CZECH TECHNICAL UNIVERSITY, PRAGUE

Master Thesis on 'Simulation of Electric Vehicle Including Different Power Train Components'

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Faculty of Electrical Engineering

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[2] JAZAR, Reza N.: Vehicle dynamics: theory and application. 2nd ed. New York: Springer, 2014
[3] Pera, M.-C., Hissel, D., and Gualous, H.: Electrochemical Components. Somerset, NJ, USA: John Wiley & Sons, 2013.

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Declaration:

I hereby declare that I have completed this thesis independently and that I have listed all the literature and publications used in accordance with the Methodological guidelines about adhering to ethical principles in the preparation of the final university theses.

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Abstract:

The aim of this master thesis work 'Simulation of electric vehicle including different power train components' is to construct an energy model of electric vehicle including different power train components with the help of a simulation tool, which in this work will be MATLAB Simulink. With this model, we expect to obtain energy consumption by a vehicle by virtue of different forces acting on vehicle when subjected to different standard driving cycles. This work also covers up a survey of different vehicles which runs on electric propulsion either solely or in assisted mode in the present market.

Abstract:

Cílem této diplomové práce "Simulace elektrického vozidla s různými komponenty hnacího ústrojí" je konstrukce energetického modelu elektrického vozidla s různými komponenty pohonné soustavy pomocí simulačního nástroje, který bude v této práci MATLAB Simulink. Pomocí tohoto modelu očekáváme, že budeme získávat energii z vozidla díky různým silám působícím na vozidlo, pokud jsou vystaveny různým standardním jízdním cyklům. Tato práce také pokrývá průzkum různých vozidel, které běží na elektrickém pohonu buď výhradně nebo v asistovaném režimu na současném trhu.

Keywords:

Electric Vehicles, Electrochemical cell, Vehicle Dynamics, Energy Modelling, MATAB, Simulink, Driving Cycles, State of Charge, Voltage, Power, Energy, Lithium Ion Batteries, Aerodynamic Drag, C-Rate .

Klíčová slova:

Elektrická vozidla, elektrochemický článek, dynamika vozidel, modelování energie, MATLAB, Simulink, jízdní cykly, stav nabíjení, napětí, energie, energie, lithium-iontové baterie, aerodynamické tažení, C-rychlost

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Chapter 1

Introduction

1.1 Introduction

The nature of the *fossil fuel,* as the name suggests, '*Fossil*', which takes millions years to get replenished in abundance. The rate of consumption of the fuel is just making its way higher than the rate of productions, which inevitably will reach on a point where it will be absolutely exhausted with no more fossil fuels to satire the demand. Imagine life with mobile phones, but without any electricity to charge it, seems like dark ages, not a pretty picture to imagine. Other prominent concern related to the exhaustible use of fossil fuel is environmental issues. Impact of carbon di oxide gas (CO_2) on the environment is not new to be known. It has been first theorized by noble prize laureate Svante Arrhenius back in 1896. However, the emission of the CO_2 can be divided majorly into two causes: Natural Phenomena and Anthropogenic. Natural phenomenon such as volcanic aerosol and anthropogenic economic activities has been seen as significant contributors to temperature rise over past years, apparently leading to temperature rise leading to glacier meltdown. (1) (2)

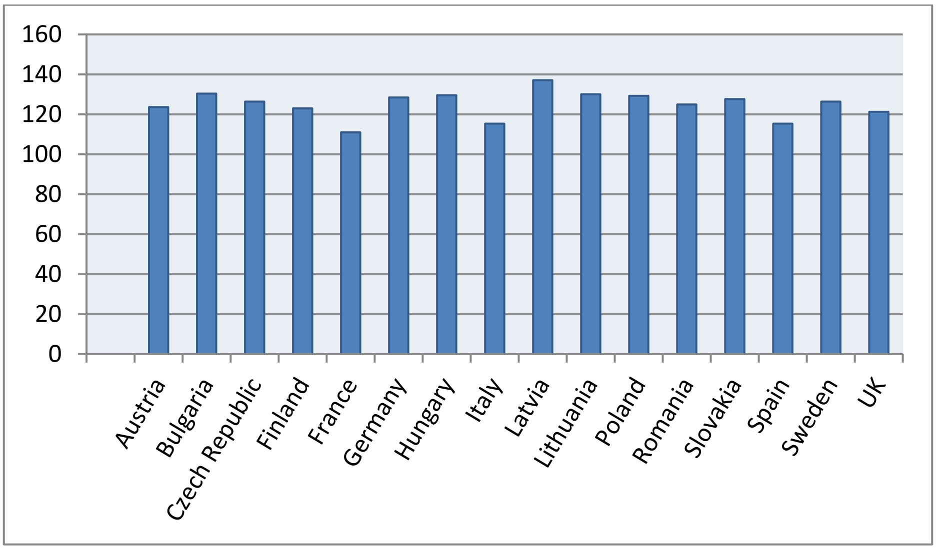


Figure 1: CO_2 emission in 2015

The problems just do not persist with the exhaustible nature of the hydrocarbons and environment. 'Oil' in this contemporary world scenario is not just an energy resource but also heavily influence the international politics and policies of nations. Different war conflicts and wars are waged to acquire the oil. (1)

With the current trend and peer pressure from the perspective of Environment, limited resource, and political interventions, vigorous researches are done through which lead to the advancement of existing technology. New family of storage devices, advanced electronic drives, fabrication of sophisticated semiconductor materials, fabrication material, ultra-capacitors have played their major part in bringing back the trend of EVs with much more economy introduced in it. Intense research and development is being carried out in order to develop new concepts, low cost, more reliability of hybrid powertrains. As it can be seen as future of transportation, almost all major automobile manufacturers from all across the world are jumped into the market of EV, HEV and FCEV . 'Prius' from Toyota, to name few available models. This competition has led to the creation of such cars which are economically viable and are being used now. Although, there are a lot of scope in the improvement of storage technology, which will open new doors for EVs.

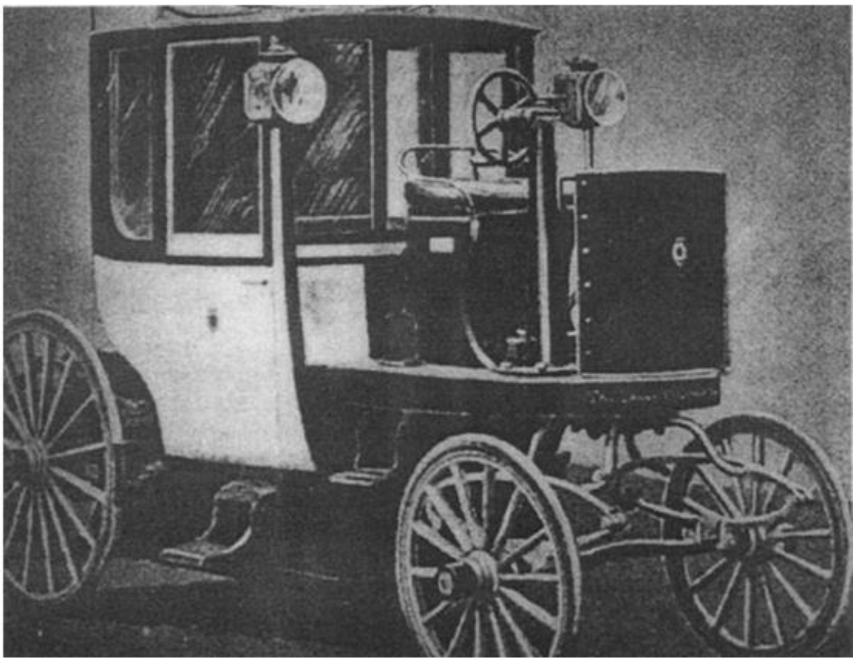


Figure 2 : London electric cab company's taxi

Since BEV's is now being totally dependent of the electrical storage technology and will improve as storage and energy density will improve. Nowadays, Hybrid Electric vehicles are in trend. Hybrid vehicles.

As per proposed by the Technical Committee 69 (Electric Road Vehicles), International Electrotechnical Commission. "A hybrid road vehicle is one in which propulsion energy, during specified operational missions, is available from two or more kinds or types of energy stores, sources, or converter. At least one store or converter must be on-board. "A hybrid electric vehicle (HEV) is a hybrid vehicle in which at least one of the energy stores, sources, *or* converter can deliver electric energy.
"A series hybrid is an HEV in which only one energy converter can provide propulsion power.
"A parallel hybrid is an HEV in which more than one energy converter can provide propulsion power."

As we can notice, Hybrid vehicle uses two or more different type of sources in order to facilitate motion requirement of the HEV.

Chapter 2

Overview of Vehicles in Production

Electric mobility has come a long way since first electric vehicle introduced. Earlier vehicles possessed drawbacks of technology of that era, but in contemporary scenarios development and advancement in technologies, such as Nanotechnology, are facilitating the rapid advancement of electric mobility. Most of the car manufacturers have found the potential of electric vehicle as future of transportations. Down below are enlisted some of the state of art electric vehicles in production.

2.1) Pure Electric Vehicles:

2.1.1 Nissan Leaf

Figure 3: Nissan leaf

→ Variant: Nissan Leaf S

→ 30 kWh lithium-ion (Li-ion) battery

→ 80 kW AC synchronous electric motor

→ Range up to 200 km(city)/ 162 km(highway)/180 km (combined)

→ 3.6 kW onboard charger (optional 6.6 kW)

→ Normal/ Quick charge port

→ Curb weight: 1500 kg

→ Drag coefficient: 0.28

→ 5 seats

2.1.2 BMW i3

Figure 4: BWM i3

→ Variant: BMW i3 (94 Ah)
→ 27.2 kWh lithium-ion (Li-ion) battery
→ Fast charging (125A, 80% SOC: under 40 min.)
→ Normal charging (60A , 80% SOC: 7.5 hours)
→ 125kW AC motor, 250 Nm maximum torque
→ Range up to 300 km
→ Laden weight 1320 kg
→ 5 seats

2.1.3 Tesla Model S

By Andrzej Otrębski - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=51775137

Figure 5: Tesla Model S

- Variant: Model S (P85D)
- 85 kWh Li –ion battery
- 11kW, 265 V onboard charger three phase 16A
- Supercharger for 120kW DC offboard charging.

- Three phase Induction Motor
- all-wheel drive with combined motor power output of 691 hp (515 kW)
- Range of 407 km.
- Curb weight of 2,239 kg with drag coefficient of 0.24***Invalid source specified.***.

