REPUBLIC OF TURKEY
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DEVELOPMENT AND MANAGEMENT OF A FUEL CELL/BATTERY/ULTRA-CAPACITOR HYBRID SYSTEM THROUGH A MULTI-PHASE MULTI-INPUT CONVERTER

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A thesis submitted INSTITUTE OF GRADUATE STUDIES Aykut CAN in partial fulfillment of the requirements for the degree of **MASTER OF INSTITUTE OF GRADUATE STUDIES** is approved by the committee in the Department of Electrical and Computer Engineering.

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DECLARATION

This thesis study is my own work, I do not have unethical behavior in all stages from the planning to the writing of the thesis, that I have obtained all the information in this thesis within academic and ethical rules, that I refer to all the information and comments that have not been obtained with this thesis and that I have included these sources in the list of references. I declare that I did not violate patent and copyright rights during the study and writing of this thesis.

23 August 2021

Aykut CAN

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23 August 2021 **Aykut CAN**

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LIST OF ABBREVIATIONS

DC	Direct Current
DLC	Double Layer Capacitor
EV	Electrical Vehicle
EMS	Energy Management System
ESS	Energy Storage System
ECMS	Equivalent Consumption Minimization Strategy
ESR	Equivalent Series Resistance
FCT	Flatness Control Technique
FC	Fuel Cell
FCEV	Fuel Cell Electrical Vehicle
FCHEV	Fuel Cell Hybrid Electric Vehicle
FL	Fuzzy Logic
FLC	Fuzzy Logic Controller
GA	Genetic Algorithm
HWFET	Highway Fuel Economy Driving Schedule
HEV	Hybrid Electrical Vehicle
HPS	Hybrid Power System
ICE	Internal Combustion Engine
LPF	Low Pass Filter
LHV	Lower Heating Value of Fuel
LF-LRV	Low-Floor Light Rail Vehicle
MIC	Multi Input Converter
MPC	Multi Phase Converter
MPMIC	Multi Phase-Multi Input Converter
PD	Proportional and Derivative
PI	Proportional and Integral
PID	Proportional and Integral and Derivative
RMS	Root Mean Square
SIC	Single Input Converter
SOC	State Of Charge
UC	Ultra-capacitor
UDDS	Urban Dynamometer Driving Schedule
VSB	Volt Second Balance
VSD	Voltage Drop of the Switches of the Body Diodes
WT	Wavelet Transformation

LIST OF SYMBOLS

A	Ampere
B	Exponential Zone Time Constant Inverse
C	Capacitance
E	No-load Voltage
E_0	Battery Constant Voltage
h	Hour
I	Current
K	Polarisation Voltage
kA	Kiloampere
kF	Kilofarad
kHz	Kilohertz
kW	Kilowatt
L	Inductance
Q	Battery Capacity
R	Resistance
s	Second
V	Volt
W	Watt
β	Adjustment Coefficient
°C	Celcius

ABSTRACT

DEVELOPMENT AND MANAGEMENT OF A FUEL CELL/BATTERY/ULTRA-CAPACITOR HYBRID SYSTEM THROUGH A MULTI-PHASE MULTI-INPUT CONVERTER

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Increasing environmental concerns, unstable oil prices, and advancements in the technology of batteries have accelerated studies on electrical vehicles (EVs). Moreover, environmentally friendly and cost-effective energy production makes a great contribution to EV research. Unfortunately, recent batteries fail to meet the dynamic profiles of EVs owing to their low power density. Moreover, their limited energy densities result in a low range on a full charge. Long charging times of batteries are another issue with batteries. To overcome the aforementioned problems, the utilization of hybrid power systems (HPSs) in EVs has been offered in the literature. For example, the battery/ultra-capacitor (UC) HPSs allow building systems with high power/energy density and longer battery life. Moreover, through a fuel cell (FC) system, the travel range can be extended in an environmentally friendly and economic way. HPSs classes are mainly: passive and active. The passive HPSs have no power electronics converter; thus, these systems are simple, economic, and efficient; however, they cannot control source energies fully. Conversely, in the active HPSs, the power electronics structures, which can be classified as single-input converters (SICs) and multi-input converters (MICs), are used to process the power. Separate SICs for each input are used in the multiple converter approach in which high cost, complex design, and control difficulties are expected. Alternatively, HPSs having MPCs offers many advantages; such as compact design, low component count, and high energy density. Additionally, MICs can be designed as having single-phase or multi-phase. The parallel legs that ideally split the power equally in multi-phase MICs (MPMICs) help to build efficient HPSs having many advantages in terms of filter requirements, inductor sizes, electromagnetic interference, and thermal management in spite of the increased complexity and cost. This thesis aims to develop a FC/battery/UC HPS by a single dc-dc converter which is a MPMIC. The source energies in this HPS are controlled by a fuzzy logic-based energy management strategy (EMS) to assure a sustainable operation. In this thesis, the proposed HPS along with the developed EMS is first analyzed, then it is tested via a simulation study.

Keywords: Electric vehicles, Energy management strategy, Fuel cell, Fuzzy logic, Multi-phase Multi-input converter.

ÖZET

BİR ÇOK FAZLI ÇOK GİRİŞLİ DÖNÜŞTÜRÜCÜ İLE YAKIT HÜCRESİ – BATARYA - ULTRAKAPASİTÖR HİBRİT SİSTEMİNİN GELİŞTİRİLMESİ VE YÖNETİLMESİ

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Artan çevresel kaygılar, değişken petrol fiyatları ve batarya teknolojisindeki gelişmeler, elektrikli araçlar (EV'ler) üzerindeki çalışmaları hızlandırmaktadır. Ayrıca çevre dostu ve uygun maliyetli enerji üretimi, EA araştırmalarına büyük katkı sağlamaktadır. Ne yazık ki, bataryalar, düşük güç yoğunlukları nedeniyle henüz EA'lerın dinamik profillerini tam anlamı ile cevap verememektedir. Ek olarak, sınırlı enerji yoğunluklarından dolayı tam şarjda EA'ların menzili sınırlı olmaktadır. Bataryaların uzun şarj süreleri ise başka bir sorun olarak ortaya çıkmaktadır. Yukarıda bahsedilen sorunların üstesinden gelmek için, literatürde EA'larda hibrit güç sistemi (HGS) yapılarının kullanımı önerilmiştir. Örneğin, batarya/ultra-kapasitör (UK) HGS, yüksek güç/enerji yoğunluğuna ve daha uzun batarya ömrüne sahip sistemlerin geliştirilmesine olanak sağlamaktadır. Ayrıca, bir yakıt hücresi (YH) sisteminin dahil edilmesi aracılığıyla, seyahat menzili çevre dostu ve ekonomik bir şekilde genişletilebilir. HGS sınıfları başlıca şunlardır: pasif ve aktif. Pasif HGS yapılarında güç elektroniği dönüştürücüsü yoktur; dolayısıyla bu sistemler basit, ekonomik ve verimlidir; ancak kaynak enerjilerini tam olarak kontrol edemezler. Tersine, aktif HGS yapılarında, gücü işlemek için tek girişli dönüştürücüler (TGD'ler) ve çok girişli dönüştürücüler (ÇGD'ler) olarak sınıflandırılabilen güç elektroniği yapıları kullanılır. Yüksek maliyet, karmaşık tasarım ve kontrol güçlüklerinin beklendiği çoklu dönüştürücü yaklaşımında her giriş için ayrı TGD'ler kullanılır. Alternatif olarak, ÇGD'lere sahip HGS yapıları kompakt tasarım, düşük bileşen sayısı ve yüksek enerji yoğunluğu gibi birçok avantaj sunar. Ek olarak, ÇGD'ler tek fazlı veya çok fazlı olarak tasarlanabilir. Çok fazlı ÇGD'lerde (ÇFÇGD'ler) gücü ideal olarak eşit olarak bölen paralel bacaklar, artan karmaşıklığa ve maliyete rağmen filtre gereksinimleri, indüktör boyutları, elektromanyetik girişim ve termal yönetim açısından birçok avantaja sahip verimli HGS yapıları oluşturmaya yardımcı olur. Bu tez, bir ÇFÇGD olan tek bir dc-dc dönüştürücü ile bir YH/batarya/UK HGS geliştirmeyi amaçlamaktadır. Bu HGS'ndeki kaynak enerjileri, sürdürülebilir bir operasyon sağlamak için bulanık mantık tabanlı bir enerji yönetimi stratejisi (EYS) tarafından kontrol edilmektedir. Bu tezde, geliştirilen EYS ile birlikte önerilen HPS önce analiz edilmiş, daha sonra bir simülasyon çalışması ile test edilmiştir.

Anahtar sözcükler: Bulanık mantık, Çok-fazlı çok-girişli dönüştürücü, Elektrikli araçlar, Enerji yönetim stratejisi, Yakıt hücresi.

1. INTRODUCTION

Vehicles having internal combustion engines (ICEs) still dominate the market since petroleum base fuels have high energy density and low cost [1]. However, ICEs are one of the greatest contributors to the carbon dioxide emissions that result in global warming and the greenhouse effect. Thus, there has been a great tendency to switch to electric vehicles (EVs) in recent years [2]. EVs are zero-emission vehicles namely, solar vehicles, fuel cell (FC) vehicles, and battery electric vehicles (BEVs) that use other energy sources. The ideal EVs are expected to have high efficiency/power density, extended operation life, and affordable power storage systems costs. Unfortunately, these expectations cannot be met by a sole energy storage system (ESS) presently, with the inclusion of the batteries [3], [4]. The hybrid power systems (HPSs), are the key mechanisms that seek to integrate the advantages of ESSs and to remove their weaknesses [5], [6], [7]. In the development of such structures, the power converters are extremely important. The power converters in HPS systems may be categorized as isolated and non-isolated. Isolation transformers offer magnetic insulation and high voltage gains between the sources and the output in isolated structures [8], [9], [10], [11]. Since the transformers increase complexity and cause losses, the efficiency of these systems is often low. In non-isolated structures, connecting some of the sources directly to the output port and some of them via bidirectional converters offers a simple method of creating hybrid power systems [12], [13]. In addition, hybrid power systems can be created using different non-isolated power converters for each input [14], [15], [16], [17], [18]. This method has an expensive solution since it requires more than one power converter to provide the output voltage control. The most powerful and attractive applicants to solve these problems are the multi-input converter (MIC) structures [19], [20], [21], [22].

There has been a remarkable interest in FC systems owing to the many advantages of, e.g. high energy density, environmentally friendly operation [23], [24]. FCs are the systems that produce electrical energy directly from fuels such as hydrogen, methanol, gasoline without noise and combustion. When hydrogen is used as a fuel, the theoretically released product will be only water. FC hybrid electric vehicles (FCHEVs) consist of hybrid power systems (HPSs) including a fuel cell (FC) and energy storage systems

(ESSs) to increase the robustness of the FC, maximize energy density and reduce fuel consumption [25]. Two common designs are seen in FCHEVs are FC/ultra-capacitor (UC) and FC/battery/UC. In [14], it is shown that FC/battery/UC system is preferable over the FC/UC system given various factors like system capacity, energy consumption, and operation life. Utilizing MICs in FC/battery/UC systems can help to reach high efficiency and high power/energy density [26].

The power electronics converters may be built as having single-phase or multi-phases. In [27], [28] it is noted that MPCs do not only make the efficient conversion possible but they also minimize filter needs, inductor sizes, difficulties with electromagnetic interference, and heated surfaces on printed circuit boards despite that they increase the complexity and cost. Thus, in literature, various architectures merging the benefits of two-input MICs and MPCs are proposed as in [29], [30]; nevertheless, the three-input situation requires further investigation.

In addition to the power electronics structures in HPSs having FCs, energy management strategies (EMSs) play a crucial role in the favorable operation. Fuzzy logic (FL) and wavelet transform (WT) can be pronounced as the most popular methods used in EMSs as analyzed in detail in the following studies:

In [31] is analyzed in an FC/UC HPS study. A full-bridge DC-DC converter and a bidirectional DC-DC converter are applied to FC and UC, respectively. A Fuzzy Logic (FL) performs the load sharing between two sources. A very complicated structure with 5 input and 3 output variables identified in this controller has been developed. Under that arrangement, FC performs the tasks of providing base power and controlling the UC's SOC while UC is in charge of DC bus stabilization.

A FC/battery HPS is built in [32]. This structure is controlled by an EMS based on FL. Here, the battery is connected directly and the FC with a DC-DC converter connects to the DC bus. DIRECT algorithms have been used to optimize FL Controler's (FLC) membership functions and maximize the system efficiency. While the optimization of the approach proposed is focused on known driving cycles, its closeness to standardized parameters of the different driving periods suggests good results for applications in real-time.

In [33] the transformation of the wavelet (WT) to an FC/UC HPS and an EMS with the FL is suggested. The low-frequency components generated from the output power following WT and the SOC of the battery are the input variables of the FLC in this system that uses 2 separate converters. FC's referral power is the output variant.

In [34] an electric vehicle is examined for FC/UC HPS through empirical tests on two distinct EMS using only the FL and the FL with WT in conjunction. The FC is connected straightly with the DC bar through a converter and UC in this analysis. In EMS, where only FLC is applied, the input variables are Output Power, Battery SOC, and FC reference power, whereas the output variable is FC reference power. The reason for taking into account the previous value of FC reference power is to limit the rate of change of FC's power. In the same way as in [33], EMS using FL and WT, the input variables of FLC are the FC reference power and UC's SOC obtained after WT.

In [35] the FC / battery HPS membership functions are also utilized as a method for designing a Genetic Algorithm (GA)-optimized FLC EMS. For optimizing the tram's load profile was utilized in Eskişehir city. The FLC inputs are the battery power and output load, while the output parameter is FC's reference power. In [36], an FL-based EMS, similarly GA-optimized, was developed for FC/battery/UC HPS and analyses were carried out for 22 different driving cycles.

