Design and Analysis of a Micro Solar Electric Vehicle for Application in Pakistan

By

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Abstract

Global transport sector is the third largest contributor of greenhouse gas emissions. Governments around the world as well other global stakeholders realize the intensity of the situation and are transitioning towards zero or low-emissions transportation modes in order to reduce greenhouse gas emissions and stop climate change. While the global electric vehicle (EV) adoption is on rise, developing countries like Pakistan have been facing many obstacles in the face of EV adoption such as shortfall of electricity, high EV prices, low average income and absence of commercial and residential charging infrastructure. This thesis proposes a design of a micro solar electric vehicle, which would address the existing challenges and provide an economical yet feasible solution. The design and system sizing of the micro solar EV was done in HOMER Pro. Based on the techno-economic feasibility analysis completed in HOMER, a dynamic model of the micro solar EV was created in Simulink. This comprehensive model includes PV generation, maximum power point tracking, battery charging and discharging, DC-motor operation and speed control of the electric vehicle, while taking into consideration environmental factors like irradiance and temperature. Moreover, a detailed ready to build, instrumentation and control design of the car was developed in Tinkercad. The Tinkercad model was divided into two parts with the first part covering the control and monitoring circuit for the vehicle, and the second part covering the auxiliary circuit for the vehicle. Lastly, conclusions are provided based on the research conducted in each section of this thesis, and areas for future research have been identified.

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List of Abbreviations

EV	Electric Vehicle
GHG	Greenhouse Gas Emissions
PV	Photovoltaic
DC	Direct Current
AC	Alternating Current
O&M	Operations and Maintenance
NPC	Net Present Cost
HOMER	Hybrid Optimization of Multiple Energy Resources
SOC	State Of Charge
MPPT	Maximum Power Point Tracking
PWM	Pulse Width Modulation
COE	Cost Of Energy
HOMER	Hybrid Optimization of Multiple Energy Resources
P&O	Perturb and Observe
SEPIC	Single-ended Primary Inductor Converter
CEMF	Counter-Electromotive Force
CCCV	Constant Current Constant Voltage
LCD	Liquid Crystal Display
RPM	Rotations per Minute
PROM	Programmable Read Only Memory

CHAPTER 1: INTRODUCTION & LITERATURE REVIEW

1.1. Introduction

For most of our history, human beings have always relied on some form of energy. These forms of energy used to be very basic in the beginning such as burning biomass or animal muscle. The energy dynamic of the world changed with the advent of industrial revolution, which unlocked a new source of energy, i.e., fossil fuels.

Even today, a few centuries later, our world is still heavily reliant on the consumption of fossil fuels (coal, oil, gas) in order to meet the needs of the modern society. However necessary these fossil fuels might be, their consumption comes at the price of the environment. When burned, fossil fuels produce carbon dioxide and a variety of other greenhouse gases, which are largest contributor to global climate change and air pollution across the globe.

Global transport sector is one of the biggest consumer of fossil fuels. However, the advent of electric vehicles (EVs) marks a new era in the history of transport by providing a cleaner alternative to hydrocarbon-powered transportation.

1.1.1. Electric Vehicle Adoption around the World

Governments around the world as well other global stakeholders have realized the intensity of situation and are taking steps to counter the global climate change by reducing the emissions of greenhouse gases. Transport sector being the third largest contributor to GHG emissions [1] automatically becomes a priority. The steps taken to reverse the global warming effect and stop climate change include but are not limited to;

- transition towards zero or low-emissions transportation modes,
- increase public transit ridership,
- increase the use of cleaner fuels, and
- encourage denser communities.

The transition from internal combustion powered cars to electric vehicles falls under the first category, i.e., zero or low-emissions transportation modes and has been the number one driver towards a cleaner future. For the past ten years, electric vehicle deployment has been growing rapidly. According to the Global EV Outlook 2019, published by International Energy Agency, the global stock of passenger EVs passed 5 million in 2018, which is a 63% increase as compared to the year before. Figure below shows the growth in EV deployment around the globe for years 2010-2020 [1].

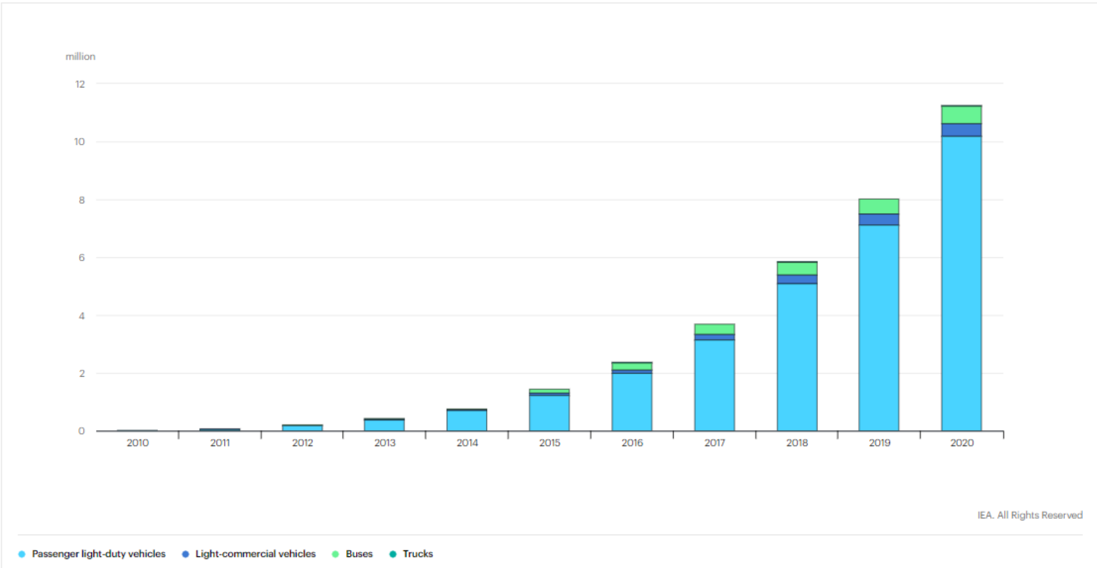

Figure 1: Electric vehicle deployment around the globe, 2010-2020[1]

1.1.2. EV Deployment Scenario in Pakistan

While the global EV deployment is growing at a rapid rate, the same cannot be said about Pakistan and a number of reasons are to be blamed for this stagnancy in EV deployment across Pakistan.

Firstly, the energy scenario in Pakistan is not ideal to support the EV infrastructure at a large scale. In the past decade, Pakistan has suffered from one of the worst energy crisis when the country faced a persistent gap between the demand and available system generating capacity. The power shortages as a result of this energy crisis impacted the country's annual output, employment and exports.

In the recent years, Pakistan has focused a lot on developing large-scale power generation projects in order to meet the growing electricity demand, and to some extent, they have succeeded. According to the Pakistan Economic Survey 2019-20, the country's installed generation capacity reached 37,402 MW in 2020 [2], whereas the maximum total demand from both industrial and residential estates was never above 25,000 MW. However, the distribution and transmission capacity is stalled at approximately 22,000 MW, meaning at peak demand times Pakistan was suffering with a shortfall of electricity by about 3000 MW [3].

Apart from the electricity shortfall, there are a number of other reasons why Pakistan is lagging behind in EV adoption including but not limited to, high prices of electric vehicles, low average income, absence of commercial charging infrastructure, and last but not least the inability of residential electrical infrastructure to charge an electric vehicle.

Talking about the prices of the cars, an average electric car costs anywhere between $30,000 to $40,000 and while no additional taxes or import duties are imposed by the

Pakistani government on the import or development of EVs in the country, the price is still higher than most cars sold in Pakistan. The average income of a Pakistani household is 81,800 PKR (Pakistani Rupee) per month [4], which translates to $485.46 as per the September 2021 conversion rates. This number is significantly lower than the US average of $7900 per month. Similarly, if we look at the price of cars in Pakistan, Suzuki's 660cc Alto was the best-selling car for the year 2020 [5]. This car retails for 1,113,000 PKR (Pakistani Ruppee) which translates to $6,605 as per the September 2021 conversion rates. Therefore, the price difference between an average EV and the cars in Pakistan is just too exorbitant to ignore.

Since there are not many EVs being offered by automobile manufacturers in Pakistan, there is a complete lack of commercial charging infrastructure in the country. As compared to US, which has nearly 43,000 public EV charging stations and the leader in EV adoption Norway, which has nearly 16,000 public EV charging stations, Pakistan only has less than half a dozen public EV charging stations. Although plans are underway to develop more charging stations, these projects would only be making an addition of 24 new public EV charging stations [6].

Lastly, the idea of charging an EV at a residential charging port also seems far fetched as the average amount of current needed by an EV to charge at a reasonable speed of 25 miles per hour is about 32 A. This amount of current is simply not available for a single -phase residential meter in Pakistan, which are rated at about 10 A at most.

1.2. Literature Review

A solar powered electric vehicle or as it is commonly referred to, 'solar car' is a vehicle used for land transport and runs either entirely or partially on power from the sun in the form of solar energy. Most solar powered EVs utilize a photovoltaic array consisting of PV cells in order to convert the solar energy shinning on to the photovoltaic array, which converts it into a usable form of energy, i.e., electricity. This electricity is used to drive the electric motors, which carry out the propulsion of the vehicle [7].

Most solar cars make the use of batteries as a form of energy storage devices in order to save the electricity being produced by the photovoltaic array mounted on the body of the vehicle. These batteries not only help ensure a constant supply of electricity but also serve as a power bank for when there is no sunlight and the photovoltaic array mounted on the car is not producing any electricity. In solar powered EVs, which only take a part of their energy from the sun, the same batteries act as a secondary source of energy and can be charged by a utility EV charger connected to the grid [8].

1.2.1. History of Solar Cars

The world's first solar powered vehicle was presented at the General Motors Powerama auto show held in Chicago, Illinois, by William G. Cobb, a General Motors Corp. executive, in 1955 [9]. The showcased vehicle was a miniature 15-inch long vehicle, called 'Sunmobile', which made use of 12 photoelectric cells made of selenium (a non-metal substance, which also possesses conducting properties). The cells were built into the car and when sunlight shined on them, they produced enough energy to turn a tiny motor connected to the drive shaft of the sunmobile [9]. More than 65 years later, we are yet to see a mass-produced solar car to hit the consumer market.

1.2.2. Solar Races

When it comes to the development of a road worthy solar powered electric vehicle, solar car races have contributed a lot. There is a large number of racing events being held globally for the past decade or so, in which innovative designs of solar powered cars from around the world come together to compete over distances of up to a few thousand kilometers. These solar car races have pushed solar design teams across the world to achieve high efficiencies, aerodynamics and low energy consumption when working on the design of these solar cars.

The solar races being held around the world have a wide variety of cars competing in them from racing cars to small sized solar powered EV and a cruiser that comfortably fits a family of five. Two of the most popular solar challenges are the World Solar Challenge held in the Australian continent, over a distance of 3000 kilometers [10], and the American Solar Challenge which stretches all the way from Omaha, Nebraska to Bend, Oregon [11].

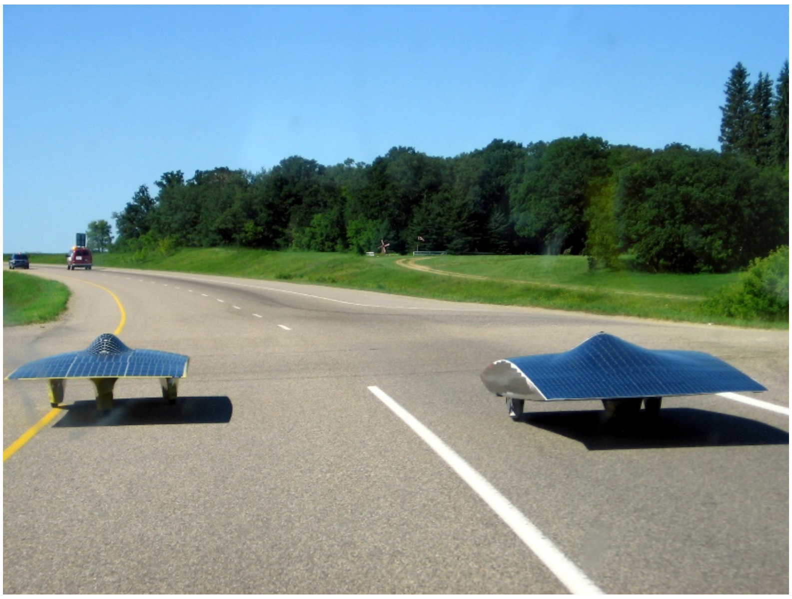

Figure 2: University of Michigan and University of Minnesota solar cars compete in the American Solar Challenge[11]

1.2.3. Commercial Solar Cars

In the past decade, multiple automobile manufacturers and electric vehicle technology startups have come forward with their own version of solar powered electric vehicles. While none of these vehicles have made it to the consumer, they all represent a big step towards the realization of a dream, that a solar powered electric vehicle will one day be the most common mode of transport.

The first one to come out with a solar powered electric vehicle was a US based startup called Aptera [12]. The company showcased a prototype with exceptional design and very low drag coefficient of only 0.13. The company also claims that the 3D designed car can produce up to 700 watts of electricity in good solar conditions, thus providing a range of up to 40 miles per day [12]. The second solar car to be presented to the world was by a Netherlands based startup called Lightyear, who recently came out with their first car Lightyear One [13]. The solar car is a full-sized luxury sedan with a very aerodynamic design and as per company claims has a range of up to 725 kilometers (solar and battery combined). The company also claims that Lightyear One can add a range of 7,000 to 20,000 kilometers annually from the sun, if you live in an area with appropriate amount of sunlight [13].

Similarly, a Swedish startup has come up with a solar powered electric car called Sion, which is a family sized van, with a range of up to 305 kilometers [14]. The car has 248 solar cells seamlessly integrated into the body of the car, which according to the company add up to 112 kilometers of range per week to the car's battery [14].

Another Swedish startup called Clean Motion, which focuses on providing urban transport solution through solar-powered electric vehicles [15]. Clean Motion has recently launched their latest small, modular delivery van, which is powered by the sun. The prototype boasts about 600 watts of solar panels and can supposedly add a range of 130 kilometers per day on a bright sunny day [15].

Last but not least, one of the most interesting design was put forward by a startup named Squad Mobility, who recently launched their first solar car named Squad [16]. The Squad is a micro car, which gives a range of about 20 kilometres from solar energy and as per the average micro car usage in Europe of 12 kilometres, Squad can be fully sustainable [16].

1.2.4. Design of Small Solar Cars

When talking about the design of small solar cars, there has been plenty of research done on the topic. In this section, some of the designs that were put forward for small solar powered electric vehicles will be discussed.

To start, P.O. Babalola and O.E.Atiba from Covenant University did a comprehensive review of solar powered cars. The review covers everything from the history of solar cars to how the design and efficiency considerations have changed over the period of 65 years. Some of the principles that need to be kept in mind when designing a small solar powered electric vehicle include but are not limited to: the design should be less complex than conventional cars, the number of solar cells that can be integrated on to the car depend on the size of the car as well as allowable solar cells per Winston rules, and due to high maximum efficiency of 80-90%, a DC brush permanent magnet motor should be used as the primary driver [17]. H. Koten et al. in his research on the design consideration of solar powered cars also discusses some important principles to be kept in mind when designing a solar car including low drag resistance, being light-weight, and must have low rolling resistance [18]. In this same study, the authors make the use of solar powered Stirling engine technology instead of a conventional PV conversion technology [18].

The first car design that is going to be discussed in this paper was made by Engineering students at University of Kentucky, who designed a solar car for the North American Solar Car Challenge [19]. The car called Gato del Sol III was powered by 480 silicon monocrystalline PV cells, integrated making the use of MPPTs. The car was powered by a 90% efficient brushless DC motor. The car with its battery back of 5kWh was able to travel over 75 miles, in the absence of sun [19].

In another comprehensive research published in the Journal of Progress in Photovoltaics, the authors present innovative design solutions for solar powered electric mobility applications [20]. The paper discusses 11 of the designs that were developed at University of Twente, which encompass a variety of mobility applications. The authors discussed four of those conceptual designs as case studies and discusses the design challenges that needed to be addressed. These challenges included: limited space available for integrating PV cells, effective visual communication of concept's intended function, and technical limitations of some proposed charging methods [20].

Another important solar powered electric vehicle design is known as the UltraCommuter designed by researchers at University of Queensland [21]. The paper showed that the solar array on-board the vehicle provides substantial supplementation of electricity required for normal driving. By normal driving, the authors mean that the UltraCommuter can power almost 90% of the journey of an average QLD passenger vehicle [21].

Ashrafee et al. discusses the design and fabrication of a solar powered toy car. The concept is very much similar to an actual solar powered car, however, given the small amount of power required to propel the toy car, the design does not translate to a car to be considered practical [22].

S. Ahmed et al. conducted a research that proposed a design of a prototype solar powered lightweight vehicle, capable enough to carry two people. The study also presents an economic analysis of the car, which shows that over a period of 20 years, the cost of ownership of the solar car is $1/9^{th}$ the total cost of ownership of a gas powered car [23].

1.2.5. Solar-Powered Rickshaw

In developing countries, rickshaws are an important mode of public transport. These vehicles are usually equipped with small motors and are capable of carrying up to 5 people at low cruising speeds. The use of solar-power as the main source of power in a rickshaw makes a lot of sense as their watt/mile energy consumption is low and only a few kWh of energy lasts a long way.

N. Saleh et al. proposes the design of solar-powered hybrid rickshaw for commercial use in Pakistan. The study presents four prototypes of passenger rickshaws and one prototype for cargo loading type rickshaw. The authors then performed an average speed analysis test of the rickshaw prototypes and found that the rickshaw could produce enough power to last for 40 miles per charge [24].

Similarly, researchers from Institute of Information Technology in Bangladesh, presented the design of a solar powered rickshaw, where they took a traditional battery operated auto-rickshaw and proposed a microcontroller based design to convert the rickshaw into a solar powered vehicle. The paper also presents a performance evaluation of the rickshaw, which shows that the life cycle cost (LCC) analysis is minimum as compared to battery-operated auto-rickshaw [25].

1.3. Motivation

There exists a significant gap in the research being performed on solar powered electric vehicles and what is needed in the market. A large number of studies and research projects, which focus on the design of a solar powered car have been discussed. However, almost all of them, with the exception of few lack one or another crucial component that is stopping the mass adoption of a solar powered electric vehicle.

Starting from the solar races, most of the solar cars participating in those competitions are the epitome of innovation, efficiency and aerodynamics. These cars can produce a record amount of energy from solar arrays integrated into them, they can achieve high speeds. However, the number of amenities that these cars come equipped with are very small to none, making these cars not suitable for commercial use. Also to be kept in mind is the fact that these cars barely have the space to hold the driver of the car, let alone a passenger. Most of these cars are also made from fiber, in order to keep their weight low, which makes them unsuitable to be used on the road.

Talking about the commercial choices available for a solar powered electric vehicle, most of the options available are only prototypes and while the claims made by their manufacturers are impressive, they have almost zero proof when it comes to backing those claims. Most of these cars seem nothing more than a marketing gimmick, as all of these prototypes have been launched for over 4-5 years now, but the market is yet to see them on the road. Another important fact to note here is that most of these cars come with an enormous price tag of more than $100,000 USD, which is even more expensive than a traditional electric vehicle.

Finally, there are design propositions for small solar car designs. While there are some reasonable designs and prototypes showcased by those studies, almost all of them fail to provide a comprehensive design for a solar powered electric vehicle. Some of the studies focus on the sizing part of the electric vehicle, others study it from an economical point of view and last but not least, most studies focus on the performance evaluation of the car. A study that provides a one-window solution to the design of a solar powered car i.e. cover everything from the design, sizing, economic analysis, dynamic modelling, and controller design of the solar powered car is yet to be found.

When talking about the studies found on solar-powered rickshaw, they present very reasonable designs; however, they can only be used as a commercial mode of transport and are not suitable for everyday personal use.

The gaps in the existing literature present a great opportunity to work on the design and modelling of a small solar powered car, especially for application in Pakistan, as the dynamics there are different from the ones discussed in the studies mentioned above.

In addition to the literature gap, there are a few other reasons why this topic is an ideal choice for the thesis project. Technologists and scientists believe that electric vehicles are the future of transportation. However, given the lack of electricity abundance throughout the world, and the high prices of EV technology due to it being in its initial phases, it is difficult if not impossible for the developing countries to compete with the developed countries. This motivated me to work on the design of a micro solar EV, which is not only cheaper to develop but also utilizes solar energy as its primary source, thus overcoming the electricity shortfall problem.

In addition, solar powered electric vehicles provide a number of benefits over their internal combustion engine counterparts. These benefits include but are not limited to less maintenance, lower running cost, lower registration costs, better for the environment, better for the network and for our energy security.

The reason why a solar powered electric vehicle requires less maintenance is that it has a lot less parts than an internal combustion car. According to a report done by Forbes, an electric vehicle on average consists of about 20 moving parts, which make up its drivetrain in comparison to an internal combustion engine vehicle, which has over 2000+ moving parts [26].

