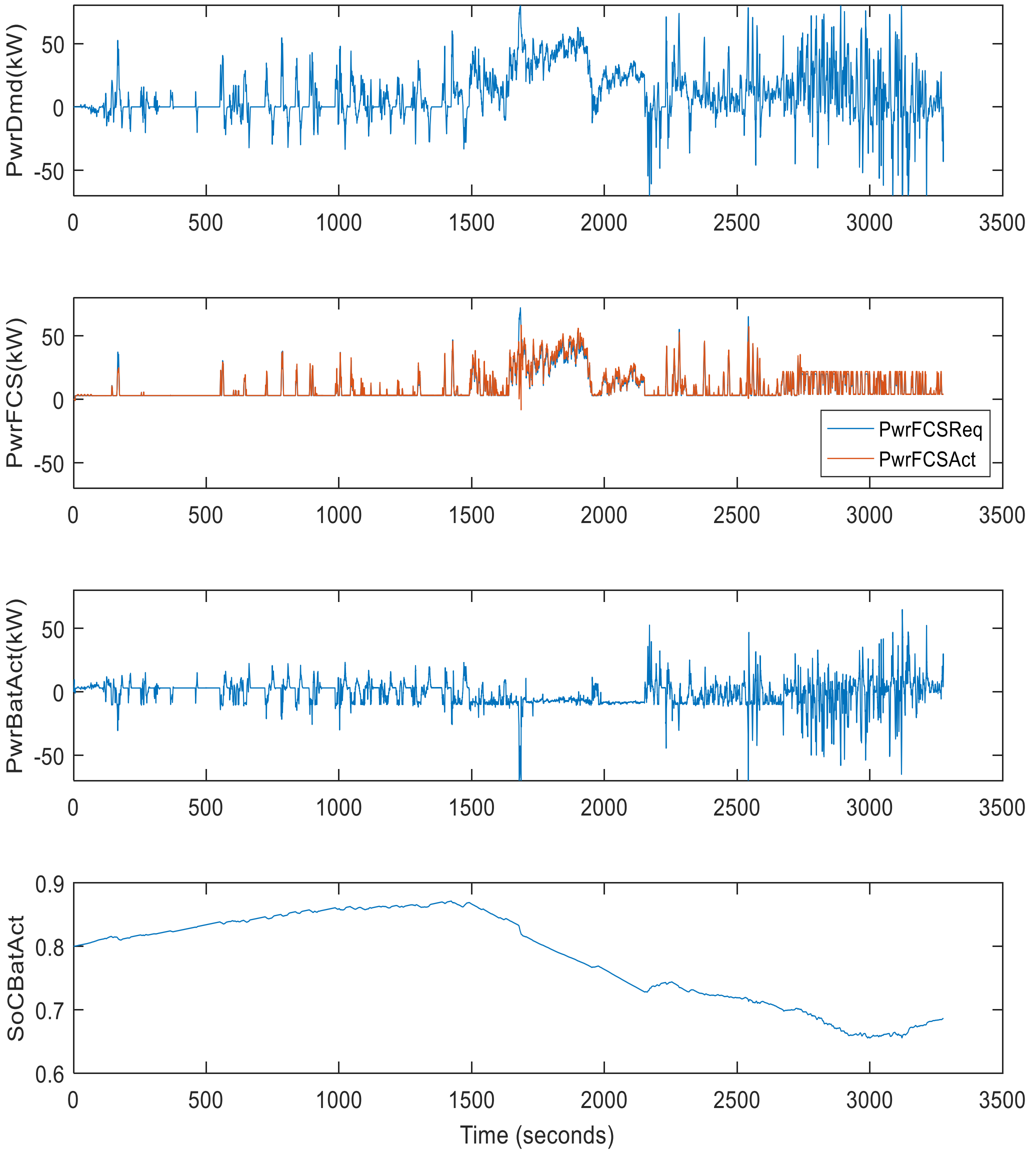


Figure 31 Graz driving cycle with initial SoC 80% in LoadFollowing

The x-axis in Figure 31 is simulation time, which is from 0 to 3277 second in Graz driving cycle in LoadFollowing strategy. The first diagram is the curve of demand power. The second diagram is the actual power of FCS. Its behavior changes according to established LoadFollowing EMS. The first half part before 1500s, FCS works in idle operation point most time, at other time, follows the positive demand power. When demand power increases, FCS follows positive demand power. At the last part period, beginning from 2600s, FCS works within the efficient range due to the SoC range. The third diagram demonstrates performance of battery. Based on the design of strategy concept, battery will cover the residual power automatically. So in this case, battery covers the peak power most time and absorbs the breaking energy, at the latter part, power of battery changes due to drastic change of demand power. The last diagram is the SoC changing of battery. It is shown that SoC begins with 80%, and increases until near 90% from 0 to 1500s, then decreases due to high level demand power, finally stay within the target range, around 70%.

FCS works more dynamically in LoadFollowing strategy. In this control strategy, FCS works at idle operation point at least even under much negative demand power (vehicle braking) as frequent FCS on/off should be avoided. This results in a battery electric energy, and SoC still goes up if average demand power is low. For the other time steps, FCS behavior is based on rules of LoadFollowing strategy concept. As for battery, residual of demand power is covered by it, and finally SoC of battery can stay within the desired range.

In Figure 32, details from 1800s to 2000s have been demonstrated. Demand power stay at high level most time, around 50 kW, a short low power period appears from 1940s. In this 200 seconds period, FCS follows the demand power, and because of power rate limitation (-10 to 10 kW/s in this work), FCS actual power is not same with demand power. Battery provides residual power dynamically, in this period, battery discharges steadily most time. Due to discharging in this period, SoC of battery goes down from 79% to 76%.

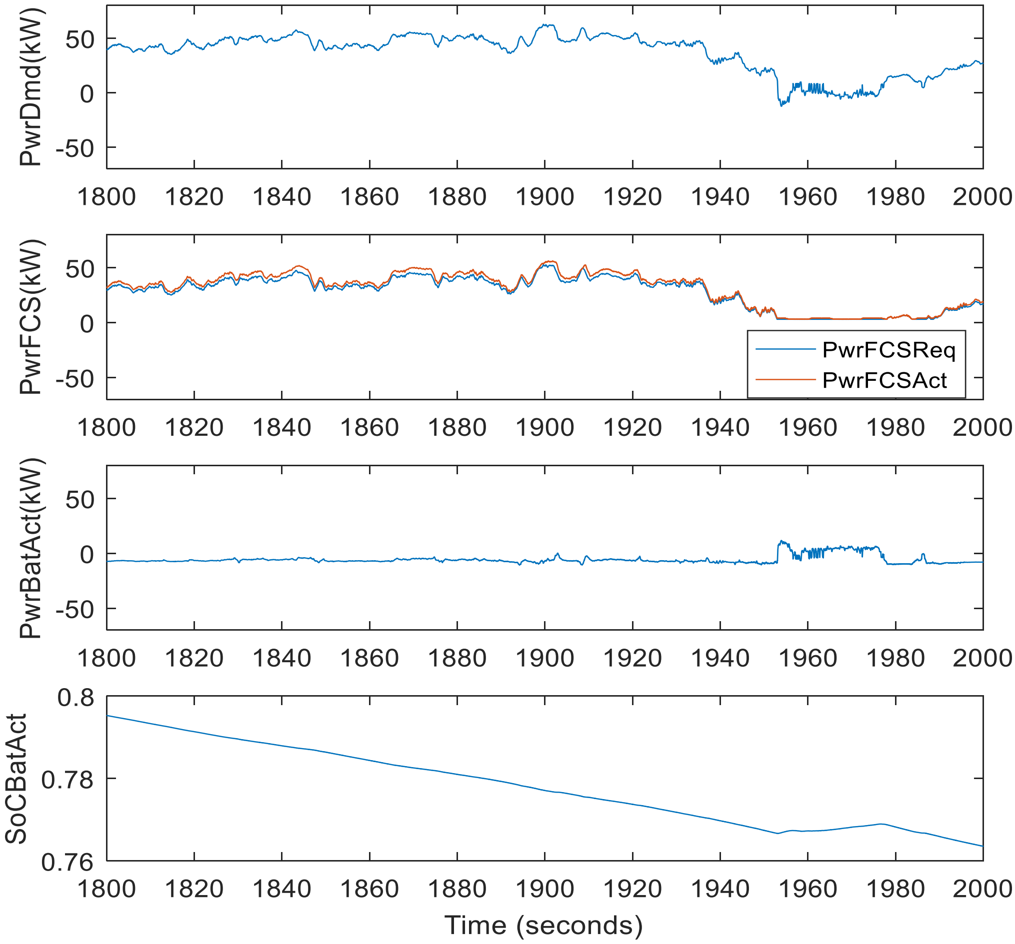


Figure 32 **Graz driving cycle with initial SoC 80% in LoadFollowing (1800-2000s)**