In [37], WT and FL supported EMS for FC/UC HPS are introduced and generated using individual converters. In this system, the low-frequency components of the power demanded by WT, the UC's SOC, and the FC current constitute the input variables of the FLC; the output variables are the FC reference voltage and the FC fuel compressor. The goal of the compressor voltage modifications is to decide the optimum oxygen ratio by reducing the risk of oxygen saturation and thus to increase the overall performance efficiency.

In [38] an FL-based energy management system (EMS) is evaluated for the FC/battery and FC/battery/UC HPS concept for an electric vehicle. Batteries are directly connected to the DC bar in these devices while the power from other sources is passed through independent converters. The simulation model developed during various driving cycles (UDDS, HWFET, etc.) measured the performance of the systems offered. In FC / battery HPS, four modes are specified for the EMS: (1) Start mode, (2) FC driving and battery charge mode, (3) FC and battery combined driving mode, (4) regenerative braking mode. The FLC built for these modes consists of two input variables, as motor power and battery charge status (SOC), and as FC reference power output parameter. The FC / battery / UC

HPS modes are the same as the FC / battery system, but they are five components because of UC. Two FL-based controls were proposed to this system. First, the motor power, UC SOC, battery SOC are presented in 3 input parameters, whereas the output parameter is FC; second, additional motor power, UC SOC, battery SOC are input parameters, whereas the battery power is the output parameter. In [38], there are 54 elements to the membership of functions identified in the analysis. This aims to improve the lifespan of the FC and battery by reducing the fluctuations in energy and preserving battery and UC SOC at a certain rate. The findings reflect the performance of FLC UC/FC/battery.

The study in [39] presents an EMS for a UC/battery/FC HPS, where WT and FL are utilized in conjunction. The requested power adjusts the battery reference power and the FC reference power, which form two of the FLC input parameters and are split into high and low-frequency parts with the WT-established on the load-sharing algorithm. The battery SOC and UC SOC are other FLC's input parameters. The power to be used by the FC and the battery are the output parameters of an FLC utilizing the identified member functions. In that research, sources energies are performed with different DC-DC converters. It is proved to be the most effective area for the FC, and WT restricts the battery and power changes of the FC and can be held at the required values between the battery and the UC SOC, even though the difficulty just rises with the use of the FL.

In [40], a hybrid bus with FC is proposed. The battery and UC are composed of a power storage system. The battery is directly attached to the DC Bus whereas the energy of FC and UC is controlled by different DC-DC converters. This research is based upon the EMS FL too. The power need of FLC's for input parameters are SOC values of UC and battery, for output parameters reference powers of UC and FC respectively. A delay unit system is powered by the converter attached to the FC, fluctuations of FC power are restricted.

The analysis [16] uses different converters to build the FC / battery / UC HPS for each input source. FLC is interoperated with the flatness control technique (FCT) for EMS. The FCT and FC regulate the flow of energy between power storage and load. Power transfer between energy storage systems is regulated by FLC. Input parameters of FLC are UC-battery couple's voltage value and output power respectively. Output parameter for FLC is the percentage of power-sharing through UC-battery couples.

In [41] FC / battery / UC is presented with a WT-based EMS for HPS. There are two preferences for a power conditioning system: The first is the current-controlled operation of different converters attached to each source, whereas another converter controls the output voltage, the second; converter attached to the battery is controlled on by voltage regulation and the output voltage control is done. The power requirement of WT-based EMS is separated into FC, battery, and UC-reference power elements with different frequencies for analysis. It ensures that the FC and battery power are not easily modified. Besides, UC and battery charges are supplied with a switch control on FC in this research.

In [42] - [43], FC/battery/UC HPS is being analyzed. Even though it is mentioned that the proposed systems use multi-input converters, they are built by simply connecting two-way riser-low converters to a parallel output capacitance. An FL-based model for EMS was developed in both of the research. The FLC inputs in [42] are output current, battery power, and UC energy, whereas the outputs are a correction factor defined for the current of the battery and a reference of FC's current. In [43], the inputs are the output power and the battery and the SOCs of the UC, whereas the outputs are in FC's reference power and the change on battery power. UC regulates output voltages for each of the researches.

In [44], systems were checked for FC / battery, FC / UC and FC / battery-UC HPS. While each system is built with the use of different input converters, BMCs are optimized for EMS. For the FC / battery and FC / UC HPS, the FLC input parameters are the energy-storing entity's (battery or UC) SOC for the energy requirements, while the output parameter is the reference power FC. Moreover, for the FC/battery/UC system two FLCs were improved; the first one identified the input parameters as the battery SOC and required power; the latter identified as UC SOC and required power. The output parameters of the two FLCs are FC's reference power and the last FC reference power is defined by the minimum of these two outputs.

In [45], a FC / battery / UC HPS is developed. A single-input converter is attached to the FC and a dual input converter unit is connected to the battery. In the EMS two filtering with time invariable of 20s and 10s are used to calculate FC and battery reference capacity. These two references determine the final reference powers by the FLCs utilized. Consequently, FC delivers steady-state power and the battery delivers average power, whereas the UC corresponds to fast load fluctuations and arranges the DC bus.

In [46], specific EMS algorithms like Predictive Control, FL, Equivalent Consumption Minimization Strategy (ECMS) were contrasted. In [33], ECMS attempts to measure the optimal FC power in the form of hydrogen usage equivalents by transmitting the input from the battery and UC, thus reducing hydrogen usage. FL-based EMS was considered to be the best strategy for productivity in FC, although the findings showed that there were no major variations between the approaches tested. The minimum consumption of hydrogen is accomplished using a hydrogen elimination technique similar. On suggested FLC, the output power input parameters with the UC and battery SOCs, the ideal FC power, and the shifts in the battery reference power compose the output parameters. The FC power and battery state shifts were smoothed after the filters were applied. On [18], it was deduced that FL-based EMS worked well against the hybrid system developed with single input converters.

Research in [47] suggests a hybrid tram with a system FC / battery / UC, based on a tram called LF-LRV, which has been proclaimed to be a continuous improvement, in Samsun. This method has been established on a power-sharing algorithm, which incorporates WT and FL. Every source is worked with a different converter and EMS utilizes 2 FLC. On these controllers, the reference power of FC and UC is calculated by taking into account the signals received after WT and battery-UC SOCs. Consequently, FC corresponds to low-frequency load variations and UC corresponds to high-frequency load variations.

In [48], an FL-derived EMS for FC / battery / UC HPS is the basis of the recommended system. Two independent FLC modes are configured for two specified modes utilizing separate DC-DC converters for each input. On amplifier mode, all resources are supplied with the load. In buck mode, the battery is supplied by FC, UC, and regenerative braking energy. FLC input parameters that are used in the amplifier mode are the output voltage's error, output voltage's rate of changing, current error of inductance. FLC input parameters that are used in the buck mode are output voltage error, charge current's rate of change, and charge current's error. Both of FLC's output parameters are changing the modulation signals that drive the switches.

In [49], analysis has been performed a ship simulation with FC / battery / UC HPS. In this recommended structure FC and UC are connected to the output via separate converters, while the battery is directly connected. The purpose of this research is to operate with FL-based EMS in the most effective region of FC. FLC's input parameters consist of SOC of

UC, motor power, and battery respectively. FLC's output parameters consist of a battery and UC couples power.

A 90 kW FC experimental analysis is described in [50]. In [50], FC/battery/UC HPS was created by using 3 different converters, and power-sharing was carried out with a rule-based EMS.

In analysis [51], a two-way bidirectional converter, which is designed in electric vehicle implementations such as the Battery / UC HPS, was used. The switch-diode pairs attached to the inductance terminals of this converter provide an active power distribution between the sources. The power of these inductances is regulated by a pair of switches in which the energy stream is supplied from the sources to the output or from the output to the sources. So this reduces effective keys. In addition to the power electronics structures, the energy management strategies (EMSs) are another key actor that affects the performance of the FCHEVs. Researchers have studied on many EMSs based on numerous approaches, such as optimization methods [52], wavelet transformation (WT) [41], adaptive control [53], and fuzzy logic controller (FLC) [43]. Among these approaches, the FLC-based ones come to the forefront thanks to their simple implementations; moreover, they do not require mathematical models or a prior knowledge of the applied systems.

In [54], an FC/battery/UC HPS is structured via a single-phase MIC; therefore, this system may suffer from the aforementioned issues associated with the single-phase converters. Moreover, the proposed system in [54] is supervised an energy management strategy (EMS) which is essentially a frequency decoupling method consisted of two low-pass-filters (LPFs) and a polynomial. Although the mentioned EMS successes to smooth FC and battery power profiles and regulate UC voltage, it does not offer flexibility in terms of managing source energies. Thus, this paper proposes an FLC-based EMS for an FCHEV in which an FC/battery/UC HPS is built by a three-input multi-phase MIC (MPMIC). In research [55], the converter was studied further in on their another analysis and tested with their battery / UC HPS battery and energy management strategies experimentally by the authors. Test results demonstrate that this converter can share effective energy across resources effectively. The 3-input version of this converter was analyzed in outline and its operability was demonstrated by simulation.

In this thesis, the multi-phase version of the converter in [55] is offered for a FC/battery/UC HPS, and its energy management is realized by a FL-based EMS.

2. PROPOSED FUEL CELL/BATTERY/ULTRA-CAPACITOR HYBRID AND ITS COMPONENTS

FCs look extremely encouraging to meet the high energy demands for EVs. For dynamic responses under different load circumstances, power management of the hybrid system is highly crucial. A single FC system is not enough to meet the load requirements for transitional situations and startups. In addition, a sole FC system results in a big size system and high system installation cost for high power applications. By hybridizing and downscaling FC with UC/battery system, it will reduce system installation cost and increase efficiency. This hybrid system delivers greater power density with high power and energy storage ability.

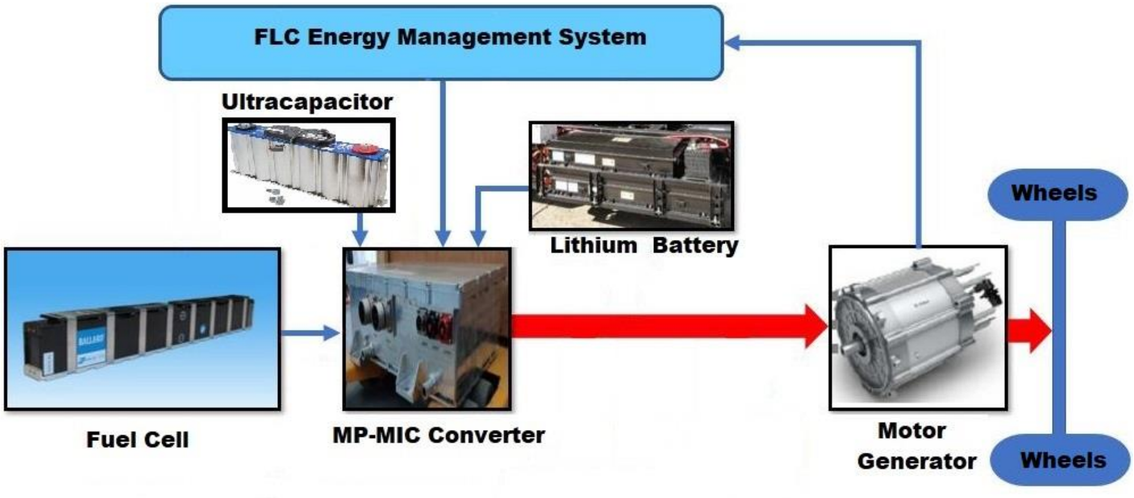


Figure 2.1. Basic block diagram of the system.

This thesis proposes to build a FC/battery/UC hybrid system by a bidirectional MPMIC as shown in Fig. 2.1. A FLC-based EMS is also developed to adjust source energies. In Fig. 2.2, the MPMIC is illustrated. This converter has buck and boost capabilities in both directions. Although it is possible to have an n-phase converter, a two-phase case is considered here. The converter will be analyzed in detail in the following sections.

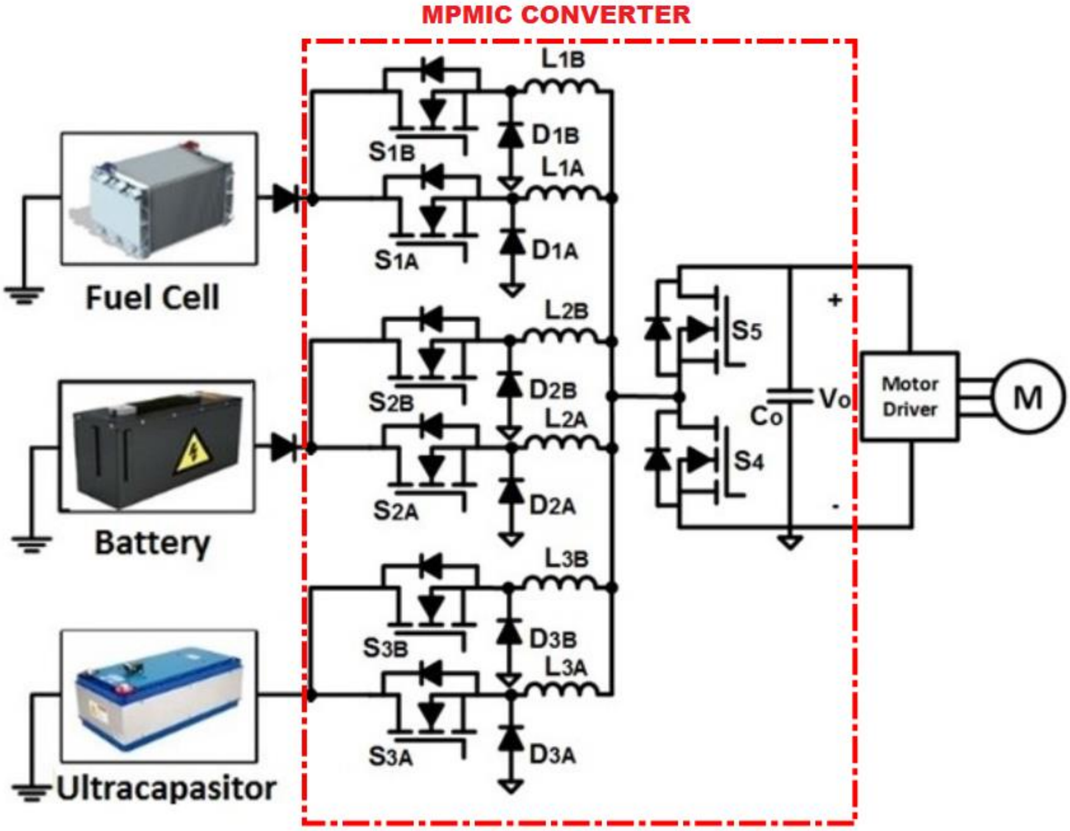


Figure 2.2. Structure of FC/Battery/UC HEV.

