UNIVERSITI PUTRA MALAYSIA

FUZZY-PI BASED HYBRID ENERGY STORAGE SYSTEM TOPOLOGY FOR ELECTRIC VEHICLES

ALI MOHSEN MOHSEN AL-SABARI

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ALI MOHSEN MOHSEN AL-SABARI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman : Associate Professor Ir. Ts. Mohd Khair bin Hassan, PhD
Faculty : Engineering

Nowadays, electric vehicles have inspired many researchers and manufacturers to use them as an alternative to fuel vehicles with zero carbon emissions, making them safer for the environment. However, there are significant technical barriers to widespread adoption of battery electric vehicles (BEVs), such as shorter driving ranges, longer charging times, and limited battery capacity and volume. Previous research has suggested using hybrid energy storage systems (HESS) such as supercapacitors, flywheels, and solar power as auxiliary power sources rather than batteries alone to extend battery life and driving range. As a HESS in electric vehicles, the supercapacitor and battery are used to complement each other in this thesis. Due to their high power density and lack of chemical reaction, supercapacitors can be used in BEVs to mitigate instantaneous power requirements. The modelling of battery, supercapacitor, and battery-supercapacitor models has been studied and developed using Matlab simulation with experimental validation data. The proposed energy management system (EMS) with the control strategy of the fuzzy-PI validated the proposed topology between battery-supercapacitor. This EMS with the proposed fuzzy rules enables the battery to supply average power and also enables the supercapacitor to supply high peak power to achieve the battery's current peak reduction in a short period of time. The different speed profile patterns in EVs differ from smooth driving to aggressive driving, so three different driving cycles are used in this thesis. These driving cycles are the urban dynamic driving cycle (UDDS), the New European Driving Cycle (NEDC) and the Supplemental Federal Test Procedure (US06). EV was tested in four different case scenarios with initial battery state of charge (SoC) conditions of 100, 80, 60, and 40 percent of battery capacity for each full driving cycle.

The results of the proposed topology and control strategy using HESS in comparison to BEV have been highlighted in terms of SoC, voltage, current, power, and battery energy consumption. This research improves the modelling process of a battery by estimating the remaining capacity inside the battery cell by using terminal voltage. The model has been validated against experimental data with a maximum relative error of 0.015V compared to 0.045V in previous work. In supercapacitor modeling, a novel method for parameter identification is proposed for comparison to the sophisticated methods in the literature. The terminal voltage was validated experimentally with a maximum relative error of 0.045 V, compared to a standard deviation of 0.19 V for a similar experimental test profile used in the literature. The proposed topology is validated against the full active topology in the literature. The results showed an improvement in the proposed topology of 55% in SoC compared to 30% in full active topology in the literature. The EMS (Fuzzy-PI) results showed that using HESS instead of BEV resulted in 82.6 percent increase in energy consumption. Also, the battery's current peak decreased by 81.8 percent using HESS compared to BEV.After benchmarking to eight prior studies using three different cycles (UDDS, NEDC, and US06), the greatest increase in energy consumption was 38.8%, compared to 17% in the literature. The proposed HESS reduces battery peak current by 45 A, compared to 59 A in previous work. The HESS has been proven to be useful in the near future for electric vehicles.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

TOPOLOGI SISTEM PENYIMPANAN TENAGA HIBRID BERASASKAN FUZZY-PI UNTUK KENDERAAN ELEKTRIK

Oleh

ALI MOHSEN MOHSEN AL-SABARI

Februari 2022

Pengerusi : Profesor Madya Ir. Ts. Mohd Khair bin Hassan, PhD
Fakulti : Kejuruteraan

