CONTROL DESIGN AND EMBEDDED SOFTWARE OF A FUEL CELL POWERED UPS

Lappeenranta–Lahti University of Technology LUT

LUT School of Energy Systems

Electrical Engineering

2024

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ABSTRACT

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Control design and embedded software of fuel cell powered UPS

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The objective of this thesis is to design a hydrogen-based fuel cell powered uninterruptable power supply. In UPS use backup sources or long-term energy storage options are almost exclusively diesel generators. This does pose a lot of problems in terms of environmental concerns. The thesis is done for the company Eaton.

A model-based design approach was used in this thesis. First a literature review of the system components was done, then controls were designed and selected. System was tested in an offline Simulink.

The designed control system was cascaded systems with parallel inner loops. Outer loop creates a power reference that is then divided between the two inner control loops. This results in the battery being used for fast transient response and the fuel cell to be used as the primary power source. PI-controllers were utilized in each loop. With the inner fuel cell loop the control of the rate of change was done with a rate limiter which calculates the derivative of the power reference and limits it to a maximum fall and rise times. Additionally, a battery charger was designed to be used with the system. Because batteries are also used for absorbing transients the batteries can never be fully charged. Thus, the battery charger generates aims to keep batteries at a specific setpoint.

Fuel cell in testing was simplified model of an actual fuel cell. The dynamic response that was observed in the literature review was simulated artificially with slowing the controller down. This resulted in a sufficient model of the fuel cell.

Overall, the system performance was within acceptable limits. In Simulink DC-link voltage could be kept within 2 per cent with low rise times and negligible steady state error. The

system could be running indefinitely as batteries can be charged with the fuel cell. Batteries could be used to dampen the effects of transients. Next step in research would be to create a Hardware-in-the-Loop simulation, where the system could be tested with real hardware with the other functionality of the UPS. Further research could be done with a more active use of the fuel cell to downsize the batteries. Also integrating other energy sources to the system could be done.

TIIVISTELMÄ

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Polttokennokäyttöisen UPS:n ohjaussuunnittelu ja sulautettu ohjelmisto

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Tämän diplomityön tavoitteena oli suunnitella vetypolttokennokäyttöisen keskeytymättömän teholähteen ohjausjärjestelmä. Yleensä UPS:ien kanssa varateholähteenä tai pitkäaikaisina energiavarastona käytetään diesel generaattoreita. Dieselgeneraattoreiden käyttö tuotaa ongelmia ympäristön kannalta. Tämä työ tehtiin Eatonille.

Mallipohjaista suunnitelu periaatetta käytettiin työn tekemiseen. Ensin toteuttiin kirjallisuuskatsaus järjestelmän eri komponenteihin, jonka jälkeen ohjaimet valittiin ja ohjausjärjestelmä suunniteltiin. Ohjausjärjestelmä testattiin Simulink simulaatiolla.

Kehitetty ohjausjärjestelmä hyödyntää kaskadisäätöä, jossa on kaksi rinnakkaista sisempää silmukkaa. Ohjausjärjestelmän ulompi silmukka tuottaa järjestelmän vaatiman kokonaisteho vertailuarvon, joka jaetaan kahden rinnakaisen sisemmän silmukan välillä. Akusto tuottaa järjestelmään nopean vasteen, jolla nopeita transientteja pystyttään tasoittamaan, kun polttokennoja käytetään pääteholähteenä, jonka vaste on huomattavasti hitaampi. PI-ohjaimia käytettiin jokaisessa silmukassa tuottamaan tarvittava käyttöjakso kytkentälaiteille. Polttokennon sisemmässä silmukassa teho-ohjeen muutosta rajoitettiin niin sanotulla ’muutoksen rajoittalla’, joka laskee teho-ohjeen derivaatan ja rajaa sen korkeimpaan nousu- ja laskuaikaan. Lisäksi akkulaturi suunniteltiin järjestelmään. Koska akkuja käytetään myös transienttien vaimentamiseen ei akkuja voida pitää täysin ladattuina. Täten akkulaturi pyrkii pitämään akkujen lataustason tietyssä asetusarvossa.

Testeissa polttokennosta käytettiin yksinkertaistettua mallia, jonka parametreja pyrittiin mallintamaan mahdollisimman lähelle oikeata polttokennoa vastaavaksi. Kirjallisuuskatsauksessa havaittua polttokennojen ominaista hitautta simuloitiin tuottamalla keinotekoinen viive ohjausjärjestelmällä.

Kokonaisuudessaan järjestelmä todettiin toimivaksi. Akkujen ja polttokennojen välinen kuormasiirto toteutui. DC-linkin ylitys ja alitus oli alle 2 prosenttia simulaatioden ajan, toimintapisteen säätövirhe oli mitätön. Akkujen lataus myös onnistui suunnitellusti. Jatkokehityksenä järjestelmää tulisi testata Hardware-in-the-Loop simulaatiolla, jolla järjestelmän toimivuus voidaan todeta muun UPS:n toiminnalisuuden mukana. Jatkotutkimuksena polttokennojen käyttö aktiivisempana osana jäjestelmää tulisi tutkia. Myös muidenkin kuin polttokennojen integrointia järjestelmään tulisi tutkia.

SYMBOLS AND ABBREVIATIONS

Roman characters

P	power	[W]
p	pressure	[bar]
T	temperature	[ºC]
G	Gibbs free energy	[kJ]
g	Gibbs free energy per mole	[kJ · mol^{-1}]
h	enthalpy	[J · kg^{-1}]
I	current	[A]
U	voltage	[V]

Greek characters

η	efficiency	[%]

Constants

F	Faraday constant	[C · mol^{-1}]
N_A	Avogadro constant	[x · mol^{-1}]
R	Molar gas constant	[J · mol^{-1} · K^{-1}]

Dimensionless quantities

Δ	Change

Subscripts

in	input
out	output
C	Carnot
r	reversible
max	maximum
c	cell
act	activation
conc	concentration
tot	total
t	total
p	proportional
i	integral
d	derivative
batt	battery
ref	reference
FC	fuel cell

Abbreviations

ATS	Automatic transfer switch

DC	Direct current
DMFC	Direct methanol fuel cell
HHV	High heating value
HIL	Hardware-in-the-Loop
LHV	Low heating value
PEMFC	Proton exchange membrane fuel cell
SOFC	Solid oxide fuel cell
UPM	Uninterruptable power module
UPS	Uninterruptable power supply

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1 Introduction

As the current development of green transition requires a global effort to reduce emissions. Pressure to be zero emissions is increasing in the form of regulations from governments, and most companies themselves are committing to be net zero in the next few decades. Renewable energy sources are intermittent and may vary depending on the current weather. This and the increasing demand of electricity, make it difficult for the electricity network to ensure consistent and reliable energy supply. One way to combat this problem while still ensuring net zero mindset, is to develop methods to locally store and generate energy. With energy storage methods, the fluctuations that is caused by renewables could be stabilized. When the grid lacks power then power is fed from storage devices towards the grid, and vice versa. (Glassmire et al., 2020)

Common energy storage method is fossil fuels. Fossil fuels can be used in combustion engines to produce electricity. Combustion of fossil fuel causes significant emissions. Fossil fuels are also finite, which is a future problem also (Abas and Kalair, 2015).

Other popular option is batteries which can be used to store energy chemical potential. This means that batteries have a limit on how much energy they can store. Other problems regarding batteries are their limited cycles and their manufacturing from precious metals. Most notably lithium and cobalt. Their sourcing creates environmental pollution. So, a large demand for new energy storage and conversion exists. (Cheyns et al., 2014)

Hydrogen is a promising option as the next energy storage method as it has great potential as an energy storage option. Interesting developments and investments regarding hydrogen are currently underway. With increasing invest in hydrogen production and development in different hydrogen powered applications, there are massive opportunities in the industry to advance the green transition. (Pahwa and Pahwa, 2014)

Converting hydrogen into electricity is done with a fuel cell. First fuel cells where already demonstrated in the 19th century, but their commercial success is still limited at best. Even though hydrogen is the most common element in the universe, obtaining a supply of pure hydrogen is problematic, since hydrogen exist almost exclusively combined with other atoms. In 2021 under 1 per cent of hydrogen was produced using renewables, thus only transferring emissions to the production side in the process. Though with the increase in renewables sources, it could be assumed that hydrogen production will also shift to a greener state. (Global Hydrogen Review 2022, 2022)

One of the main contributors to the increase in electricity demand, is the need for more data centers. Data centers require a great deal of power, and thus a lot of power devices to facilitate the delivery of power to the servers. In these kinds of applications where the reliability and the quality of power is of critical importance uninterruptible power supply (UPS) is required. Most critical power systems require a backup power supply, which is used in case of utility power outage. Currently almost all backup power supplies are diesel generators. These not only have the aforementioned environmental impact, but also regulations can make it harder to get new building permits to build more data centers if planned backup supply is running on diesel. (Faraji et al., 2019)

1.1 Purpose, goals and limitations

The purpose of this thesis is to research a hydrogen-based fuel cell backup power system which can be utilized with UPS. The main goal is to design a proof-of-concept control system for a UPS that can enable the use of fuel cell as a primary power source.

Relevant research questions were:

- What are the limitations of fuel cells as backup power supplies?
- How can fuel cells be utilized as backup power supply with a UPS.
- Can the performance of the designed system be acceptable.

Some limitations for the scope of the thesis were made to keep the work more concise. No actual fuel cell system was available for use in the thesis, so approximations about the topology and the performance was made. Big part of the thesis was to create a system that could work with the worst-case performance of the fuel cell. It was decided that a proton exchange membrane fuel cell without integrated power conditioning was used.

1.2 Research methodology

This thesis employs a literature review method in which information about fuel cells, uninterruptable power supplies and control systems is gathered from various scientific and technical publications.

Model-based design is used in the proposed control system for a fuel cell powered UPS. As system components are first analyzed in theory, and then modelled. After that control strategy and controllers are designed and selected. Then system is tested in Simulink and automatic code generation is run to compile it.

1.3 Thesis organization

First, in the second chapter, a general is overview of fuel cells, its relevant parameters and supporting components is conducted. This will cover the operating principle, different types of fuels, balance-of-plant components and fuel cell electrical characteristics. The main focus in on the proton exchange membrane fuel cell.

Third chapter consist of a general overview of uninterruptable power supplies and their use in an industrial application. The chapter concludes with a brief review of the possible topologies of electrically connecting fuel cells to the UPS.

In the fourth chapter the components of the control system are discussed. Then the proposed control system and its design and operation is presented. Implementation of aforementioned control system and a created fuel cell model in Simulink environment is discussed and presented.

Fifth chapter will discuss the validation of the control system. This is done with an offline simulation in Simulink. Test methodology is presented and discussed. After that the simulation results are presented and discussed.

Finally, in the sixth chapter, results of the thesis are summarized and discussed, also future research topics are proposed.

2 Fuel cell

2.1 Introduction to fuel cells

Fuel cells are electrochemical devices that convert chemical energy into electrical energy directly. In a sense, fuel cells are closely related to electrolysers and generally fuel cells operate identically as reverse electrolysers would. Currently most fuel cells are powered by directly by hydrogen or compounds that are converted to hydrogen internally. (Dicks and Rand, 2018)

Since power generation can be done directly, fuel cells are not affected by the same thermodynamic constraints as more traditional power generation methods where normally fuel is firstly converted into mechanical energy before ultimately producing electrical energy. Therefore, with fuel cells higher efficiencies of can be reached, efficiencies of over 60 % have been achieved. Additionally, fuel cell physical structure is very reliable since there are no moving parts. (Dicks and Rand, 2018)

2.2 Operating principle of a fuel cell

An individual fuel cell consists of two electrodes and an electrolyte in between them. The electrochemical reactions take effect on the electrodes and the electrolyte provides spatial separation to force the flow of electrons through an external circuit. Figure 1 is an Illustration of a fuel cell’s structure.

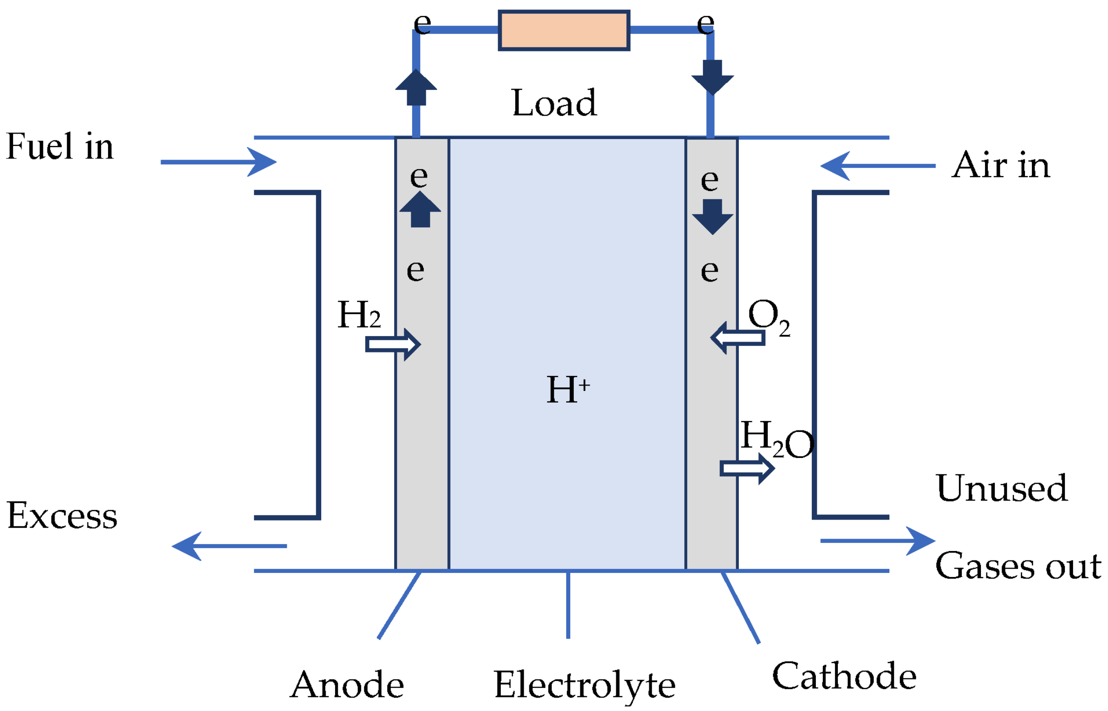

Figure 1. Unit fuel cell structure. Fuel and air are supplied to the fuel cell to produce a current and water. (Belhaj, F.Z. et al., 2021).