2.1. FUEL CELL

2.1.1. Historical Development of Fuel Cells

Fuel cells were first developed in the late 19th century, and in practice, the fuel cell was first used for the Apollo space program in the 1960s. Fuel cells are used for the production of electricity in today's space technologies. The production of electrical energy from hydrogen and oxygen was achieved by William Robert Grove in 1838 by reversing the electrolysis of water, which can be defined as the basic principle of operation of fuel cells. The 'Grove cell' generated a voltage of around 1.8 Volt and 12 Ampere current by the immersion of platinum electrodes into zinc sulfate, zinc electrodes, and nitric acid. Grove found that two platinum electrodes, one in a container of sulfuric acid and the other in an oxygen and hydrogen box, would have a continuous stream. By ensuring the sealing of the containers, the exposed water and gases were able to be accumulated and thus observed that the amount of water that came out to the lover increased as the current flowed. Although British scientists William Nicolas and Anthony Carlisle demonstrated in 1800 that water can be separated into hydrogen and oxygen with the help of electricity, they have not discovered that two gases can be combined to produce water and electricity. Grove observed that coupling in the series connection of several electrodes and adjusting its composition can affect the speed and amount of separation of water. He achieved this with the device shown in Figure 2.1, which he called a gas battery and which we can define as the first fuel cell [58].

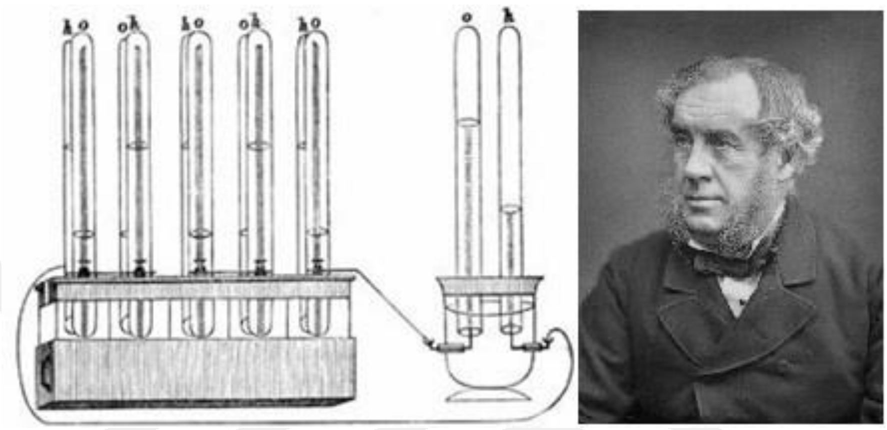


Figure 2.3. Fuel cell developed by W. R. Grove [56].

After Grove, many scientists made efforts to develop fuel cells, and in 1882 Lord Rayleigh conducted several studies to increase the efficiency of platinum electrodes. The solid electrode increased the contact surface to increase the interaction between gas and liquid and also used coal gas as well as hydrogen. Grove's work was repeated in 1889 by chemists Ludwig Mond and Carl Langer; a fuel cell that produces 1.5 W of power and operates with 50% efficiency has been developed using industrial coal gas as a hydrogen source and air as an oxygen source. 1.47 V voltage was expected to be obtained from the fuel cell, but this value was measured as 0.97 V. Figure 2.2 shows the fuel cell designed by Mond and Langer.

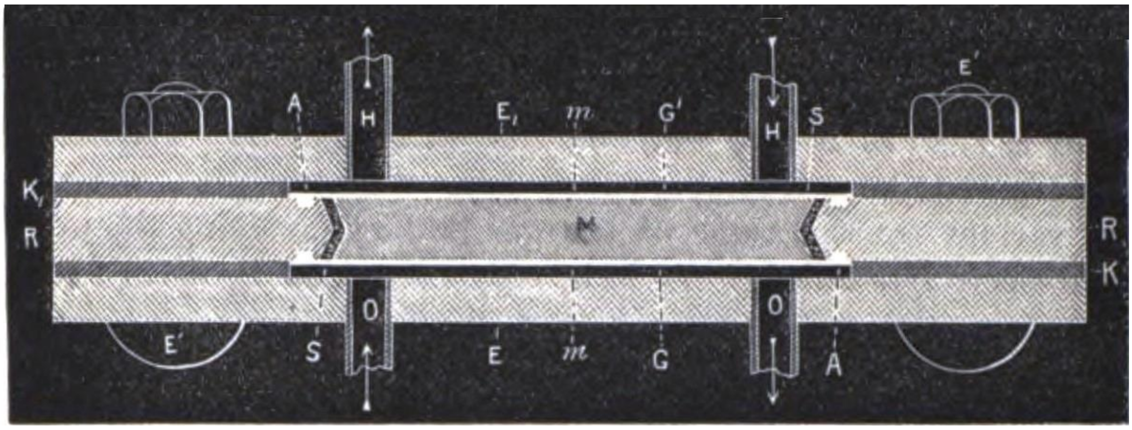


Figure 2.4. A new form of gas battery by L. Mond and C. Langer [57].

In 1894, Wilhelm has made an electrochemical battery working with Oswalt coal derivative fuels. By 1932, Francis T. Bacon has managed to develop the first successful fuel battery, using hydrogen-oxygen cells and alkaline electrolytes. The comprehension of the importance of this project, the Pratt & Whitney Company has provided licensing to this project in NASA programs. In 1959, Bacon and his friends have a fuel battery with 5 kW power. By the end of the same year, Harry Karl Ihring has designed a tractor working with 15 kW fuel batteries and this design has been inspired by the machines working with the fuel battery [58].

In the 1950s and 1960s, NASA invested densely in fuel cell technology. Fuel cells have been preferred for space applications, because of their lightness and producing water as a byproduct. In addition, the use of fuel cells provides advantages such as high efficiency and energy density, low noise, and chills. It was first used in the proton exchange membrane fuel cell Gemini spacecraft produced by General Electric.

In the 1970s, General Motors developed a fuel cell-powered vehicle called "Electrovan". In the 1970s, with government support, Los Alamos National Laboratory and Brookhaven National Laboratories were established for fuel cell research. In recent years, major car manufacturers have been trying to develop fuel cell technologies for fuel cell cars, and some international companies have also been trying to develop fuel cell technologies for use in other applications. Fuel cells are expected to replace traditional power supplies in the near future.

2.1.2. Features of Fuel Cells

Fuel cells are structures that convert chemical energy directly into electrical energy. The fuel cell is a kind of battery that produces energy instead of combustion by the electrical reaction of fuel and oxygen and utilizes hydrogen as a fuel in general. The usage of fuel cells as an energy converter machine has several benefits, the two most essential of them are high efficiency and no harm to the environment. In contrast to traditional methods, the fuel cells provide direct electricity regardless limits of the Carnot cycle. In the classical cycle, the chemical energy of the fuel is converted to heat by the combustion reaction, and this heat obtained is converted to mechanical energy by the Carnot cycle to drive a generator for electricity generation. During this conversion, both the Carnot cycle limit is not exceeded, and mechanical energy causes new losses in the process of converting it to electricity with a generator, thus causing a decrease in the efficiency of the system. In fuel cells, **as** shown in Figure 2.5, chemical energy is converted directly into electrical energy [59].

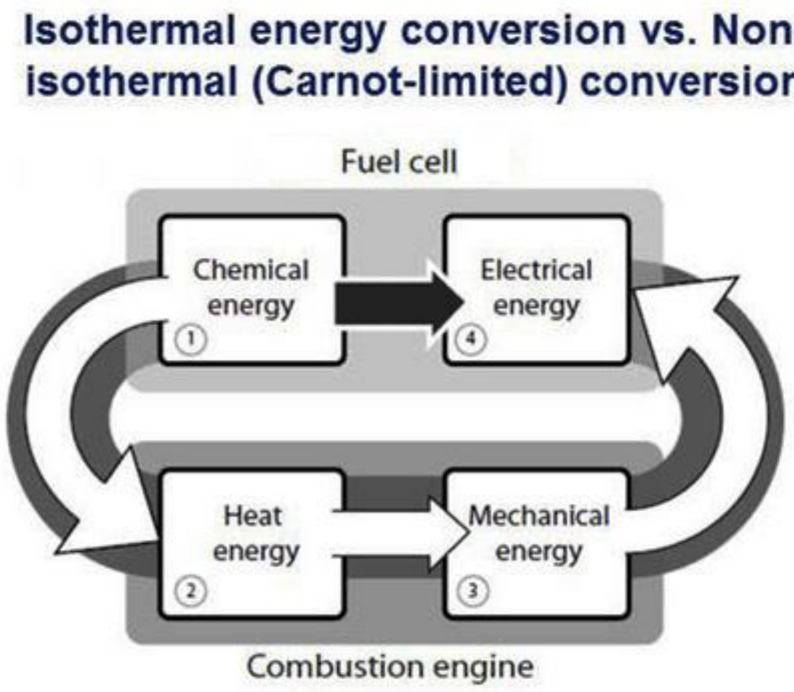


Figure 2.5. Energy conversion in conventional technology and fuel cells [60].

Fuel cells have an efficiency of about 40-60% depending on the type of electrolyte (based on LHV - Lower Heating Value of the Fuel). In addition to high efficiency, fuel cells are operated at constant temperature and the total efficiency can be increased to 80% by heat cogeneration applications resulting from electrochemical reactions. However, the average efficiency of fossil-fueled thermal power plants is 30%. Fuel cells are superior to thermal power plants with their small sizes and high efficiency. The advantages and disadvantages of systems designed with fuel cells and fuel cells can be sorted into substances.

Table 2.1. Advantages and disadvantages of fuel cell [60].

ADVANTAGES	DISADVANTAGES
Direct electric power generation (no combustion process),	High costs
No moving parts	For some types of fuel (hydrogen, methanol, etc.) lack of distribution infrastructure.
Relatively silence working	It takes time for a new technology to be accepted within the power generation industry,
Having types that can operate at low temperatures	The reliability of working on high-temperature types cannot be fully provided
Fuel variety	
Performs well in except nominal load	
Designed to meet a variety of power and safety needs	
Remote operation	
Flexibility to design in different sizes for the same power value	
Ability to make load tracking faster.	

2.1.3. Fuel Cells Operating Principles

The operating principle of fuel cells is similar to batteries in that they convert chemical energy directly into electricity. The biggest difference between them is that in batteries, the electrical energy that can be obtained is stored as chemical energy and it is limited by this amount, while in fuel cells, electricity production can continue as long as fuel is provided. Instead of pure hydrogen in the fuel cell, hydrocarbons containing hydrogen can also be used. However, it is not preferred as it reduces both efficiency and causes harmful gas emissions.

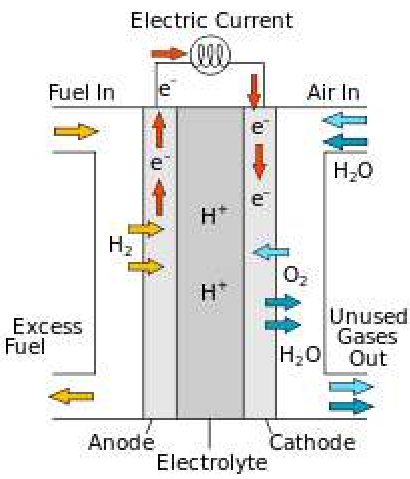


Figure 2.6. Operating principle of fuel cell [61].

In the fuel cell, catalytic oxidation of hydrogen at the anode and reduction of oxygen at the cathode creates a potential difference between the electrodes. If the electrolyte that provides insulation between the electrodes allows ionic mass and charge transfers, this potential difference can be used in an external circuit. As a result, water is obtained as the product and in this reaction, the chemical energy polarization transforms into heat energy due to electrical and resistance losses. With conductors connected between the two electrodes of the fuel cell, the generated DC-character electricity is taken from the fuel cell for use. In fuel cells, hydrogen gas, natural gas, methanol, or ethanol can be used as fuel; oxygen gas or air can be used as an oxidant. If pure hydrogen is used as a fuel and oxygen is used as an oxidant, pure water is obtained as a byproduct. The lack of moving parts of fuel cells allows low noise and vibration levels, extended service life, increased reliability, and reduced product cost [58].

2.1.4. Fuel Cell Types

Fuel cells are named by operating temperature, electrolyte type, or fuel type. A fuel cell with an operating temperature of less than 150 °C is called a "low-temperature fuel cell", and one between 500-1000 °C is called a "high-temperature fuel cell". Low-temperature fuel cells require good and expensive materials such as hydrogen as fuel and platinum as a catalyst, while high-temperature fuel cells can use hydrocarbon fuels and cheaper catalysts. Although the operating principles of fuel cells are similar, the operating conditions and application areas are different. Fuel cells are classified as follows according to the type of electrolyte used.