Above it is shown and discussed the simulation results of two strategies with the initial battery SoC of 80%. But in order to get more accurate and comprehensive results, many simulations with various initial battery SoC from 5% to 95% have been performed, all data shown in Table 4. Final SoC values of two control strategies are different. Average demand power of Graz driving cycle is between FCS maximum efficiency point and maximum power, due to that reason, FSC working with maximum efficiency power cannot fulfill demand power during the whole driving cycle, which leads to SoC jumping over SoC_{Lo} line. As for final SoC in LoadFollowing strategy, they are dependent on initial SoC, but can still stay at a high level.

And based on equation [3.17], equivalent hydrogen consumption per 100 km has been calculated and correspondent results of two strategies are compared with results of basic strategy. Fuel saving of FixedPoint and LoadFollowing strategy are 3.60% and 4.79% respectively.

Table 4 Simulation results of strategies in the Graz driving cycle

Strategy	Initial SOC	Final SOC	ActH$_2$Cns_g	EquivH$_2$Cns_g	EquivH$_2$Cns_kg/100km	EquivH$_2$CnsAvg_kg/100km	% Compare to basic Strategy
Basic	0,05	0,4345	786,9	660,6	1,404	1,4705	0,00%
	0,2	0,551	778,2	668,1	1,43		
	0,4	0,751	778,2	668,1	1,43		
	0,6	0,9189	760,9	670,3	1,435		
	0,8	0,9046	678,6	718,1	1,537		
	0,95	0,8895	593,3	741,3	1,587		
FixedPoint	0,05	0,3519	882,8	790,7	1,424	1,4175	3,60%
	0,2	0,3589	656	669,9	1,434		
	0,4	0,3535	499,1	651,8	1,396		
	0,6	0,3582	411,4	659,1	1,411		
	0,8	0,3492	296,6	659,7	1,412		
	0,95	0,3802	224,8	666,9	1,428		
LoadFollowing	0,05	0,534	828,6	662,6	1,419	1,4000	4,79%
	0,2	0,5341	749,4	661,1	1,415		
	0,4	0,534	619,6	642,5	1,376		
	0,6	0,5341	491,9	623,6	1,335		
	0,8	0,6867	507,4	660,5	1,414		
	0,95	0,6741	422,8	681,2	1,441		

3.3.2.2 FraVie driving cycle

Frankfurt to Vienna driving cycle is corresponding to highway behavior, for which performance of the two control strategies are also necessary to be discussed. FCS and battery behaviors are illustrated in Figure 33 and Figure 34, FixedPoint and LoadFollowing strategy respectively. FCS works with maximum efficiency power and maximum power most of the time, meanwhile, battery follows residual demand power dynamically. SoC stays around SoC_{Lo} (30%) lots of time steps during the whole driving cycle - the reason of which is average demand power of highway driving cycle is much higher than FCS maximum efficiency power, but at the same time less than maximum power. That is to say, FCS operation points jump over between P_{FCS_EffMax} and P_{FCS_Max}. At the end of the driving cycle, average demand power reduces, and consequently SoC increases.

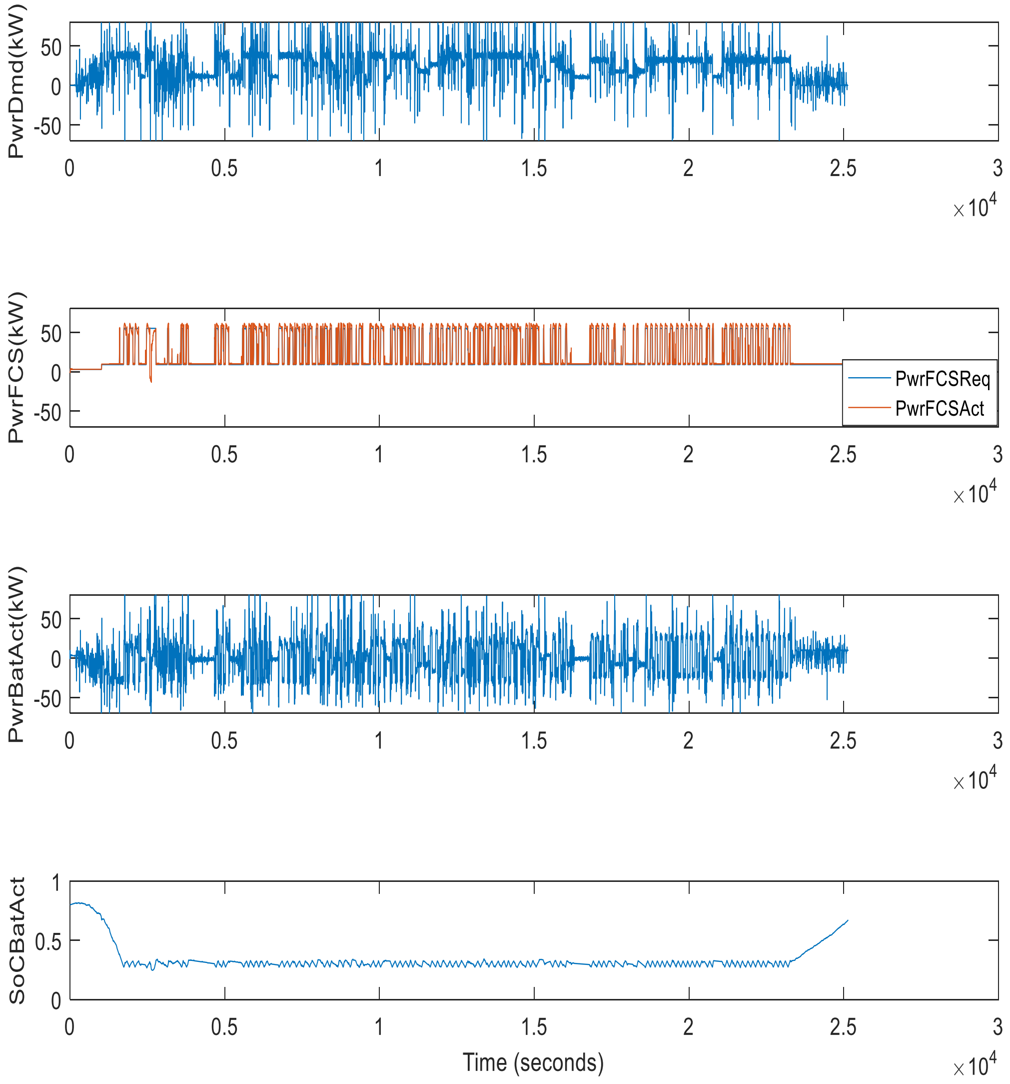


Figure 33 **FraVie driving cycle with initial SoC 80% in FixedPoint**

The x-axis in Figure 33 is simulation time, which is from 0 to 25148 second in Frankfurt to Vienna driving cycle in FixedPoint strategy. The first diagram is the curve of demand power. Demand power of it is from -90 kW to 110 kW roughly. Except the beginning and ending part, demand power stays in a high level, and it is obvious that Frankfurt to Vienna driving cycle changes more dramatic than Graz driving cycle. The second diagram is the actual power of FCS. Its behavior changes according to established FixedPoint EMS. Except the beginning working in idle operation point, FCS works with maximum efficiency point and maximum power. The third diagram demonstrates performance of battery. Based on the design of strategy concept, battery will cover the residual power automatically. So in this case, battery covers the peak power most time and absorbs the breaking energy. Due to that FCS works only with three operation point, most part of demand power have been covered by battery, that is the reason battery has a very dynamic performance. The last diagram is the SoC changing of battery. It is shown that SoC begins with 80%, and decreases at the beginning, then stay around 30% for a long time because of high power demand, finally starts to increase to near 80% at the end.