The electrochemical reaction inside fuel cell can be considered as a hydrogen combustion as expressed in the following equation (O'Hayre *et al.*, 2016):

$$H_2 + \frac{1}{2}O_2 \ \rightarrow H_2O \ + Heat \tag{1}$$

In a fuel cell the hydrogen combustion reaction occurs in anode and cathode. At the anode hydrogen is oxidized so hydrogen ions are created, and electrons are released, as expressed by (O'Hayre *et al.*, 2016):

$$H_2 \rightarrow 2H^+ + 2e^- \tag{2}$$

At the cathode, oxygen is fed to the system to react with the electrons and the H^+ ions, as expressed by (O'Hayre *et al.*, 2016):

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O \tag{3}$$

When using hydrogen directly as fuel, fuel cells only emit pure water and heat. The electrochemical reactions vary based on the type of fuel cell used, but the electron flow is always from anode to cathode. (O'Hayre *et al.*, 2016)

2.3 Types of fuel cells

Fuel cells are usually classified by the type of electrode or the type of fuel they use. According to the Fuel Cell Industry review of 2020 the most produced fuel cells were proton exchange membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC) and direct methanol fuel cell (DMFC). (Hart 2022)

2.3.1 PEMFC

PEMFCs have been the most successful in commercial market. PEMFCs use a proton-conducting polymer as the electrolyte. These fuel cells usually use hydrogen as fuel and operate at low temperatures. The dynamic response of these fuel cells is the best among fuel cells, and they have the most versatility. However, they cannot use other hydrocarbon fuels due to their low operating temperature. Also, a higher temperature version of PEM exists, simply called High-temperature PEM, and they operate at around 200 degrees. (O'Hayre *et al.*, 2016)

2.3.2 SOFC

SOFCs are class of high temperature fuel cells, current iterations operate anywhere between 600 and 1000 degrees. In SOFCs a solid ceramic electrolyte is used. Higher temperatures create different set of considerations when designing the system, since the start-up of the system will take a lot longer than a fuel cell with lower operating temperature. Higher temperatures make it possible to use more cost-effective materials as catalyst reducing the costs of the system and allow the use of wide variety of usable fuels to power the system. (O'Hayre *et al.*, 2016)

2.3.3 DMFC

DMFC are the most common direct liquid fuel cell, that use methanol directly. DMFC are a variant of PEMFCs in that polymer membrane is used as the electrolyte. But their capabilities with higher power demands remains limited. The main research focus concerning DMFC is mostly to replace rechargeable batteries as portable power supplies. (Dutta, 2020)

2.4 Balance-of-Plant Components

Fuel cell systems require substantial consideration in terms of auxiliary subsystems. Typical auxiliary subsystems are fuel clean-up processor, steam reformer and shift reactor for fuel, carbon dioxide separator, Humidifier, fuel and air delivery units, facilities for the management of heat and water, overall control and safety systems and thermal insulation and packaging. (Dicks and Rand, 2018)

Individual components used in these subsystems are fuel storage tanks and pumps, compressors, pressure regulators and control valves, fuel or/and air pre-heaters, heat-exchangers and radiators, motors and in some cases batteries for fuel cell initial startup. Representation of a fuel cell system is presented in Figure 2. (Dicks and Rand, 2018)

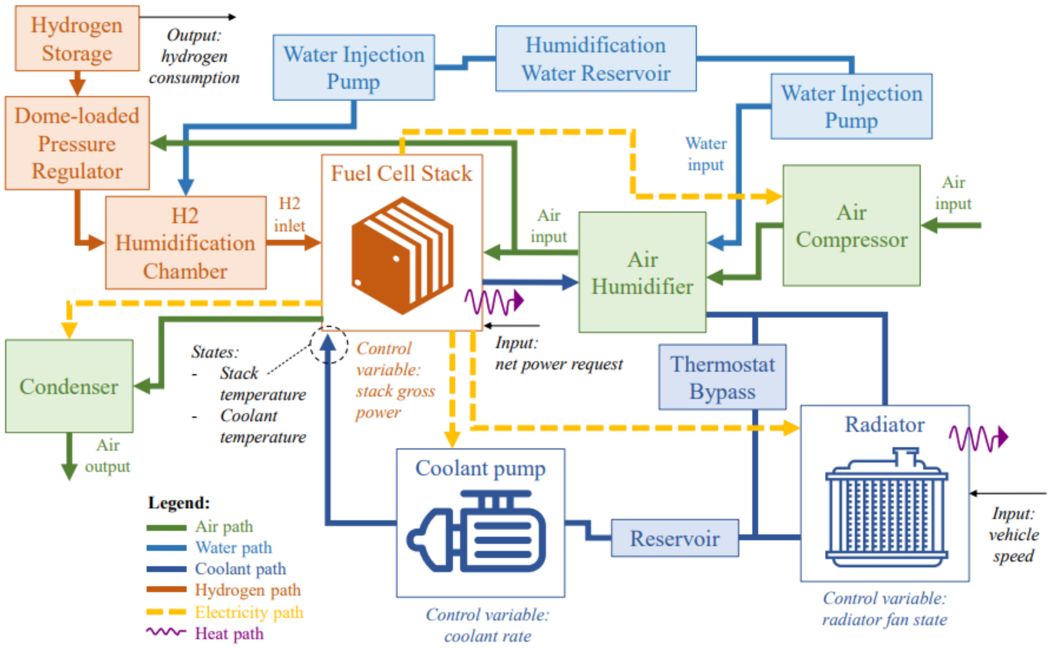

Figure 2. Full fuel cell system structure. A lot of auxiliary components are required in order to have working fuel cell system. (Anselma, P. et al. 2023)

Stationary and mobile fuel cell systems have very different requirements and therefore possess very different constraints. Stationary power applications the auxiliary components are a physically bigger part of the system than in mobile applications and often may require external power for startup. (Dicks and Rand, 2018)

The auxiliary components themselves possess very differing performance characteristics and this will influence the overall system design and performance, in terms of efficiency, dynamic response, startup time and the external control design of the system. This makes it hard to model fuel cell systems accurately since the used auxiliary components will vary substantially between manufacturers.

2.5 Fuel cell efficiency

Efficiency in an electrical power supply is a critical aspect of the system that measures how effectively energy is converted into usable electricity. High efficiency is a desirable feature in the system since it will save costs for to user and reduce the heat produced by the system. It is often represented as the ratio between the useful work produced to the energy consumed.

$$\eta = \frac{P_{\mathrm{out}}}{P_{\mathrm{in}}} \tag{4}$$

Where η is efficiency [-], P_{out} is power produced by the system [W] and P_{in} power that was used by the system [W]

A typical combustion engine operates on the Carnot cycle. Carnot cycle is a model in thermodynamics that describes the most efficient way an engine can work, and it can be used to create an ideal benchmark for a combustion engine. Carnot efficiency at peak power can be calculated with the equation:

$$\eta_{\mathrm{carnot}} = \frac{W}{\Delta H} = 1 - \sqrt{\frac{T_{\mathrm{C}}}{T_{\mathrm{H}}}} \tag{5}$$

Where η is efficiency [-], W is the generated work [J] ΔH is the heat of combustion of the fuel [J/mol]. T_{C} is the Carnot engine temperature [°C] and T_{H} is the ambient temperature [°C].

Since fuel cells do not operate on the Carnot cycle, they are not restricted by the Carnot efficiency, and instead they operate on an electrochemical principle, there is not as simple to define as the conventional combustion engine. To understand fuel cell operation the concept of Gibbs free energy is essential. Gibbs free energy is a concept thermodynamics which describes whether a chemical reaction can occur spontaneously and how much work it can do. Gibbs free energy of formation is represented as (Dicks and Rand, 2018):

$$\Delta G_{\mathrm{f}} = \ G_{\mathrm{f}}(products) - \ G_{\mathrm{f}}(reactants) \tag{6}$$

where ΔG is the change in Gibbs free energy of formation [kJ], $G_{\mathrm{f}}(products)$ is the energy stored in the products [kJ] and $G_{\mathrm{f}}(reactants)$ is the energy stored in the reactants [kJ].

However, to compare the free energy properly it is advisable to use the quantities in their per mole form. When converting equation 6 to molar form it can be written as (Dicks and Rand, 2018):

$$\Delta \bar{g}_{\mathrm{f}} = \ \bar{g}_{\mathrm{f}}(products) - \ \bar{g}_{\mathrm{f}}(reactants) \tag{7}$$

where $\Delta \bar{g}_f$ is the change in Gibbs free energy of formation per mole [kJ/mole], $\bar{g}_{\mathrm{f}}(\mathrm{products})$ is the energy stored in the products per mole [kJ/mole] and $\bar{g}_{\mathrm{f}}(\mathrm{reactants})$ is the energy stored in the reactants per mole [kJ/mole].

For hydrogen-oxygen fuel cell with reaction presented in chapter 2.2, this leads to:

$$\Delta\bar{g}_{\mathrm{f}} = (\bar{g}_{\mathrm{f}})_{\mathrm{H_2O}} - (\bar{g}_{\mathrm{f}})_{\mathrm{H_2}} - \frac{1}{2}(\bar{g}_{\mathrm{f}})_{\mathrm{O_2}} \tag{8}$$

For every mole of hydrogen that is consumed by the fuel cell $2N_{\mathrm{A}}$ electrons pass through the external circuit and given that every electron carries a negative charge, the corresponding charge is (Dicks and Rand, 2018):

$$-2N_{\mathrm{A}}e^{-} = -2F \tag{9}$$

where N_{A} Avogadro constant and F is the Faraday constant.

If the system is ideal the electrical work will be equal to the Gibbs free energy released by the system. Thus:

$$\Delta\bar{g}_{\mathrm{f}} = -2FV_{\mathrm{r}} \tag{10}$$

And given in terms of reversible individual cell voltage:

$$V_{\mathrm{r}} = \frac{\Delta\bar{g}_{\mathrm{f}}}{-2F} \tag{11}$$

maximum theoretical fuel cell efficiency which can be modelled as:

$$\eta = \frac{W_{\max}}{\Delta H} = \frac{\Delta G}{\Delta H} \tag{12}$$

Where $T\Delta S$ is the heat exchanged with the surroundings. (Dicks and Rand, 2018),

For equation 12 determining the value of ΔH is not that simple since the reaction can occur in steam and liquid state of hydrogen resulting in two different values. These values are often referred simply as higher heating value (HHV) and lower heating value (LHV). (Dicks and Rand, 2018)

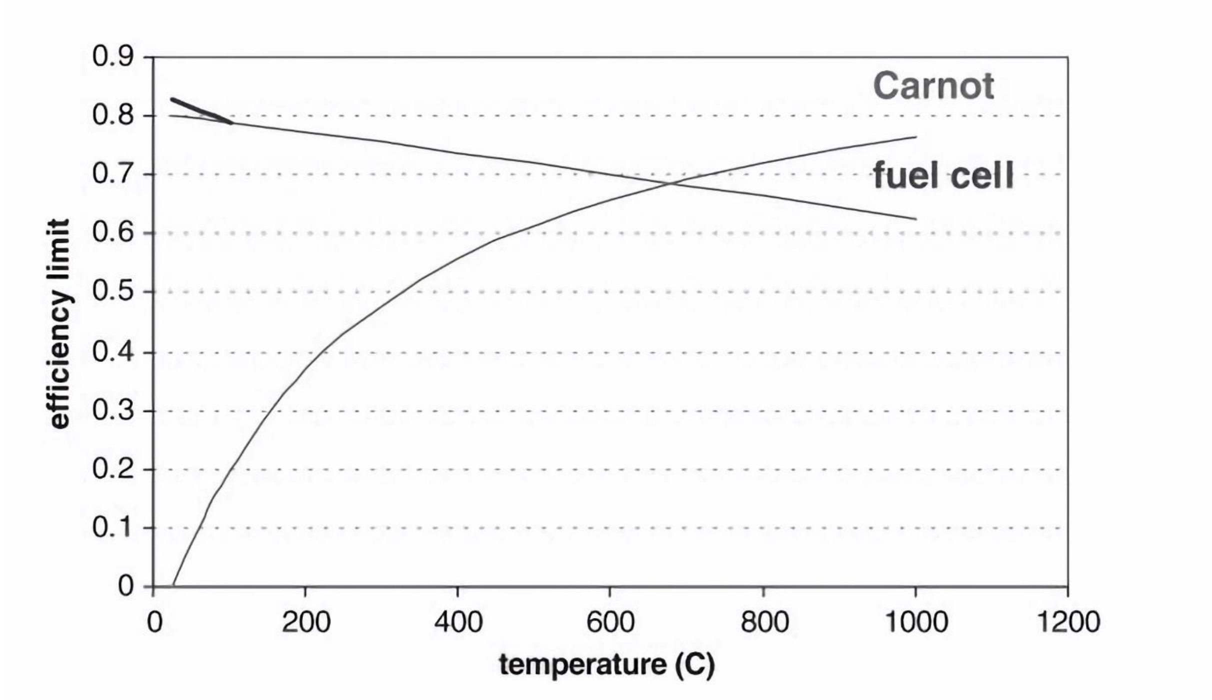

Figure 3. Comparison of fuel cell and conventional combustion engine efficiencies. (Barbir, 2013).

As can been seen in Figure 3 the efficiency of fuel cells in lower temperatures is significantly better, but the theoretical efficiency doesn't account that the fuel cells will almost always have greater voltage losses when operating at lower temperatures. Also, it is important to note that fuel cells are not always more efficient than combustion engines. (Dicks and Rand, 2018)

From equation 11 can be derived that if all the energy from hydrogen is transformed into electrical energy, the voltage is (Dicks and Rand, 2018):

$$V_{\mathrm{r}} = \frac{\Delta \bar{h}_{\mathrm{f}}}{-2F} \tag{13}$$

where $\Delta \bar{h}_{\mathrm{f}}$ is the enthalpy of formation in the chosen state and pressure [$\mathrm{J \cdot mol^{-1}}$].

From the individual cell voltage, a more realistic estimate of the efficiency can be calculated by using a value of 1.48 for HHV and 1.25 for LHV and considering that not all fuel can be transformed into energy. The actual working individual fuel cell efficiency for HHV can be calculated with the following formula (Dicks and Rand, 2018):

$$\eta = \mu_{\mathrm{f}} \frac{V_{\mathrm{c}}}{1.48} 100\% \tag{14}$$

where μ_f is the fuel utilization for which a good estimate is 0.95 and V_c is the voltage of a single cell.

And similarly, for LHV (Dicks and Rand, 2018):

$$\eta = \mu_f \frac{V_c}{1.25} 100\% \tag{15}$$

The individual cell voltage and its characteristic losses are discussed more in chapter 2.6.1. But even then, the efficiency of fuel cells is huge benefit over the more traditional combustion engine.

2.6 Characteristics of fuel cells

2.6.1 Polarization curve

One of the key performance indicators of the fuel cell is the polarization curve or current-voltage curve, which shows the output voltage for given current output. The curve is shaped by the individual fuel cell voltage and the losses of the fuel cell. Individual fuel cell has a voltage that was presented in equation 11.

However, in real operation the pressure and concentration of hydrogen and oxygen will influence the change in the Gibbs free energy, and this will have impact on the output voltage. The Nernst equation can be used to model these effects, for example, in the case of water product in the form of steam (Dicks and Rand, 2018):

$$V_r = V_r^0 + \frac{RT}{2F} ln \frac{P_{H_2} P_{O_2}^{\frac{1}{2}}}{P_{H_2O}} \tag{16}$$

where V_r^0 is the reversible cell voltage in standard pressure [V], R is molar gas constant, T is the gas temperature [°C], P_{H_2} is the partial pressure of hydrogen [Bar], P_{O_2} is the partial pressure of oxygen [Bar] and P_{H_2O} is the partial pressure of water [Bar].

The characteristic losses for the system are activation, Ohmic and mass-transport losses. Activation losses are caused by the slowness of the chemical reactions, these are the majority losses when dealing with small loads and result in a sharp voltage drop on fuel cell startup.

On higher currents the effect will be negligible in relation to the other losses. The effect can be modelled with the Tafel equation (Dicks and Rand, 2018):

$$\eta_{\mathrm{act}} = \frac{RT}{\alpha nF} ln \frac{i}{i_0} \tag{17}$$

where i is the current density [A/cm^2], i_0 is the current density at zero overpotential [A/cm^{-2}] and α is called the 'charge-transfer coefficient' it indicates the proportion of the electrical energy that must be supplied to the system that contributes to changing the rate of the electrochemical reaction. Its rate will depend on reaction and the electrode but must always between 0-1. For hydrogen electrode the value will usually be very close to 0.5.

Ohmic losses are caused by resistances of different component of the system such as: electrodes, electrolyte, lines and contact resistance of the connector. These resistances are usually divided into ionic resistance, electronics resistance and contact resistance. The effect of the ohmic losses can modelled with (Dicks and Rand, 2018):

$$\eta_{\mathrm{ohmic}} = i r_{\mathrm{tot}} \tag{18}$$

where r_{tot} is the total area specific resistance [Ω/cm^2].

Mass-Transport losses are caused by the changing concentration of reactants at the surface of the electrodes, and because the voltage is dependent reactant concentration this will cause losses. The effect can be modelled with (Dicks and Rand, 2018):

$$\eta_{conc} = \frac{RT}{nF} \ln\left(1 - \frac{i}{i_{\mathrm{L}}}\right) \tag{19}$$

where i_L is the current density when pressure falls linearly down to zero [A/cm^2].

