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Design and simulation of a hybrid electric vehicle's energy management system using PV, Fuel Cell and Super Capacitor

by

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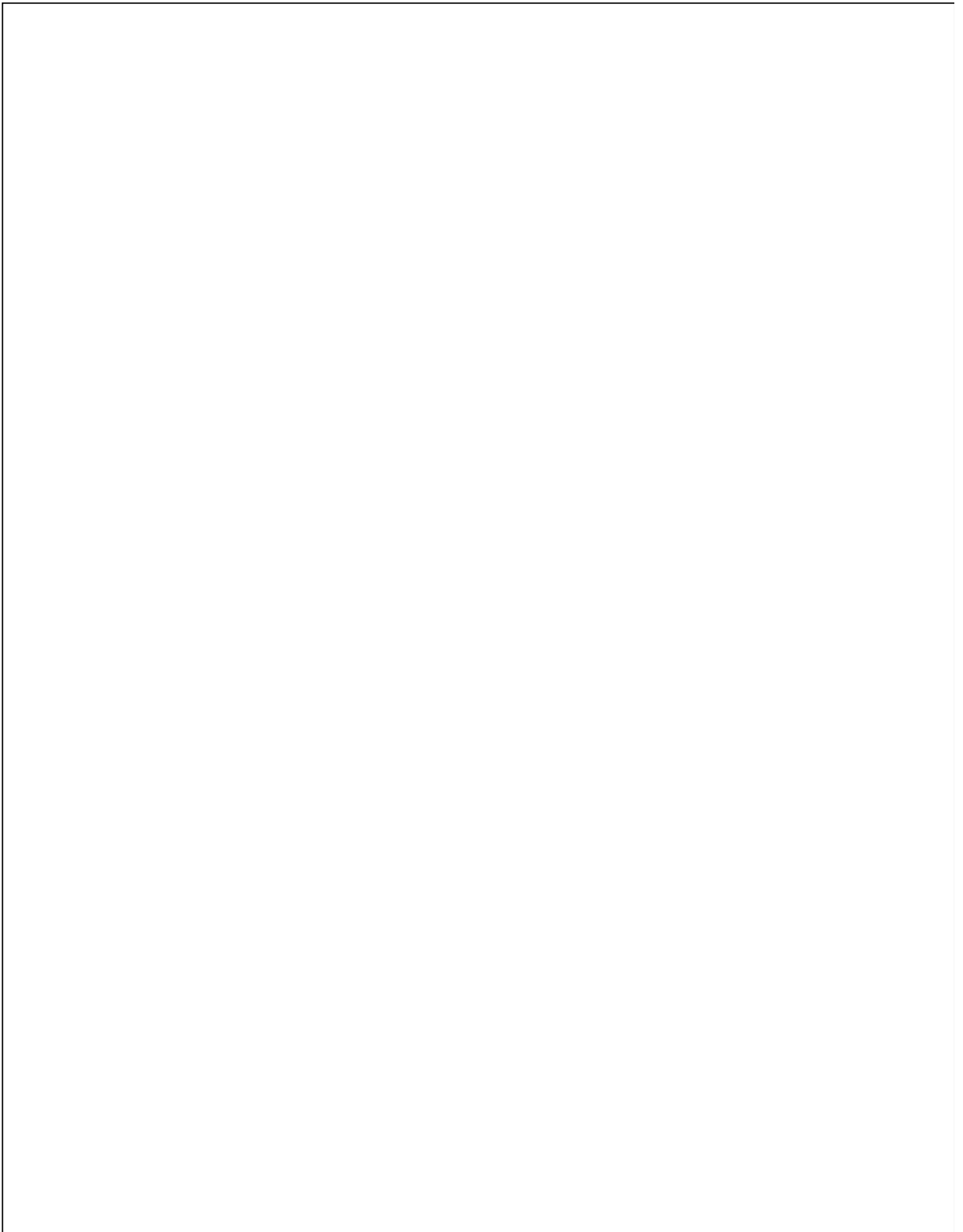
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BACHELOR OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING



Department of Electrical and Electronic Engineering
INTERNATIONAL ISLAMIC UNIVERSITY CHITTAGONG

MAY 2021



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by

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ARIF MAHMUD MAJUMDER (ET-161062)

2

A thesis/project

submitted as partial fulfilment of the requirement for the degree of

BACHELOR OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING

Department of Electrical and Electronic Engineering
INTERNATIONAL ISLAMIC UNIVERSITY CHITTAGONG

MAY 2021

CERTIFICATE OF APPROVAL

The thesis entitled “**Design and simulation of a hybrid electric vehicle's energy management system using PV, Fuel Cell and Super Capacitor**” submitted by **S.M. Abrar Saleh** bearing Matric ID: **ET-161031** and **Arif Mahmud Majumder** bearing Matric ID: **ET-161062** of session **Autumn 2019**, to the Department of Electrical and Electronic Engineering, International Islamic University Chittagong, has been accepted as satisfactory in partial fulfilment of the requirements for the degree of Bachelor of Science in Engineering and approved for the examination held on **May, 2021**.

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DECLARATION

It is hereby declared that this work has been done by us and no portion of the work contained in this thesis has been submitted elsewhere for the award of any degree or diploma.

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ABSTRACT

In the context of global warming, clean energy generation and effective utilization of renewable sources like solar energy, fuel-cells are needed to develop hybrid electric vehicle that overcomes conventional vehicle issues global warming and increasing price of fuel and also to reduce the use of fossil fuel. In this work, we tried to develop an efficient Energy Management System (EMS) for a photovoltaic cell, fuel cell based hybrid electric vehicle with combination of supercapacitor and battery, which is known as PVFCHEV. The vehicle energy management system is designed using Matlab/Simulink compiler. In order to supplement the use of solar energy in the face of rapidly changing power interests, the distinction of solar energy must be considered. The solar energy used as auxiliary power source for the vehicle whereas, the primary source is fuel cell. Supercapacitor is used to boost the total power of the vehicle system while the system needs more power to accelerate. There also dc/dc converters are used to step up individual voltage of each source. A dc/ac converter is used before an three phase induction motor to supply the power on it. The valuable test results reveal that the planned vehicular force framework and the EMS function admirably at different sunlight-based radiations and battery states. Under the guidance of the EMS, the force framework demonstrates viability and adaptability in a variety of situations. Finally, with the proposed energy management system it can provide reasonably better fuel economy and less emission than a commonly used power following control procedure.

TABLE OF CONTENTS

CERTIFICATE OF APPROVAL	ii
DECLARATION	iii
ACKNOWLEDGEMENT	iv
ABSTRACT	v
TABLE OF CONTENTS	vi
LIST OF FIGURES	ix
LIST OF TABLES	xi
LIST OF ABBREVIATIONS	xii
CHAPTER 1: INTRODUCTION	
1.1 Introduction	1
1.2 Motivation	2
1.3 Objectives	2
1.4 Methodology	3
1.5 Thesis Outline	4
CHAPTER 2: LITERATURE REVIEW	
2.1 Introduction	5
2.2 Photovoltaic Cell	5
2.2.1 Model of Solar Cell	6
2.2.2 Current-Voltage (I-V) Characteristics	6
2.2.3 Parameters of Solar Cell	7
2.3 Model of PV module	7
2.3.1 Computation of I_M by algorithm	8
2.3.2 Algorithm's Flowchart	10
2.4 Fuel Cell	10
2.5 Operation of Fuel Cell	11
2.6 Classification of Fuel Cell	12
2.6.1 Based on Fuel and Oxidant Types	12
2.6.2 Based on reaction temperature	12
2.6.3 Depending on the Electrolyte	13
2.6.3.1 Alkaline fuel cell	13
2.6.3.2 Phosphoric Acid Fuel cell (PAFC)	14
2.6.3.3 Proton Exchange Membrane Fuel Cell	14
2.6.3.4 Molten carbonate fuel cell	15

2.6.3.5 Solid oxide fuel cell	15
2.6.3.6 Direct Methanol Fuel Cell	16
2.6.4 Comparison of the fuel cell types	17
2.6.5 Hydrogen as a Fuel	19
2.6.6 Hydrogen Production and Storage	19
2.6.7 Fuel Cell for Vehicle Application	21
2.6.7.1 Proton Electron Membrane Fuel Cell	21
2.6.7.2 PEM fuel cell	22
2.6.7.3 Assembly of Membrane Electrodes	22
2.6.7.3.1 Hardware	24
2.6.7.4 Detail of the PEMFC Stack	24
2.6.7.5 Material's	24
2.6.7.6 Some Stack Components Fabrication	25
2.6.7.7 Measuring the Performance of PEMFCs	26
2.6.7.8 Membrane Electrode Assembly Preparation	26
2.6.7.9 Consolidating (1,3,5 and 7) Cells	26
2.6.7.9.1 By varying gas flow rate for single cell	27
2.6.7.9.2 By varying cell number	27
2.6.7.10 Result and Discussion	28
2.7 Catalyst	30
2.7.1 Types of Catalyst	30
2.7.1.1 Heterogeneous Catalyst	30
2.7.1.2 Homogeneous catalysts	31
2.7.2 Pt as a best catalyst	31
2.7.2.1 As a catalyst	31
2.7.2.1.1 Research of catalyst	32
2.8 Comparison between ICE and PVFCHEV	32
2.8.1 ICE	32
2.8.2 ICE Operation	32
2.8.3 Photovoltaic fuel cell hybrid electric vehicle	33
2.9 PEMFC Application	34
2.9.1 PVFCHEV	35
2.9.2 HEV's	35
2.9.2.1 Model in Production	35
2.9.2.2 Prototype model created by Toyota	36
2.10 Summary	36
 CHAPTER 3: SYSTEM DESIGN AND SIMULATION	
3.1 Introduction	37
3.2 System Methodology of Vehicle	37
3.2.1 Hybrid System Modules	38
3.3 PVFC Hybrid vehicle system	40
3.3.1 Module of Photovoltaic Cell	40

3.3.2 Module of Fuel Cell	42
3.3.3 Module of Battery	44
3.3.4 Module of SC	47
3.3.5 Converter Model (DC/DC)	49
3.3.6 Model of DC/AC Converter	51
3.3.7 The Load	52
3.3.8 Energy Management Strategi	52
3.3.8.1 Control Strategy for State Machin	53
3.3.8.1.1 Discharge Converter	55
3.3.8.1.2 Charge Converter	55
3.3.8.1.3 Power Outcome	56
3.4 Control Scheme for State Machin	58
2 3.5 Hydrogen Consumption	59
3.6 Summary	59

CHAPTER 4: RESULT AND DISCUSSION

4.1 Introduction	60
4.2 Vehicle Model	60
4.3 Simulation Diagram	60
4.4 Simulated Results	61
4.4.1 FC Module	61
4.4.2 Battery Module	62
4.4.3 SC Module	63
4.4.4 Photovoltaic Array(PVA)	65
4.4.5 Inverter Output	67
4.4.6 Output power vs. Time config	68
4.5 Result Analysis	69
4.6 The designed model and other HEVs are compared	69
4.7 Evaluation	70
4.8 Summary	70

CHAPTER 5: CONCLUSION AND FUTURE WORK

5.1 Introduction	71
5.2 Conclusion	71
5.3 Merits and Demerits PVFC Hybrid Vehicle Configuration	71
5.3.1 Merits	71
5.3.2 Demerits	72
5.4 Certain restrictions apply	73
5.5 Work in the Future	73

REFERENCES	74
APENDIX	78

LIST OF FIGURES

Fig.1	The methodology's flow chart	3
Fig.2.2	PV cell uncovered to sunlight	5
Fig.2.2.1	Diagram of individual solar cell's equivalent circuit	6
Fig.2.2.2	Solar cell's IV characteristic	6
Fig.2.3	Photovoltaic module	7
Fig.2.3.2	Model of a solar module flowchart	10
Fig.2.5(a)	Basic dialysis	11
Fig.2.5(b)	Fuel Cell Operation	12
Fig.2.6.3.1	Alkaline Fuel Cell	13
Fig.2.6.3.2	PA Fuel Cell	13
Fig.2.6.3.3	PEM Fuel Cell	14
Fig.2.6.3.4	MC Fuel Cell	15
Fig.2.6.3.5	Solid Oxide Fuel Cell	15
Fig.2.6.3.6	Direct Methanol Fuel Cell	16
Fig.2.6.7.1	Water condensation on the air channel wall caused by a PEMFC	21
Fig.2.6.7.2	Operation of PEMFC	22
Fig.2.6.7.3	PEMFC Stack Layers	23
Fig.2.6.7.4	Z type gas flow configuration	25
Fig.2.6.7.5	Design of bipolar-plates (a) diagram, (b) picture	25
Fig.2.6.7.6	Power output and polarization curves for single cell	28
Fig.2.6.7.7	Power output & polarization for (a)1cell,(b)3cells,(c)5cells,(d)7cells	29
Fig.2.9.2	HEV's	35
Fig.3.1	Block Diagram of the Vehicle System	37
Fig.3.2	Model of a Solar Array	41
Fig.3.3	Model of a FC Stack	43
Fig.3.4	Li-Ion Battery Model	46
Fig.3.5	SC model	48
Fig.3.6	(a) DC/DC Boost converter and (b) DC/DC buck converter model	50
Fig.3.7	Model of a DC/AC converter	51
Fig.3.8	State Machine Control Block used in the simulation	53
Fig.3.9	Discharge Converter for Batteries (DC/DC)	55
Fig.3.10	Charge Converter for DC/DC Batteries	55

17		
Fig.3.11	State Machine Control Hysteresis	56
Fig.3.12	Power Output	57
Fig.3.13	State Machine Control Energy Management Scheme	58
Fig.3.14	State Machines Control Scheme	58
Fig.4.1	Proposed Vehicle Model	60
Fig.4.2	PVPEMFC energy supply simulation in Simulink	60
Fig.4.3	Fuel Cell polarization plots	61
Fig.4.4	Fuel-cell simulation results for 12.5 kW PEMFC	62
Fig.4.5	Battery Discharge Plots	62
Fig.4.6	Li-ion battery simulation results	63
Fig.4.7	Supercapacitor discharge plots	64
Fig.4.8	SC Simulated results with charge and discharge for 270-V 15-F	65
Fig.4.9	PV Array characteristic plots	65
Fig.4.10	PV Battery Discharge plots	66
Fig.4.11	Simulation results for PV Batteries	66
Fig.4.12	The inverter's output voltage	67
Fig.4.13	Simulated PEMFC output power	68

LIST OF TABLES

18	Table 2.1	Comparison among operating temperature, stack size, and efficiency of various fuel cell types based on basis electrodes.	17
	Table 2.2	Compares the applications, advantages, and disadvantages of various fuel cell types	18
	Table 2.3	A comparison of more storage systems	20
	4	Table 2.4 Gas flow rate & back pressure variation for single cell	27
	Table 2.5	No. of cells variation.	27
	Table 2.6	Data extracted from power output & polarization of 1cell, 3cells, 5cells, 7cells.	29
	Table 2.7	Comparision between ICE and PVFCHEV	34
	Table 3.1	Input Parameter for Solar Array Model	42
	Table 3.2	Fuel Cell Model Input Parameter	44
	Table 3.3	Input parameters for the battery model	46
	Table 3.4	Input Parameters for the Supercapacitor System Model.	49
	Table 3.5	Rating for Traction motors	52
	Table 3.6	Energy Management Design Requirements	53
	Table 3.7	Demonstrates the control plan for the state machine	54
	Table 4.1	The inverter's rating and output.	67
	Table 4.2	FCHEV Model's parameter values and output power.	68
	Table 4.3	Analysis of the Results	69
	Table 4.4	FCHEV's proposed PV/FC/SC/Battery Hybrid energy Source vs. other models	69

LIST OF ABBREVIATIONS

FHEV	⁷³ Fuel Cell hybrid Electric Vehicles
PHEV	Plug-in Hybrid Electric Vehicle
BEV	Battery Electric Vehicles
ICE	Internal Combustion Engine
PVFCHEV	¹⁰⁴ Photovoltaic Fuel Cell Battery Hybrid Electric Vehicle
HEV	¹⁰ Hybrid Electric Vehicle
EMS	Energy Management System
SOC	State Of Charge
BMS	Battery Management System
AFC	²³ Alkaline Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
MCFC	Molten Carbonate Fuel Cell
SOFC	Solid Oxide Fuel Cell
DMFC	Direct Methanol Fuel Cell
SPEFC	Solid Polymer Electrolyte Fuel Cell
PTFE	Poly Tetra Fluro Ethylene
MEA	¹¹⁵ Membrane Electrode Assembly
PEM	Polymer Electrolyte Membrane
GDE	Gas Diffusion Electrodes
GHG	Green-House Gas
MPPT	Maximum Power Point Tracking
SC	Super Capacitor
EDLC	Electric Double Layer Capacitor
PMSM	Permanent Magnet Synchronous Motor

CHAPTER 1

INTRODUCTION

1.1 Background

Some key topics to keep an eye on for a safe, renewable, and clean energy future include reducing the usage of fossil fuels for transportation, using environmentally friendly energy supplies, and developing innovative energy-saving techniques [1],[2]. Energy experts have perceived that burning-through oil-based commodities for our customary techniques for transportation is one of the critical purpose behind an overall temperature modification and ecological change [3],[4]. As to decrease carbon impressions and become all the more harmless to the ecosystem, conventional transportation frameworks require consideration [5],[6]. Due to growing concerns regarding fossil fuel use and air pollution, researchers have been particularly interested in electrification and hybridization of fuel-powered land vehicles in the last decade [7],[8]. Electric vehicles have been viable options in the energy industry, but they are subject to a regulatory framework that requires their batteries to be recharged [9].

⁴¹ An electric vehicle uses a number of three separate energy storage elements, like fuel cells, batteries, and super-capacitors, to power its electrical drive mechanism. Electric vehicles include fuel cell hybrid electric vehicles (FHEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs). Any model has their own characteristics, such as HEVs having both an ICE and an electric motor, but they are not environmentally friendly. HEVs have the ability to lower carbon emission while maintaining the vehicle's visual quality. BEV is an environmentally efficient platform with a limited driving range, PVA-FC-battery hybrid electric vehicle (PVAFCHVEV) specifically tried to explain its practicality by price and energy consumption and has a long drive range. ¹ PHEV needs an external source to re-energize the ¹ batteries and has high effectiveness, and FHEV has been proposed to outperform all previous issues but at a high cost. Ezzat and Dincer, who are working on the implementation of HEVs, have suggested building a PVFCHVEV and have broken down the effects of integrating PV ⁵⁸ clusters into the effect of a fuel cell power system on vehicle efficiency and performance [10]-[13].

1.2 Motivation

The understanding of how to reduce fuel consumption and outflow appetite without losing performance has been greatly aided by the charge of vehicle powertrains. An electric vehicle (EV) has been thought to be a suitable option to a conventional vehicle because of its high general proficiency, low perceptible commotion, and zero on-board discharges. The production of electric vehicles has been hampered by technological and financial problems of electrical capacity structures such as batteries and super-capacitors. In any case, the industry's widely accessible EVs face higher risks costing and range-nervousness issues.

HEVs (hybrid electric cars, a former alternative) have been on the marketplace since 1997, and their sales have risen as well. PHEVs blend the best aspects of both standard HEVs and hybrid vehicles. PHEVs may be a stopgap mechanism before the technical hurdles to full vehicle zapping are resolved. The most advanced version of powertrain monitoring in HEVs or PHEVs is an Energy Management System (EMS), which analyses the vehicle's energy interests for drivetrain parts. The EMS comes to a conclusion on how to effectively relay vehicle power interest between the electric and mechanical force directions. It could be more effective to merge a PV array with the standard FCHEV. In comparison to HEVs, where the engine is just the primary source of electricity, PVFCHEVs' external usable power supply, the battery charge, adds to the complexity of the EMS controller design. As a consequence, in order to make the most of having an additional fuel supply on board [14],[15].

The thesis discussed in this paper is about hybridization and energy efficiency. A half-breed device composed of photovoltaic solar-powered boards and a control module, we claim, is undeniably superior. This configuration should include converters and a capacity system (battery and supercapacitors). The goal is to establish control strategies that will allow the most force to be derived from the available sources while still advancing the overall energy system to meet the heap's requirements. Our technique relies on the use of compensators and the tracking of the greatest force point to accomplish this.

1.3 Objectives

1. To develop new energy arrangements for HEVs using fuel cells, battery, and super capacitor and photovoltaic array.
2. To design the FC, Battery, Super capacitor, and PV array unit integration.
3. To evaluate the performance of the built model with other HEV models.

1.4 Methodology

MATLAB Simulink 2020b, a powerful simulation software, were placed to use to obtain the results in this study. Following are some of the simulation's main features:

- Discuss the architecture needed to provide a hybrid vehicle's energy supply.
- Photovoltaic (PV) array panel combination of power converting and energy storage source systems.
- PEMFC stack module integration of power converting and energy storage systems.
- The PEMFC stack module is used to integrate the battery, supercapacitor, and traction electric motor.
- The whole model is simulated.

As seen in Fig.1, a flowchart of the whole technique aids in reaching the objectives.

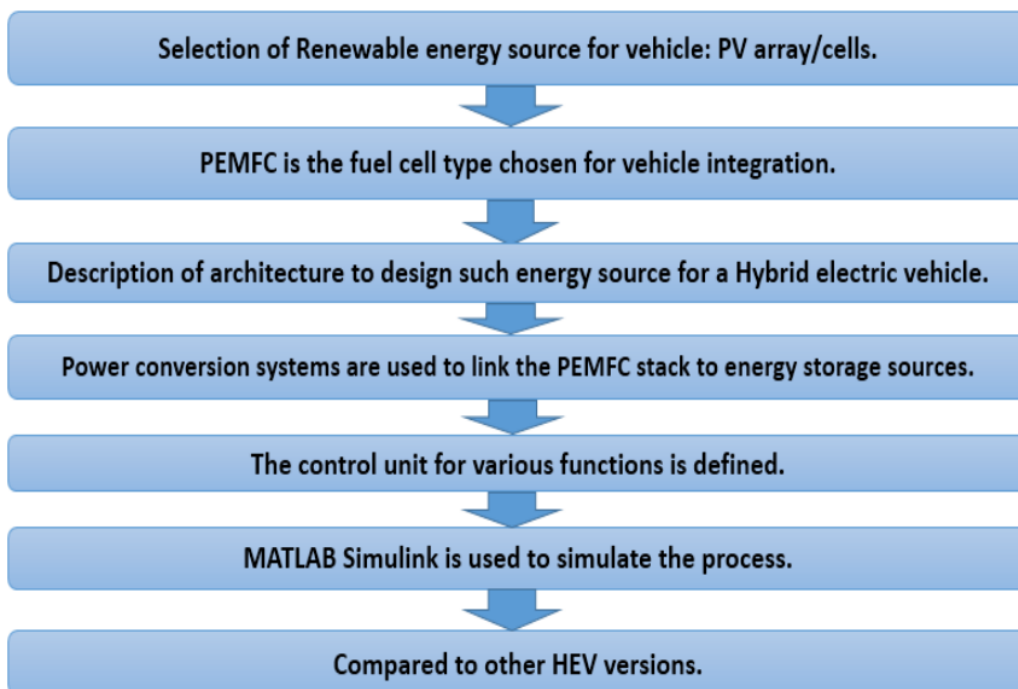


Fig.1 The methodology's flow chart

1.5 Thesis Outline

To achieve the work's performance targets, MATLAB, Simulink 2020b is used. The following is a list of the topics included in this thesis.

- Chapter 2: This chapter includes summary of the literature on photovoltaic and fuel cells, as well as their operating methods, types, and performance configurations. A contrast of the styles to get a clearer view of which form is best for the application and what properties are needed for the FC to be more effective.
- Chapter 3: This chapter covers the architectural details needed to create the ideal model.
- Chapter 4: The modeling scheme, energy management system, and model simulation in MATLAB Simulink 2020b are the topics of this chapter. The system's required performance is analyzed, and the proposed model is compared to other HEV models, resulting in an analysis.
- Chapter 5: Based on the proposed model, we have included merits, demerits, limits, and potential scopes in this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

As a result of environmental issues as well as financial considerations, electric vehicles (EVs) are becoming more popular than cars with internal combustion engines. Electric vehicles are friendly to the environment and are expected to help in the reduction of harmful pollution of the atmosphere. Batteries, ultra-capacitors, fuel cells, and photovoltaic (PV) cells make up the vast majority of the electric energy sources under consideration at the moment. Another benefit of electric cars is that they help to reduce running costs compared to engines powered by gas or oil the photovoltaic (PV) cell and the fuel are the focus of this thesis. The working principle of the PV cell and fuel cell is dissected step by step in this chapter because it is a developing technology. PV and fuel cells form a more efficient combined power system, environmentally friendly & may be prohibitively expensive due to development, but through proper production, it can be reduced to a user-friendly figure. Because there are so many different types of combined systems based on particularity, this chapter classifies them and compares them. Finally, we'll mention the particular type that's best for our desirable design.