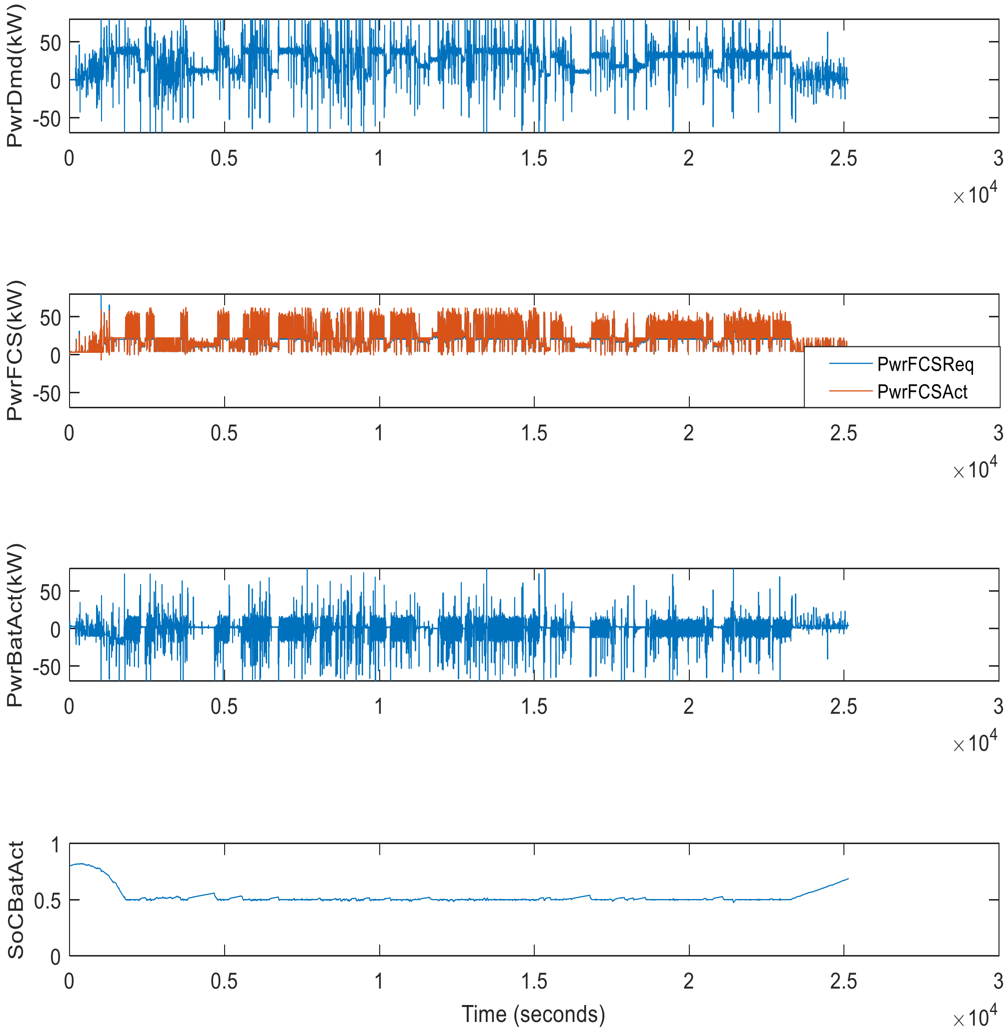


Figure 34 FraVie driving cycle with initial SoC 80% in LoadFollowing

The x-axis in Figure 34 is simulation time, which is from 0 to 25148 second in Frankfurt to Vienna driving cycle in LoadFollowing strategy. The first diagram is the curve of demand power. The second diagram is the actual power of FCS. It is shown that FCS follows the demand power and changes as dramatic as demand power. The third diagram demonstrates performance of battery. Although FCS has covered most of demand power, battery still needs to supply residual peak power. The last diagram is the SoC changing of battery. It is shown that SoC begins with 80%, and decreases at the beginning, then stay around 50% for a long time, finally starts to increase to near 80% at the end.

Instead of working with three fixed operation points, FCS can partly follow the demand power in LoadFollowing strategy. Similar with FixedPoint strategy, SoC remains around SoC_{Mid} (50%) during plenty of time. That is because FCS will work within efficiency range (4 kW to 20 kW) when SoC is from SoC_{Mid} (50%) to SoC_{Hi} (70%), and work with maximum power (55 kW) when demand power is higher than P_{FCS_Max}. At the end, SoC will remain near the SoC_{Mid}.

Except of examples with initial SoC 80% shown above, SoC from 5% to 95% is also simulated in model, results are available in Table 5 5. Based on simulation outputs, it is not difficult to find that fuel consumption of the two strategies is not ideal. What is worse is that fuel consumption of FixedPoint increases when comparing with basic strategy. The reason is that FCS does not work with high efficient range as expected, due to high average demand power of highway driving cycle. FCS works with maximum power operation point mostly, which equals to working with a lower efficient operation point.

3.3.3 Comparison of the two strategies

Based on simulation results it is shown that two strategies FixedPoint and LoadFollowing, are effective for Graz driving cycle, which can reduce 3.60% and 4.79% equivalent hydrogen consumption, respectively. For FraVie driving cycle, the two strategies cannot save any fuel consumption. On the contrary, it increases by 12.30% fuel consumption, the latter nearly save nothing, by 0.44%. Therefore, it can be stated that both strategies developed are suitable for city center driving cycle, not for highway. And this conclusion will be confirmed again in the next chapter, optimization about both strategies.

From the point of hydrogen consumption view, LoadFollowing strategy has a better performance than another. This conclusion will also be shown more obviously in next chapter. From the dynamic response view, FCS easily works with lower efficient operation points instead of high one in FixedPoint strategy. It requires demand power from driver with high compatibility. Additionally, working range of battery is also wider as it has to meet the residual power of demand power, which could mean battery works in a relative lower efficient range shown in Table 2 2.

3.4 Conclusions of section

a. Based on FCS efficiency map as well as battery general efficiency map, different operation points of FCS and SoC limitation of battery have been defined. Then FixedPoint and LoadFollowing strategies have been developed and corresponding models have been built in Simulink.
b. One theory about the concept of equivalent hydrogen consumption has been used to calculate hydrogen consumption, which is a significant principle to evaluate EMS.
c. Graz and FraVie driving cycles have been used to test the two energy management strategies. As result it is visible that these two EMS are not good enough for highway driving cycle. In city center driving cycle, LoadFollowing strategy is better than the other strategies.

Table 5 Simulation results of strategies for the FraVie driving cycle

Strategy	Initial SOC	Final SOC	ActH$_2$Cns_g	EquivH$_2$Cns_g	EquivH$_2$Cns_kg/100km	EquivH$_2$CnsAvg_kg/100km	% Compare to basic
Basic	0,05	0,9922	10209,9	10101,4	1,393	1,3925	0,00%
	0,2	0,8998	10115,5	10112	1,391		
	0,4	0,8998	9946	10063,4	1,384		
	0,6	0,9149	9475	9656	1,399		
	0,8	0,8999	9729	10086,3	1,387		
	0,95	0,8922	9747	10187,3	1,401		
FixedPoint	0,05	0,6426	11819,1	11264,7	1,549	1,5638	-12,30%
	0,2	0,6426	11702,3	11253	1,547		
	0,4	0,661	11719,2	11386,2	1,566		
	0,6	0,6715	11333,8	11209,1	1,541		
	0,8	0,661	11469,1	11366,7	1,563		
	0,95	0,661	11977,1	11761,4	1,617		
LoadFollowin	0,05	0,6769	10071,2	10099,6	1,389	1,3863	0,44%
	0,2	0,6768	9969	10082,4	1,386		
	0,4	0,6769	9841	10062,1	1,384		
	0,6	0,6869	9714	10067,4	1,382		
	0,8	0,6769	9618	10131,2	1,384		
	0,95	0,677	9596	10131,2	1,393		

4 Energy management strategy optimization

In this work, two energy management strategies are developed based on the efficiency map and system characteristics of FCS, as well as considerations of battery safety and efficiency. Working status of FCS is divided by the SoC and FCS operation points, under the basic idea of optimal efficiency. And strategies can be used in real driving conditions, not only in offline simulation of the model.