And thus, the total voltage can be modelled with:

$$V_t = E - \eta_{act} - \eta_{ohmic} - \eta_{conc} \tag{20}$$

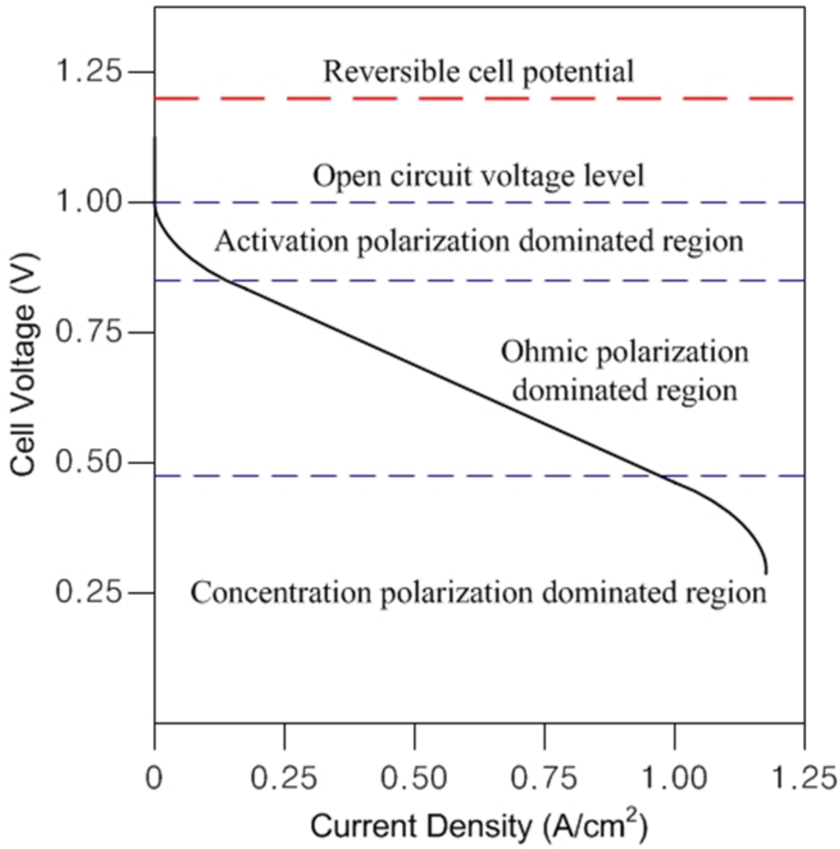

Figure 4. Fuel cell typical polarization curve. Theoretical Gibbs free energy potential and Nernst potential marked with dashed line. Noticeable losses can be observed and a sharp decline in voltage after the mass transport region. (Jung and Ahmed, 2010)

As can be seen from Figure 4 the voltage-current curve has non-linearities in the activation region and in the mass-transport region, but in the ohmic region the curve is linear. In mass-transport region the voltage will start to exponentially decrease. Not only will this have negative impact on the lifetime of the fuel cell, but also this will be difficult to control. Also control system for this heavy nonlinearity will be difficult as a separate reset functionality would be needed to recover the system if voltage drops too low. With limiting the operation to the ohmic region system will be more stable and the control system can be substantially simpler.

2.6.2 Dynamic response

Another key performance indicator for fuel cells is the dynamic response. Dynamic response refers to the ability of a system or component to react quickly and effectively to changes or fluctuations in its input, environment or load conditions. In the context of uninterruptable power supplies and similar power systems, dynamic response specifically refers to how rapidly the system can adjust its output voltage and current in response to sudden changes in the electrical load it is supplying power to. In Figure 5 comparison of typical power sources is presented.

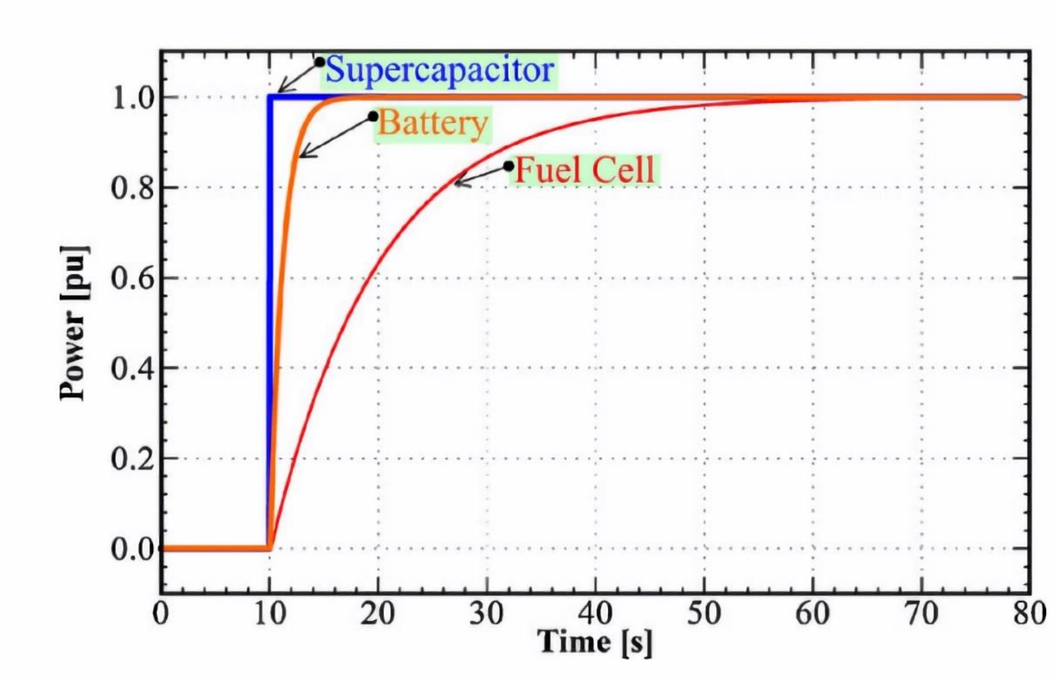

Figure 5. Supercapacitor, battery and fuel cell step responses. Fuel cell is a significantly has a significantly slower response to loads, than batteries and supercapacitors. (Thounthong, Raël and Davat, 2009)

Often in UPS use, batteries are used as the energy storage to provide power and generally, batteries have some of the fastest and most precise dynamic response capabilities. They can very rapidly release or absorb energy to respond to load changes, making them ideal for grid stabilization, frequency regulation and providing short term backup power. Using batteries as long-term backup power source is inadvisable since battery systems often have limited capacity, self-discharge and the financial investment will raise significantly when scaling up a battery backup system. (Wong *et al.*, 2011)

Supercapacitors are sometimes used with UPS. Even though supercapacitors have exceptional dynamic response compared to other technologies, they still have their own issues. As supercapacitors usually cannot hold enough charge to be a sole option for a power supply in larger systems. In a typical UPS application supercapacitor supply power for some seconds.

As can be seen in Figure 5 fuel cells have a lot slower dynamic response than batteries, supercapacitor or combustion engines. The dynamic behavior of PEMFCs can be affected by the discharge of double layer, but the impact on the response time is relatively minor because the electrochemical reaction rate of PEMFC occur at a rapid rate. The primary determinants of dynamic performance are reactant transport and membrane hydration. (Guo *et al.*, 2022)

It is important to note the difference between individual fuel cell and a fuel cell stack. Fuel cells stack are comprised of individual cells that are electrically connected to output adequate voltage and have specific power rating. The individual structure of the cells makes fuel cell systems very well scalable and often the systems are in the range of a few individual cells to hundreds of cells with power rating varying from a few W to multiple MW.

In a real fuel cell stack, there are performance differences between the individual cells. This is caused by the inherent differences in the properties of the components and the design of the flow patterns in the system. (Park and Choe, 2008)

The flow pattern will determine how the reactants flows through the system, as often the pressure of the reactants will be highest for first cell and subsequently lowest for last cell. When quick load changes occur the latter cells reactant pressure will be insufficient and the cell will act as load rather than a source, resulting in negative voltage across the cell. Typical flow pattern is presented in Figure 6 (Jia *et al.*, 2007)

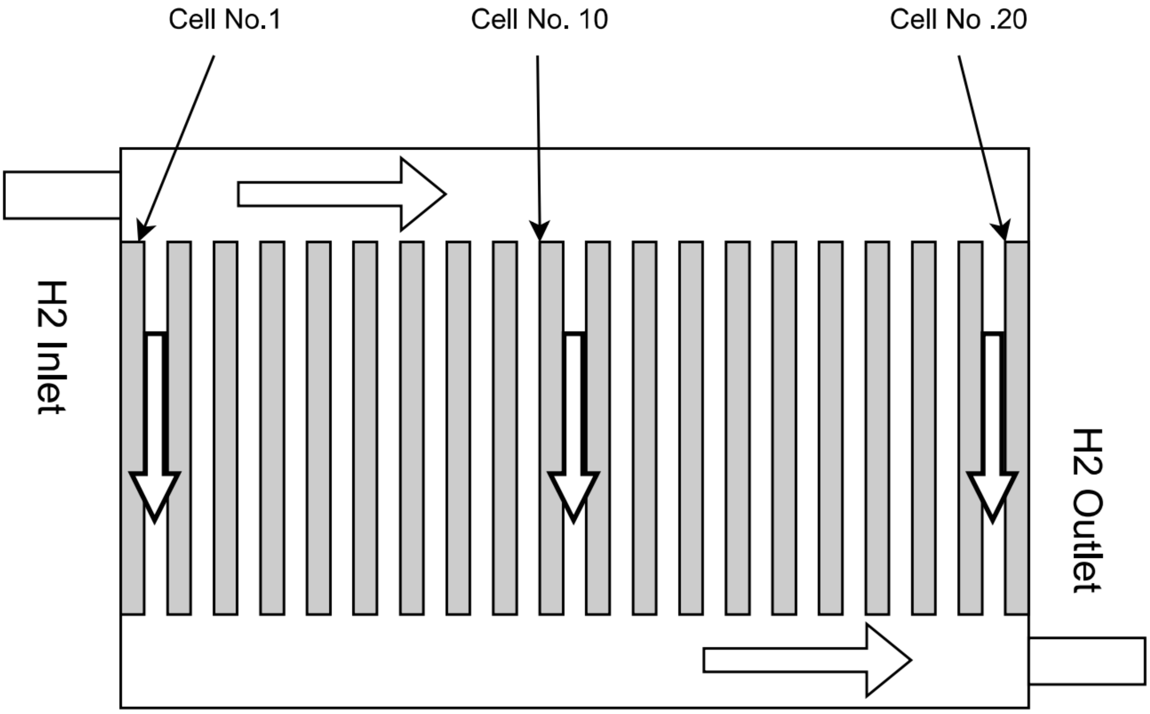

Figure 6. 20 individual fuel cells connected in series to create a fuel cell stack. Hydrogen flow represented as white arrows (Jia et al., 2007)

This phenomenon is often described as gas starvation, hydrogen starvation or fuel starvation. It will result in weaker dynamic performance and can cause damage to the membrane. (Kulikovsky, Scharmann and Wippermann, 2004)

As shown in equation 3 as a result of the chemical reaction, water is formed in the cathode of the fuel cell. But this also results in a problem concerning the hydration level of the cathode side gas diffusion layer. Limited water content can lead to drying, which will have a negative effect on the conductivity of the fuel cell and on the other hand, excessive water content results in flooding. The latter being a significantly more important problem, since flooding will obstruct the gas transfer, thus exacerbating the dynamic performance, and increasing overshoot and undershoot. (Guo *et al.*, 2022)

2.6.3 Initial startup sequence of fuel cell

In a backup application the starting characteristics of the backup supply are of a great interest, since the starting time will determine how long the system needs to be able to supply the load without a primary power supply, thus in the case of UPS this will determine the required minimum capacity of the batteries. The battery system will need to be designed so that it can supply the entire system and providing startup power for the auxiliary components of the fuel cell system for the duration of the fuel cell startup. In some cases, fuel cell systems have an internal battery to power up the startup sequence, and it is not necessary to provide external power to the fuel cell.

Starting characteristics vary depending not only on the fuel cell type but also the ambient temperature. Consequently, the startup sequence is divided into cold starting and hot starting. In this case, cold start means startup when ambient temperature is lower than the fuel cells operating temperature. Like discussed before fuel cells not only produce water, but also require internal moisture in the cells to achieve proper conductivity, so startup at below 0 ℃ creates its own issues regarding freezing and is one of the most difficult problems concerning fuel cells. Hot start means startup when ambient temperature is within the operating temperature range of the fuel cell. (Lu *et al.*, 2021)

Table 1. Starting times of a 90 kW PEMFC. (Lu *et al.*, 2021)

Temperature [℃]	Starting time [min]
-30	8-16
-20	5-7
-10	3-4
0	2
10	0.7-1
20	0.5

From Table 1 can be seen that the starting times vary significantly based on the ambient temperature. Ambient temperature needs to be considered when designing battery capacity as the batteries need supply the whole system until fuel cell has reached its operating temperature.

2.7 Fuel cell modelling

Since the fuel cell output can differ drastically based on the balance-of-plant components that have drastic impact on the systems performance and they differ based on the manufacturer and the specific fuel cell system. Thus, creating a detailed general model is very difficult and exact modelling of fuel cell will not be possible in the scope of this thesis.

Instead, a Simulink general fuel cell model will be used. The model's dynamic response will be slowed since the model since based on the literature the model is too fast and since it is preferable that gas starvation and flooding will be avoided. The exact timing will not be of significance since the goal of thesis is to develop as general control scheme for a fuel cell powered ups, therefore in the system the fuel cell will be limited to 1.5 second from idle to full load by the control system. The limitation will also help avoid gas starvation and cell flooding. The Simulink model will be discussed in more detail in chapter 4.3.1.

3 Power electronics

3.1 Introduction to uninterruptable power supplies

The objective of UPS systems is to provide uninterrupted, reliable, and high-quality power source to connected electronic devices and critical systems, even when the primary power source experiences interruptions or fluctuations. (Loeffler and Spears, 2019)

Sensitive equipment can be affected by outages and disturbances of less than 1 second. Which will make the power quality a lot more important. An outage is very expensive for any industry and based on a study conducted by Vertiv in 2011 an outage will cost a data center an average of 5600 dollars per minute. (Vertiv, 2016)

Although utility power is actually very reliable it still is never 100 percent available, in 2022 Fingrid reported that the power grid had an availability of 99.99993%. (Fingrid, 2023)

UPS can be classified in to three main topologies based on the power conditioning required: Single-conversion, double-conversion and multi-mode systems. (Loeffler and Spears, 2019)

Single-conversion systems feed utility power directly to the load and only perform power conditioning if power is not in predefined limits. Single-conversion systems can be further separated into standby and line-interactive UPS. Standby UPS only perform power conditioning when a loss of power is detected, then current is drawn from the battery. Line-interactive UPS perform power conditioning when the utility power is not in the predefined limits and then the batteries are used to regulate the output power. Single conversion UPS internals are presented in Figure 7. (Loeffler and Spears, 2019)

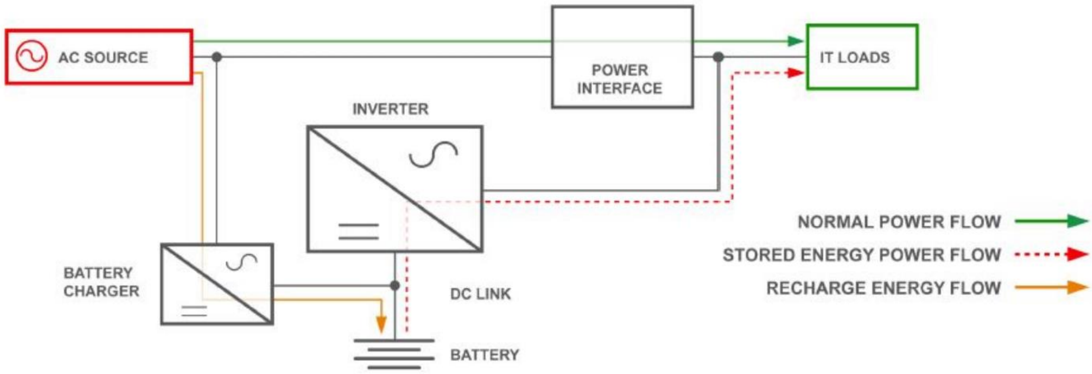

Figure 7. Single conversion UPS. The default operation of UPS is to feed utility power directly to the load. (Loeffler and Spears, 2019)

In double-conversion systems two conversions are performed as shown in Figure 8. First, the utility AC-power is converted into DC with a rectifier, and then the DC is converted back into AC using an inverter. The batteries are connected in the DC-link which connects the output of the rectifier into the input of the inverter. When a utility power loss is detected, the rectifier is shut down, and the batteries will supply the needed power into the system. If batteries run out of charge or there is a major overload in the inverter, then a bypass switch is activated that will feed the unconditioned utility power directly to the load. (Loeffler and Spears, 2019)

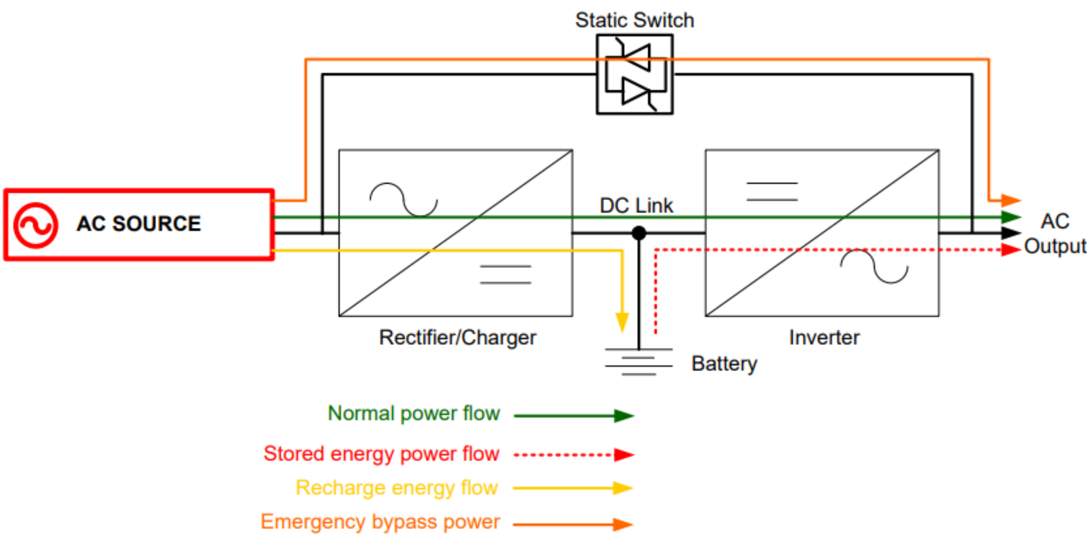

Figure 8. Double conversion UPS. Utility power is conditioned with a rectifier and an inverter by default. (Loeffler and Spears, 2019)