Pada masa kini, kenderaan elektrik telah memberi inspirasi kepada ramai penyelidik dan pengilang untuk menggunakannya sebagai alternatif kepada kenderaan bahan api dengan pelepasan karbon sifar, menjadikannya lebih selamat untuk alam sekitar. Walau bagaimanapun, terdapat halangan teknikal yang ketara terhadap penggunaan meluas kenderaan elektrik bateri (BEV), seperti jarak pemanduan yang lebih pendek, masa pengecasan yang lebih lama dan kapasiti dan volum bateri yang terhad. Penyelidikan sebelum ini telah mencadangkan penggunaan sistem penyimpanan tenaga hibrid (HESS) seperti supercapacitors, roda tenaga, dan tenaga suria sebagai sumber kuasa tambahan dan bukannya bateri sahaja untuk memanjangkan hayat bateri dan jarak pemanduan. Sebagai HESS dalam kenderaan elektrik, supercapacitor dan bateri digunakan untuk saling melengkapi dalam tesis ini. Oleh kerana ketumpatan kuasa yang tinggi dan kekurangan tindak balas kimia, supercapacitors boleh digunakan dalam BEV untuk mengurangkan keperluan kuasa serta-merta. Pemodelan model bateri, supercapacitor, dan bateri-supercapacitor telah dikaji dan dibangunkan menggunakan simulasi Matlab dengan data pengesahan eksperimen. Sistem pengurusan tenaga (EMS) yang dicadangkan dengan strategi kawalan fuzzy-PI mengesahkan topologi yang dicadangkan antara bateri-supercapacitor. EMS ini dengan peraturan fuzzy yang dicadangkan membolehkan bateri membekalkan kuasa purata dan juga membolehkan supercapacitor membekalkan kuasa puncak yang tinggi untuk mencapai pengurangan puncak semasa bateri dalam tempoh yang singkat. Corak profil kelajuan berbeza dalam EV berbeza daripada pemanduan lancar kepada pemanduan agresif, jadi tiga kitaran pemanduan berbeza digunakan dalam tesis ini. Kitaran pemanduan ini ialah kitaran pemanduan dinamik bandar (UDDS), Kitaran Pemanduan Eropah Baharu (NEDC) dan Prosedur Ujian Persekutuan Tambahan (US06). EV telah diuji dalam empat senario kes yang berbeza dengan keadaan keadaan cas bateri (SoC) awal sebanyak 100, 80, 60 dan 40 peratus kapasiti bateri untuk setiap kitaran pemanduan penuh.

Keputusan topologi dan strategi kawalan yang dicadangkan menggunakan HESS berbanding BEV telah diserlahkan dari segi penggunaan tenaga SoC, voltan, arus, kuasa dan bateri. Penyelidikan ini menambah baik proses pemodelan bateri dengan menganggar baki kapasiti di dalam sel bateri dengan menggunakan voltan terminal. Model ini telah disahkan terhadap data eksperimen dengan ralat relatif maksimum 0.015V berbanding 0.045V dalam kerja sebelumnya. Dalam pemodelan supercapacitor, kaedah baru untuk pengenalpastian parameter dicadangkan untuk perbandingan dengan kaedah canggih dalam literatur. Voltan terminal telah disahkan secara eksperimen dengan ralat relatif maksimum 0.045 V, berbanding sisihan piawai 0.19 V untuk profil ujian eksperimen serupa yang digunakan dalam kesusasteraan. Topologi yang dicadangkan disahkan terhadap topologi aktif penuh dalam literatur. Keputusan menunjukkan peningkatan sebanyak 55% berbanding 30% dalam topologi aktif penuh berbanding topologi aktif penuh yang digunakan dalam literatur. Keputusan menunjukkan bahawa menggunakan HESS dan bukannya BEV menghasilkan peningkatan 82.6 peratus dalam penggunaan tenaga. Selain itu, kemuncak semasa bateri menurun sebanyak 81.8 peratus menggunakan HESS berbanding BEV. Selepas menanda aras kepada lapan kajian terdahulu menggunakan tiga kitaran berbeza (UDDS, NEDC dan US06), peningkatan terbesar dalam penggunaan tenaga ialah 38.8%, berbanding 17% dalam kesusasteraan. HESS yang dicadangkan mengurangkan arus puncak bateri sebanyak 45 A, berbanding 59 A dalam kerja sebelumnya. HESS telah terbukti berguna dalam masa terdekat untuk kenderaan elektrik.
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This thesis is a special gift to the soul of my brother Maeen. May Allah bless his soul, as he was my supporter and advisor. It was his dream that I would be a PhD holder with academic achievement to serve my community, country, and world. My father, Mohsen alsubari, and my mother, Qabool Alquhaif, are the ones who have given me full confidence since childhood. My brothers, lawyer Motaee, Dr. Nabil, Dr. Zeyad, and my beloved wife, Afrah Alquhaif, have been the pillars of my strength in completing this difficult PhD journey. This thesis is also dedicated to my friends and relatives, especially Dr.Taha sadeq,Dr.Mohammed Albaom, and Dr Saddam alnamar for their prayers, encouragement, and understanding in order to see me another step ahead in academic achievement.

Alhamdulillah, I have finally accomplished my PhD journey.