From previous chapter, it is known that some parameters defined in the concept of control strategies are fixed, such as SoC_{Min} and SoC_{Max}, with safety consideration. However, others can be flexible, which means changing of these parameters could change hydrogen consumption, so it is meaningful to discuss that influencing parameters.

4.1 Efficiency range optimization

Except idle, maximum efficient power and maximum power of FCS, which are usually dependent on system characteristics and fixed, the efficiency range (from low efficiency operation point to high efficiency operation point) is flexible, shown in Figure 35, which can be adapted in different control strategies. Consequently, the first set of parameters optimized is FCS efficiency range. Because efficiency range is only implemented in LoadFollowing strategy, FixedPoint strategy will not discussed here.

In the first version of LoadFollowing strategy, operation points of FCS have been defined in Table 6. Now P_{FCS_EffLo} and P_{FCS_EffHi} will be changed to find out the influence on FCS hydrogen consumption.

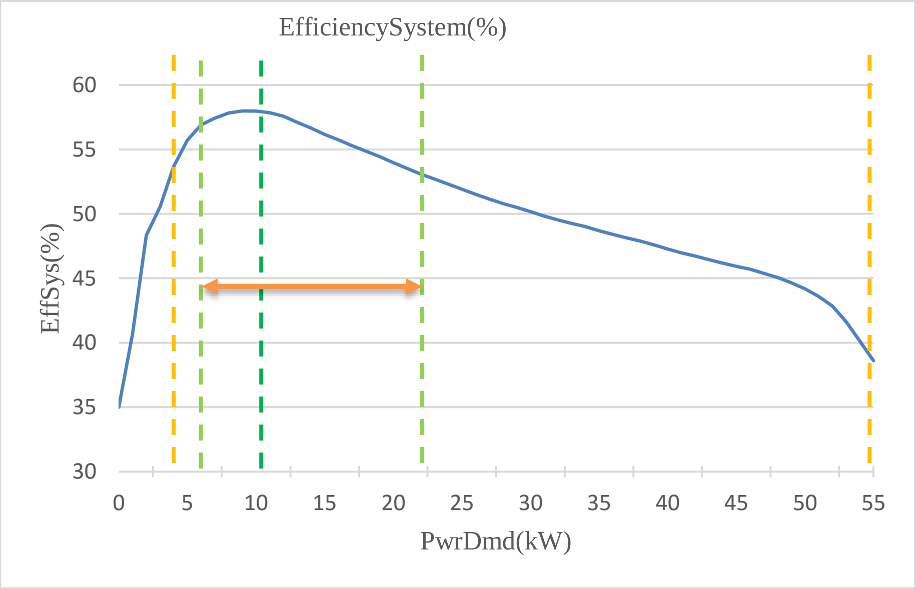


Figure 35 Efficiency range of FCS

Table 6 Initial values of FCS operation points

Parameters:	***Initial Values***
PwrFCSIdle P	3kW
PwrFCSEffLo P	4kW
PwrFCSEffMax P	9kW
PwrFCSEffHi_P	20kW
PwrFCSMax P	55kW

Before setting rules of efficiency range change, pre-conditions are:

$$\begin{cases} P_{FCS\_Idle} < P_{FCS\_EffLo} < P_{FCS\_EffMax} \\ P_{FCS\_EffMax} < P_{FCS\_EffHi} < P_{FCS\_Max} \end{cases} \qquad [4.1]$$

Then P_{FCS_EffLo} and P_{FCS_EffHi} are presented by P_{FCS_EffMax}:

$$\begin{cases} P_{FCS\_EffLo} = \alpha * P_{FCS\_EffMax} \\ P_{FCS\_EffHi} = \beta * P_{FCS\_EffMax} \end{cases} \qquad [4.2]$$

And values of α and β are limited by:

$$\begin{cases} 0.33 \leq \alpha < 1 \; [0.4, 0.1, 0.9] \\ \;\; 1.5 \leq \beta \leq 6 \; [1.5, 0.5, 6] \end{cases} \qquad [4.3]$$

The efficiency between idle and maximum efficiency changes more dramatically than the range from maximum efficiency and maximum power, so different steps are taken under consideration for the change of P_{FCS_EffLo} and P_{FCS_EffHi}. Therefore, there are 6 * 10 = 60 combinations totally from the equation 4.2 and 4.3. Work of next step is simulating in model with various sets of P_{FCS_EffLo} and P_{FCS_EffHi}.

By simulating with different combinations of α and β in Graz and FraVie driving cycles with initial SoC of 60%, equivalent hydrogen consumptions have been calculated shown in Table 7 and Table 8 respectively. From these results, the best combination is (α, β) = (0.9, 2), which are P_{FCS_EffLo} and P_{FCS_EffHi} being 8 kW and 18 kW, and corresponding equivalent hydrogen consumption is 1.312 kg, saving 1.72% in Graz driving cycle. Correspondingly, the best combination is (α, β) = (0.9, 6), which are P_{FCS_EffLo} and P_{FCS_EffHi} being 8 kW and 54 kW, and corresponding equivalent hydrogen consumption is 1.358 kg, saving 1.74% in FraVie driving cycle.

Three-dimensional map of each driving cycle about simulation results have also been created in Matlab, showing results more intuitively, demonstrated in Figure 36 and Figure 37.

Table 7 Simulation equivalent hydrogen consumption per 100km (kg) results in Graz driving cycle with 60% initial SoC

EquivH$_2$Cns_kg/100km	**β**	**1,5**	**2**	**2,5**	**3**	**3,5**	**4**	**4,5**	**5**	**5,5**	**6**
α											
0,4		1,338	1,337	1,337	1,334	1,333	1,333	1,336	1,339	1,341	1,344
0,5		1,333	1,332	1,33	1,328	1,33	1,33	1,332	1,333	1,34	1,345
0,6		1,329	1,329	1,323	1,324	1,326	1,327	1,328	1,334	1,342	1,342
0,7		1,324	1,321	1,32	1,321	1,324	1,324	1,328	1,337	1,342	1,347
0,8		1,319	1,315	1,317	1,319	1,321	1,322	1,328	1,337	1,343	1,347
0,9		1,314	1,312	1,313	1,316	1,32	1,322	1,329	1,337	1,342	1,346

Table 8 Simulation equivalent hydrogen consumption per 100km (kg) results in FraVie driving cycle with 60% initial SoC

EquivH$_2$Cns_kg/100km	**β**	**1,5**	**2**	**2,5**	**3**	**3,5**	**4**	**4,5**	**5**	**5,5**	**6**
α											
0,4		1,394	1,393	1,391	1,388	1,386	1,384	1,382	1,38	1,379	1,378
0,5		1,392	1,391	1,387	1,385	1,383	1,381	1,378	1,376	1,375	1,375
0,6		1,39	1,388	1,385	1,382	1,38	1,377	1,375	1,373	1,372	1,371
0,7		1,393	1,389	1,386	1,384	1,381	1,378	1,374	1,372	1,37	1,37
0,8		1,39	1,387	1,384	1,38	1,376	1,373	1,369	1,367	1,365	1,365
0,9		1,388	1,383	1,379	1,374	1,37	1,365	1,362	1,361	1,36	1,358