Multi-mode conversion systems are a combination of single and double-conversion systems as shown in Figure 9. In normal operation they operate as single-conversion systems where they feed the utility power directly to the load. When disturbance or power loss is detected, they switch to double-conversion operation. (Loeffler and Spears, 2019)

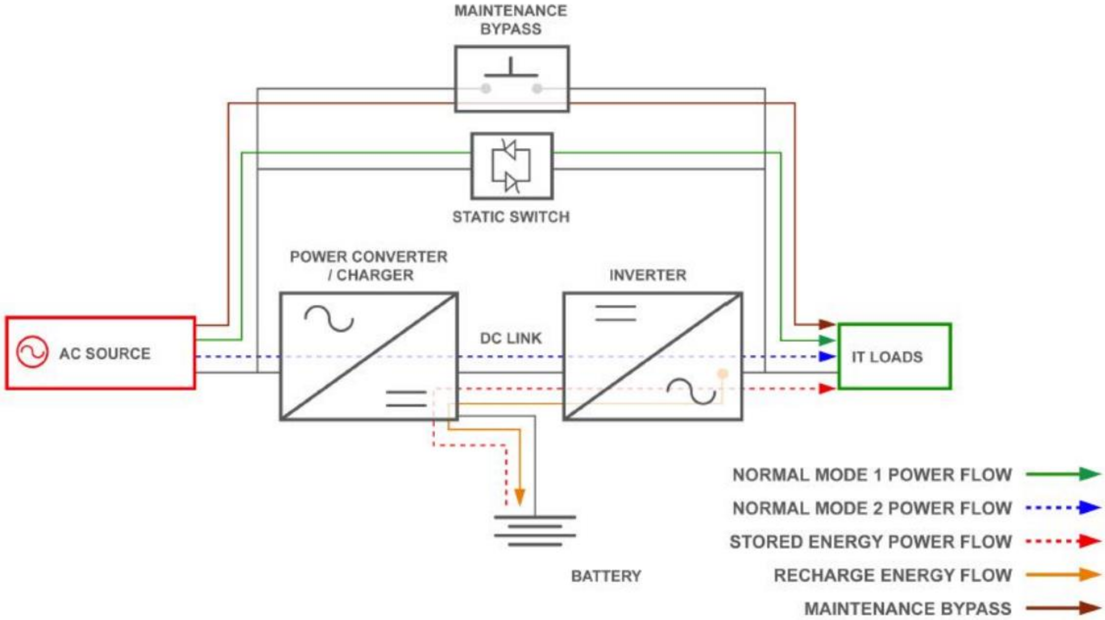

Figure 9. Multi-mode UPS. The multi-mode UPS combines the single conversion and double conversion versions. (Loeffler and Spears, 2019)

3.2 UPS with a backup power supply

In a critical application a backup power source is required. The typical way to design the power supply of a data center is presented in Figure 10. The backup generator is connected in parallel with the utility supply with an automatic transfer switch (ATS), thus from the perspective of an UPS the generator will function almost identically to the grid. The control of the generator is left to the generator itself. Since the overall goal of the system is to replace the diesel generator with a fuel cell, there will be benefits when connecting the fuel cell directly to the UPS. A major benefit of changing the system level topology is reducing the needed switchgears in the system. The change will also allow UPS to be utilized to negate the major problems of fuel cells regarding the dynamic response and the polarization curve by supplementing the fuel cell with a secondary power source. (Eaton 2010)

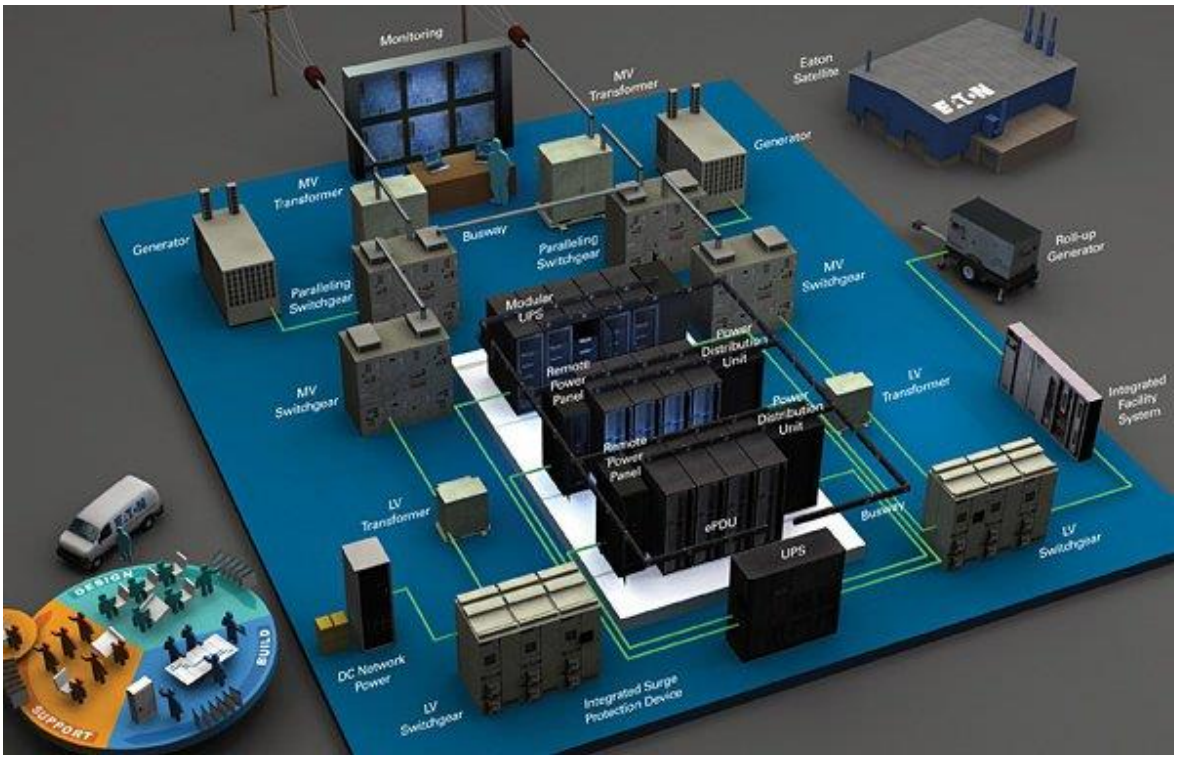

Figure 10. Typical data center electrification scheme. Usually, the diesel generators are connected to the UPS from the mains side, with a paralleling switchgear. (Eaton 2010)

3.3 Fuel cell powered UPS

Since fuel cell system is not suitable to be connected directly to the UPS, power conditioning is required. Main concern for the control system design is the slow dynamic response of the fuel cell as discussed in chapter 2.6.2 This is why a supporting supply for fast transients in needed. Added benefit of a secondary source is redundancy, as in case of fuel cell malfunction batteries could supply the system as in regular UPS operation.

As demonstrated in chapter 2.6.1 fuel cell voltage is not constant, so a DC/DC converter is needed to step up the voltage to a desired level. A very simple boost converter could be used to boost the voltage to a specified DC-link level, but in system design it is needed to take in to account that startup current might be required for the fuel cell itself, so a bidirectional buck-boost converter will be used.

There are several different topologies that could be used to connect the batteries and the fuel cell to the system each with their own specific positives and negatives. The explored topologies are passive, active and direct online battery hybridization.

3.3.1 Passive hybridization

In passive hybridization the battery and the fuel cell will be directly connected to a DC/DC converter that is connected to the DC-link as shown in Figure 11.

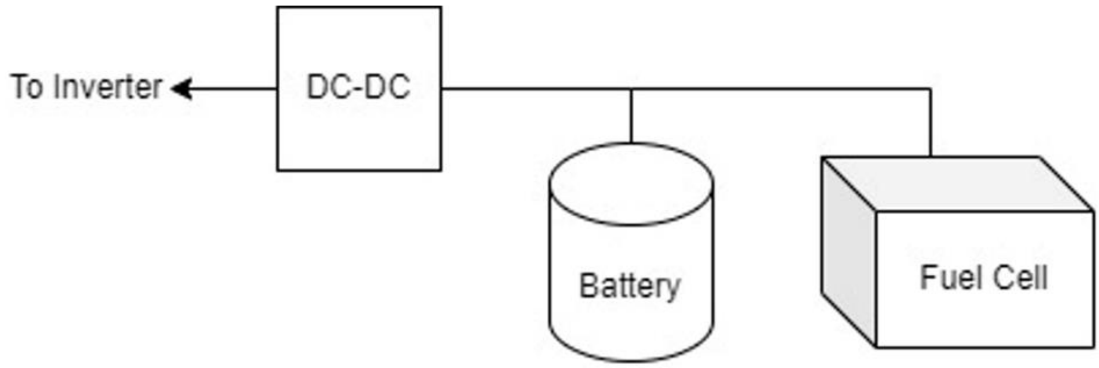

Figure 11. Passive hybridization scheme. Passive hybridization would have the least number of converters, but with the sizing of components would require a lot of effort.

Using this topology would allow the user to only have one DC/DC converter in the DC-link, thus having minimal amount of conversion to minimize the losses of the converters and making the UPM a mechanically more simplistic as only one connector for the DC-link is necessary. But the user needs to be careful with the sizing of the batteries and the fuel cell to ensure their compatibility, optimization of the system is also difficult as individual control of the sources will not be possible. This topology would also result in additional battery cycles causing extra wear and tear to the battery.

3.3.2 Active hybridization

Active hybridization the battery and the fuel cell will be connected to the DC-link with their individual DC/DC converters as shown in Figure 12.

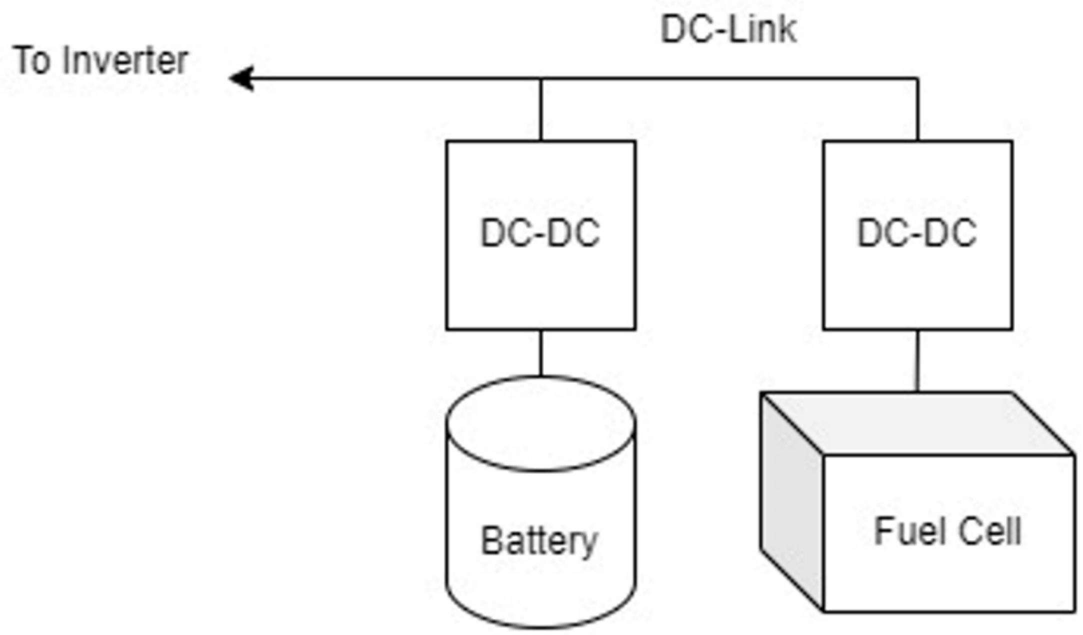

Figure 12. Active hybridization. For every source a DC/DC converter is required, but this will allow for individual control of the sources.

Using this topology user would have individual control of both sources, thus allowing for optimization and independent control. This would make the battery and fuel cell sizing independent. Although with more converters more losses in converters will happen and more components will be required, this will also require mechanical design change to the UPM two mechanical connectors to the DC-link will be needed.

3.3.3 Direct online hybridization

In direct online battery hybridization, the DC/DC converters are connected in series as shown in Figure 13. Using only one DC/DC converter to connect to the DC-link UPM will only need one mechanical connector. This topology will result in additional battery charge cycles.

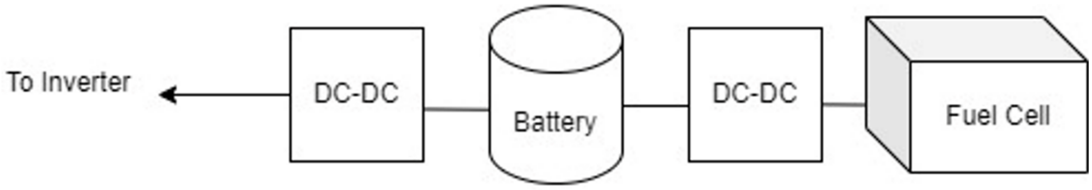

Figure 13. Direct online hybridization. Battery is in active use, which will cause additional battery cycles. This would accelerate battery degradation.

3.3.4 Proposed topology

All the topologies have their own benefits and drawbacks, but to compensate for the difficulties of modelling the fuel cell with the most universal hybridization will be chosen, thus active hybridization will be used in designing the test system.

Since the batteries and fuel cell will have their own converter, they are not dependent on each other. This will beneficial since no exact prior knowledge of the fuel cell dynamics will be required. The limiting parameter would be the fuel cell maximum voltage, which cannot ever surpass the DC-link voltage to properly control the bidirectional DC/DC converter.

4 Control system

4.1 Control system introduction

The purpose of control systems is to regulate and manage the behavior of dynamic systems or processes to achieve the desired outcomes. Control systems are a crucial part of various applications, especially in electrical systems and automation. (Wade, 2017)

A great deal of research has been performed for different types of control strategies and controllers, but to keep the introduction in the scope of the thesis only key topics concerning the proposed control system will be discussed in this section.

4.1.1 PID controllers

PID controllers are comprised of three blocks: proportional, integral and derivative. Their main benefits are their versatility and simplicity in terms of integration and overall usage. PID controllers also exist in different forms of the three components such as P, PI, PD and PID, with PI controller being the most used, as often derivative action is not used. Only using PI-control is adequate for processes, where the dynamics are of first order. Also processes where robust control is not needed are usually also well suited for only PI-control. These type controllers are implemented with a feedback loop to calculate the output to maintain a desired setpoint value. A PID controller is presented in Figure 14. (Wade, 2017)

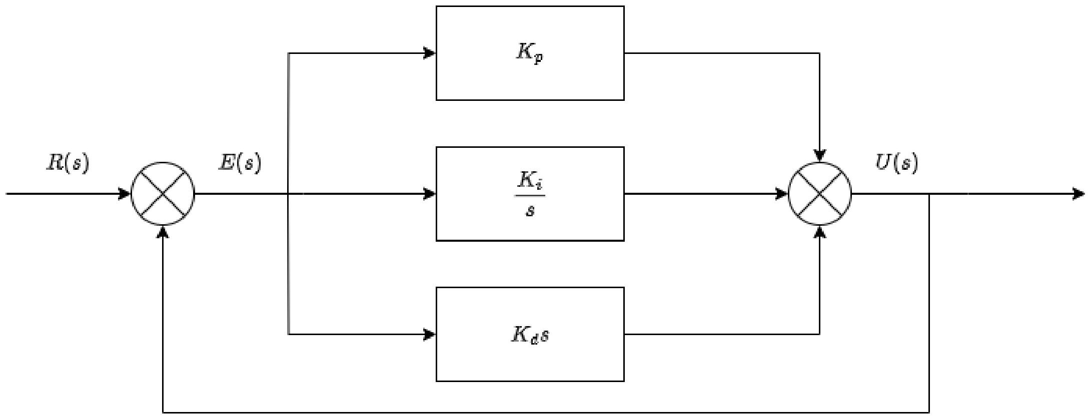

Figure 14. Basic form of a parallel PID-controller. The PID-controller is one of the simplest controllers. Often the derivative block is left out, to only have a PI-controller.