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Mohd Khair bin Hassan, PhD
Associate Professor, Ir. Ts.
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Azura binti Che Soh, PhD
Associate Professor, Ts.
Faculty of Veterinary Medicine
Universiti Putra Malaysia
(Member)

Ribhan Zafira binti Abdul Rahman, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Nik Rumzi Nik Idris, PhD
Professor
Power Electronics and Drives Research Group
UTM,School of Electrical Engineering
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 19 May 2022

Declaration by graduate student

I hereby confirm that:

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature:	
Name of Chairman of Supervisory Committee:	Associate Professor, Ir. Ts Dr. Mohd Khair bin Hassan
Signature:	
Name of Member of Supervisory Committee:	Associate Professor, Ts. Dr. Azura binti Che Soh
Signature:	
Name of Member of Supervisory Committee:	Dr. Ribhan Zafira binti Abdul Rahman
Signature:	
Name of Member of Supervisory Committee:	Professor Dr. Nik Rumzi Nik Idris

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LIST OF ABBREVIATIONS

AC	Alternating Current
AMPS	Advanced Mobile Integrated Power System
CL	Comfort Limit
COMF	Comfort Driving Mode
DC	Direct Current
DOD	Depth-of-discharge
EM	Electrical Motor / Machine
EMR	Energetic Macroscopic Representation
EMS	Energy Management System
ECO	Economic Driving Mode
EV	Electric Vehicle
EVD	EV Driving Mode
FCEV	Fuel Cell Electric Vehicle
FIS	Fuzzy Inference System
FTP-75	US Urban Driving
GHG	Greenhouse gases
HESS	Hybrid Energy Storage System
HEV	Hybrid Electric Vehicle
HF	Hybridization Factor
HLSC	High Level Supervisory Control
HV	High Voltage
HWFET	US Highway Driving
ICE	Internal Combustion Engine

ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
I-FUZZY	Integrated Fuzzy Driving Mode
LEV	Low Emission Vehicle
LLC	Low Level Control
LLCC	Low Level Component Control
LS	Load Shedding / Shifting
LV	Low Voltage
MESS	Multiple Energy Storage System
ND	Normal Distribution
NEDC	New European Urban and Extra Urban Driving
PCU	Power Control Unit
PEMS	Power and Energy Management System
PES	Power Electronic Shell
PEV	Pure Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
PMAC	Permanent Magnet AC Motor
PMC	Power Management Controller
PMS	Power Management System
RB	Rule based
RTO	Real-Time Optimization
SC	Super-capacitor
SL	Safety Limit with Load Scheduling Distribution
SoC	State-of-charge
TPES	Total Primary Energy Supply

UC	Ultra-capacitor
ZEV	Zero Emission Vehicle

LIST OF SYMBOLS

a	Linear acceleration
vlm	Top cruising speed
bm	Acceleration time
kp	Proportional gain
kl/s	Integrator gain
Tr	Reset time
(s)	Controller
(s)	Plant
(b)	Error
vr	Reference speed
vre	EV speed
F	Force
M	Vehicle mass
Fl	Traction force
Fr	Resistive force
Fr	Rolling resistance force
Fma	Aerodynamic drag force
$F\hbar c$	Hill climbing force
g	Gravitational acceleration
Sr	Tire rolling resistance coefficient
α	Slope or incline angle of the road
ρ	Air density
Sc	Vehicle frontal area

Sa	Aerodynamic drag coefficient
V	Vehicle speed
Pl	Traction power
Pb	Battery power
Pb	Battery output power
$PDCD$CDC-DC converter output power	
Tr	Electromagnetic torque
Nr	Electromagnetic rpm speed
Te	Vehicle torque
Ne	Vehicle rpm speed
Fe	Vehicle tractive force
rw	Wheel radius
SOC0	Battery state of charge initial
ib (b)	Battery current
Cn	Battery rated or nominal capacity
Vc	Output voltage
Vl	Input voltage
Ic	Output current
Il	Input current
η	Efficiency of DC-DC conversion
D	Duty cycle
Ip	Peak current (stator)
Tr	Electromagnetic torque
θr	Rotor angle
ωr	Rotor angular speed

Fe_lm	Maximum tractive force
P	Power
E	Energy
T(s)	Trip time
mE	Rate of change in energy
Eb	Battery energy
Ib	Battery output current
Vb	Battery terminal voltage
Econs	Energy consumption
Pcons	Power consumption
Paverage	Average power
Eregen	Regenerative energy

CHAPTER 1

INTRODUCTION

1.1 Preface

The fast development in the last decade, especially in industry and transportation, makes them the most common factors in climate change and global warming.One of the sectors that contributes to pollution and harmful substances entering the environment is transportation.Vehicles such as hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and electric vehicles (EVs) can help to reduce dependence on non-renewable fossil fuels such as gasoline and diesel [1].Electric vehicles are considered one of the most promising transportation tools for addressing global energy and environmental issues.The technologies used in electric vehicles vary, but their performance is heavily influenced by the energy storage system (ESS) [2] and [3].The energy consumption by sectors is shown in Figure 1.1.