2.2 Photovoltaic Cell:

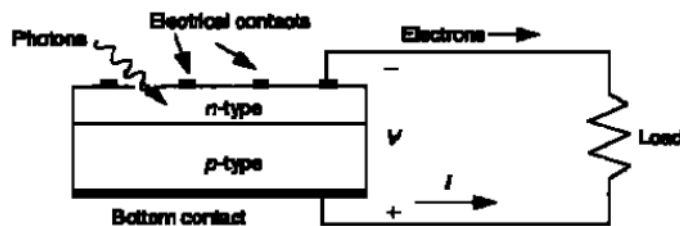


Fig. 2.2: PV cell uncovered to sunlight [16].

Solar panels typically have silicon cells that have been processed to produce an electric field. The positive side is boron-doped, while the negative side is phosphorus-doped and faces the sun. [17,18] Photons from the sun enter the solar cell, they displace electrons from the semiconductor material's atoms, forming electrons holes pairs. When the positive and negative sides are connected by electrical conductors, forming an electrical circuit (Fig.2.2), and the moving electrons carry electric current I_{ph} (photocurrent). The movement of energy is proportional to the strength of sunlight.

1

2.2.1 Model of Solar Cell

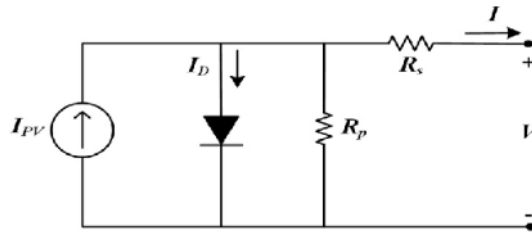


Fig.2.2.1 Diagram of individual solar cell's equivalent circuit [19]

The solar cell is a passive device, when there is no sunlight; it acts as a diode. It produces a current I_D , also known as diode current or dark current, when it's plugged into a power source.

As a consequence, the solar cell electric circuit model looks like **Fig.2.2.1**, a diode, a source for current I_{ph} , & a resistance in series that represents the cell's resistance which is internal R_s are all included in this circuit. As a consequence, the difference between I_{ph} and I_D is the net current. [20]

$$I = I_{ph} - I_D = I_{ph} - I_0 \left(e^{\frac{q(V+IR_s)}{mkT_c}} - 1 \right)$$

here,

k = Boltzmann constant for gas.

I_0 = Saturation current of diode.

q = Charge.

m = Idealizing factor.

V = Cell voltage.

T_c = Cell absolute temperature.

40

2.2.2 Current-Voltage (I-V) Characteristics

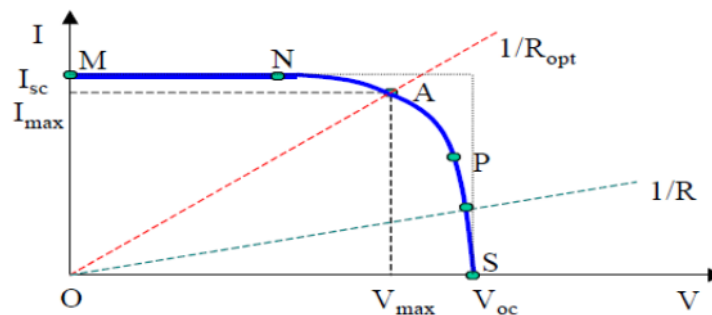


Fig.2.2.2 Solar cell's IV characteristic [21].

21

If the cell's terminals are connected to a resistor R , the intersection of the solar cell's IV characteristic determines the operating point with the slope $1/R$ straight line.

2.2.3 Parameters of Solar Cell

Solar cell has some basic parameters:

a) **Current in a short circuit:** $I_{sc} = I_{ph}$ Under short circuit conditions, it is the most accurate estimation of a cell's current, i.e $V = 0$.

b) **Voltage in an open circuit:** When the induced current $I = 0$, it corresponds to the voltage of the cell at night. In terms of mathematics,

$$V_{oc} = V_t \ln \left(\frac{I_{ph}}{I_0} \right), \quad \text{where } V_t = \frac{mkT_c}{q}$$

c) **Max. Power Point:** The maximum power is dissipated at t on the IV curve (**Fig.4**).

d) **Max. efficiency:** It's the proportion of maximum to incident light capacity.

$$\eta = \frac{P_{max}}{P_{in}}$$

e) **Fill factor:** It's the proportion of full power to the amount of I_{sc} and V_{oc} .

$$FF = \frac{P_{max}}{V_{oc} I_{sc}}$$

2.3 Model of PV module

Modules are made up of cells. A PV module is made up parallel branches of NPM are connected in series with NSM solar cells.

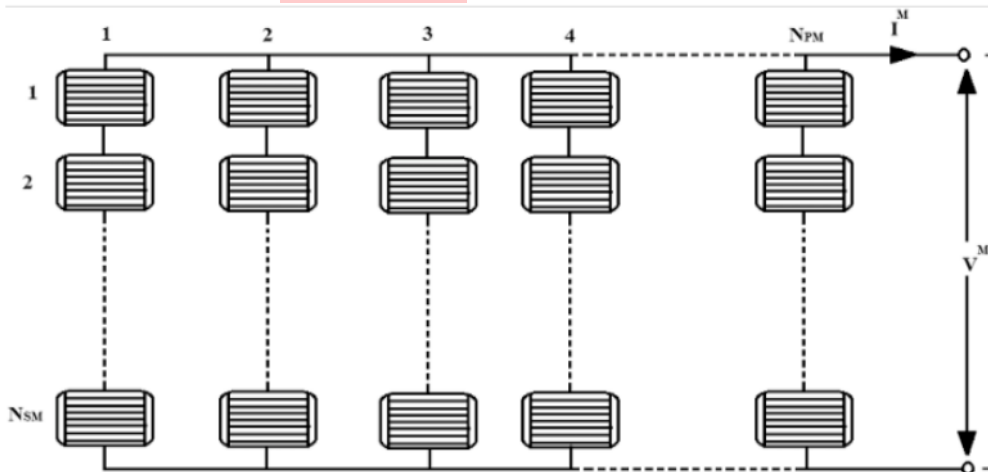


Fig.2.3 Photovoltaic module [22]

1 This PV module model can be acquired by supplanting every cell by comparable circuit of Fig. 2.3. At that point the current for the modules I_M can be disclosed as -

$$I_M = I_{SC}^M \left[1 - \exp \left(\frac{V^M - V_{OC}^M + R_S^M \cdot I^M}{N_{SM} V_t^C} \right) \right]$$

here,

'M' superscript represents the module

'C' superscript represents a cell

I_{SC}^M = Module's short circuit current = $N_{PM} I_{SC}^C$

V_{OC}^M = Module's open circuit voltage = $N_{SM} V_{OC}^C$

R_S^M = Equivalent series resistance of module = $\frac{N_{SM}}{N_{PM}} R_S^C$

V_M = Load voltage

2.3.1 Computation of I_M by algorithm

1st step: Under normal circumstances, the manufacturer's catalogue contains the following details.

- Maximum power of the module, $P_{max,0}^M$
- Short circuit current of the module, $I_{SC,0}^M$
- Open circuit voltage of the module, $V_{oc,0}^M$
- Number of cells in series, N_{SM}
- Number of cells in parallel, N_{PM}

2nd step: The following is a formula for calculating the data in a cell:

- Maximum power of a cell, $P_{max,0}^C = \frac{P_{max,0}^M}{N_{SM} N_{PM}}$
- Short circuit current of a cell, $I_{SC,0}^C = \frac{I_{SC,0}^M}{N_{PM}}$
- Open circuit voltage of a cell, $V_{OC,0}^C = \frac{V_{OC,0}^M}{N_{SM}}$
- Thermal voltage of a cell, $V_{t,0}^C = \frac{mkT^C}{q}$

- $V_{OC,0} = \frac{V_{OC,0}^C}{V_t^C}$
- $FF_0 = \frac{P_{max,0}^C}{V_{OC,0}^C I_{SC,0}^C}$
- $FF = \frac{(V_{OC,0} - \ln(V_{OC,0} + 0.72))}{(V_{OC,0} + 1)}$
- $r_s = 1 - \frac{FF}{FF_0}$
- *Series resistance of the cell, $R_S^C = r_s \frac{V_{OC,0}^C}{I_{SC,0}^C}$*

3rd step: Module voltage V^M , ambient temperature T_a and irradiance G_a can now be determined under working conditions-

- $C_1 = \frac{I_{SC,0}^C}{G_{a,0}}$
- $I_{SC}^C = C_1 G_a$
- $T^C = T_a C_2 G_a$
- $V_{OC}^C = V_{OC,0}^C + C_3 (T^C - T_0^C)$
- $V_t^C = \frac{mk(274 + T^C)}{q}$

4th step: The current of the module under operating conditions is now measured using the equation below-

$$I_M = I_{SC}^M \left[1 - \exp \left(\frac{V^M - V_{OC}^M + R_S^M \cdot I^M}{N_{SM} V_t^C} \right) \right]$$

2.3.2 Algorithm's Flowchart

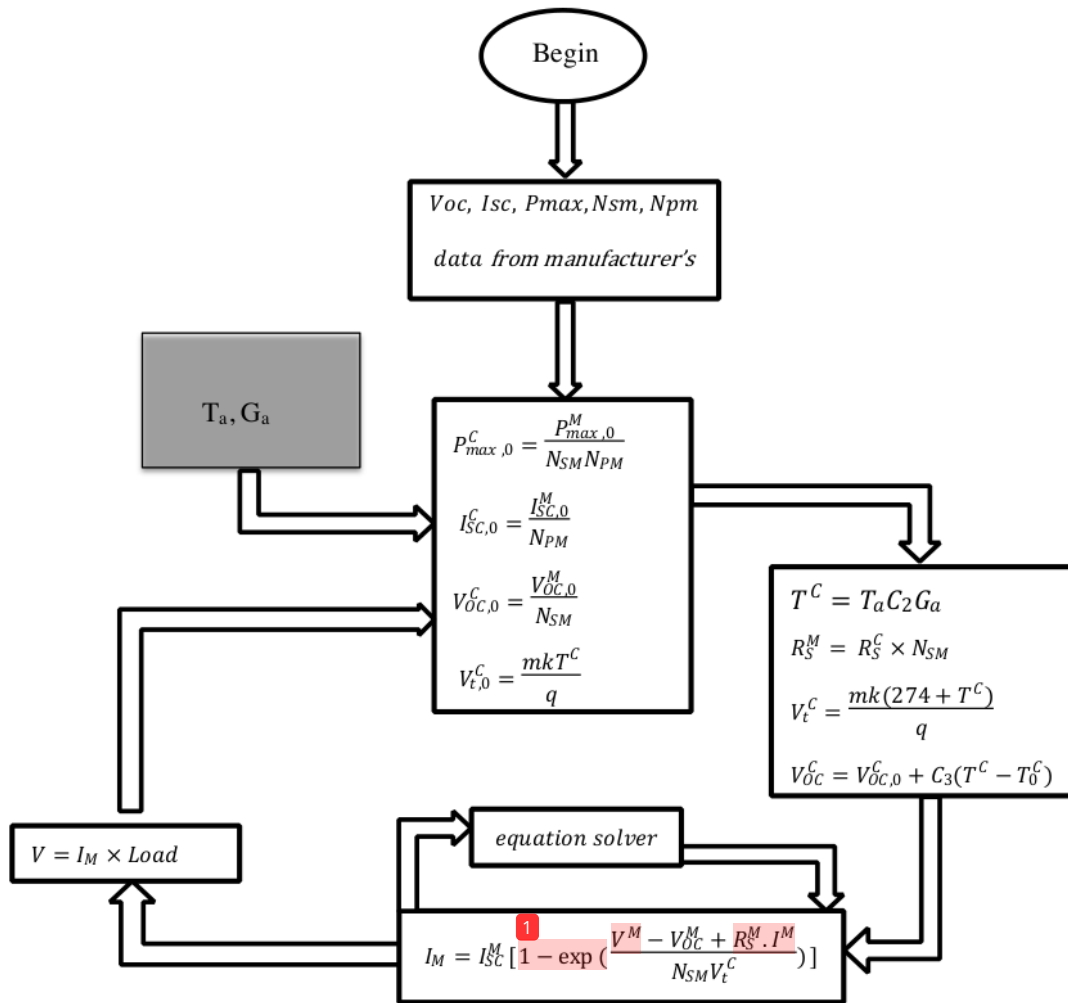


Fig.2.3.2 Model of a solar module flowchart [16]

2.4 Fuel Cell

A fuel cell is an electrochemical device that converts chemical energy from fuel into electricity by combining hydrogen fuel with oxygen from another oxidizing agent. [23]. Fuel cells differ from batteries in that they require a constant supply of fuel and oxygen (usually from the air) to maintain the chemical reaction, while batteries derive their chemical energy from chemicals already present in the battery. William Grove, a Welsh scientist and barrister, published a paper in 1838 that detailed the construction of his first crude fuel cells. Sheet iron, zinc, and porcelain plates, as well as copper sulphate and a dilute acid solution, were among the materials he used. Forklifts, trucks, buses, boats,

motorcycles, and submarines all use them to power fuel cell vehicles. The amount of power produced by a fuel cell is calculated by a number of factors, including:

1. Type of fuel cell
2. Size of fuel cell
3. Operating temperature of fuel cell
4. The pressing factor at which the gases are provided to the cell

Only the tiniest of applications can be powered by a single fuel cell. Individual fuel cells are usually connected in series to form a fuel cell stack. Hundreds of fuel cells can be found in a standard fuel cell stack [24].

2.5 Operation of Fuel Cell

A fuel cell is an electrochemical system that generates electricity from hydrogen (or hydrogen rich fuel) & oxygen. An electrolyte is sandwiched between two thin electrodes in a single fuel cell (a porous anode and cathode). As hydrogen or a hydrogen-rich fuel is fed to the anode, a catalyst separates negatively charged electrons from positively charged ions (protons). Oxygen interacts with electrons and, in some cases, protons or water at the cathode to form water or hydroxide ions. The membrane prevents electrons from entering the positively charged cathode from the anode side of the cell. They must, however, migrate around it via an electrical circuit.

Two most important components used

- Hydrogen and
- Oxygen.

Within the fuel cell, they react to produce electricity, heat, and water.

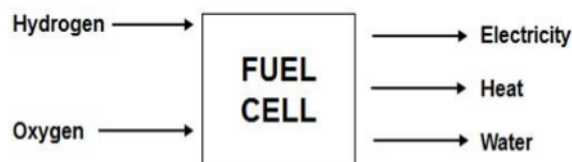


Fig.2.5(a) Basic dialysis [24]

Water, oil, methane, methanol, and ethanol, as well as natural gas, landfill gas, coal-based gas, can all be used to generate hydrogen.

A fuel cell is made up of two electrodes: one on the positive side and the other on the negative side-

- Anode and
- Cathode

An electrolyte separates the two. A thin layer of platinum or other metals is coated on each electrode, depending on the type of fuel cell, to cause as the oxygen and hydrogen pass through the electrodes, a reaction occurs.

The following equation depicts the ultimate reaction:

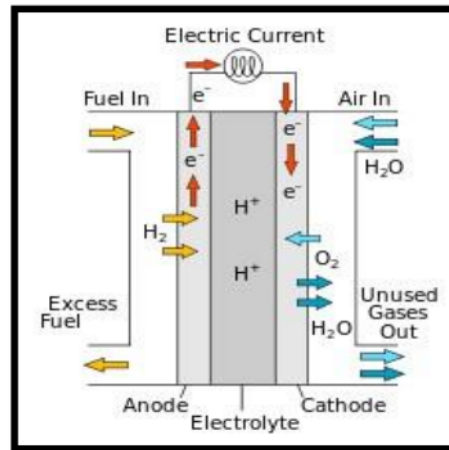
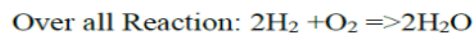
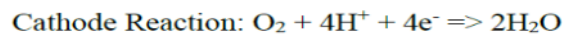
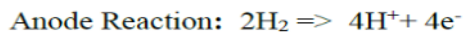


Fig.2.5(b) Fuel Cell Operation [24]

2.6 Classification of Fuel Cell

2.6.1 Based on Fuel and Oxidant Types

1. Fuel cell based on hydrogen (pure) and oxygen (pure).
2. Gas-air fuel cell with a high hydrogen content.
3. Fuel cell based on ammonia and air.
4. Fuel cell based on synthesis gas and air.
5. Air-hydrocarbon (gas) fuel cell.

2.6.2 Based on reaction temperature

- 1) Low temperature (less than 100°C)
- 2) Medium temperature (100 to 250°C)
- 3) High temperature (greater than 500°C)

2.6.3 Depending on the Electrolyte

- Alkaline Fuel Cell (AFC).
- Phosphoric Acid Fuel Cell (PAFC).
- Proton Exchange Membrane Fuel Cell (PEMFC) or Polymer Electrolytic Membrane Fuel Cell (PEMFC).
- Molten Carbonate Fuel Cell (MCFC).
- Solid Oxide Fuel Cell (SOFC).
- Direct methanol fuel cell (DMFC). [24]

2.6.3.1 Alkaline fuel cell:

- The Alkaline Fuel Cells work by combining compressed hydrogen and oxygen.
- Their electrolyte is usually a solution of potassium hydroxide (chemically, KOH) in water.
- The performance is about 70%, and the working temperature is between 150 and 200°C.
- Cell production varies between 300 and 5 kilowatts.
- In the Apollo spacecraft, both electricity and drinking water were provided by alkaline cells.
- They necessitate the use of pure hydrogen fuel. Their platinum electrode catalysts, on the other hand, are costly.[24]

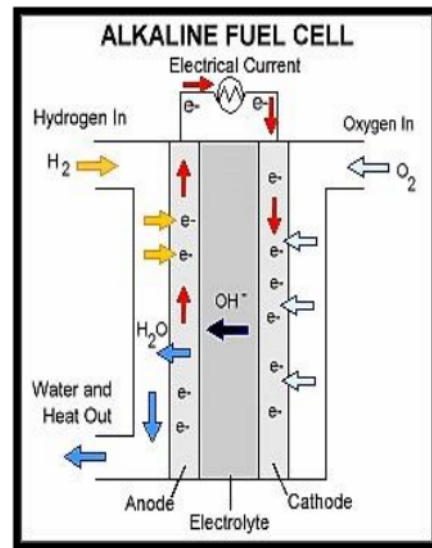
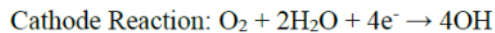
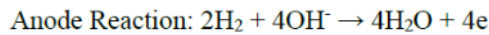


Fig.2.6.3.1 Alkaline Fuel Cell [24]



⁴⁸
2.6.3.2 Phosphoric Acid Fuel cell (PAFC):

- The electrolyte in a phosphoric acid fuel cell is phosphoric acid.⁹⁶
- The working temperature is somewhere in the range of 150 and 200°C (around 300 to 400°F) and the efficiency varies from 40 to 80 percent.⁸¹
- Phosphoric Acid Cells with outputs up to 200 KW have been tested, and 11 MW units have been tested.
- PAFCs can withstand a carbon monoxide concentration of around 1.5 percent, allowing them to use a wider range of fuels.
- Sulfur must be separated from gasoline before use.^[24]

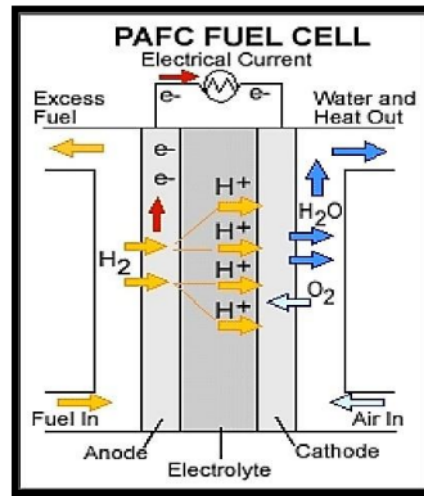
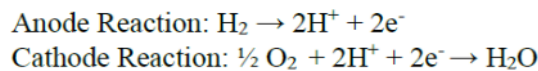


Fig.2.6.3.2 PA Fuel Cell [24]



¹
2.6.3.3 Proton Exchange Membrane Fuel Cell:

- In a proton exchange membrane fuel cell, a polymer electrolyte in the form of a flat, permeable sheet is used.⁹
- The productivity varies between 40 and 60 percent.
- The working temperature is around 80°C.³⁵
- Cell outputs usually vary between 50 and 250 KW.
- The solid, flexible electrolyte will not leak or crack, and the cells will work at a low enough temperature to be ideal for use in homes and automobiles.
- However, both membranes use a platinum catalyst, and their fuel must be filtered, which raises costs. [24]

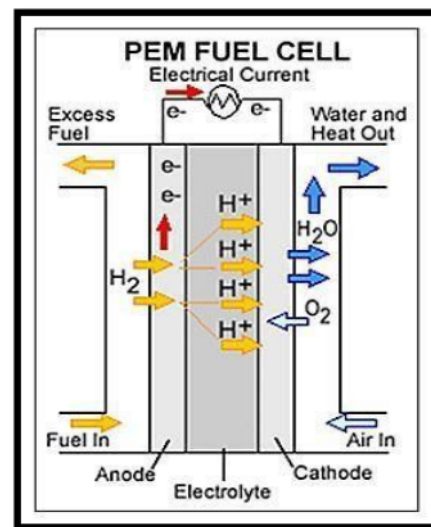
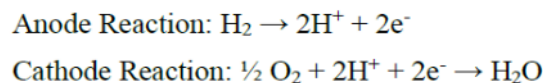


Fig.2.6.3.3 PEM Fuel Cell [24]



28
2.6.3.4 Molten carbonate fuel cell:

- Carbonate in its molten state the electrolyte in fuel cells is made up of high-temperature salt carbonate compounds.
- The operating temperature is about 650°C, and the performance varies from 60 to 80 percent.
- Units with outputs as high as 2MW have been designed, and designs for units with outputs as high as 100MW have been developed.
- The high humidity protects the cell, waste heat can be recycled to produce more energy and carbon monoxide poisoning can be avoided.
- The high temperature, on the other hand, limits the materials and applications of MCPs, they're probably too hot for home use.
- In addition, the electrolyte's carbonate ions are depleted during the reactions, necessitating the injection of carbon dioxide to compensate. [24]

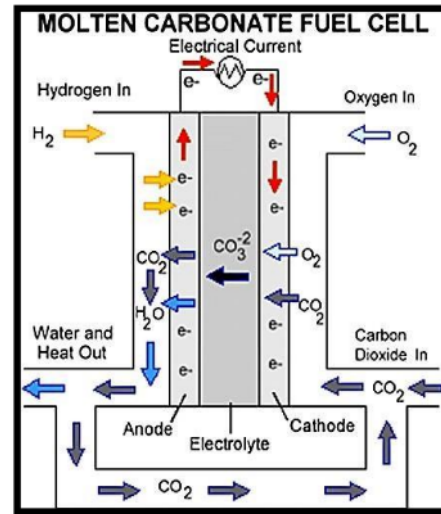
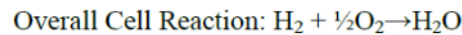
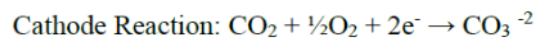
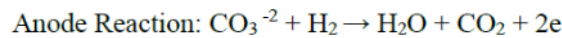


Fig.2.6.3.4 MC Fuel Cell [24]



64
2.6.3.5 Solid oxide fuel cell:

- The electrolyte in solid oxide fuel cells are made up of metal oxides that are rigid and ceramic in nature. The efficiency is around 60%, and the operating temperature is around 1000°C. The cell's production can reach 100 kilowatts.
- At such high temperatures, a reformer isn't needed to remove hydrogen from the fuel, and waste heat can be recycled to generate more electricity.