The proportional term produces an output that is directly proportional to the current error. It operates by multiplying the error with a constant proportional gain also known as K_p. This will affect how strongly the controller will react as higher K_p value will cause a larger action. Proportional control is effective way to reduce the steady state error, but K_p term will not remove steady state error by itself. This is because the output is error multiplied by K_p, thus the error will be zero only in specific case as described in equation 21. (Åström and Hägglund, 2006)

$$E(s)K_\mathrm{p} = U(s) \tag{21}$$

The main function of the integral term is to remove steady state error. The integral term accumulates the error over time and produces an output that is proportional to the integral of the error. Increasing the integral gain constant K_i term will increase how strongly the controller will react to the accumulation of the integral error. With proper tuning of the integral term steady-state error will be removed. With too high K_i term the integral of the error will accumulate excessively causing it to oscillate. (Åström and Hägglund, 2006)

The derivative term anticipates the future error based on the rate of change of the current error. Increasing the derivate gain constant K_d term will increase how strongly the controller will react to the rate of change. K_d term is used to dampen the effect of sudden changes to the system and reduce overshoot. (Åström and Hägglund, 2006)

Based on the Figure 14 the transfer function of the PID controller can be represented as:

$$G(s) = \frac{U(s)}{E(s)} = K_\mathrm{p} + \frac{K_\mathrm{i}}{s} + K_\mathrm{d}s \tag{22}$$

where $U(s)$ is the output of the system and $E(s)$ is the error of the system.

The combination of these terms is the actual strength of the controller, as their successful integration creates a combination that can react to fast transients quick and smooth manner, while also eliminating steady-state errors. (Åström and Hägglund, 2006)

While the PID controller and its different variations are suitable and usable in various processes they are still lacking in certain aspects of optimal control. Since for proper operation the controllers require proper tuning, which can be difficult in more complex operations. Various tuning methods have been developed to tune the PID controllers. Trial-and-error based methods such as Ziegler-Nichols method are powerful, yet a simple way to tune controllers even in complex systems. Ziegler-Nichols method is often combined with manual tuning to obtain better results than the initial calculation. (Wade, 2017)

Another problem with the PID controllers is their linearity so naturally that does not make them optimal for nonlinear systems. This may lead to instability and non-optimal performance when used with nonlinear processes. (Wade, 2017)

4.1.2 Bidirectional DC/DC converter control

Bidirectional converters are common in battery applications, because with the same converter discharge and charge actions can be controlled. However, since option for startup power is required, using bidirectional DC/DC converter creates its own challenges when using it with unidirectional power supply like fuel cells. The control system needs to be designed so that during normal operation the current will only flow towards the DC-link from the fuel cell. (Gorji, S. et al. 2019)

A typical bidirectional consists of an inductor, two capacitors and two switching devices as shown in Figure 15.

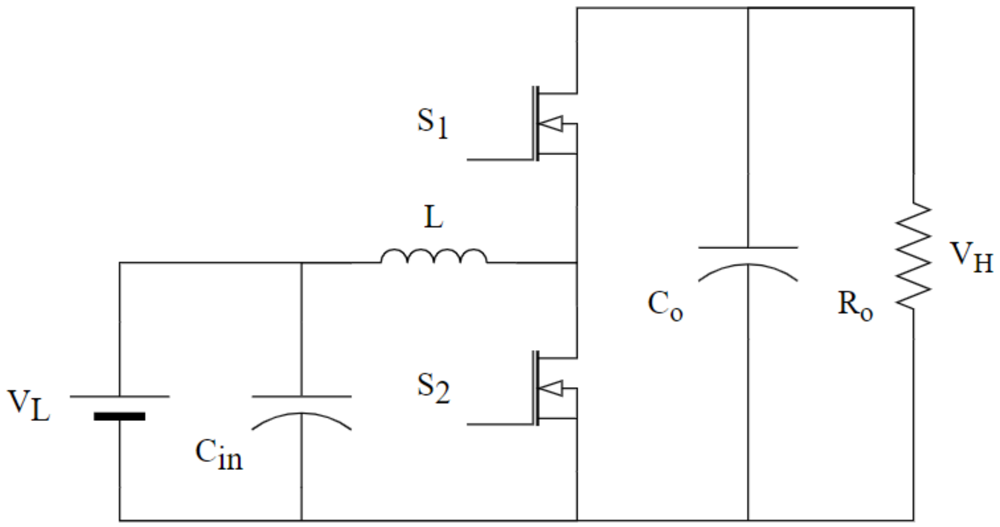

Figure 15. Typical bidirectional DC/DC converter. It acts as a boost converter when current flows towards the DC-link and as buck converter when current flows toward the battery. (Gorji, S. et al. 2019)

The relationship of the voltages is described as (Gorji, S. et al. 2019):

$$V_{\mathrm{bat}} = dV_{\mathrm{DC-link}} \tag{23}$$

Where V_{bat} is battery voltage, d is the duty cycle of the switching devices and $V_{DC-link}$ is DC-link voltage.

Table 2. Bidirectional DC/DC converter truth table

	Current direction
$V_{bat} = dV_{DC-link}$	No current flow
$V_{bat} > dV_{DC-link}$	Current flows from battery to the DC-link
$V_{bat} < dV_{DC-link}$	Current flows from DC-link the battery

As can be seen from Table 2 the converter needs to be limited within no current flow and current flows from battery to the DC-link. Deriving the equation 22 within terms of the duty cycle:

$$d \leq \frac{V_{\mathrm{bat}}}{V_{\mathrm{DC-link}}} \tag{24}$$

So, the duty cycle control needs to be limited to never be smaller than the ratio of fuel cell voltage and DC-link voltage.

4.1.3 Cascade control

Cascade control is a control strategy often used in in systems with complex and interacting dynamics. It has hierarchy of control loops, where one loop controls a primary process, and another loop to control secondary process. The general idea of this topology of the control is to address the shortcomings of a single-loop control system by allowing individual control of the primary variable and a secondary variable. Cascade system structure is presented in Figure 16. (Wade, 2017)

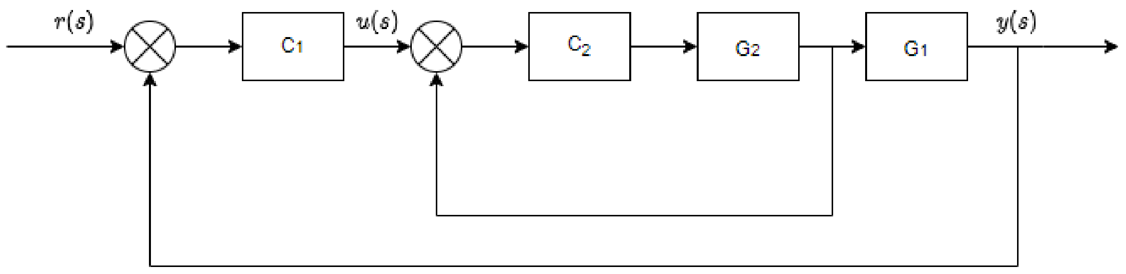

Figure 16. Simplified cascade control model. Cascade control is based on two or more nested controllers that control a primary and a secondary variable.

The outer and inner loops work in tandem. When changes occur in the secondary variable the secondary loop will act faster to counteract it, this will in turn effect the setpoint of the primary loop, causing it to react and control the primary variable more efficiently. (Wade, 2017)

In general design of the cascade system, the inner loop usually is faster the than the outer. The idea is for the outer loop to respond to slow changes of the system and for the inner loop to respond to the quick disturbance of the system. Designing a cascade system should be done carefully since poor tuning will make the controllers work against one another. (Wade, 2017)

Cascade control will also allow for different topologies for different types of setups, as multiple inner loops can be used either in series or in parallel. Parallelization in cascade systems allow for quite effective load sharing strategies. However, cascade system will generally require more complex control as the response of the loops is highly dependent on each other. Because of the complexity tuning is often done in parts, as the inner loop should be tuned first, with the chosen method, and then moving on to the outer loop tuning.

4.2 Proposed control system

4.2.1 System overview

Active hybridization is a researched topic in the field of hybrid electric vehicles, with different combinations of power sources such as combustion engines, fuel cells, batteries and supercapacitors. In vehicle use this type of control has been researched to improve performance and overall system efficiency. (Wong, J. *et al.* 2011)

Parallel connection to the DC-link will require a will load sharing strategy to take advantage of the fuel cells and batteries respective benefits and compensate for their weaknesses. The overall goal is to use the batteries to respond to fast transients of the system when load increases current is drawn from the battery or when load decreases then current is drawn into the battery. This battery behavior will protect the fuel cell from fuel starvation and flooding. Fuel cell will be set to be a slow response constant high-power source. Critical requirement for the system is also to be able to charge batteries with the fuel cell.

Design of the control system is considered as independent. This means that the inverter and the rectifier of the UPS have their own independent control systems. This will allow for a modular implementation. This is also done for future considerations since back feeding into the grid will be a requirement for future UPS devices.

In Figure 17 load sharing behavior is demonstrated. On startup, battery will carry the main load and slowly transfer the load over to the fuel cell.

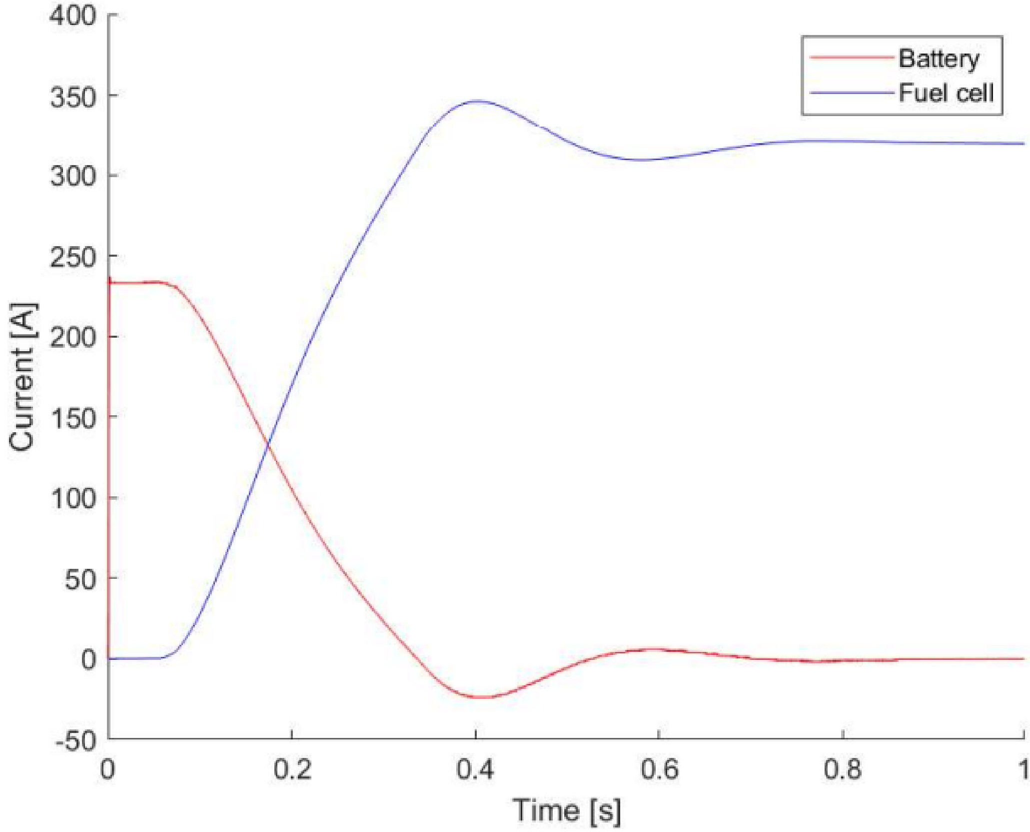

Figure 17 Illustration of fuel cell current relative to battery current. The battery supplies all the energy at first, then when fuel cell current ramps up, battery is then charged.

Active hybridization designed for UPS use is presented in Figure 18.

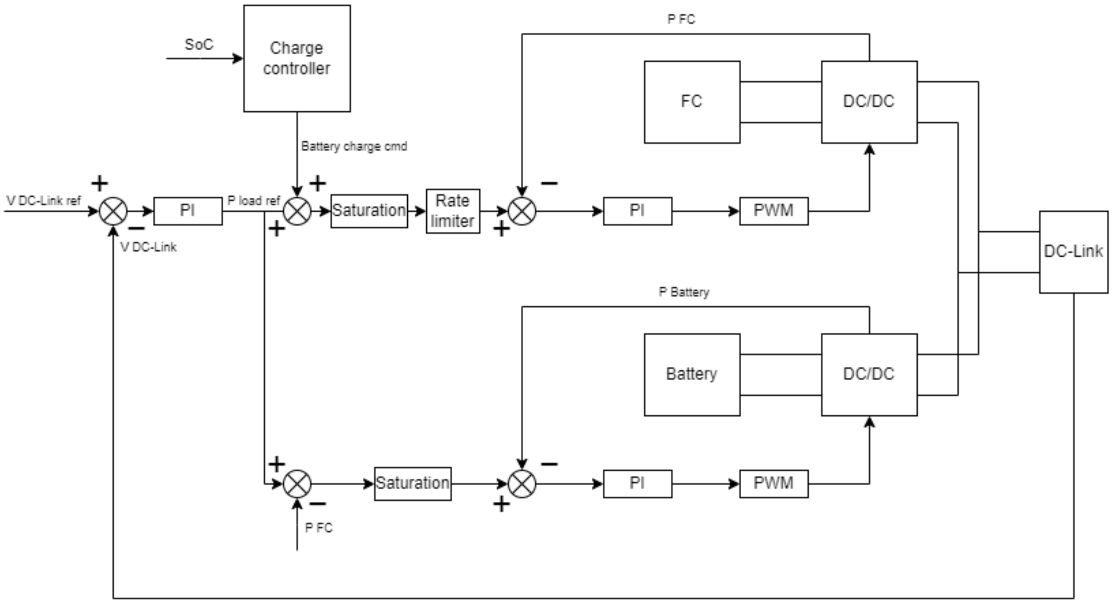

Figure 18. Design of the active hybridization system. The is a parallel cascade control system with an external battery charge controller. The main idea is to use outer loop to generate a total power demand command and then split it between the fuel cell and battery inner loops. The fuel cell is used as the primary inner loop.

Basic operation of the system is a cascade control system with parallel internal loops to adjust the load sharing with the use of PI-controllers, rate limiters and saturation control. The system control will start, as an initial power reference is created from the DC-link error, which is then split between the two power supplies. A power reference is used since the fuel cell has a non-linear voltage-current curve, which will make a power reference work better when using linear PI-controllers.

In simple terms the outer loop controls the system to maintain a steady DC-link voltage, by creating power reference output, and the inner loops control the duty cycle to minimize the power demand from the outer loop.

In more depth the system works by generating a power reference based on the DC-link error with PI-controller, if error is negative then there is too much energy in the DC-link, so a negative power reference is created, and if error is positive, then there is not enough energy and positive power reference is created. Power reference derivative is limited for the inner fuel cell control loop to simulate the fuel cell dynamics more accurately and to limit the fast transients. For the inner loops, the power reference is limited with a saturation block, to never provide the inner loop with a power demand it cannot produce. An inner loop PI-controller will control the power output of the fuel cell by changing the duty cycle of the DC/DC converter.

Based on the explanation, the reference signals can be summarized as below:

$$V_{\text{bus ref}} = constant \tag{25}$$

$$P_{\text{FC ref}} = P_{\text{load ref}} + P_{\text{batt charge cmd}} - P_{\text{FC}} \tag{26}$$

$$P_{\text{batt ref}} = P_{\text{load ref}} - P_{\text{FC feedback}} - P_{\text{batt}} \tag{27}$$

where $V_{\text{bus ref}}$ is the target DC-link voltage, $P_{\text{FC ref}}$ and $P_{\text{batt ref}}$ are the inner loop reference signals for the fuel cell and battery respectively, $P_{\text{load ref}}$ is the load power demand, P_{FC} and P_{batt} are feedback signals from fuel cell and battery respectively, and $P_{\text{batt charge cmd}}$ is the battery charge command.