Secondly, the average price of running an electric vehicle is significantly lower than that of running a gas-powered vehicle. A case study done by Idaho National Laboratory found out that if the average price of electricity and fuel in US were assumed, an electric vehicle with energy efficiency of 3 miles per kWh costs about 3.3 cents per mile. Similarly, a gas-powered vehicle with an energy efficiency of 22 miles per gallon costs about 15.9 cents per mile [27]. This number becomes even lower when we rule out the cost used to charge the electric vehicle, as in our case the vehicle is being charged directly from solar energy.

Solar electric vehicles, alongside electric vehicles qualify for tax exemptions as well as relief from custom duties from the governments around the world. Even in Pakistan, where most vehicles are subjected to a custom duty of as much as half of their price, EVs are exempt from any kind of tax and customs duty.

Talking about the betterment of environment, there is an ongoing argument about how EVs may not be as clean as they claim to be. However, a solar powered EV has some of the key differences when it comes to its carbon footprint. Firstly, a solar powered EV is charged directly from solar energy and thus does not utilize electricity from the grid, which is often produced using fossil fuels. Secondly, it is true that the production of an EV and solar panels itself is a carbon positive activity, it is nowhere even close to the carbon footprint of an ICE car. The carbon footprint of a solar powered EV is also significantly less than a traditional EV.

1.4. Research Scope

In this thesis, a comprehensive design and modelling of a micro solar electric vehicle for application in Pakistan will be carried out. The research will be divided in three portions starting from the sizing of the electric vehicle and choosing all the suitable components that go on it, in order to make a fully functional micro solar charged electric vehicle. After this, the detailed modelling of the system in Simulink in order to analyze how all the parts would come together to form our micro EV, will be carried. Lastly, an instrumentation and control system for a micro solar electric vehicle will be designed.

Since the EV being designed is for application in Pakistan, the solar irradiation data from Punjab, Pakistan will be used.

The research spanned over a period of one year starting from September, 2021 to August 2022. Each part of the research spanned over a period of 2.5 months.

1.5. Thesis Structure

This thesis is divided into five chapters in total. The details of what each chapter would cover are given below;

Chapter 1 starts with an introduction of the global energy scenario, and how the current transport sector happens to be the third largest contributor to greenhouse gas emissions. The global EV adoption, as well as the Pakistani context, when it comes to the deployment of electric vehicles is discussed. The chapter also includes a detailed literature review or all the research and development that has been done in this field from the inception of solar cars, to solar races, commercial solar cars, small solar powered cars, and solar powered rickshaws. Further, the chapter identifies the gap in the literature and talks about our motivation to pursue this research.

Chapter 2 of the thesis focuses on the sizing of the system. This chapter includes everything from the choice of location, choice of vehicle, collection of solar irradiance data, sizing of the system, selection of the components to be used, feasibility study and finally an economic analysis of the system.

Chapter 3 of the thesis would focus on the dynamic modeling of the system. In this part, choice of the software, modelling of all individual components of the system, simulation of the model and lastly, the results of the simulation will be discussed.

Chapter 4 of the thesis will focus on the design of an instrumentation and control system for the car. This chapter would outline the software to be used, major components of the instrumentation and control system, and finally the modeling of the system.

Chapter 5 of the thesis would discuss the conclusions drawn from the previous chapters and will propose future areas of research that can be undertaken as an extension to this research.

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CHAPTER 2: SYSTEM DESIGN AND PV SIZING OF A MICRO SOLAR ELECTRIC VEHICLE FOR PAKISTAN

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A version of the manuscript in this chapter has been presented as a conference paper in the 2022 IEEE Conference on Technologies for Sustainability (SusTech). As the primary author in this paper, Ali Husnain carried out the research under the supervision of M. Tariq Iqbal, the co-author. The MEng candidate performed the literature review and was involved in system selection, designs, calculations, simulation, and data analysis. Moreover, he prepared the first draft of the paper. The co-author supervised the research by actualizing the research ideas, reviewing and correcting the manuscript.

Abstract

The transport sector is the third largest contributor of GHG emissions globally. To counter this, global EV adoption has been increasing at a rapid rate. However, Pakistan has been left far behind in this race and is very slow to EV adoption, due to a number of factors including energy shortfall, lack of purchase power and absence of charging infrastructure to name a few. Therefore, a design for simple yet economical micro solar electric vehicle has been proposed. This paper covers the sizing and system design for the solar PV system for a solar electric vehicle on HOMER Pro. It also gives an economic analysis of all the components involved.

Keywords

solar EV, solar car, electric vehicle, EV design

2.1. Introduction

Climate change has been identified as one of the biggest problems of the modern world. However, we as human beings, continue to rely heavily on the consumption of fossil fuels (coal, oil, gas) to meet our daily needs. No matter how necessary it is, the consumption of fossil fuels comes at the price of environment. When burned, fossil fuels produce carbon dioxide and a variety of other greenhouse gases, which are largest contributor to global climate change and air pollution across the globe.

Global transport sector is one of the biggest consumer of fossil fuels and the third largest contributor of greenhouse gas (GHG) emissions globally. However, the advent of electric vehicles marks a new era in the history of transport by providing a cleaner alternative to gas-powered transportation.

For the past ten years, electric vehicle deployment has been growing rapidly. According to the Global EV Outlook 2019, published by International Energy Agency, the global stock of passenger electric vehicles (EVs) passed 5 million in 2018, which is a 63% increase as compared to the year before [1].

2.1.1. EV Deployment Scenario in Pakistan

Firstly, the energy scenario in Pakistan is not ideal to support the electric vehicle (EV) infrastructure at a large scale. Pakistan has suffered from one of the worst energy crisis over the past decade, due to a large and persistent gap between the demand and available system generating capacity. In more recent years, Pakistan has focused a lot on developing large-scale power generation projects in order to meet the growing electricity demand, and to some extent, they have succeeded. The current installed generation capacity stands at 37,402 MW in 2020 [2], whereas the maximum total demand was never above 25,000 MW. However, the distribution and transmission capacity is stalled at approximately 22,000 MW, meaning at peak demand times Pakistan was suffering with a shortfall of electricity by about 3000 MW [3].

Apart from the electricity shortfall, there are a number of other reasons why Pakistan is lagging behind in EV adoption including but not limited to, high prices of electric vehicles, low average income, absence of commercial charging infrastructure, and last but not least the inability of residential electrical infrastructure to charge an electric vehicle. At typical electrical service is 5A or 10A at 220V to supply house load, which is not enough to charge an EV at home.

In this chapter, a preliminary design of a micro solar electric vehicle is proposed. The chapter includes the selection of a location, where the solar electric vehicle will be driven. This is done in order to use the solar insolation data of the chosen location, as it varies from region to region. The chapter will also discuss the major components that are going to be used in the design of solar electric vehicle. Finally, a solar powered system design tool called HOMER Pro will be used to do the sizing of the solar electric vehicle.

2.2. Site Selection

The major motive behind carrying out this research is to design a small solar electric vehicle for application in Pakistan. Therefore, the country chosen for the selection of solar radiation data is Pakistan. However, that does not narrow it down any further, as Pakistan has a diverse geographical landscape and the amount of sun available throughout the day, is different across different regions of the country. For this purpose, the city of Bahawalpur, a region with mixed landscape, which can be used as a representative of the region of Pakistan was selected.

Figure 3: Map of Bahawalpur, Pakistan

2.2.1. Solar Radiation at the Chosen Location

The solar radiation and the clearness index data for the chosen location i.e. Bahawalpur, Pakistan is retrieved from the National Renewable Energy Laboratory (NREL) global database. This database is integrated into the system design software, HOMER Pro that we are utilizing in order to carry out the sizing of the system. The solar radiation and clearness index of the location can be seen in figure 4.

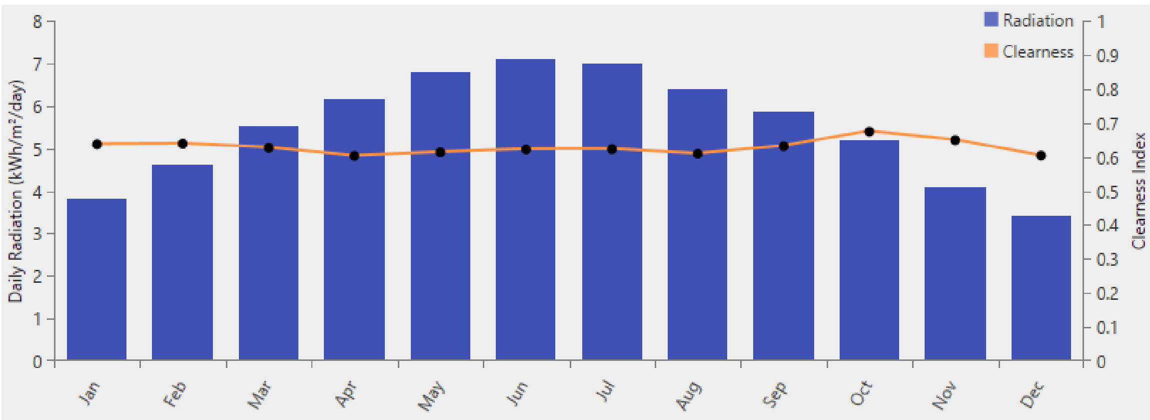

Figure 4: Solar radiation data for Bahawalpur, Pakistan. (Source: NREL*)*

Another important dataset that goes into the modelling of how much solar power is needed for the load; is the temperature data for our chosen location. This data has been retrieved from NASA Prediction of Worldwide Energy Resource (POWER) database. The monthly average temperature data for Bahawalpur, Pakistan can be seen in figure 5.

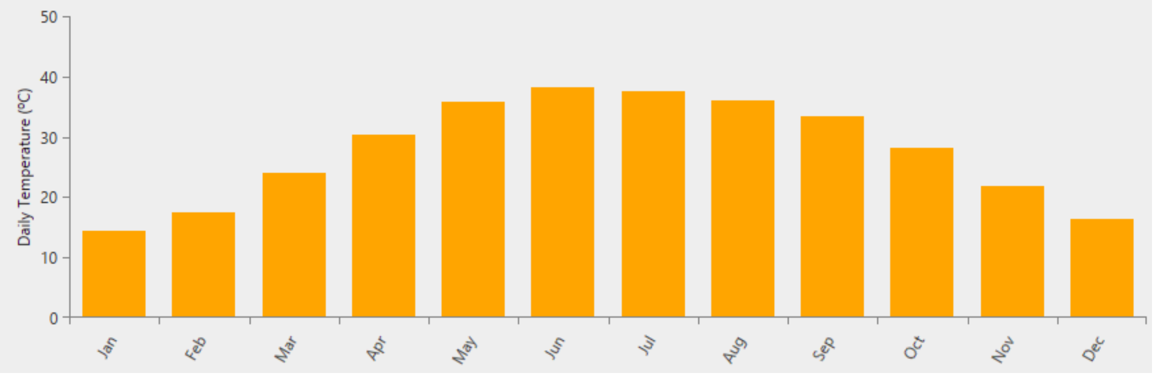

Figure 5: Monthly average temperature data for Bahawalpur, Pakistan (Source: NASA POWER)

2.3. System Sizing

2.3.1. Choice of a System Sizing Tool

In order to perform the sizing of our small solar electric vehicle, a design tool called HOMER Pro is chosen. Developed by the National Renewable Energy Laboratory (NREL) in the United States, HOMER stands for Hybrid Optimization of Multiple Energy Resources, and is a software application that is used to design and analyze both the technical and financial aspects of a power system for stand-alone, remote and distributed generation application. HOMER Pro is simple to use, detailed and takes in all of the necessary variables when it comes to analyzing a power system.

2.3.2. Major Components of the System

When sizing a system in HOMER Pro, a few key components must be added into the simulation. The first and most important component of the system is the load, which in our case is a small solar electric vehicle. Other than that, a renewable energy source needs to be added to the system as well as a battery storage solution. Most systems in HOMER also require a backup generator, a grid source or a converter. However, in this case, since we are designing an electric vehicle, we would not have a generator or a grid source. Moreover, the use of a DC electric motor also eliminates the need for a converter. So the remaining components that we need to model for our system design in HOMER Pro are load, renewable energy source, and a battery storage solution.

2.3.2.1. Load

As emphasized earlier in this thesis, a small solar powered electric vehicle is to be designed. Some of the design requirements that we abide by throughout this research include that the vehicle should be able to fit at least 3 passengers and drive at average city driving speeds. Therefore, the vehicle design that we have selected is the one proposed by a Chinese manufacturer called Chang Li [4]. Chang Li is a small automobile manufacturer, which specializes in producing small electric vehicles at a very economical price point. The specific vehicle that is being chosen is the 2021 Chang Li XYZ electric car [4]. The vehicle can be seen in figure 6.

Figure 6: Choice of vehicle for solar system design [4]

The specifications of the vehicle are as following:

Table 1: Vehicle specifications

Item	Description
Brand Name	Chang Li
Max. Range	100 km
Dimensions	2450 mm*1350 mm*1750 mm
Wheelbase	1500 mm
No. of seats	3
Motor Size	1200 W
Total Motor Torque	100 Nm
Max Speed	43 km/hr

Now, in order to build a load profile to be input into HOMER, the amount of power the vehicle would consume over a set distance needs to be calculated. For this load consumption, we have assumed that the vehicle would cover a distance of 30 km per day, which happens to be equal to the average distance covered by a commuter in Pakistan.

Distance covered: 30 km

Average speed: 30 km/hour

Motor nominal power: 1.2 kW

Energy consumption = Motor power * Time

= 1.2 kW * (1 hour) = 1.2 kWh.

Hence, the load profile in HOMER Pro was set accordingly, as shown in figure 7.

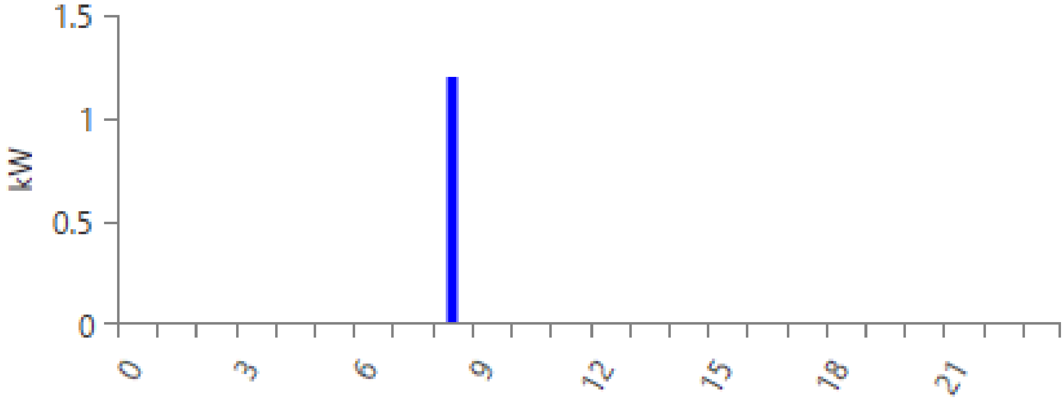

Figure 7: Daily load profile

2.3.2.2. Renewable Energy Source: Solar Panels

In order to meet the load demand, a renewable energy source, i.e. solar panels were added. The solar panel chosen is Kyocera KD 145 SX-UFU [5]. There are multiple reasons behind the choice of this solar panel, which include easy availability, high efficiency and a low temperature coefficient. The chosen solar panel module has the following specifications:

- Name: Kyocera KD 145 SX-UFU
- Abbreviation: Kyoc145
- Panel type: Flat Plate
- Rated capacity (kW): 0.145
- Temperature coefficient: -0.460
- Operating temperature (°C): 45.00
- Efficiency (%): 14.4

Figure 8: Kyocera KD 145 SX-UFU module [5]

- Capital cost (Rs): 6,960.00
- Replacement cost (Rs): 6,960.00
- O&M cost (Rs): 0.00
- Time (Years): 25.00

When talking about the placement of solar panels on the electric vehicle, they will be laid flat on the roof the vehicle.

2.3.2.3. Battery Storage

In addition to the solar panels, a battery storage system is needed for the electric vehicle in order to ensure a continuous supply of electricity, when the sun is not providing enough solar power. The battery size can also be increased to provide longer range to the electric vehicle and the battery can also be charged passively by connecting it to an electrical outlet in the case of bad weather or absence of sun etc. The battery module chosen is Discover AES 1.0 kWh 24 VDC [6]. It is a LI-Ion LFP battery and has the following specifications.

- Name: Discover AES 1.0kWh 24VDC
- Nominal voltage (V): 24
- Nominal capacity (kWh): 0.96
- Nominal capacity (Ah): 40
- Roundtrip efficiency (%): 95
- Maximum charge rate (A/Ah): 1
- Maximum charge current (A): 40
- Maximum discharge current (A): 200
- Capital cost (Rs): 54,376.00
- Replacement cost (Rs): 54,376.00

Figure 9: Discover AES 1.0 kWh 24 V DC battery [6]

- O&M cost (Rs): 0.00
- Time (Years): 10

2.4. System Design

After making the choice of all important components, HOMER Pro was used to carry out a detailed technical and economic analysis of the system and provide a feasible outcome for the research. The system modeled by HOMER Pro is shown in the figure 10 below:

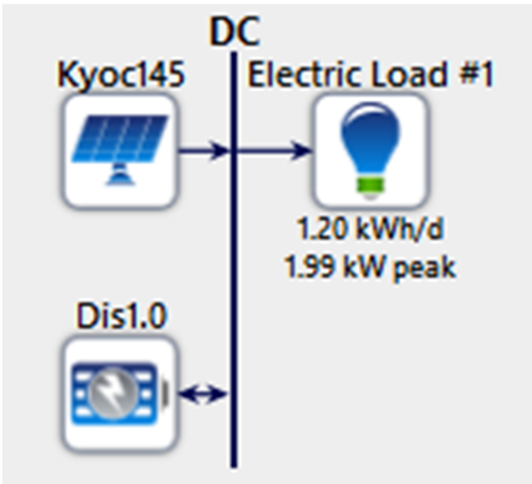

Figure 10: System modelled in HOMER pro

For this modeled system, HOMER Pro also provided us with the most feasible sizing of the system as shown in the table below.

Table 2: Simulation results of HOMER pro

Item	**Quantity**
Architecture/Kyoc145 (kW)	0.4375
Architecture/Dis1.0	3
Cost/NPC (Rs)	177013.7

Cost/COE (Rs)	54.62492
Cost/Operating cost (Rs/yr)	961.2305
Cost/Initial capital (Rs)	184128
System/Ren Frac (%)	100
System/Total Fuel (L/yr)	0
Kyoc145/Capital Cost (Rs)	21000
Kyoc145/Production (kWh/yr)	766.9749
Dis1.0/Autonomy (hr)	57.6
Dis1.0/Annual Throughput (kWh/yr)	392.1335
Dis1.0/Nominal Capacity (kWh)	2.88
Dis1.0/Usable Nominal Capacity (kWh)	2.88

2.4.1. Simulation Results

The simulation carried out using HOMER Pro gives a few more insights into the design of the system. This includes financial analysis, monthly energy production, cash flow, comparison of economics, emissions reports and much more.

The cost summary of the system is as shown in the figure below:

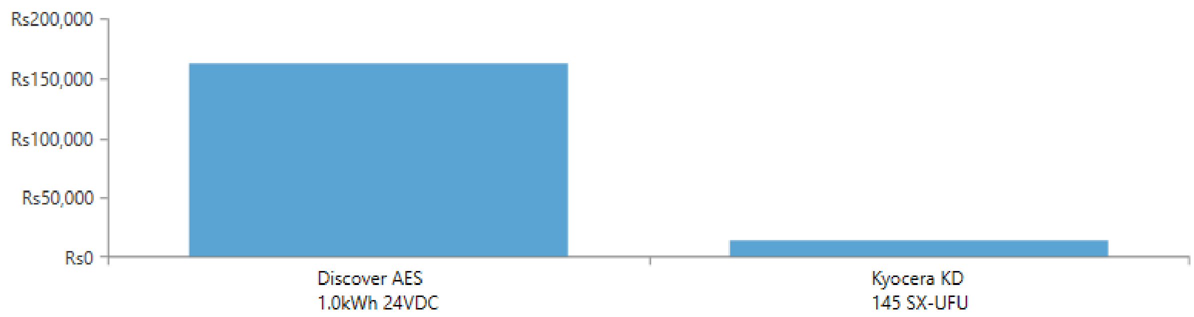

Figure 11: Cost summary of the system

Before diving into the detailed results of the system, let us take a look at the monthly electric production by our designed solar system.