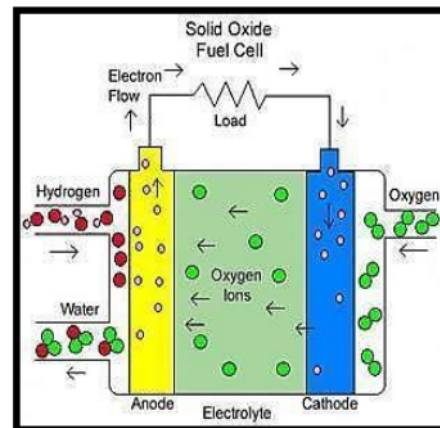
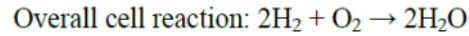
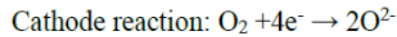
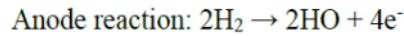


Fig.2.6.3.5 Solid Oxide Fuel Cell[24]

- However, the high temperature restricts SOFC unit applications, and they are typically very broad.
- Strong electrolytes, though not leaking, will break. [24]



2.6.3.6 Direct Methanol Fuel Cell:

- A polymer membrane acts as the DMFC's electrolyte.
- On the anode, a platinum-ruthenium catalyst is used, and on the cathode, a platinum catalyst is used.
- The cell's name comes from the fact that this catalyst extracts hydrogen atoms from liquid methanol, which is used instead of hydrogen as a fuel.
- It operates in a temperature range of 60°C-130°C.
- DMFCs are well-suited to mini power applications requiring not more than 250W of output. [24]

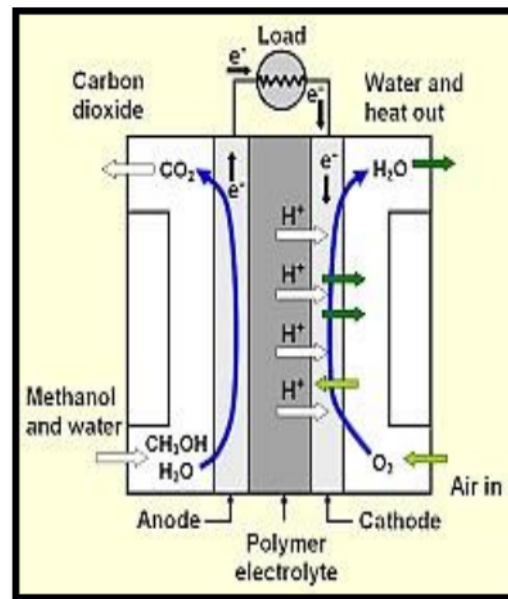
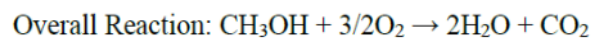
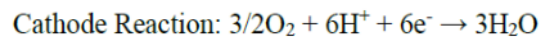
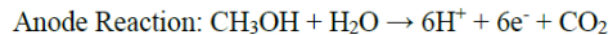


Fig.2.6.3.6 Direct Methanol Fuel Cell [24]



2.6.4 Comparison of the fuel cell types

Table 2.1 Comparison among operating temperature, stack size, and efficiency of various fuel cell types based on basis electrodes. [24]

Fuel Cell Type	Common Electrolyte	Operating Temperature	System Output	Electrical Efficiency
Polymer Electrolyte Membrane (PEMFC)	Perfluoro sulfonic acid	typically, 80°C	<1 KW-100KW	60%
Direct Methanol (DMFC)	Aqueous solution of potassium hydroxide soaked in a matrix	90-100°C 194212°F	UP TO 1.5KW	20-25%
Alkaline (AFC)	Phosphoric acid soaked in a matrix	150-200°C 302392°F	10KW-100KW	60%
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a matrix	300 - 400° F	400KW 100KW MODULE	32-38%
Molten Carbonate (MCFC)	Solution of lithium, sodium, and/ or potassium carbonates, soaked in a matrix	600-700°C 11121292°F	300KW-3MW 300KW MODULE	45-47%
Solid oxide (SOFC)	Yttrium stabilized zirconia	700-1000°C 1202-1832°F	1KW – 2 MW	35-43%

The differences between the different fuel cells are shown **Table 2.1** shows the electrolyte, operating temperature, normal cell stack sizes, and efficiencies in terms of electrolyte, operating temperature, and efficiencies. [24]

Table 2.2 illustrates how each fuel cell type differs from the others in terms of application versatility and constraints.

Table 2.2 compares the applications, advantages, and disadvantages of various fuel cell types.[24]

Fuel Cell Type	Applications	Advantages	Disadvantages
Polymer Electrolyte Membrane (PEM)	<ul style="list-style-type: none"> • Backup power • Portable power • Distributed Generation • Transportation • Specialty vehicles 	<ul style="list-style-type: none"> • Solid electrolyte reduces corrosion & electrolyte management problems. • Low temperature • Quick start-up 	<ul style="list-style-type: none"> • Expensive catalysts • Sensitive to fuel impurities • Low temperature waste heat
Alkaline (AFC)	<ul style="list-style-type: none"> • Military • Space 	<ul style="list-style-type: none"> • Cathode reaction faster in alkaline electrolyte, leads to high performance 	<ul style="list-style-type: none"> • Sensitive to CO₂ in fuel and air • Electrolyte management
Phosphoric Acid (PAFC)	<ul style="list-style-type: none"> • Distributed generation 	<ul style="list-style-type: none"> • Higher temperature enables CHP 	<ul style="list-style-type: none"> • Long start up time • Low current and power
Molten Carbonate (MCFC)	<ul style="list-style-type: none"> • Electric utility • Distributed generation 	<ul style="list-style-type: none"> • High efficiency • Fuel flexibility • Can use a variety of catalysts • Suitable for CHP 	<ul style="list-style-type: none"> • High temperature corrosion and breakdown of cell components • Long start up time • Low power density
Solid Oxide (SOFC)	<ul style="list-style-type: none"> • Auxiliary power • Electric utility • Distributed generation 	<ul style="list-style-type: none"> • High efficiency • Fuel flexibility • Can use a variety of catalysts • Solid electrolyte • Suitable for CHP & CHHP • Hybrid/GT cycle 	<ul style="list-style-type: none"> • High temperature corrosion and breakdown of cell components • High temperature operation requires long start up time and limits

2.6.5 ¹Hydrogen as a Fuel

Hydrogen is the most abundant element in the universe. It is known as the "forever fuel," and it can be made oil, coal, nuclear power, natural gas, a number of other primary energy sources, renewable energy sources and grid electricity. Hydrogen is economically, climatically, chemically, and societally sustainable.

2.6.6 Hydrogen Production and Storage

The hydrogen chain has five links, unlike the other energy conversion chains: processing, storage, transportation, distribution, and usage. Hydrogen can be obtained from fossil fuels, renewable energy sources, a variety of other sources and nuclear fission.

- o Reformation, partial oxidation, or gasification of fossil fuels such as coal and natural gas. Hydrocarbons are found in fossil fuels, and a reformer will separate the hydrogen from the carbon. The reformers, on the other hand, release this fuel into the environment as carbon dioxide.
- o Solar irradiance and wind energy are used for electrolysis to convert de-mineralized water into hydrogen and oxygen.
- o Biomass is converted to biogas in an anaerobic digester, then divided into hydrogen and CO² in a fuel cell or by Pyrolysis. [25]

The majority of hydrogen is now derived from natural gas. It is a safe, reliable and low cost method of transportation.

The most important factor to remember when storing and transporting hydrogen is protection. Hydrogen is a gas of low viscosity and density, as well as high thermal conductivity and molecular velocity. It is a highly flammable and volatile gas. Hydrogen must be treated with caution, and systems must be configured to minimize the risk of leaks.

The cost and distribution system of hydrogen are influenced by the method of production. Hydrogen delivery technologies can aim to reduce delivery costs, improve energy efficiency, preserve purity of hydrogen and reduce the leakage of hydrogen. To meet these challenges, it is important to consider development and distribution options as a framework, both separately and together.

Hydrogen can now be transported via pipeline, rail, barges, or trailers from the point of production to the point of use.

It is possible to adapt a portion of the natural gas distribution system if it is transported via pipelines. This is the most cost-effective method of delivering massive amounts of gaseous hydrogen. Other options, on the other hand, include delivering cryogenic liquid hydrogen, compressed hydrogen gas, or new hydrogen liquid or solid carriers are all possibilities through trucks, railcars, barges, and ships.

Compressed, liquified, or preserved hydrogen, methanol, ammonia, and sodium borohydride hydrogen carriers are examples of hydrogen stored as a man-made fuel are the two different methods for storing hydrogen.

The simplicity, unlimited storage time, and lack of purity limits are the main advantages of storing hydrogen as a high-pressure compressed gas. This is the most widely used technique. At about 22 Kelvin, large quantities of hydrogen can be contained as a liquid. The various types of hydrogen storage systems for fuel cells are shown in **Table 2.3**.

117

Table 2.3 A comparison of more storage systems: [26,27]

Method	Gravimetric storage efficiency, % mass H ₂	Volumetric mass (in kg) of H ₂ per liter	Comments
High pressure in cylinders	0.7-3	0.025	Cheap, widely used
Metal hydride	0.65	0.028	Suitable for small systems
Cryogenic liquid	14.2	0.040	Bulk storage widely used
Methanol	6.9	0.055	Low chemical cost
Sodium hydride pellets	2.2	0.02	Problem of disposing of spent solution
NaBH ₄ solution in water	3.35	0.036	Expensive to run

2.6.7 Fuel Cell for Vehicle Application

2.6.7.1 Proton Electrolyte Membrane Fuel Cell

The electrolyte solution that separates the anode and cathode sides in the archetypical hydrogen-oxide proton exchange membrane fuel cell configuration is contained in a membrane made of a proton-conducting polymer (typically nafon). Before the proton exchange process was fully understood in the early 1970s, this was referred to as a "solid polymer electrolyte fuel cell" (SPEFC). [17]

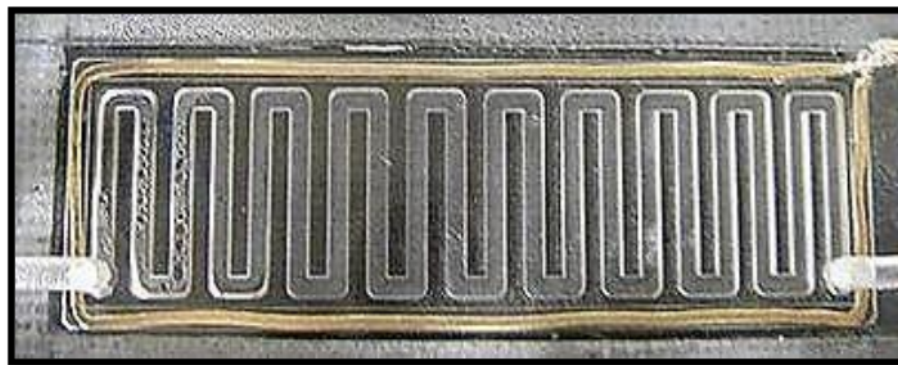


Fig.2.6.7.1 Water condensation on the air channel wall caused by a PEMFC. [17]

The anode catalyst absorbs hydrogen as it diffuses on the cathode side, it splits into protons and electrons at this point. As these protons come into contact with oxidants, they form what are known as proton membranes with multiple facilitation. Since the membrane is electrically insulating, the protons are forced to travel in an external circuit (supplying power) while the electrons are forced to travel in a circuit that isn't internal (supplying power). Oxygen molecules react with electrons (which have passed through the external circuit) and protons on the cathode catalyst to form vapor. There are also hydrocarbon fuels for fuel cells, such as gasoline, methanol (direct and indirect methanol fuel cells), and organic hydrides, in addition to pure hydrogen. Carbon dioxide and water are the waste products of these forms of gasoline. CO₂ is produced when natural gas methane is mixed with steam to produce hydrogen in a process known as steam methane reforming. This would occur outside of the fuel cell, allowing for the use of hydrogen fuel cells indoors, such as in transportation vehicles such as cars and buses.

2.6.7.2 PEM fuel cell

The current subject of research for fuel cell vehicle applications is polymer electrolyte membrane (PEM) fuel cells. PEM fuel cells are built from several layers of various materials. The key components of a PEMFC are described in the following sections-

- Polymer electrolyte membrane
- Gas diffusion layer
- Bipolar plates
- Gaskets
- Catalyst layer

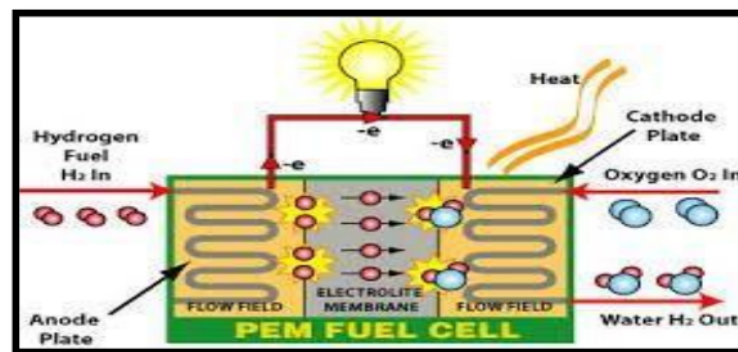


Fig.2.6.7.2 Operation of PEMFC [28]

2.6.7.3 Assembly of Membrane Electrodes

A PEM fuel cell's membrane electrode assembly (MEA) is made up of the membrane and electrodes, catalyst layers (anode and cathode), and diffusion media. [28]

▪ Polymer Electrolyte Membrane (PEM)

The PEM (which is known as a proton exchange membrane) is a special type of plastic wrap that conducts only positively charged ions while blocking electrons. Because it must allow only the necessary ions to move between the anode and cathode, the PEM is vital to fuel cell technology. The chemical reaction would be disrupted if other compounds passed through the electrolyte. The membrane used in transportation applications is very thin—under 20 microns in some cases. [28]

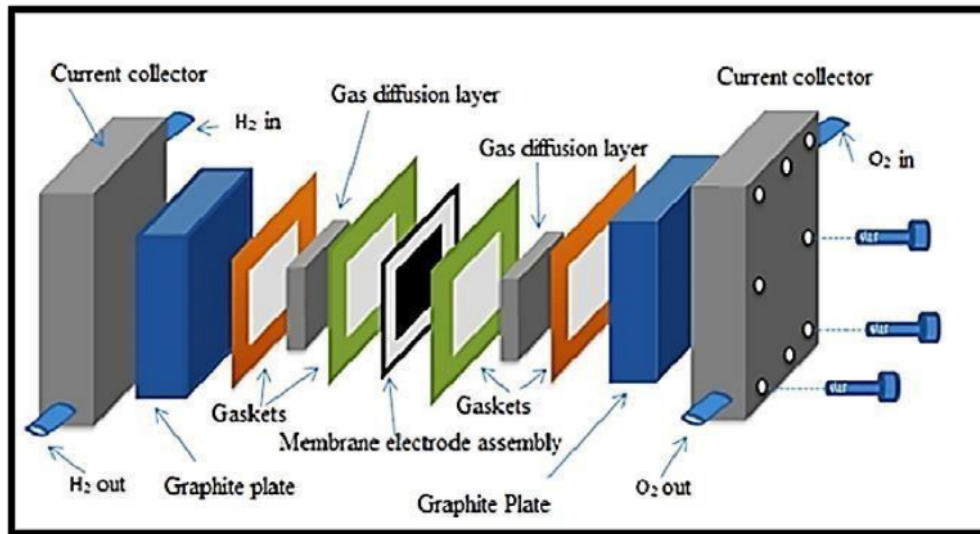


Fig.2.6.7.3 PEMFC Stack Layers [28]

- Layers of catalyst

On all sides of the membrane, a layer of catalyst is applied—the anode layer on one side and the cathode layer on the other. Nanometer-sized platinum particles are spread on a carbon support with a large surface area in typical catalyst layers. This assisted platinum catalyst, as well sandwiched between the membrane and the GDLs are ion-conducting polymers (ionomer). Hydrogen ions are separated into protons and electrons by the platinum catalyst on the anode. By reacting with protons generated by the anode and producing water, the platinum catalyst on the cathode reduces oxygen. The ionomer that is incorporated into the catalyst layers allows protons to pass through. [28]

- Layers of gas diffusion

The GDLs are located outside of the catalyst layers and help with reactant transport as well as product water removal. A sheet of carbon paper is commonly used for each GDL with polytetrafluoroethylene partially coated carbon fibers (PTFE). Gases migrate quickly through the GDL's pores. The hydrophobic PTFE keeps these pores free, preventing excessive water accumulation. The microporous layer is a thin layer of carbon with a large surface area combined with PTFE that is applied to the inner surface of the GDL in many cases. Retention of water (which is required to maintain membrane conductivity) and water release can be balanced by the microporous layer (to allow hydrogen and oxygen to diffuse into the electrodes, the pores must remain open.). [28]

2.6.7.3.1 Hardware

The MEA is a component of a fuel cell that produces electricity, but it requires hardware components to function properly.

- Bipolar Plates

Under normal operating conditions, each MEA produces less than 1 volt, although most applications demand higher voltages. To deliver a voltage that can be used as an output, multiple MEAs are normally by stacking them on top of each other, they can be connected in a series. To hold neighboring cells apart, each cell in the stack is sandwiched between two bipolar plates. These plates, which can be made of metal, carbon, or composite materials, provide both electrical conduction and physical strength to the stack. A "flow area," which is a series gases will flow over the MEA through channels machined or stamped into the plate, is usually located on the plate's surface. A liquid coolant could be circulated through additional channels within each plate.

- Gaskets

Each MEA during a electric cell stack is sandwiched between 2 bipolar plates, however to create a air-tight seal, gaskets should be inserted round the edges of the MEA. Typically, these gaskets area unit made from a rubbery chemical compound. [29]

2.6.7.4 Detail of the PEMFC Stack

Because of its high power density, low operating temperatures, and low local emissions, quiet activity and fast start-up-shutdown, proton exchange membrane fuel cells are a promising technology. One use for PEMFC is as a portable power supply. The PEMFC is normally built as a stack of several cells for this reason. The output of PEMFCs was investigated by assembling 1, 3, 5, and 7 cells, then evaluating the polarization curves generated by the fuel cell test system. [29]

2.6.7.5 Material's

PEMFC stacks included components such as MEA, aluminum end-plates, gold-covered copper current collectors, silicon elastic gaskets (sheet thickness 0.5mm), FU4369 graphite bipolar plates, and other frills (Swagelok tubing fitting, rods, stainless steel nuts and bolts, ring, heat-resistant shells, silicone tubing). MEA was made up of a Nafon 117 membrane, 60 percent Pt/C gas diffusion electrodes (GDE) with a 0.5 mg/cm² Pt loading, and a 5% Nafon 117 solution. Hydrogen UHP (99.99 percent purity) and oxygen were used as reactant gases, with nitrogen serving as a purging gas. The reactant gases flowed in Z form in this assembly, as shown in Fig.2.5.6.4

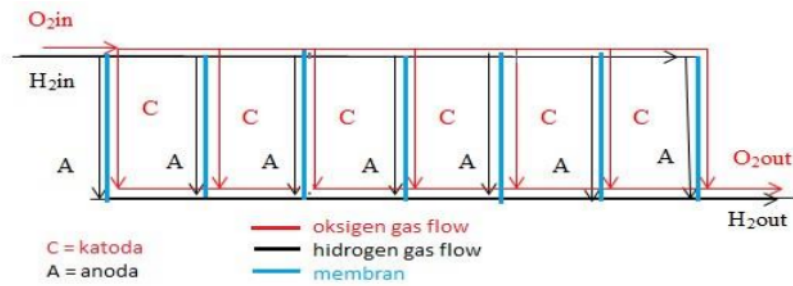
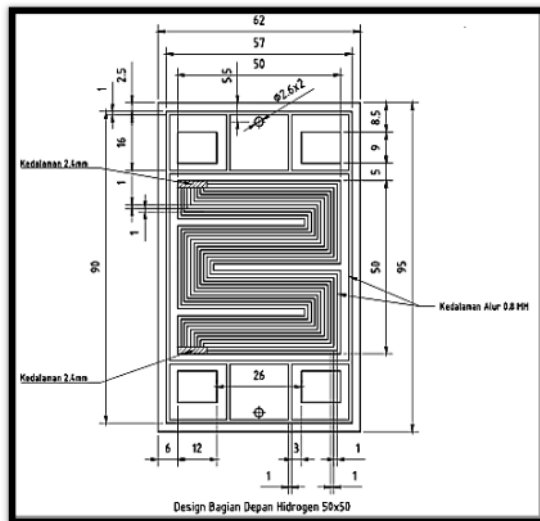


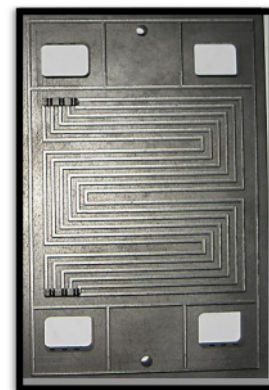
Fig.2.6.7.4 Z type gas flow configuration [29]

2.6.7.6 Some Stack Components Fabrication

In the hydrogen flow field, the bipolar plates were fuel cell grade FU 4369 graphite bipolar plates with a 6-channel serpentine pattern and dimensions of 62 mm x 95 mm x 5 mm in the oxygen flow field. The rib was 0.8mm wide, and the channels were 1mm deep and wide (Figure 2.12). Gold-coated copper plates with a thickness of 0.2 mm and dimensions of 62 mm x 120 mm x 1.0 mm were used for the new collector plates. The dimensions of the aluminum end-plates were 80 mm x 115 mm x 16 mm. [29]



(a)



(b)

Fig.2.6.7.5 Design of bipolar-plates (a) diagram, (b) picture. [29]

2.6.7.7 Measuring the Performance of PEMFCs

In the cell study, high immaculateness hydrogen (99.99 percent) and as a fuel and oxidant, oxygen gases were used, individually. The Smart-2 PEM/DM cross breed energy unit test framework was utilized to assess the stacks (WonATech Co., Ltd. Korea). The test station had two major systems: a gas feeding system and a control system. The cell's gasoline and oxidant gases were supplied and handled by a gas feeding system, while the FC stack's operation conditions were measured and controlled by a regulating system. Mechanical valves in the test station could be used to change the back pressure of the fuel cell for each reactant.[29]

2.6.7.8 Membrane Electrode Assembly Preparation

MEAs (membrane electrode assemblies) were created for the experiment by hot pressing two industrial gas diffusion electrodes (GDEs) (60 wt% Pt/vulcam XC72 on carbon cloth, Pt loading 0.5 mg/cm^{-2}) on each side of a DuPont! Nafon 117 membrane, 1 minute at 120°C , 20 kg To ensure good interaction between the GDE and the membrane, the Nafon 117 solution (5 percent solution of 1 mg cm^{-2} (Neroflash PTE Ltd.)) was screen printed on the catalyst surfaces of two GDEs. [29]

To extract organic impurities, the Nafon 117 membrane was treated with three percent hydrogen peroxide (H_2O_2) at $70\text{-}80^\circ\text{C}$ for one hour. To completely H form the membrane, it was boiled in $0.5 \text{ M H}_2\text{SO}_4$ for 1 minute at $70\text{-}80^\circ\text{C}$, then rinsed twice with distilled water at $70\text{-}80^\circ\text{C}$ for one hour to extract any H_2SO_4 that remained on the surface of the membrane. [29]

2.6.7.9 Consolidating (1 , 3 , 5 And 7) Cells

One cell, three cells, five cells, and seven cells make up the PEMFC stack, which has a total a 25 cm^2 active region 2 aluminum end plates with eight threaded stainless-steel rods, bolts, and nuts sandwiched the MEAs, gasket, 2 monopolar plates (for hydrogen and oxygen flow), bipolar plates, and current collectors between two monopolar plates (for hydrogen and oxygen flow). Gaskets are used to seal the gap between the electrolyte membrane and the bipolar layer, and they must be supple, durable, and corrosion-resistant. [29]

Two positioning rods were used to align the stack during assembly. One by one, all of the components were stacked and aligned. The measures of SS 316 bolts are M6 x 0.8 mm with 58 mm, 70 mm, 90 mm and 100 mm length for the 1cell, 3cells, 5cell and 7cell stacks individually. To

mount the PEMFC 1cell, 3cells, 5cells and 7cells, each bolt received the same clamping torque (20kgf).