In order to have the battery respond to the fast transients, on the battery side the fuel cell power is subtracted from the original power reference, this will allow for a smooth transition of the power sources in high transient situations. When the original power reference is negative the fuel cell output will be zero and the battery will draw power from the DC-link.

To tune the PI controllers Ziegler-Nichols method was first used for the inner controllers and then same method was used to tune the outer loop.

4.2.2 Battery charging

The usual battery charging strategy in UPS design is to charge as much as the batteries can be charged and charging should be done whenever it is possible. This is a proven and a well working strategy of a traditional UPS, since it will ensure that the batteries will have charge when needed and it is a simple to implement as a state of charge (SoC) calculations are not necessary as battery charging logic can be controlled based on the measured voltage.

In the case of the designed control system the traditional strategy will require changes since batteries now need to have charge potential to absorb the transients, but also batteries need to have enough charge to be reliably always available to compensate the slow dynamics of the fuel cell. The new battery charging strategy will depend on a SoC calculation to keep the battery within a specific charge level. The exact level of charge will require consideration of the battery chemistry to not damage the battery itself.

Battery charger will be based on SoC measurement, with a smooth transition. Practically the charge controller will be fuzzy-like. The logic of the controller is presented in Table 3 the controller behavior is demonstrated in Figure 19.

Table 3. Logic table of the charger. The middle section of the controller will reduce unwanted oscillations.

SoC	Charge amount
< 75 %	Max charge
75 - 85 %	y = SoC * x + b
> 85 %	No charge

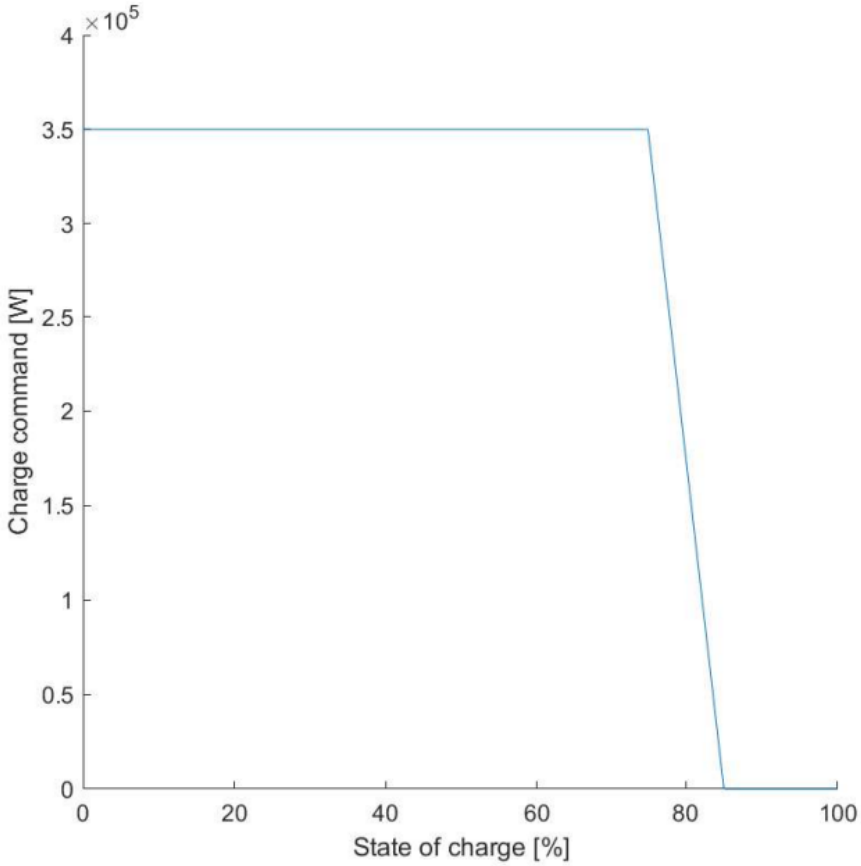

Figure 19. Battery charging controller dynamics. Max command is given at low charge levels. Linear transition zone is during 75 – 85 % and then no command is given when battery is over 85 % charged. This scheme will make the battery setpoint at 85 %

Rate limiter already eliminates the significant transients in the control signal, but to reduce further enhance the performance in frequent transient situations, a transition state was created for the controller. The used controller will have setpoint at 85 per cent SoC, this should be enough to have the battery operational at all times and still have capacity to absorb transients from the DC-link. Like mentioned before the setpoint could and should be changed depending on the battery type.

4.2.3 Startup sequence

As discussed in chapter 2.4 it is likely that a stationary large scale fuel cell will require external power, this will be provided to the fuel cell by using the same bidirectional DC/DC converter as used with the batteries. During the startup all the power in the system must be supplied with the batteries, in the most probable fuel cell configuration the power will be routed to the auxiliary components via a switchgear controlled by the UPS. This will be done with a simple startup routine which will be implemented in the firmware of the fuel cell powered UPS.

4.3 Implementation

4.3.1 Control system

The UPS firmware is based on a state machine. The implementation of firmware will require some new states, as the initial startup sequence and the control system itself will require their own states. Implementation of a simplified fuel cell startup routine is presented in Figure 20. Batteries will operate as the primary source of the system until fuel cell system reaches operational temperature.

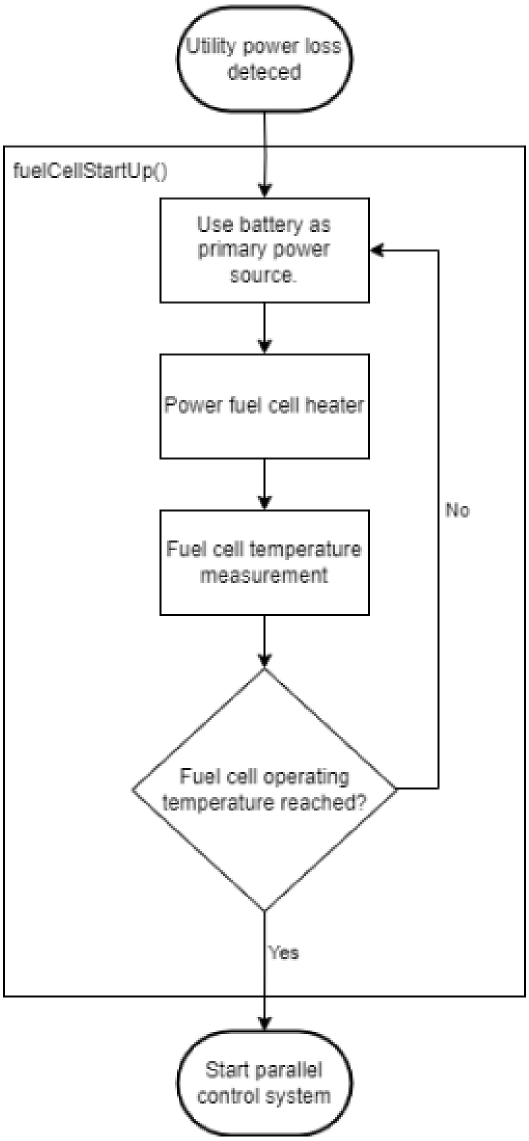

Figure 20. Fuel cell startup routine. Using battery power to power the system and the fuel cell heater unit will be required for the startup. When operational temperature is reached parallel control system is started.

The control system implementation flowchart is presented in Figure 21. The shutdown feature is expected to be automatic. The shutdown sequence should include internal fuel cell functions such purging the excess water and hydrogen. This should be run with just a command from the control system.

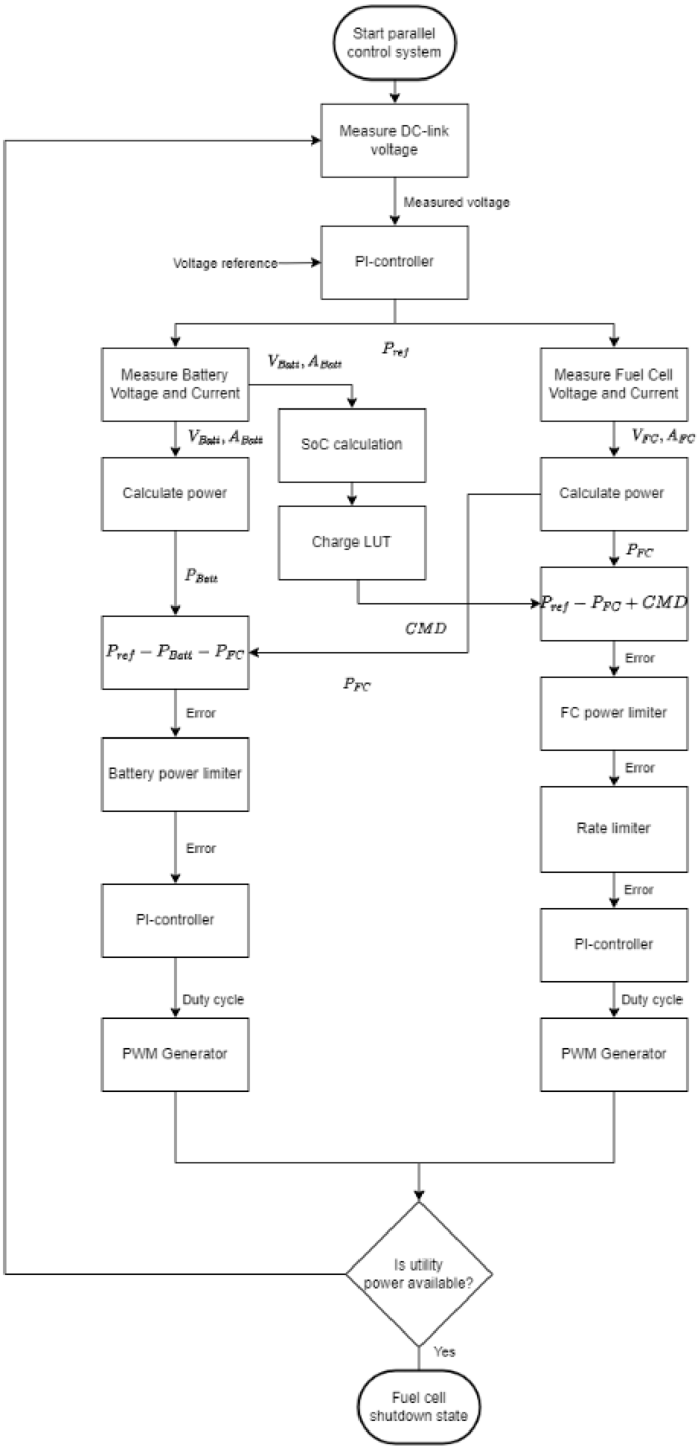

Figure 21. Control system implementation flowchart. Needed functions to create the system are described. When utility power is available state is changed to fuel cell shutdown state.

4.3.2 Fuel cell in Simulink

To have a more accurate representation of a fuel cell, Eaton internal data for Fuel cell was provided. The data was acquired from a GT-suite model that was modelled after a 90kW fuel cell used automotive applications.

For the validation of the proposed control system fuel cells are modelled with the built in Simscape fuel cell model. A detailed version of the model is used to create a more realistic simulation. In Figure 22 provided fuel cell polarization curve is presented. The configuration of the fuel cell parameters in Simulink was done based on this information. In Figure 23 the fuel cell modelled in Simulink is presented.

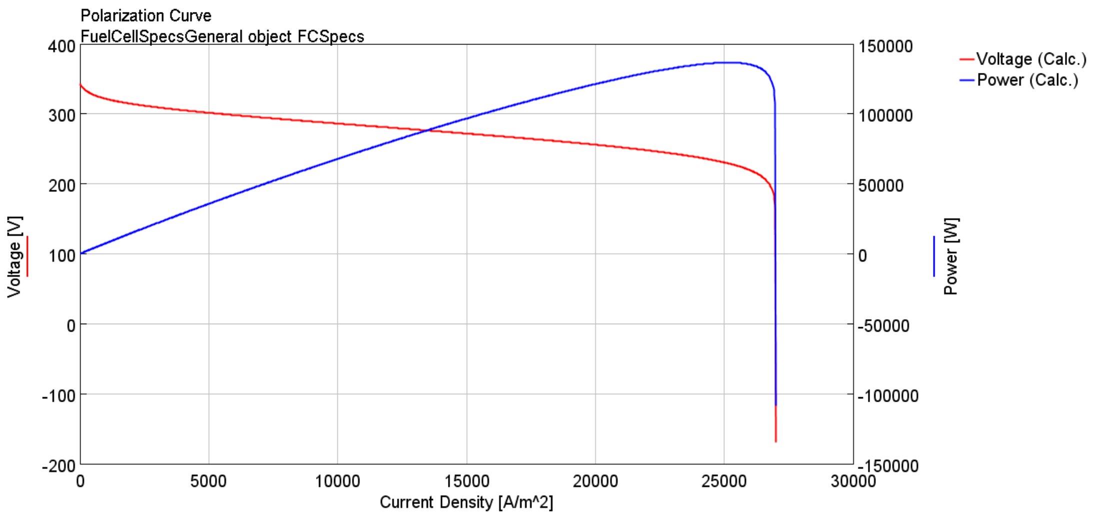

Figure 22. Polarization curve and the power curve, that was simulated with the GT-Suite simulation. After peak power output the system output collapses almost instantly.

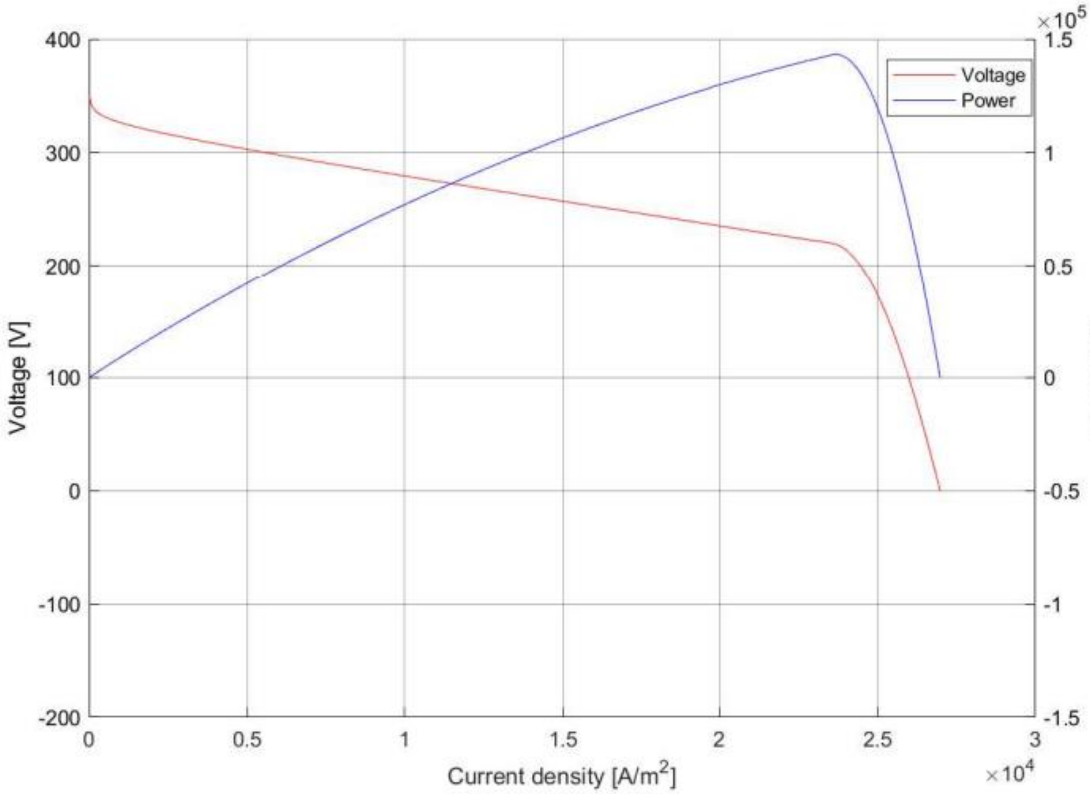

Figure 23. Polarization curve and the power curve, of the created fuel cell in Simscape. Similar shape as the more advanced simulation has been achieved, but still major differences exist between the two models in terms of polarization curve.

As can be seen from Figure 22 and Figure 23 the overall curves are relatively similar and thus the obtained results can be expected to be very comparable. The major difference is after the maximum operating point, where the GT-suite model falls off near instantly whereas the Simulink model the fall not nearly as instantaneous.

To test the dynamic response, the overshoot and undershoot of the system, a load step experiment was conducted on the GT-suite model. The fuel cell was operated on idle and then the maximum nominal load of 90 kW was applied. Voltage and current were measured, and power was calculated based on these results. The result of the experiment is presented in Figure 24. Same experiment was conducted on the created Simulink model and its results are presented in Figure 25.