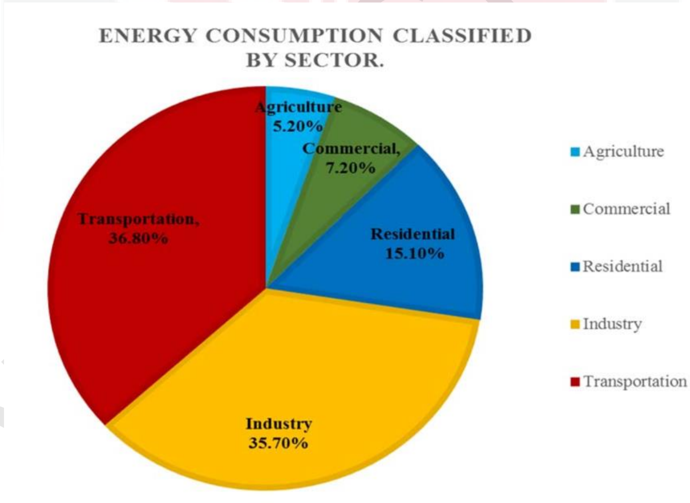


Figure 1.1 : Energy consumption classified by sector adopted [4]

The increasing number of automobiles on the road results in the generation of various gases such as carbon dioxide (CO_2), nitrogen dioxide (NO_2), nitrogen oxides (NO), with 25–30% of total greenhouse gas emissions mainly CO_2 [5]. There has become a concern over problems associated with environmental pollution caused by fueled vehicle emissions and an increase in oil prices worldwide, as shown in Figure 1.2.

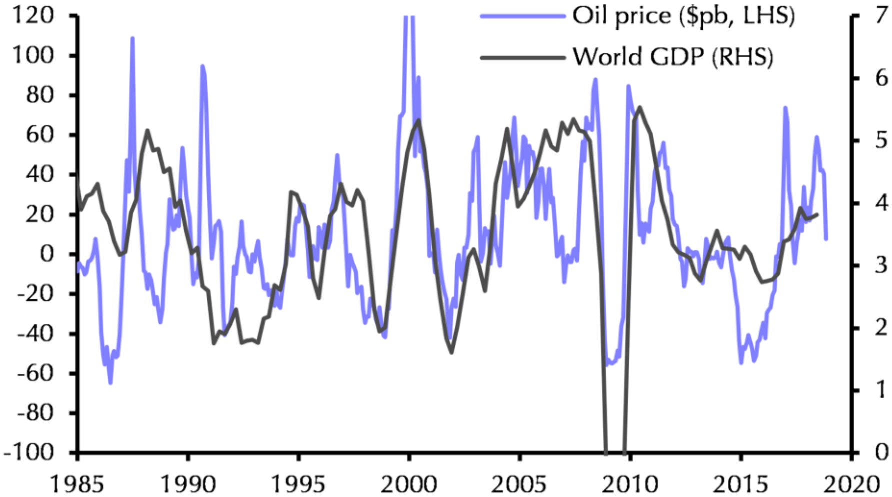


Figure 1.2 : World oil price

The price of oil per barrel increased over time until it reached $150 per barrel in 2009, which was a major concern in the transportation sections [4]. Environmental concerns and energy issues have led to the mass transfer of effort in the automotive industry from the internal combustion engine vehicle (ICEV) to the electric vehicle (EV) [6]. Therefore, different vehicles have been produced in the industry. Their types in the industry can be categorised as shown, in Figure 1.3.