2.6.7.9.1 By varying gas flow rate for single cell

The number of cells in the first step was kept constant at one. After varying the gas flow rate, each of its performances was evaluated. Back pressure was also used to demonstrate the effect. [29] Every condition is mentioned in Table 2.4.

Table 2.4 Gas flow rate & back pressure variation for single cell. [29]

	Condition 1	Condition 2	Condition 3	Condition 4
Volumetric flow rate of H ₂ /O ₂ (mL/min)	100 / 140	60 / 140	100 / 100	100 / 100, with ¾ psi back pressure

2.6.7.9.2 By varying cell number

In the second phase, the number of cells was different. On the other hand, gas flow rates were kept proportional to the number of cells. Back pressure was not used in this phase due to the fuel cell test device's limitations. After that, each of its performances was assessed.[29]

Every condition is mentioned in Table 2.5.

Table 2.5 No. of cells variation. [29]

	1 cell	3 cells	5 cells	7 cells
Volumetric flow rate of H ₂ /O ₂ (mL/min)	100 / 100	300 / 300	500 / 500	700 / 700

2.6.7.10 Result and Discussion

Fig.2.6.7.6 shows that for single cells, the condition of 100/100 with back pressure yielded the best results, followed by 100/100, 100/140, and 60/140, respectively.

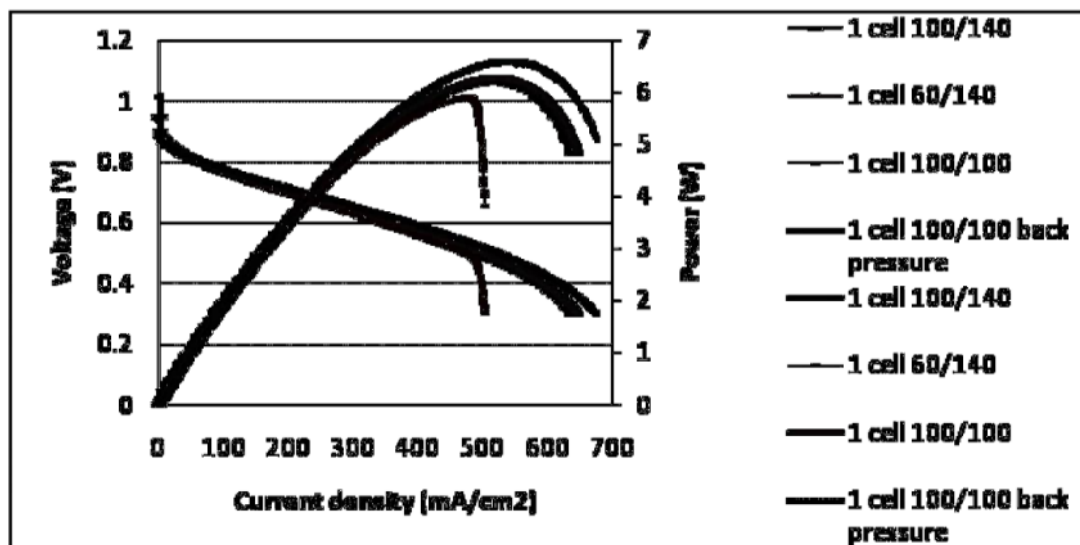


Fig.2.6.7.6 Power output and polarization curves for single cell. [30]

To begin with, it demonstrated that back pressure has a major influence on power device proficiency, as evidenced by numerous logical books and diary papers [30-32].

Second, it was discovered that the immersed stream rate for a single cell is 100/100 mL/min, and that the best stoichiometry proportion for these reactants is 1:1. In principle, the mole percentage of hydrogen and oxygen gases in the arrangement of water is 2:1.

Further research is required to explore the difference between the theoretical and experimental ratios.

The efficiency test results for 1cell, 3cells, 5cells and 7cells are shown in Fig.2.6.7.7.

Table 2.6 data could be extracted from these curves as follows.

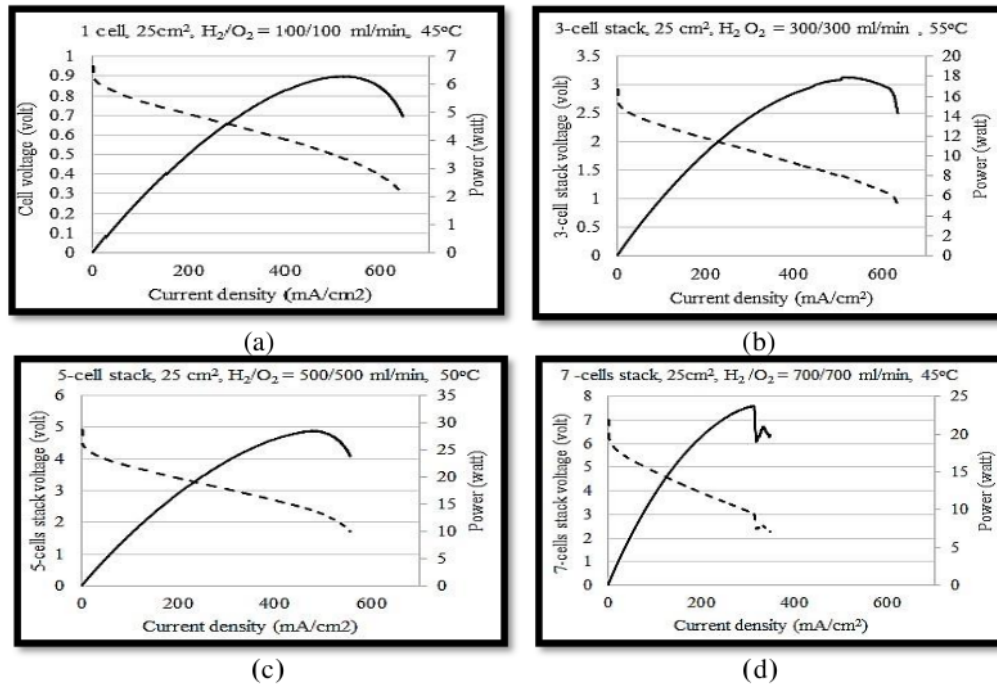


Fig.2.6.7.7 Power output and polarization for (a) 1cell, (b) 3cells, (c) 5cells, (d) 7cells.

Table 2.6 Data extracted from power output & polarization of 1cell, 3cells, 5cells, 7cells. [32]

Parameter	1 Cell	3 Cell	5 Cell	7 Cell
H ₂ /O ₂ volumetric flow rate(mL/min)	100/100	300/300	500/500	700/700
Open circuit voltage, OCV(volt)	1.0	2.9	4.9	7.0
Operational voltage, Vop(volt)	0.6	1.8	3.0	4.0
Operational current density Jop (mA/cm ²)	379	297	316	165
Operational power density, Pop(mW/cm ²)	227	535	948	693

Table 2.6 demonstrates that each cell's opencircuit voltage values is natural, as predicted by theoretical studies and verified by numerous research papers [32]. The operational voltage was calculated using a formula [33]. The operational current density findings were very shocking. On operation/testing, the 7cells suggested a come up short or broken state. If all of the Jop expected values were the same or similar, four combinations, that would be natural. However, the outcome was unexpected. 1 cell had the strongest Jop, followed by 5 cells, 3 cells, and 7 cells, in that order. As a result, the operating power density Pop pattern became erratic. Many factors may have contributed to this unexpected outcome, including the efficiency of MEA assembly (hot-pressing), reactant gas leakage, and so on. When the number of cells grows, so does the chance of a defect.

2.7 Catalyst

Catalysis is the process of increasing the rate of a chemical reaction through the use of catalysts involving an external element called a Catalyst [34], in the catalyzed reaction, which is not consumed and can act repeatedly. In theory, only a small quantity of catalyst is frequently required. [35]

Catalyzed responses are quicker overall since they require less actuation energy. In catalyzed components, the impetus generally responds to create an impermanent moderate that is then used to recover the beginning of a cyclic stage.

2.7.1 Types of Catalyst:

- 1) Heterogeneous,
- 2) Homogeneous.

2.7.1.1 Heterogeneous Catalyst:

Catalysts that are heterogeneous operate in a different step than the reactants. In a liquid or gaseous reaction mixture, solids that work on substrates are the most common heterogeneous catalysts. Depending on how adsorption occurs, various mechanisms for reactions on surfaces are known. The reaction rate is influenced by the total surface area of the solid. For a given mass of particles, the smaller the catalyst particle size, the greater the surface territory. [36]

The active sites of a heterogeneous catalyst reaction take place on the atoms or crystal faces. A crystal edge with an imperfect metal valence, a planar exposed metal surface, or a complex

combination of the two may be the active site, depending on the mechanism. As a result, a heterogeneous catalyst's surface, as well as the majority of its volume, can be catalytically inactive. The design of the active site necessitates technically difficult analysis. As a result, empirical research into new metal combinations for catalysis is continuing. [36]

2.7.1.2 Homogeneous catalysts:

While homogeneous catalysts work similarly as the reactants, heterogeneous catalysis is governed by universal mechanistic principles. The substrates and homogeneous catalysts are usually dissolved in the same solvent. Homogeneous catalysis can be seen in the effect of H^+ on the esterification of carboxylic acids, such as the formation of methyl acetate from acetic acid and methanol. A Hydro formylation, which involves the process of combining carbon monoxide with an alkene to produce an alkyl aldehyde is a high-volume operation that necessitates the use of a homogeneous catalyst. Alcohols, acids (such as detergents), and polyols are some of the products that can be made from the aldehyde (for polycarbonate and polyurethane plastics). Homogeneous catalysis is frequently confused with organometallic catalysts by inorganic chemists. [37,38]

2.7.2 Pt as a best catalyst:

Platinum is an atomic number 78 chemical element and the symbol Pt. It's a silverish white transition metal that's dense, malleable, ductile, and extremely unreactive. Its name comes from the Spanish word *platina*, which means "little silver." [39,40]

Platinum is used in catalytic converters, laboratory instruments, electrical contacts and electrodes, platinum resistance thermometers, dentistry equipment, and jewelry. Since it is a heavy metal, exposure to its salts causes health problems, but metallic platinum has not been linked to negative health effects due to its corrosion resistance. [41]

2.7.2.1 As a catalyst:

Platinum is most widely used in chemical reactions as a catalyst, frequently in the form of platinum black. Platinum powder has been used as a catalyst since the early nineteenth century, when it was used to catalyze the combustion of hydrogen. Its most common use is as a catalytic converter in vehicles, where it allows for complete combustion of unburned hydrocarbons in exhaust to produce carbon dioxide and water vapor. Platinum is also used in the petroleum industry as a catalyst for a

variety of methods, including catalytic reforming of straight run naphtha into aromatic-rich higher octane gasoline, the hydrogenation catalyst PtO₂, known as Adams' catalyst, used in the hydrogenation of vegetable oils. Platinum is also used to catalyze the breakdown of hydrogen-peroxide into water & oxygen as an oxygen reduction catalyst in fuel cells [42-44].

2.7.2.1.1 Research of catalyst:

The majority of current catalyst research for PEM fuel cells can be listed as having one of the following key goals:

- To outperform the carbon supported platinum particle catalysts currently used in PEM fuel cells in terms of catalytic activity.
- To prevent impurity gases from poisoning the PEM fuel cell catalyst.
- The use of platinum based catalyst would lower the cost of the fuel cell.

2.8 Comparison between ICE and PVFCHEV

Internal combustion engine that generates motive power by combusting gasoline, oil, or another fuel with air inside the engine. A PVFC hybrid electric vehicle (PVFCHEV), on the other hand, is an electric vehicle with a solar panel as an auxiliary power source, as well as a fuel cell, a battery, and a supercapacitor.

2.8.1 ICE

Internal combustion engines (ICE) offer excellent drivability and dependability, as demonstrated by their use in more than 250 million highway transportation vehicles in the United States. In addition to gasoline and they should use renewable or alternative fuels instead of gasoline and diesel (e.g., natural gas, propane, biodiesel, or ethanol). They can also be combined with hybrid electric powertrains to improve fuel efficiency or with plug-in hybrid electric systems to increase hybrid electric vehicle range.

2.8.2 ICE Operation

Combustion is the most fundamental chemical method for releasing energy from a fuel and air mixture, also known as burning. The fuel is ignited and burnt inside the engine in an internal combustion engine (ICE). The engine partially converts the energy from combustion into function.

The engine is made up of a fixed cylinder and a moving piston. The expanding combustion gases push the piston, which rotates the crankshaft. The vehicle's wheels are gradually pushed through a series of gears in the powertrain as a result of this motion.

Internal combustion engines are currently available in two types: spark-ignition gasoline engines and compression-ignition diesel engines. The majority of these engines are 4-stroke cycle engines, which require 4-piston strokes to complete a cycle. Intake, compression, combustion and power stroke, and exhaust are the four distinct processes that make up the cycle.

The way gasoline engines supply and ignite fuel differs from how compression ignition diesel engines do. The fuel is mixed with air and then inducted into the cylinder during the intake process of a spark ignition engine. After the piston compresses the fuel-air mixture, the spark ignites it, causing combustion. During the power stroke, the combustion gases expand and drive the piston. Just air is inducted into a diesel engine, which is then compressed. Diesel engines then spray the fuel into the hot compressed air at a controlled rate, igniting it.

2.8.3 Photovoltaic fuel cell hybrid electric vehicle

A Photovoltaic fuel cell hybrid electric vehicle (PVFCHEV) is an electric vehicle that uses a solar module as a secondary power source and a fuel cell in conjunction with a battery and supercapacitor to power its on-board electric motor. In vehicles, PV cells as a secondary source and fuel cells deliver energy to power the engine, with compressed hydrogen and oxygen from the air. The majority of fuel cell vehicles are emission less vehicles, emitting only heat and water. Unlike internal combustion engines, hydrogen vehicles concentrate pollution at the hydrogen manufacturing site, which is normally produced from reformed natural gas. It's possible that transporting and storing hydrogen would pollute the environment. [54]

Critics question whether hydrogen would be as reliable or cost-effective as other zero-emission technologies for cars.

All fuel cells have three components: an electrolyte, an anode, and a cathode [45]. In theory, a hydrogen fuel cell works like a battery, generating enough energy to power an electric motor. The fuel cell would be refilled with hydrogen instead of being recharged. [46].

Table 2.6 Comparison between ICE and PVFCHEV [54]

ICE	PVFCHEV
An engine which generates motive power by the burning of petrol, oil, or other fuel with air inside the engine.	A pvfc hybrid electric vehicle (PVFCHEV) is a type of electric vehicle which uses a pv panel as auxiliary source with a fuel cell, in combination with a battery and supercapacitor.
By fuel combustion it is converted into mechanical energy.	By fuel consumption it is converted chemical energy into electrical energy then mechanical energy.
Maximum thermal efficiency is about 25%-50%.	Theoretically maximum efficiency is 85-90%.
Combustion high.	No combustion.
High CO ₂ Emitted During Fossil Fuel Burned.	Zero CO ₂ Emission
Reasonable Vehicle Price at Present	High Vehicle Price at Present Due to Stack, Model Development.
Gasoline, Petrol, Octane and Diesel	Photovoltaic energy with pure Hydrogen and Oxygen.

2.9 PEM Fuel Cell Application

PEM fuel cells are used for a variety of purposes in transportation, owing to their possible effect on the environment and the reduction of green-house gas emission (GHG). Other applications include distributed/stationary and portable power generation. Because of their advantages, the majority of major car manufacturers depend exclusively on PEM fuel cells. Some advantages are-

- Light weight
- Power density is high
- Low temperature and
- Outstanding Dynamic Assets.

Transportation applications are the perfect fit for PEMFCs. PEMFCs for buses can achieve up to 40% efficiency by using compressed hydrogen as a fuel. Because the availability of space to house the machine store the fuel, PEMFCs are typically mounted on buses rather than smaller vehicles. PEMs must be incorporated into current vehicle and energy systems technology must be upgraded as technological issues in transportation.[46]

However, ²⁹ if hydrogen is obtained from fossil fuels, fuel cell vehicles are not ⁹¹ beneficial. When used as hybrids, however, they prove to be beneficial. PEMFCs have the ability to be used as a source of stationary electric power generation, they compete with other types of fuel cells because they can produce 5 kW at 30% efficiency, primarily SOFCs and MCFCs. Methane can be used in other kinds of fuel cells and are therefore more versatile than PEMFCs, which require high purity hydrogen to operate. As a result, before economically scalable pure hydrogen is usable, for small-scale systems PEMFCs are best.[45]

2.9.1 PVFCHEV:

¹⁰ A photovoltaic fuel cell hybrid electric vehicle (PVFCHEV) is an ev that powers its onboard electric motor with a solar module as a secondary source and a fuel cell combined with a battery and super capacitor. PV cells as a secondary source and fuel cells in vehicle produce energy to drive the engine, usually by using compressed hydrogen and oxygen from the atmosphere. PVFC vehicles are zero-emission vehicles, emitting only heat & water. Unlike internal combustion engines, hydrogen fuel powered vehicles concentrate pollution at hydrogen manufacturing area, which is normally produced from reformed natural gas. It's possible that transporting and storing hydrogen would pollute the environment. [47]

2.9.2 HEV's [48-51]

2.9.2.1 Model in Production

□ ECO 3GL

- **Manufacturer:** Economia.
- **Model years:** 2017 to present.
- **Range:** upto 160+ km. (est.)
- **Price** US\$ 4,500
- **Solar batt. cell conv. Efficiency:** 25% plus
- **Rated power generation output:** 130 W



Fig.2.9.2 [48]

□ Hyundai Sonata HEV

- **Manufacturer:** Hyundai
- **Model years:** 2019 to present.
- **Range** 1100+ km. (est.)
- **Price** US\$ 35,300
- **Solar batt. cell conv. Efficiency:** 22.8%
- **Rated power generation output:** 143 kW



¹ Fig.2.9.2 [49]

□ Squad Solar City Car

- **Manufacturer:** Squad Mobility
- **Model years:** 2019 to present.
- **Range** 60+ km. (est.)
- **Price** US\$ 6,100
- **Solar batt. cell conv. Efficiency:** 22%
- **Rated power generation output:** 100 W



1
Fig.2.9.2 [50]

2.9.2.2 Prototype model created by Toyota

□ Toyota solar powered drive

- **Manufacturer:** Toyota (prototype)
- **Model years:** 2019 to present.
- **Range** 100+ km. (est.)
- **Solar batt. cell conv. Efficiency:** 34% plus
- **Rated power generation output:** 860 W



1
Fig.2.9.2 [51]

2.10 Summary

This section is tightly linked to a better comprehension of solar cells & fuel cells, as well as their capacity and characterization. PEMFC stack detail; creation of some stack segments; testing PEMFC exhibitions; hydrogen certificate as a perfect source; proton electron power module film; anode get together; Layer terminal arrangement; PEM energy component applications; examination of PV cell types and power module types; correlation of energy unit types based on their utilizations, advantages, and disadvantages; PEMFC stack detail; creation of some stack segments; testing PEMFC exhibitions; hydrogen certificate as a perfect source; proton electron power module film; amassing 1cell, 3cell, 5cell, and 7cell; changing gas stream rate for single cell; varying the number of cell impulse structures.

CHAPTER 3

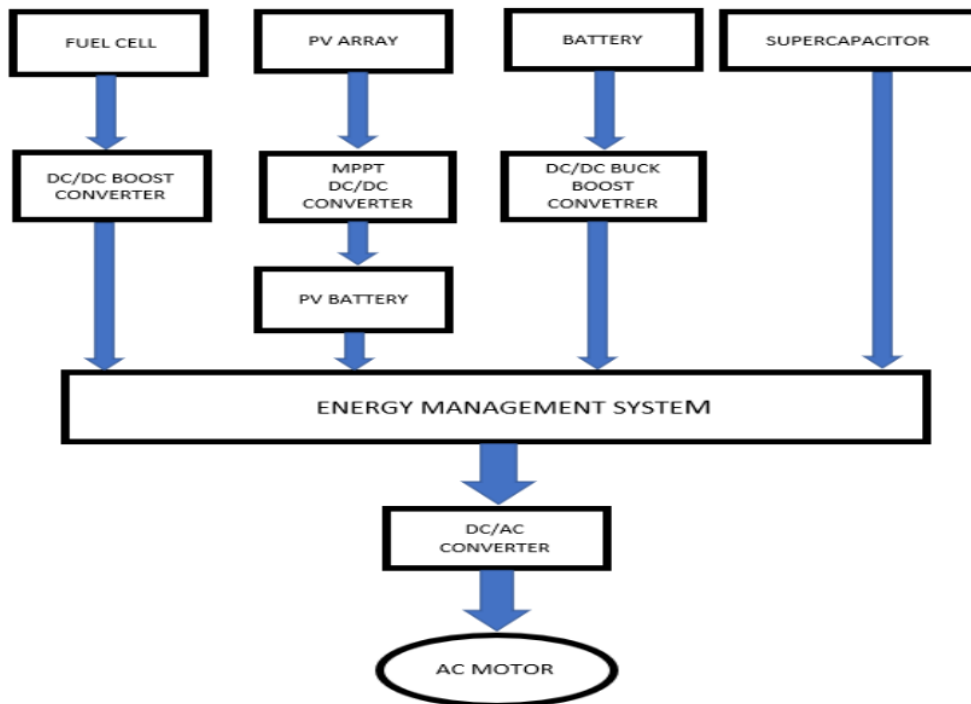
SYSTEM DESIGN AND SIMULATION

3.1 Introduction

In this chapter, the block diagram of photovoltaic cells combined with PEMFC vehicle simulation is explained. The most reliable renewable energy source is solar energy, as well as the most practical as a backup source of energy. One of the future generation truck models that runs on a mix of hydrogen and oxygen fuel is the solar cell with PEMFC car. Fuel-cell vehicles have been developed over the last decade as a result of the transportation industry's ability to produce effective and environmentally friendly traction systems. Fuel cells are also used in cars, taxis, tramways, railways, and airplanes. When compared to conventional internal combustion engines, they deliver electrical power with high efficiency, low noise, and near-zero emissions [52].

3.2 System Methodology of Vehicle

Block Diagram of the Vehicle System is given below:



1 Fig.3.1 Block Diagram of the Vehicle System

3.2.1 Hybrid System Modules

A photovoltaic cell framework is designed to meet a 5kW secondary demand, while the fuel cell unit framework is intended to fulfill a normal need (6-13kW), with batteries and supercapacitors helping the latter during constant and transient peak demand, individually. The hybrid method, on the other hand, is constructed using the procedure and the topology used is discussed in [26,27].

Battery modules with four valences (12.5 V, 40 Ah) and six NESSCAP supercapacitor modules are used in this system (291.6V,15F). A 12.5kW fuel cell power module FCPM with proton exchange membrane (PEM) from Hydrogen is used in the fuel cell system. The energy management system determines a maximum input/output current reference and an output voltage reference for the dc/dc converters (implemented in the controller). Owing to a specified time, two converters are used for the battery configuration because a bidirectional dc/dc converter was not readily available. The battery system is covered by a battery management system (BMS) from overcharging, overheating, and over discharge. A shielding resistor is often used to avoid supercapacitor or inverter input voltage overvoltage [21].

The following are the key characteristics of the hybrid power system:

- A standard lightweight vehicle has a surface area of about 5m² and can be equipped with a PV array of up to 1250 W. Every panel contains a 245W Isofoton ISFP-245 Black polycrystalline solar cell with an open circuit voltage of 37.52 V and a short circuit current of 8.54 A. In a later section of this article, the PV array requirements for the 5kW type lightweight PVFCHEV will be discussed.
- The fuel-cell system auxiliaries are built into the PEM FCPM, rated at 12.5kW and 48V_{dc} (coolant pump and fans, air blower, filter, H₂ recirculation pump, H₂ pressure regulator and valves, etc.). A built-in controller (engine control unit) for interfacing with the main controller and protections is also included in the FCPM (H₂ low pressure, overheating, overcurrent, and undervoltage in the stack).
- The battery system is made up of four Li-ion battery modules with a voltage of 12.5V and a power of 40Ah attached in series. Each module has an internal controller for cell-to-cell (or intra-module) balancing, cell temperature and voltage/current sensing, SOC calculation, and RS485 communication with a larger BMS.