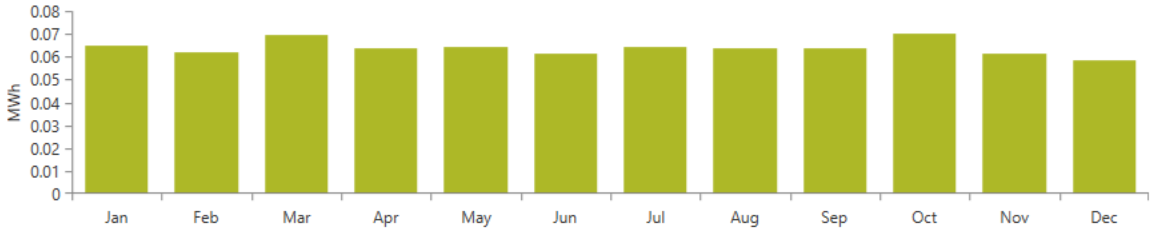

Figure 12: Monthly electric production by solar panels

Since, we have seen how the electric production by the solar panels would vary over different months throughout the year; let us dive into the detail of our monthly production, battery operation and load fulfillment.

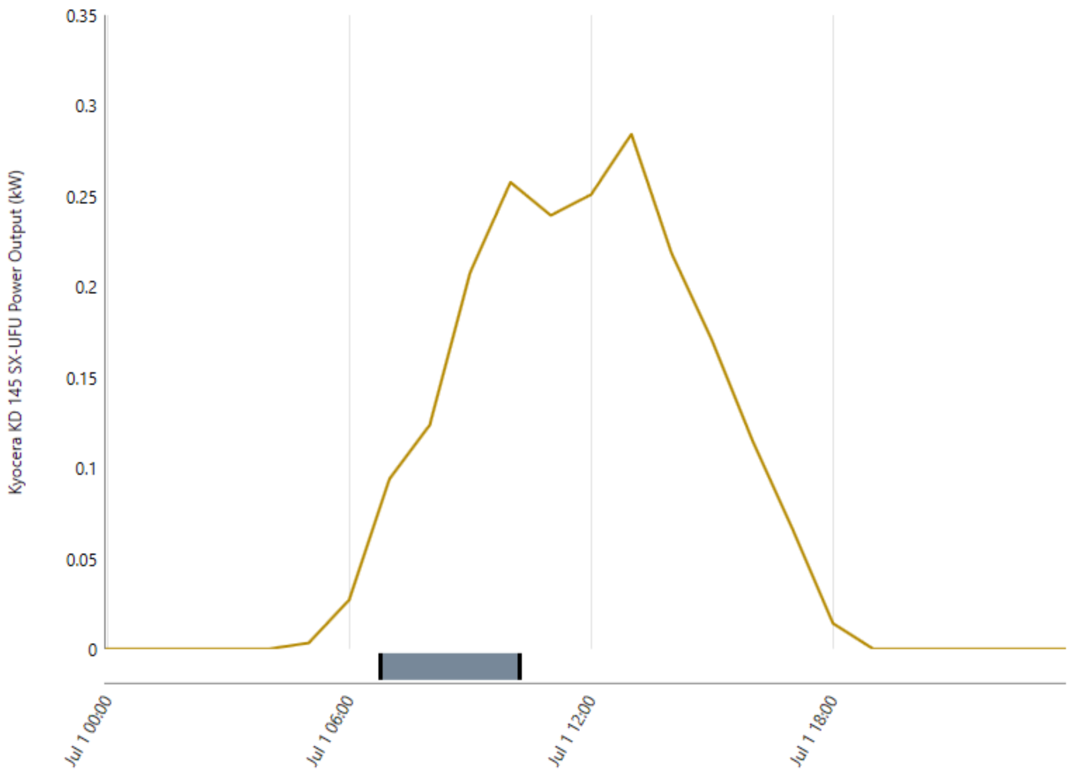

Figure 13: Daily solar output by the solar panels

As shown in the figure 13, the daily solar output by the solar panels varies throughout the day, where it starts from almost zero and goes all the way up to 0.28 kW. The chosen location Bahawalpur is located in the south region of Pakistan, which means it gets plenty of sun, especially during the summer months. This explains the extended solar output throughout the day as compared to a city located in the Northern region.

The next figure shows the total electrical load served during a day. As per the load profile, the amount of time, that the car was utilizing solar power was restricted to a single hour. While the car can still drive throughout the day, given the battery has been charged directly via an electrical outlet, the curve in the figure given below shows the amount of time, when the electrical load is being served by the electricity generated by solar panels.

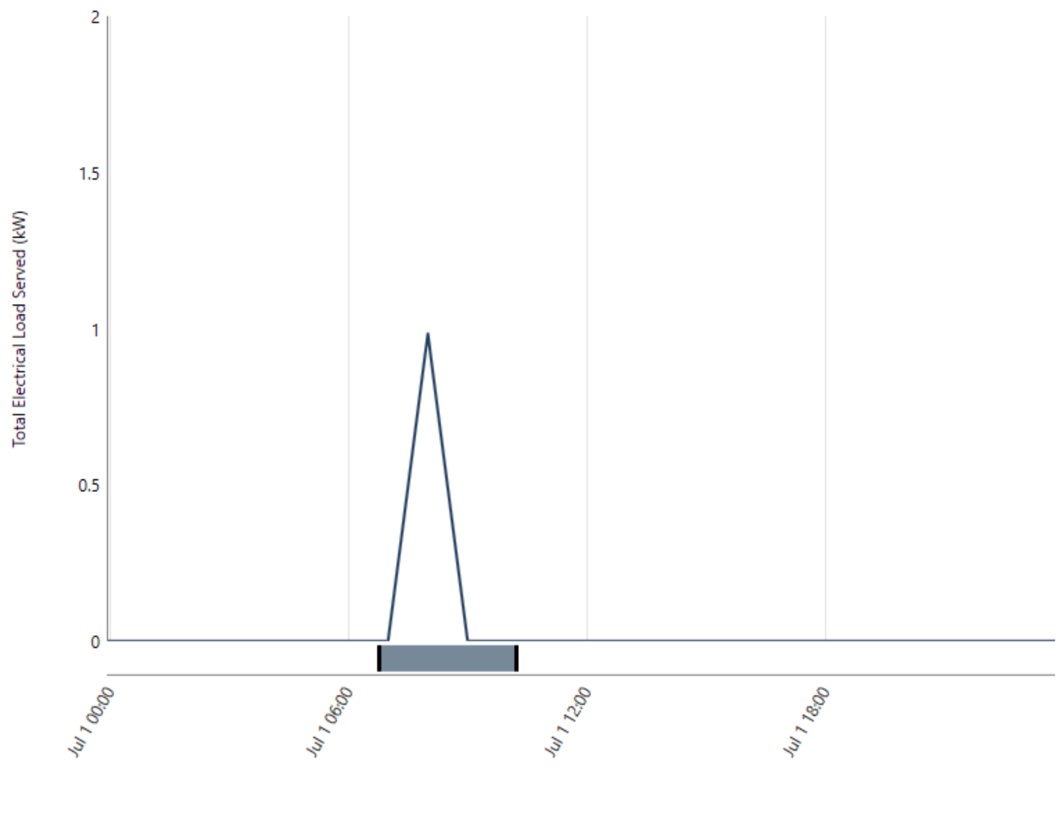

Figure 14: Electrical load served by solar panels throughout the day

Moving on, figure 15 shows the input power that is going into the battery storage system. The battery shows a negative input power during the time that the electrical load was served and then once the load is served, the input power is in positive, until the battery is fully charged.

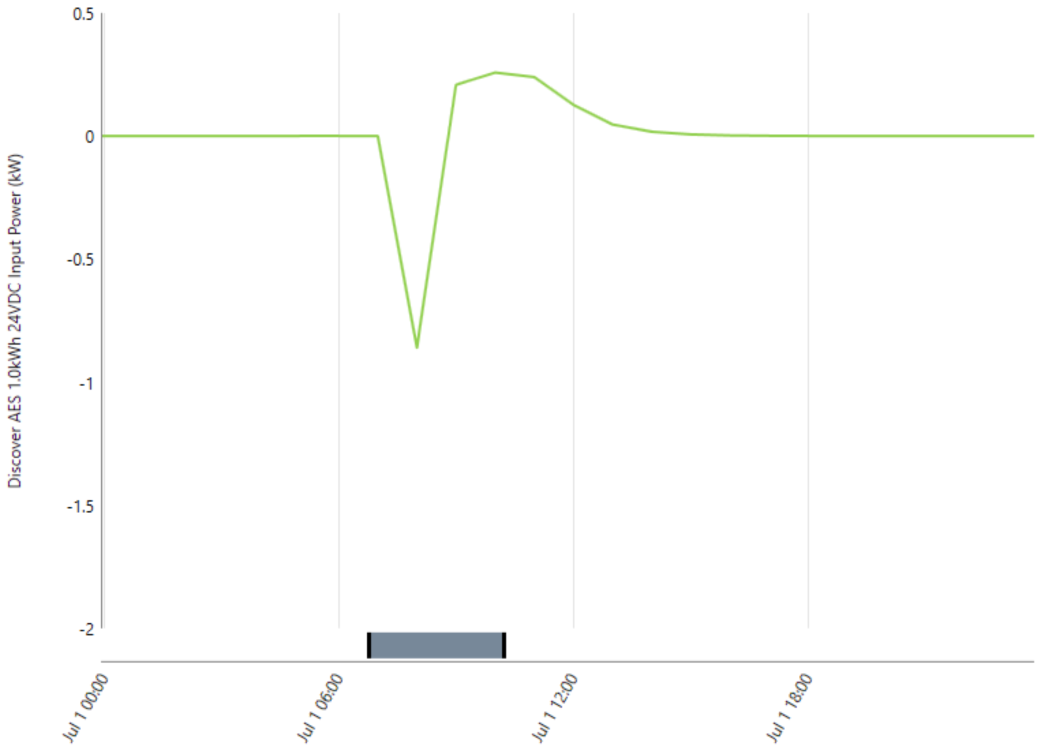

Figure 15: Battery input power

This becomes clearer, when comparing all three of these variables together in a graph as shown in figure 16. The graph shows that the solar power output is distributed throughout the day with the exception of early morning and night. Throughout this time, the solar panels would charge the batteries placed in our system. However, when the load utilizes the power, it will be done all in an hour; therefore the batteries would chip in, as indicated by the negative input power in the figure below. This indicates the flow of power from the batteries to the load. Soon after the load is served, the batteries will start charging.

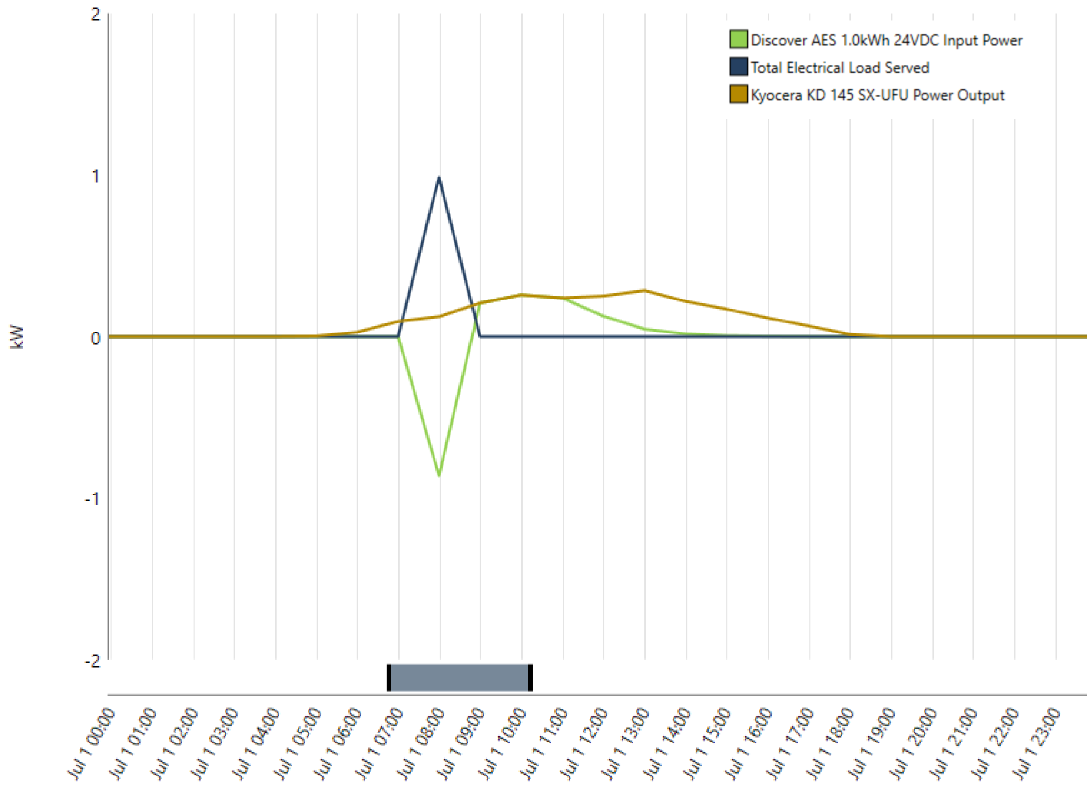

Figure 16: Power sources comparison

Last but not least, HOMER Pro also provides the emissions report of the power system simulated. In this case, since the entire system is making the use of 100% solar power, the emissions drop to almost zero (only considering the emissions during operation of the vehicle on solar PV, does not include life cycle emissions). The table below shows the various emissions by our designed system as simulated on HOMER Pro.

Table 3: Emissions by the designed system

Emission Type	**Quantity**	**Unit**
Carbon Dioxide	0	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr

Sulfur Dioxide	0	kg/yr
Nitrogen Oxides	0	kg/yr

2.5. Conclusion

This paper presents the basic design of a solar EV for Pakistan. HOMER Pro is used for system sizing. Presented results shows a successful design and sizing of a micro solar powered electric vehicle. The designed solar PV system is capable of serving the electrical load i.e. the DC electric motor of the electric vehicle over a set distance of 30 km. Since the power generation by solar panels is distributed over the day, battery storage is used to store this surplus energy and supply it when the load requires it.

In the future part of this research, we plan on building a dynamic model for this solar PV charged electric vehicle, which would include major calculations including passenger load variation, resistance calculations, load profile over steep/uneven roads and multiple load profiles throughout the day.

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CHAPTER 3: DYNAMIC MODELING OF A MICRO SOLAR ELECTRIC VEHCLE USING SIMULINK

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A version of the manuscript in this chapter has been presented as a conference paper in the 2022 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS). As the primary author in this paper, Ali Husnain carried out the research under the supervision of M. Tariq Iqbal as the co-author. The MEng candidate performed the literature review and was involved in system selection, designs, calculations, simulation, and data analysis. Moreover, he prepared the first draft of the paper. The co-author supervised the research by actualizing the research ideas, reviewing and correcting the manuscript.

Abstract

While the global electric vehicle (EV) adoption is on rise, developing countries like Pakistan have been facing many obstacles in the face of EV adoption such as shortfall of electricity, high EV prices, low average income and absence of commercial and residential charging infrastructure. In this thesis, we propose a design of a micro solar electric vehicle, which would help overcome all of these problems and provide an economical yet feasible solution. The design and system sizing of the micro solar EV was done in HOMER Pro. A dynamic model of the micro solar EV was created in MATLAB/Simulink, which implemented PV generation, maximum power point tracking, battery charging and discharging, DC-motor operation and speed control of the electric vehicle, while taking into consideration environmental factors like irradiance and temperature.

Keywords

solar EV, solar car, electric vehicle, EV design, dynamic modeling

3.1. Introduction

Climate change is one of the most pressing issues of the modern world and steps are being taken around the world to help slow down and mitigate climate change. The use of electric vehicles is one such bold step that helps reduce the GHG emissions of the global transport sector and slow down the impact of climate change. Global EV adoption has been growing at a rapid pace, in developed countries. However, the same cannot be said about developing countries, such as Pakistan.

The EV adoption in Pakistan is facing many obstacles including but not limited to electricity shortfall, high prices of electric vehicles, low average income, absence of commercial charging infrastructure and the inability of residential electrical infrastructure to charge an electric vehicle. At typical electrical service is 5A or 10A at 220V to supply house load, which is not enough to charge an EV at home.

Therefore, in this paper, we propose the design of a micro solar electric vehicle, which holds against all the above-mentioned challenges. This solar EV would have the ability to take power from the sun in the form of solar energy, throughout the daytime. It would also be very economical in price and would easily be charged from the existing residential electrical infrastructure.

3.2. Literature Review

While it has roughly been less than a decade since EV commercialization has become mainstream and automakers are selling fully functional EVs to consumers. There has been plenty of research on EVs before that as well. During the literature review part of this research we came across multiple designs and dynamic models of all types of

EVs from micro electric vehicles, to passenger sedans, vans, buses and other commercial vehicles.

Qingqing Xie et al. present a MATLAB/Simulink model for advanced vehicle dynamic model for EV emulation, while taking into consideration actual environmental conditions. The model also takes into account the rotational inertia of each component involved in developing the model [28]. Another research published in University of Washington discusses the dynamics of an electric vehicle by preparing a model which uses enhanced techniques such as torque vectoring [29]. Similarly, another research uses modelica methodologies to model EV pickup attributes to study the dynamic response of an electric vehicle [30]. Other such models for battery dynamics and solar hybrid vehicles have been given in [31] and [32] respectively. In conclusion, there is enough research material that can be found for developing a model to study the vehicle dynamics of an electric vehicle.

Talking about solar electric vehicles, there is limited research present on the design of solar electric vehicles, let alone, dynamic models of solar electric vehicles.

As outlined in [33] the research on solar electric vehicles can be divided into three major segments a) commercial solar cars, b) solar electric vehicles for solar races and c) small solar cars. Research groups and universities from all around the world take part in solar car design for solar races such as World Solar Challenge [10] and American Solar Challenge [11].

Talking about the second segment of solar electric vehicles, there are multiple automakers, who have undertaken the task of designing and selling commercial solar electric vehicles [12] [13] [14]. Finally some interesting designs have come forward for the small solar electric vehicle segment as well [18] [20].

However, there exists a huge gap, when it comes to developing and studying a dynamic model of a solar electric vehicle. In the previous chapter, we proposed a design for a micro-solar electric vehicle for application in Pakistan [33]. In this chapter, we are going to develop a dynamic model of our micro-solar electric vehicle using MATLAB/Simulink.

3.3. Design of a Micro Solar EV

Before getting into the dynamic model of the micro solar electric vehicle, let us briefly discuss the system design and PV sizing. The specifications of the vehicle used in the design are as following;

Table 4: Vehicle Specifications used for the design [6]

Item	Description
Max. Range	100 km
Dimensions	2450 mm*1350 mm*1750 mm
Wheelbase	1500 mm
No. of seats	3
Motor Size	1200 W
Total Motor Torque	100 Nm
Max Speed	43 km/hr

The design and PV sizing was carried out in HOMER Pro and the system can be seen in the figure below:

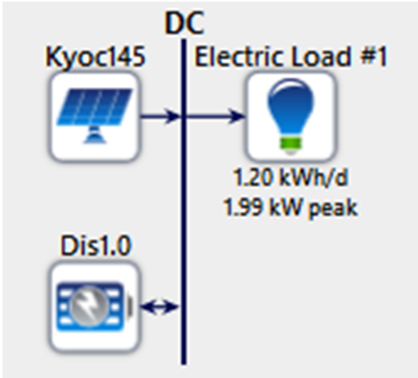

Figure 17: System design of micro-solar electric vehicle in HOMER pro [6]

The sizing of the system was as follows:

Table 5: System sizing carried out in HOMER pro [33]

Item	**Quantity**
Solar Panels/ Advance Solar Hydro Wind Power API – 150 W	3
24V, 1kWhr Li-Ion battery, 72V bus	3
Cost/NPC (Rs)	177013.7
Cost/COE (Rs)	54.62492
Cost/Operating cost (Rs/yr)	961.2305
Cost/Initial capital (Rs)	184128
System/Ren Frac (%)	100

Kyoc145/Capital Cost (Rs)	21000
Kyoc145/Production (kWh/yr)	766.9749
Dis1.0/Autonomy (hr)	57.6
Dis1.0/Annual Throughput (kWh/yr)	392.1335
Dis1.0/Nominal Capacity (kWh)	2.88

Based on this system design and sizing, a detailed dynamic model of the solar electric vehicle was developed.

3.4. Dynamic Modeling of a Micro Solar EV

Electrical dynamic modeling is an important part of research and helps us understand how a system would be working in real-life. A dynamic model of a PV system would not only help us understand how the system would perform, but also how it would reach to the changes in the environment. This dynamic model would also help us simulate the system in various conditions that an electric vehicle has to go through during its course of operation.

Figure 18 shows a block diagram of the dynamic model of the system. As shown in the figure, the system consists of seven major blocks, which are further made of tens of components, all coming together to form a dynamic model of our micro-solar electric vehicle. The first block i.e. PV arrays generate power by converting solar energy into electrical energy, which is then supplied to the DC-DC converter. This converter is then connected to the battery storage block of our system, which not only stores this power, but also supplies to the DC motor, when in operation. The battery storage block can also be charged by an external AC source i.e. the electrical grid. There are two control blocks used in the system, one is an MPPT controller, which helps the system extract the maximum amount of power from the PV panels, and the second one is a speed controller, which helps the DC machine operate at desired speeds, as per the speed reference provided.