2.1.4 Skoda Perun HE:

Figure 6: Skoda Perum HE

→ Equipped with 222kWh, 60 V battery
→ SKODA *Ultra Fast Charging* with DC Charging 200A (0.5C)
→ Fast Charging in 70 minutes/ Normal Charging with balancing 6-8 hours
→ Range per charge of 150 km
→ 160 kW three phase Induction (Asynchronous) Motor.
→ Total passenger capacity of 82.

2.2 Hybrid Electric

2.2.1 Chevrolet Volt:

Figure 7: Chevrolet Volt

→ Variant: Chevrolet Volt LT

- → Pure electric range of 85 km and total range of 675 km (extended range)
- → 18.4kWh Li-ion battery
- → 16-valve Atkinson-cycle 1.5-liter inline-4, 75kW, 140 Nm
- → 2 Permanent-Magnet Synchronous Motors, 111kW, 399Nm
- → Curb weight of 1607kg

2.2.2 Toyota Prius

Figure 8: Toyota Prius

- → Variant: Prius Three
  - → 1.8-Liter, 4-cylinder, 71 kW @ 5200 rpm and 142 N•m @ 3600 rpm
  - → Li-ion battery, 207.2 V
  - → Permanent Magnet AC Motor with 53kW, 163Nm
  - → Hybrid combined net power 90kW
  - → Range of 87km (city)/ 80km (highway)/ 84km (combined)
  - → Curb weight is 1398kg
  - → Seating capacity of 5
  - → Fuel tank capacity: 42.8 L

2.2.3 Mitsubishi Outlander

Figure 9: Mitsuibishi's outlander

- → Variant: Outlander S Edition

→ IC engine: 2.0-litre 16-valve DOHC MIVEC,1998cc
→ Emission level of EURO-6b; CO_2 emission 41 g/km
→ Engine: 89kW and 190 Nm @ 4,500 rpm
→ Li-ion battery of 12kWh, 300V
→ Electric drive range of 54 km
→ Front motor: 60kW, and 137 Nm
→ Rear Motor: 60 kW, and 195 Nm
→ Regular Charging in approximately 5 hours (for 240V,10A)/ fast charging in 25 minutes (80%)
→ Operating modes: Pure electric + series hybrid + parallel hybrid mode
→ Fuel consumption: 1.7 litre/100 km

2.3 Fuel Cell Vehicles

2.3.1 Hyundai ix35 Fuel Cell

Figure 10: ix35

→ Variant: ix35 Fuel Cell
→ Fuel type: Hydrogen
→ Proton Exchange Membrane Fuel cell technology
→ Fuel cell power output of 100kW
→ Hydrogen tank pressure 700 bar/ tank capacity 144 litre
→ 24kW Li-ion battery
→ Front Mounted Induction Machine of 100kW/300 Nm
→ Fuel Consumption(kg/100 km): 0.8896 (city)/0.9868 (highway)/0.9512 (comb)
→ driving range of 594km
→ 5 seat

2.3.2 FCX Clarity

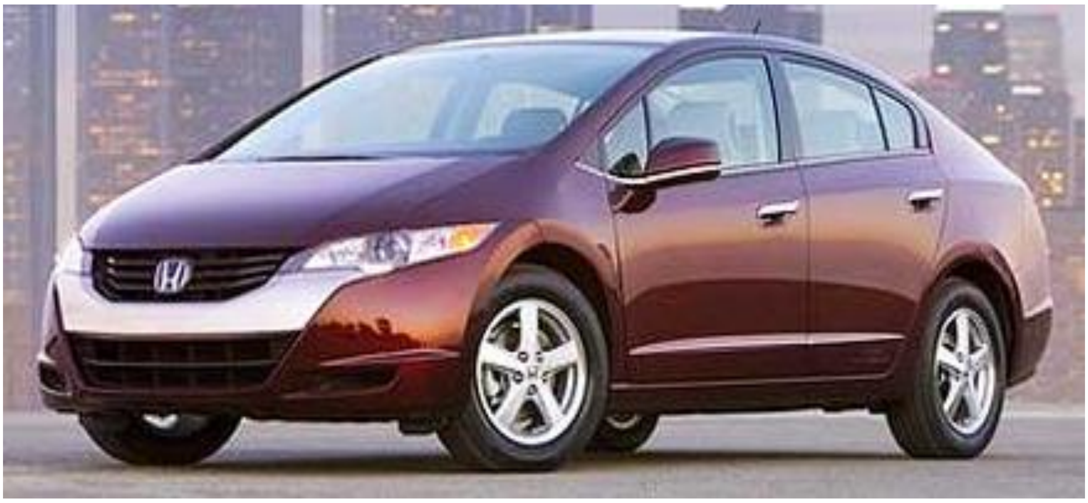


Figure 11: Honda's FCX clarity

- → Variant: FCX Clarity
- → Fuel Type: Hydrogen
- → Proton Exchange Membrane Fuel Cell
- → Fuel cell maximum output 100kW
- → Hydrogen tank pressure of 344 bar
- → Li-ion battery, 288 V
- → Permanent Magnet Synchronous Machine/100kW output/256 Nm
- → Range of 450km
- → Fuel capacity of 4.1 kg
- → Occupants: 4 (3)

Chapter 3

Electric Propulsion

Electric Propulsion is nothing less than heart of Electric Vehicle. It consists of Electric Machine, Power Converters and electronic converters. The main workforce to mobilize vehicle comes from electrical machines employed for purpose. Power converter's function is to provide electrical input according to instantaneous requirement of machine according to the coupled load. Electronic converter provides control signals to the power converter according to command given by the driver. The scope of EVs travelled side by side as with introduction and advancement of semiconductor switches devices. Electric machines have been in use with more than a century due to its relatively characteristic to deliver according to the load. The efficiency of electric machines can be generally more than 90%, which when compared to IC engine is much higher. Electric machine converts electrical to mechanical energy and vice versa. Electrical energy is just not efficient but also regenerative in nature. In the braking mode, electric machine can recuperate energy by extracting kinetic energy from wheel (generating mode) and store in the energy accumulators, either in Battery (High energy density) /or Ultracapacitor (High Power Density). Practically only a portion of energy is recovered since irreversible energy conversion takes place in the form of mechanical losses. Due to this energy recovery, overall efficiency of EV is increased.

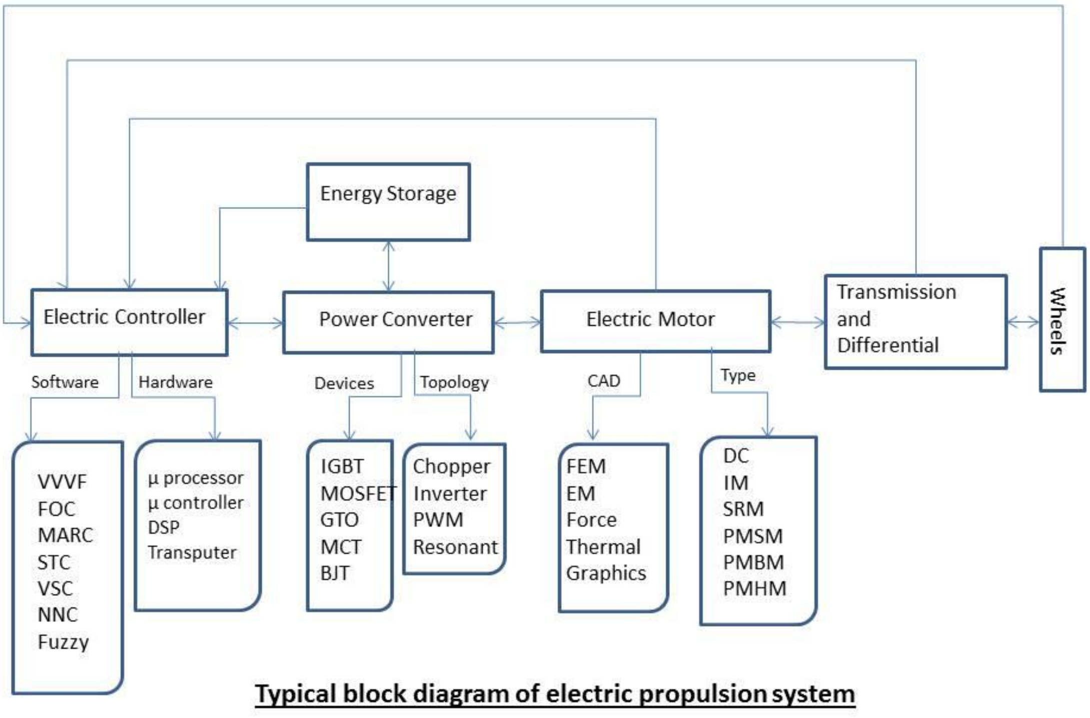


Figure 12: representation of electric propulsion systems

(4)

Electrical machines can be classified mainly into two groups depending upon nature of electricity employed, DC machine and AC machine. Both family of machines have their pros and cons, and found their application according to the load requirement. DC machines were incorporated in the 1980's decade due to its torque to load characteristics and controllability. In spite of such fine traits, DC machine are no longer being preferred due its size and maintenance requirement. Now a days, latest vehicles manufacturers are employing AC and brushless motors, including Induction Motors, Switched Reluctance Motor and Permanent Magnet Motors. This chapter aims to render a brief overview of electrical machines.