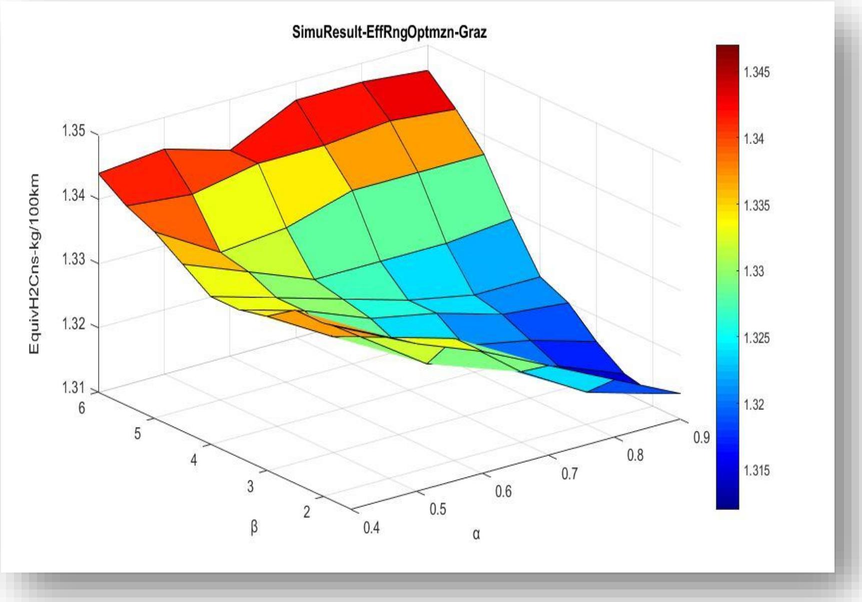


Figure 36 Influence of efficient range in Graz driving cycle

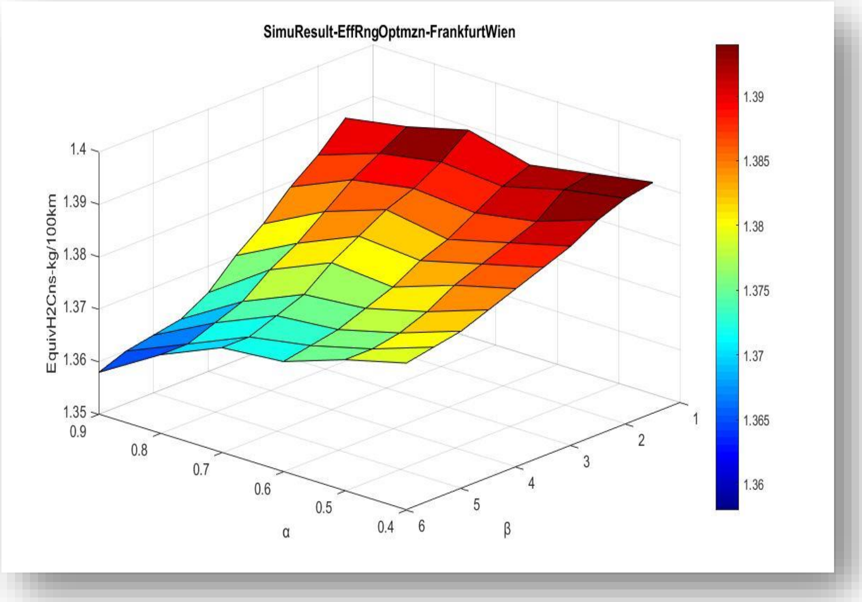


Figure 37 Influence of efficient range in FraVie driving cycle

Finally, the optimal combinations of P_{FCS_EffLo} and P_{FCS_EffHi} for Graz and FraVie driving cycle are shown in Table 9.

Table 9 Optimal combinations of efficiency range

Driving cycle	α	β	P_{FCS_EffLo}	P_{FCS_EffHi}	Equivalent hydrogen consumption (kg/100km)	Hydrogen saving (%)
Graz	0.9	2	8 kW	18 kW	1.312	1.72
FraVie	0.9	6	8 kW	54 kW	1.358	1.74

4.2 SoC limitation optimization

Except the minimum limitation SoC_{Min} and maximum limitation SoC_{Max}, other three thresholds, SoC_{Lo}, SoC_{Mid} and SoC_{Hi}, are changeable to achieve a better goal of energy management strategy, see Figure 38.

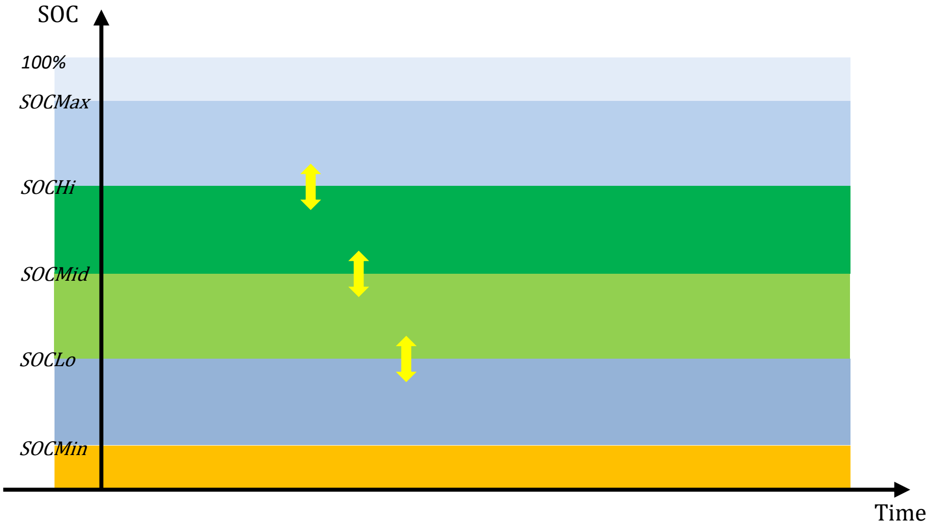


Figure 38 Schematic diagram of SoC limitation optimization

Initial values have been defined shown in Table 10 at the beginning of the work. SoC_{Lo}, SoC_{Mid} and SoC_{Hi} might be changed based on specific rules to check if they influence performance of hydrogen consumption.

Table 10 Initial values of battery SoC limitations

Parameters:	*Initial Values*
SOCMin	10%
SOCLo	30%
SOCMid	50%
SOCHi	70%
SOCMax	90%

Changing of SoC_{Lo}, SoC_{Mid} and SoC_{Hi} firstly should comply with the following rules:

$$20\% < SoC_{Lo} < SoC_{Mid} < SoC_{Hi} < 90\% \qquad [4.4]$$

Then combinations can be acquired.

$$\begin{cases} 30\% \leq SoC_{Lo} \leq 50\% \; [30\%, 10\%, 50\%] \\ SoC_{Lo} < SoC_{Mid} < SoC_{Hi} \\ 60\% \leq SoC_{Hi} \leq 80\% \; [60\%, 10\%, 80\%] \end{cases} \qquad [4.5]$$

Finally, 18 combinations are simulated in FixedPoint and LoadFollowing strategies with Graz and FraVie driving cycles. All simulation results are shown in Table 12 and Table 13, Graz and FraVie driving cycle respectively.

It is shown in Table 11 that, for different strategies, the optimal combination of SoC could have many sets. Therefore, a same setin one driving cycle is chosen as the final optimal combination, for instance, $SoC_{Lo} = 50\%$, $SoC_{Mid} = 70\%$ and SoC_{Hi} 80% is final combination for both EMS in Graz driving cycle, which reduces 5.85% and 4.55% hydrogen consumption respectively, comparing with strategies without optimization. Similarly, for FraVie driving cycle, $SoC_{Lo} = 30\%$, $SoC_{Mid} = 60\%$ and SoC_{Hi} 80% is the optimal combination, which reduces 1.75% and 0.15% fuel consumption in FixedPoint and LoadFollowing strategy respectively.

Table 11 Optimal results of SoC limitation optimization

Driving cycle	EMS	Combination of SoC_{Lo}, SoC_{Mid} and SoC_{Hi}	Equivalent Hydrogen Consumption (kg/100km)	Hydrogen Saving (%)
Graz	FixedPoint	SocLo0.5,SocMid0.7,SocHi0.8	1.319	5.85
	LoadFollowing	SocLo0.3,SocMid0.7,SocHi0.8 SocLo0.4,SocMid0.7,SocHi0.8 SocLo0.5,SocMid0.7,SocHi0.8	1.237	4.55
FraVie	FixedPoint	SocLo0.3,SocMid0.6,SocHi0.7 SocLo0.3,SocMid0.6,SocHi0.8	1.404	1.75
	LoadFollowing	SocLo0.3,SocMid0.6,SocHi0.8 SocLo0.4,SocMid0.6,SocHi0.8 SocLo0.5,SocMid0.6,SocHi0.8	1.336	0.15

Furthermore, one final optimal combination of SoC limitation should be chosen. Result of simulation is good for Graz driving cycle, therefore, $SoC_{Lo} = 50\%$, $SoC_{Mid} = 70\%$ and SoC_{Hi} 80%, is the final optimal combination for SoC limitation optimization.