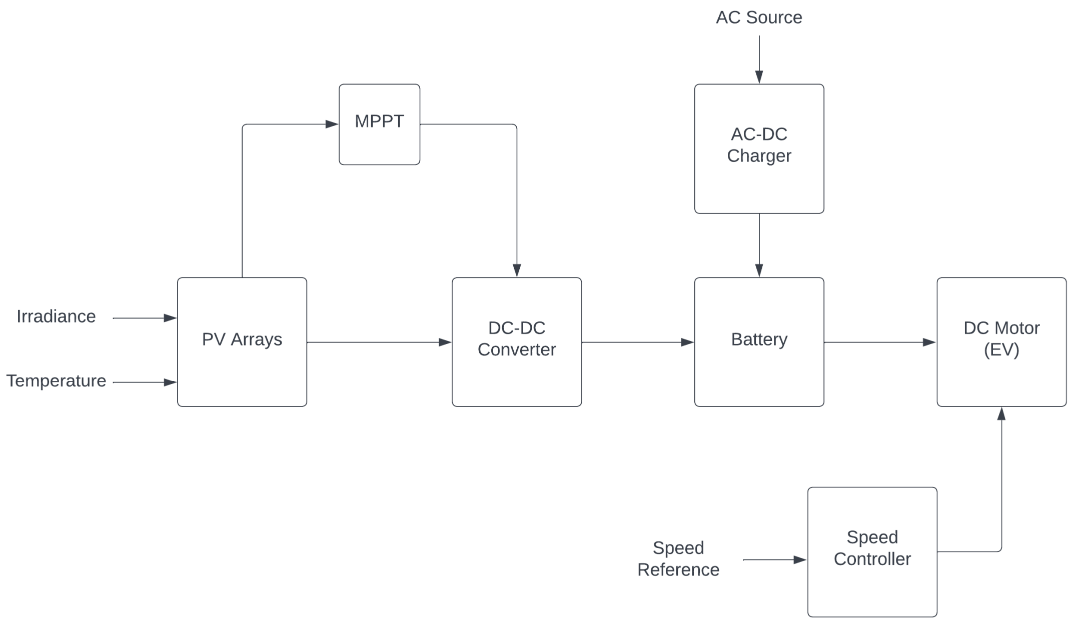

Figure 18: Block diagram of the dynamic model

3.4.1. PV Array

PV arrays are the most fundamental part of the dynamic model, as a micro solar electric vehicle is being developed, meaning the focus is on extracting the most amount of power from the PV array, given the available space to mount PV panels. It is important to note that the non-linear output of PV modules is affected by environmental parameters such as irradiance, temperature, clearness index, dust, cloud and other shading effects etc. However, in this model, only irradiance and temperature are being taken into account.

A PV array can be made up of multiple PV modules, which in turn consist of series of PV cells. To better understand the performance of a PV module, let us take a look at the equivalent circuit of a PV module as show in figure 19 [34].

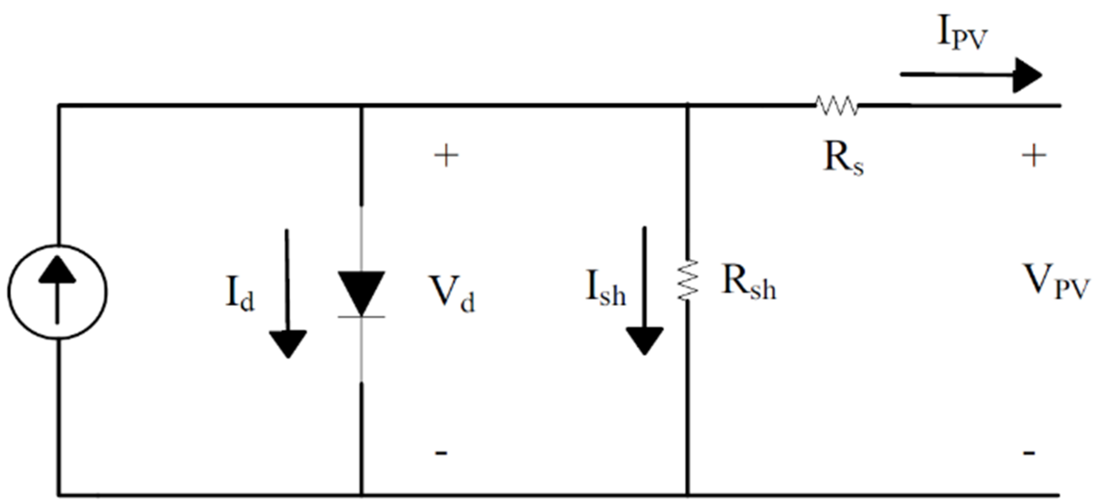

Figure 19: Equivalent circuit of a PV module [34]

This equivalent circuit gives us some basic equations to help calculate the values of current and voltages under consideration.

$$I_d = I_o \left[\exp\left(\frac{V_d}{V_T}\right) - 1\right] \quad (1)$$

$$V_T = \frac{KT}{q} \times A \times N_{cell} \quad (2)$$

$$V_d = V_{PV} + R_S I_{PV} \quad (3)$$

$$I_{PV} = I_{ph} - I_D - \frac{V_D}{R_{sh}} \quad (4)$$

In the above equations Eq. (1) to Eq. (4) [35], I_d is the diode current, I_{ph} is the light-generated current, , I_0 is the diode saturation current, V_T is thermal voltage equivalent, V_d is the diode voltage, V_{pv} and I_{pv} are module voltage and current, respectively, K is the Boltzman constant equal to 1.3806×10−23 J/K, A is the diode ideality factor, T is the cell temperature, q is the electron charge equal to 1.602×10-19 C, and N_{cell} is the number of cells connected in series in a module. As evident, from equations 1 to 4, almost every parameter of the PV module is subject to change as per the variations in temperature and irradiance.

Based on the results from HOMER Pro [33] the model consisted of three 24 V, 150 W solar PV (Advance Solar Hydro Wind Power API – 150) modules connected in series, making the bus voltage to be 72 V.

3.4.2. Maximum Power Point Tracking (MPPT) Controller

As discussed before, the performance of a PV module is very much dependent on environmental factors like irradiance and temperature. For each PV module, there is a point in the P-V curve, where the PV module is giving the maximum amount of power. This point is called maximum power point, and it can be different for different condition. This can be observed in figure 20, where two different temperatures result in two different MPPs.

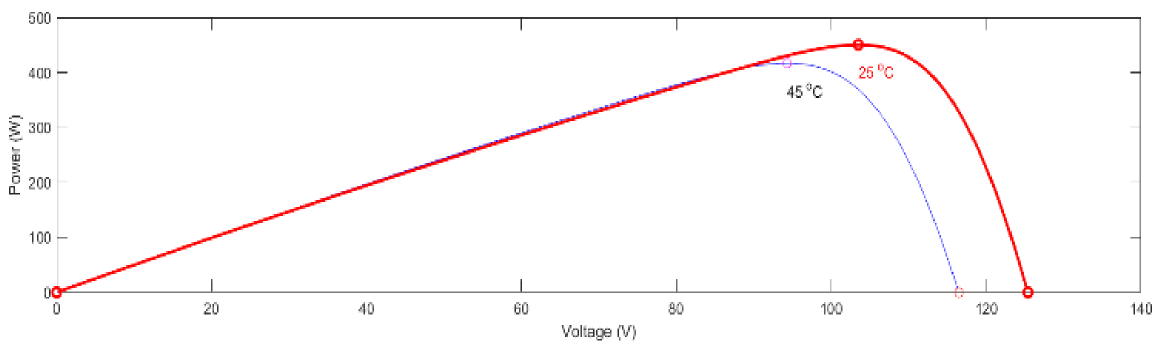

Figure 20: PV curve of our chosen PV module

Maximum power point tracking is a process, controls the power generation from a PV panel in a manner that it is always operating at maximum power point. There are numerous techniques to achieve maximum power point tracking such as incremental conductance method, perturb and observe (P&O) method etc. In this model, the perturb and observe (P&O) method is used, in order to implement maximum power point tracking.

The way P&O technique is used is that a minor perturbation is introduced into the system, which causes the power of the PV module to vary. After the perturbation is introduced, the algorithm then observes the output power periodically and compares it with previous power. A similar perturbation is introduced to vary the voltage of the PV array. By doing so, the algorithm identifies, where the system is lying on the PV curve. Depending on that, the duty cycle is either increased or decreased.

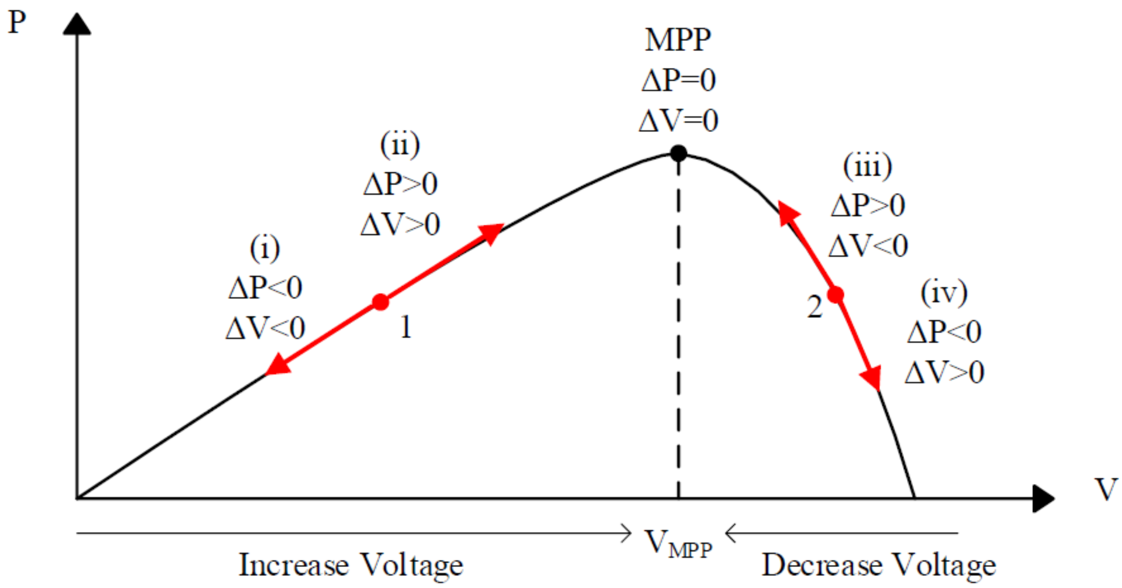

Figure 21: P&O algorithm working principle [34]

As seen in the figure 21, the system can have two operation points. The first one is indicated as point 1 and the second one is indicated as point 2 on the graph. In the case that the system was on point 1, the voltage needs to be increased. Similarly, if it was on point 2, the voltage need to be decreased. In order to implement this operation, we used a code-based function, according to the flowchart shown in figure 22.

The MPPT starts by measuring the current and voltage of the PV modules using sensors, and outputs a duty cycle. This duty cycle is going to be used to generate a PWM signal, which will enable or disable the switch used in our DC-DC converter. A change in the duty cycle generated by the MPPT means that the voltage of the module would change and subsequently, the power of the PV module would also change. The P&O algorithm can be best described by the flowchart given in figure 22.

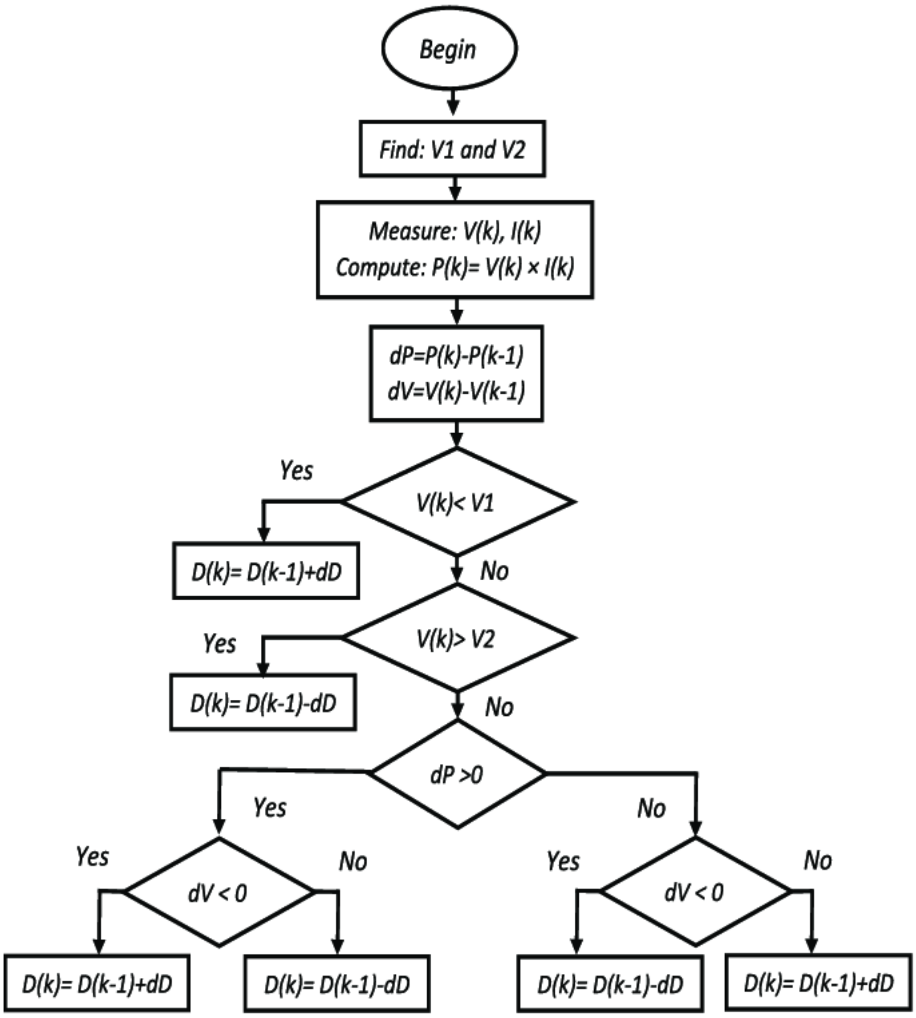

Figure 22: P&O algorithm flowchart

3.4.3. DC-DC Converter

As evident from the name, DC-DC converters are used where both the input voltage and output voltage are in DC. The main purpose of using a DC-DC converter is to produce a regulated voltage from an uncontrolled source to a load that may or may not be constant, in a manner that is efficient. A DC-DC converter is a high-frequency power conversion circuit, which makes use of high-frequency switching, transformers, inductors, and capacitors.

There are many different topologies of DC-DC converter including buck, boost, buck-boost and SEPIC converters. A buck converter is used in applications where the output voltage needs to be lower than the input voltage, boost converter is used when output voltage needs to be higher than input voltage, whereas, buck-boost and SEPIC can be used in both situations. In this model, a buck converter is being used, since the input voltage or PV module voltage in this case is higher than what is needed at the battery terminal. Figure 23 shows the circuit of a buck converter.

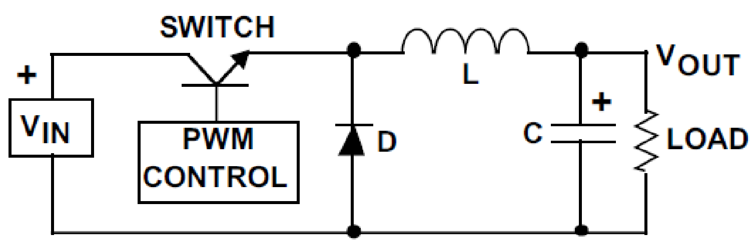

Figure 23: DC-DC converter (buck converter) [36]

The buck converter operates in two steps. The first step of operation is when the switch is turned ON. During this step, the current is flowing to the output capacitor, thus charging it up. Since the voltage of a capacitor does not rise instantly, as well as the inductor limiting the charging current, the capacitor voltage is not the full voltage of the source during the switching cycle [36]. This is depicted in figure 24, the highlighted part of the circuit shows the flow of current.

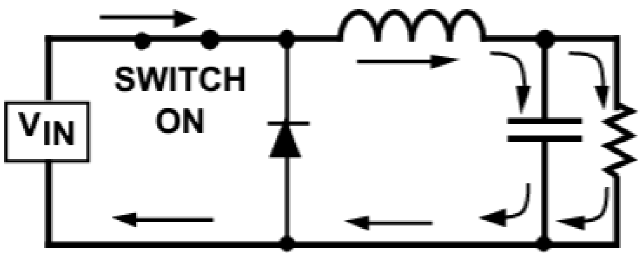

Figure 24: Buck converter operation (switch ON) [36]

During step two, the switch turns off and a voltage is created across the inductor due to the fact that inductor cannot change current suddenly. This voltage allows the capacitor to charge and power the load when switch is off [36]. This can be seen in figure 25.

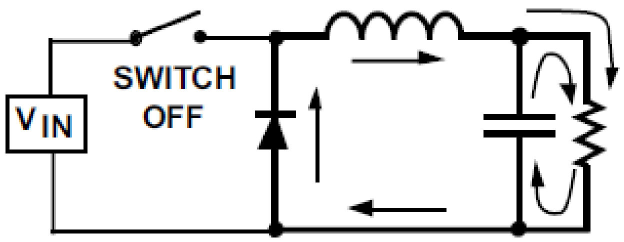

Figure 25: Buck converter operation (switch OFF)[36]

Now in order to design the buck converter, the values of the components used to form the buck converter need to be calculated [37]. Following are the mathematical equations that help design a buck converter.

$$D_{max} = \frac{V_{OUT}}{V_{IN(max)} \times \eta} \quad (5)$$

Where, $V_{IN(max)}$ = maximum input voltage

V_{OUT} = output voltage

ŋ = efficiency of the converter

$$L = \frac{V_{OUT} \times (V_{IN} - V_{OUT})}{\Delta I_L \times f_s \times V_{IN}} \quad (6)$$

Where, f_s = minimum switching frequency of the converter

ΔI_L = estimated inductor ripple current

$$\Delta I_L = (0.1\ to\ 0.4) \times I_{OUT\ (max)} \quad (7)$$

$$C_{OUT} = \frac{\Delta I_L}{8 \times f_S \times \Delta V_{OUT}} \quad (8)$$

Where, C_{OUT} = minimum output capacitance

ΔV_{OUT} = desired output voltage ripple

$$\Delta V_{OUT} = ESR \times \Delta I_L \quad (9)$$

Where, ESR = equivalent series resistance of the used output capacitor [37].

The buck converter design is complete once the values for the inductance and the capacitance to be used are calculated.

3.4.4. Li-Ion Battery

For the battery storage system of the PV system, a Li-Ion battery is used. The model present in Simulink is called a generic battery model, which allows you to mimic the charging and discharging characteristics of any rechargeable battery. Figure 26, shows the equivalent circuit of the rechargeable battery model [38].

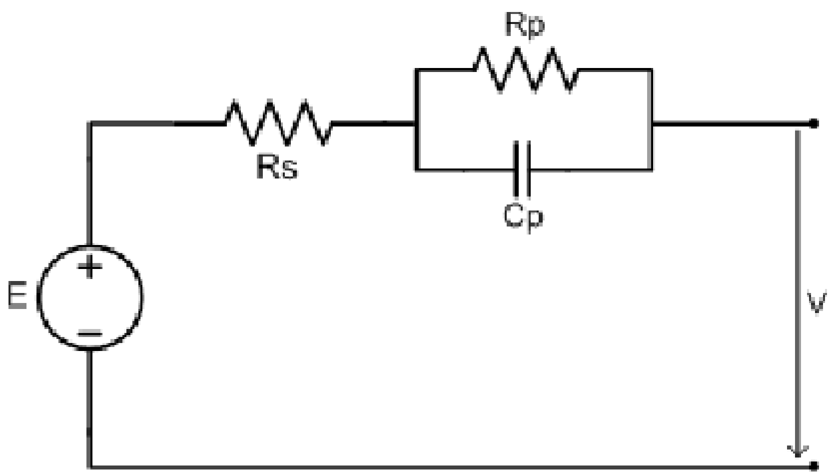

Figure 26: Equivalent circuit of a rechargeable battery model

The battery model has three observable parameters i.e. battery voltage, battery current and SOC. As evident from the name, battery voltage is the rated voltage of battery. A positive battery current represents that the battery is discharging, whereas a negative battery current represents that the battery is charging. Similarly, SOC is the battery state of charge, and gives information about the state of charge of the battery at any given moment. An increasing SOC represents battery charging and a decreasing SOC represents battery discharging.

3.4.5. AC-DC Charger

In addition to the battery being able to charge from the PV panels, the micro solar electric vehicle would also have the ability to charge from an AC source, if needed. This represents the time of the day when there is no sun, and the vehicle needs charging. In such a case, the car battery could be directly plugged into an AC wall outlet. This is where the AC-DC charging block comes in handy. Figure 27, shows the equivalent circuit of an AC-DC charging block [39].