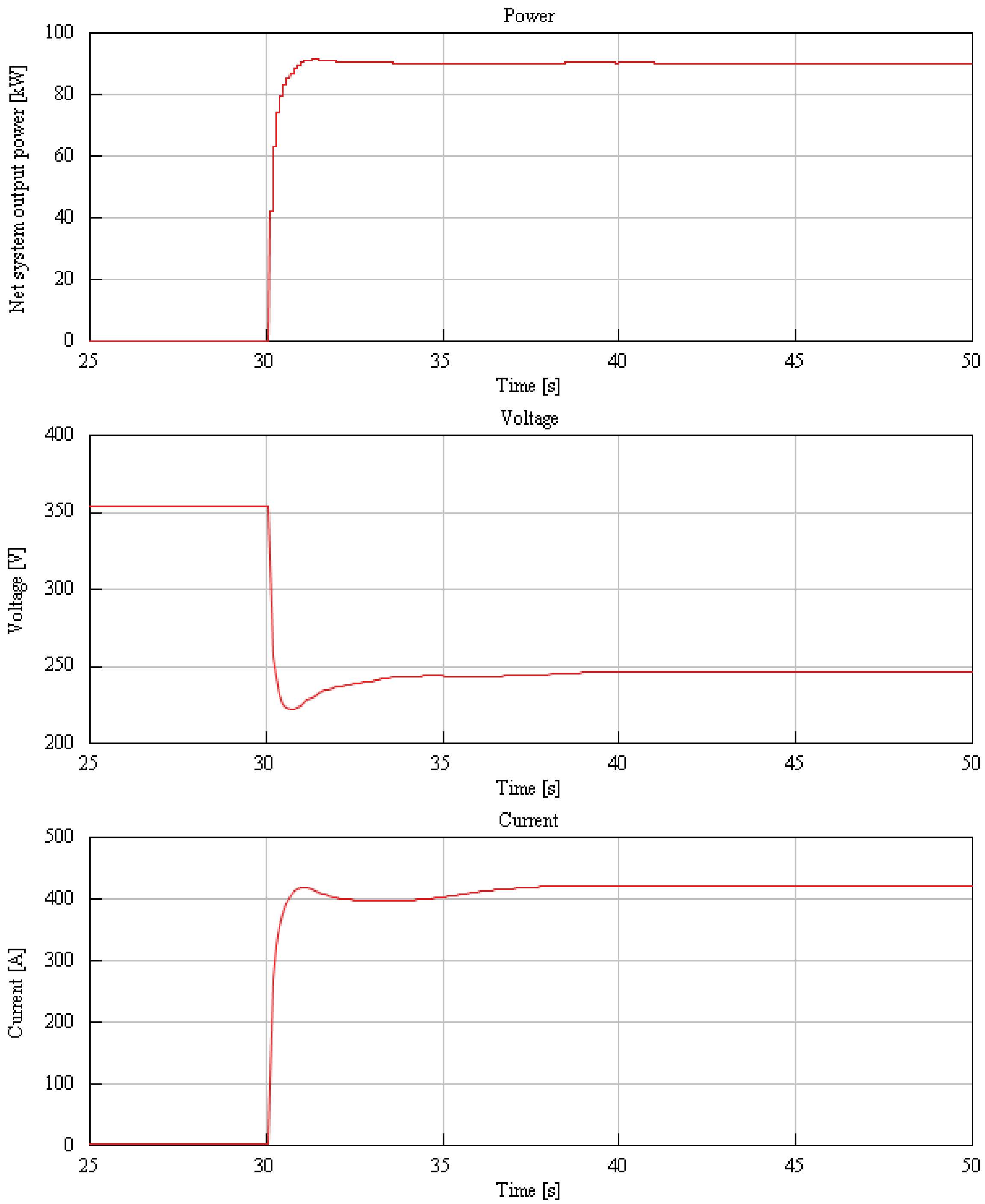

Figure 24. Dynamic response, overshoot and undershoot test results from the GT-suite model. The system has a noticeable delay and undershooting of the voltage can be clearly seen.

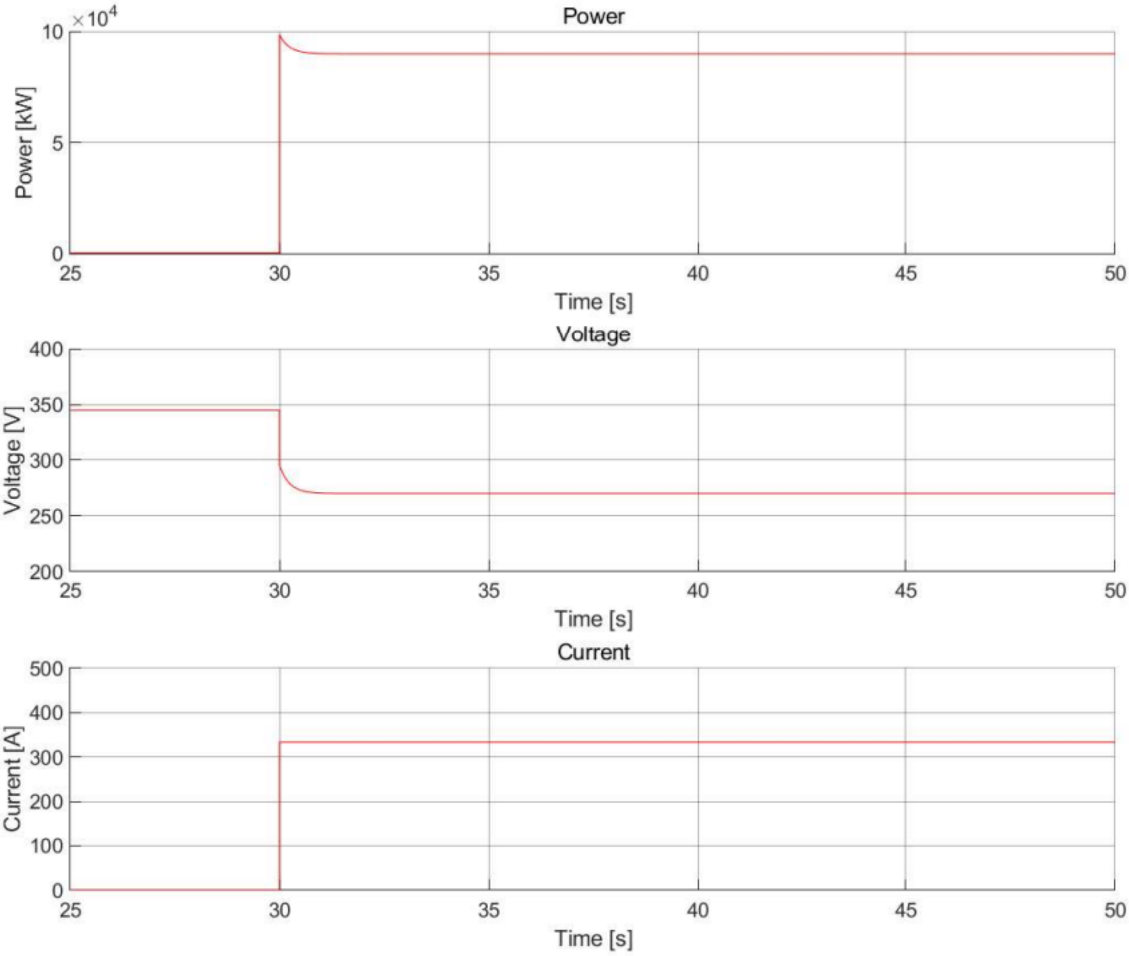

Figure 25. Dynamic response, overshoot and undershoot test results from the Simulink model. The created model does not show any slowness of the dynamic response, nor does it have any current overshoot. Voltage has some non-linearity reacting to the step.

Comparing Figure 24 to Figure 25 the dynamics of the systems are vastly different as created Simulink model lacks all rise time and does not have any of the overshoot and undershoot behavior of the GT-suite model. However, as the control system will limit the rise time of the fuel cell these inaccuracies will not matter in terms the of overall outcome, since slowing the transient will also reduce the overshoot and undershoot behavior. Also, the GT-suite model has significant voltage drop when load was applied to the system.

The modelled parameters of the are presented in Table 4.

Table 4. Details of fuel cell systems used in simulations.

Parameter	Value
Voltage at 0A	350V
Voltage at 1A	345V
Nominal operating power	90kW
Nominal operating voltage	270V
Nominal operating current	333A
Maximum operating power	143kW
Maximum operating voltage	220V
Maximum operating current	650A
Number of cells	390
Nominal efficiency	55%
Operating temperature	65
Nominal air flow rate	9840lpm
Nominal fuel supply pressure	1.5bar
Nominal air supply pressure	1bar
Nominal composition H_2	99.95%
Nominal composition O_2	21%

Overall, the modelling of the fuel cell is within acceptable limits and missing features have been considered and compensated for in the control system. For a 340 kW UPM a single 90 kW fuel cell will be insufficient, so to get a higher capacity fuel cell four fuel cells will be connected in parallel to achieve a 360 kW. Connection of the fuel cells blocks is presented in Figure 26.

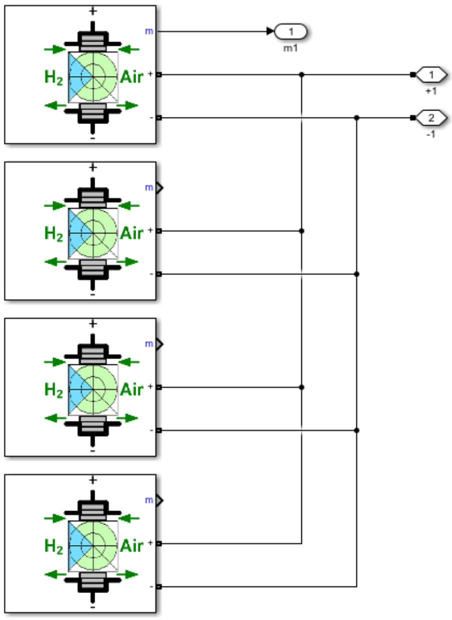

Figure 26. 360 kW fuel cell system in Simulink. Fuel cell model is a parallel model of four individual 90 kW fuel cells. This was done to remain as close to the real model as possible. Even though realistic results can be had with the design. Multiple fuel cell model will result in worse computational performance.

5 Simulations

5.1 Test arrangements

To validate the control system, design was verified with an offline Simulink model. In Simulink an engineering test design of an existing simulation model of the UPM model was modified to be used as a plant model. The changes required to the Simulink model were the total change of the control system, adding additional connections to the DC-link and implementing the fuel cell block to the system as demonstrated in chapter 4.3.2 that was based on a real fuel cell.

Two different test cases were created to be tested in simulations. Two were needed to have enough coverage of different situations. Firstly, a from idle state to maximum load back to idle test was performed to test the basic operation of the system. The test will be a good indicator of operation in the maximum limits of the system.

Secondly a more application specific test was run where load demand changed more frequently and was more in real use case area of 30 -70 %. This test will be more applicable, since it will include more transients and test the performance where it will really matter.

No further test cases were deemed necessary at this point in the development. Chosen test will cover enough of the use cases and maximum limits. The need for more test cases may arise when using an actual fuel cell since parameters will be different and a real fuel cell can be otherwise vastly different depending on the manufacturer.

In the test fuel cell was expected to be on idle mode, such as the internal temperature was already at the operating temperature. No fuel cell startup or shutdown test were done because of the variety of different strategies that could be implemented.

5.2 Offline simulation

A test harness was created for the system, where specific tests with predetermined load where chosen. The harness includes the control system, a DC-link circuit and a test plan. This interaction is demonstrated in Figure 27.

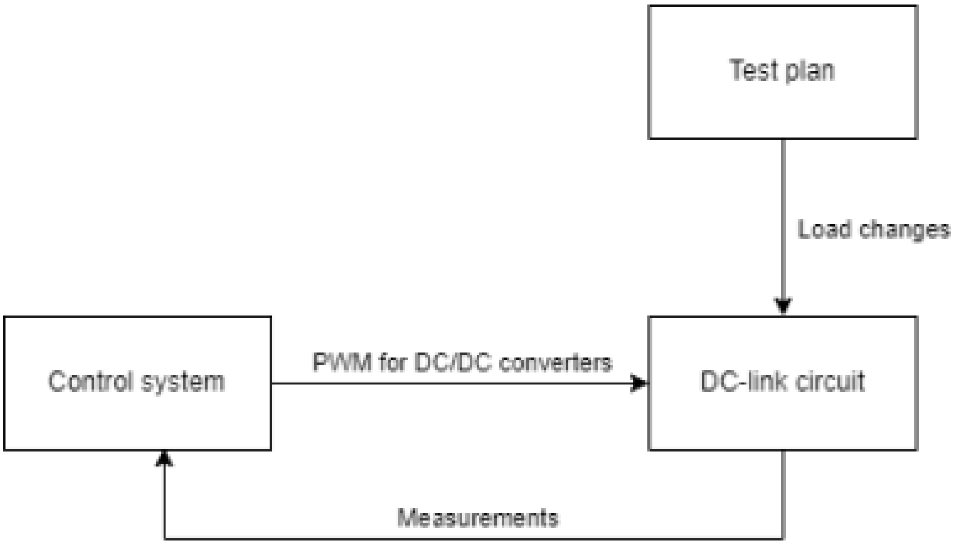

Figure 27. MATLAB test setup. Control system sends PWM signal to the electrical circuit and the electrical circuit passes measurements to the control system. Test plan block control the current demand.

For the first test plan following load steps were used. For the first simulation results are presented in Figure 28 and in Figure 29.

Table 5 load steps for the first simulation.

Time [s]	Load [kW]
0.01	350000
0.22	5000
0.24	350000
1.5	5000

Table 6 Load steps for the second simulation

Time [s]	Load [kW]
0.01	350000
0.22	100000
0.26	200000
0.46	250000
0.54	200000
0.72	100000
0.8	250000
1	5000

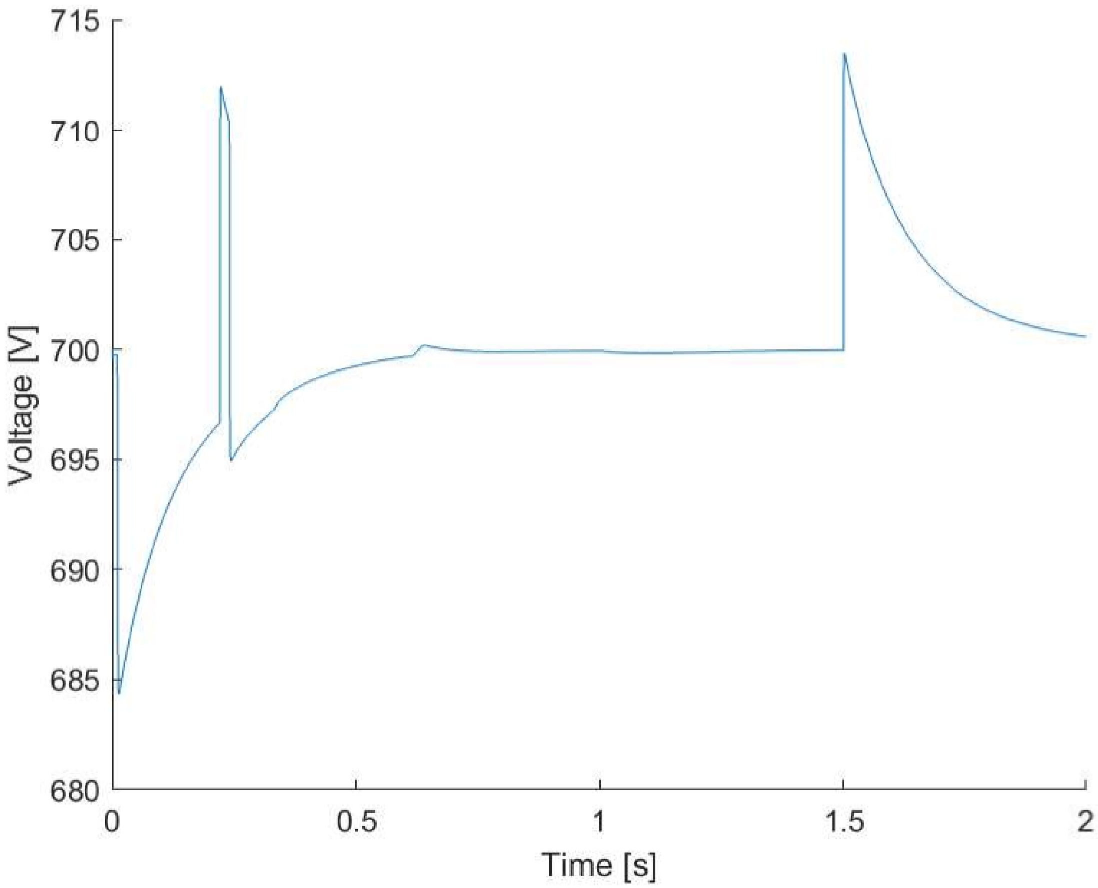

Figure 28. DC-link voltage in offline simulation 1. Load steps at 0.22 and 1.5. Rise time of the system is within acceptable region and steady error is within acceptable limits.