Table 12 Optimization of SoC limitations in Graz driving cycle with initial SoC 60%

Strategy	Set	SocLo	SocMid	SocHi	FinalSoc	ActH_2Cns_g	EquivH_2Cns_g	EquivH_2Cnskg/100km
LoadFollowing	1	0,3	0,4	0,6	0,5449	505,9	627,2	1,343
	2	0,3	0,4	0,7	0,5369	476,5	606,5	1,298
	3	0,3	0,4	0,8	0,5895	500	591,6	1,267
	4	0,3	0,5	0,6	0,5488	507,8	623,3	1,341
	5	0,3	0,5	0,7	0,5416	478,8	605,5	1,296
	6	0,3	0,5	0,8	0,5961	503,2	590,1	1,263
	7	0,3	0,6	0,7	0,6415	549	597,1	1,278
	8	0,3	0,6	0,8	0,6426	532,8	583,4	1,249
	9	0,3	0,7	0,8	0,7415	604,7	578	1,237
	10	0,4	0,5	0,6	0,5488	507,8	626,3	1,341
	11	0,4	0,5	0,7	0,5416	478,8	605,5	1,296
	12	0,4	0,5	0,8	0,4961	503,2	590,1	1,263
	13	0,4	0,6	0,6	0,6415	549	597,1	1,278
	14	0,4	0,6	0,7	0,6426	532,8	583,4	1,249
	15	0,4	0,7	0,8	0,7415	604,7	578	1,237
	16	0,5	0,6	0,7	0,6415	549	597,1	1,278
	17	0,5	0,6	0,8	0,6426	532,8	583,4	1,249
	18	0,5	0,7	0,8	0,7415	604,7	578	1,237
FixedPoint	1	0,3	0,4	0,6	0,3604	421,8	662,9	1,419
	2	0,3	0,4	0,7	0,3658	399,3	656,1	1,405
	3	0,3	0,4	0,8	0,3894	390,2	652	1,396
	4	0,3	0,5	0,6	0,3684	426,6	661,4	1,416
	5	0,3	0,5	0,7	0,3696	401,1	654,2	1,401
	6	0,3	0,5	0,8	0,3947	393	650,7	1,393
	7	0,3	0,6	0,7	0,3701	401,2	653,5	1,399
	8	0,3	0,6	0,8	0,3997	396,6	649,6	1,391
	9	0,3	0,7	0,8	0,4028	397,2	648,9	1,389
	10	0,4	0,5	0,6	0,4652	509,7	648,6	1,389
	11	0,4	0,5	0,7	0,453	464,3	639,5	1,369
	12	0,4	0,5	0,8	0,4658	442,9	633,3	1,356
	13	0,4	0,6	0,6	0,462	469,7	639	1,368
	14	0,4	0,6	0,7	0,4696	444,8	631,3	1,352
	15	0,4	0,7	0,8	0,4702	444,9	630,6	1,35
	16	0,5	0,6	0,7	0,5627	667,1	729	1,561
	17	0,5	0,6	0,8	0,5531	507,9	616,5	1,32
	18	0,5	0,7	0,8	0,5618	513	616,2	1,319

Table 13 Optimization of SoC limitations in FraVie driving cycle with initial SoC 60%

Strategy	**Set**	**SocLo**	**SocMid**	**SocHi**	**FinalSoc**	**ActH$_2$Cns_g**	**EquivH$_2$Cns_g**	**EquivH$_2$Cns kg/100km**
LoadFollowing	1	0,3	0,4	0,6	0,5879	9585	9750	1,341
	2	0,3	0,4	0,7	0,5942	9564	9732	1,338
	3	0,3	0,4	0,8	0,6007	9557	9724	1,337
	4	0,3	0,5	0,6	0,6314	9641	9763	1,343
	5	0,3	0,5	0,7	0,6878	9641	9729	1,338
	6	0,3	0,5	0,8	0,6942	9632	9720	1,337
	7	0,3	0,6	0,7	0,7314	9691	9720	1,339
	8	0,3	0,6	0,8	0,7878	9706	9737	1,336
	9	0,3	0,7	0,8	0,8314	9753	9716	1,337
	10	0,4	0,5	0,6	0,6314	9641	9722	1,343
	11	0,4	0,5	0,7	0,6878	9621	9763	1,338
	12	0,4	0,5	0,8	0,6942	9632	9729	1,337
	13	0,4	0,6	0,6	0,7314	9691	9720	1,339
	14	0,4	0,6	0,7	0,7878	9706	9737	1,336
	15	0,4	0,7	0,8	0,8314	9753	9722	1,337
	16	0,5	0,6	0,7	0,7314	9691	9737	1,339
	17	0,5	0,6	0,8	0,7878	9706	9716	1,336
	18	0,5	0,7	0,8	0,8314	9753	9722	1,337
FixedPoint	1	0,3	0,4	0,6	0,6334	12005	10731	1,476
	2	0,3	0,4	0,7	0,6547	11503	10336	1,421
	3	0,3	0,4	0,8	0,6547	11503	10336	1,421
	4	0,3	0,5	0,6	0,6316	11544	10401	1,43
	5	0,3	0,5	0,7	0,6723	11537	10388	1,429
	6	0,3	0,5	0,8	0,6723	11537	10388	1,429
	7	0,3	0,6	0,7	0,6722	11361	10212	1,404
	8	0,3	0,6	0,8	0,6722	11361	10212	1,404
	9	0,3	0,7	0,8	0,6722	11372	10228	1,407
	10	0,4	0,5	0,6	0,6412	11433	10247	1,409
	11	0,4	0,5	0,7	0,7334	11570	10322	1,42
	12	0,4	0,5	0,8	0,9547	11579	10318	1,419
	13	0,4	0,6	0,6	0,7316	11605	10396	1,43
	14	0,4	0,6	0,7	0,7723	11623	10387	1,428
	15	0,4	0,7	0,8	0,7722	11593	10365	1,425
	16	0,5	0,6	0,7	0,7413	11764	10469	1,44
	17	0,5	0,6	0,8	0,8334	11805	10447	1,437
	18	0,5	0,7	0,8	0,8316	11783	10483	1,442

4.3 Hysteresis of fuel cell state change optimization

The last possibility for optimization of two EMS is a variation of the value of FCS status changing hysteresis. Due to the reason that there is only one non-continuous power changing (startup and shutdown) in LoadFollowing strategy, it should be focussed on FixedPoint strategy, shown in Figure 39.

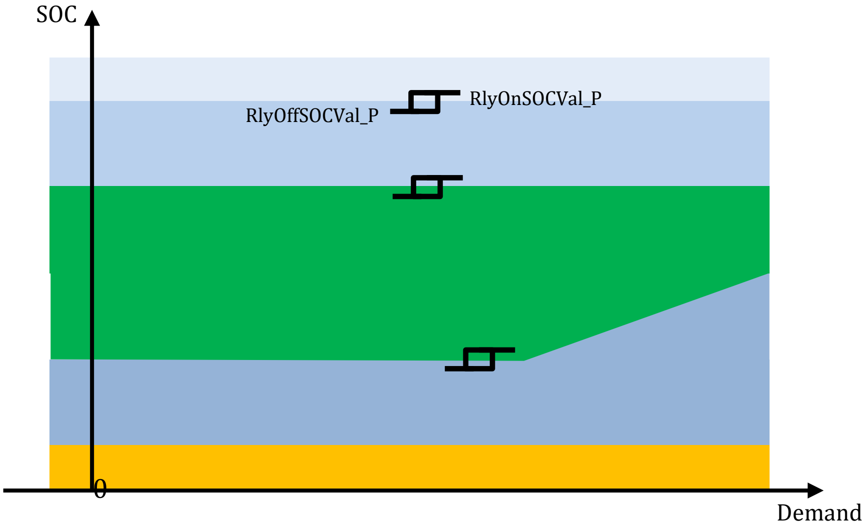


Figure 39 **Schematic diagram of FCS status changing hysteresis**

Initial value of RelayOn switch-on is 2.5%, Table 14, so the hysteresis range is 5%.