3.1 DC Machine: The electrical machine which uses the direct current as power input (motoring mode) and generating direct current (generation mode) are termed as DC machine. DC machines consists of two set of windings, on the rotor(rotating body mounted on shaft) and stator (stationary part which holds current carrying conductive wiring in order to cause the interaction between two field fluxes, resulting in torque generation producing necessary torque to overcome the inertia and friction. Simply put, force (F) experienced by any current (I) carrying conductor of length (L) in the magnetic field density (B) is,

$$F = B \times I \times L \qquad (1.1)$$

And when the current carrying conductor is in coil shape then, Torque (T) produced will be,

$$T = B \times I \times L \times \cos(\alpha) \qquad (1.2)$$

a is angle between the coil plane and magnetic field (B). (4)

The winding on the rotor is known as *armature winding* and winding on stator as *field winding*. The Orthogonality of the two mmf is essential to produce the maximum torque and this orthogonality is maintained by the help of the *commutators and brushes*. Both windings are provided with DC to flow from them. Armature winding carries higher magnitude of current whereas field winding carries small field excitation current. Depending upon the nature of sources and topology of connection between field and armature winding DC machine can be categorized as follows,

- Separately excited DC machine
- DC shunt machine
- DC series machine
- Cumulative compound DC machine

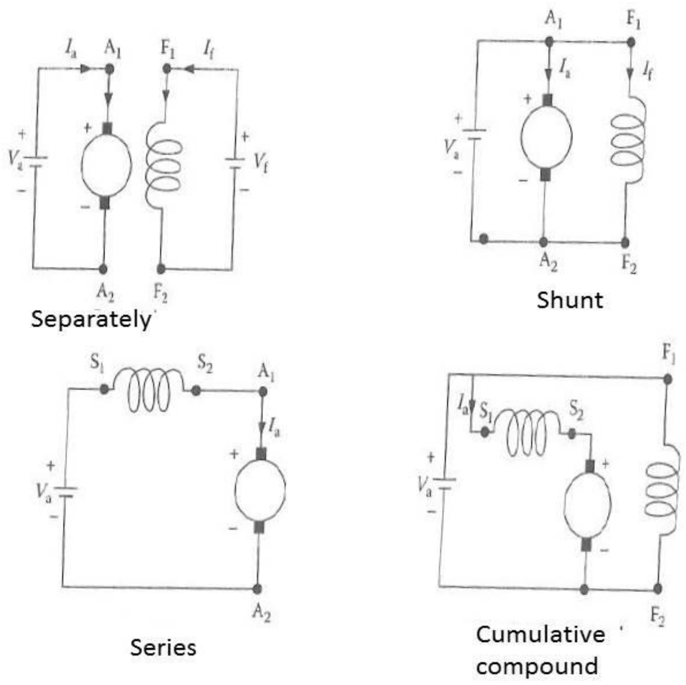
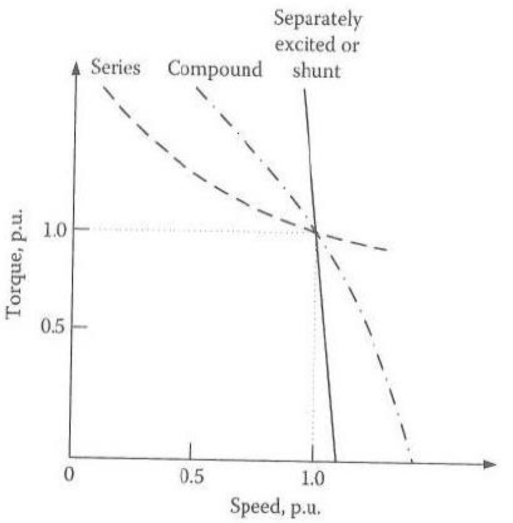


Figure 13: different schemes of stator field winding

(4)

As it goes without saying all the topologies have its own advantage and drawbacks, and their application depends upon the load requirement as well. Typical torque- speed characteristics of the DC machines are mentioned as following.

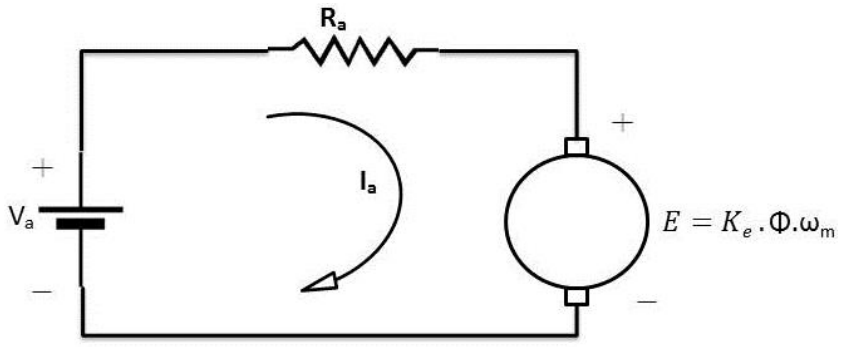


Torque vs. Speed Characteristics of different excitations

Figure 14: Torque vs Speed characteristics for DC machine

(4)

In separately excited DC machine, it is easy to control field and armature voltage independently. Whereas, in shunt winding, which has same speed torque characteristics as separately excited machine, controlling is possible only when using inserting resistance in the circuit. However, it is an inefficient method due to the presence of the resistance in the circuit. But, if we replace the mentioned resistance in circuit by the power electronic devices(DC-DC converter) we can actively control production of proper armature and field voltage. (4)



Equivalent circuit of the armature circuit DC motor

Figure 15: Equivalent DC Aarmature circuit

Basic equations of DC machines are as follows;

$$V_a = E + R_a . I_a ; \tag{1.3}$$

$$E = K_e . \Phi . \omega_m ; \tag{1.4}$$

$$T = K_e . \Phi . I_a ; \tag{1.5}$$

Where,

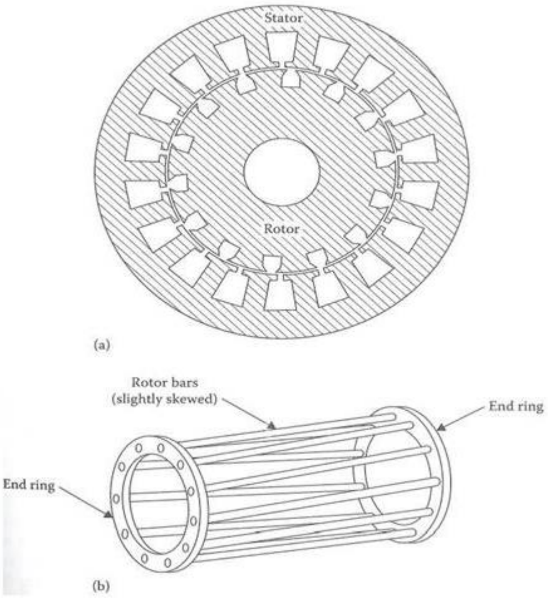
V_a = DC supply voltage (volts) ; φ = flux per pole (webers); E = emf(volts),
T = torque (N m); Ra = armature resistance(ohms); I_a = armature current(amps);
ω_m = armature speed (rad/s); K_e = constant.

3.2 Induction Machines:

One of the basic and widely used AC machine in majority of drive and non-drive applications today due to its relatively low cost, lesser maintenance, ruggedness and good operating characteristics matching up wide variety of load's characteristics. (5) The concept of IM comes way back from Serbian-American genius, Nikola Tesla sometime before 1889 (6). Ratings of IM varies from fractional hp(horse powers) to about 40,000 hp. Application of IM varies from domestic applications to heavy industrial application, including EV propulsion (5). In drive technology, using power electronic converters wide speed range operation can be obtained, and thus it is one of the most favoured machine for the electric propulsion. Although, latest technologies like brushless DC machine and Permanent Magnet machines are being favoured by latest vehicle manufacturers but still IM has its position maintained. (6)

IM can be comes with two main variant of *single phase IM* and *three phase Induction machine*. Heavy load application (above 5hp) incorporates *three phase IM* (5). In general, IM consist of stator and rotor as in DC Machine but with the difference that IM is singly –fed electrical machine, i.e. only supply is required to the stator, and torque is generated by the interaction of rotor and stator. Keep note that *three phase IM* is self-starting but *single-phase IM* is not self-starting. Different methods are adopted to aid the *single phase IM* for self-starting. In IM, stator winding is provided with alternating current (AC) which produces in rotating magnetic field. This rotating field induces currents in the closed loops of the conducting material in the rotor. (5) Evidently, this induced current produces rotating magnetic field of its own, which produces torque when interacted with the stator magnetic field. As the rotor current is induced thus no external contact to source is required (*singly-fed machine*) result into lower losses compared to DC machine and higher efficiency.

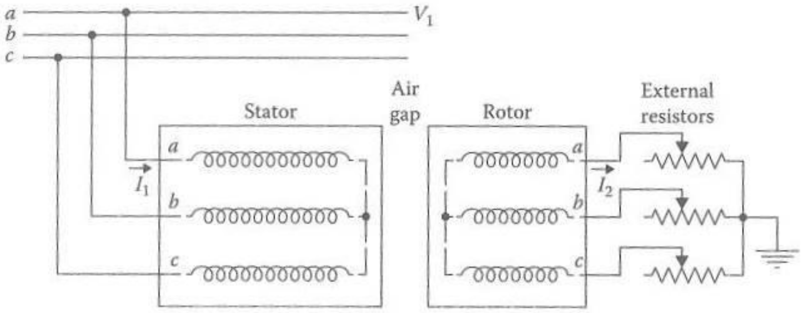
According to the rotor construction IM can be divided into two categories; *Squirrel Cage IM* and *Wound Rotor IM*.



Cross-sectional view of (a) IM with wound rotor and (b) with squirrel cage rotor

Figure 16: Construction of Induction Machine

(5)

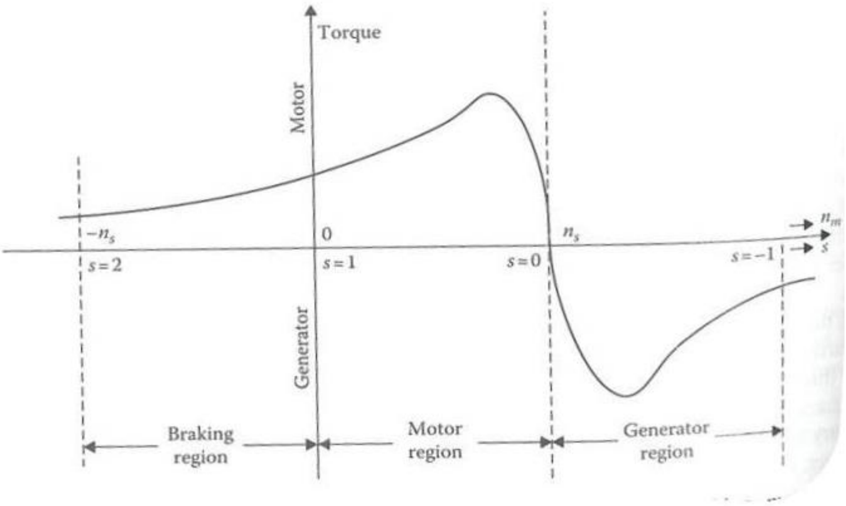


Circuit representation of wound rotor IM with external resistors

Figure 17: Schematic of external resistor in wound rotor IM

(5)

The IM can have starting current (inrush current) up to 4 to 7 times the rated current in the case of medium- large induction motor and these value can be as high as 10-12 times for smaller motors. (7). Typical characteristic of IM is shown below;



IM's torque-speed characteristic curve

Figure 18: Tourque-speed characteristics of Induction Machine

(5)

From shown figure above it is apparent that the torque-speed characteristic is divided into three regions or modes namely *generator mode, motor mode, and braking mode*. In *motor mode*, IM's operating speed is less than it synchronous speed and in *generator mode* operating speed is slightly higher than the synchronous speed. In addition to it, it requires magnetizing power reactive power from the system to provide power. IM needs lagging power from the source and thus operates at the lower *power factor (about 0.85)* because machine cannot produce its own excitation. *Braking mode*, the three phase induction motor running at operating speed in steady state brought to standstill by interchanging the two winding connection of the motor, resulting into reversal of *phase sequence* leading to opposite torque experienced by the running motor. When the motor comes to zero rotational speed electrical power input is removed in order to prevent motor to run in the opposite direction. This method of braking is called as *Plugging Braking.* (5).