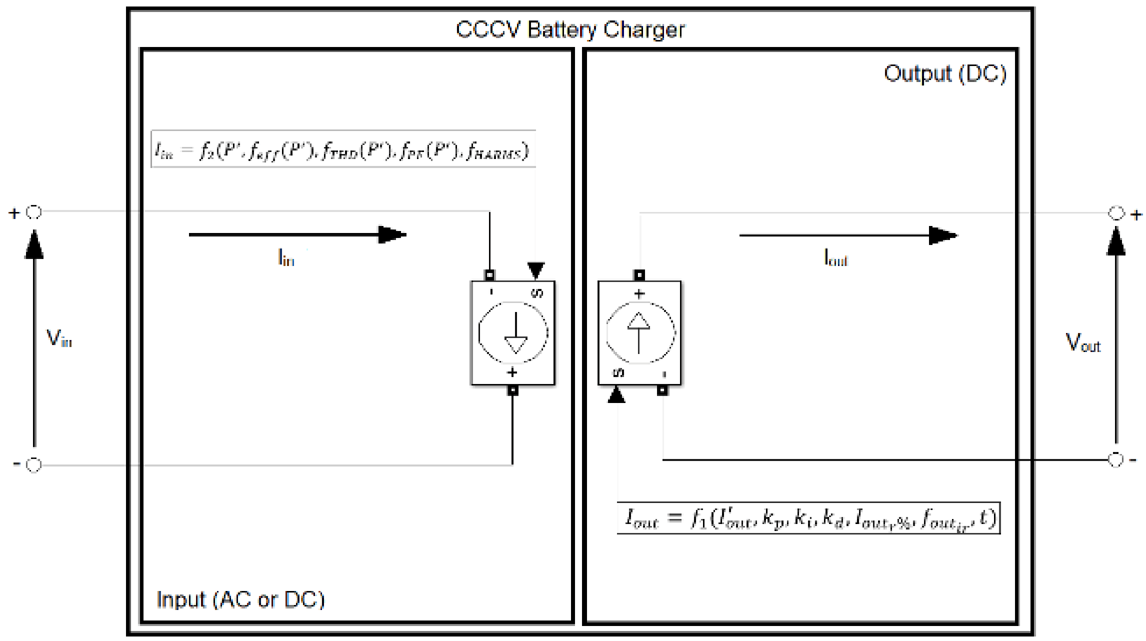

Figure 27: AC-DC charging block

3.4.6. DC Machine

Since the micro solar electric vehicle would be running a DC motor, in order to develop the model of such a motor, we have used the DC machine block in Simulink. The DC machine block allows us to implement both a wound-field or permanent DC machine. However, in this case, a wound-field DC machine in series configuration is being used.

The armature circuit of the DC machine consists of an inductor La and resistor Ra in series with a counter-electromotive force (CEMF) E, which is proportional to the machine speed.

$$E = K_E \omega \qquad (10)$$

Where, K_E is the voltage constant and ω is the machine speed.

$$Electromechanical\ Torque = T_e = K_T I_\omega \qquad (11)$$

Where, K_T is the torque constant.

There is a mechanical part of the DC machine, which is used to calculate the speed of the machine from the net torque applied to the rotor.

$$J\frac{d\omega}{dt} = T_e - T_L - B_m\omega - T_f \qquad (12)$$

Where, J = inertia,

B_m = viscous friction coefficient, and

T_f = Coulomb friction torque.

3.4.7. Speed Controller

The last block of the model is a speed controller, which is being used in order to regulate the speed of the motor. The speed controller is a simple PWM Chopper circuit. Figure 28, shows the model of the circuit

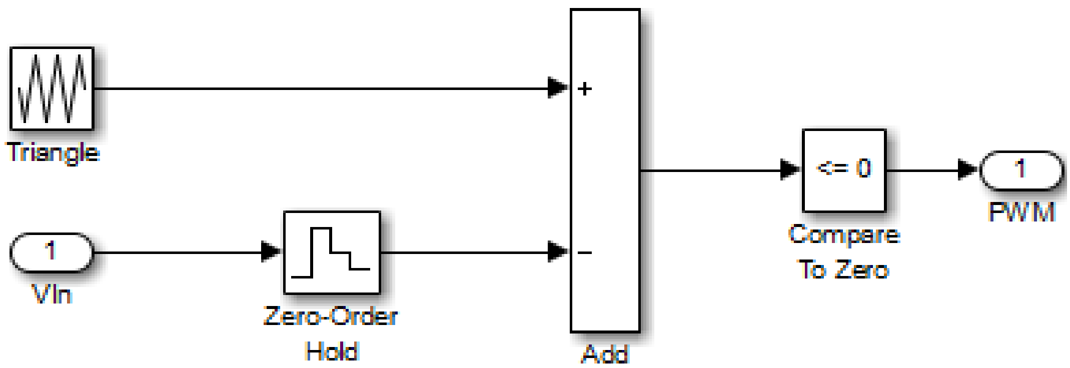

Figure 28: voltage to PWM signal converter block

By taking into account the reference voltage set on the input side of this circuit, it generates a PWM signal, which operates a high-frequency switch thus changing the average value of current supplied to the motor, which results in an increase or decrease in the motor speed as required.

3.5. Simulation Results and Discussion

A dynamic model of the block diagram shown in figure 18, was implemented in Simulink, which consisted of all the major blocks discussed in the previous section. The detailed model can be seen in figure 29.

3.5.1. PV Operation

Now let us take a look at the results of each part of the simulation. First one is the PV array, the output of which is very much dependent on the irradiance values. A variable irradiance curve was fed into the PV model, to see how PV output varies accordingly. Figure 30, shows the changing irradiance values. At these values, the PV is generating the amount of current and voltage shown in figure 31. Notice, how the voltage and current values change with the irradiance values.

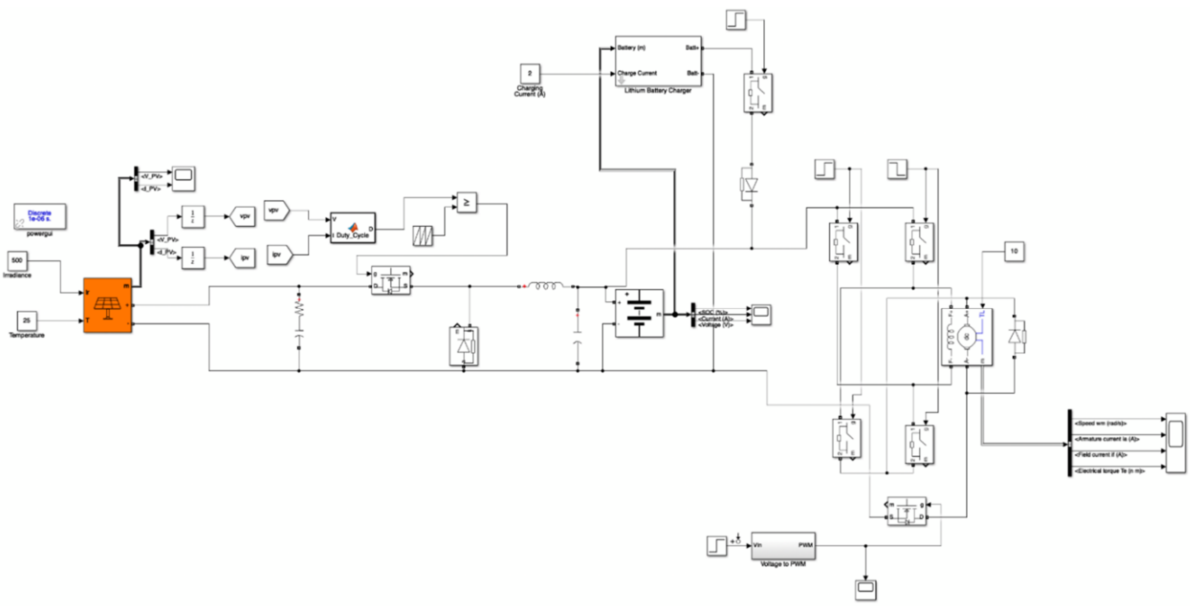

Figure 29: Simulink model of the proposed micro solar electric vehicle

3.5.2. Battery Operation

Now let us move on the battery parameters, when PV modules are in operation and actively generating power, this power is being directly transferred and deposited into the battery. This is being demonstrated in figure 32. Notice that the SOC of the battery is increasing over the course of the simulation, and the battery current is in negative, which shows the influx of current into the battery.

Similarly, when the PV is disconnected due to any reason including bad weather or absence of sun during night time, the PV panels will not be producing any power. Hence, the EV motor will be drawing power from the battery. Looking at figure 33, it can be seen that the SOC of the battery is decreasing and the battery current is also positive, which shows the outflow of current from the battery.

In the last scenario, the battery is being charged directly from the AC source, through the CCCV charging block. In this scenario, once again the battery SOC is positive and the battery current is in negative as shown in figure 34.

3.5.3. DC-Machine Operation

In this section, the operation of the DC machine will be discussed, which represents the electric vehicle motor. The DC machine operation can be observed in two different modes.

The first one is the normal mode, in which the DC machine is drawing power from the battery and generating a normal response. This can be seen in figure 35, from the armature current, field current and electrical torque values.

The second mode of operation is when the DC machine is put in reverse, which represents the electric vehicle moving in reverse direction. In a DC series machine, in order to reverse the direction of motion, the polarity of field windings needs to be changed. In this model, that is achieved by using ideal relay modules, which can be switched at any instant at the start of, or during the simulation to reverse the direction of the vehicle. Figure 36 shows the vehicle direction changing at the 5 second mark during the simulation. This change is denoted by a change in the direction of field current.

3.5.4. DC-Machine Operation Under Variable Load

In order to understand the response of the electric vehicle over uneven or steep roads, the simulation is run for 60 seconds, a variable load profile is introduced and the impact on the dynamics of the electric vehicle is observed. Figure 37, shows the dynamic load profile used in the simulation. Figure 38, shows DC Machine dynamics under that changing load profile. The electrical torque and armature current of the DC-machine varies accordingly to keep up with the uneven roads.

3.5.5. Speed Control

The final step is understanding how the speed control circuit works. In this case, the simulation is run for 60 seconds, a signal which changes the speed reference every 10 seconds is introduced, and the impact on dynamics of the electric vehicle can be observed Figure 39, shows the changing speed reference. Figure 40, shows the dynamic response of the DC-machine to keep up with the changing speed reference.

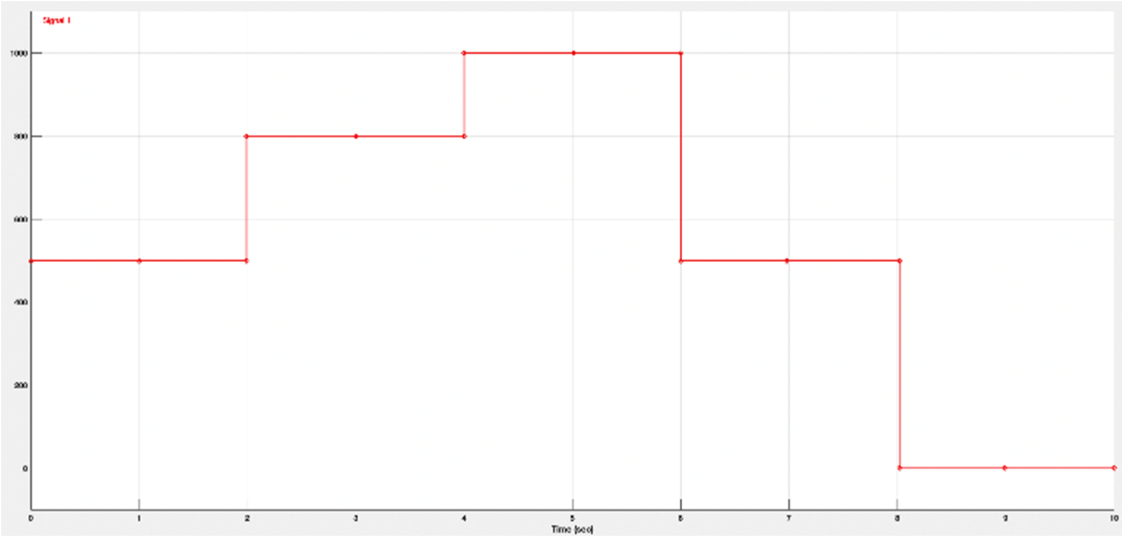

Figure 30: Variable irradiance values to measure PV response

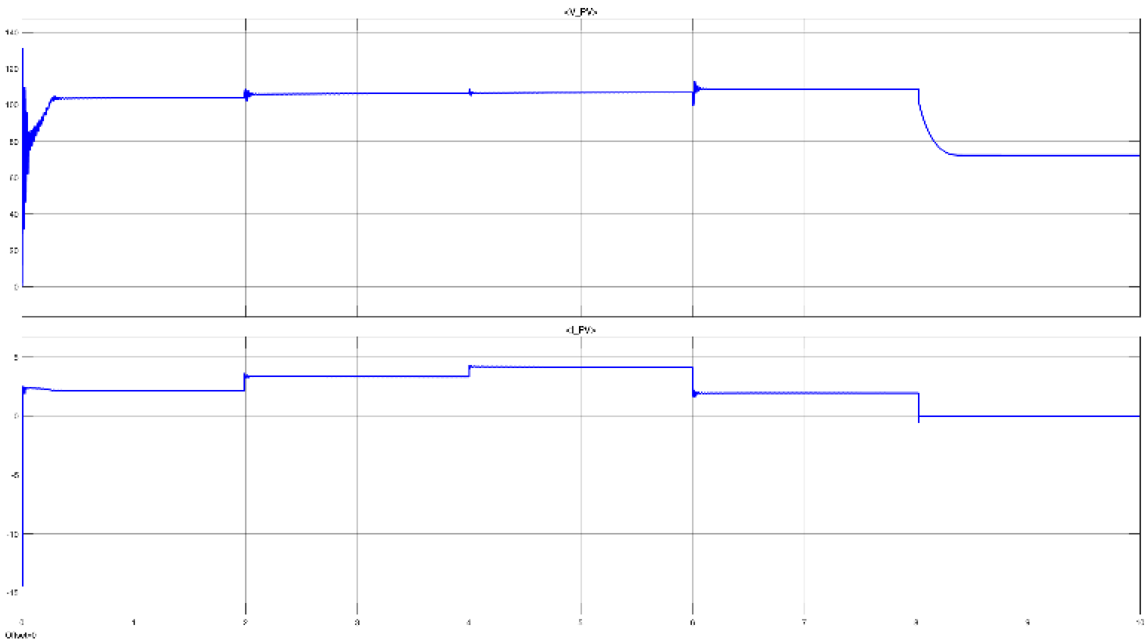

Figure 31: PV voltage and current variance as per changing irradiance

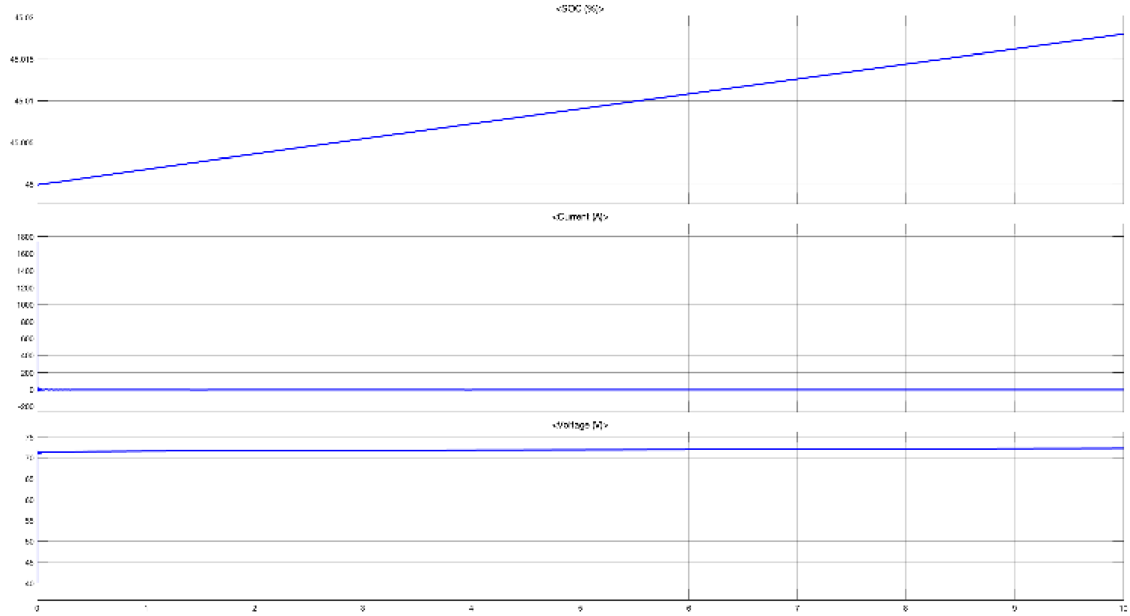

Figure 32: Battery charging mode (from PV modules)

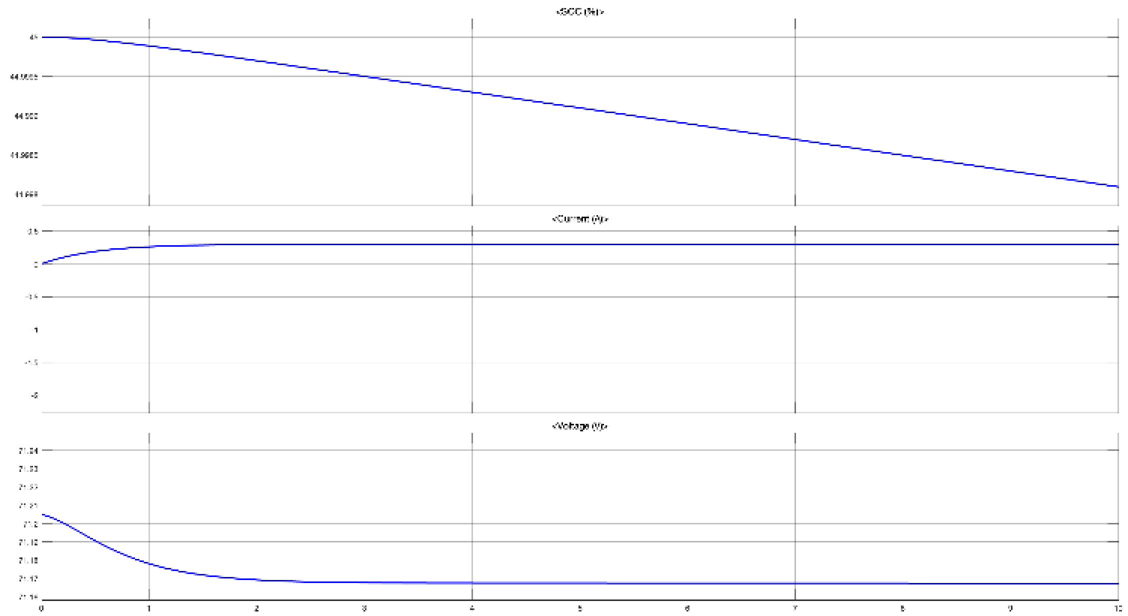

Figure 33: Battery discharging mode (during motor operation)

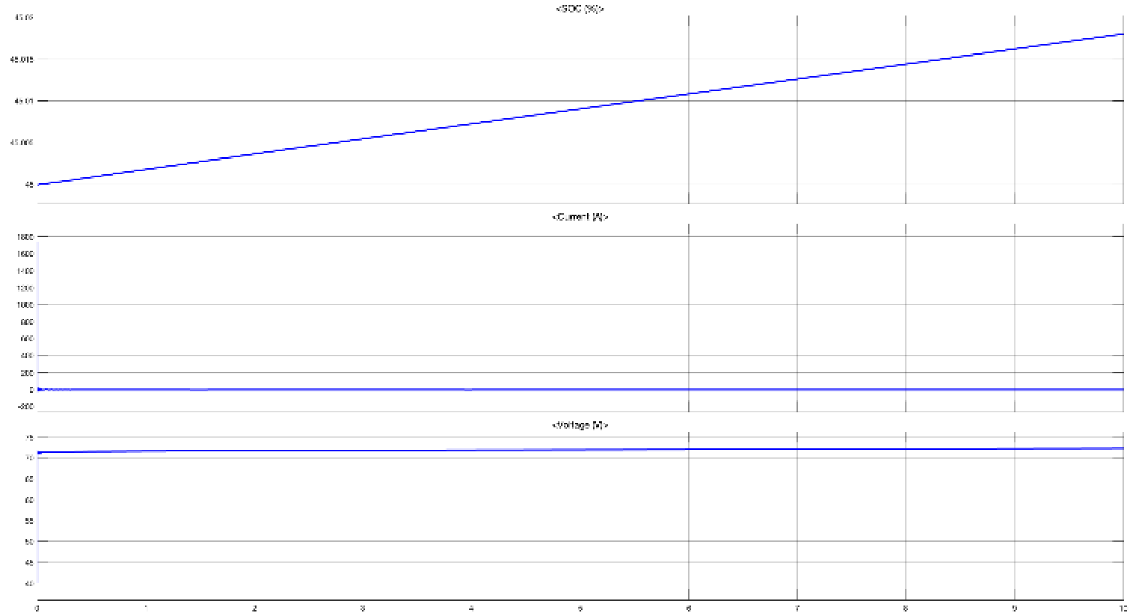

Figure 34: battery charging mode (from AC source)