- Six 291.6V - 15.6F supercapacitor modules are attached in series to form the supercapacitor system. For cell-to-cell balance, each module has an internal controller (ultracapacitor management unit), voltage and temperature sensing, and cell-to-cell balancing [53].
- The MPPT converter maintains the operating point of the PV panel in the specified irradiation and temperature, and the MPPT technique is based on the Perturb and Observe (P&O) algorithm at the maximum power point [53].
- The fuel-cell dc/dc converter assembly is made up of the following components: It's made about five paralleled (40–64 V) dc-in 270-V (adjustable 243–297 V) dc-in dc/dc independent boost converters with a 9.2-A_{dc} output. Every module in the device is secured against overload and over-voltage. The use of decoupling diodes allows for redundant operation. To achieve current balance, active current sharing is used. The output voltage and input current are controlled by external signals (0–10 V). [53]
- The following components make up the battery dc/dc converter system: It is made up of two (40–58.4 V) dc-in 270-V power supplies. 7-A_{dc} (adjustable 243–297 V) dc/dc independent boost converters connected in parallel plus a single (243–297 V) power supply 48-V dc-in (adjustable from 0 to 58.4 V) out 20-A_{dc} (max) isolated buck converter (dc/dc). The characteristics of both converters are identical to those of the fuel cell dc/dc converter [53].
- The inverter device is made up of three (160–320 V) dc inverters. In a 200-V_{ac} environment 5-kVA at 400 Hz parallel link of dc/ac independent converters overload, overvoltage, and short-circuit security are all built into the device. With less than 3% total harmonic distortion, each converter's output voltage is regulated to the nominal voltage. [53].

3.3 PVFC Hybrid vehicle system

This section describes each aspect of the hybrid power system's modeling methodology as follows:

3.3.1 Module of Photovoltaic Cell

A Simulink PV array block with an analogous circuit is used to create the PV array model [54]. The following equations illustrate the mathematical models [55]. The current in a solar cell is the formula for :

$$I = I_L - I_0 \left[\exp \left(\frac{q(V + IR_s)}{nkT} \right) - 1 \right] \dots \dots \dots (1)$$

Q indicate electron charge, n indicate the diode factor value, and k is Boltzman's constant. V indicate cell voltage, I₀ indicate the diode saturation current, T indicate the cell temperature (K). Current source I_L is defined as follows in equation (2):

$$I_L = I_{SC} \left(1 + \alpha_t(T - T_{ref}) \frac{G}{G_{ref}} \right) \dots \dots \dots (2)$$

G_{ref} is the reference nominal shortcircuit current at the standard condition, t is the temperature coefficient, and T_{ref} is the standard condition temperature, which is set to 25°C. I_{SC} is the reference nominal short-circuit current at the standard condition, t is the temperature coefficient, and T_{ref} is the standard case temperature, which is set to 25°C. A diode's saturation current I₀ is described as:

$$I_0 = I_{0(ref)} \left[\left(\frac{T}{T_{ref}} \right)^3 \exp \left(\frac{-qE_g}{nk} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right) \right) \right] \dots \dots \dots (3)$$

The bandgap voltage is E_g, and the saturation current is I_{0(ref)} at general conditions.

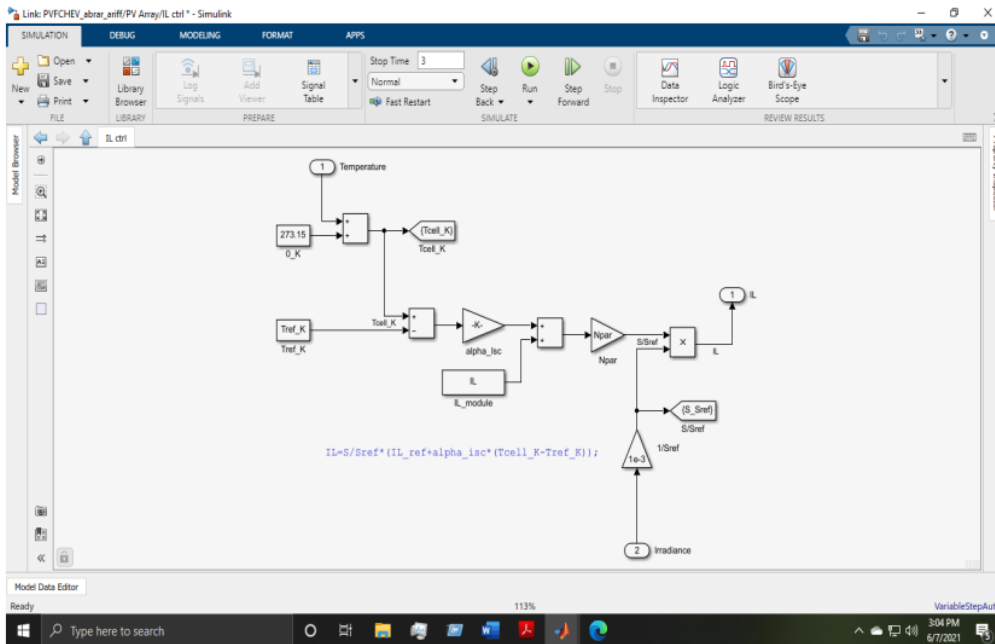


Fig.3.2 Model of a Solar Array [Matlab View]

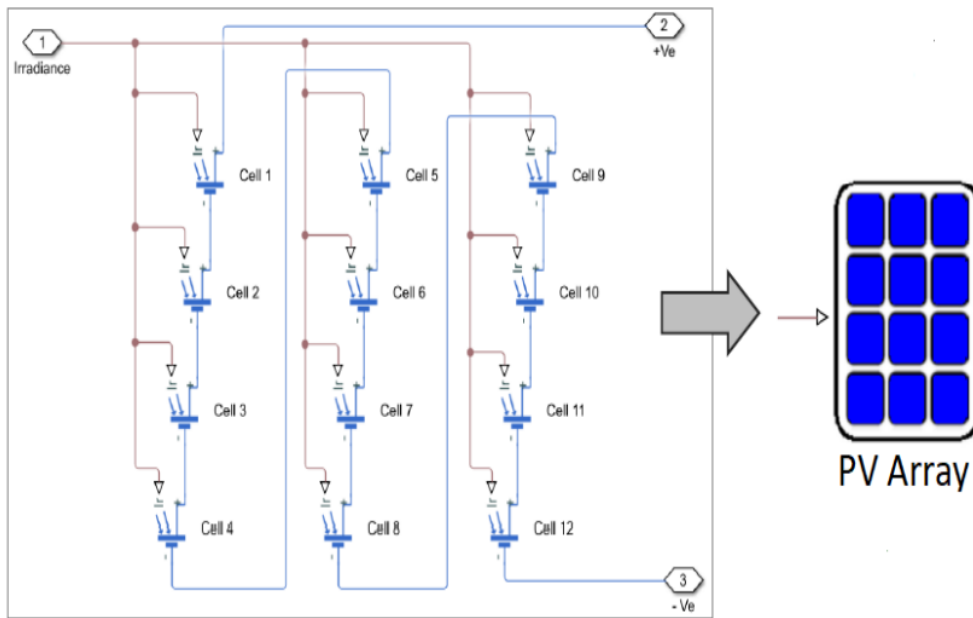


Fig.3.2 Model of a Solar Array [55]

Table 3.1 Input Parameter for Solar Array Model

Photovoltaic Array Model Input Parameter	
Series-connected modules per string	5
Modules per cell	72
MPP's maximum current	7.99
MPP's maximum voltage	30.65
Current in a short circuit (I_{sc})	8.55
Open circuit voltage (V_{oc})	37.53
Maximum power per module	245

3.3.2 Module of Fuel Cell

PEM fuel cells are the most popular fuel cells used in automotive applications. That's also attributable to the fact that they run at low temperatures (-20 to 100 degrees Celsius), allowing for fast transfers from idle to full load service. In MATLAB/Simulink, the hybrid system model, which includes a fuel-cell stack model, is developed. The fuel-cell design in Simulink is an updated version of the old. [56], which ignores the dynamics of the rate of reaction movement inside the electrode. As a consequence, the determination of partial pressure of reactants is decoupled from electrode characteristics (such as anode/cathode volume and orifice area). A fascinating aspect of this model is that the model parameters can be derived from a datasheet or a basic polarization curve test. [57] Below are the primary equations. For this thesis, this model was selected. When reaction kinetics (activation losses) and charge transfer (resistive and diffusion losses) are factored in, the net result is the cell output voltage is calculated as follows:

$$V = E_{oc} - V_{act} - V_{ohm} \dots \dots \dots (4)$$

$$V_{act} = A \ln \left(\frac{I_{fc}}{I_o} \right) \cdot \frac{1}{\frac{sT_d}{3} + 1} \dots \dots \dots (5)$$

$$V_r = r_{ohm} \cdot i_{fc} \dots \dots \dots (6)$$

T_d is the time it takes for the cell to settle to a current step, where A represents the T_{afcl} slope (in volts), i_0 represents the exchange current (in amperes), and r_{ohm} represents the cell and diffusion resistance combined (in ohms) During a rapid shift in cell current, it is known that the cell voltage will exhibit a three-times-the-time constant delay. A fuel-cell stack's output voltage (multiple cells connected in series) is measured as follows:

$$V_{fc} = N \cdot V \dots\dots\dots(7)$$

N stands for the number of cells.

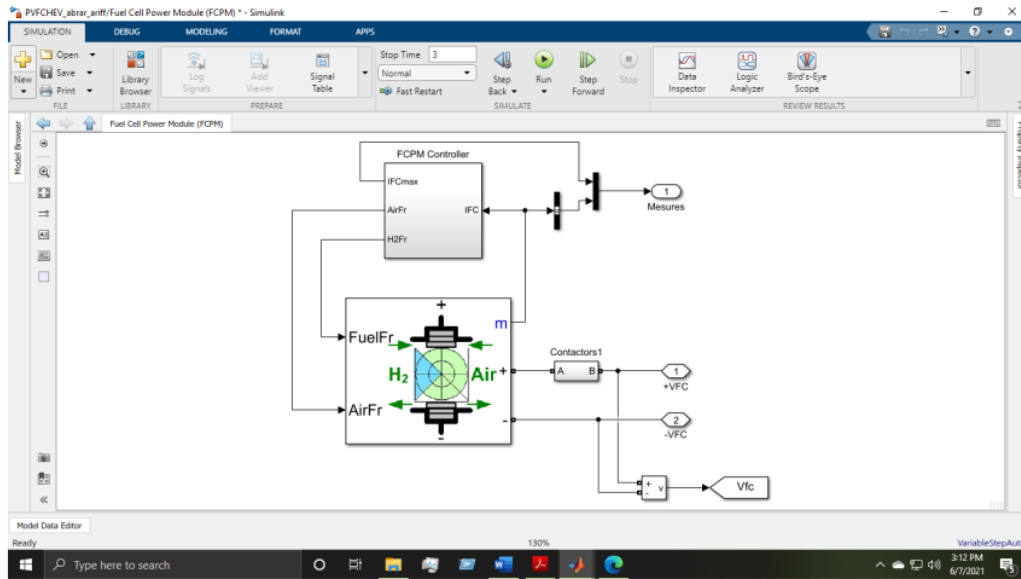


Fig.3.3 Model of a FC Stack [Matlab View]

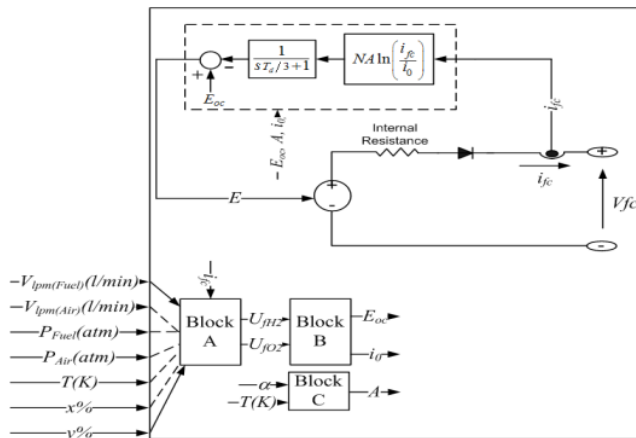


Fig.3.3 Model of a FC Stack [55]

⁶ Fig.3.3 shows the Simulink diagram of the fuel-cell stack. Present measures are applied in compliance with the fuel-cell limit permissible current as soon as the FCPM is initiated at no load. This enables the FCPM's steady and intermittent output with the load demand to be observed, which is needed for validation. Table 3.2 lists the model's desired parameters.

¹ Table 3.2 Fuel Cell Model Input Parameter

Input Parameter for the Fuel Cell Model	
Voltage at 0A and 1A [0(V), 1(V)]	[52.5,52.46]
Operating point (nominal) [Inom (A), Vnom (V)]	[250, 41.15]
Operating point (maximum) [Iend(A), Vend (V)]	[320,39.2]
Count of cells	65
Stack efficiency (nominal) (%)	50
Temperature in use (Celsius)	65
Nominal air flow rate (Ipm)	732
Supply pressure (nominal) [Fuel (bar), Air(bar)]	[1.16,1]
Nominal composition(%) [H2,O2,H2O(Air)]	[93.5,21,1]
Response time of fuel cell (sec)	2
O ₂ utilization at its peak (%)	120
O ₂ utilization undershoot (V) peak voltage	2

3.3.3 Module of Battery

In this analysis, ⁸⁰ Li-ion batteries were found to have a higher energy capacity and reliability than other types of batteries (such as lead-acid, NiCd, or NiMH). As a result, they're more attractive for use in cars and aircraft. In Simulink, there is a battery model. [56,57]

This system is based on an updated Shepherd slope model that uses a new word in the battery ⁶⁷ discharge voltage expression (voltage polarization) to help describe the influence of battery SOC on battery output. Furthermore, rather than using the actual battery current, the polarization resistance is compensated for using a filtered battery current to maintain simulation stability. Datasheets or ¹ basic dynamic checking may be used to find product parameters like the fuel-cell model. The key equations for a Li-ion battery are as follows [59].

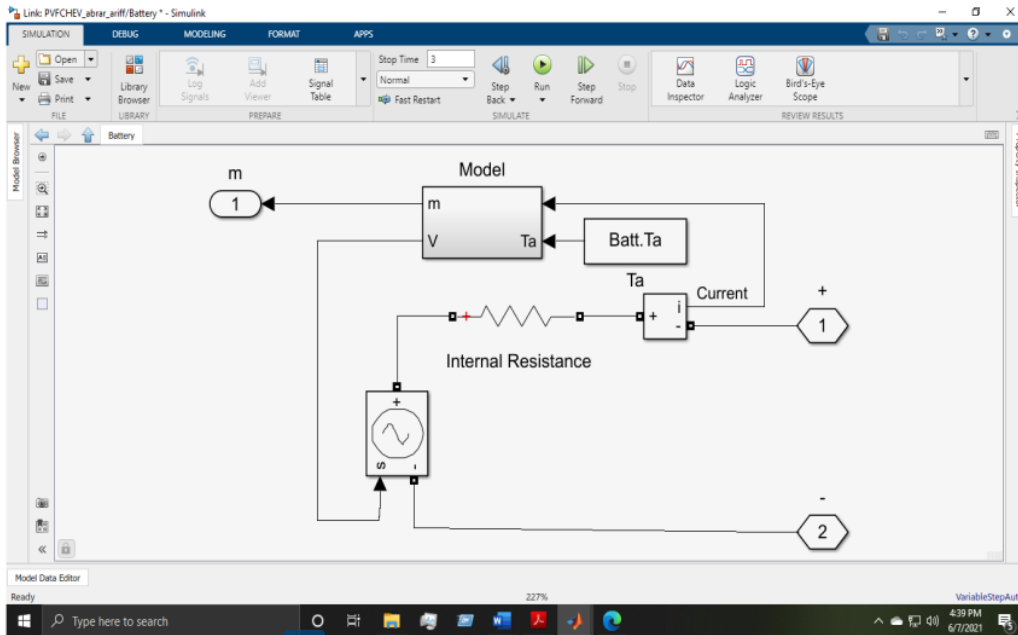
The battery's voltage is written as,

$$V_{batt} = E_o - K \frac{Q}{Q - it} \cdot it - R_b \cdot i + A_b \exp(-B \cdot it) - K \frac{Q}{Q - it} \cdot e^* \dots \dots (8)$$

where E_o represents the battery's constant voltage (in volts), K represents the polarization constant (in volts per ampere-hour), Q represents the battery power (ampere-hour), I represents the filtered battery current (in amperes), and it represents the real battery charge (in ampere-hours), B is the exponential zone time constant reciprocal, and A_b is the exponential zone amplitude (in A_{h-1}), and R_b denotes the internal resistance of the unit (in ohms). Polarization voltage is denoted by it in (5), while polarization resistance is denoted by $P_{ol_{res}}$. After being fully charged, the battery voltage increases abruptly during charging. This is reflected by changing the polarization resistance as follows (only during charging): [59]

$$Pol_{res} = K \frac{Q}{it - 0.1Q} \dots \dots \dots (9)$$

The battery model introduced in Simulink is shown in **Fig.3.4**



116 **Fig.3.4** Li-ion Battery Model [Matlab View]

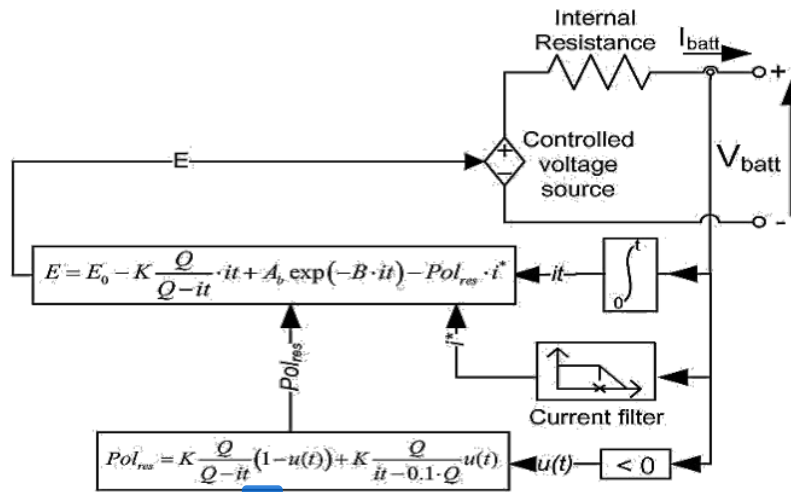


Fig.3.4 Li-ion Battery Model [59]

Table 3.3 Input parameters for the battery model

Input parameters for the battery model	
Voltage nominal (V)	48
Capacity stated (Ah)	40
Capacity maximum (Ah)	40
Voltage is fully charged (A)	55.87
Current of nominal discharge (A)	17.39
Internal opposition (ohms)	0.012
Capacity (Ah) at nominal voltage,	36.17
[Voltage(V), Capacity (Ah)] at exponential zone	[51.8585, 1.9652]
Voltage response time for battery (sec)	300

Table 3.3 contains the battery system's model input parameters as well as simulated discharge curves (four 12.8V,40Ah valence Li-ion battery modules).

3.3.4 Module of SC

Electric double layer capacitors (EDLCs), also known as supercapacitors, are similar to traditional electrostatic or electrolytic capacitors, but they have a higher capacitance that enables them to retain or release further energy [60]. The supercapacitor model in Simulink is based on the stern model [61]. The Helmholtz and Gouy-Chapman models are combined in this model. The capacitance of an EDLC cell is determined as follows:

$$C = \left[\frac{1}{C_h} + \frac{1}{C_{gc}} \right]^{-1} \dots \dots \dots (10)$$

$$C_H = \frac{N_e \epsilon \epsilon_0 A_i}{d} \dots \dots \dots (11)$$

$$C_{GC} = \frac{FQ_c}{2N_e RT} \sinh \frac{Q_c}{2N_e A_i \sqrt{8Q_c RT \epsilon_0 \epsilon_c}} \dots \dots \dots (12)$$

where C_H represents the Helmholtz capacitance in farads, C_{GC} represents the Gouy-Chapman capacitance in farads, N_e represents the number of electrode layers, and ϵ_0 represents the permittivity values of the electrolyte material and free space, respectively, in farads per meter. The supercapacitor model in Simulink is based on the stern model [61]. The Helmholtz and Gouy-Chapman models are combined in this model. The cell electric charge is measured in coulombs, the interfacial area between electrodes and electrolyte is measured in m^2 , the Helmholtz layer length (or molecular radius) is measured in m , and the molar concentration is measured in $mol \cdot m^{-3}$. A supercapacitor module with N_s cells are in series and N_p cells are in parallel has a total capacitance of,

$$C_T = \left(\frac{N_p}{N_s} \right) \cdot C \dots \dots \dots (13)$$

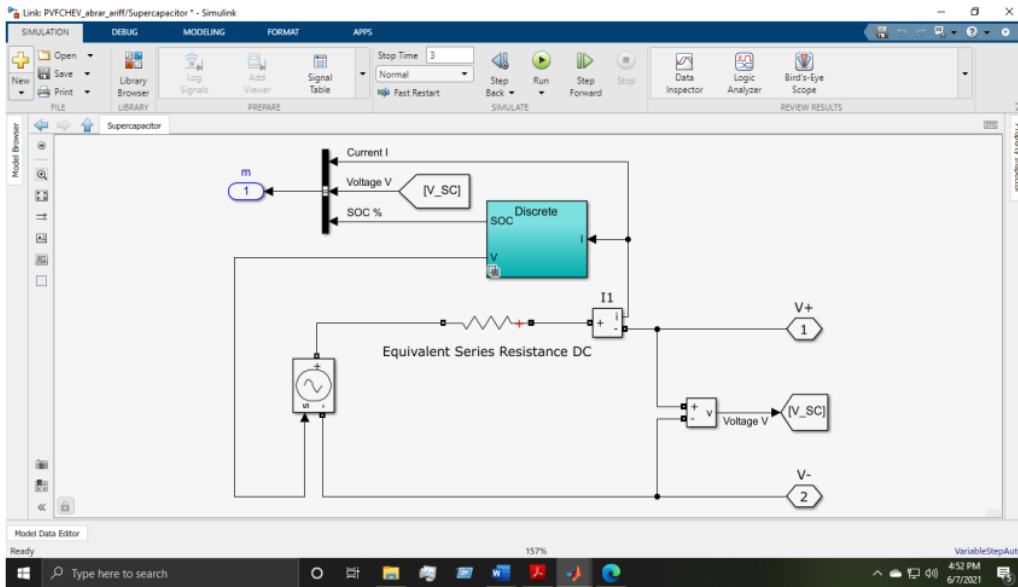


Fig.3.5 SC model. [Matlab View]

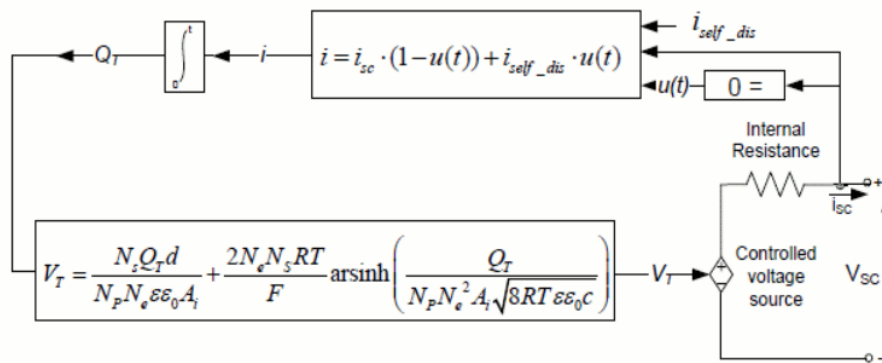


Fig.3.5 SC model. [62]

When resistive losses are taken into account, the output power of a supercapacitor is represented as,

$$V_{SC} = \frac{Q}{C_t} - R_{SC} \cdot i_{SC} \dots \dots \dots (14)$$

$$Q_T = N_p \cdot Q_c = \int i_{SC} \cdot dt \dots \dots \dots (15)$$

Q_T stands for total electric charge (in coulombs), R_{SC} stands for supercapacitor module resistance (in ohms), and i_{SC} stands for current through the supercapacitor module (in amperes). Table 3.4 and the specifications provide the critical parameters required by the model (dc resistance, as well as rated capacitance and voltage.). Experiments show that increasing the number of electrode layers and molecular radius improves precision.