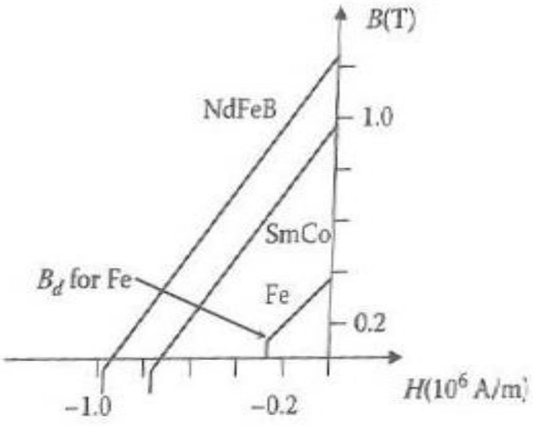
For variable speed applications such as in EV, the torque-speed characteristics are very important to dimension machine. It determines the bulk of machine and rating of the power electronic converter used. In EV application, high torque in low speed region and wide constant power region is required (usually 3-4 times the base speed or more). (7)

3.3 Permanent Magnet Machines

Permanent Magnet (PM) machines are the machine which employs permanent magnet to produce air-gap magnetic flux instead of field coils as in DC machines or magnetizing component in IM. Apparently, since there is no need to maintain any excitation thus no rotor current which results in no rotor copper losses. PM machines can be majorly categorize as, *Permanent Magnet Synchronous Machine (PMSM)* and *Permanent Magnet Brushless DC Machine (PM BLDC).*

The PM machines now a days are being preferred in the hybrid and electrical vehicles by the manufacturers since it has significant advantages over the conventional machines such as IM and DC machine, or Synchronous machines. Since, we already know that using excitation winding in machine always comes with the *excitation penalty* (8). The initial cost of the PM machines can be high but when we talk about the small motors for vehicular application, using of excitation winding can be complex and undergo losses. In addition to this, the field winding's current will lead to the deterioration of the winding which means increase of maintenance cost. Also, absence of excitation winding facilitates compact arrangement of the PM machines in the vehicle. On the other hand for the heavier machines excitation penalty is more economical as compared to the initial cost of PM machine. (8)

Discussion of PM machines is incomplete without discussing permanent magnets incorporated in PM machines. The main purpose of permanent magnet is to provide constant *mmf*, as a constant current source (8). The magnetic flux density remains constant as long as operating point is under the linear region, but as soon as operating point goes beyond, *knee-point* (B_d) of the characteristics, some of the characteristic is lost permanently. When the demagnetizing field is removed beyond the limit, new characteristic will exist but lesser than last characteristics. But most PMs are designed to withstand considerable magnitude of current (up to 2-4 times the rated current). Some of the permanent magnets are enlisted and discussed below;



Characteristics of discussed permanent magnets

Figure 19: BH curve of permanent magnets

<u>3.3.1 Ferrities</u> (8)

- → They have low cost
- → Residual flux density(B_r) at 0.3-0.4T, insufficient as per desired range of air gap flux density
- → High resistivity and low core losses
- → Operating temperature up to 100°C
- → *knee point* (B_d) is higher for ferrites having higher (B_r)

- → As B_d and B_r are inversely and directly proportional to temperature respectively.

3.3.2 Samarium Cobalt (8)

- → Higher B_r in the range of 0.8 – 1.1 T
- → B_d is in third quadrant
- → Sensitivity increases toward demagnetization as the temperature increases
- → Resistivity (ρ) is 50 time higher than that of copper.
- → Higher cost, expensive rare earth metal

3.3.3 Neodymium-Iron_Boron: (8)

- → Developed in 1983 in Japan, encouraging PM motors
- → B_r is in the range of 1.1 – 1.25 T at room temperature. Adequate for producing 0.8-0.9T air gap flux density.
- → With per degree rise in temperature B_r decreases by 0.1%
- → B_d increases rapidly with rise in temperature which leads to limit the operating temperature by 100°C - 140°C (depends upon detailed compostion)
- → Cost of sintered NdFeB is currently high because of manufacturing complexity but may reduce in future with increase of volume of Fe and B used. Since Neodymium(Nd) is relative higher in cost as compared to iron(Fe) and boron (B).

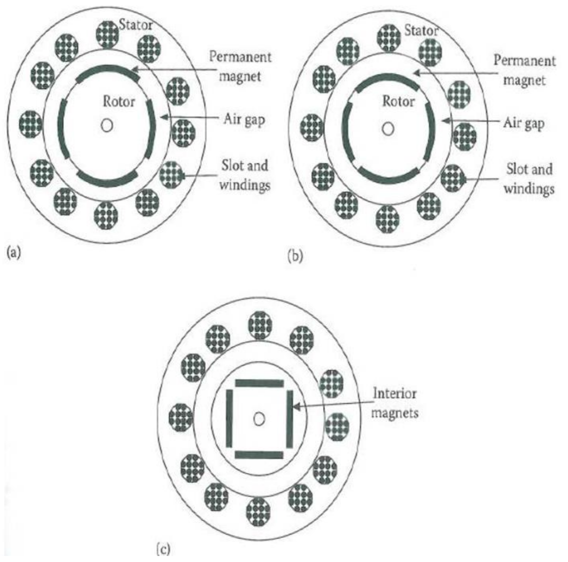
3.4 PM Synchronous Motors

Simply put, PM synchronous motor is a synchronous motor which produces sinusoidal mmf, voltage and current provided by the permanent magnets. PMs used in PMS motor ensure high flux density in air gap consequently increasing power density and torque to inertia ratio. Due to PMSM’s fast response, high power density, and high efficiency it found its application in high performance control application such as robotics and aerospace applications. The PMSM is fed from supply via power electronic converters with its smooth torque operation depends upon the shaping of current waveform. Field weakening mode is possible in PMSM by applying stator flux opposite to rotor flux. The speed is limited because of current rating, back-emf and maximum output of inverter. Although, PMSM and IM have good torque response but slip speed calculation makes IM more complex than that of PMSM. According to construction, PMSM has lower inertia due to absence of heavy rotor cage as in IM. Both IM and PMSM have limited field weakening range, a limitation.

PMSM has a higher temperature and load sensitivity which is the major drawback of PMSM, therefore, PMSMs are typically limited to low or medium power applications, however some of the high-power applications are employing PMSM.

PMSM has two main sections, rotor and stator, like in all rotating machines. Stator in incorporated with three phase sinusoidally distributed copper winding similar to AC machines winding. On the other hand Rotor, does not have any winding but permanent magnets are settled over the rotor instead. The three phase balanced supply is provided to the stator winding which in turn establishes a rotating mmf of constant amplitude in the air gap. The stator current is regulated by the position feedback of rotor in order to maintain the frequency in synchronism to the rotor. The interaction of these stator and rotor fields results in the torque development on the rotor. (8)

The PMSMs can be classified on the position and shape of the magnets on/in rotor. Illustrative figure of the PMSM types are provided below;



a) Face Mounted b) Inset c) Interior

Figure 20: Different arrangements of Permanent Magnets on Rotors

Face mounted and insets are also called surface-mount PMSMs. In inset the magnets are inside the rotor surface but exposed to air gap whereas in face mounted magnets are protruding. The magnets are attached to rotor by the help of epoxy glue. It implies that the ability to perform surface- mount PMSM during operation depends upon the adhesiveness of epoxy glue. But these types of PMSMs are easier and simpler to construct. In contrast to them, in interior PMSM, magnets are actually buried inside the rotor, thus mechanical strength is higher as compared to the previous ones. However this technology is costly and complicated. (8)

3.5 PM Brushless DC Motor

The PM AC machine having back-emf waveform in trapezoidal shape is PM BLDC machines. The shape of the waveform is due to the concentrated windings on stator of the machine instead of distributed winding as in the case of PMSMs. With the huge range of applications, PM BLDC machine can be used ranging from computer drives to medical equipment due to ease of controlling. Six discrete rotor positions are required per electrical revolution which is sensed by set of three *hall sensors* at 120° apart mounted on stator facing the magnetic wheel on the rotor. Thus, eliminating high resolution position sensors as in PMSMs. But due to this simplification, performance parameter of the PMSMs is higher than that of PM BLDC. Because of trapezoidal waveform the vector control is not possible in the PM BLDC machines. (8)

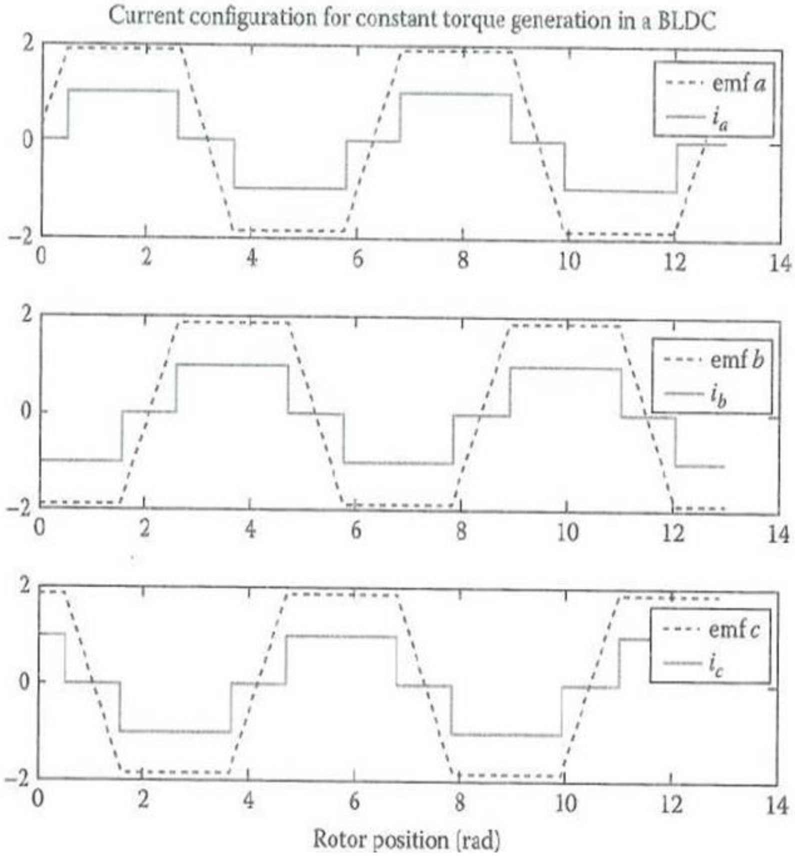
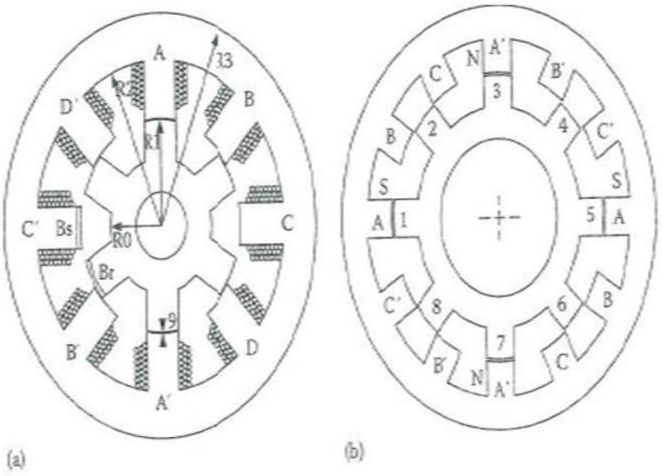