- Proton exchange membrane fuel cells (PEMFC),
- Alkaline fuel cells (AFC),
- Phosphoric acid fuel Cells (PAFC),
- Molten Carbonate fuel cells (MCFC),
- Solid oxide fuel cells (SOFC).

The operating temperature and operating life of fuel cells depend on the physicochemical and thermomechanical properties of the materials used in the structure of the fuel cell. Since the chemical reaction occurs very slowly in low-temperature fuel cells, it is used as a platinum catalyst, an expensive element to accelerate the reaction and increase battery efficiency. This leads to increased fuel cell costs. In high-temperature fuel cells, this disadvantage is eliminated by itself, since the operating temperature is sufficient to speed up the reaction. For this reason, cheaper materials can be used as catalysts in high-temperature fuel cells.

Table 2.2. Comparison of fuel cell types [62].

	PAFC	**SOFC**	**MCFC**	**PEMFC**	**AFC**
Electrolyte	Orthophosphoric acid,	Stabilized zirconium	Carbonate	Polymer membrane	Potassium hydroxide
Fuel type	Hydrogen, hydrocarbon, Fossil fuel	Hydrogen, hydrocarbon	Hydrogen, hydrocarbon	Hydrogen, hydrocarbon	Hydrogen
Power density (kW/m^2)	0,8 - 1,9	0,1 – 1,5	1,5 – 2,6	3,8 – 6,5	1
Power/weight ratio (W/kg)	120 - 180	15 - 20	30 - 40	350 - 1500	35 - 105
Temperature (°C)	200	700 - 1000	600 - 700	80	80
Cell voltage (V)	1,1	0,8 – 1,0	0,7 – 1,0	1,1	1,0
Efficiency (%)	37 - 42	60 - 70	45 - 60	60	42 - 73
Scope of application	Hotels, hospitals	Industrial applications	Power plants	Transportation, military - space systems,	Space systems

2.1.4.1. *Phosphoric Acid Fuel Cells (PAFC)*

Phosphoric acid fuel cells use phosphoric acid or sulfuric acid as an electrolyte. In these batteries, which have an average operating temperature of 200 ºC, hydrocarbon gases are used as fuel, and the air is used as an oxidizer. It is necessary to use platinum as a catalyst. Platinum becoming susceptible to CO poisoning at temperatures around 200 ºC is a major problem for such fuel cells [63].

2.1.4.2. *Alkaline Fuel Cells (AFC)*

Potassium hydroxide solution (KOH), which is used as an electrolyte in alkaline fuel cells, also provides cooling of the battery. Moving ions are hydroxyl (OH-) ions and move from cathode to anode. Operating temperatures average 80 ^oC. Pure hydrogen is used as fuel, pure oxygen is used as an oxidizer. Electrolyte poisoning caused by electrolyte reaction with CO_2 significantly affects battery performance [64].

2.1.4.3. *Molten Carbonate Fuel Cells (MCFC)*

The carbonate salt mixture used as electrolytes in molten carbonate fuel cells operating at temperatures above 650 ^oC is located in a porous ceramic structure. CO_2, whose moving ions are required for the transmission of CO_3^{-2} from cathode to anode, appears as a product on the anode side. Used in stationary power plants [63].

2.1.4.4. *Solid Oxide Fuel Cells (SOFC)*

Solid oxide fuel cells operate in the temperature range of 600-1000 ^oC and zirconium oxide with yttrium additive is used as an electrolyte. Their mobile ions, O^{-2}, move from cathode to anode. It can use hydrocarbons such as pure hydrogen and natural gas as fuel. Due to its high temperatures, hydrogen separation is not required and allows the resulting waste heat to be used in cogeneration. The batteries with the highest yields among fuel cells are solid oxide fuel cells [63].

2.1.4.5. *Proton Exchange Membrane Fuel Cells (PEMFC)*

In PEM-type fuel cells, a very thin polymer membrane that contains fluorine in its structure as an electrolyte and can exchange ions, such as sulfonic acid polymers, is used. The thickness of this membrane is on average 16 microns and its efficiency increases as it thins. Metals such as Pt (platinum) or Pd (palladium) are used as catalysts in anodes and cathodes. Pemfc uses hydrogen as fuel and oxygen in the air as an oxidizer. The operating temperature is generally under 100 ° C and the typical operating temperature of these batteries is around 70 °C [65]. Pemfc has two electrodes, anodes and cathodes separated from each other by polymer membrane electrodes. On one side of these electrodes is a thin platinum catalyst. Hydrogen atoms given to the anode side of the battery are ionized here. Protons pass through the permeable membrane, are positively charged, and turn to the cathode. Electrons, on the other hand, follow an external path as they pass from the anode to the cathode, causing the formation of electrical energy. Electrons passing through the cathode combine here with hydrogen protons and oxygen taken from the air to form water. For this type of fuel cell to work, the polymer membrane must allow hydrogen protons to pass, while preventing the passage of electrons and other heavy gases [66].

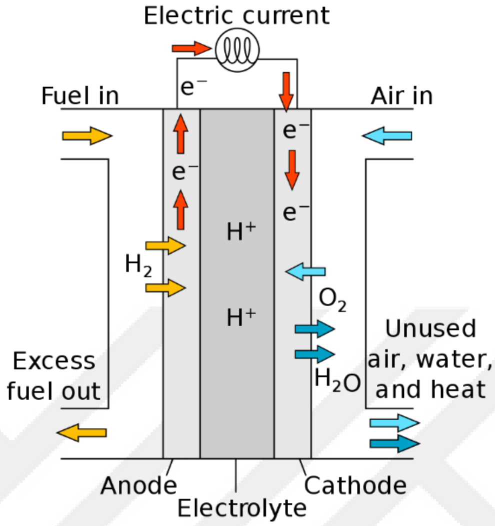


Figure 2.7. Proton exchange membrane fuel cell [67].

The chemical reactions are given below equations.

$$\mathrm{H_2} \rightarrow 4\mathrm{H}^+ + 4e^- \text{ (anode)} \tag{2.1}$$

$$4e^- + 4H^+ + O_2 \rightarrow 2H_2O \text{ (cathode)} \tag{2.2}$$

$$2\mathrm{H_2} + \mathrm{O_2} \rightarrow \mathrm{H_2O} \text{ (total)} \tag{2.3}$$

Since pemfc does not have moving parts in it, they do not have wear problems, work quietly, and do not produce any waste. The efficiency of pemfc is quite high and is approximately 50%. Pemfc works more efficiently at low power levels, and their efficiency decreases linearly with increasing power [68]. Because of its advantages in terms of volume and weight, as well as high efficiency among fuel cells, pemfc is the most suitable fuel cell system for vehicle applications today [69]. In addition, pemfc works at lower temperatures compared to other FC types and can be activated faster at the time of the first operation [70].

2.2. ULTRA-CAPACITOR

UCs come from the electrochemical capacitor family, generally called double-layer capacitors (DLC). Although they have a high power density (up to 10kW/kg), their energy density is quite low (l0Wh/kg). It can be easily used in cold climates due to its ability to give high power at low temperatures. They are especially ideal for start-stop applications because they have a long life span. UCs are a good source of alternative energy for the automotive industry with their high charge and discharge capacities, low internal resistance, and long service life. Figure 2.8 shows the collector, electrode, and separator structure that creates UCs.

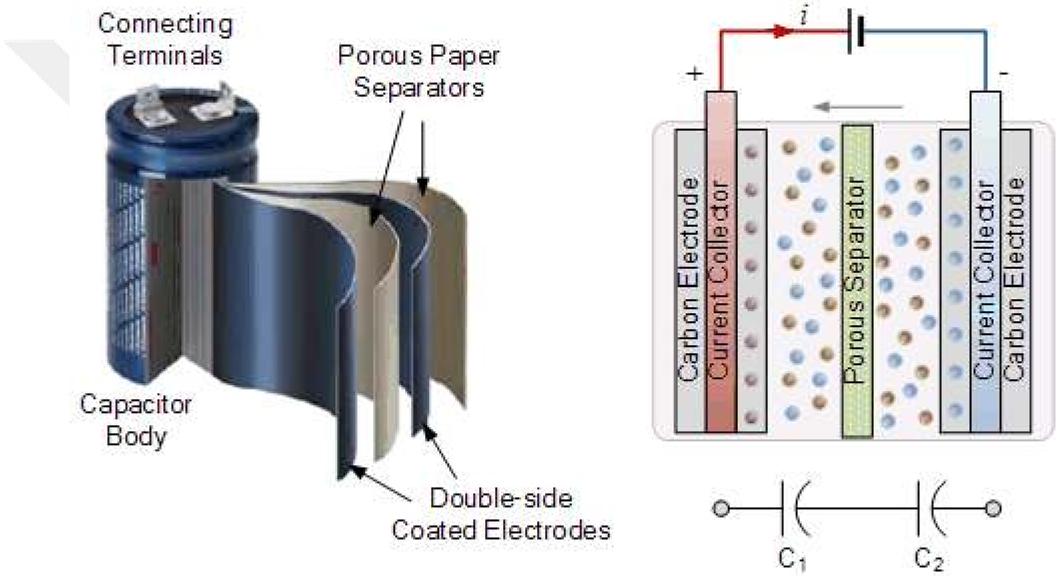


Figure 2.8. Construction of an UC [71].

Nowadays, most UCs include activated carbon electrodes obtained from the coconut shell. In addition, there are studies for the development of UCs with higher-capacity ceramic electrodes. As with batteries, the electrodes are separated from each other by a separator and the electrolyte is impregnated with liquid.

UCs are devices that store energy by the decomposition of positive and negative electrostatic loads. It consists of two-conductor plates (electrodes) and separating them and an insulator (separator). In UCs, the space between the plates is filled with an electrolyte consisting of solid polymer. Electrostatic charges are stored in the electrolyte in the form of ions. Therefore, chemical reactions do not occur as in batteries, only ionization occurs on electrode surfaces. Electrodes are made of perforated material with a very high surface area. The amount of stored load depends on the surface area of the plates and the distance between them. For high capacity, the surface area should be large and the gap between the plates should be small. The power density of UCs is nearly 15 times that of lithium-ion batteries and their internal resistance is much smaller than those of batteries. Charge and discharge times are much faster than batteries. The coulomb and peukert effect, which is effective during the charge and discharge of batteries, do not apply to UCs. Charge and discharge currents are very high (around 1kA). In addition to these advantages of UCs, there are considerations in use. For example, ultracapacitors should not be allowed to be completely discharged, since it becomes quite difficult to draw current from the UCs, as the ultracapacitor voltage approaches zero. Many definitions applicable to batteries also apply to UCs. To achieve the desired operating voltage, energy, and power density, ultracapacitors can also be connected in series and parallel as modules. Today, UCs consist of cells with capacitance up to 10kF and can operate in a voltage range of 2.5V-3V.

2.3. BATTERY

Batteries are tools that transform chemical energy into electricity. The batteries contain cells, and the cells are also made up of positive and negative electrolyte anodes. Direct current (DC) electricity is produced as a result of the chemical reaction between electrolytes and electrodes [72]. The battery is an electrochemical cell that converts chemical energy into electrical energy and it is separated by an electrolyte and consists of an anode and a cathode. Electrons are produced at the anode and flow through the external circuit towards the cathode [73], [74].

Batteries used in fuel cell vehicles have higher specific energy than an UC, so they can provide extra power for a longer time. Typically, today's commercially available UCs have only a tenth of the energy of a battery in comparable weight. However, UCs provide much faster energy than a battery and have also quickly gained a place in the market by battery manufacturers [75], [23].

Batteries used in electric vehicles are required to have a long life, high specific power, high specific energy, and long cycle life. Along with the developing technology, battery technologies with different energy densities are currently being used and are still being developed.

Table 2.3. Comparison of batteries [76], [77].

	$LiFePO_4$	Pb-Acid	NiMH	LiPo	Li-S	Li-ion	NiCd
Nominal voltage (V)	3,2	2	1,2	3,7	2,5	3,6	1,2
Energy Density (Wh/kg)	120	35	70-95	130-225	350-650	118-250	50-80
Volumetric Energy Density (Wh/L)	220	100	180-220	200-250	350	200-400	300
Operating Temperature (C°)	-45, +70	-15, +50	-20, +60	-20, +60	-60, +60	-20, +60	-20, +50
Life cycle	>2000	1000	<3000	>1200	300	2000	2000
Memory effect	No	No	Rarely	No	No	No	Yes
Specific Power (kW/kg)	2-4,5	0,18	0,2-0,3	0,26-0,45	-	0,2-0,43	0,2
Self discharge (% per month)	< 5	< 5	< 20	< 5	8-15	< 5	< 10
Production cost ($/kWh)	350	60	200-250	150	100-150	150	250-300

2.3.1. Lithium Iron Phosphate ($LiFePO_4$) Type Battery

Lithium iron phosphate batteries are another type of battery with a high energy density. In addition, their high cycle rate also allows them to be preferred. Reliable operation can also be seen as another advantage for these batteries. But compared to lithium-ion batteries, they seem to have lower performance [76].

2.3.2. Lead-acid (Pb-Acid) Type Battery

They are the oldest-tech batteries. The negatively charged electrode has lead, the positively charged electrode has lead dioxide (PbO_2), and an electrical insulation layer. In addition, sulfuric acid (H_2SO_4) materials are used as electrolytes. These active substances form a large surface area for the storage of energy. Micro-pored separators allow the chemical reaction to occur in there, preventing the electrodes from short-circuiting. Lead-acid batteries have significant advantages due to their high performance in situations where they do not require maintenance, their cost is low, their energy density is high and the temperature difference is variable (at high and low temperatures). Disadvantages are; excessive floor coverings, heavy and bulky, short-term service life, and self-discharge.