Table 3.4 Input Parameters for the Supercapacitor System Model.

Input Parameters for the Supercapacitor Model	
Capacitance rated (F)	15.6
DC Resistance Equivalent Series (Ohms)	0.15
Rated/Specified Voltage (V)	291.6
Voltage at the Start (V)	270
Capacitor Series Number	108
Capacitor Count in Parallel	1
Count of Layers	6
Radius of Molecule (M)*	0.4×10^{-9}
Temperature of operation ($^{\circ}$ C)	45

3.3.5 DC/DC Converter Model

The fuel-cell and battery systems are connected to the dc/ac converter using dc/dc converters. This allows for voltage conversion (from low to high voltage) as well as full control of the fuel-cell/battery current and dc-bus voltage.

The fuel-cell system uses a boost type dc/dc converter, and the battery system uses one boost type (discharge converter) and one buck type dc/dc converter (charge converter). There are two kinds of models that can be used to describe dc/dc converters: switching models and average-value models. The switching models are mainly used for design and research into the switching harmonics and losses of various pulse width-modulated schemes.

The simulation takes a long time since these models need a brief sampling period in order to observe all switching operations. Average-value models, on the other hand, take less time because the switches are replaced with controlled voltage/current sources. These models are attractive because they can use a longer sampling time because the switching harmonics are not represented, so the entire converter dynamics are maintained. Models of dc/dc average-value converters are used, as shown in Fig.3.6.

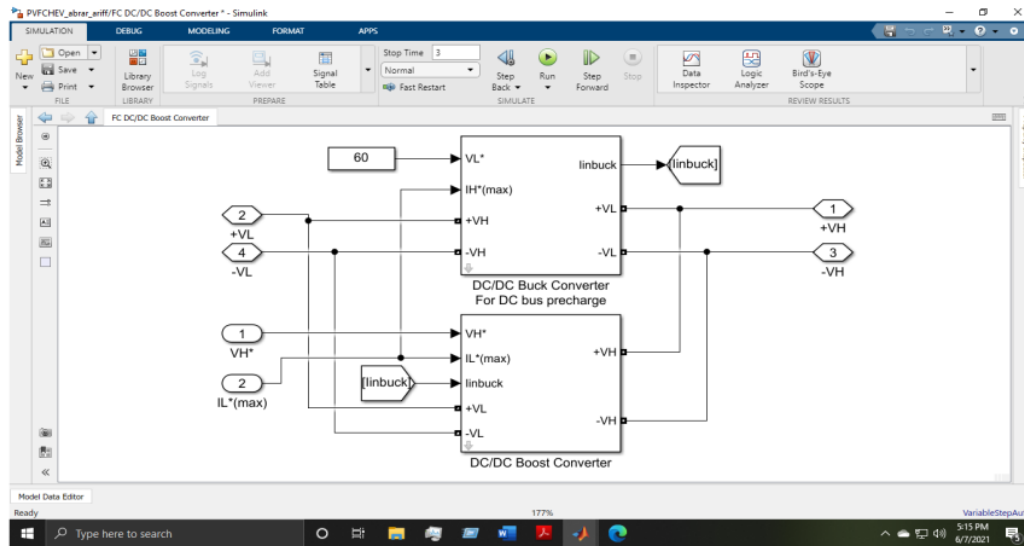


Fig.3.6 (a) Dc/dc Boost converter and (b) Dc/dc buck converter model. [Matlab View]

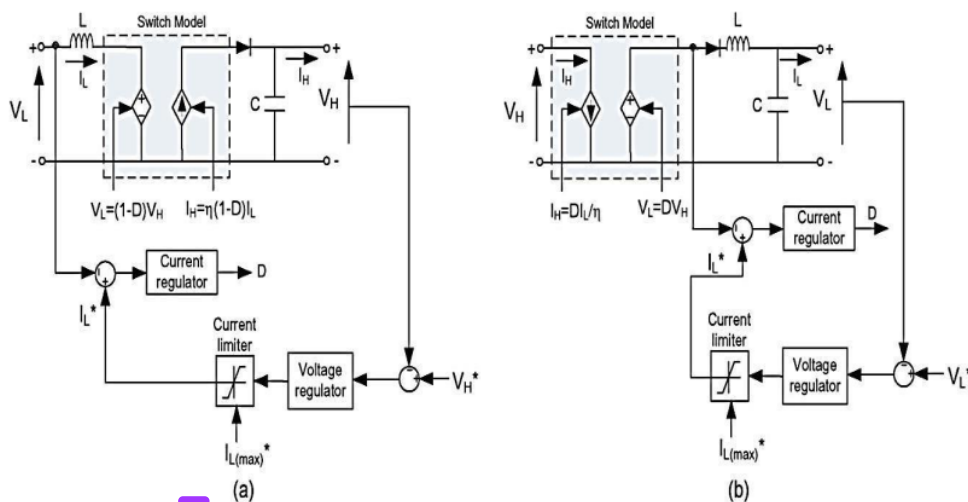


Fig.3.6 (a) Dc/dc Boost converter and (b) Dc/dc buck converter model. [21]

3.3.6 Model of Inverter

Similar to the dc/dc converter model shown in Fig.3.7, the dc/ac converter is defined by an average-value model. A three-phase 300-V 50-Hz voltage signal is used as a reference for voltage-controlled sources. In order to compute the input current, the output power and dc-bus voltage are used.

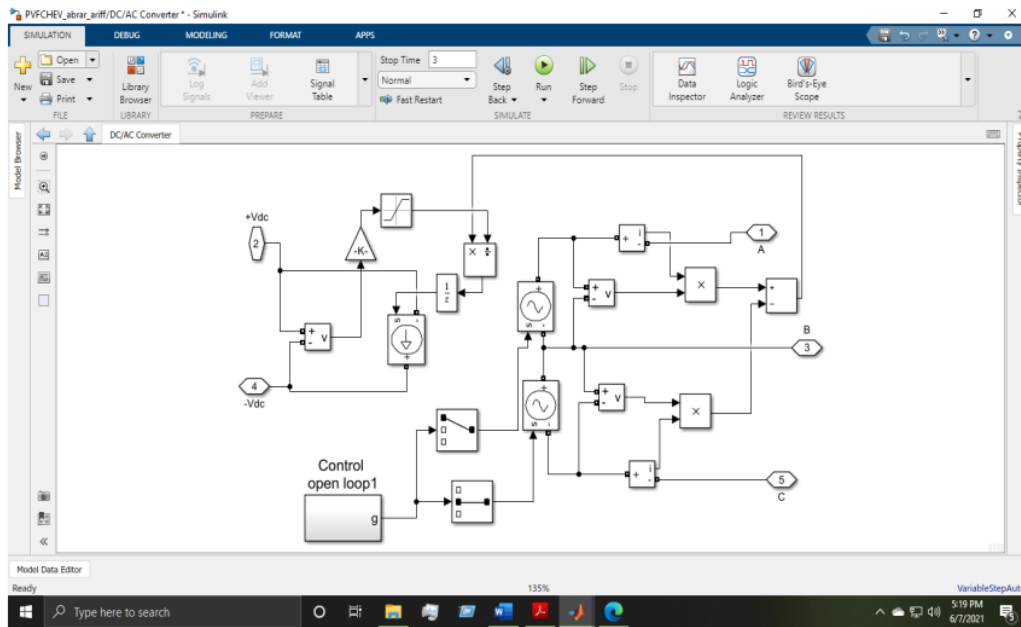


Fig.3.7 Model of a DC/AC converter [Matlab View]

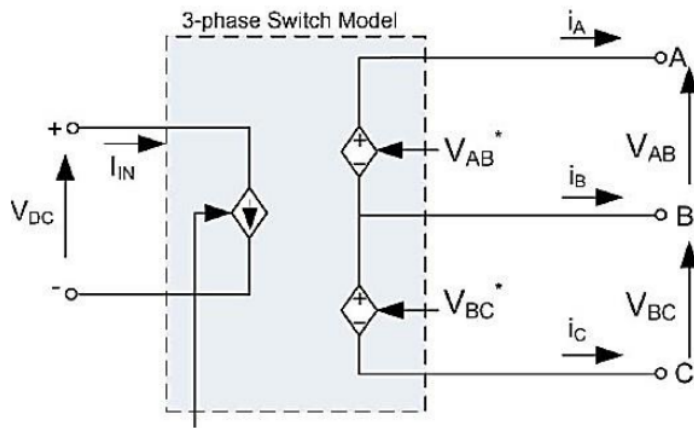


Fig.3.7 Model of a DC/AC converter [21]

3.3.7 The Load

Traction Motor [66]

An electric traction engine powers a vehicle such as an electric locomotive or a highway truck. Electric rail vehicles and other electric cars, such as electric hybrid cars, use traction motors. [63]. In a complete hybrid or battery electric car, an electric traction motor is installed, allowing the car to run completely on electricity. The two major motor principles currently driving electric traction motors are permanent magnet synchronous motors (PMSM) and asynchronous motors.

Table 3.5 Rating for Traction motors [64]

Rating for Traction Motors	
Voltage nominal	350V
Current in phase (at 460 nm)	1000A pk
Continual shaft torque (dependent on speed)	75kW to 125kW
Continual shaft torque (dependent on speed)	233Nm to 248Nm
Mass of motor assembly	75kg
Maximum speed of operation	12,200rpm
Temperature of typical coolant	65°C
The total number of poles	8
Qualification in the automotive industry	Yes
Maximum output (60 second)	[90-122 kW]

3.3.8 Energy Management System

The best outcomes must be provided by the energy management system:

- The use of hydrogen is low.
- The overall effectiveness of the system is high.
- The battery/Supercapacitor SOC's is limited.
- Maximum life expectancy

These are achieved using an EMS to control the power response of each energy source in relation to load demand through the converters that are connected to it. Five cutting-edge technologies were used to create this paper.

The specifications in **Table 3.6** are taken into account and EMSs are designed accordingly,

Table 3.6 Energy Management Design Requirements

Design Requirements for Energy Management	
[Pfc _{min} -Pfc _{max}] Fuel cell power (kW)	[1-10]
[Pbatt _{min} -Pbatt _{max}] Battery power (kW)	[-1.2-4]
Battery state of charge [SOC _{min} -SOC _{max}] (%)	[60-90]
Super-Capacitor Voltage (V)	270
[Vdc _{min} -Vdc _{max}] dc bus voltage (V)	[250-280]
Traction motor power (kW)	[95-122]

3.3.8.1 Control Strategy for State Machine

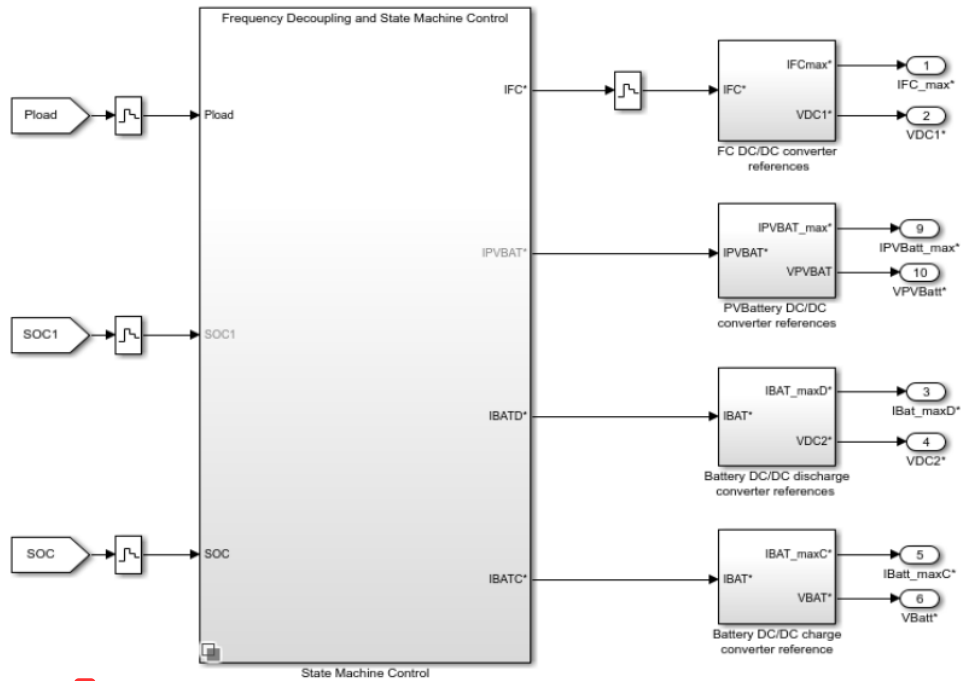


Fig.3.8 State Machine Control Block used in the simulation. [Matlab View]

Table 3.7 Demonstrates the control plan for the state machine. There are eight states in the state machine control plan that was adopted.

State Machine Control Decisions			
If SOC High	$P_{load} < P_{fc_{min}}$	State=1	$P_{fc}^* = P_{fc_{min}}$
If SOC High	$P_{load} \in [P_{fc_{min}}, P_{fc_{max}}]$	State=2	$P_{fc}^* = P_{load}$
If SOC High	$P_{load} \geq P_{fc_{max}}$	State=3	$P_{fc}^* = P_{fc_{max}}$
If SOC Normal	$P_{load} < P_{fc_{opt}}$	State=4	$P_{fc}^* = P_{fc_{opt}}$
If SOC Normal	$P_{load} \in [P_{fc_{opt}}, P_{fc_{max}}]$	State=5	$P_{fc}^* = P_{load}$
If SOC Normal	$P_{load} \geq P_{fc_{max}}$	State=6	$P_{fc}^* = P_{fc_{max}}$
If SOC Low	$P_{load} < P_{fc_{max}}$	State=7	$P_{fc}^* = P_{load} + P_{char}$
If SOC Low	$P_{load} \geq P_{fc_{max}}$	State=8	$P_{fc}^* = P_{fc_{max}}$

Here,

- When the SOC is high, the load power is less than the fuel cell minimum power, and the fuel cell initial power is the same as the fuel cell minimum power.
- When SOC is high, load power is equal to the dot product of fuel cell minimum and maximum power, and fuel cell initial power is equal to load power at that time.
- When the SOC is high, the load power is higher than the maximum power of the fuel cell, and the fuel cell initial power is equal to the maximum power of the fuel cell.
- When the SOC is usual, the load power is less than the fuel cell optional power, and the fuel cell initial power is the same as the fuel cell optional power.
- When SOC is regular, load power is equal to the dot product of fuel cell optional power, and maximum power is equal to load power.
- When the SOC is usual, the load power is higher than the maximum power of the fuel cell, and the fuel cell initial power is equal to the maximum power of the fuel cell.
- When the SOC is low and the load power is less than the maximum power of the fuel cell, the fuel cell initial power is equal to the sum of the load and charging power.
- When the SOC is low, the load power is higher than the maximum power of the fuel cell, and the fuel cell initial power is equal to the maximum power of the fuel cell.

SOC High \rightarrow SOC $>$ SOC_{max} P_{char} = -P_{batt_min}

SOC Normal \rightarrow SOC \in [85, 65]

SOC Low \rightarrow SOC $<$ SOC_{min}

3.3.8.1.1 Discharge Converter

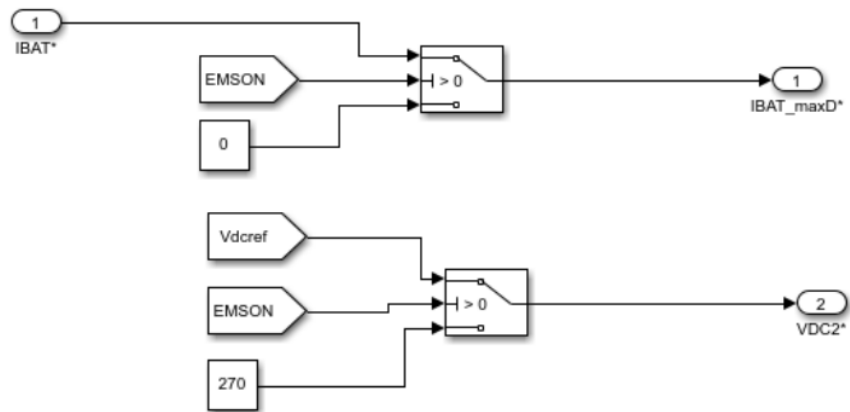


Fig.3.9 Discharge Converter for Batteries (DC/DC) [Matlab View]

¹ The battery input current flows through the bus when the management system is switched on, as illustrated in **Fig.3.9**. When the battery's SOC reaches a minimal constant value of 0, the switch1 switches off. After that, the super-capacitor begins to charge.

3.3.8.1.2 Charge Converter

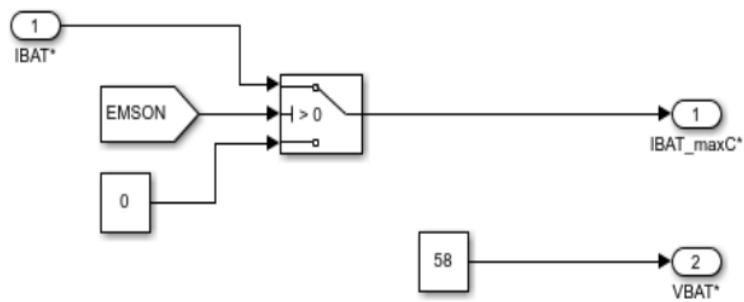


Fig.3.10 Charge Converter for DC/DC Batteries [Matlab View]

The fuel cell keeps up with the load ⁹² until the battery's state of charge (SOC) goes to zero, at which point it begins to recharge it (shown on **Fig.3.10**). ⁹⁸ When the battery's state of charge falls below zero, the fuel cell charges the supercapacitors above their reference voltage (270 V), causing the dc-bus voltage regulator to require a negative current to recharge the battery. One disadvantage of this technique is that when switching states, it necessitates hysteresis control, as illustrated in Fig.3.11, which affects the EMS' response to changes in load demand [63].

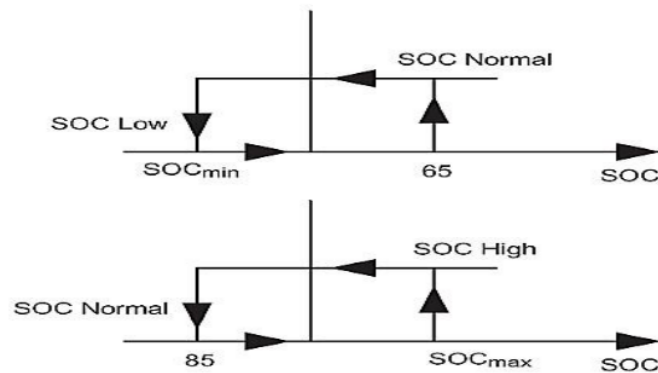
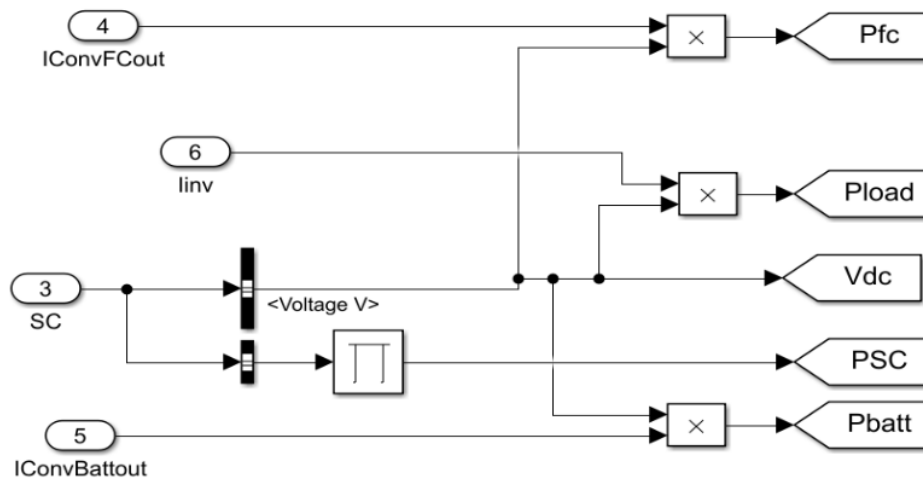


Fig.3.11 State Machine Control Hysteresis [58]

3.3.8.1.3 Power Result



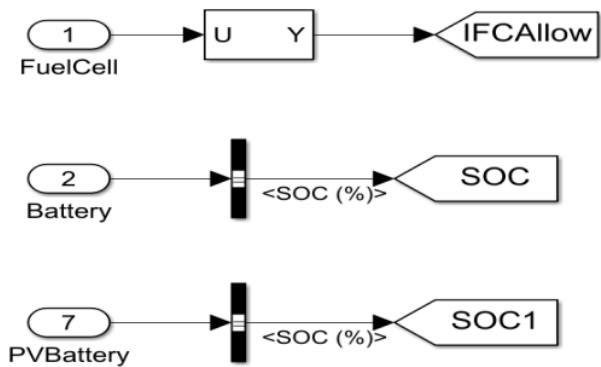


Fig.3.12 Power Output [Matlab View]

As shown in **Fig.3.12**,

- To generate fuel cell power, the output current of the fuel cell converter is multiplied by the super-capacitor voltage.

$$I_{ConvFCout} * SC(V) = P_{fc} \dots\dots\dots(16)$$

The input current and voltage of SC are combined at this point, resulting in a power for load. Supercapacitor voltage and current are multiplied by product during this action, resulting in Super-capacitor power.

$$I_{sc} * V_{sc} = P_{sc} \dots\dots\dots(17)$$

- The output current and voltage of the super-capacitor of the battery converter were multiplied, resulting in Battery power.

$$I_{ConvBattOut} * SC(V) = P_{batt} \dots\dots\dots(18)$$

- PV battery power was calculated by multiplying the output current and voltage of the PV battery converter's super-capacitor.

$$I_{ConvPVBattOut} * SC(V) = P_{PV bat} \dots\dots\dots(19)$$

The current and voltage from the fuel cell module flow to the dc link bus, allowing the fuel cell module to function. The SOC range, which is explained in state machine control decision Table 3.6, provides battery power. [58]

The same technique used for state machine control as used in [65].

The fuel-cell power is calculated using the battery's SOC range and the load power P_{load} .

Fig.3.13 depicts the EMS scheme. [58]

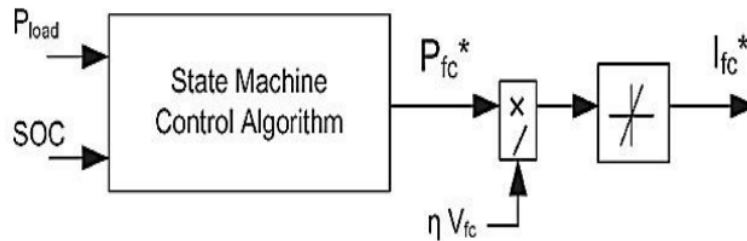


Fig.3.13 State Machine Control Energy Management Scheme [58]

3.4 Control Scheme for State Machines

The fuel-cell power (in watts) and battery voltage (in volts) are measured at the 270V dc bus. As can be seen, the results of the tests match those of the simulation. As illustrated in Fig.3.14, the fuel cell in the state machine control scheme follows the load until the battery SOC reaches a minimum, at which point it tries to recharge the battery.