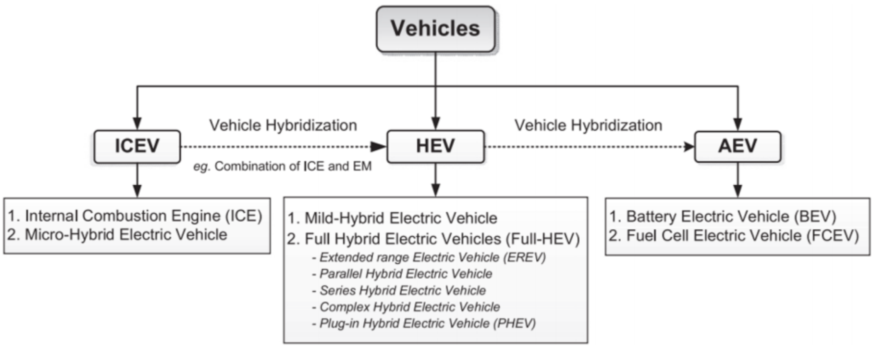
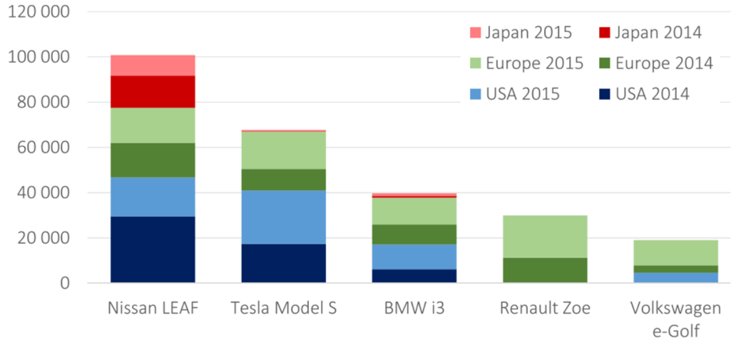
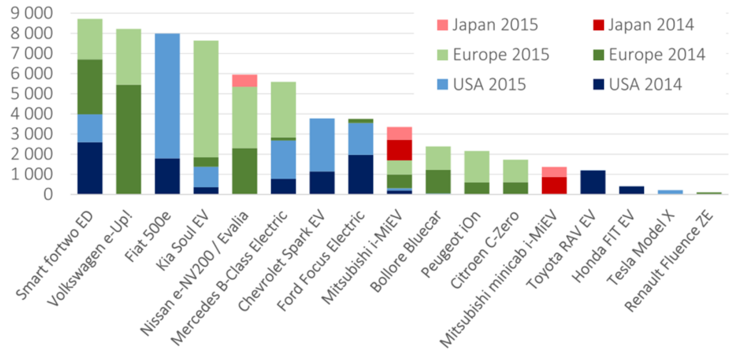


Figure 1.3 : Classification of vehicles adopted [7]

Due to these aforementioned issues, vehicle manufacturers are introducing their own hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and EV to overtake and lead the competitive market [8]. Many companies, such as Tesla, Nissan, BMW, and many others, have shifted most of their production development toward electrifying vehicles, as shown in Figure 1.4.



(a)



(b)

Figure 1.4 : Production of EV (a) manufacturers type (b) year and country [6]

Figure 1.4 shows that many countries across the globe have moved toward electrification of vehicles in recent years. Some of the models include the Nissan Leaf, Tesla Model S, BMW i3, Renault Zoe, and Volkswagen e-golf in different countries such as the USA, Japan, and across Europe. Some examples of those countries in detail are listed as displayed in Figure 1.5.

EV status.

Country	EV stock	EVSE stock	National EV target
United States	71,174	15,192	1,000,000 by 2015
Japan	44,727	5009	20% of total vehicle sales by 2020
France	20,000	2100	2,000,000 by 2020
China	11,573	8107	500,000 by 2015
United Kingdom	8183	2866	1,500,000 by 2020
Netherlands	6750	3674	1,000,000 by 2025
Germany	5555	2821	1,000,000 by 2020
Portugal	1862	1350	750,000 by 2020
India	1428	999	6,000,000 - 7,000,000 by 2020
Denmark	1388	3978	200,000 by 2020
Sweden	1285	1215	6000 by 2015
Spain	787	705	250,000 by 2014
Finland	271	2	80,000 by 2020

Figure 1.5 : A review on the state-of-the-art technologies of EV [7]

According to Figure 1.5, most developed countries tend to produce millions of EVs each year, which gives a clear picture of the manufacturing mission toward electric vehicles. The simple definition of an EV is an automobile propelled by one or more electric motors powered by rechargeable batteries or other energy storage devices. The major components of an EV system are the electric motor, controller, power supply, charger, drive train (the system in a motor vehicle that connects the transmission to the drive axles and batteries). The EV configuration is shown in Figure 1.6.