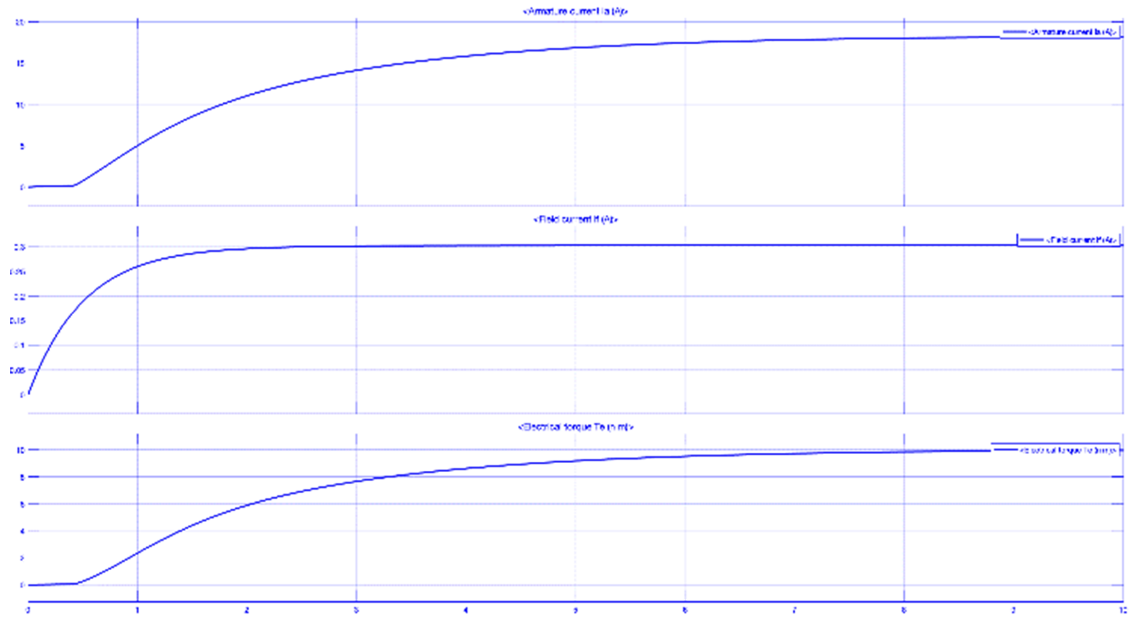

Figure 35: DC machine normal operation

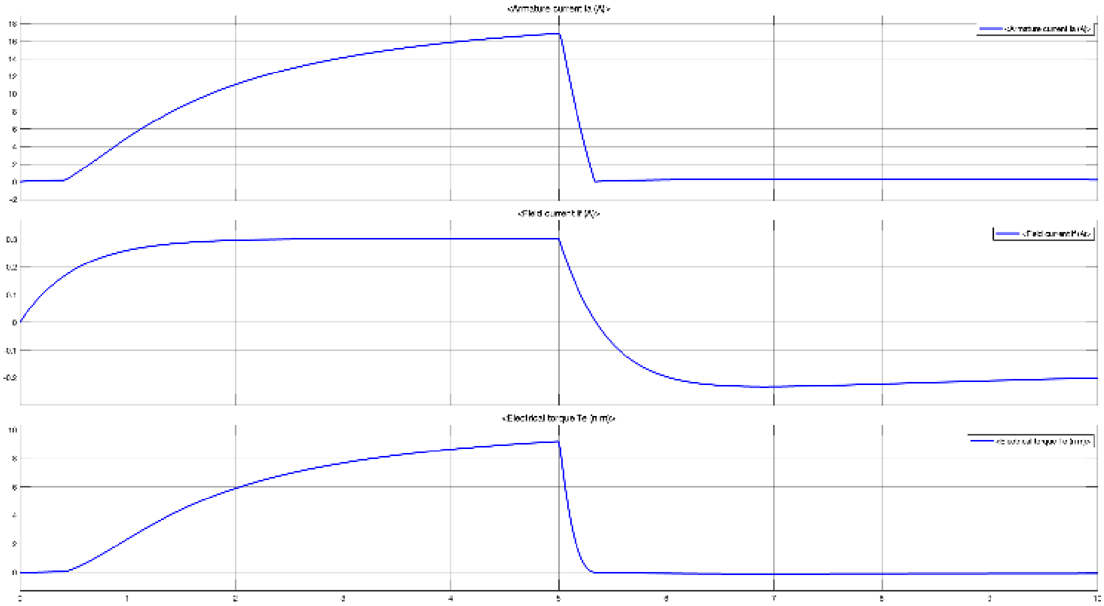

Figure 36: DC machine forward and reverse operation

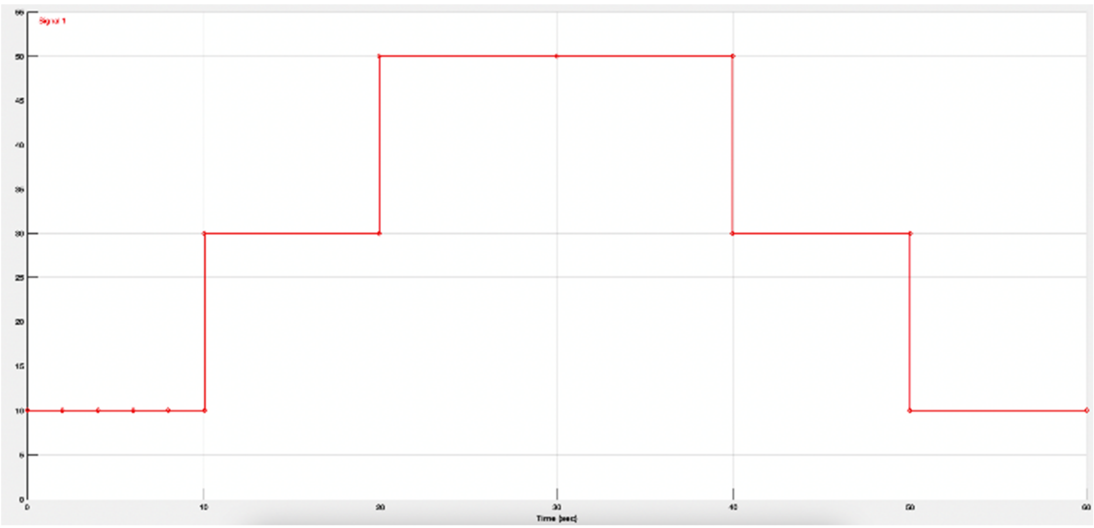

Figure 37: Variable load profile for DC machine

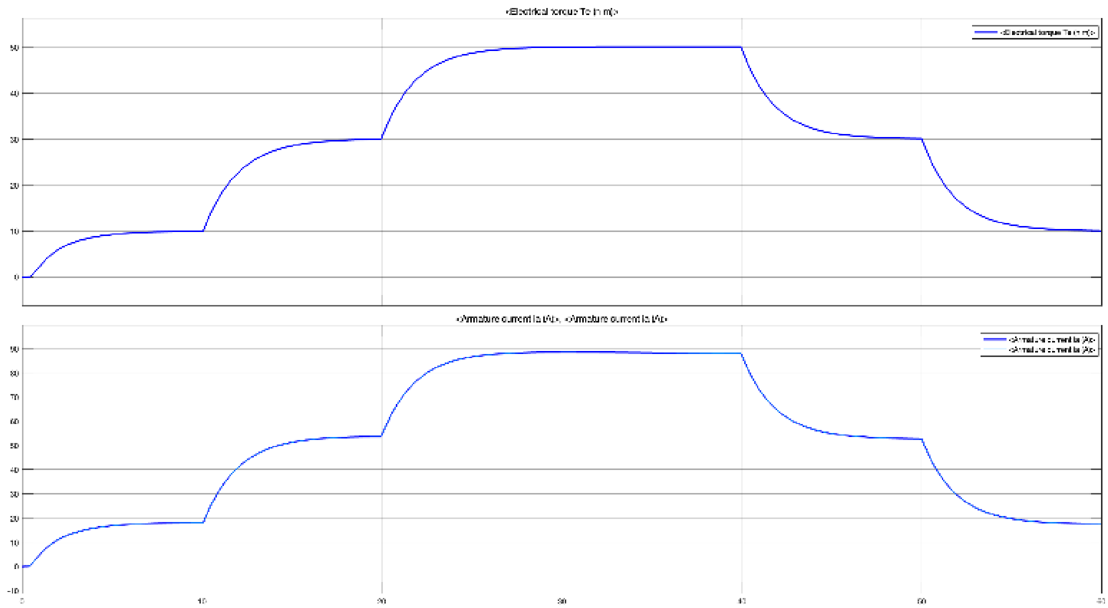

Figure 38: DC machine dynamics under variable load

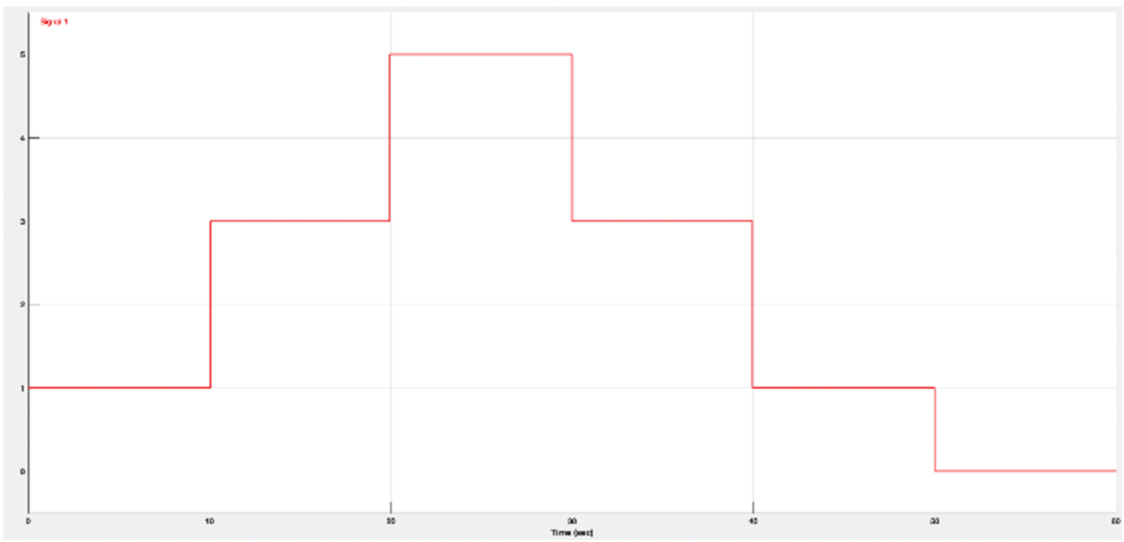

Figure 39: Variable speed reference for DC machine

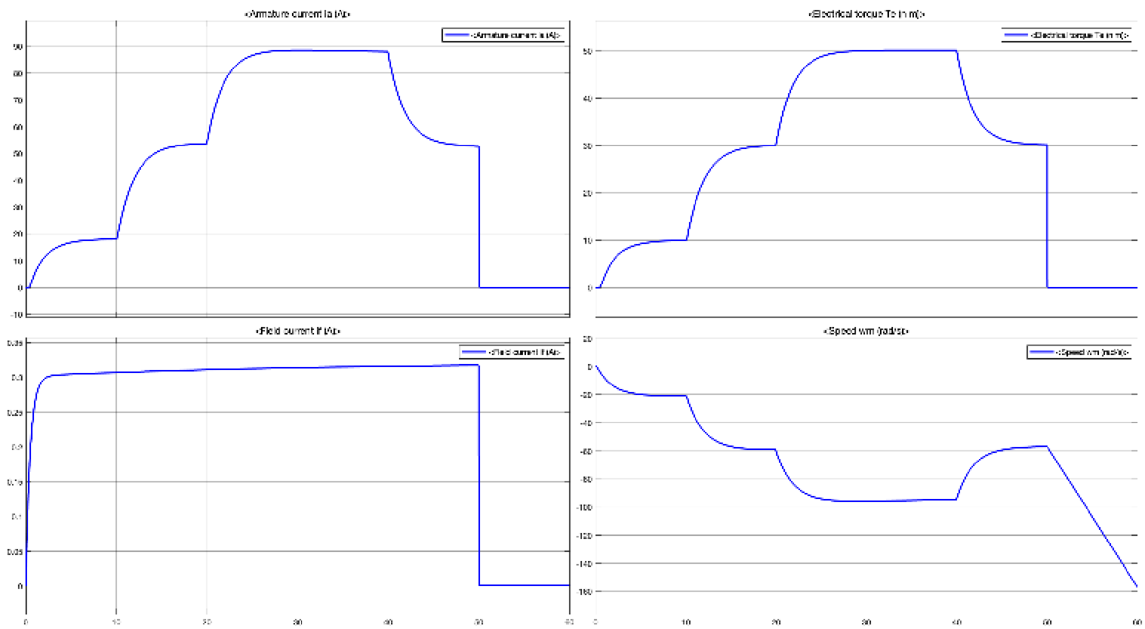

Figure 40: DC machine dynamics under variable speed reference

3.6. Conclusion

A novel design for a micro solar electric vehicle for application in Pakistan has been presented in this paper. Not only does this micro solar electric vehicle provide the basis for the design of a new class of cars, but it also helps solve almost all of the problems that are currently slowing the growth of EV market share in Pakistan and other developing countries.

The said micro solar electric vehicle was designed in HOMER Pro, and a system sizing was done. According to this system sizing, the micro solar electric vehicle would require 3, 24 V, 150 W PV modules (Advance Solar Hydro Wind Power API – 150) to add a range of approximately 30 KMs to the pre-existing battery range of the electric vehicle.

The electric vehicle can also be charged from a 220 V AC outlet with the help of the onboard AC-DC charging block, which allows the electric vehicle to charge at extremely low currents, easily supported by the current residential electricity infrastructure in Pakistan.

In addition, a dynamic model of the micro solar electric vehicle was developed to be studied in much more details. The dynamic model focused on three different aspects of the systems i.e. power generation by PV modules that are to be mounted on top of the vehicle, battery charging from PV modules as well as an external AC source, and finally DC-motor operations in forward and reverse mode. Other notable features of the model include a maximum point power tracker and a PWM chopper based speed control circuit.

The dynamic model of the system not only helped us fully understand the working of the system in different modes, conditions and situations, but also helped us understand how the system will react to any variations in the environmental factors such as irradiance and temperature etc.

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CHAPTER 4: INSTRUMENTATION AND CONTROL DESIGN FOR A MICRO SOLAR ELECTRIC VEHICLE

4.1. Introduction

In this chapter, the design of instrumentation and control for a micro-solar electric vehicle is presented. The instrumentation and control circuit of our micro solar electric vehicle utilizes a small microcontroller to monitor, control and operate a set of electronics such as headlights, turn signals, speedometer etc. While in most modern vehicles, instrumentation and control can be very complex, since they come equipped with hundreds if not thousands of features.

In the case of the micro-solar electric vehicle designed as a part of this research, one of the goals is to keep the price point of the vehicle affordable and in reach of the target demographics. Therefore, most luxury features can be skipped and only features necessary for the safe operation of the car are to be added.

4.2. Choice of Design Tool

In order to design instrumentation and control circuit for the micro solar electric vehicle, Tinkercad will be used. Tinkercad is a web-based software application that breaks down highly complicated circuit drawings and 3D models into easy to design layouts. The software allows designers to choose components from a library of pre-existing components, instead of having to design the components from the scratch. The software also has a library of various microcontrollers, that can be used along with other components and code can be embedded into it. Tinkercad provides a live simulation view of all the circuits designed in it, thus eliminating the need to implement the circuit with hardware.

4.3. Design Principle

In order to understand the design of the instrumentation and control circuit for the micro solar electric vehicle, let us first try to come up with a general idea of what the circuit should be. The way instrumentation and control circuit works in a car, is that every single electronic component in a car comes with its own set of controls. These controls require human input from the driver, for when they are to be used. For instance, if the driver were to turn on their right turn signal, they will have to push a lever or a slider switch and give the input to the microcontroller to make that happen. The microcontroller would then operate the relay, which then turns that component on for as long as the user input is there.

Let us take a look at a block diagram of the control and monitoring circuit as well as the auxiliary circuitry for the micro solar electric vehicle.

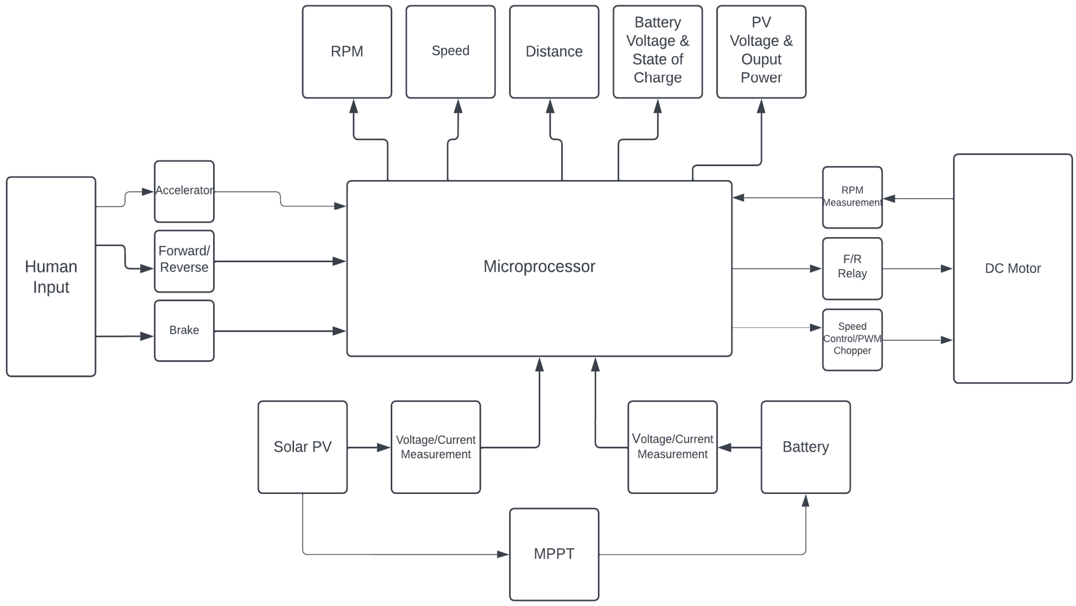

Figure 41: Block diagram for control and monitoring circuit for micro solar electric vehicle

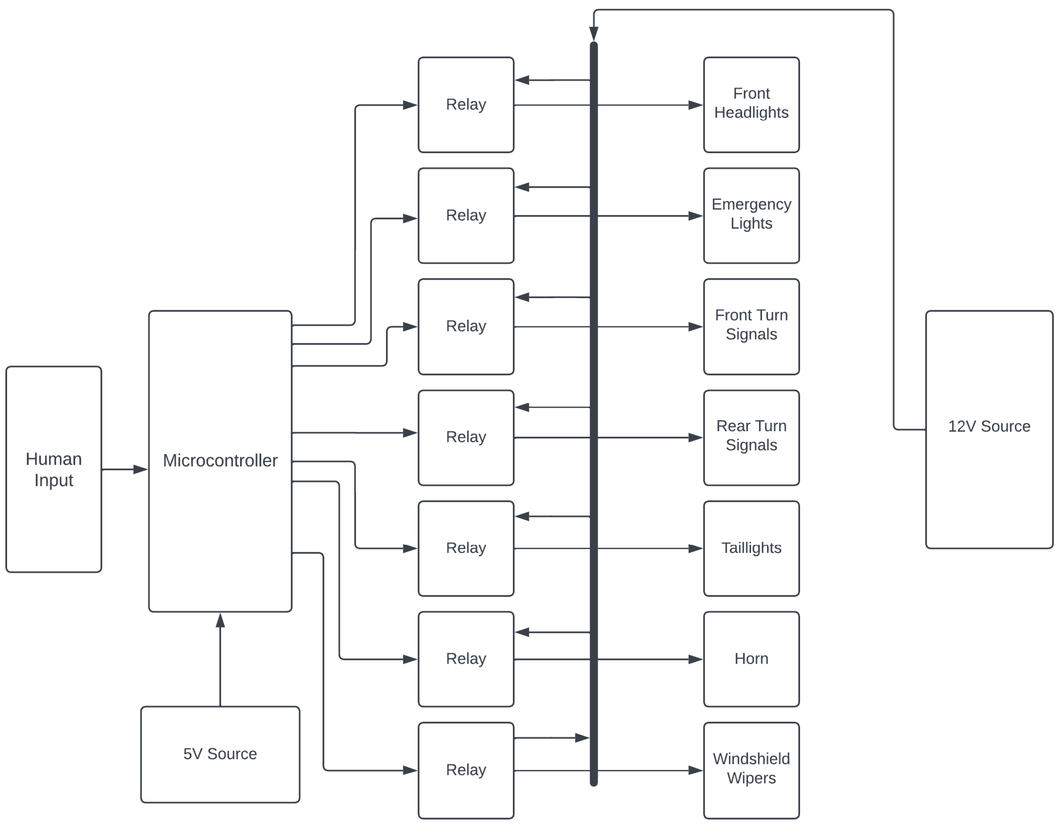

Figure 42: Block diagram for auxiliary circuitry for a micro-solar electric vehicle

Figure 41, shows the block diagram for control and monitoring circuit for the micro solar electric vehicle, whereas figure 42, shows the block diagram of the auxiliary circuitry for the vehicle.