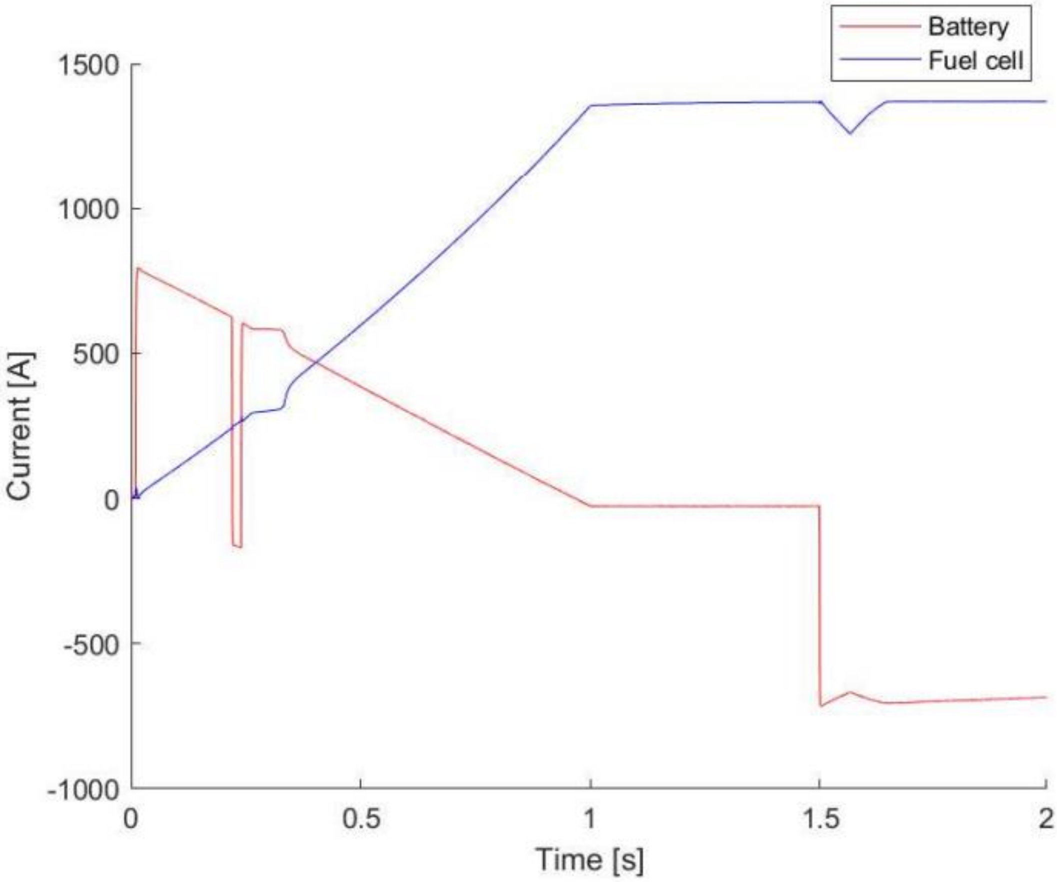

Figure 29. Fuel cell and battery current during simulation 1. The system shifts the main power source as intended. Some ripple is seen in the battery current.

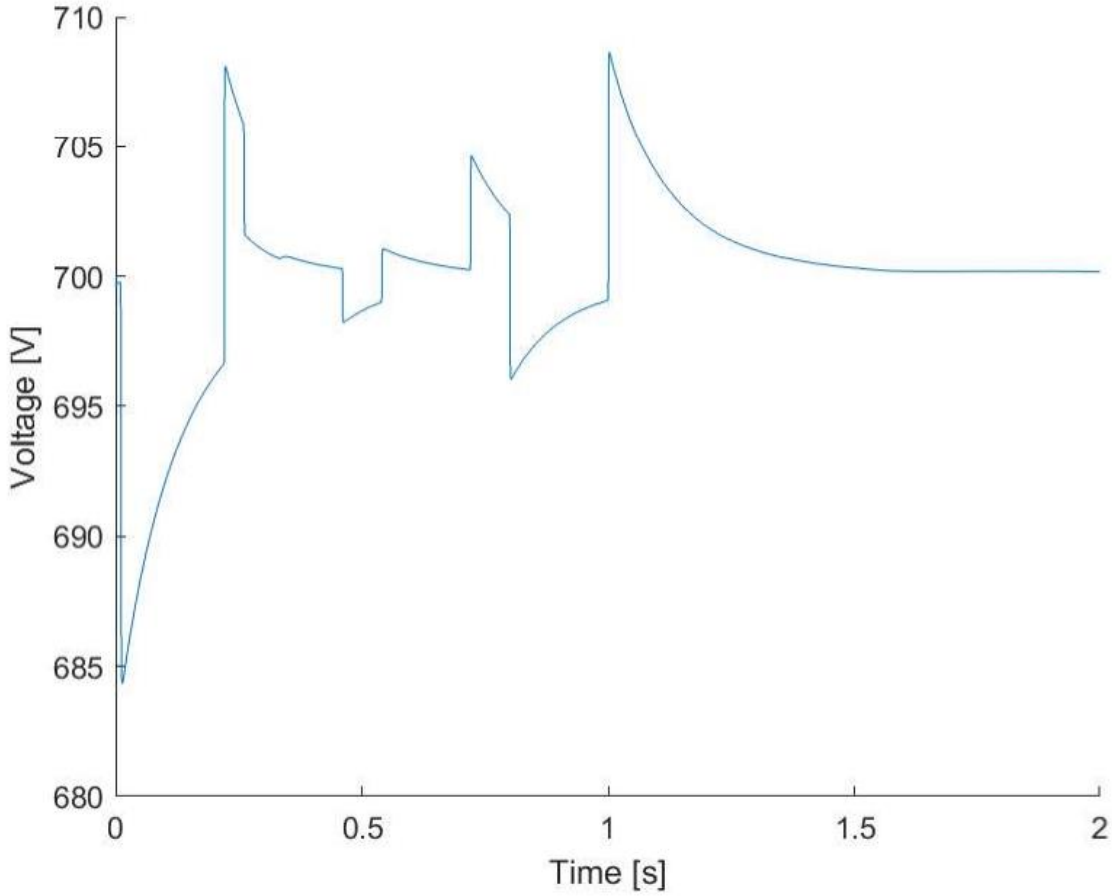

Figure 30. DC-link voltage during simulation 2. DC-link voltage is the main controlled variable. The control system is able to withstand transients very well.

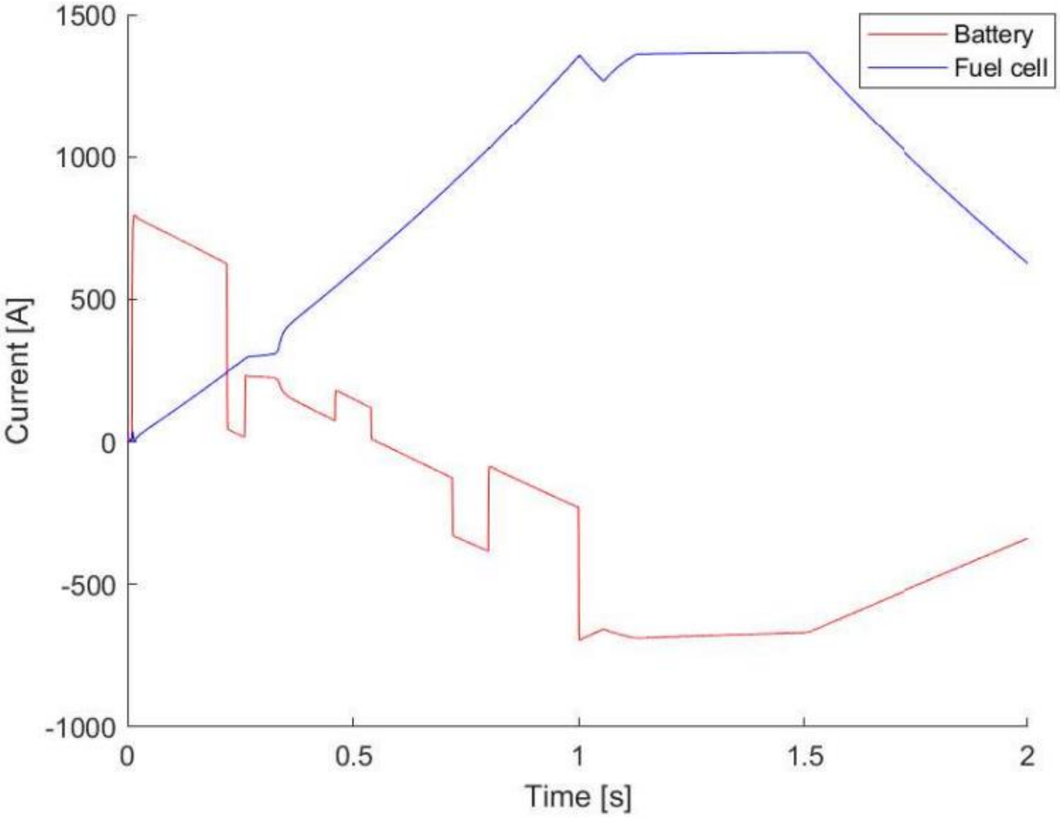

Figure 31. Fuel cell and battery current during simulation 2. Batteries were at half charge in the beginning, so all excess power is used to charge the batteries. As the transients were smaller the system recovered very rapidly.

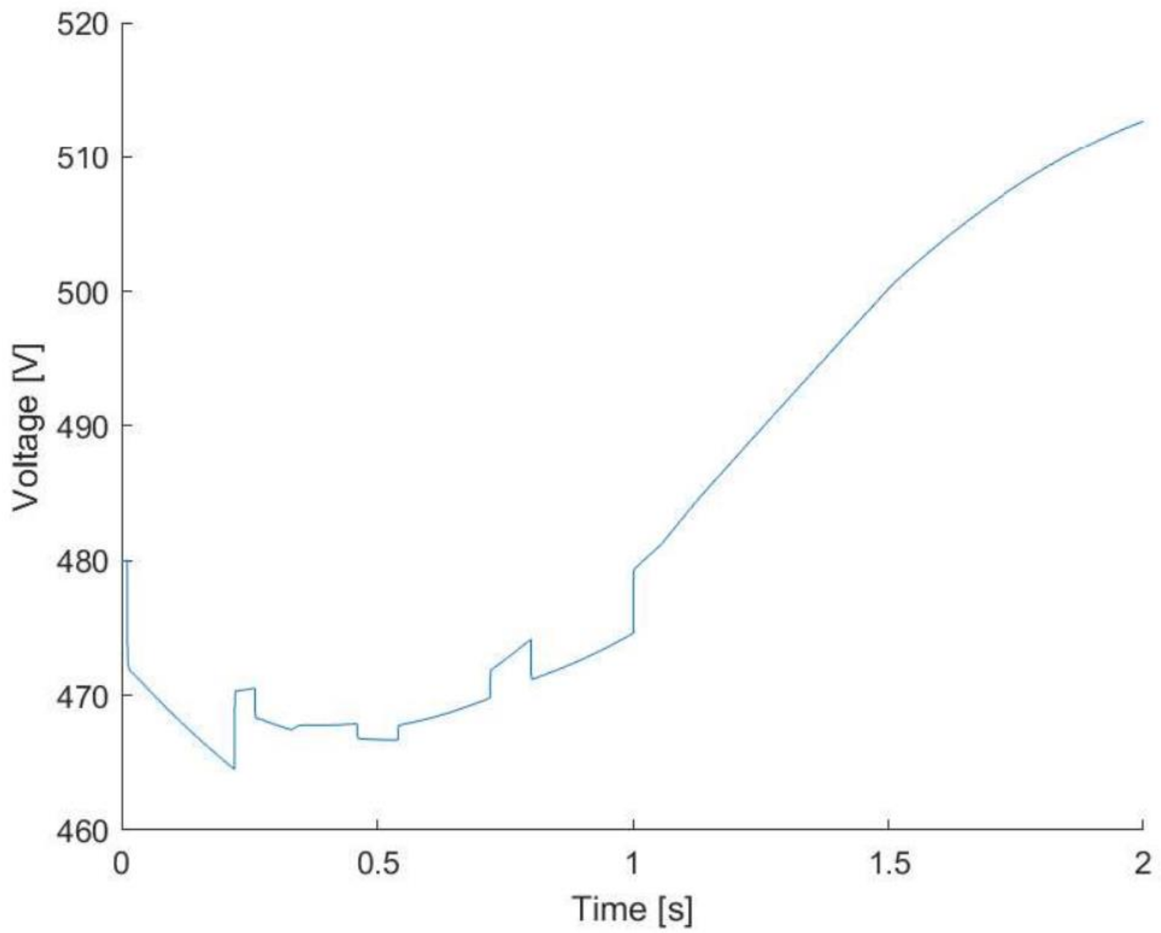

Figure 32 Battery voltage curve during simulation 2. The batteries were at 50% SoC at the start and reached 85% at the end. Batteries can handle transients even though they are being charged. Once batteries reach 75 % charge the charging slows down.

Simulation overall results are all within acceptable limits. Like designed, the fuel cell slowly ramps up to the desired power level as the battery responds to the fast transients. DC-link voltage is also kept within 2% margin of the target of 700 V at all times and the steady state error is negligible. Transient response worked as expected as the fuel cell current barely changes and batteries do the work. Also, the battery charging function behaves as expected.

6 Conclusion

Fuel cells are promising energy conversion method with a lot of potential to replace diesel generators. In this thesis, fuel cells for UPS backup were studied. A literature review about fuel cells was conducted. Based on the literature review a control system was designed, created and tested. The main problems of fuel cells in use with UPS's were identified as poor dynamic response, large voltage range and the considerations for the startup time of the fuel cell.

Based on the literature review and the UPS setup, active hybridization was chosen as the preferred topology and the control system was designed around that. Control system was cascaded system with parallel inner loops, controlled with PI-controllers. Control system was tested with an offline.

The results from the simulations were deemed promising and further study on the subject is recommended. Based on the simulations the active hybridization of batteries and PEMFC will provide a solid performance for the system and performance wise is a valid replacement for diesel generator.

Due to the lack of a physical fuel cell for test use a lot of approximations were used for the modelling of the fuel. The startup and shutdown properties of the fuel cell were not used in the simulations, but their effect on the system was discussed and they should not impact the behavior of the control system itself. Communication protocols between the UPS main controls and the fuel cell will need to be further researched for a real use case prototype.

6.1 Future research

Since the test done for this thesis were just using the DC-link as isolated standalone system, the most sensible next step for further research would be to create a Hardware-in-the-Loop (HIL) set up with a fuel cell to test the control system in more realistic working environment. After a working HIL system, piloting could be done using all of the hardware. This would require the development of a two DC-link connector UPM and acquiring an appropriately sized fuel cell. Testing the system in a real case application would verify and validate the design and remove the approximations that were made in the designing process. Also, potential shortcomings of the system could be fixed, and the overall system could be fine-tuned.

Another interesting topic for future research would be to use the system in a more active manner. As using the system as the default configuration allows for a bottomless UPS design. This would allow to downsize the batteries and ultimately eliminate batteries totally to change to a more robust transient response auxiliary source such as supercapacitors. Expansion of the energy-aware controller could be implemented with a bottomless UPS. This could allow for a more liberal use of DC-link power to help stabilize the grid power and opens possibility incorporate some cost analysis to make the customer a profit on energy storage. This would also encourage the customers to become consumer-producers in the grid and, thus advancing the future energy grid ideology.

In theory the proposed parallel cascade control system could be infinitely expanded to support a vast variety of other DC sources or loads, as the load balancing operates on basic addition and subtraction and is only modified by saturation and rate limiters. It would not be too difficult to incorporate similar set up to have solar-type renewables where maximum power point tracking controller could be used. Also, the use of electrolysers could be investigated in parallel of the fuel cell to create its own fuel supply. Combined with an energy-aware-type controller that could monitor the grid and enable back feeding, a future UPS combined with renewable sources could be an independent power supply of a datacenter. This could allow for more of a “UPS as interface”-level thinking for future research.

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