2.3.3. Nickel metal hydrate (NiMH) Type Battery

This battery technology was developed as an alternative to nickel-cadmium battery technology by using metal hydrate instead of cadmium electrodes. However, although nickel Metal hydrate battery technology has a high energy density, it does not receive much attention due to developing new technologies. Nickel metal hydrate batteries are projected to have 30–40% more capacity than Nickel-cadmium batteries, as well as an energy density much higher than these values. It is less prone to memory effects than nickel-cadmium batteries and needs fewer periodic discharge cycles. It contains a small amount of toxic substances. Also, the recycling of these batteries is easy [77].

2.3.4. Lithium-Ion Polymer (LiPo) Type Battery

It has the same characteristics as lithium-ion batteries in general. In addition, the polymer material is used in the electrolyte part.

2.3.5. Lithium-Sulfur (Li-S) Type Battery

It is a type of battery that uses sulfur as a cathode material from lithium-based battery groups. They have a high-energy density, high charging efficiency, low cell voltage, and average cycle life [76].

2.3.6. Lithium-Ion (Li-ion) Type Battery

Lithium-ion batteries are one of the types of batteries commonly used in technological devices due to their high energy storage capacity and efficiency. It is also frequently used in distribution systems and the automotive industry. The technical structure is; the minus pole of the battery is made of lithium metal oxide, and the plus pole is made of a graphical carbon layer. Electrodes containing lithium salt are solved by organic carbonates. As the battery is charged, the lithium atoms in the cathode ionize and merge with the electrons, then the carbons, where they are stored between the carbon layers as lithium atoms, move along the electrolyte in the direction of the anode. This process moves/moves in reverse during discharge. Charge and discharge times in Li-ion batteries are very short durations compared to PB-acid, NiMH batteries. In addition, to get the same amount of energy, NiMH requires 40% less space than batteries. The advantages of this type of battery are that it is a closed-cell and does not require maintenance, long-term service life, quick charging ability, high energy density, portable, durability and can work in a wide temperature range. The disadvantages can be called high installation costs, degradation at high temperatures, the need for protective circuits, and the danger of overcharging overcapacity [78]. It is the most widely used battery group in developed electric vehicles. As a result, Li-ion batteries are capable of storing three times more energy per unit volume and weight than conventional Pb-acid, NiMH batteries. With their high energy properties, Li-ion batteries are widely used in applications requiring high torque, such as aerospace electric vehicles and hybrid electric vehicles. The self-discharge rate is about 5% in Li-ion batteries and 20% in conventional batteries [79].

Figure 2.9. Lithium-ion battery [80].

2.3.7. Nickel Cadmium (NiCd) Type Battery

Nickel-cadmium batteries are not very common in use and are approximately less than 80% efficient. It is not widely used because it is coated with cadmium metal, a toxic and heavy metal. These batteries have used two-third of the world's cadmium reserves in the last three decades. This type of battery must be fully discharged at certain intervals. Otherwise, crystallization occurs on the plates. This is also called the memory effect, as a result of which the efficiency of the battery begins to decrease over time. In this case, the efficiency of the battery decreases significantly. These batteries are generally used in lighting, solar power stations, spacecraft, and telecommunications systems [81].

2.4. MODELS

2.4.1. Fuel Cell Model

Despite many FC technologies for utilization in vehicle systems are accessible for scientists and developers, proton exchange membrane FC (PEMFC) [82], [83], [84], [85], [53], [86] is the primary choice since PEMFC has a greater power density and less working temperature than other varieties of FC systems. Because of FC systems are huge, costly, precise it is needed to overcome problems with the design and construction of new models. The practical choice is therefore to correctly design and simulate the system [84]. There are lots of fuel cell parameters shown in the below table.

Table 2.4. Parameters of fuel cell model [87].

B,C	constants to simulate the activation overvoltage in the PEMFC system $[A^{-1}]$ and [V]	$q_{H_2}^{req}$	amount of hydrogen flow required to meet load change $[kmol(s)^{-1}]$
K_{H_2}	hydrogen valve molar constant $[kmol(atms)^{-1}]$	K_{H_2O}	Water valve molar constant $[kmol(atms)^{-1}]$
K_{O_2}	oxygen valve molar constant $[kmol(atms)^{-1}]$	R	universal gas constant $[(1\ atm)(kmolK)^{-1}]$
q_{o_2}	input molar flow of hydrogen $[kmol\ (s)^{-1}]$	M_{H_2}	molar mass of hydrogen $[kmol\ (s)^{-1}]$
$q_{H_2}^{r}$	hydrogen flow that reacts $[kmol(s)^{-1}]$	V_{cell}	dc output voltage of FC system [V]
N_0	Number of fuel cells in stack	E	Nernst instantaneous voltage [V]
E_0	standard no load voltage [V]	F	Faraday's constant $[C\ kmol\ (s)^{-1}]$
I_{FC}	FC system current [A]	K_{an}	anode valve constant $(\sqrt{kmolkg}(atms)^{-1})$
K_{H_2O}	Water valve molar constant $[kmol(atms)^{-1}]$	K_r	modeling constant $[kmol(sA)^{-1}]$
M_{H_2}	molar mass of hydrogen $[kg(kmol)^{-1}]$	P_{H_2}	hydrogen partial pressure [atm]
p_{H_2O}	water partial pressure [atm]	p_{O_2}	oxygen partial pressure [atm]
$q_{H_2}^{out}$	hydrogen output flow $[kmol(s)^{-1}]$	$q_{H_2}^{in}$	hydrogen input flow $[kmol(s)^{-1}]$
R^{int}	FC internal resistance [Ω]	T	absolute temperature [K]
U	utilization rate	V	volume of anode $[m^3]$
${}^{\tau}H_2$	hydrogen time constant [s]	τ_{O_2}	oxygen time constant [s]
τ_{H_2O}	water time constant [s]	η_{act}	activation overvoltage [V]
η_{ohmic}	ohmic overvoltage [V]		

An equation may be stated as below among the molar flow of any gas (hydrogen) via the valve and its partial pressure within the channel.

$$\frac{q_{H_2}}{p_{H_2}} = \frac{K_{an}}{\sqrt{M_{H_2}}} = K_{H_2} \tag{2.4}$$

There are three important elements for hydrogen molar flow: the inlet and outlet flow of hydrogen and hydrogen flow in the reaction [88]. These variables might depict the connection as;

$$\frac{\mathrm{d}}{\mathrm{d}t} p_{\mathrm{H_2}} = \frac{RT}{V_{\mathrm{an}}} \left(q_{\mathrm{H_2}}^{\mathrm{in}} - q_{\mathrm{H_2}}^{\mathrm{out}} - q_{\mathrm{H_2}}^{\mathrm{r}} \right) \tag{2.5}$$

The flowing rates of reacted hydrogen are shown by [88], based on the basic electrochemical relation among the hydrogen flow and the FC system current.

$$q_{\mathrm{H_2}}^{\mathrm{r}} = \frac{N_0 I_{\mathrm{FC}}}{2F} = 2K_{\mathrm{r}} I_{\mathrm{FC}} \tag{2.6}$$

The hydrogen partial pressure may be derived in the s main using equations (2.2) and (2.4) and the Laplace's Transform [88].

$$p_{\mathrm{H_2}} = \frac{1/K_{\mathrm{H_2}}}{1 + \tau_{\mathrm{H_2}} s} \left(q_{\mathrm{H_2}}^{\mathrm{in}} - 2K_{\mathrm{r}} I_{\mathrm{FC}} \right) \tag{2.7}$$

$$q_{\mathrm{H_2}}^{\mathrm{r}} = \frac{N_0 I_{\mathrm{FC}}}{2F} = 2K_{\mathrm{r}} I_{\mathrm{FC}} \tag{2.8}$$

$$\tau_{\mathrm{H_2}} = \frac{V_{\mathrm{an}}}{K_{\mathrm{H_2}} RT} \tag{2.9}$$

Likewise, the oxygen and water partial pressures may be generated using partial pressure and the oxygen pressure. The pemfc polarization curve is derived by means of Nernst voltage, activation, and ohmic overvoltages respectively. The output voltage of the FC may be stated as [89], [90], [91] provided that the temperature and the oxygen content are constant. With combining activation and ohmic overvoltages given below equations;

$$V_{\mathrm{cell}} = E + \eta_{\mathrm{act}} + \eta_{\mathrm{ohmic}} \tag{2.10}$$

$$\eta_{\mathrm{act}} = -B \ln \left(C I_{\mathrm{FC}} \right) \tag{2.11}$$

$$\eta_{\mathrm{ohmic}} = -R^{\mathrm{int}} I_{\mathrm{FC}} \tag{2.12}$$

the instant voltage of the Nernst can be stated below [93];

$$E = N_0 \left[E_0 + \frac{RT}{2F} \log \left[\frac{p_{\mathrm{H_2}} \sqrt{P_{\mathrm{O_2}}}}{p_{\mathrm{H_2O}}} \right] \right] \tag{2.13}$$

Depending on the power requirement, the system of cell uses hydrogen. The hydrogen is supplied for stacking by use of a highly pressurized hydrogen container. In working circumstances, a feedback control method is used to manage the hydrogen flow rate depending to the FC output. The FC current from the output is transported back to the input while the hydrogen is transformed into a molar form to perform this feedback management [89], [90], [91], [92]. So below equation is provided for the amount of hydrogen accessible from the hydrogen storage.

$$q_{\mathrm{H}_2}^{\mathrm{req}} = \frac{N_0 I_{\mathrm{FC}}}{2FU} \tag{2.14}$$

UC bank is developed to supply the difference value among load demand and FC system's output power produced.

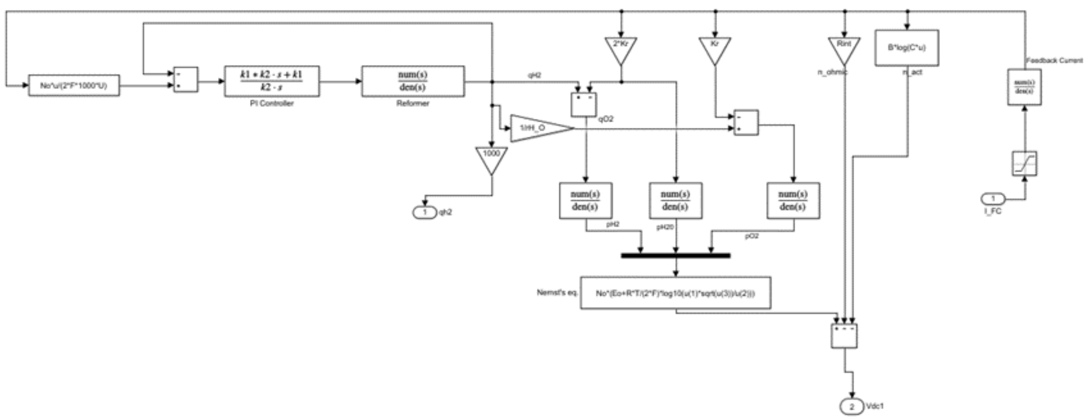


Figure 2.10. Simulink model of the FC.

2.4.2. Ultra-capacitor Model

A conventional UC unit's equivalent circuit is illustrated in Figure 2.9. Modeling a UC, capacitance (C), an equivalent series resistance (ESR, R) representing charging and discharging resistance, and an equivalent parallel resistance (EPR) indicating self-discharging losses build up the model [92], [93].

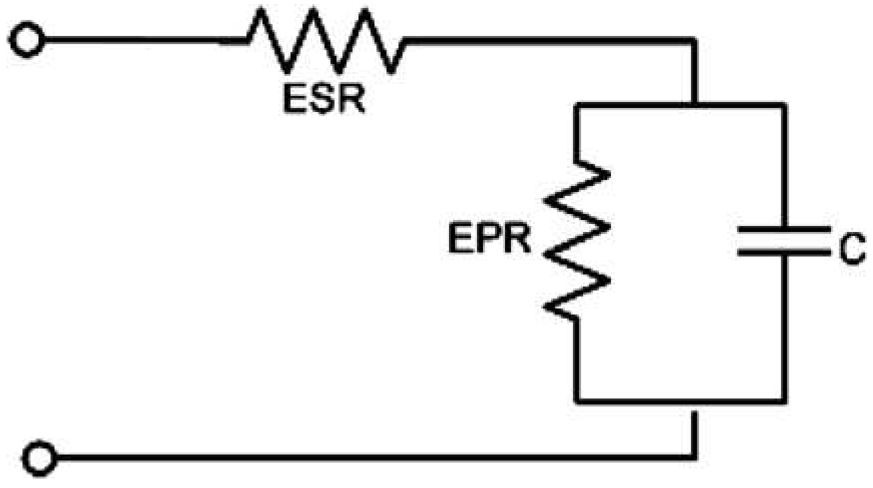


Figure 2.11. The conventional UC model [87].

Equations are given below belongs to UC:

$$v_{UC,oc}(t) = v_{UC,oc}(t_0) \tag{2.15}$$

$$-\frac{1}{C_{UC}}\int_{t_0}^{t}\left(i_{UC}(t)+\frac{v_{UC,oc}(t_0)}{R_{P,UC}}\right)dt \tag{2.16}$$

$$v_{UC}(t) = v_{UC,oc}(t) - R_{S,UC}i_{UC}(t) \tag{2.17}$$

The current value of UC is indicated by i_{UC} in equations (2.13)-(2.15). Furthermore, v_{UC} is UC's terminal voltage, whereas $v_{UC,oc}$ is UC open-circuit voltage. ESR and parallel resistance of UC are denoted by $R_{S,UC}$ and $R_{P,UC}$.