Figure 21 *Waveform of ideal PM BLDC machine with respect to rotor positions in radians.*

Square current waveforms are supplied so that they in synchronization with peak back –emf of respective phase. Rotor position feedback information is processed by the controller and thus motor behaves as DC motor, hence, motor is called as brushless DC motor.

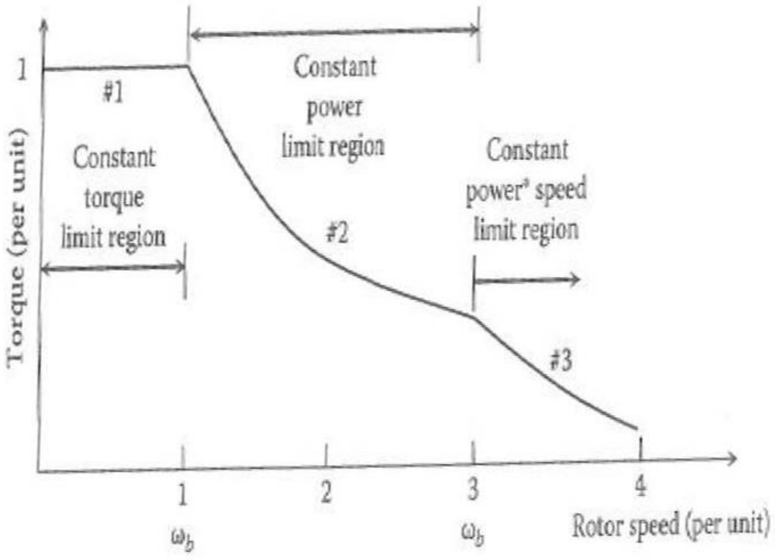
3.6 Switched Reluctance Machines

The main constructional feature of Switched Reluctance Motor (SRM) is its salient rotor and stator. SRM are singly excited with phase winding on the rotor. Both stator and rotor are laminated with rotor having neither winding nor magnets. The stator winding is connected to the diametrically opposite pole in series or parallel to make one phase.
When the stator is energized from the supply, the closest rotor pole pair is attracted towards the energized stator pole in order to minimize the reluctance. Evidently, constant torque can be developed by energizing the stator phase in either direction of rotation. The stator- rotor pole can be of various types. Below are shown the diagram of (a) four-phase, 8-6 SRM and (b) three phase, 12-8 machine.



Cross sectional areas of 3 phase Switched Reluctance machines
a) four-phase 8/6 structure
b) 12/8, two repetition (two channel) structure.

Figure 22: Switched reluctance motor



Torque-speed characteristics of SRM Drive

Figure 23: Torque vs Speed characteristics, SRM [**(8)**

Chapter 4

Vehicle Dynamics

Vehicle design's fundamentals are a direct implementation of Newton's second law of motion, which relates force and acceleration. The acceleration of vehicle is caused by the fact of presence of non-zero resultant force. This force to move the vehicle forward comes from the propulsion unit overcoming the resisting force imposed by gravity, and air and tire resistance. The road and aerodynamic condition along with power available from traction unit determines the acceleration and speed of the vehicle. In this chapter we will get into basic governing factors affecting the design of the vehicle focussing on electric.

The force from the propulsion unit is known as the tractive force. Once the force required is known, energy and power consumption can be calculated.

4.1 Centre of Gravity

According to newton's second law of motion,

$$\sum F_i = m \times a; \qquad (4.1)$$

Where,
F_i = net force,
m = mass,
a = acceleration.

As a complex conjunction of subsystems, there exist different individual masses at several points of contact of the vehicle with reference to outside world leading to be a bit complex task to analyse and calculate forces at each and every point of mass' contacts . Thus in order to simplify this problem we consider one location where all these point will merge and net force due to gravity can be realised. This location is known as *Centre of gravity* (COG) of the vehicle. For the calculation purpose, we shall consider vehicle to be a particle mass concentrated at the COG.

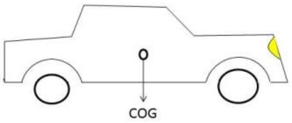


Figure 24: Center of Gravity

The motion of particle is defined by *acceleration* and *velocity* characteristics. let *x*, be the distance travelled by the particle and *v* be the velocity and *a* be the acceleration of the particle then the mathematical relation in these quantities are as follows,

$$\vec{v} = \frac{d\vec{x}}{dt}; \tag{4.2}$$

$$\vec{a} = \frac{d\vec{v}}{dt} \tag{4.3}$$

The input power *P* for the force *F*, to the particle mass is,

$$P = \vec{F}\,.\vec{v} = \left|\vec{F}\right| |\vec{v}|\, cos\theta \tag{4.4}$$

Where, θ is angle between *F* and *v*.

Torque *T* on the rigid body rotating about a fixed axis,

$$T = J \times \alpha\,; \tag{4.5}$$

Where, J = polar moment of inertia of the rigid body
α = angular acceleration (rad/ s^2)

Also,

$$\alpha = \frac{d\omega}{dt}; \tag{4.6}$$

$$\omega = \frac{d\theta}{dt}; \tag{4.7}$$

Where, ω = angular speed (rad / sec)
θ = angular displacement.

The relation between power input and torque input is important and is given below,

$$P = T \times \omega \tag{4.8}$$

4.2 Vehicle kinetics

The propulsion unit generates and exerts the *traction force* to the wheels to provide motion to the vehicle. In order to move vehicle, tractive force must overcome the opposing force acting on the vehicle. This opposing force is known as *road load force*, F_{RL}.

$$F_{RL} = F_{gxT} + F_{ROLL} + F_{AD}; \tag{4.9}$$

Where,
F_{gxT}=Gravitational force,
F_{ROLL} = Rolling resistance,
F_{AD} = Aerodynamic drag force,
xT is tangential direction on the roadway.

We will discuss these terms and, their cause and effect on the vehicle motion.

4.2.1 Force due to gravity

The force on vehicle due to gravity is a function of slope of the road, the mathematical relation is given as follows,

$$F_{gxT} = m\, g\ \sin\beta\ ; \qquad (4.10)$$

Where,
m = mass of the vehicle,
g = acceleration due to gravity,
β = slope angle (grade angle) with respect to horizon.

4.2.2 Rolling Resistance Force

Coming to the rolling resistance, F_{ROLL}, is produced when the deformation of vehicles' tire takes place when in contact with road surface. Resistance due to flattening (deformation) of tires plays a significant role in the vehicle dynamics and thorough understanding is required. Considering tire with perfect circular shape in contact with the road surface, the reaction force of the ground on the tire in directly under the wheel axle with no net force to cause any motion. But ideally, tires are not circular but are a bit flat at the point of the contact. Therefore, when the vehicle moves forward it results into misalignment of the weight on the wheel and road normal force. This misalignment leads to couple forces exerting retarding torque on the wheels. This retarding force couple is known as rolling resistance force, F_{ROLL}.. In order to keep FROLL minimum, tires should be inflated as much as possible.

$$F_{roll} = C_{rr} * m * g \qquad (4.11)$$

Where,

C_{rr} = coefficient of rolling resistance, (~ 0.01 to 0.035, for tires on road) (9)

m = mass of vehicle
g = acceleration due to gravity

4.2.3 Aerodynamic Drag:

The resistance offered by the air in the atmosphere while vehicle travelling through it is known as Aerodynamic drag. It can be of two types, drag due to frontal area (shape) and skin friction at the surface of the body. Aerodynamic drag exerts opposite force due to creation of two pressure zones as vehicle moves into the air. The high pressure zone is created in the front of the vehicle and low pressure area behind the vehicle . These couple of pressure zones exerts force against the motion of the vehicle. The skin friction is caused due to interaction of moving air with the external body part. The major part of aerodynamic drag is being played by the shape drag when compared to the skin friction of almost 90% of total dynamic drag experienced by the vehicle. Mathematical relation of the aerodynamic drag is mentioned below,

$$F_{AD} = \frac{1}{2} \rho A C_d (V + V_w)^2 ; \quad (4.12)$$

Where,
ρ = air density,
A = frontal area,
C_d = aerodynamic drag coefficient, (depends upon design of the vehicle)
V = vehicle longitudinal speed,
V_w = wind speed

4.3 Propulsion power

Using Internal Combustion engine for propulsion does come with its pros and cons. Major advantage is it power to weight ratio but it has disadvantage. Apart from emission, speed-torque characteristics of the IC engine do not correlate with required characteristics of the traction.

To size the electric traction motor in the vehicle, parameters such as starting acceleration, vehicle rated and maximum velocity, and vehicle gradeability are to be considered. The requirement of energy drawn from the propulsion unit (IC + Batteries) can be calculated by the equations. The torque at the wheel will be,

$$P = T_{TR} . \omega_{wh} = F_{TR} . v_{xt}; \quad (4.13)$$

Where,
T_{TR} = Tractive torque (N m)
ω_{wh} = angular velocity of the wheel (rad/ s),
F_{TR} = Tractive power (Newton),
v_{xt} =velocity (m/s).

The following relation gives relation between angular velocity of wheel and vehicle speed,

$$v_{xt} = \omega_{wh} . r_{wh}; \quad (4.14)$$

Where, r_{wh} = radius of the wheel (m).