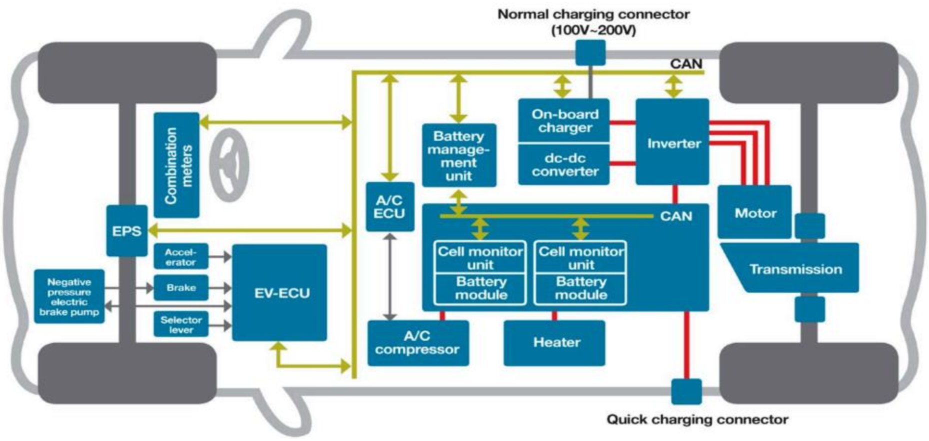


Figure 1.6 : Components of the EV

Figure 1.6 shows the basic components of an EV. It begins with the electric motor that drives the vehicle. The electric motors then convert electrical energy into mechanical energy. Two types of electric motors are used in EVs to provide power to the wheels: direct current (DC) motors and alternating current (AC) motors. The electric motor gets its power orders from a controller, but the controller gets its power information from rechargeable batteries in the battery pack. Since the main source of energy in an EV is the battery as an energy storage system, the focus of EV development studies is the battery characteristics. There are many types of batteries being used in EVs, which depend on the battery's power density, lifecycle, and capacity and vary according to the targeted travel distance of an EV produced. The characteristics of each energy storage type and their parameters are shown in Figure 1.7.

Energy storage Type	Specific energy (Wh/kg)	Energy density (Wh/L)	Specific power (W/kg)	Life cycle	Energy efficiency (%)	Production cost ($/kWh)
Lead acid battery						
Lead acid	35	100	180	1000	> 80	60
Advance lead acid	45	–	250	1500	–	200
Valve regulated lead acid (VRLA)	50	–	150+	700+	–	150
Metal foil lead acid	30	–	900	500+	–	–
Nickel battery [24]						
Nickel–iron [25]	50–60	60	100–150	2000	75	150–200
Nickel–zinc	75	140	170–260	300	76	100–200
Nickel–cadmium (Ni–Cd)	50–80	300	200	2000	75	250–300
Nickel–metal hydride (Ni–MH)	70–95	180–220	200–300	< 3000	70	200–250
ZEBRA battery [24,25]						
Sodium–sulfur	150–240	-	150–230	800+	80	250–450
Sodium–nickel chloride	90–120	160	155	1200+	80	230–345
Lithium battery						
Lithium–iron sulphide (FeS) [24]	150	–	300	1000+	80	110
Lithium–iron phosphate ($LiFePO_4$)	120	220	2000–4500	> 2000	–	350
Lithium-ion polymer (LiPo)	130–225	200–250	260–450	> 1200	–	150
Lithium-ion	118–250	200–400	200–430	2000	> 95	150
Lithium–titanate ($LiTiO/NiMnO_2$)	80–100	-	4000	18000	–	2000
Metal-air battery						
Aluminum-air	220	–	60 [25]	–	–	–
Zinc-air	460	1400	80–140	200	60 [25]	90–120
Zink-refuelable	460	–	–	–	–	–
Lithium-air	1,800	–	–	–	–	–
Ultracapacitor						
Electric double-layer capacitor (EDLC)	5–7	–	1–2M	40 years	> 95	–
Pseudo-capacitors	10–15	–	1–2M	40 years	> 95	–
Hybrid capacitors	10–15	–	1–2M	40 years	> 95	–
Flywheel	10–150	–	2-10k	15 years	80	–
Hydrocarbon [25]						
Hydrocarbon fuel (gasoline/propane)	12,890	9500	–	–	< 30	–
Hydrogen	39,720	1600* 2800**	–	–	ICE: < 25 FC: 50	4**
Natural gas (250bar)	14,890	101	–	–	–	–

Figure 1.7 : Comparison of energy storage specifications based on energy storage device adopted [7]

Figure 1.7 shows the characteristics of energy storage devices with their parameters listed. Some of the best batteries according to literature, have high voltage, light mass, low self-discharge, and a prolonged lifetime. Some of the existing batteries and their comparisons [7]. EVs face significant energy storage related challenges, including the range of anxiety for traveling distances, high cost, battery degradation, and short cycle life, despite their advantages of high overall efficiency and regenerative braking capabilities to reduce CO_2 gas emissions [9]. Furthermore, electric vehicles need charging stations and electric infrastructure adaptations [10], which add more costs to be marketable. So, by looking at the heart of the EV's energy, the total performance of the vehicle depends on efficient energy utilisation [11].To conclude, these issues of energy storage and power efficiency in EVs have an area of research and a problem statement highlighting the current trend and development in EVs and the obstacles facing the EV, which will be covered in the next section of this research.