4.4. Major Components

4.4.1. DC-DC Converter

When building the instrumentation and control circuit for a vehicle, one important consideration is how to power the on-board computer and all the auxiliary components like headlights, taillights etc. There are two different approaches being undertaken by automobile manufacturers. First one is by making use of a separate 12 V battery in order to supply power to the auxiliaries. The second approach is popular amongst electric vehicles, which usually have a high voltage battery to power the electric motor. This approach makes use of a DC-DC converter in order to lower the voltage supply from the primary battery and make it suitable for use in the auxiliary components. Similarly, this approach is once again needed when giving power supply to the micro-controller used in the on-board computers. While most auxiliary components such as headlights, horn, turn signals etc. operate at 12 V, the microcontroller usually operates at 5 V. Therefore, once again a converter is used to step down the voltage from 12 V to 5 V. The first approach, which uses a separate 12 V battery, requires the use of a separate charging system which charges the 12 V battery. Since, in this case, a low price point was one of the desired outcomes, the second approach is more suitable, as this way the use of a separate battery and a charging system can be avoided.

Figure 43 shows a block diagram of the main power stage of the micro electric vehicle. The block diagram shows how two DC-DC converters are utilized in the main power stage of the vehicle. The 72 V power supply is stepped down to 12 V with the help of a DC-DC converter #1 to power all the auxiliary components of the circuit, and this 12 V supply is further stepped down to 5 V with the help of DC-DC converter #2 to power the micro-controller.

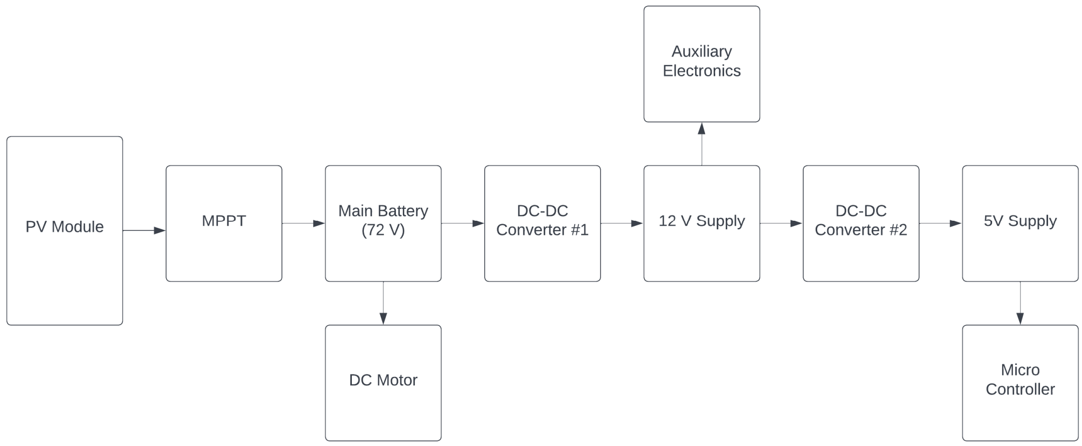

Figure 43: Block diagram for main power stage of the vehicle

4.4.2. LCD Display

LCD display is an important component of the control and monitoring circuit. Throughout the operation of the micro solar electric vehicle, there are multiple sensors and measurement modules, which will be monitoring the data in real-time. This real-time data needs to be displayed in order for the user to be aware of the state that the vehicle is currently in, and then provide input accordingly. Figure 44, shows the LCD display, which is to be utilized in the circuit. Some of the important data displayed on the LCD includes RPM, speed, distance, battery voltage, battery state of charge, PV voltage, and PV output power.

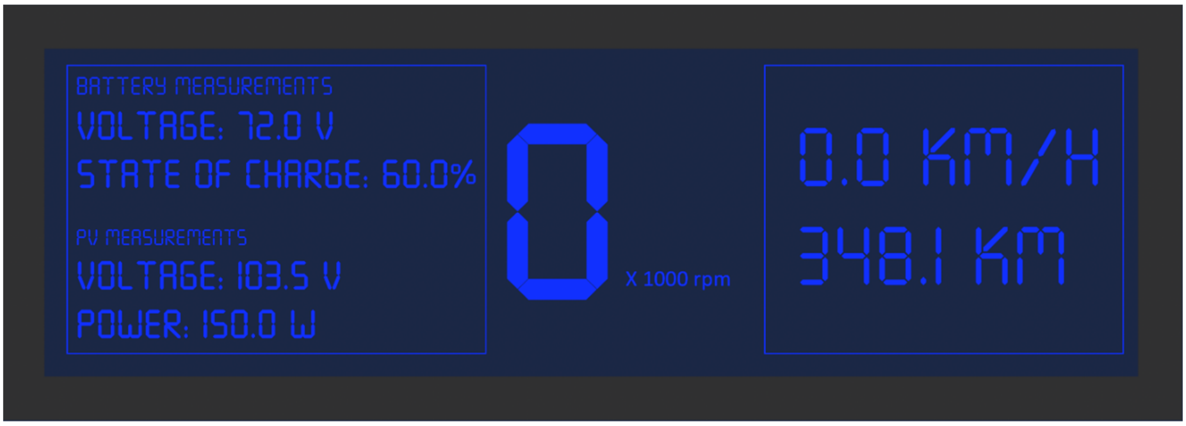

Figure 44: LCD used to display real-time data

4.4.3. Forward/Reverse Control

The first major component of the control circuit is the forward/reverse lever, which allows the car to move in the forward or reverse direction. The forward and reverse control has been implemented by making the use of a slide switch, which is connected with a DC motor. When the slide switch is in Forward position, it would allow the current to flow to the motor's field windings in a normal manner, so as to allow it to drive the car forward. When the slide switch is in reverse direction, it would change the wiring connections in such a way, that the polarity across the field windings of the motor is reversed, which allows the motor to run in a reverse direction. This change of polarity is achieved by making the use of four high current relays, as demonstrated in the dynamic model of the vehicle, discussed in previous chapter.

4.4.4. Speed Control

The second most important block in the control circuit is the use of speed control. The speed control allows the motor speed to be increased or decreased as per user requirements in real time. Referring to the dynamic model of the micro solar electric vehicle, which was developed in the previous chapter, the speed control was an essential part of the model. In the dynamic model, the speed control mechanism was implemented with the help of a simple PWM Chopper circuit. However, in this circuit, the implementation has been made with the help of a potentiometer, which limits or increases the current flowing to the motor in order to increase or decrease its speed. Both of these speed control methods use a very similar technique, which is to limit the amount of current flowing to the motor.

4.4.5. RPM Meter

Next major components of the circuit are being used to perform monitoring tasks. The first one being the RPM meter. RPM measurements can be taken in a variety of ways. The device used to measure RPM is called a tachometer, which can be made up of either a laser sensor, proximity sensor, optical sensor or even shaft encoders. In this circuit, the RPM data can be extracted directly from the motor with the help of the microprocessor and without using any sensor. The data is in revolutions per minute and can be directly displayed on to the LCD screen in the dashboard.

4.4.6. Speedometer

After the RPM data has been recorded, it becomes fairly easy to calculate the speed of the car. The microprocessor records the RPM values and then converts them into Km/hr values. The radius of the car wheels is also an important factor in determining the current speed of the car. The speed data is then also displayed along with the RPM in the dashboard.

4.4.7. Odometer

The Odometer of the car shows the total amount of mileage that the car has covered. The distance covered can be calculated from the speed data of the car and the amount of time that the car has been running for. An important feature of the odometer is that not only should it constantly update the distance traveled, but also retain its reading even when the battery is turned OFF. To do that, the odometer uses what is called a programmable read-only memory or PROM. With the help of PROM, each time a new reading is recorded, it permanently replaces the old reading. This reading is now stored in the memory indefinitely without the need for a battery. The distance data is also displayed in the LCD display on the dashboard.

4.4.8. Battery Voltage & SOC

Most internal combustion engine cars display the fuel level in the car's fuel tank on the dashboard as an important indicator for the user to know when to fill-up. Since, electric cars do not use fuel, indicators like battery voltage and battery state-of-charge are important indicators, which allow the users to know when to charge the battery of the car. A measurement block is used alongside the battery, which extracts all important data from the battery including battery voltage and state of charge. Then with the help of the microcontroller, it is displayed in the LCD on the dashboard.

4.4.9. PV Voltage & Output Power

Since this is a micro-solar electric vehicle, throughout the design, the main focus has been on charging the car's battery from solar power. In order to achieve this, solar modules were mounted on the car's roof. This makes it essential for a monitoring circuit to be present on-board the car, which provides the user with all the necessary information regarding the solar modules. A voltage/current measurement block is connected to the PV modules, which provides the PV module voltage and current values. Using these two values, the microcontroller can calculate the output power of the module. Thus PV module voltage and output power can be displayed in real-time on the dashboard.

4.4.10. Headlights

Next is the auxiliary circuit for the micro solar electric vehicle. The first major component of the auxiliary circuit the 12 V headlight bulbs. The headlights are a crucial part of a vehicle in maintaining visibility during night time. Most headlights are either halogen bulbs or LED lights that require a 12 V battery supply. The headlights are turned ON and OFF using a relay, which isolated the 12 V system from the 5 V system at which the microcontroller is operating. After obtaining input from the user, the microcontroller sends the signal to the relay, which then operates the 12 V circuit thus turning on the headlight bulbs.

4.4.11. Turn Signals

The second function being performed by the auxiliary circuitry is the left and right turn signals. Turn signals are blinking lights that are used as indicators for other vehicles, when a driver wants to take a turn on the road. Turn signals are usually yellow/orange in color. In this circuit, orange 12 V LED bulbs for the four turn signals of the car and two turn signal indicators in the dashboard were used. For the turn signals to function, the microcontroller sends a signal to the relays, which then operate the 12 V circuit thus turning on the turn signals.

4.4.12. Hazard Lights

Next up, the vehicle needs to have emergency/hazard lights which are red 12 V LED bulbs that blink at regular intervals to alert the approaching vehicles, in case there is an emergency on the road.

4.4.13. Taillights

Another fundamental function of the auxiliary circuit is rear taillights. Taillights are red 12V LED bulbs that turn ON on two different occasions. One is when the driver applies the break, and the second is during night when the headlights are ON. In this case, taillights are used to alert the vehicles approaching from behind that there is a vehicle on the road. Taillights are also operated using relays, which are triggered by the microcontroller.

4.4.14. Horn

The vehicle also needs to have a 12 V audio horn that is used to alert other drivers. The horn is operated when the user gives an input to the microcontroller, which sends a signal to the relay. The relay then operates the 12 V horn.

4.4.15. Windshield Wipers

Last but not least, windshield wipers are also a part of the circuit, The windshield wipers make use of small 12 V servo motors in order to do a half rotation to clean the windshield of the car, and improve visibility for the passengers. The servo motor used in the windshield wipers is a 12 V motor, operated by a relay, which is triggered when the microcontroller sends a signal to the relay.

4.4.16. User Interface

Figure 45, shows the user interface for the control, monitoring and auxiliary circuit of the micro solar electric vehicle. All of the above discussed major functions can be seen in the user interface. The upper rectangle of the image shows the dashboard, where values of different parameters will be visible, whereas, the lower rectangle shows the input panel, where human input will be registered.

Figure 45: UI for micro solar electric vehicle

4.5. Tinkercad Model

Figure 46, shows a simplified Tinkercad model of the control and monitoring circuit of our micro solar electric vehicle.

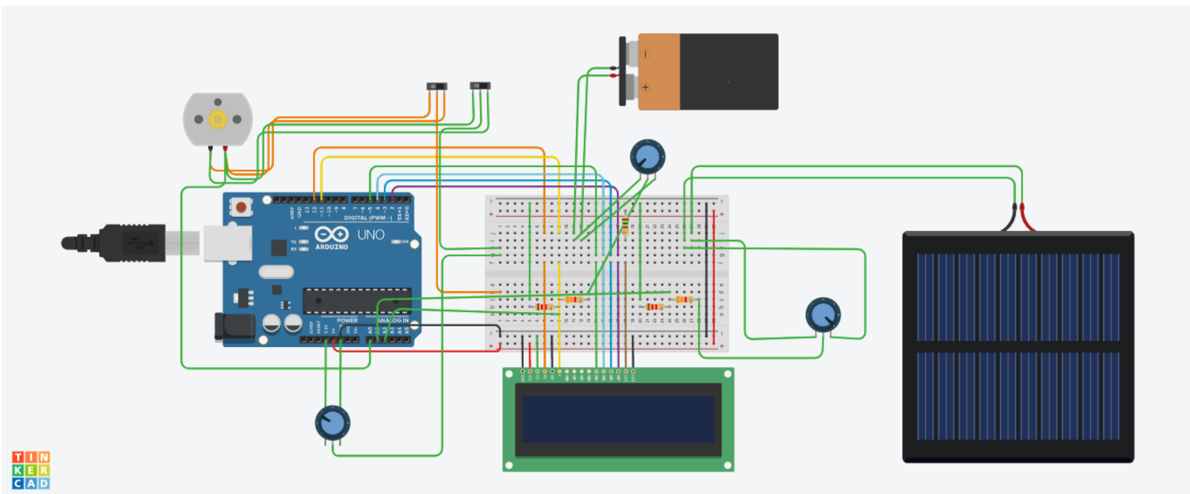

Figure 46: Tinkercad model of control and monitoring unit

The model shown in figure 46 implements all of the control and monitoring functions shown in figure 41 and discussed in the section above. The human input can be registered with the help of the various switches as shown in figure 46. PV and battery voltages and current are measured with the help of voltage/current measurement circuits. These values are then sent to the microcontroller, which then after all the required calculations displays them on the LCD screen. The microcontroller also sends signal to relays in order to perform any task that the user defines, whether it is increasing or decreasing the motor speed or putting the motor into forward/reverse mode.

Figure 47, shows a simplified Tinkercad model for the auxiliary circuit of the micro-solar electric vehicle.

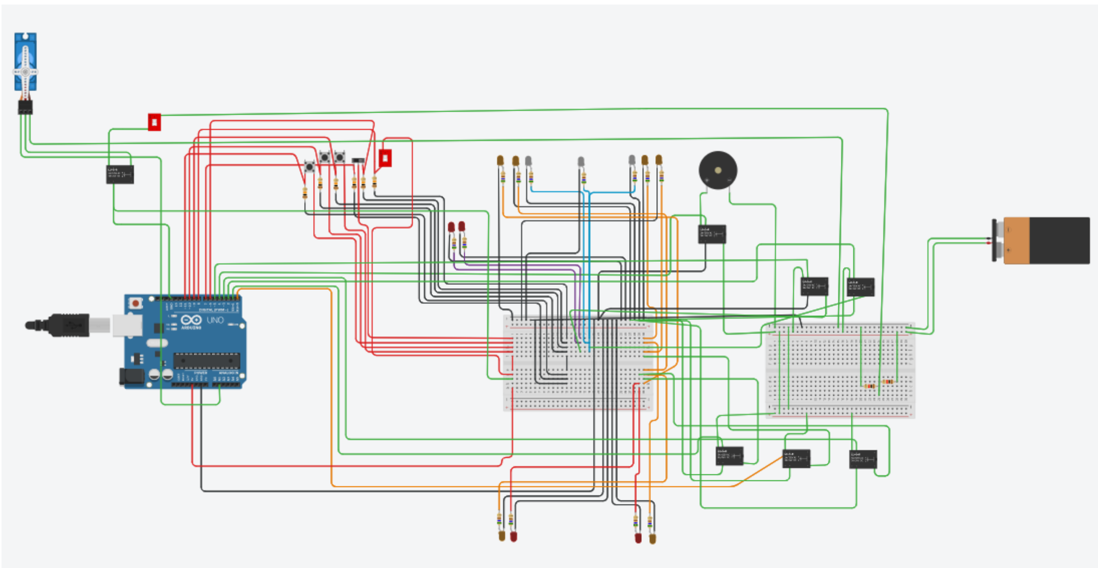

Figure 47: Tinkercad model of the auxiliary circuit

The Tinkercad model shown in figure 47 corresponds to the block diagram shown in figure 42 in the start of the chapter. This circuit performs all the tasks when it comes to operating the auxiliary electronics such as headlights, turn signals etc. As discussed in the previous sections, all the components used in this model are 12 V components, whereas the microcontroller is a 5 V electronic. Therefore, it cannot directly turn ON and OFF a 12 V component. In order to do perform that task, relays are utilized throughout the circuit. The human input once again is registered through the switches shown in figure 6. Based on the input registered, the microcontroller then sends a signal to the relay to turn ON the corresponding electronic whether it is a 12 V headlight bulb, a 12 V horn, or a 12 V DC servo motor for the windshield wipers.

4.6. Conclusion

The Tinkercad models shown in figure 46 and figure 47, mark the successful design of a complete instrumentation and control system of the micro solar electric vehicle to be designed. The instrumentation and control system is divided into two major parts, first one being the monitoring and control circuit, which not only monitors all the essential parameters that a user needs to be aware of while driving the vehicle, but also provides all the important controls such as braking, forward and reverse control etc. The second part of the system is the auxiliary circuit, which basically includes all the features of the car that are necessary for its safe operation. These include headlights, turn signals, emergency lights, taillights, horn, windshield wipers etc.

Tinkercad being a comprehensive design tool, helps design models that can be converted into functioning hardware systems with very little to no modifications. The Tinkercad model also enlists all the components that are to be used, when making a hardware model of the system. It also comes with wiring schematics, which can be used a wiring guide when connecting the different components on the hardware model. The Arduino code that was used in the Tinkercad model can be loaded onto the Arduino used in the hardware model in order to control all the associated components. The wiring schematics are attached in the Appendix section.

CHAPTER 5: CONCLUSION AND FUTURE WORK

5.1. Conclusion

The global transport sector is responsible for the third largest sector wise emissions and is a huge cause for concern, for governments and organizations fighting climate change worldwide. Almost all of these stakeholders have realized that electric vehicles are the future of transportation and are actively taking steps to increase the rate of adoption of electric vehicles. Automobile companies around the world, especially in most developed countries have laid out there EV strategies in which they plan on converting their entire fleets of vehicles to electric vehicles by either 2030 or soon after.

Until that happens, EV adoption and affordability has a number of challenges in its way. These challenges are further amplified when the discussion is about developing countries like Pakistan. In today's modern world, where electricity is a basic needs, Pakistan still struggles to meet the electricity demands of its residential, commercial and industrial sectors. This energy landscape poses a huge challenge to the mainstream adoption of electric vehicles throughout the country. The shortfall of electricity not only means that the power is not available 24/7 but it also means the cost of electricity being on a continuous rise, thus pushing the EV affordability further out of the reach of the general public.

In today's market (2022), when the price of electric vehicles starts anywhere from 40,000 USD and can go all the way up to 100,000 USD, being able to purchase an EV is a challenge even for someone living in the developed part of the world, where average income is relatively high. In comparison, Pakistan's average household income is even lower, approximately 587.069 USD in 2019 [40], which means people are simple unable to afford a new electric vehicle from the legacy automakers.

Moreover, lack of charging infrastructure is a problem that has been recognized globally, and is a common cause for concern amongst new EV buyers. This is also referred to as range anxiety. In order to overcome this, there is need for widespread availability of commercial charging infrastructure. However, in the case of Pakistan, once again this challenge is amplified due to the economic constraints. Not only does Pakistan lacks a commercial charging infrastructure of any kind, the residential electrical infrastructure in the country is also unable to support EV charging. The electricity supply from utility companies is usually 220V at 5 or 10A at most, which is insufficient to charge any electric vehicle at a reasonable speed.

All these issues presented a huge gap in the market as well as the research world, thus creating an opportunity to pursue this research.

To start, a comprehensive literature review was conducted in which all the problems facing the EV adoption across the world and in Pakistan were identified. The review also included looking for solutions to overcome these problems. While the long-term solution is to build a more reliable and powerful electrical infrastructure in the country, it does not seem to be happening anytime soon. Thus starts the search for a more feasible solution. The use of micro solar electric vehicles seemed like a promising solution to the problems at hand.

Once again a deep look was taken in to all the research present on the topic of micro electric vehicle, their design, sizing and modeling etc. The review showed that there is a huge gap in the research present on the topic. The design of solar electric vehicles can be majorly categorized into two different categories; solar race cars, and commercial solar cars. The first category does not satisfy even the basic requirements of what a road legal vehicle should be and the second category is in very early stages of development. Therefore, the motivation to undertake the design of a micro solar electric vehicle increased.