One of the biggest advantages of the electric propulsion over the conventional IC engine is elimination of the multiple gear system coupled in order to match vehicle speed and engine speed. Only a single gear-ratio transmission system can match the available motor torque with desired tractive torque instantaneously. The elimination of multiple gear system from the vehicle is being possible by electric motor's wide speed range operation by the help of power electronic semiconductor drives. The ratio and size of gear system is determined by,

- Maximum motor speed

- Maximum vehicle speed
- Wheel radius

Higher motor speed with relation to the vehicle speed implies higher gear ratio, larger size and resulting into higher cost. However, higher motor speed is desired to increase power density of it.

4.4 Maximum Gradeability

The characteristic trait of vehicle which measures ability of vehicle to climb the maximum grade from standstill when all of its wheel are on the slope(grade) when the maximum force is available from the propulsion unit. It is an important performance characteristic of the vehicle. On the maximum grade, the vehicle is expected to be in very slow motion, thus assumptions for maximum gradeability:

1. $v \cong 0$; as vehicle will be very slow.
2. $\frac{dv}{dt} = 0$; as vehicle is not accelerating.
3. $F_{TR}$is the peak force delivered by motor/s at nearly zero speed.
4. F_{AD} &$F_{roll} \cong 0$.

After constituting above assumptions in the equation at velocity V ≅ 0,

$$F = F_{TR} - F_{gxT} = 0; \qquad (4.15)$$

$$F_{TR} = F_{gxT} = mg\sin\beta\,; \qquad (4.16)$$

Chapter 5

Electric Power Source

In this chapter we will go through primary power source employed in our model to provide the required traction power to the vehicle. The two main energy sources and storage used in this work are, Electrochemical batteries and Ultracapacitor (also known as Supercapacitor). We will discuss about these components in terms of their construction, working and significance in the model.

5.1 Electrochemical Sources

Also known as *electric batteries* in general, are made by connecting individual *cells* in order to get a specific standard voltage at their terminals. Batteries are energy devices which converts chemical energy to electrical energy, hence the name Electrochemical device. Batteries now a days plays an important role in as an energy producing source as well as energy storage devices.

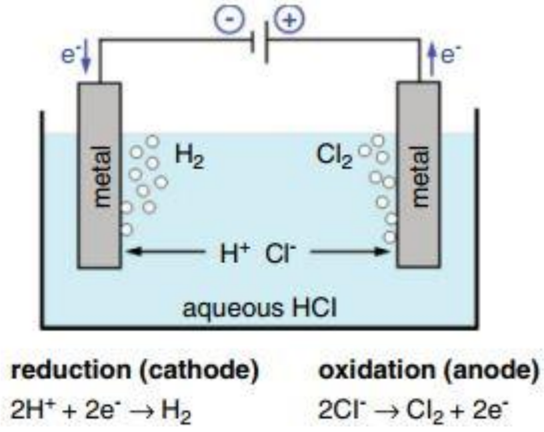
As mentioned before, batteries are primarily made up of individual cells by a suitable connection, therefore we will now focus on the cells to have further understanding of batteries.

5.1.1 Electrochemical Cells

Electrochemical cells or cells, are primarily a separation of electrodes, one is positive and another negative, filled with electrolyte (must be ionically conductive and electronically insulating) and separated by separator. The voltage produced by a cell is governed by chemical reaction going inside the cell in between the electrodes, facilitated by the electrolyte. We can consider electrochemical cells in two types, *Electrolytic cells* and *Galvanic cells*. When chemical energy converted to electrical energy, then it is known as *galvanic cell* and when electrical is converted to chemical energy then it is called as *electrolytic cell.* Hence, we can say that electrochemical cell works in two different modes, while charging it is *electrolytic cell* and while discharging it becomes *galvanic cell.* (10)

During discharging, electrolytic cell operation, oxidation or release of electron occurs at the anode while charging, reduction or electron is absorbed on the anode. On the cathode opposite occurs, reduction or electron is absorbed at the cathode while discharging and while charging oxidation or reduction of electro occurs. As it can lead to confusion that both electrodes are undergoing both anodic and cathodic reaction depending on if cell is in under charging mode or discharging mode. Thus in order to avoid any confusion, negative electrode is referred as *anode,* and positive electrode is termed as *cathode,* and it is widely accepted. Considering electrolytic cell, electrons are absorbed at the negative electrode and released at positive electrode. Thus it is apparent that there reduction going on negative electrode and oxidation going on positive electrode, due to result of chemical reaction interaction at both electrodes. These chemical reactions are known as half reactions, when combined leads to the total cell reaction, i.e. *redox* reaction, by virtue of which our cell works.

Considering an simple example of HCL electrolytic cell,



(10)

Figure 25: Simple electrolytic cell

The figure above demonstrates decomposition of dilute HCl into Hydrogen and Oxygen, also we can see that reduction is going on cathode and oxidation is going on anode. The reactions at anode and cathode are the reactions referred as half reactions, and adding both equations we get cell equation which in this case would be,

$$2HCl = Cl_2 + H_2 \qquad (5.1)$$

;

5.1.2 Electrical Equivalent Circuit:

Out of different method to model electrochemical cell, electrical equivalent modelling is the most convenient. It is relatively simple as compared to other model such as electrochemical model and also easy to understand.

Equivalent circuit diagram is mentioned following, Ideal and Practical representation

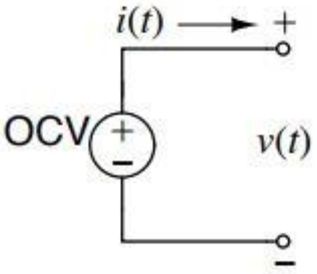


Figure 26: equivalent circuit of ideal cell

Properties of an ideal cell;

- OCV, open circuit voltage is not a function of current
- Voltage is not a function of past usage
- Voltage is constant throughout its life time. (11)

As we know that ideal cell does not exist in real world. Every cell will have an internal resistance, which can explain of battery's rise in temperature when loaded (12).

In addition to it, battery model also consists of a parallel connected resistance and capacitance in addition to the internal resistance to show the transient nature of battery. In order to improve accuracy of the practical model, we can add more parallel connection of resistance and capacitance. But in general modelling, accuracy obtained by single parallel branch is sufficient. (13) (11)

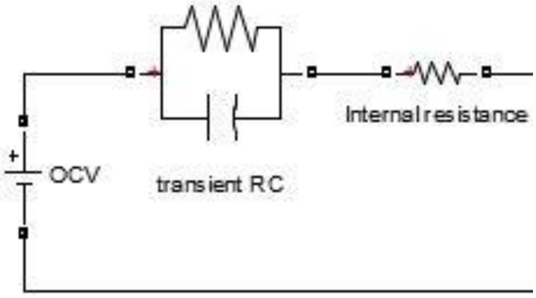


Figure 27: practical quivalent diagram of cell

(13)

With the introduction of electric cell, we will move to the technical parameters and characteristic of the cell which plays a vital role in selecting right battery source of specific application.

5.1.3 Practical Cell Measures

As we did learnt about cells, both ideal and practical, now we can further study about cell under load. The discharge curve of lead acid cell is shown below,

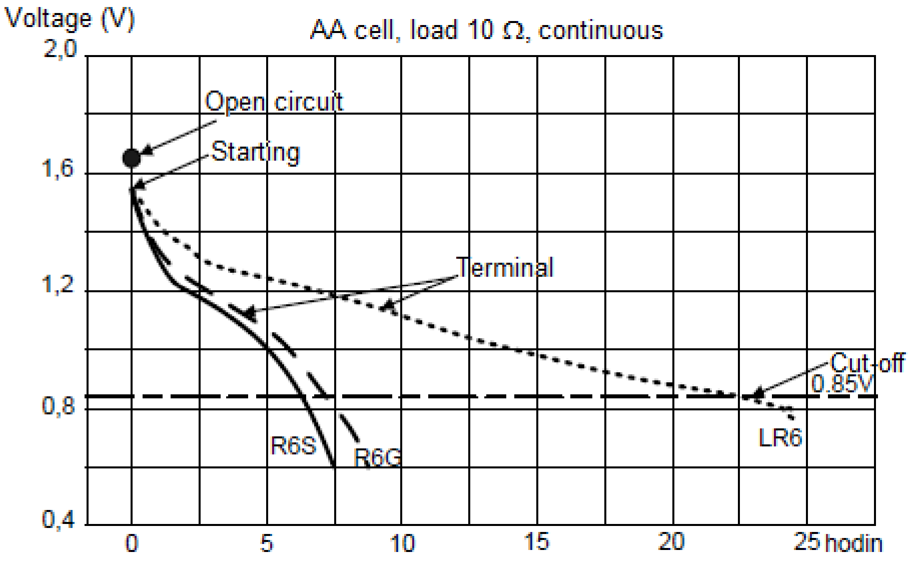


Figure 28: General discharge characteristics of a Lead acid cell **(14)**

The cell properties which are of our interest are as follows;

1. Terminal Cell Voltage: The voltage measured across the terminals of cell is known as cell voltage when the cell is applied to any application with certain load. Thus, Open circuit voltage is higher than the nominal cell voltage (15). It is because during discharge, as the chemical energy is transformed into electrical energy the open circuit voltage also drops to the nominal voltage due to the losses in cell. *Polarisation* or *overpotential* occurs when a load current is passing through the cell. The dominant cause of loss in the cell is due to *internal resistance* resulting into *ohmic* losses In addition to it, causes voltage drop, when load current is passed through during discharge which is referred as *ohmic polarisation*, which is directly proportional to discharge current applied. (15) (16)
2. Cut-off voltage: Voltage level at the terminals of the battery at which battery is said to be empty or zero state of charge. And prohibited to use in the application in order to prevent permanent loss in *capacity* of the battery. (14)
3. State of Charge (SOC): It is a percentage of instantaneous battery capacity left out of total battery capacity. SOC can be calculated by integrating battery current over a period of time. (14) (16)

4. Depth of Discharge (DOD): the percentage of battery capacity discharged in the terms of total capacity is known as depth of discharge. Generally, DOD can be related to SOC as follows;

   $\text{DOD} = 1 - \text{SOC}$; (when expressed in fraction) (11)
5. Capacity: Also known as coulometric capacity, absolute *Ah (ampere hours)* available at a certain *C-rate*, when battery goes from 100% *SOC (state of charge)* to 0% *SOC.* (16)
6. Charge and discharge rates: The charging and discharging of the battery is termed as C-rate. The discharge and charge rate depends upon the electrochemical reaction and movement of ion in the electrolyte of cell. Also, it depends upon internal resistance of cell.