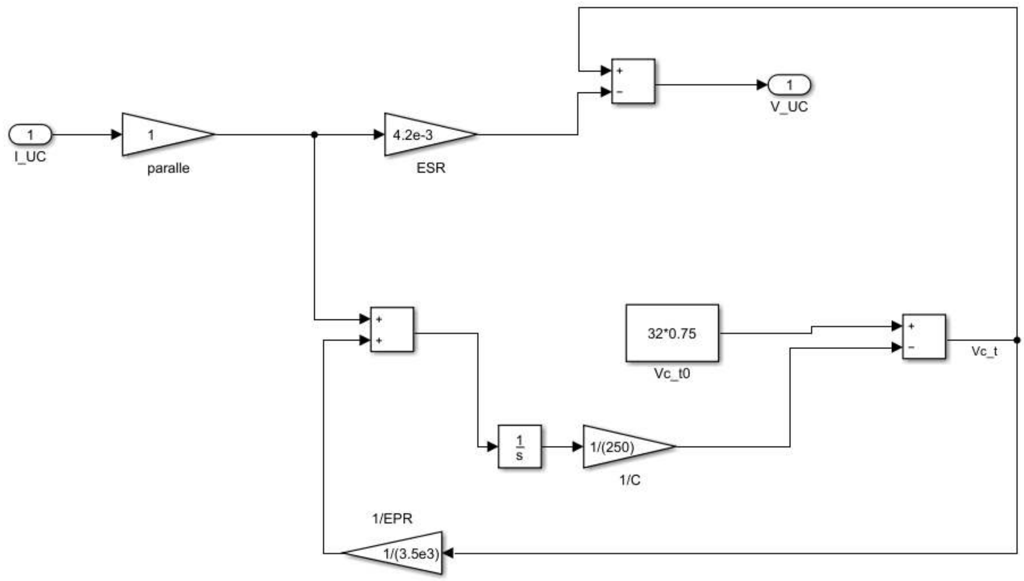


Figure 2.12. Simulink model of the UC.

2.4.3. Battery Model

The literature mainly includes three kinds of battery technologies: electric circuit-based, experimental, electro-chemical. For state-of-charge (SOC) calculations of battery packs, experimental and electrochemical models are not well adapted to reflect cell dynamics. Electric circuit-based models, on the other hand, might help express battery electrical properties. The simplest basic electric model is composed of an ideal voltage source connected in series with an internal resistance [94]. Unfortunately, this model fails to consider the SOC battery. Shepherd has constructed a formula to explain a battery's electrochemical properties, which is applied for both discharge and charge, directly in point of terminal voltage, open-circuit voltage, internal resistance, discharge current, and state of charge [95]. Non-Linear Shepherd model is shown below figure with equations.

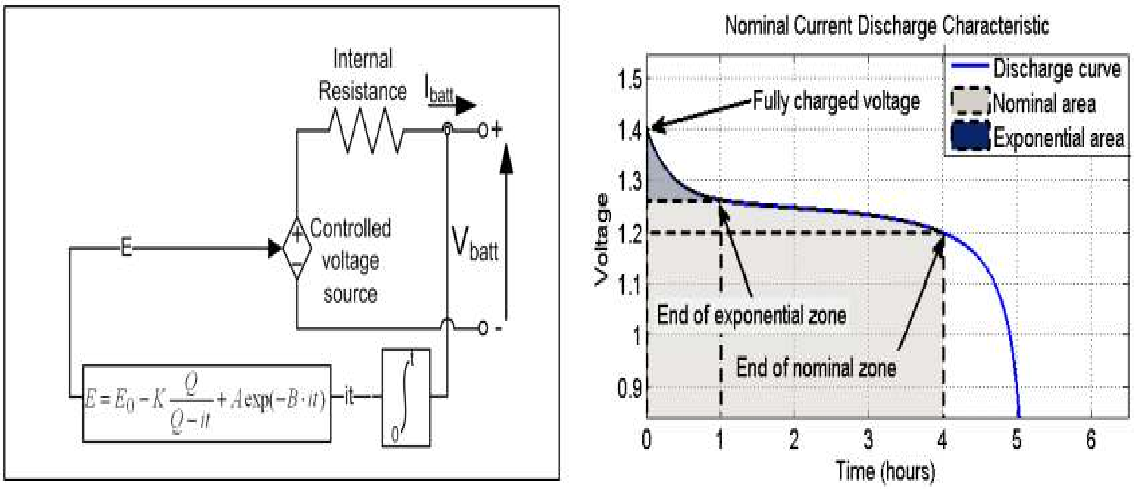


Figure 2.13. Non-linear model of battery and discharge curve [96].

$$E = E_0 - K \cdot \frac{Q}{Q - i_k \cdot T} + A \cdot e^{-B \cdot i_k \cdot T} \tag{2.18}$$

$$V_{\text{batt}} = E - R \cdot i \tag{2.19}$$

Table 2.5. Parameters of battery model [95].

E = no-load voltage (V)	E_0 = battery constant voltage (V)
K = polarisation voltage (V)	Q = battery capacity (Ah)
∫idt = actual battery charge (Ah)	A = exponential zone amplitude (V)
B= exponential zone time constant inverse $(Ah)^{-1}$	V_{batt} = battery voltage (V)
R = internal resistance (Ω)	i = battery current (A)

But also there are some assumptions and limitations in Shepherd's model. Internal resistance is highly crucial to ensure the voltage drop due to current fluctuations in the battery is correctly represented. An algebraic relationship between the model's internal resistance and the nominal voltage and the rated capability of the battery is consequently presented. Internal resistance impacts battery output voltage, hence efficiency.

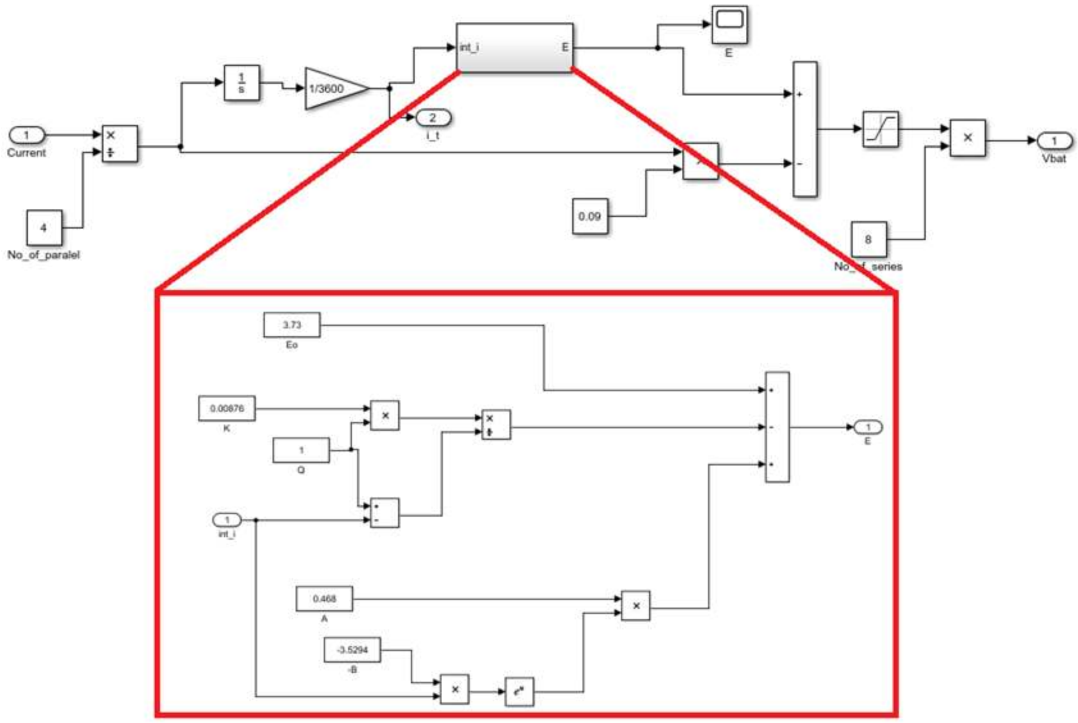


Figure 2.14. Simulink model of battery.

3. ANALYSIS OF PROPOSED CONVERTER

The proposed three-input MPMIC is given in Figure 3.1. As can be seen, each input is connected to a pair of switch-diode-inductor groups while these groups are connected to a switch pair. Therefore, the proposed structure is a two-phase MIC consisted of 8 switches, 6 diodes, 6 separate inductors, and a capacitor. Since FC and battery inputs are unidirectional, 2 diodes are attached to these inputs. The proposed system has three operation modes. In Mode-1, the output is powered through all input sources. In this mode, the input switches (S_{1A}, S_{1B}, S_{2A}, S_{2B}, S_{3A}, S_{3B}) and the low-side output switch S_4 are controlled via pulse-width-modulation (PWM). The duty cycles of $S_{1A,B}$, $S_{2A,B}$, $S_{3A,B}$, and S_4 are denoted by d_1, d_2, d_3, d_4, respectively. Please note that there are 180° between gate signals of input switches for interleaving operation and the switching frequency of the output switch is twice of one of the input switches for obtaining the same effective switching frequency. Furthermore, UC is charged by FC and battery in Mode-2 in which the charging energy is transferred through L_{3A}, L_{3B}, and the body diodes of S_{3A} and S_{3B}. Finally, UC is charged by the regenerative energy flowing from the output in Mode-3. In this mode, only S_5 is controlled with PWM; therefore the converter operates like a traditional buck converter in this case. Here, the duty cycle of S_5 is d_5.

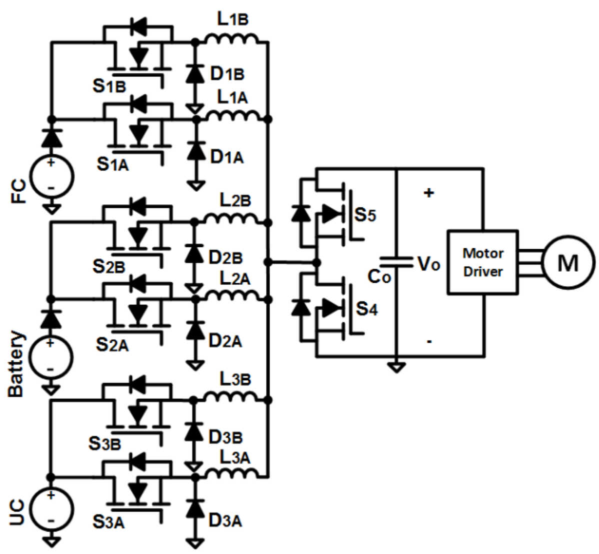


Figure 3.1. The proposed FC/battery/UC hybrid system with the MPMIC.

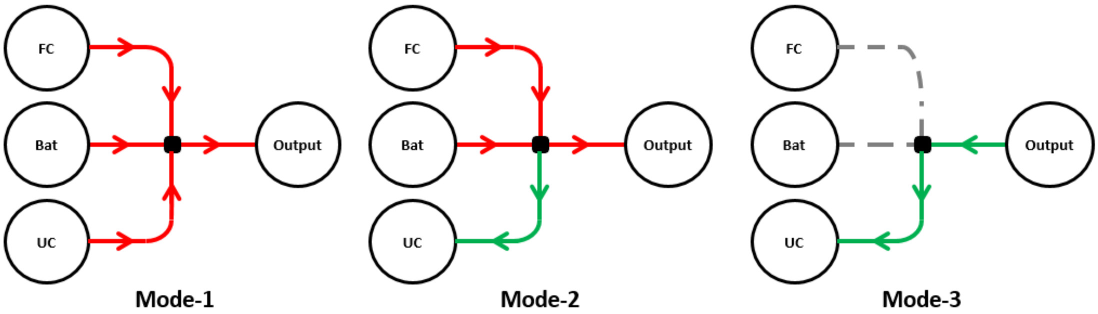


Figure 3.2. Operation modes.

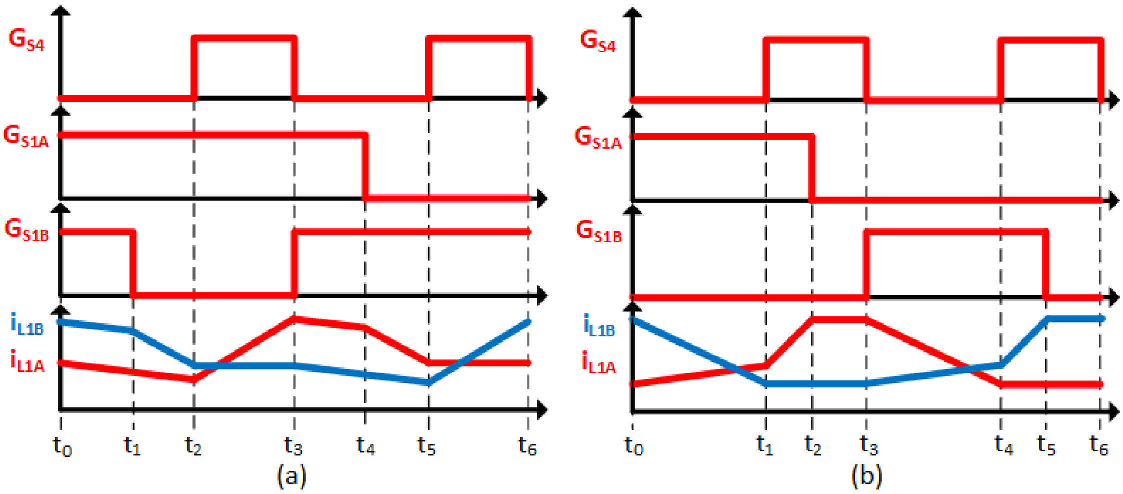


Figure 3.3. Waveforms for Case-1 in the motoring mode a) boost mode, b) buck mode.