1.2 Problem Statement

The battery in an EV is the primary and only supply source of energy compared to the fuel tanks in conventional vehicles. Hence, studying the problems related to the battery and its issues will help researchers solve or improve these issues in order for manufacturers to develop BEVs as alternative solutions for conventional vehicles. The battery, as the energy storage component, in the majority of current BEVs functions to deliver energy to the electric machine during propulsion and braking. Many studies suggest making a battery with materials that have a high voltage, are light, have low self-discharge, and last a long time to meet the needs of BEVs.Their energy and power densities, reliability, cycle-life, and management, however, remain issues [12].

Currently, the problems related to electric vehicles are the battery life, as it is limited and expensive, with a maximum of 5-8 years if there is no over (charge/discharge) [13], [14], [15], and [16], and short driving range, as in 2012, the all-electric range of the Chevy Volt and the Nissan Leaf is 56 km and 117 km, respectively. The driving range is currently 200–250 km [13], [16], and [17].Long charging times are also an issue as the Nissan Leaf's 24 kWh battery pack charges in about 8 hours [13] and [8]. The main focus of this research is battery lifetime, as the main objective of manufacturers and consumers of EVs is to increase the lifetime of the batteries and reduce their cost [18]. Therefore, hybrid energy storage systems (HESS) are becoming a fundamental step towards the development of the EV industry as those auxiliary sources help to reduce the stress on the battery, leading to the extension of the driving range and prolonging the lifetime of the rechargeable batteries used in EVs. Therefore, supercapacitors were added to the battery as an auxiliary source in the EV in many studies and were used as a buffer. This is due to the supercapacitor characteristics having high power density to sustain the dynamic power profile, i.e., instantaneous power requirements of a vehicle, but they do not have the energy density to propel the vehicle for a sufficiently long driving range. Supercapacitors also have an almost quasi-infinite cycle life relative to lithium-ion batteries since, operationally, they lack the chemical reactions compared to the battery degradation. Thus, adding a supercapacitor with a high power density and a long cycle life to a battery that has a high energy density can be coupled to obtain the HESS. This will combine the benefits of HESS that can improve the performance of EVs compared to the BEV [19], [20], [21], and [22].

It is important to choose an appropriate topology between the energy storage devices (battery and supercapacitor) to prolong the battery lifetime. The literature uses mainly passive, semi-active, and full-active topologies.The passive topology connects the battery and supercapacitor directly to the load without using power converters. The passive topology can not be controlled since there are no power converters, only internal resistance of each energy storage device. The semi-active topology has one power converter in parallel with either a battery or a supercapacitor connected to the EV load (DC bus), but if high current is applied during charge and discharge, this will affect battery life [23] and [3]. For energy storage device control, two bidirectional dc/dc power converters are connected in parallel to the DC bus in full active topology[24] and [25]. The full active topology has the advantage of flexibility control, but it may have a battery lifetime issue if a sudden peak current is applied while the supercaictor is fully charged. Thus, this study proposed using only a DC/DC boost converter instead of a bidirectional DC/DC converter to regulate battery voltage, reduce battery peak current, and avoid any negative current during discharge mode. A topology between the battery and the supercapacitor could help the battery last longer.

The energy sources can either supply or capture the required power for the motor driving system. The power that is delivered is the power that is available. The energy management system knows how much power is needed and gives it to the battery and supercapacitor, so the power split logic determines how much power each has.Therefore, it is necessary to have a reliable energy management system with a control strategy to help improve the performance of the EV with the advantage of a combination. There have been two basic types of EMSs for the HESS for Evs that have been extensively investigated in the literature, which are the heuristic concept-based EMSs [27] and the optimal control theory-based EMSs such as Dynamic Programming [19], Stochastic Dynamic Programming [27], Model Predictive Control [28], and Neural Networks [29]. The heuristic EMS is based on expert knowledge and is defined by a set of rules or fuzzy logic. In [24] and [25], it is shown that a well-tuned rule-based strategy outperforms the globally optimal algorithm derived from the DP approach. In [3], a driving condition-adaptive rule-based energy management strategy (EMS) is proposed for the HESS, which considers the superiority achievement of each ESS as well as the protection of each ESS. In the literature, studies use different indicators, making results difficult to compare and interpret. The different topologies and EMSs used in the literature [30]. However, fuzzy control is an interesting method for researchers to control such a power system [3] and [31].Because fuzzy logic is simple and has a clear logic relationship, it is easy to apply [3] and [31]. As a result, this study proposed the Fuzzy-PI energy management system to enhance the battery lifetime using HESS. Two indicators will be analyzed; the final SoC of the battery and the current peak reduction using three standard driving cycles to compare HESS and the battery only in EV.