   As we change our discharge and charge rate, other parameters such as *State of Charge (SOC), lifetime period, life cycle*, etc.

   Charge and discharge rate is governed by the *C-Rate*. The *capacity* of the battery is rated as 1C, which implies that fully charged battery of 1Ah rating is going to deliver 1 Ampere for 1 Hour. Following the table below, meaning of C-rate can be comfortably understood. (17) (16)

C-Rate	Time
5C	12 mins
2C	30 mins
1C	1 hour
0.5C or C/2	2 hours
0.1C or C/10	5 hours

Table 1: Discharge times at different at different C-Rates

7. Battery lifetime: the time when battery is unable to meet 80% of rated capacity after certain number of charge and discharge cycles. Conditions like rate of discharge, depth of discharge, temperature, humidity, etc. are responsible for determining battery operating life. (14)
8. Specific Energy: Specific energy depends upon the battery chemistry and packaging. It is primarily ratio of energy battery holds to the total weight of the vehicle with unit of

Watt-hour/kg. It is one of most vital information, as it is used to determine the size of battery required to go up to a certain range. (16)

9. Specific Power: Specific power also depends upon chemistry and packaging. It is defined by the ratio of available maximum power over the mass. Specific power has a unit of *watt/kg*. It is vital to know about the battery capability to deliver power to meet high power application, such as start, acceleration and climbing a slope (16).
10. Energy Density: The battery energy per unit volume is known as energy density. It is required to determine the range of vehicle. Its unit is *watt-hour/L.* (16)
11. Power Density: It is the maximum available power per volume of battery. Its unit is *watt/kg*. (16)

5.1.4 Classification of Batteries:

5.1.4.1 Primary and Secondary cells/batteries: Primary cells/ batteries are the electrochemical devices which can operate as *galvanic cell*s i.e. only chemical energy can be converted to electrical energy, but vice versa is not possible due to irreversible chemical reaction involved in such cell types. Common examples of primary galvanic cells are, *Dry cell, Zn-HgO, Zn-*Ag_2O *cells*. These type of cells are preferred to be in small applications, such as wrist watches, small flashlights etc. Secondary cells/ batteries/ accumulators are the electrochemical devices which can work as *electrolytic* and *galvanic cells,* while charging and discharging respectively. It means that accumulators are rechargeable and can be used for several cycles and have much more application scope as compared to the primary cell. Primary application includes, *UPS(uninterrupted power supply),* Automotive applications, etc. Accumulators are rechargeable due to the reversible chemical reaction involved, that means when the direction of current reverse, the decomposition of electrodes are reversed as well so that it can be used once again as new accumulator when it is recharged again. There is a long list of accumulator's application areas but in this document our primary application will be automotive with the focus on *traction batteries* for EVs. Some of the primary example (14) of the secondary vehicles are *Lead acid battery, Ni based batteries, Lithium ion batteries, Li-Pol and flow batteries etc.*

5.1.4.2 Based upon electrode materials: Based upon electrode material, with respect to EV application, there are majorly 5 types of accumulators available.

a) Lead Acid Accumulator: Being in existence from approx. last 140 years, it is one of the most widely used technologies in automotive technology; in order to provide electric power to the starter motors. (14) (15)

Negative electrode: Lead metal plate (Pb)
Positive electrode: Lead dioxide grid (PbO_2)
Electrolyte: Sulphuric acid (H_2SO_4).

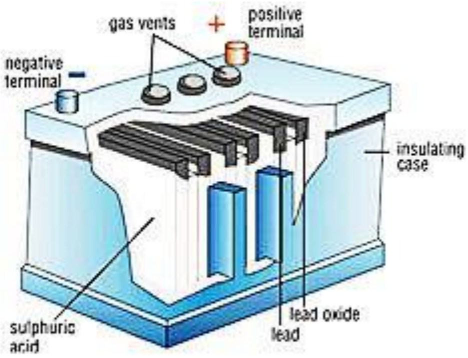


Figure 29: Construction of Lead Acid battery (18)

1. Lead acid practical construction can be observed from the above figure.

Oxidation : $Pb + HSO_4^- \rightarrow PbSO_4 + H^+ + 2\,e^-$

Reduction : $PbO_2 + HSO_4^- + 3H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O$

Overall reaction :$PbO_2 + Pb + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$ (15) (14)

During discharge of cell, Pb is oxidised and PbO_2 is reduced. When fully discharge, both electrode will have $PbSO_4$ along with the decrease in concentration of sulphuric acid due to production of water as can be observed from the overall reaction mentioned above. The lead cell has a nominal voltage of 2.0 volt, and standard pack battery with 6 serially connected cells should have 12volts. During discharging , battery pack mentioned above should not be discharged below 10.5, due to creation of crystal $PbSO_4$ which can't be reconverted into original active materials during electrolytic cell mode, or while charging. In addition to it, 12 volt battery pack should not be charged over 14.1 volts to avoid rapid creation of gasses. The overvoltage at which gassing starts is referred as *Gassing voltage.* (14)

Discharge behaviour:

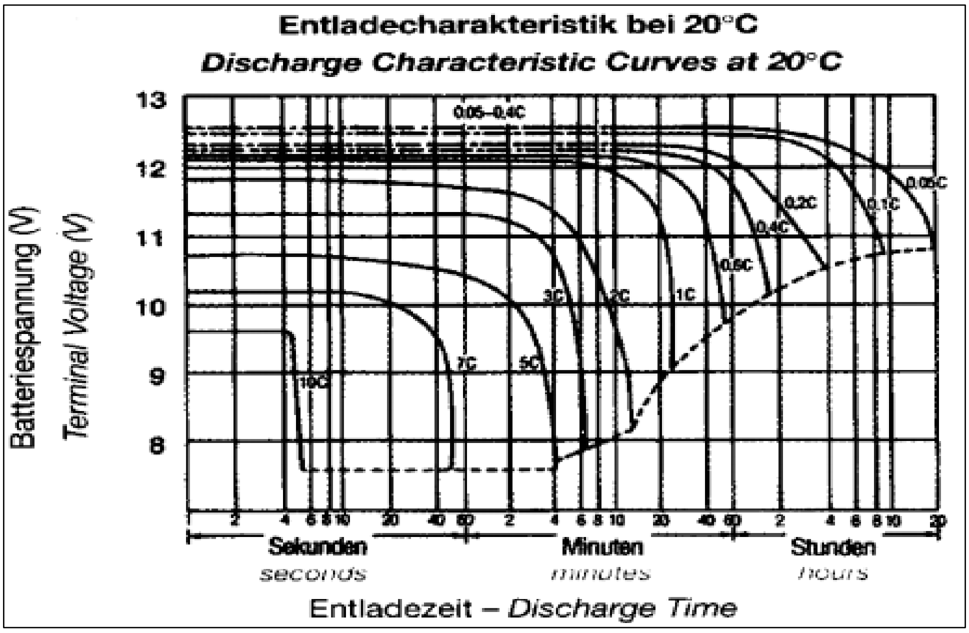


Figure 30: Discharge of Pb acid battery (14)

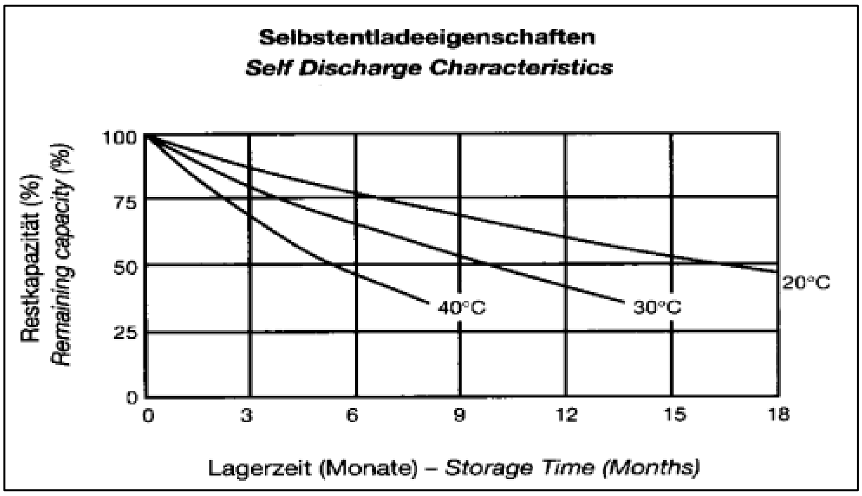


Figure 31: Capacity vs time **(14)**

Charge behaviour:

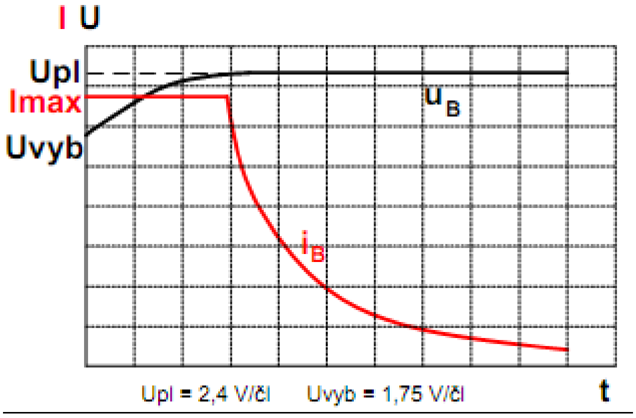


Figure 32: Charging of Lead acid battery (14)

b) Nickel Based Accumulators:

There are three well known *Ni based* accumulators, namely Nickel Zinc (NiZn), Nickel Cadmium (NiCd) and Ni metal hydride (NiMh) accumulator.