Since the design of the solar electric vehicle that is being undertaken is for application in Pakistan, the data that is to be utilized in designing and running the model needs to be from Pakistan. Therefore, solar irradiance data and daily average temperature data was collected from a city called Bahawalpur, located in the Southern Punjab region of Pakistan.

After data collection, HOMER Pro was used to not only build a system design and do PV sizing for the micro solar electric vehicle, but also to carry out a techno-economic feasibility analysis of the designed system. To decide upon the EV design to be utilized in this research, some baseline values were required for example the dimensions of the car, weight of the car, motor power, no. of passengers, average speed etc. For this purpose, a commercially available and economical electric vehicle called Chang Li Electric vehicle was used. Chang Li is an electric vehicle being manufactured by a Chinese EV automaker and can be easily imported to Pakistan and that too at an economical price point. Based on these baseline values, HOMER Pro simulated a model of the micro electric vehicle which can then be used to design the micro solar electric vehicle. The model specified the number of solar modules and batteries that were to be utilized in order to meet the load demand, if the car were to travel a set distance. The model also provided all relevant cost information including capital cost, maintenance cost, NPC cost etc.

Once the PV sizing of the micro solar electric vehicle was complete, a dynamic model of the vehicle could be built. In order to that, Simulink was used. Simulink is a comprehensive modeling tool, which allows the design, simulation and modeling of a variety of systems. For the dynamic model of the vehicle, the parameters outlined by the HOMER Pro software were used. The dynamic model consisted of a number of different blocks from solar modules, MPPT, to DC-DC converters, Li-Ion battery model, on-board AC-DC charger, DC Motor, and a PWM Chopper based speed control circuit. Once the model was complete, it was used to run tests for a variety of different scenarios that the micro solar electric vehicle might encounter when being used in real life. These scenarios included the power generation by solar PV modules under variable irradiance values, charging of battery from different source i.e. PV modules and AC outlet, discharging of battery to run the DC motor, DC motor operation in forward/reverse mode, DC motor operation under variable load conditions i.e. uneven roads, DC motor operation under variable speed conditions i.e. the use of accelerator by the driver. All these test gave successful results i.e. the micro solar electric vehicle behaved as expected under all the above mentioned conditions.

Finally, the design of an instrumentation and control system for the micro solar electric vehicle was also presented. As with any road legal vehicle, there are a set of features that the vehicle must have in order to ensure its safe operation. These features include everything from accelerator, brakes, forward/reverse control, different indicators in the dashboard, turn signals, headlights, emergency lights etc. To carry out the design of the instrumentation and control system of the car, a software called Tinkercad was used. Tinkercad is a basic design software which allows the design of simple to complex ready to build circuit designs. It provides a comprehensive wiring schematic, which can then be used to build the hardware of the circuit. The design was divided into two different parts; first part being the control and monitoring of the micro solar electric vehicle, and the second part being the auxiliary circuitry of the vehicle.

The contributions of this thesis are listed below:

- Identification of the challenges to EV adoption in the global context as well as the context of developing countries like Pakistan.

- Gap analysis of both academic and industrial research on the use of on-board solar PV modules to power electric vehicles.

- System design and PV sizing of a micro-solar electric vehicle based on the 3 passenger Chang Li electric vehicle for application in Pakistan.

- Dynamic modeling of a micro solar electric vehicle, including PV to battery charging, AC source to battery charging, maximum power point tracking, and the operation of DC motor under variable loads and speeds.

- Design of a ready to build, instrumentation and control system for a micro solar using Tinkercad with all the monitoring, control and auxiliary electronics along with detailed wiring schematics.

5.2. Future Work

While the research presented in this thesis focused on the design of a micro solar electric vehicle, the innovative design approach used is highly multi-faceted and can be used for a number of different applications. Moreover, there are a number of things that can be further investigated in the design and analysis of a micro solar electric vehicle to ensure that the design can easily be translated into reality.

1. Firstly, the resources used for the PV design and system sizing of the micro-electric vehicle were specific to Pakistan and a region of Pakistan, called Bahawalpur to be precise. This region had excellent solar irradiance throughout the year and thus provided an ideal situation for the micro-solar EV to be driven in. It would be worthwhile to investigate the feasibility of the electric vehicle in different conditions, perhaps in areas with less sun throughout the year. This could have some implications on the PV design and system sizing of the car as well.

2. Secondly, vehicle dynamic modeling is a vast field and there is a huge number of factors that can be considered in order to make the dynamic model as accurate as possible. These factors could involve acceleration and braking characteristics, body design of the vehicle, passenger weight, passenger driving behavior, suspension characteristics, drag produced by tires etc.

3. As mentioned above, the design approach is versatile and can be applied to a number of different applications for example the design of golf-carts, auto-rickshaws, agricultural equipment, commercial fleets etc.

Appendix A

Wiring Schematics

Figure 48 shows the wiring schematics for the control and monitoring circuit. The wiring guide can be used to connect components when making a hardware model of the system.

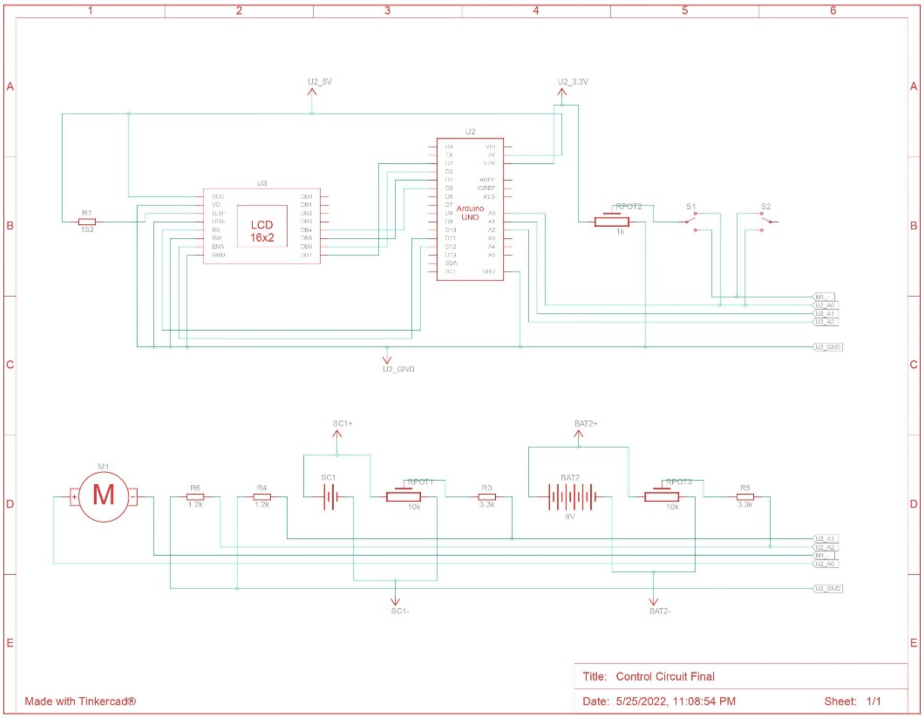

Figure 48: Wiring schematics for control and monitoring circuit

Figure 49, 50, and 51 show the wiring schematics for the auxiliary circuitry of the micro solar electric vehicle. This wiring schematic can be used as a wiring guide when making the hardware model for all the auxiliary circuitry of the vehicle.

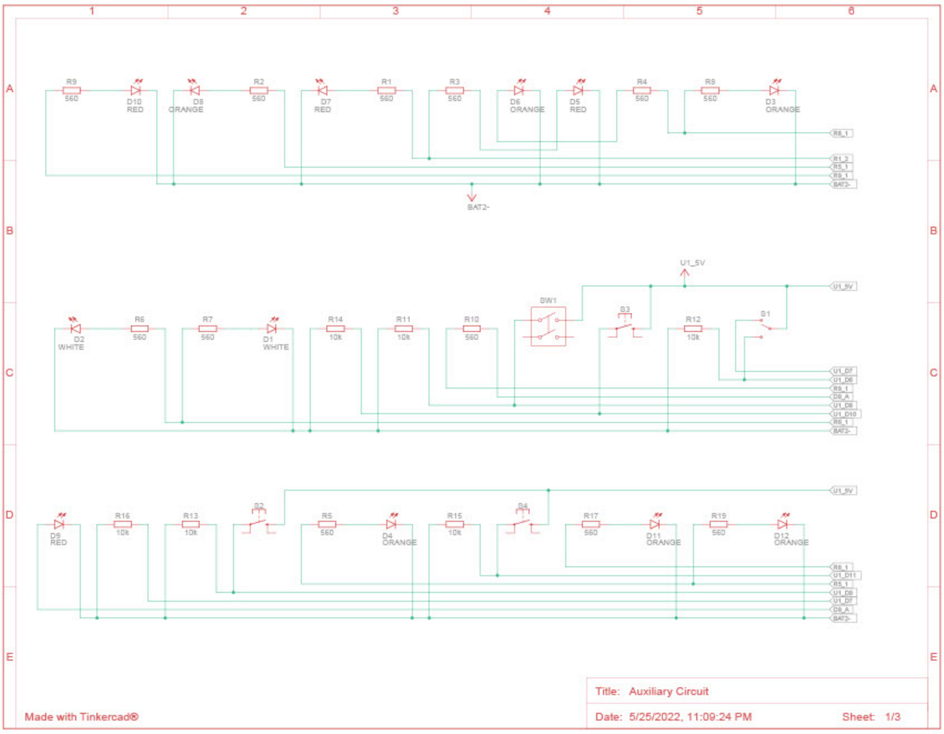

Figure 49: Wiring schematic for auxiliary circuitry Part 1

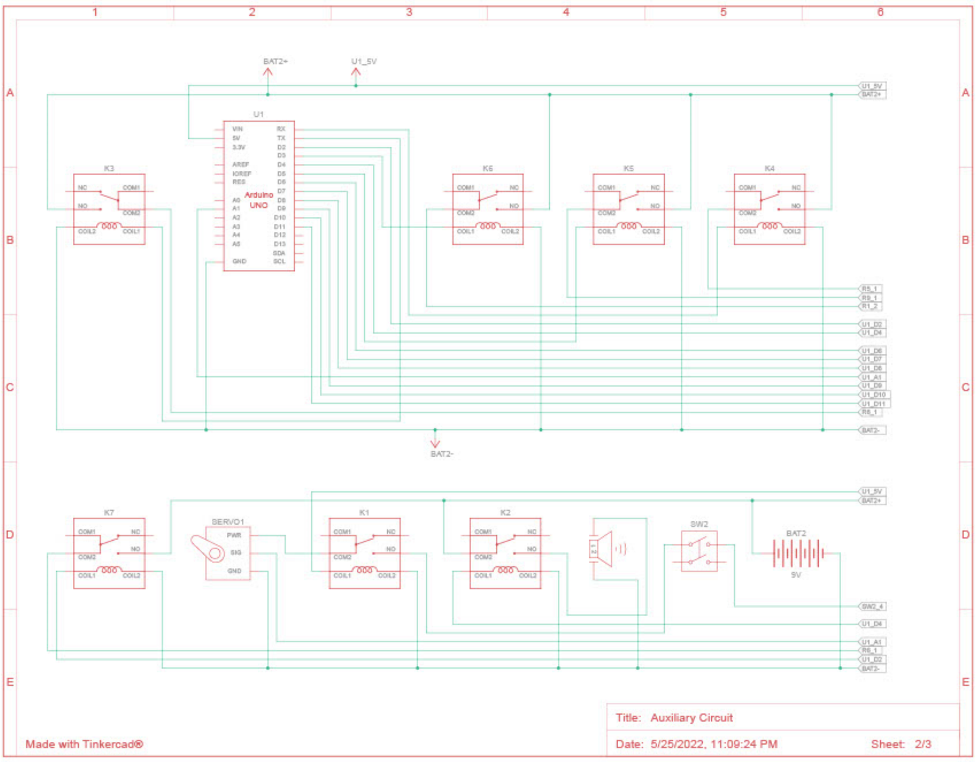

Figure 50: Wiring schematic for auxiliary circuitry Part 2

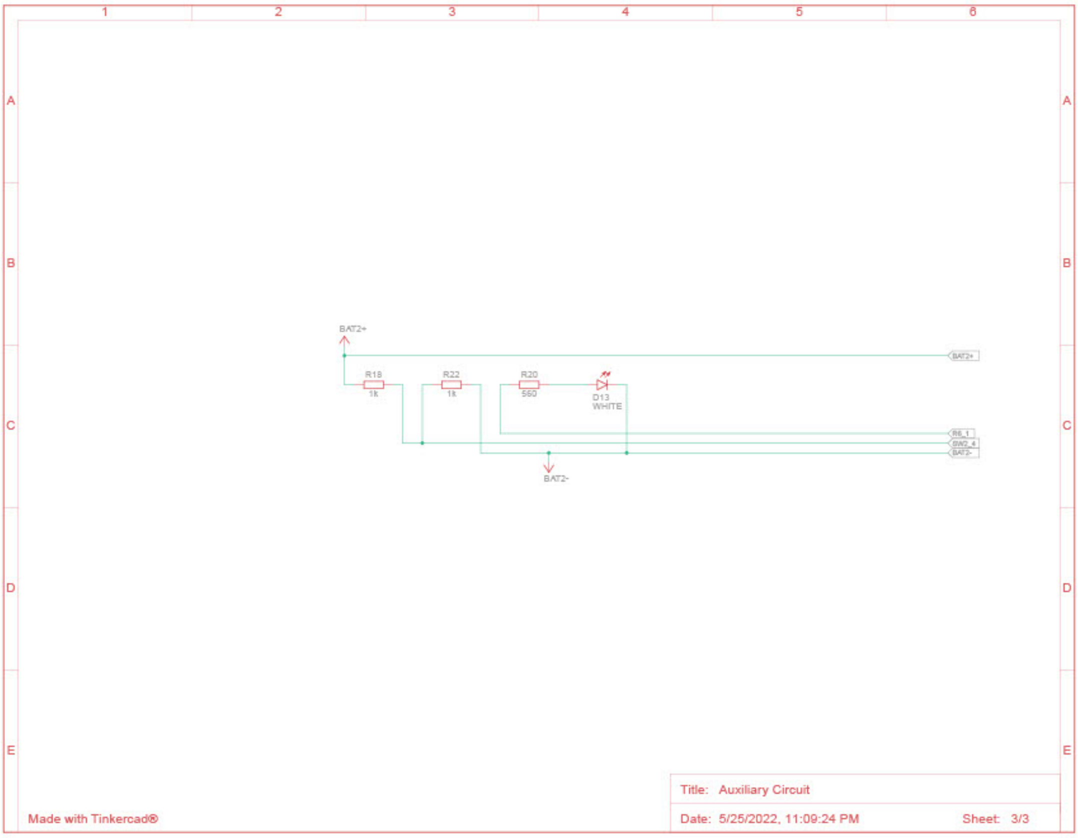

Figure 51: Wiring schematic for auxiliary circuit Part 3

Appendix B

Arduino Code for Control Circuit

```
#include <LiquidCrystal.h>

//  initialize  the  library  with  the  numbers  of  the
interface pins

LiquidCrystal lcd(12, 11, 5, 4, 3, 2);

int A;

int B;

float C;

int Analog = 0;

float Voltage = 0;

float SOC = 0;

int Analog1 = 0;

float Voltage1 = 0;

float SOC1= 0;

float aa = 9;


void setup() {

  // set up the LCD's number of columns and rows:

  pinMode(A0, INPUT);

  pinMode(A1, INPUT);

  pinMode(A2, INPUT);

  lcd.begin(16, 2);


}


void loop() {

  lcd.setCursor(0, 0);
```

```
lcd.print(map(analogRead(A0), 0, 1023, 0, 5000));
lcd.print("RPM  ");
lcd.setCursor(8, 0);

A = map(analogRead(A0), 0, 1023, 0, 5000);
B = 0.1885*A*0.254;
lcd.print(B);
lcd.print("Km/Hr  ");
lcd.setCursor(3, 1);

A = map(analogRead(A0), 0, 1023, 0, 5000);
B = 0.1885*A*0.254;
C = B*((millis()*0.01)/3600);
lcd.print(C);
lcd.print("Km  ");

delay(10000);
lcd.setCursor(0, 0);
lcd.print("                                      ");
lcd.setCursor(0, 1);
lcd.print("                                      ");
delay(5000);

lcd.setCursor(0,0);
lcd.print("VOLTS : ");
lcd.setCursor(13,0);
lcd.print("V");
Analog = analogRead(A1);
Voltage = ((Analog / 1023.0) * 5)*3.75;
lcd.setCursor(8,0);
```

```
 lcd.print(Voltage);
 SOC = Voltage*(0.1);
 lcd.setCursor(0,1);
 lcd.print("Power:  ");
 lcd.setCursor(7,1);
 lcd.print(SOC);
 lcd.setCursor(10,1);
 lcd.print("   W");

  delay(3000);
 lcd.setCursor(0, 0);
 lcd.print("                                      ");
 lcd.setCursor(0, 1);
 lcd.print("                                      ");
    delay(3000);

lcd.begin(16,2);
 lcd.setCursor(0,0);
 lcd.print("VOLTS : ");
 lcd.setCursor(13,0);
 lcd.print("V"); Analog1 = analogRead(A2);
 Voltage1 = ((Analog / 1023.0) * 5)*3.75;
 lcd.setCursor(8,0);
 lcd.print(Voltage1);
 SOC1 = (Voltage1/aa)*100;
 lcd.setCursor(0,1);
 lcd.print("SOC:  ");
 lcd.setCursor(5,1);
 lcd.print(SOC1);
 lcd.setCursor(9,1);
```

```
  lcd.print("   %");

  delay(3000);
  lcd.setCursor(0, 0);
  lcd.print("                                      ");
  lcd.setCursor(0, 1);
  lcd.print("                                      ");
     delay(3000);
}
```

Arduino Code for Auxiliary Circuit

```
// C++ code

//

#include <Servo.h>

Servo servoBase;//Asigno un nombre específico



int R_blinker = 0;

int L_blinker = 1;

int F_headlight = 2;

int B_taillight = 3;

int horn = 4;

int Emergency = 5;

int In_R_blinker = 6;
```

```
int In_L_blinker = 7;

int In_F_headlight = 8;

int In_B_taillight = 9;

int In_horn = 10;

int In_Emergency = 11;



void setup()

{

pinMode(0, OUTPUT);

pinMode(1, OUTPUT);

pinMode(2, OUTPUT);

pinMode(3, OUTPUT);

pinMode(4, OUTPUT);

pinMode(5, OUTPUT);

pinMode(6, INPUT);

pinMode(7, INPUT);

pinMode(8, INPUT);

pinMode(9, INPUT);
```

```
pinMode(10, INPUT);

pinMode(11, INPUT);

servoBase.attach(A1);//Pin a utilizar para servo

servoBase.write(0);  //asigno 0 al servo motor

}



void loop()

{

 for(int i=0; i<=180; i=i+10)

  {

   servoBase.write(i);

   delay(100);

  }



    if(digitalRead(In_R_blinker) == 1)

    {

    digitalWrite(R_blinker, HIGH);

    }

  else{
```

```
     digitalWrite(R_blinker, LOW);
}
  if(digitalRead(In_L_blinker) == 1)
  {
  digitalWrite(L_blinker, HIGH);
  }
else{
     digitalWrite(L_blinker, LOW);
}
  if(digitalRead(In_F_headlight) == 1)
  {
  digitalWrite(F_headlight, HIGH);
  }
else{
     digitalWrite(F_headlight, LOW);
}
  if(digitalRead(In_B_taillight) == 1)
  {
  digitalWrite(B_taillight, HIGH);
```

```
  }
else{
     digitalWrite(B_taillight, LOW);
}
  if(digitalRead(In_horn) == 1)
  {
  digitalWrite(horn, HIGH);
  }
else{
     digitalWrite(horn, LOW);
}
  if(digitalRead(In_Emergency) == 1)
  {
  digitalWrite(Emergency, HIGH);
      delay(1000);
      digitalWrite(Emergency, LOW);
      delay(1000);
  }
else{
```

```
        digitalWrite(Emergency, LOW);
    }
}
```

List of Publications

1. A. Husnain, M. T. Iqbal, "System Design and PV Sizing of a Micro Solar Electric Vehicle for Pakistan." Presented at the 9th IEEE Conference on Technologies for Sustainability (SusTech 2022), Sunny Riverside, California
2. A. Husnain, M. T. Iqbal, "Dynamic Modeling of a Micro Solar Electric Vehicle for Pakistan using Simulink." Presented at the IEMTRONICS 2022 (International IOT, Electronics and Mechatronics Conference), Toronto, Canada.
3. A. Husnain, M. T. Iqbal, "Design and Simulation of a Solar Parking System to meet all Energy needs of 10 Electric Cars." Presented at The 30th Annual Newfoundland Electrical and Computer Engineering Conference (NECEC 2021), St. John's, NL.