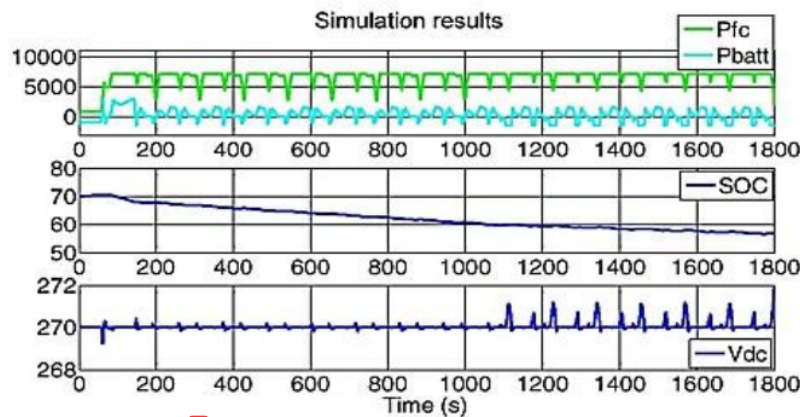


Fig.3.14 State Machines Control Scheme [67]

15
1 When the battery's state of charge (SOC) is at its lowest, the fuel cell charges the supercapacitors above their reference voltage (270 V), prompting the dc-bus voltage regulator to require a negative current to recharge the battery.

The auxiliary PV battery's parameters and characteristics, as well as the state machine control plan states, are similar to those of the main storage battery. As a result, SOC1 is ignored since it is the same as SOC. The State Machine Control program is described in APPENDIX B.

3.5 Hydrogen Consumption

The following formula is used to calculate the hydrogen consumption for each scheme gives the hydrogen consumption (in grams). [67]

$$C_{const}H_2 = \frac{N}{F} \int_0^{1800} i_{fc} \cdot dt \dots \dots \dots (20)$$

F stands for Faraday constant (in A s/mol).

3.6 Summary

The architecture for modeling the design and implementation is the focus of this chapter. The vehicle system module and the energy management system (State Machine Control) parameters were then explored for use in hybrid photovoltaic and fuel cell vehicle systems. Then there was a debate about hydrogen consumption and overall efficiency calculations, stress analysis, and state machine control overall performance. As a result, this chapter develops an overall system configuration.

1 CHAPTER 4

SIMULATION AND RESULT ANALYSIS

4.1 Introduction

In this chapter, we'll go over our simulation and its outcomes. We looked at the simulation block model in Chapter 3 it's parameters, and how it works at various times, all of which are operated by the Energy Management system. This chapter is analyzed after simulating its input, output voltage and current, and ultimately its maximum power, which is key for our Traction Motors.

4.2 Vehicle Model

The vehicle model includes solar panel as auxiliary source, fuel cell, battery as a primary source whereas battery is also a storage itself and super capacitor. All the outputs go through dc-dc converter except super capacitor to dc link and those outputs will go through an inverter to run the in-wheel traction motor. All those proceedings are managed by the Energy Management System.

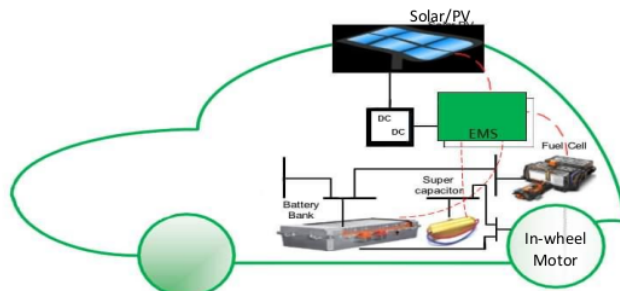


Fig.4.1 Proposed Vehicle Model

4.3 Simulation Diagram

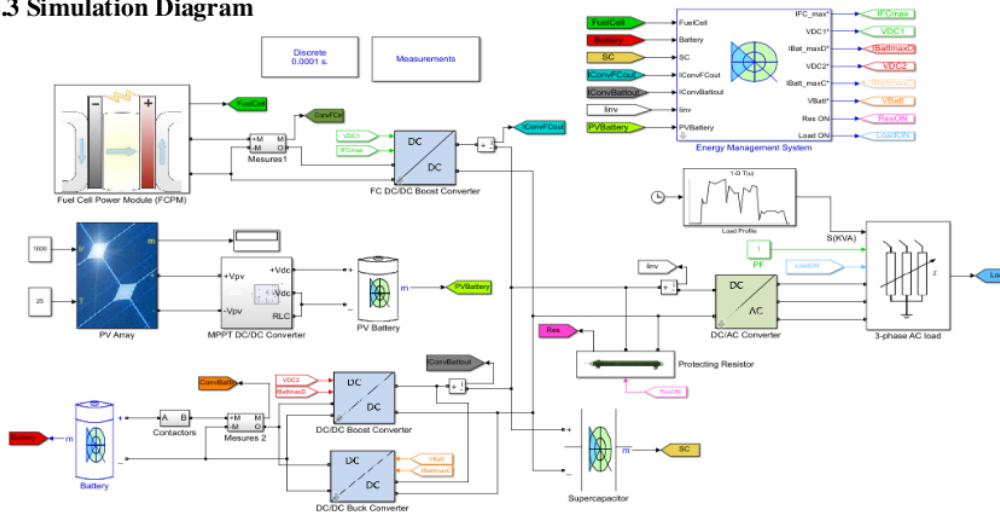


Fig.4.2 PVPEMFC energy supply simulation in Simulink

Fig.4.2 illustrates the simulation design for PVPEMFC energy system. The simulation is done within Matlab2020b. PEMFC, PV, Battery, Super-Capacitor, Converter, and Inverter modules are included in the design, as described in Chapter 3. The simulated results (Fuel cell module, Battery module, super-capacitor module, PV array module, DC/AC converter output and Output power versus time configuration) are shown and discussed below.

4.4 Simulated Results

Each module's Simulink output is shown in this section as follows:

4.4.1 Fuel Cell Module

The model's parameters, as well as the simulated polarization curves, are seen in **Fig.4.3**. The simulation results for nominal conditions are shown in **Fig.4.4**, with the temperature of 65°C. The output current is 0A while the sample time is 0.0001s. While the chemical reaction between hydrogen and oxygen occurs, this battery module begins to produce electricity. Fluctuations can be observed between 0.002s to 0.016s in sampling time. The output voltage is generated in accordance with the parameter of its unit.

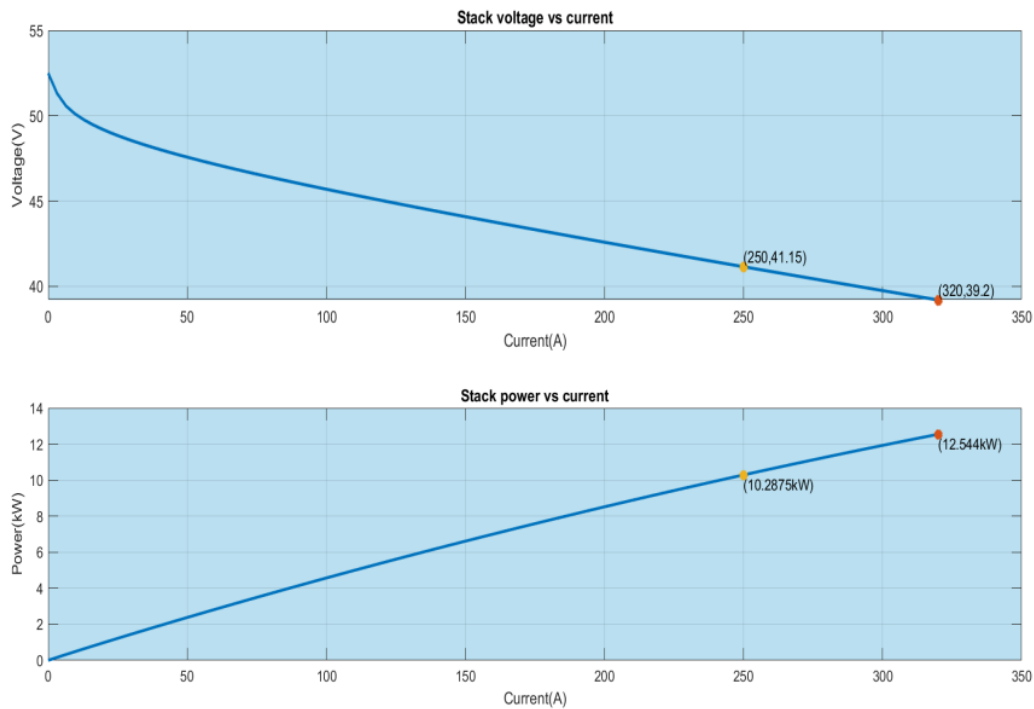


Fig.4.3 Fuel Cell polarization plots

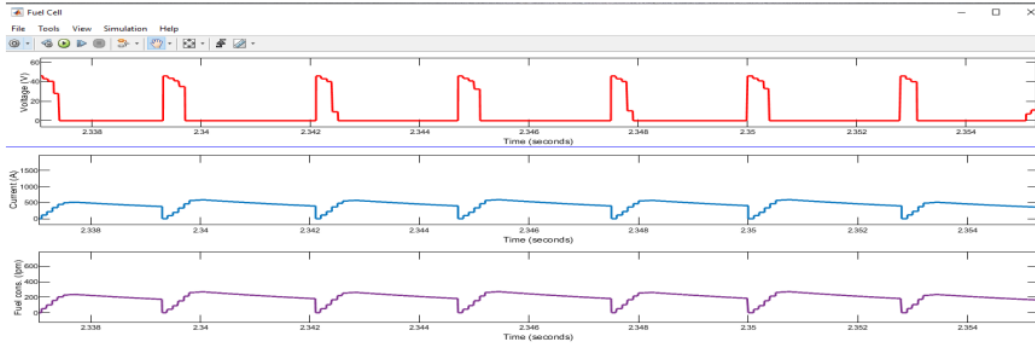


Fig.4.4 Fuel-cell simulation results for 12.5 kW PEMFC [Matlab View]

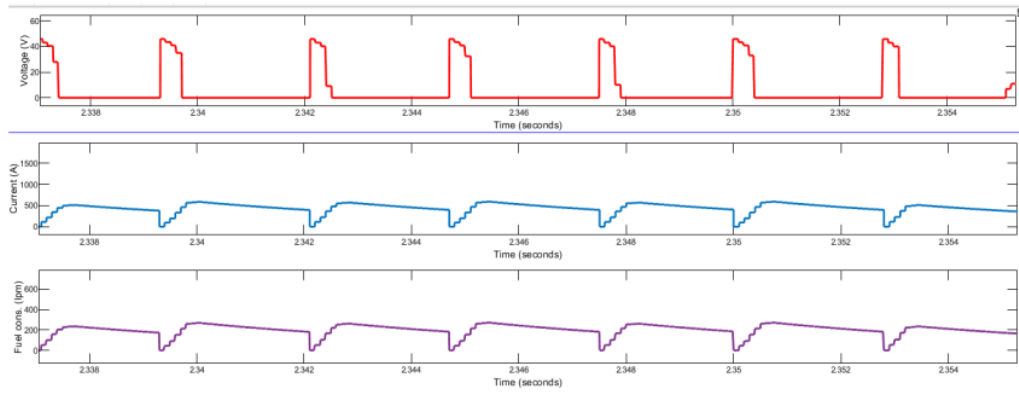


Fig.4.4 Fuel-cell simulation results for 12.5 kW PEMFC.

4.4.2 Battery Module

The simulation results for battery system output voltage and current has been shown in **Fig.4.6**. The voltage is 51.3V and the current is 0A at 0.001s sampling time. The output is varied by increasing the sampling time. The output current and voltage are -250A and 54.6V respectively, at $t=0.0025s$ and -50A and 51.6V respectively, at $t=0.015s$.

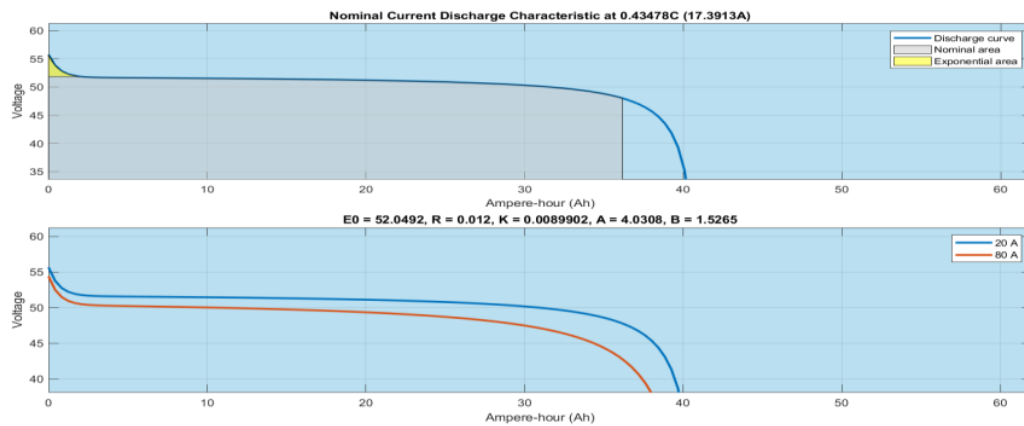
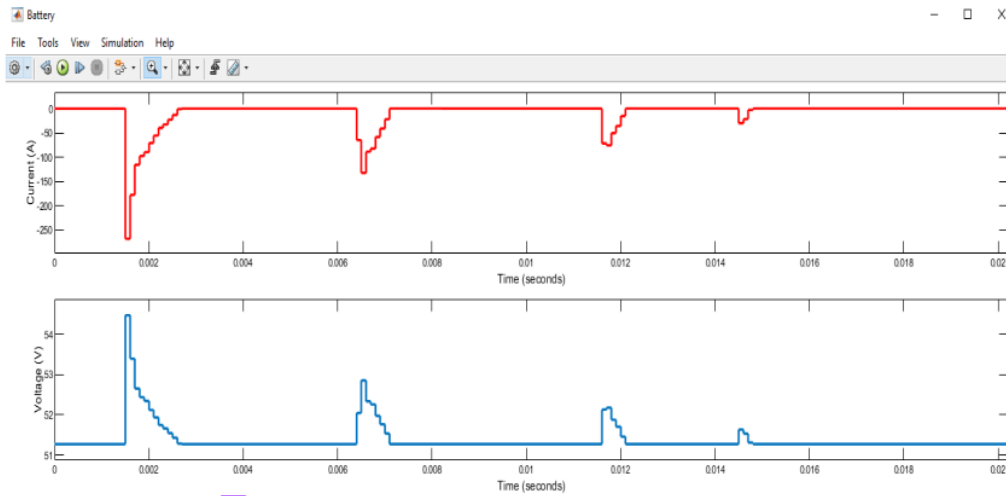
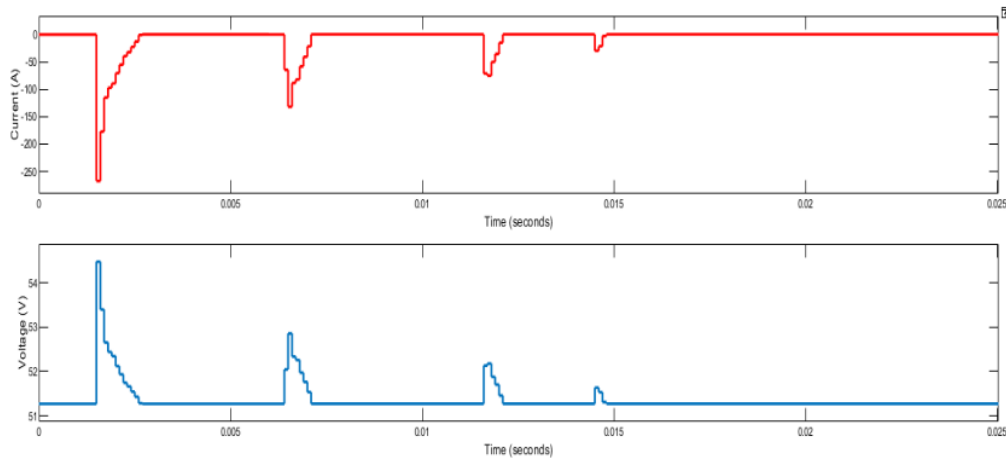


Fig.4.5 Battery Discharge Plots



63 **Fig.4.6** Li-ion battery simulation results. [Matlab View]



63 **Fig.4.6** Li-ion battery simulation results.

The **model** input parameters for the battery device, as well as simulated discharge curves, are shown in **Fig.4.5.**(four 12.5V 40Ah Li-ion battery).

4.4.3 Super-Capacitor Module

The design parameter values for the supercapacitor system, as well as simulated discharge curves, are shown in **Fig.4.7.** Figure 4.8 depicts the simulation and outputs, where the voltage is 0V and the output current is 0A at Sampling time $t=0.001s$. At sampling time 0.0025s, the functions start at output voltage and current.

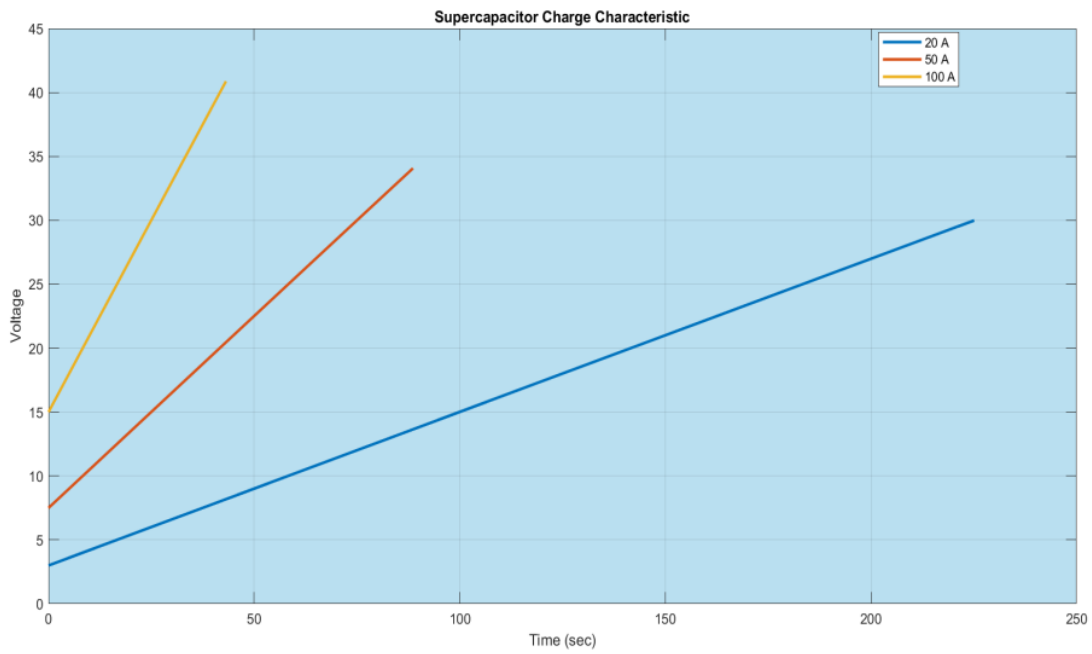


Fig.4.7 Supercapacitor discharge plots.

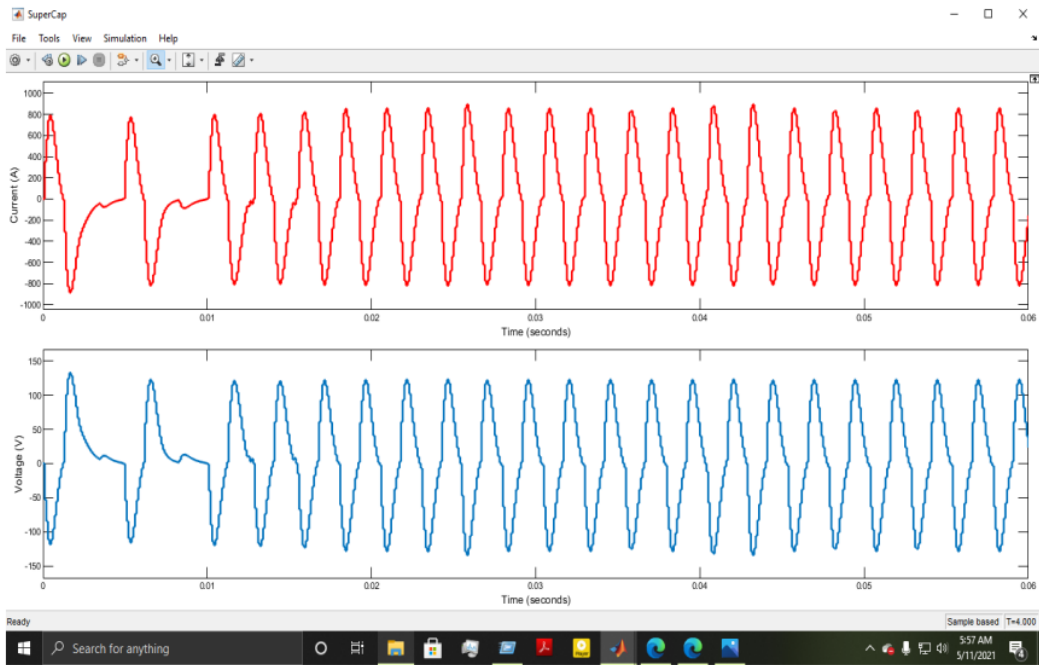
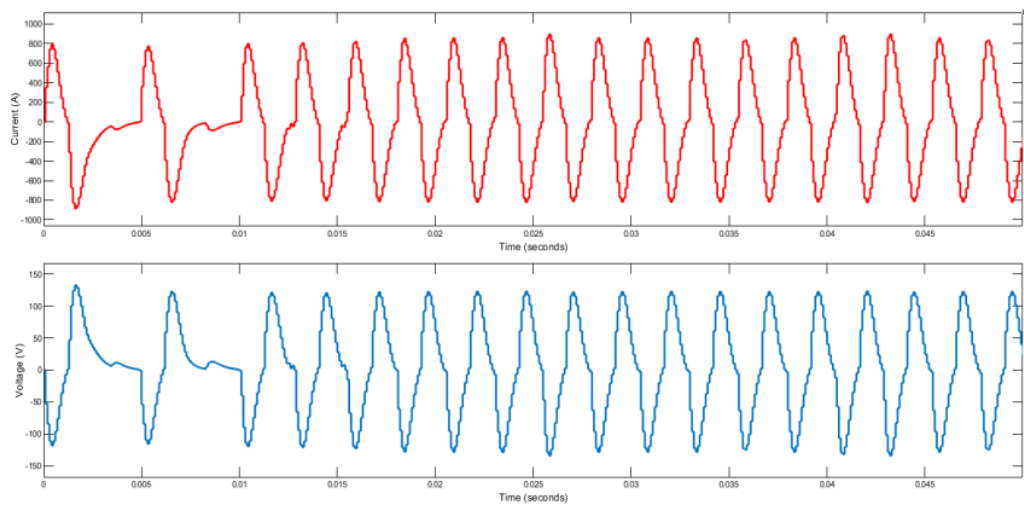


Fig.4.8 SC Simulated results with charge and discharge for 270-V 15-F. [Matlab View]



6
Fig.4.8 SC Simulated results with charge and discharge for 270-V 15-F

4.4.4 Photovoltaic Array (PVA)

A modern lightweight vehicle with a PV scope of up to 1225 W seems to have a total area of about 5 m² PVFCHEV's PV array input model, as depicted in **Fig.4.9**, was used in this thesis. The output current is 100A_{P-P} and the voltage is 102V_{P-P} on the PV battery output.

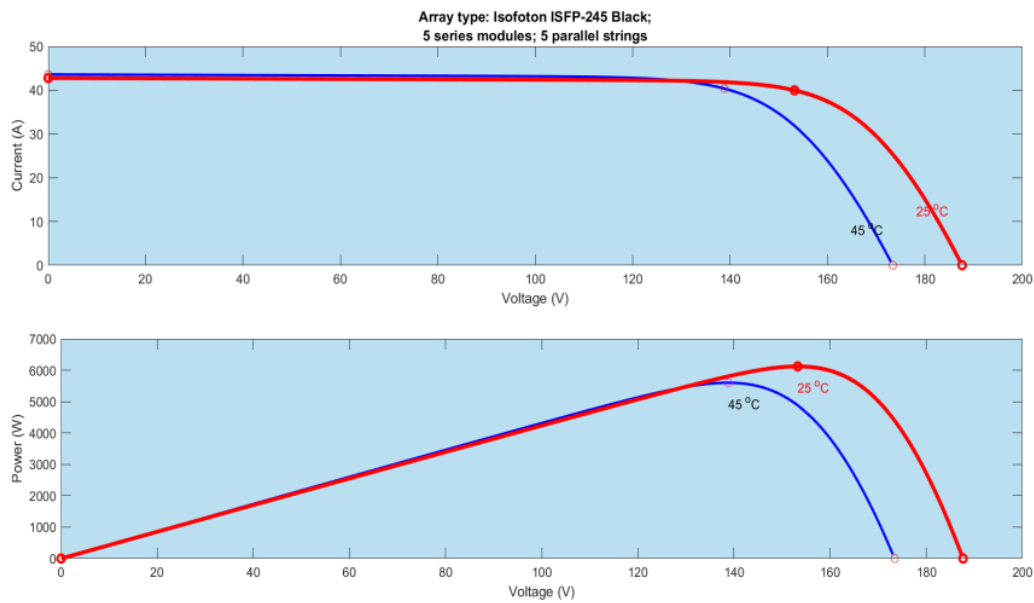


Fig.4.9 PV Array characteristic plots.