3.1. ANALYSIS OF MODE-1

In this mode, FC, battery, and UC discharge to feed the output. The proposed converter has the ability to operate in buck and boost modes according to the determined duty cycles. Since each input energy is controlled independently, the converter can be considered three separate converters connected in parallel to a common output. Therefore, the analysis can be realized for a single input then it can be extended for three-input. Accordingly, typical waveforms for the boost mode can be seen in Figure 3.3 (a) where there are 6 different stages to examine.

Stage 1 [t_0-t_1]: In this mode, S_{1A} and S_{1B} are on while S_4 is off. Moreover, D_{1A} and D_{1B} are off while the body diode of S_5 is on. Therefore, both L_{1A} and L_{1B} currents decrease since their voltages are equal to v_{FC}-v_o.

Stage 2 [t_1-t_2]: Turning off S_{1B} starts this period. D_{1B} starts to conduct therefore the voltage on L_{1B} becomes $-V_o$. As a result, L_{1B} current slope becomes more negative.

Stage 3 [t_2-t_3]: In this period, S_4 is turned on while S_{1A} and S_{1B} keep their previous states. L_{1A} starts to be charged by the input source while L_{1B} experiences the freewheeling mode. Therefore, the voltage of L_{1A} is equal to V_{FC} while the voltage of L_{1B} is equal to zero.

Stage 4 [t_3-t_4]: This mode is equivalent to Stage-1.

Stage 5 [t_4-t_5]: This mode is initiated by turning off S_{1A} while S_{1B} is on and S_4 is off. D_{1A} conducts; therefore the voltage of L_{1A} becomes equal to $-V_o$. As a result, the slope of L_{1A} current becomes more negative.

Stage 6 [t_5-t_6]: In the final stage, S_{1A} is off, S_{1B} in on and S_4 is on. Therefore, the current of L_{1A} is in freewheeling mode thus its voltage is zero. Moreover, L_{1B} starts to be charged by the FC. L_{1B} voltage is equal to V_1.

By considering other inputs and applying the volt-second-balance (VSB) principle to L_{1A} and L_{1B} voltages, the following equation can be written.

$$V_o(1 - d_4) = V_{FC}d_1 = V_{bat}d_2 = V_{UC}d_3 \quad (3.1)$$

Additionally, the output capacitor C_o current is equal to the negative output current (I_o) when S_4 is on while it is equal to the difference between the sum of inductor voltages and output current. Therefore, based on the amp-second-balance (ASB) principle, the relationship between average inductor currents (I_{L1}, I_{L2}, I_{L3}) and the output current can be obtained as in (3.2).

$$I_o = 2(I_{L1} + I_{L2} + I_{L3})(1 - d_4) \quad (3.2)$$

Additionally, typical waveforms for the buck mode are given in Figure 3.3 (b). By analyzing six stages in this mode, one can derive the same equations with the ones given in (3.1) and (3.2). From (3.1), it can be seen that the converter operates in boost mode when $1-d_4$ is lower than the duty cycle of input switches, otherwise, it operates in buck mode.

3.2. ANALYSIS OF MODE-2

In this case, UC is charged by FC and battery thus L3A and L3B carry the UC charging current. By comparing this case and Case-1, the relationship between voltages, in this case, can be written as in (3.3).

$$V_o(1 - d_4) = V_{FC}d_1 = V_{bat}d_2 = V_{UC} \quad (3.3)$$

Moreover, the current equation in this stage is the same with the one given in (3.2). Please note that I_{L3} is negative here.

3.3. ANALYSIS OF MODE-3

As declared, UC is charged by the regenerative braking energy in this mode by controlling S_5. The studied converter operates as a traditional buck converter; therefore the well-known voltage and current equations in (3.4) and (3.5) can be written for this mode.

$$V_o d_5 = V_{UC} \quad (3.4)$$

$$I_o = 2I_{L3}d_5 \quad (3.5)$$

4. FLC BASED EMS

The details of FLC-based EMS are illustrated in Figure 4.1. As can be seen, first of all, an FLC produces a reference power (P_{ref}) according to levels of output power (P_o) and SOC of UC (SOC_{UC}). Then, the reference of FC power (P_{FC-ref}) is determined by filtering P_{ref} through a low-pass filter (LPF) whose time constant is 5s. Then, the reference of battery power is obtained by filtering the difference between P_{ref} and P_{FC-ref} through another LPF whose time constant is 2s. By this way, it is aimed to smooth FC and battery power levels. Figure 4.1 also shows the developed control strategy. In Mode-1 and Mode-2, d_1 and d_2 are determined by two separate proportional-integral (PI) controllers so as to regulate FC and battery power levels according to designated references by the proposed EMS. In Mode-1, another PI controller adjusts d_3 for the output voltage regulation so as to discharge UC accordingly. Moreover, d_4 is obtained based on the following equation which basically sets d_4 to the possible lowest value for maximizing the efficiency [86].

$$d_{4-opt} = 1 - \frac{min\,(v_{FC}, v_{bat}, v_{UC})}{v_{out}}\beta \tag{4.1}$$

In (4.1), β is the adjustment coefficient that is introduced to consider the voltage drops due to inductor resistances.

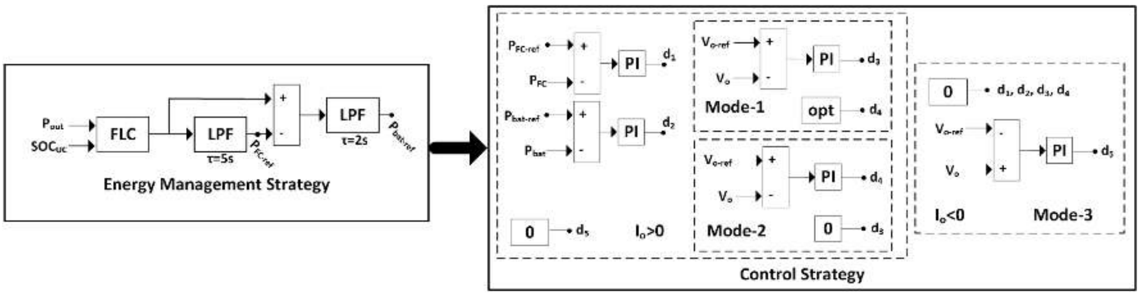
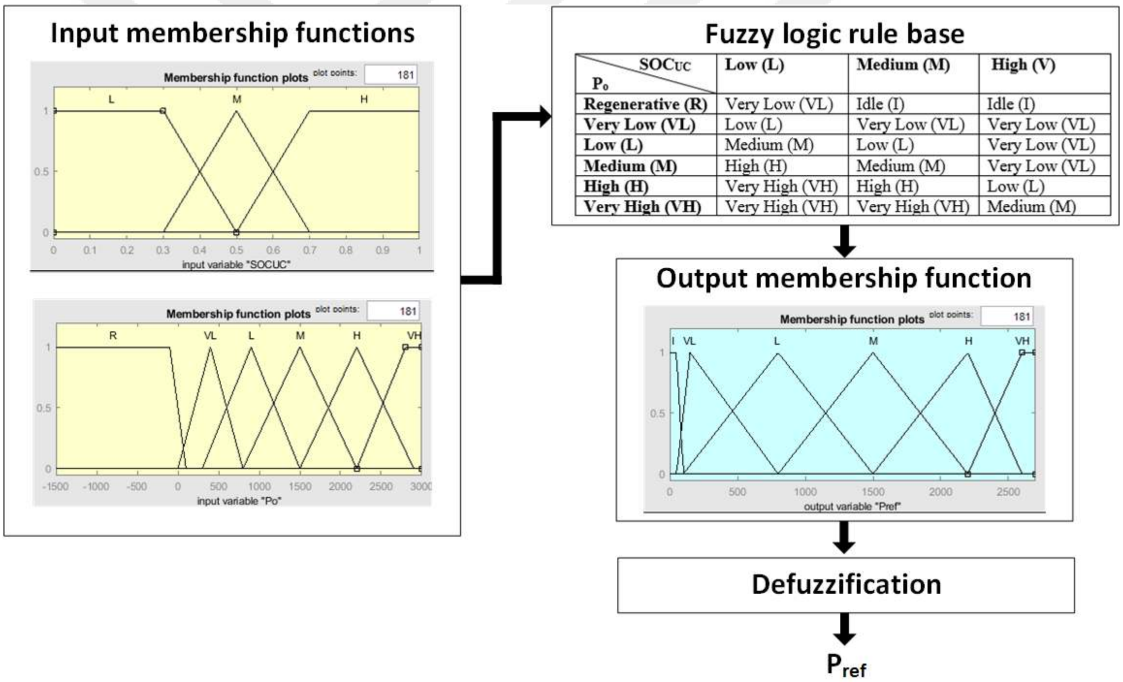


Figure 4.1. The FLC-based EMS and the control strategy.

In Mode-2, another PI controller designates d_4 for transferring excessive energy to UC thus realizing output voltage regulation. Moreover, d_5 is controlled in Mode-3 for charging UC through regenerative braking energy. In this mode, a positive feedback of the output voltage is utilized for the voltage regulation.

The design procedure of FLC is conducted in Matlab by using the Fuzzy toolbox. In Figure 4.2, the details of the developed FLC are demonstrated. As seen, there are two input membership functions: SOC_{UC} and P_o. For SOC_{UC}, three input membership functions are designed: low (L), medium (M), high (H). Besides, 6 input membership functions are designed for P_o: regenerative (R), very low (VL), low (L), medium (M), high (H), very high (VH). The output membership function, P_{ref}, has 6 output membership functions, namely, idle (I), very low (VL), low (L), medium (M), high (H), very high (VH). Figure 4.2 also shows the determined rule base. Finally, the decision surface is formed as in Figure 4.3 based on the membership functions and rule base. According to this figure, the maximum P_{ref} is 2500W which is equal to the maximum allowable power provided by FC and battery. Moreover, when SOC_{UC} increases, P_{ref} decreases, and vice versa, for regulating SOC_{UC}.



P_o \ SOC_{UC}	Low (L)	Medium (M)	High (V)
Regenerative (R)	Very Low (VL)	Idle (I)	Idle (I)
Very Low (VL)	Low (L)	Very Low (VL)	Very Low (VL)
Low (L)	Medium (M)	Low (L)	Very Low (VL)
Medium (M)	High (H)	Medium (M)	Very Low (VL)
High (H)	Very High (VH)	High (H)	Low (L)
Very High (VH)	Very High (VH)	Very High (VH)	Medium (M)

Figure 4.2. Details of fuzzy logic controller.

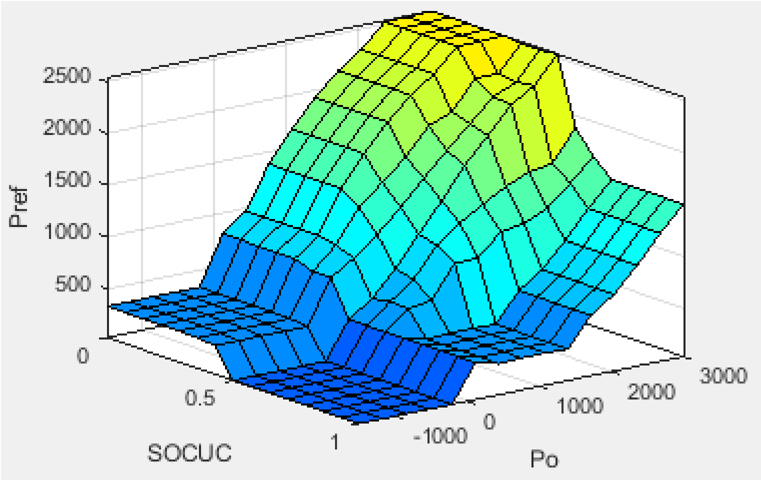


Figure 4.3. Decision surface of fuzzy logic controller.

5. TEST AND RESULTS

Table 5.1 Simulation study parameters.

Element	Power	Voltage range	Max. current	Other parameters
FC	1.2kW	20-36V	60A	Nexa 1200, PEM FC
Battery	1kW	16-32V	60A	8x9, 3.7V, 3Ah Li-ion
UC	2kW	0-32V	90A	2x BMOD0500 P016 500F
Output	3kW	48V±4.8V	62.5A	-

To test the proposed system, a simulation study is conducted in MATLAB/Simulink for considering the parameters in Table 5.1. In the simulation, a non-linear average model of the converter is built. For this task, the equations derived in the previous chapter are modified. By assuming perfect current sharing between phases and considering the inductor internal resistances which are assumed to be equal, (5.1) and (5.2) are written for Mode-1.

$$\begin{aligned} I_{FC} &= 2I_{L1} = \frac{1}{L_1}\int (V_o - V_{FC}d_1 - 2I_{L1}R_{L1})dt \\ I_{bat} &= 2I_{L2} = \frac{1}{L_2}\int (V_o - V_{bat}d_2 - 2I_{L2}R_{L2})dt \\ I_{UC} &= 2I_{L3} = \frac{1}{L_3}\int (V_o - V_{UC}d_3 - 2I_{L3}R_{L3})dt \\ V_o &= \frac{1}{C_o}\int ([I_{FC} + I_{bat} + I_{UC}][1 - d_4] - I_o)dt \end{aligned} \tag{5.1}$$

For Mode-2, only the equation related to I_{UC} changes as given in (5.2) while others are the same with the ones for Mode-1.

$$I_{UC} = 2I_{L3} = \frac{1}{L_3}\int (V_o - V_{FC} - 2I_{L3}R_{L3})dt \tag{5.2}$$

Similarly, the relationships given in (5.3) can be written for Mode-3.

$$I_{FC} = 2I_{L1} = 0 \tag{5.3}$$

$$I_{bat} = 2I_{L2} = 0$$

$$I_{UC} = 2I_{L3} = \frac{1}{L_3}\int (V_o d_5 - V_{UC} - 2I_{L3}R_{L3})dt$$

$$V_o = \frac{1}{C_o}\int (I_{UC}\, d_5 - I_o)dt$$

Here, a scaled power profile obtained according to Urban Dynamometer Driving Schedule (UDDS) is utilized. Two cases are considered in the simulation. In the first case, the initial SOC_{UC} is 0.55, while it is 0.75 in the second case. By this way, it is aimed to evaluate the performance of the proposed EMS in terms of SOC_{UC} regulation. Figures 5.1-5.3 show the simulation results.