1.3 Research Objectives

The aim of this research is to develop a topology between battery and supercapacitor with EMS in an EV for battery life enhancement and energy consumption saving by the battery. In order to achieve these aims, four research objectives are specifically formulated as follows:

1. To develop and validate a lithium ion battery model with a proposed method of initial state of charge estimation.
2. To develop and validate a supercapacitor model with a proposed internal parametric identification method.
3. To design a proposed topology between the battery-supercapacitor system for instantaneous power-sharing as HESS in an EV. To validate the proposed topology using a fuzzy-PI controller with performance evaluation based on driving cycle patterns.

1.4 Scopes of the Research

The scopes of the research are listed as follows:

1. The plan for this work is pure EV with an auxiliary source supercapacitor as HESS. The EV technical specifications are adopted from those of a Malaysian local car, the Proton IRIZ, manufactured by Proton.
2. The modeling is specifically based on the Malaysian environment and social requirements. The effect of different weather settings will be excluded from the study. The effect of the incline angle of the road on the vehicle model is also excluded in the study. The road's incline angle is set to zero.
3. The load of the vehicle comprises of (1) a battery pack, (2) a supercapacitor pack, (3) the DC-DC boost converter connected to the battery, (4) the DC-DC buck-boost converter connected to the supercapacitor, and (5) constant DC bus voltage connected to the load (power required).
4. The modelling of the battery is based on a two-branch second-order model with the contribution of the initial state of charge estimation, which was validated against experimental data using the lab at UPM University.
5. The modeling of the supercapacitor is based on the equivalent circuit model with the contribution of enhancement of parametric modeling, which was validated against the experimental data.
6. The modelling of the boost converter and battery is based on Kirchhoff current and voltage laws for manipulating the current output and load current for the desired performance.
7. The modelling of the DC-DC buck-boost converter and supercapacitor is based on Kirchhoff current and voltage laws for manipulating the current output and load current for the desired performance.
8. The size of the battery and the supercapacitor are excluded from the study due to their dependency on the technical specifications of the vehicles in UPM.

9. All modeling and simulation work is performed in the MATLAB/Simulink workspace environment and validated with experimental data for a single cell of battery and supercapacitor in UPM labs.

1.5 Thesis Outline

The thesis has been outlined based on the steps taken in the development of the vehicle model, energy management, and power management strategies for EV. It consists of five chapters, namely: (1) Introduction, (2) Literature Review, (3) Methodology, (4) Results and Discussion, and (5) Conclusion and Recommendations.

Chapter 1 is the background and overview of this research. This chapter highlights numerous efforts by researchers and automakers regarding worldwide concerns about energy conservation and environmental protection in the transportation sector. The advantages and limitations of EV as potential sustainable transportation have been briefly described. A promising solution to EV drawbacks has been proposed by implementing power and energy management strategies. On top of that, the aims, objectives, scopes, and research contributions are also included in this chapter.

Chapter 2 presents a review of the battery, supercapacitor, modeling, and energy management and power management strategies related to EV. The gaps and techniques proposed by previous researchers were investigated. A summary of previous research is also presented and discussed.

Chapter 3 comprises three key sections of the research methodology. The first section describes the comprehensive modeling of the EV. The second section focuses on the modeling of the battery based on its mathematical equations. The third section is on the HESS modeling development. The fourth section is on EV EMS with a power scheme management strategy. Subsequently, fuzzy-PI was employed.

Chapter 4 presents the simulation results and discussion according to the sections in the previous chapter. Initially, the proposed EV model was tested for its targeted performance. The results from battery and supercapacitor validation were then utilized to show the single cell performance based on the terminal voltage of the cell and SoC. The proposed topology compared with full active topology in the literature in simulation test using the same Fuzzy-PI controller during UDDS, NEDC, and US06 driving modes based on the parameters of power, voltage, SoC, and current for the battery and supercapacitor.The EMS simulation test during UDDS, NEDC, and US06 driving modes was compared based on the parameters of power, voltage, SoC, and current for the battery and supercapacitor, and for the battery only in EV with different conditions of SoC

(100%, 80%, 60%, and 40%). The maximum current, voltage drop, and final SoC at the end of each driving cycle have been investigated and analyzed based on the objectives of this research.

Chapter 5 consists of a review of the research achievements (objectives and aims) and the overall conclusion. This chapter also includes future work directions and some suggestions for further development.

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