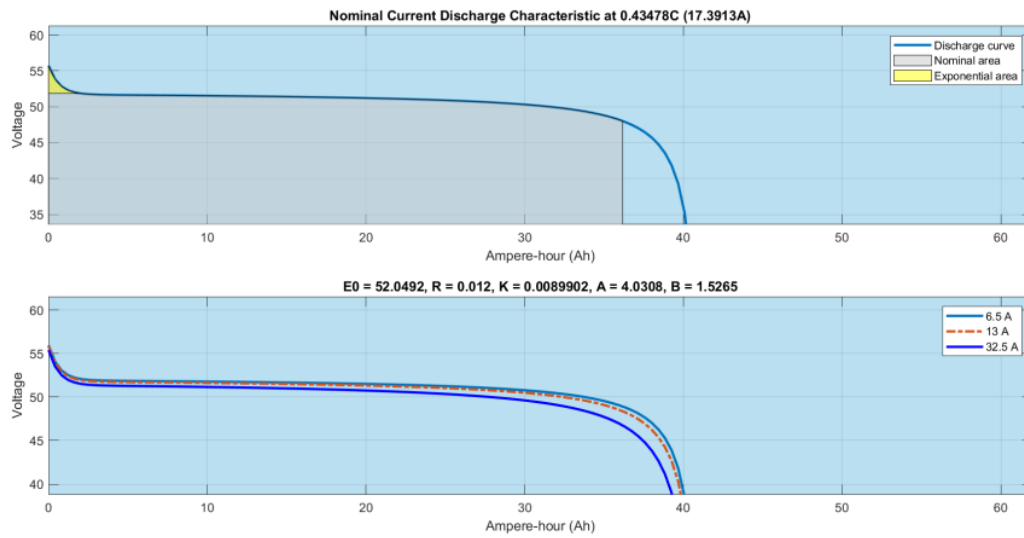


Fig.4.10 PV Battery Discharge plots.

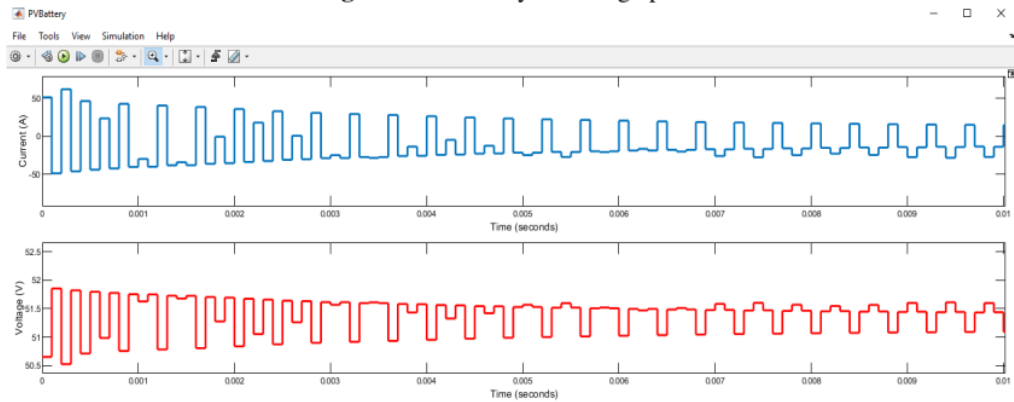


Fig.4.11 Simulation results for PV Batteries. [Matlab View]

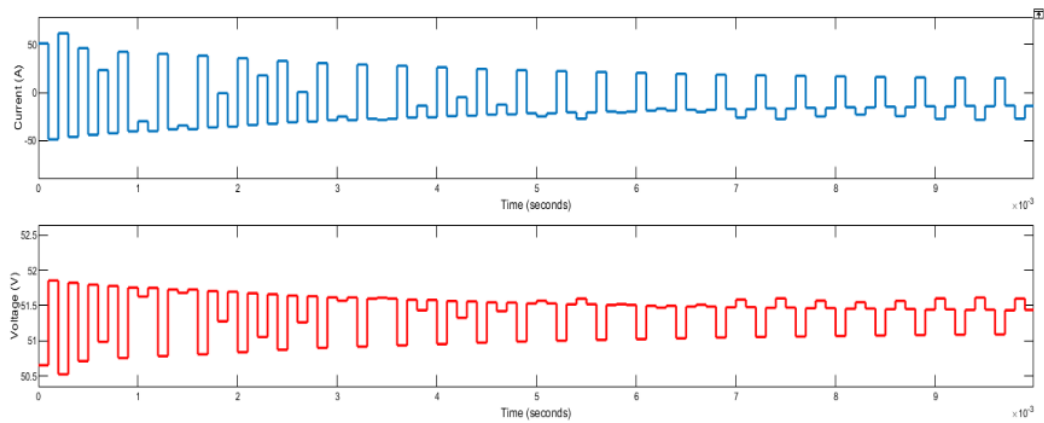


Fig.4.11 Simulation results for PV Batteries

4.4.5 Inverter Output

Fig.4.12 depicts the inverter's output voltage.

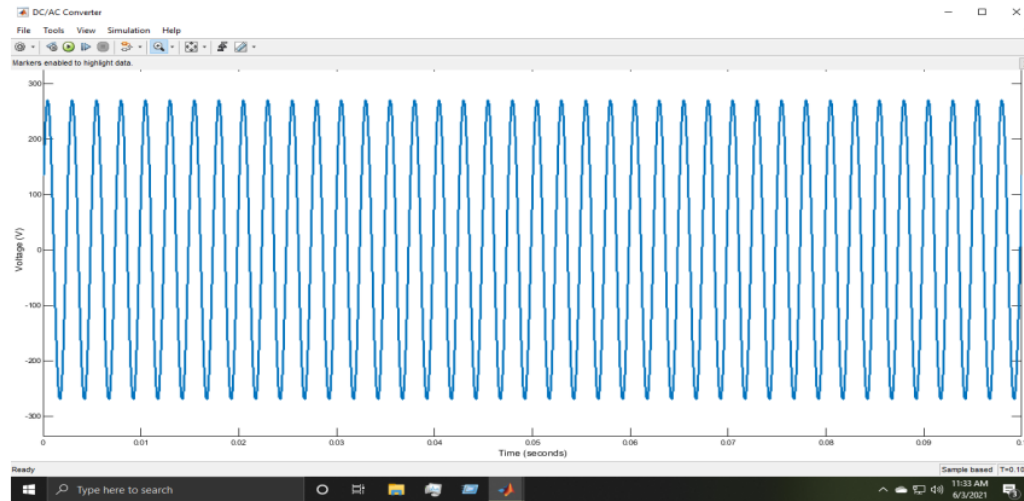


Fig.4.12 The inverter's output voltage.[Matlab View]

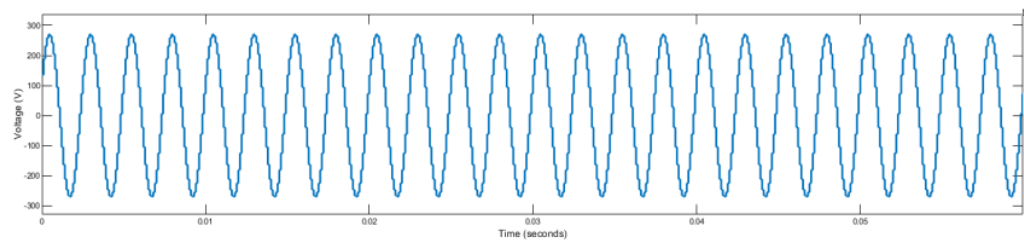


Fig.4.12 The inverter's output voltage.

Fig.4.12 shows the AC output for a 270V DC voltage. The sine wavelshape mode is activated on the inverter. The highest voltage is about 539.6V. The performance is perfect for operating a 3-phase traction motor, which is exactly what we needed. The inverter's rating and the Simulink output are seen in Table 4.1.

Table 4.1 The inverter's rating and output.

Name of the Parameter	Rating
Voltage of AC output	539.6V
Frequency	50Hz

4.4.6 Output power vs. Time config.

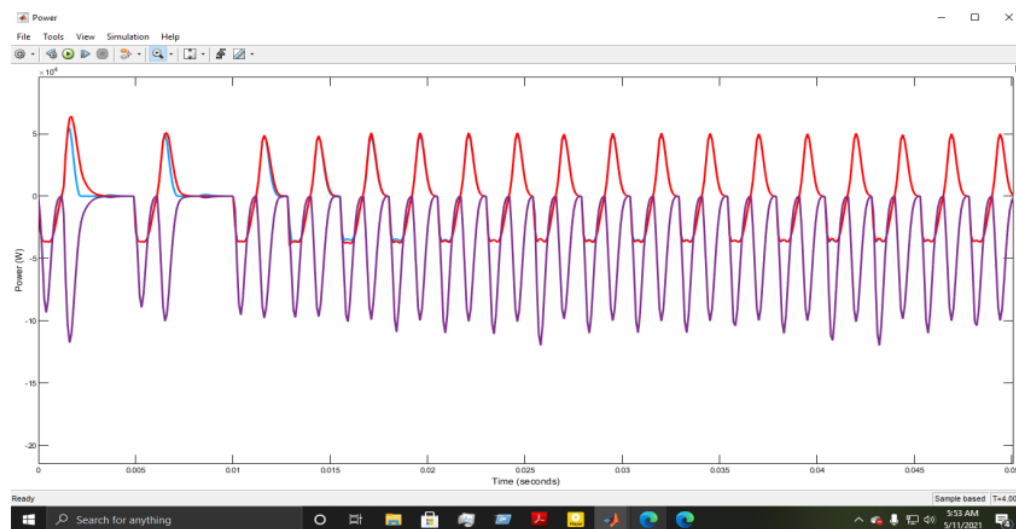


Fig.4.13 Simulated PEMFC output power. [Matlab View]

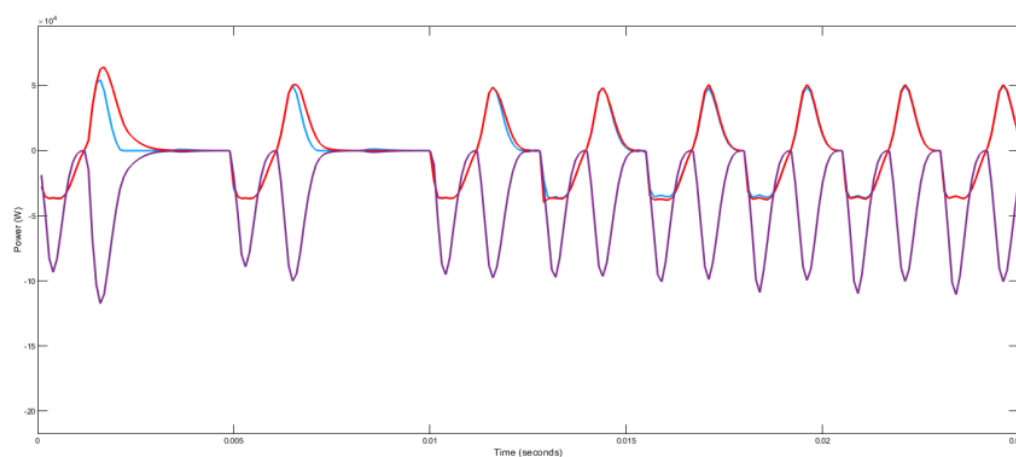


Fig.4.13 Simulated PEMFC output power.

FCHEV model's input parameters and output power were shown in ²¹Table 4.2.

Table 4.2. FCHEV Model's parameter values and output power.

Parameter's name	Rating
Output power simulation	110kW

4.5 Result Analysis

Table 4.3 Analysis of the Results

Parameter's name	Required	Simulation
FC power [$P_{min} - P_{max}$]	1kW - 10kW	5.1kW
Batt. power [$P_{batt_{min}} - P_{batt_{max}}$]	-1.2kW - 4kW	-2.6kW
Voltage of Supercapacitors	270V	262.5V
Battery SOC [$SOC_{min} - SOC_{max}$]	60% -90%	60% - 90%
DC bus voltage [$V_{min} - V_{max}$]	500V -560V	540V
Traction motor power	95kW – 125kW	110kW

4.6 The designed model and other HEVs are compared

We worked on paper in this study. After all of the analyses and simulations, we concluded at an output power of 110kW. We've covered all of the modules of a hybrid electric car in this paper. Our final result is good and can be more effective in the future. Any HEV can easily be driven with this amount of power. Many analyses about PEMFC/battery/SC are included in this table. In various periods of time, there were several differences. As a result, **Table 4.4** includes both our analysis and simulation findings.

Table 4.4 FCHEV's proposed PV/FC/SC/Battery Hybrid energy Source vs. other models

Power Supply Types	Types of Analysis	DC link voltage (V)	Maximum power (kW)
Photovoltaic Array /PEMFC/Battery/SC	Simulation	540	110
PEMFC/battery/SC	Experiment	545	99 [54]
PEMFC/Battery/SC	Experiment	560	40 [54]
PEMFC/Battery/SC	Simulation	400	120 [54]
PEMFC/Battery/SC	Simulation & experiment	750	400 [54]
PEMFC/Battery/SC	Simulation	300	100 [54]

4.7 Evaluation

In this research, we modeled also simulated energy sources for hybrid electric vehicles using fuel cells, batteries, PV arrays, and supercapacitors. We began with the basics of fuel cells before deciding which type would be best for our design. Then we talked about it with the core to see if there was something we could do to make it more effective. As a backup power source, we've included a PV array. Finally, we developed a model that helps the PEMFC to connect with each other. All of the necessary components for a hybrid vehicle were addressed. Next, in MATLAB 2020b, build a Simulink mode. After simulation, we obtained a DC voltage of 560V and an AC voltage of 560V. And the overall power is nearly 110kW, which is considerably higher than previous work. Experimentation, on the other hand, is often more effective than simulation. We may assume that our working process, simulation, and outcome interpretation are sufficient for this paper for this purpose.

4.8 Summary

This chapter discusses the simulation as a whole, covering all of the Simulink modules' inputs and outputs. As a consequence, a HEV may be paid by itself. The simulation portrays the outcome dependent on the charging capacity demand described in Chapter 3. The prospect of designing such a Hybrid Vehicle with PEMFC, Battery/SC as the main power supply and PV Array as the secondary power supply has now become viable as a result of supplying the range.

CHAPTER 5

CONCLUSION

5.1 Introduction

In this chapter, the whole thesis work is concluded. The merits and demerits of the photovoltaic fuel cell hybrid electric vehicle (PVFCHEV) configuration are explained. Restrictions during the work and the future work with the PVFC hybrid electric vehicles and the possible upgradations of the vehicle are also discussed in this chapter.

5.2 Conclusion

PVFCHEVs can use a PVA/PEMFC/Battery/SC hybrid power supply in this design. An Isofoton ISFP-245 Black polycrystalline PV cell with a capacity of 245 W, a 12.5kW PEMFC stack, a Nominal Voltage 48V battery, and a 15 F SC bank were used to design and build of the PVA/PEMFC/Battery/SC hybrid power supply. The simulation results show that when the necessary power is 95kW to 122kW, a 3-phase AC induction motor can be operated at 110kW. The DC/AC inverter is operated by a DC-link voltage of 540V DC. The inverter has a 540V AC output voltage. These are the work's key contributions. Experiments also demonstrate that the designed energy source is well suited to a PVAFCHEV. The proposed hybrid energy source was compared to the current PV/FC/battery, FC/SC, and PVA/FC/battery/SC hybrid energy sources used in PVAFCHEVs, and its superior characteristics, such as higher power, were clearly demonstrated.

5.3 Merits and Demerits PVFC Hybrid Vehicle Configuration

5.3.1 Merits

1. Accessible and Sustainable

Solar energy is the most efficient green energy source possible, as well as an unlimited source of energy. On the other hand, the abundance of H₂ is one of the reasons why it is such a good option for fuel. Hydrogen, unlike fossil fuels and other nonrenewable energy sources, is unlikely to deplete anytime quickly.

2. Toxic-free

All of the energy supplies we actually employ are hazardous and poisonous. This is true not only for humans and wildlife, but also for the climate. Both solar cells and hydrogen fuel cells are low-toxic and carry little risk to the environment.

3. Quite effective

Hydrogen fuel cells are not only non-toxic and green energy, but they are also extremely strong. They're so strong that they're also used as rocket fuel. PV cells are now so powerful as an auxiliary unit in satellites that aerospace engineers are increasingly using them as a power source alongside other fuel sources.

4. It has little impact on global warming.

Photovoltaic cells and hydrogen fuel cells have no greenhouse gas emissions. These emissions, which are emitted from other non-renewable energy sources, are blamed for global warming and major climate change.

5. Low-Cost Repairs

Solar panels and hydrogen fuel cells are very low-cost to run once installed, despite their high initial costs. The same argument could be made if vehicles were to work solely on hydrogen fuels or on solar panels.

5.3.2 Demerits

1. There Is Already a Need for Fossil Fuels

Fossil fuels are used to detach the hydrogen to oxygen atoms and actually produce hydrogen fuel. This totally negates the point by using an alternate energy source in the first place. We wouldn't be able to generate hydrogen energy if we run out of fossil fuels

2. Produced at a High Cost

One of the most significant drawbacks of hydrogen fuel cells is their high cost of production. Currently, the energy is inefficient enough to generate hydrogen energy at a reasonable rate.

3. Combustible

Although it isn't poisonous, it is extremely combustible. The danger comes from the hydrogen itself, which has a high risk of catching fire or even burning. This will unnecessarily increase the number of threats in community.

4. There is a lot of work to be done.

Fuel cells are only in their early stages of development, and even further testing and development is needed before they can be used on a large scale. Many people assume it is only a fairy tale since the plausibility of its use is unclear.

5. The ability of cells is reduced.

The hydrogen energy is deposited in cells with a finite amount of power space. This simplifies the procedure using hydrogen fuel cells to sustain stable power supplies highly impossible.

5.4 Certain restrictions apply

1. The program (MATLAB Simulink 2020b) is extremely configurable, as this is a simulation-based thesis. In this research, the results are based on a minimal time period. As a consequence, the findings of laboratory work cannot be the same.
2. Since the measurements were performed over a shorter time frame, the simulation performance values for this study might not be correct.

5.5 Work in the Future

In the future, there might be substantial research work that can be conducted on this research.

1. The PVFCHEV can be redesigned as a multi-source configuration hybrid electric vehicle by incorporating wind energy to the alternator. With the additional source, it will be more powerful and capable of covering greater distances than PVFCHEV.
2. Since H₂O is a byproduct of this chemical reaction-based energy mechanism, it can be reformed to obtain H₂, which can then be used as a green fuel.
3. A mechanism similar to this may be used. The power used to drive high-power traction motors will be improved in the future.
4. Since the efficiency of PEMFCs is only 40%-60%, the fabrication process can be improved.
5. The battery has a few drawbacks, such as a short cycle life, a long recharging period, and a low power reserve. All of this could be improved.

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











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APPENDIX [A]

Some of Simulink block used in simulation process are given below:

	Inport
	Outport
	Constant block
	Scope
	Mux
	Current measurement
	Voltage measurement
	Bus selector
	Powergui
	Goto block
	From block
	Product block

APPENDIX [B]

#Built-in Matlab Program for Battery:

```
3 numCells = 1;

% load('Kokam_LUT_3RC')%

results.T5C = load('batteryParameterEstimation_results_3RC_5degC.mat');
results.T20C = load('batteryParameterEstimation_results_3RC_20degC.mat');
results.T40C = load('batteryParameterEstimation_results_3RC_40degC.mat');
SOC_LUT = results.T5C.SOC_LUT;

%% Thermal Properties

% Cell dimensions and sizes
cell_thickness = 0.0084; %m
cell_width = 0.215; %m
cell_height = 0.220; %m
cell_area = 2 * (...
    cell_thickness * cell_width +...
    cell_thickness * cell_height +...
    cell_width * cell_height); %m^2
cell_volume = cell_thickness * cell_width * cell_height; %m^3

for idx = 1:numCells
    %% Lookup Table Breakpoints
    Battery(idx).SOC_LUT = SOC_LUT;

    Battery(idx).Temperature_LUT = [5 20 40] + 273.15;
    3 Battery(idx).Capacity_LUT = [31 31 31]; %Ampere*hours
    3 Battery(idx).Em_LUT = [ results.T5C.Em ...
        results.T20C.Em ...
        results.T40C.Em];
    3 Battery(idx).R0_LUT = [ results.T5C.R0 ...
```

```

        results.T20C.R0 ...
        results.T40C.R0];
3 Battery(idx).R1_LUT = [ results.T5C.R1 ...
        results.T20C.R1 ...
        results.T40C.R1];
5 Battery(idx).R2_LUT = [ results.T5C.R2 ...
        results.T20C.R2 ...
        results.T40C.R2];
3 Battery(idx).R3_LUT = [ results.T5C.R3 ...
        results.T20C.R3 ...
        results.T40C.R3];
3 Battery(idx).t1_LUT = [ results.T5C.tau1 ...
        results.T20C.tau1 ...
        results.T40C.tau1];
3 Battery(idx).t2_LUT = [ results.T5C.tau2 ...
        results.T20C.tau2 ...
        results.T40C.tau2];
3 Battery(idx).t3_LUT = [ results.T5C.tau3 ...
        results.T20C.tau3 ...
        results.T40C.tau3];

Battery(idx).cell_mass = 0.84; %kg
3 Battery(idx).cell_rho_Cp = 2.04E6; %J/m3/K

Battery(idx).cell_Cp_heat = Battery(idx).cell_rho_Cp * cell_volume / Battery(idx).cell_mass;
3 Battery(idx).T_init = 20 + 273.15; %K

Battery(idx).Qe_init = 0.5 * mean(Battery(idx).Capacity_LUT); %Ampere*hours

Battery(idx).SOC0 = (Battery(idx).Capacity_LUT(2) - Battery(idx).Qe_init)/...
        Battery(idx).Capacity_LUT(2);

```

```

end
3
h_conv = 5; %W/m^2/K Cell-to-cell

h_conv_end = 10; %W/m^2/K End cells to ambient

load('BatteryParameters.mat')

#State Machine Control Program:
12
STATE_DEFINE(Idle, NoEventData)
{
    printf("%s ST_Idle\n", self->name);
}
STATE_DEFINE(Stop, NoEventData)
{
    Motor* pInstance = SM_GetInstance(Motor);
    pInstance->currentSpeed = 0;
    12
    printf("%s ST_Stop: %d\n", self->name, pInstance->currentSpeed);
    SM_InternalEvent(ST_IDLE, NULL);
}
12
STATE_DEFINE(Start, MotorData)
{
    ASSERT_TRUE(pEventData);
    // Get pointer to the instance data and update currentSpeed
    Motor* pInstance = SM_GetInstance(Motor);
    pInstance->currentSpeed = pEventData->speed;
    12
    printf("%s ST_Start: %d\n", self->name, pInstance->currentSpeed);
}
STATE_DEFINE(ChangeSpeed, MotorData)
{
    ASSERT_TRUE(pEventData);
    12
    Motor* pInstance = SM_GetInstance(Motor);
    pInstance->currentSpeed = pEventData->speed;
    12
    printf("%s ST_ChangeSpeed: %d\n", self->name, pInstance->currentSpeed);
}

```

ET161031,ET161062,_AAMK (Energy Management of Hybrid Electric Vehicle)

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