Table 14 **Initial values of hysteresis range optimization**

Parameters:	*Initial Values*
RlyOnSOCVal_P	2.5%
RlyOffSOCVal_P	-RlyOnSOCVal_P

Also, the changing of hysteresis range should follow the rules:

$$5\% <= RlyOnSOCVal\_P - RlyOffSOCVal\_P <= 10\% \qquad [4.6]$$

So getting RelayOn switch-on value:

$$RlyOnSOCVal\_P = [2.5\%, 0.1\%, 5\%] \qquad [4.7]$$

Totally, there are 26 possibilities, and all are simulated in model data collected in Table 15 in Graz driving cycle. Finally, the optimal set is RlyOnSOCVal_P = 3.6%, which reduces 0.50% hydrogen consumption, comparing with initial one, being 2.5%. So conclusion shows up that the range of FCS status changing hysteresis does not influence hydrogen consumption greatly. Its main function is to protect status of FCS changing frequently, which might shorten the life cycle of FCS.

Table 15 Optimization of hysteresis in Graz driving cycle with initial SoC 60%

Strategy	Set	RlyOnSOCVal_P	FinalSoc	ActH$_2$Cns_g	EquivH$_2$Cns_g	EquivH$_2$Cns_kg/100km
FixedPoint	1	0,025	0,3696	401.1	654,2	1,401
	2	0,026	0,3699	401,4	653,5	1,399
	3	0,027	0,37	401,7	653,1	1,398
	4	0,028	0,37	401,9	653	1,398
	5	0,029	0,3701	401,9	652,9	1,398
	6	0,03	0,3711	402,7	652,6	1,397
	7	0,031	0,3734	404,2	652,5	1,397
	8	0,032	0,3788	409	652,5	1,397
	9	0,033	0,3787	408,2	652,6	1,397
	10	0,034	0,3126	359,1	670,3	1,435
	11	0,035	0,3829	413	652,3	1,397
	12	0,036	0,3798	410,5	651,2	1,394
	13	0,037	0,3104	358,3	671,4	1,437
	14	0,038	0,3107	358,4	671,3	1,437
	15	0,039	0,3108	358,5	671,3	1,437
	16	0,04	0,311	358,6	671,3	1,437
	17	0,041	0,3118	359	671,2	1,437
	18	0,042	0,3127	359,4	671	1,437
	19	0,043	0,3129	359,5	671	1,437
	20	0,044	0,3162	359,5	670,3	1,435
	21	0,045	0,3163	359,6	670,3	1,435
	22	0,046	0,3163	359,6	670,3	1,435
	23	0,047	0,3166	359,7	670,3	1,435
	24	0,048	0,3166	359,7	670,3	1,435
	25	0,049	0,3195	361	669,6	1,434
	26	0,05	0,3195	361	669,7	1,434

4.4 Conclusions of section

Table 16 Summaries of equivalent hydrogen consumption

	Graz (Basic Strategy)	Graz (NoOptmzn)	Graz (Optmzn)	FrankfurtWien (Basic Strategy)	FrankfurtWien (NoOptmzn)	FrankfurtWien (Optmzn)
Equivalent H_2 Consumption(kg/100km) **LoadFollowing Strategy**	1.435	1.335	1.229	1.399	1.382	1.361
Reduced Equivalent H_2 Consumption (%)		6.97%	14.36%		1.22%	2.72%
Equivalent H_2 Consumption(kg/100km) **FixedPoint Strategy**	1.435	1.411	1.326	1.399	1.541	1.402
Reduced Equivalent H_2 Consumption (%)		1.67%	7.60%		-10.15%	-0.21%

Table 16 illustrates a summary of all results about the two control strategies simulated with Graz and FraVie driving cycle. It is obvious that both strategies - after optimizing - have a potential to reduce equivalent hydrogen consumption for Graz driving cycle (equals city center driving cycle) dramatically, which are 14.36% and 7.60% with LoadFollowing and FixedPoint strategies respectively. On the contrary, for FraVie driving cycle (equals highway driving cycle), the two strategies have less influence on it, 2.72% with LoadFollowing and minus 0.21% with FixedPoint strategy. That is to say, both strategies can be applied in city center driving cycle, but do not show significant advantageous in highway driving cycle. More specifically, LoadFollowing strategy is the best EMS for city center driving condition.

5 Summaries and conclusions

Energy management strategy is one of the most important parts in the development of hybrid vehicles (fuel cell – battery hybrid in this research) control strategies. In the present thesis, the focus was put on the power distribution between fuel cell system and battery. Furthermore, strategy optimization in vehicle propulsion system management was performed in different driving cycles. The target of energy management system (EMS) in the applied fuel cell / battery hybrid powertrain was to reduce hydrogen consumption under consideration of vehicle dynamic requirements and to the reduction of fuel cell stack degradation. To achieve such goal, following sub-tasks have been done:

a. Based on existing fuel cell system (FCS) and battery system, the FCS behavior was analyzed. Specifically, the Balance of Plant (BoP) components power consumption and system efficiency was investigated. Also, the startup and shutdown process were defined and implemented into the Simulink model, which can also be reused for further research.
b. EMS concept development and implementation was performed. Based on FCS efficiency map and battery characteristics, two control strategies were developed and implemented in Simulink. Subsequently, the control strategies were tested by use of two pre-defined test cycles, the Graz and Frankfurt to Vienna driving cycles. Comparing with a pre-defined basic strategy, conclusions show that both strategies are better for city center driving cycles than for highway driving cycles. In total, the “LoadFollowing” strategy shows better results than the “FixedPoint” strategy in city center driving cycle.
c. After development of first versions of the two strategies, three sets of threshold in control strategies have been carried out to optimize the equivalent hydrogen consumption. For different strategies and driving cycles, limitations of different parameters vary. In the simulation, the thresholds of parameters were chosen differently, but it should keep balance to chosen one general sets if a control strategy is used for every but not a typical driving cycle.

For future work, if hydrogen consumption of FCS wants to be reduced, following research directions may be followed in EMS:

a. Prediction of driving cycle. From previous work, it is known that simulation results of different strategies in different driving cycle may differ. If real driving conditions can be predicted in advance, then Vehicle Control Unit (VCU) can choose one corresponding better strategy.
b. From comparison of simulation results of the two investigated driving cycles, there are great differences visible. If possible, another fuel cell system should be used to implement and further evaluate the introduced control strategies. If the results are similar with those of the present work, then it is certain that different driving cycles lead to that results, otherwise it could be an issue of different fuel cell systems configurations.
c. Because of time limitation, the two strategies were not be implemented in a real vehicle to test them. The research just provides reference for real EMS development. For verification of the simulation results, the introduced concepts, models and the optimization should be tested in real driving situations with a real vehicle.

List of Figures

List of Tables

Bibliography

[1] Rivlin, Paul. “World oil and energy trends: Strategic implications for the Middle East.” Vol. 57. Jaffee Center for Strategic Studies, 2000.

[2] https://ssl.toyota.com/mirai/fullspecs.html

[3] https://www.hyundai.news/eu/press-kits/all-new-hyundai-nexo-technical-specifications/

[4] https://en.wikipedia.org/wiki/Toyota_Mirai

[5] https://en.wikipedia.org/wiki/Honda_Clarity

[6] https://www.mercedes-benz.com/en/mercedes-benz/vehicles/passenger-cars/glc/the-new-glc-f-cell/

[7] Liu-Tao et al. “Logic Threshold Based Energy Control Strategy for Parallel Hydraulic Hybrid Vehicles.” (2013).

[8] Huang Y J, Yin C L , Zhang J W . “Design of an energy management strategy for parallel hybrid electric vehicles using a logic threshold and instantaneous optimization method [J].” International Journal of Automotive Technology, 2009, 10(4):513-521.

[9] Zhumu Fu, Bin Wang, Xiaona Song, Leipo Liu, and Xiaohong Wang, “Power-Split Hybrid Electric Vehicle Energy Management Based on Improved Logic Threshold Approach,” Mathematical Problems in Engineering, vol. 2013, Article ID 840648, 9 pages, 2013.

[10] G?kce, Kür?ad, Ozdemir A . “An instantaneous optimization strategy based on efficiency maps for internal combustion engine/battery hybrid vehicles [J].” Energy Conversion and Management, 2014, 81:255-269.

[11] Shi D, Chu L, Guo J , et al. “Energy Control Strategy of HEB Based on the Instantaneous Optimization Algorithm[J].” IEEE Access, 2017, 5:19876-19888.