In Figure 5.1, the output power and resultant source power variations are shown. As seen, the maximum output power is about 3kW while the maximum regenerative power is about 1kW according to the scaled UDDS power profile. Moreover, one can observe that the UC power profile exhibits sudden changes while FC and battery power profiles are smoothed as intended. When comparing the results retrieved for the considered two cases, it can be observed that FC and battery inject more power at the beginning of the simulation when the initial SOC_{UC} is set to 0.55 as an indication of charging of UC.

In Figure 5.2, the voltage levels of the output, FC, and battery along with SOC_{UC} variations are given. First of all, it is clear that the output voltage regulation is realized in two cases. Furthermore, the voltage drops due to the internal resistances of the FC and battery can be observed. The battery final voltage is slightly lower when the initial SOCUC is 0.55 since it transfers more power to charge UC in this case. When it comes to SOC_{UC} variations, it can be clearly seen that the developed EMS in coordination with the proposed MPMIC achieves SOC_{UC} regulation for the studied cases.

The variations for d_4 and its optimum values determined according to the (4.1) equation are demonstrated in Figure 5.3. At the beginning of the simulation, the optimum d_4 takes smaller values when the initial SOC_{UC} is 0.75 because of the higher UC voltages. After a while, the optimum d_4 values in the two cases coincide with each other by validating the achieved SOC_{UC} regulation.

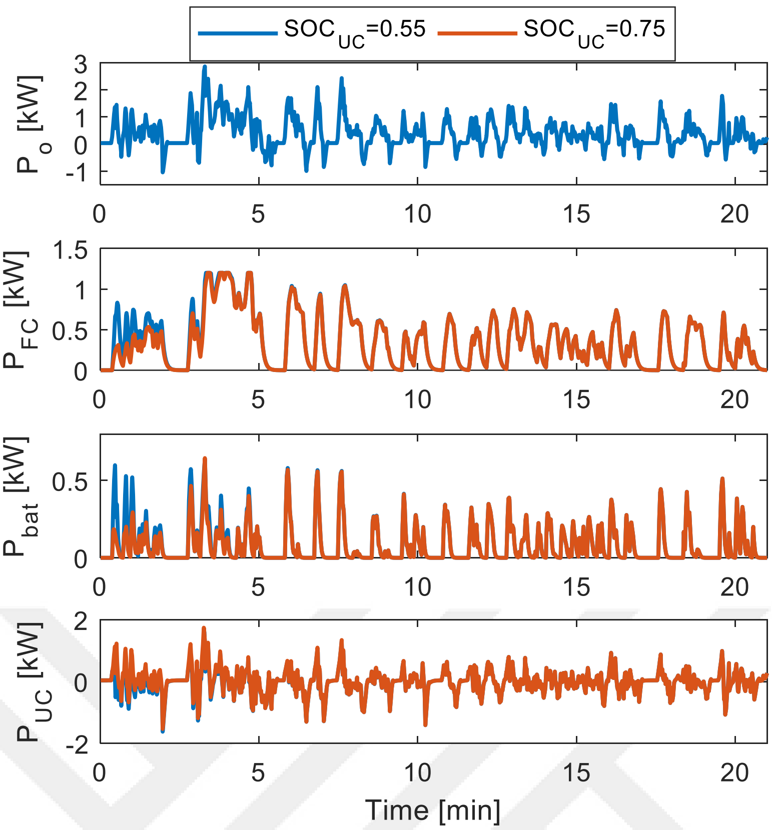


Figure 5.1. Simulation results: power variations.

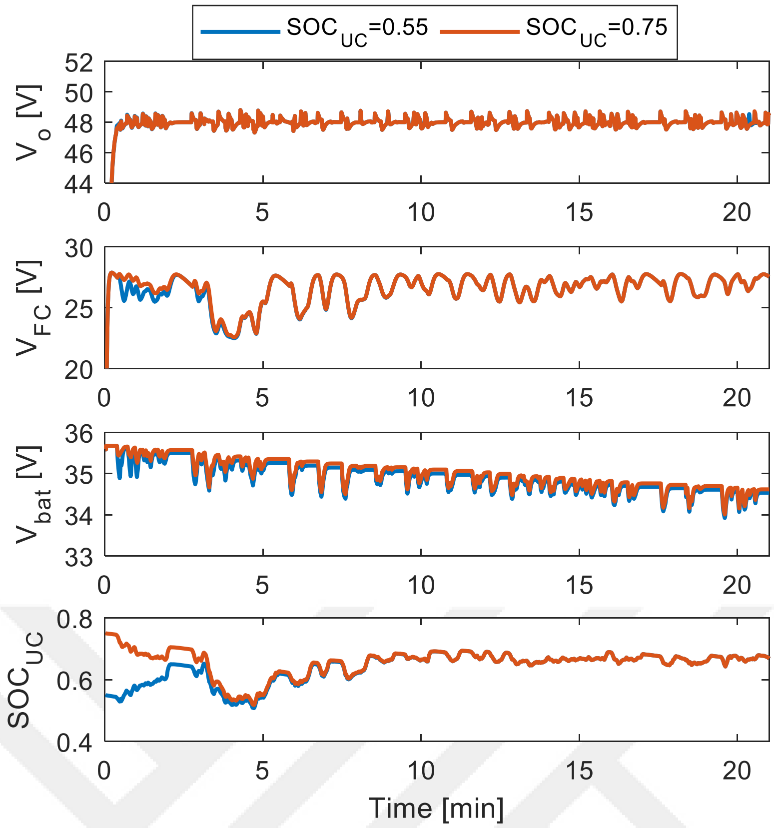


Figure 5.2. Simulation results: voltage and SOC_{UC} variations.

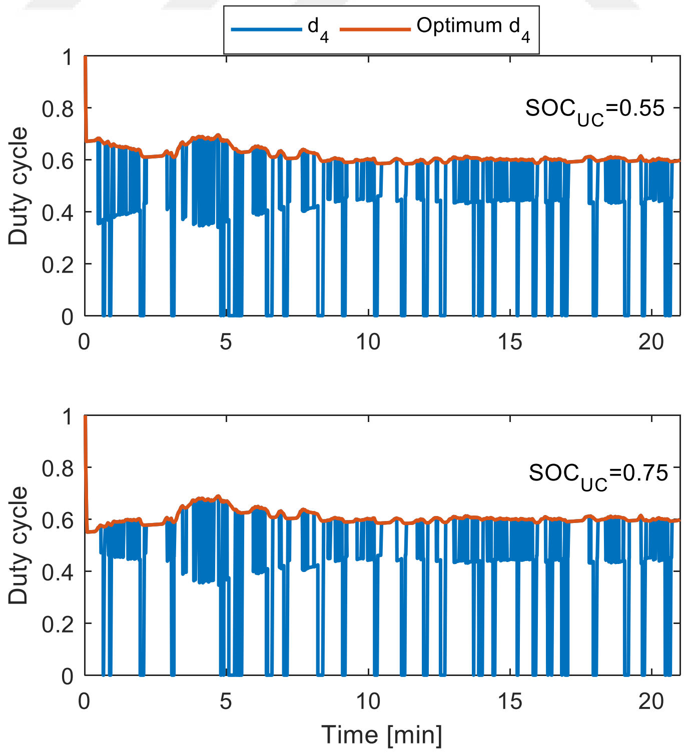


Figure 5.3. Simulation results: power variations.

Finally, the frequency distributions of power profiles in the case of 0.55 initial SOC_{UC} are shown in Figure 5.4. From this figure, one can easily observe that the FC power profile does not include high-frequency components. Additionally, although the battery power profile includes slightly higher frequency components in comparison with the one of FC as dictated by the selected time constants of LPFs, its DC component is dominant. Moreover, unlike others, the UC power profile involves high-frequency components. Therefore, it is validated that UC fulfills the duty of keeping FC and battery safe from the transient power variations.

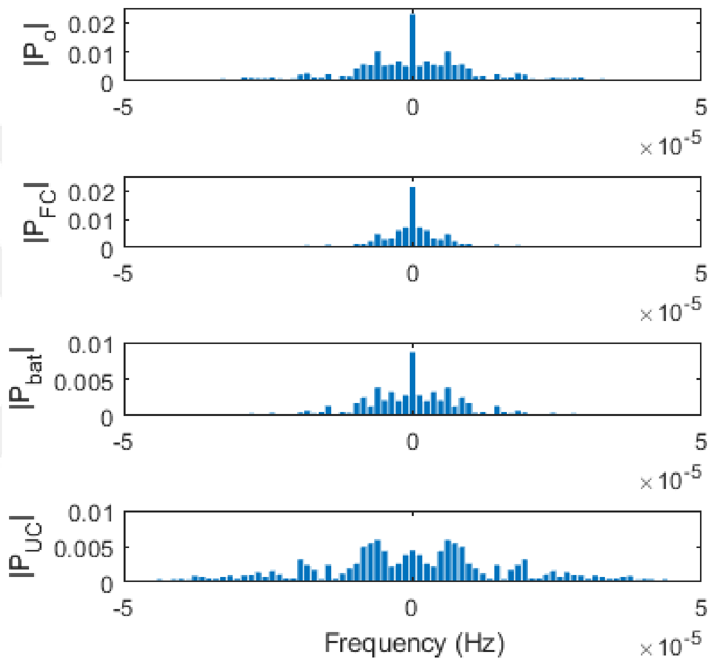


Figure 5.4. Simulation results: frequency distributions of power variations.

6. CONCLUSIONS AND RECOMMENDATIONS

The human is a social being. Transportation is of great importance in communicating people with and meeting their needs. With another statement, transportation is a basic need for people to maintain social and individual life. Therefore, many studies are carried out to have comfortable, fast, and economical transportation. Interest and need for alternative energy sources are growing due to environmental concerns and the fact that fossil fuels will run out in the future. In transportation, studies are rapidly continuing to develop high efficiency and low emission electric vehicles, rather than ICE vehicles powered by oil and derivative fuels that cause CO_2 emissions to the environment.

FCHEVs are promising candidates that can switch out ICE vehicles. Because of many advantages, FC/battery/UC HPS in these vehicles have been taken a great deal of attention. In the literature, these kinds of systems are usually formed via separate dc-dc converters. However, the literature clearly shows that MICs in HPSs help to maximize the power/energy density and efficiency.

Therefore, this thesis has proposed a FC/battery/UC HPS controlled by a single MIC. As a contribution, this converter has two phases to gather the benefits of MICs and MPCs. This converter has mainly three operation modes. In Mode-1, all source energies are transferred to the output. In Mode-2, FC and battery feed the output while charging UC. In Mode-3, the converter transfers the regenerative braking energy to UC. These modes have been analyzed in detail to build a non-linear average model of the converter.

Moreover, an FLC-based EMS has been developed in this thesis. This strategy goals not only to smooth FC and battery power profiles but also to regulate the SOC of UC. The details of the developed EMS including the design procedure of membership functions of FLC and LPFs have been given.

Finally, test results have been obtained from the simulation model of the system, consisting of the non-linear average model of MPMIC, models of the sources, and FLC-based EMS in MATLAB/Simulink. In the simulation, the UDDS power profile and two different initial SOC levels are considered for UC: 0.55 and 0.75. First of all, the simulation study has revealed that the proposed converter successfully creates such an

HPS: power levels of sources have been controlled as intended, the output voltage has been kept around its reference value, 48V. Moreover, it has been explored that the developed EMS achieves to regulate SOC of UC around 0.7 in both cases. In addition, both power variations and their frequency distributions have shown that FC and battery power profiles have been smoothed as aimed.

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8. APPENDICES

8.1. FC PARAMETERS

```
T=343;
F=96484600;
R=8314.47;
Eo=0.8;
Numb=36;
Kr=Numb/(4*F);
U=0.8;
KH2=4.22e-5;
KH2O=7.716e-6;
KO2=2.11e-5;
ToH2=3.37;
ToH2O=18.418;
ToO2=6.74;
To1=2;
To2=To1;
To3=To1;
CV=2;
B=0.04777;
C=0.0136;
Rint=0.00303*Numb;
rH_O=1.168;
k1=0.25;
k2=2;
```

9. CURRICULUM VITAE

PERSONEL INFORMATIONS

Name Surname : Aykut CAN

Foreign Language : English

EDUCATION BACKGROUND

Degree	Field	School/University	Year of Graduation
Master of Science	Electrical-Computer Eng.	Duzce University	2021
Under Graduate	Mechanical Eng.	Fırat University	2011
H. School	Science	Sakarya A. Highschool	2004

PUBLISHMENTS

Papers Presented at National Scientific Meetings and Published in Paper Books:

1. F. Akar, A. Can , “Fuzzy Logic Based Control of a Fuel Cell/Battery/Ultra-capacitor Hybrid Power System via a Multi-Phase Multi-Input Converter” *Düzce Üniversitesi Bilim ve Teknoloji Dergisi*, Yayın aşamasında, 2021.

WORK EXPERIENCES

Year	Corporation/Institute	Enrollment
2012-2012	ÇEPNI INŞAAT	Mech. Chief Eng.
2013-2014	ÇAMSAN ENTEGRE	Mech. Maintenance Eng.
2015-2017	ETİ BAKIR İŞLETMELERİ	Project Eng.
2017-2021	NATRASOFT SOFTWARE	System Eng.