[12] Laarhoven P J M , Aarts E H L . „Simulated annealing: theory and applications [M].” D.Reidel Publishing Company, 1987.

[13] Paganelli, G., M., T., Delprat, S., Santin, J.-J., Delhom, M., & Combes, E. (2000). “Simulation and assessment of power control strategies for a parallel hybrid car. Proceedings of the Institution of Mechanical Engineers”, Part D: Journal of Automobile Engineering, 214(7), 705–717.

[14] Karbowski, Dominik, et al. “Plug-in vehicle control strategy: from global optimization to real time application.” 22th International Electric Vehicle Symposium (EVS22), Yokohama. 2006.

[15] Delprat, Sébastien, et al. “Control strategy optimization for an hybrid parallel powertrain.” American Control Conference, 2001. Proceedings of the 2001. Vol. 2. IEEE, 2001.

[16] N. J. Schouten, M. A. Salman and N. A. Kheir, “Fuzzy logic control for parallel hybrid vehicles,” in IEEE Transactions on Control Systems Technology, vol. 10, no. 3, pp. 460-468, May 2002.

[17] J. Moreno, M. E. Ortuzar and J. W. Dixon, “Energy-management system for a hybrid electric vehicle, using ultracapacitors and neural networks,” in IEEE Transactions on Industrial Electronics, vol. 53, no. 2, pp. 614-623, April 2006.

[18] Baumann, Bernd, Giorgio Rizzoni, and Gregory Washington. “Intelligent control of hybrid vehicles

using neural networks and fuzzy logic." No. 981061. SAE Technical Paper, 1998.

[19] https://www.toyota-global.com/innovation/environmental_technology/technology_file/fuel_cell_hybrid/fcstack.html

[20] Pukrushpan, Jay Tawee. "Modeling and control of fuel cell systems and fuel processors." Ann Arbor, Michigan, USA: University of Michigan, 2003.

[21] Dicks, Andrew, and David Anthony James Rand. "Fuel cell systems explained." Wiley, 2018.

[22] https://www.researchgate.net/post/What_is_the_significance_of_the_heating_value_HHV_and_LHV_for_bio-oil

[23] Borup, Rod, et al. "PEM fuel cell durability." DOE Hydrogen Program Review, Report No. FC40 (2005).

[24] Cho, E., Ko, J. J., Ha, H. Y., Hong, S. A., Lee, K. Y., Lim, T. W., & Oh, I. H. (2003). "Characteristics of the PEMFC repetitively brought to temperatures below 0 C." Journal of the Electrochemical Society, 150(12), A1667-A1670.

[25] Maass, S., et al. "Carbon support oxidation in PEM fuel cell cathodes." Journal of Power Sources 176.2 (2008): 444-451.

[26] Pei, Pucheng, Qianfei Chang, and Tian Tang. "A quick evaluating method for automotive fuel cell lifetime." International Journal of Hydrogen Energy 33.14 (2008): 3829-3836.

[27] Reiser, Carl A., et al. "A reverse-current decay mechanism for fuel cells." Electrochemical and Solid-State Letters 8.6 (2005): A273-A276.

[28] Kim, Jae Hong, et al. "Effects of Cathode Inlet Relative Humidity on PEMFC Durability during Startup–Shutdown Cycling I. Electrochemical Study." Journal of the Electrochemical Society 157.1 (2010): B104-B112.

[29] Shen, Qiang, et al. "Study on the processes of start-up and shutdown in proton exchange membrane fuel cells." Journal of Power Sources 189.2 (2009): 1114-1119.

[30] Lim, Katie Heeyum, et al. "Effect of operating conditions on carbon corrosion in polymer electrolyte membrane fuel cells." Journal of Power Sources 193.2 (2009): 575-579.

[31] Kim, Jutae, Junhee Lee, and Yongsug Tak. "Relationship between carbon corrosion and positive electrode potential in a proton-exchange membrane fuel cell during start/stop operation." Journal of Power Sources 192.2 (2009): 674-678.

[32] Liang, Dong, et al. 'Study of the cell reversal process of large area proton exchange membrane fuel cells under fuel starvation." Journal of Power Sources 194.2 (2009): 847-853.

[33] Wikner, Evelina, and Torbjörn Thiringer. "Extending Battery Lifetime by Avoiding High SOC." Applied Sciences 8.10 (2018): 1825.

[34] Rabbani, Raja Abid. "Dynamic Performance of a PEM Fuel Cell System. DTU Mechanical Engineering," 2013. 288 p. (DCAMM Special Report; No. S154).

[35] Key, T., H. E. Sitzlar, and T. D. Geist. "Fast Response, Load Matching Hybrid Fuel Cell." Final Tech. Prog. Rep., EPRI PEAC Corp., Knoxville, TN NREL/SR-560-32743 (2003).

[36] Tazelaar, Edwin, et al. "Energy Management Strategies for fuel cell hybrid vehicles; an overview." Electric Vehicle Symposium and Exhibition (EVS27), 2013 World. IEEE, 2013.

[37] Feroldi, Diego, et al. “Energy management strategies for fuel cell-hybrid vehicles.” (2008).

[38] Feroldi, Diego, and Marta Basualdo. “Description of PEM fuel cells system.” PEM Fuel Cells with Bio-Ethanol Processor Systems. Springer, London, 2012. 49-72.

[39] Reiser, Carl A., Deliang Yang, and Richard D. Sawyer. “Procedure for shutting down a fuel cell system using air purge.” U.S. Patent No. 6,858,336. 22 Feb. 2005.

[40] Reiser, Carl, Deliang Yang, and Richard Sawyer. “Procedure for starting up a fuel cell system using a fuel purge.” U.S. Patent Application No. 09/742,481.

[41] Wu, Billy, Mardit Matian, and Gregory J. Offer. “Hydrogen PEMFC system for automotive applications.” International Journal of Low-Carbon Technologies 7.1 (2012): 28-37.

[42] O'hayre, Ryan, et al. “Fuel cell fundamentals.” John Wiley & Sons, 2016.

[43] Amamou, Ali Akrem, et al. “A comprehensive review of solutions and strategies for cold start of automotive proton exchange membrane fuel cells.” IEEE Access 4 (2016): 4989-5002.

[44] Kabza, Alexander. “Fuel cell formulary” (2015).

[45] ZHAO Shui-ping, et al. “On Energy Management Strategy for Fuel Cell Electric Vehicle(FCEV) Based on Cruisesimulink Cosimulation.” Journal of chongqing jiaotong university (natural science). 30.5 (2011): 1068-1072.

[46] Sarioglu, İsmail Levent, et al. “Energy management for fuel-cell hybrid vehicles based on specific fuel consumption due to load shifting.” IEEE Transactions on Intelligent Transportation Systems 13.4 (2012): 1772-1781.

[47] Gao, Dawei, Zhenhua Jin, and Qingchun Lu. “Energy management strategy based on fuzzy logic for a fuel cell hybrid bus.” Journal of Power Sources 185.1 (2008): 311-317.

[48] Li, Qi, et al. “Energy management strategy for fuel cell/battery/ultracapacitor hybrid vehicle based on fuzzy logic.” International Journal of Electrical Power & Energy Systems 43.1 (2012): 514-525.

[49] Schaltz, Erik, Alireza Khaligh, and Peter Omand Rasmussen. “Influence of battery/ultracapacitor energy-storage sizing on battery lifetime in a fuel cell hybrid electric vehicle.” IEEE Transactions on Vehicular Technology 58.8 (2009): 3882-3891.

[50] Xu, Liangfei, et al. “Optimal vehicle control strategy of a fuel cell/battery hybrid city bus.” international journal of hydrogen energy 34.17 (2009): 7323-7333.

[51] Chan, Ching Chue. “The state of the art of electric, hybrid, and fuel cell vehicles.” Proceedings of the IEEE 95.4 (2007): 704-718.

[52] Thounthong, Phatiphat, Stephane Rael, and Bernard Davat. “Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications.” Journal of Power Sources 193.1 (2009): 376-385.

[53] Gonder, Jeffrey, and Tony Markel. “Energy management strategies for plug-in hybrid electric vehicles.” No. 2007-01-0290. SAE Technical Paper, 2007.