In general, Ni based accumulators have positive electrode as Ni, and negative electrode depends upon type of accumulator being considered, e.g. for NiCd battery, Positive electrode will be made out of *Nickel(Ni)* and negative electrode will be made of *Cadmium (Cd). NiZn batteries* have higher *nominal voltage* as compared to *NiCd* and *NiMH* variant of the nickel based battery. (14)

Referring to the table below, we can observe that current battery technology, are mostly using NiMH variant of *Ni-based* battery. In this chapter we will follow *NiMH* battery than other two, but in the table at the end, electrical parameters will be mention as well. (15) (14)

NiMH batteries:

Chemical reactions

Positive electrode material and reaction: Nickel Oxyhydroxide (NiOOH)

$$NiO(OH) + H_2O + e^- \leftrightarrow Ni(OH)_2 + OH^-$$

Negative electrode material and reaction: Metal alloy (M) (able to absorb hydrogen, which is an active material during the charging).

$$OH^- + MH \leftrightarrow H_2O + M + e^-$$

Overall reaction:

$$NiO(OH) + +MH \leftrightarrow Ni(OH)_2 + M$$

Electrolyte: Potassium hydroxide (KOH)

Separator: Porous fiberglass cloth (15)

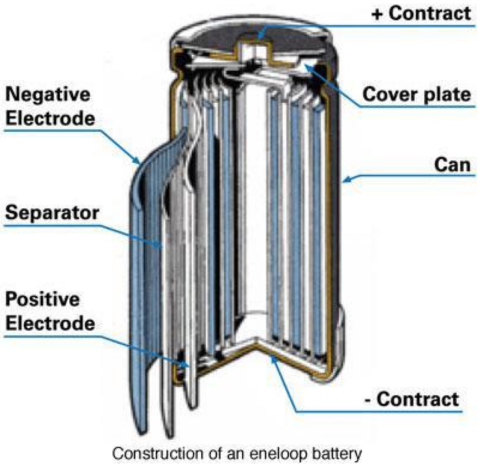


Figure 33: Contruction of coiled Ni-based battery **(14)**

During discharging, H^+ ions are extracted from metal M, when react with OH^- from electrolyte and forms water (H_2O). And during charging, H^+ ions are absorbed into metal alloy as can be observed in the reaction. Just the other way around!

Company	**Country**	**Vehicle Model**	**Battery Technology**
General Motors	USA	Chevy Volt	Li-ion
		Saturn Vue Hybrid	NiMH
Ford	USA	Escape, Fusion	NiMH
		Escape PHEV	Li-ion
Toyota	Japan	Prius	NiMH
		Lexus	NiMH
Honda	Japan	Civic	NiMH
		Insight	NiMH
BMW	Germany	X6	NiMH
Dialmer Benz	Germany	Smart EV(2010)	Li-ion
Mitsuibishi	Japan	iMiEV	Li-ion

Nissan	Japan	Leaf EV (2010)	Li-ion
Tesla	USA	Roadster	Li-ion

Table 2: Battery technologies used in Vehicles

(19)

The nominal voltage is about 1.2 volts, mostly produced in the coil designed. It can experience capacity loss *similar* to *memory effect* as in the case of NiCd batteries. According to *memory effect*, there is a reversible loss in capacity if the cell is charged after being partially discharge. We can say that cell remembers capacity during the last discharge and limit charging to about same amount of capacity. (15)

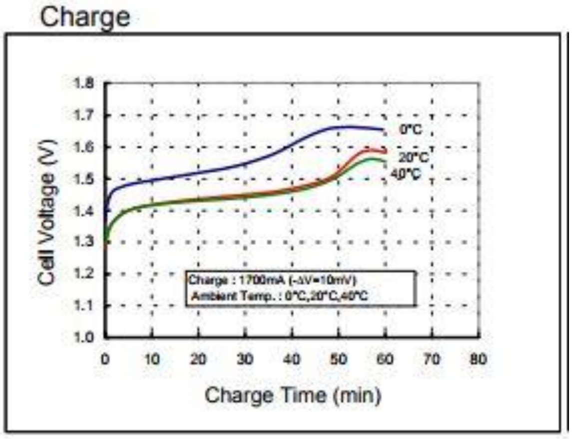


Figure 34:Charge characteristics: HR-AAU (Ni) **(20)**

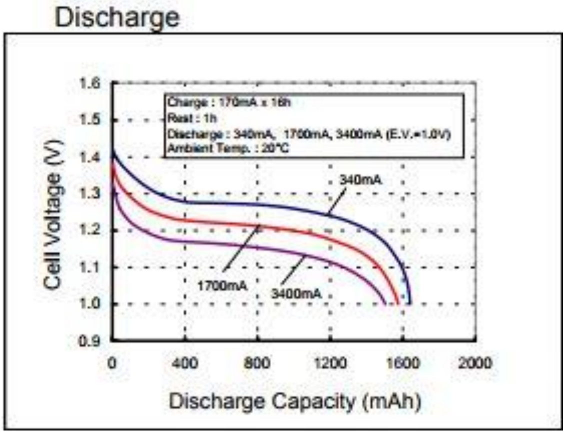


Figure 35: Discharge characteristics: HR-AAU (Ni) **(20)**

Although, it is not in the case of NiMH battery because memory effect happens due to structural change in *Cadmium (Cd)* and NiMH battery doesn't employ Cd anyway. There is a voltage depression observed in the *NiMH* in relation to capacity loss. It is due to overcharging for longer period and also may occur when cell is being repetitively partially charged. With a slight loss of capacity there will be a significant loss in voltage. It is due to NiOOH electrode, which is an issue with all *Ni-based* technology. (15)

c). Lithium –Ion battery

Lithium being lightest metal present (0.54 kg/dm^3) with low electrochemical potential of about $-3.04\ V\ vs \frac{H_2}{H^+}$, makes it most reactive metals. In addition, lithium have a very low radius of about (0.76 angstroms). Being small in radius, lithium can be easily accommodated into different host material results into achieving high energy and high power density. (15) (14)

Some of the lithium-ion battery type based upon *negative electrode* is being discussed following,

- Lithium – cobalt dioxide ($LiCoO_2$)
- Lithium- ion-managnese ($LiMn_2O_4$)
- Lithium- nickel-manganese-cobalt oxide ($LiNiMnCoO_2$)
- Lithium-iron-phosphate ($LiFePO_4$) (15)

Positive electrode of Li-ion batteries are mainly composed if graphite or hard carbon. (21) (14)

Electrolyte: Lithium tetrafluoroborate ($LiBF_4$) or $LiPF_6$ (22)

Separator: Microporous polyolefin materials

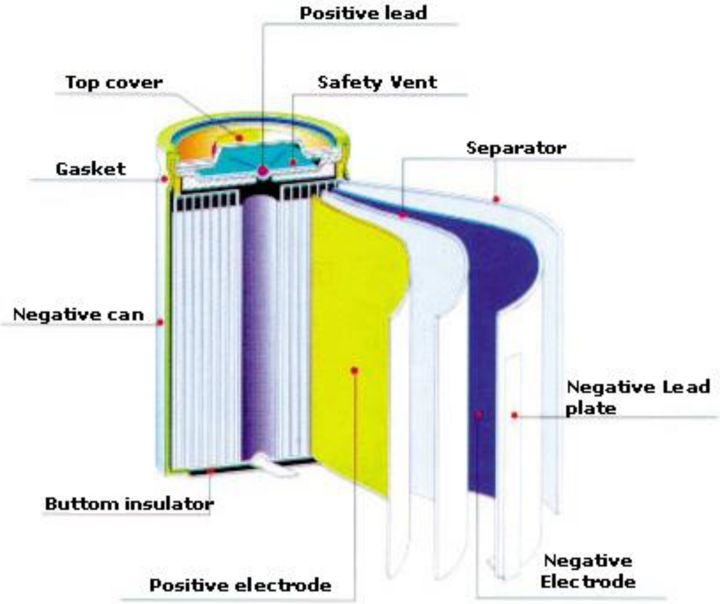


Figure 36:Li-ion battery construction **(23)**

Li-ion battery shows high nominal voltage around 4.0 V/cell, different for different variant of Li-ion battery. Some of them are being compared in the table below,

Cell Parameters	Type of Li -Ion cell		
	$LiCoO_2$	$LiMn_2O_4$	$LiFePO_4$
Nominal Voltage / cell	3.6 - 3.7	3.6 - 3.7	3.2-3.3
End Charging Volt / cell	4.2	4.35	4.25
End discharging Volt / cell	2.75	2.2	2.5
Charging Current(max)	0.3-0.5 CA	0.3-1CA	0.3-3CA
Discharging Current (max)	2-5CA	5CA	3CA (10CA Pulse)
Service life	80% DOD - 1000cycles	80% DOD -300 cycles	80% DOD -2000 cycles
Self-discharging	2% / month	3% / month	3% / month
Operating temp (°C)	(-20 to 75)	(-25 to 75)	(-25 to 75)

(14)

<u>Charging and Discharging Characteristics</u>: The figure below illustrates charging and discharging characteristics, and behaviour of electrical parameters while undergoing the process.

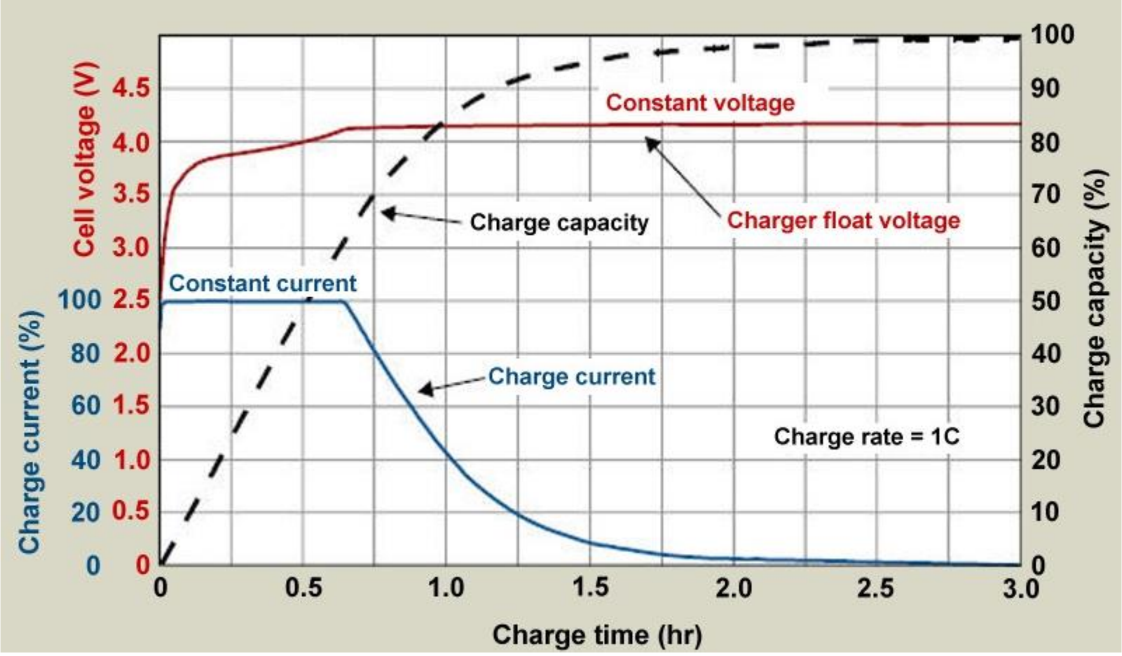


Figure 37: General charging characteristic **(24)**

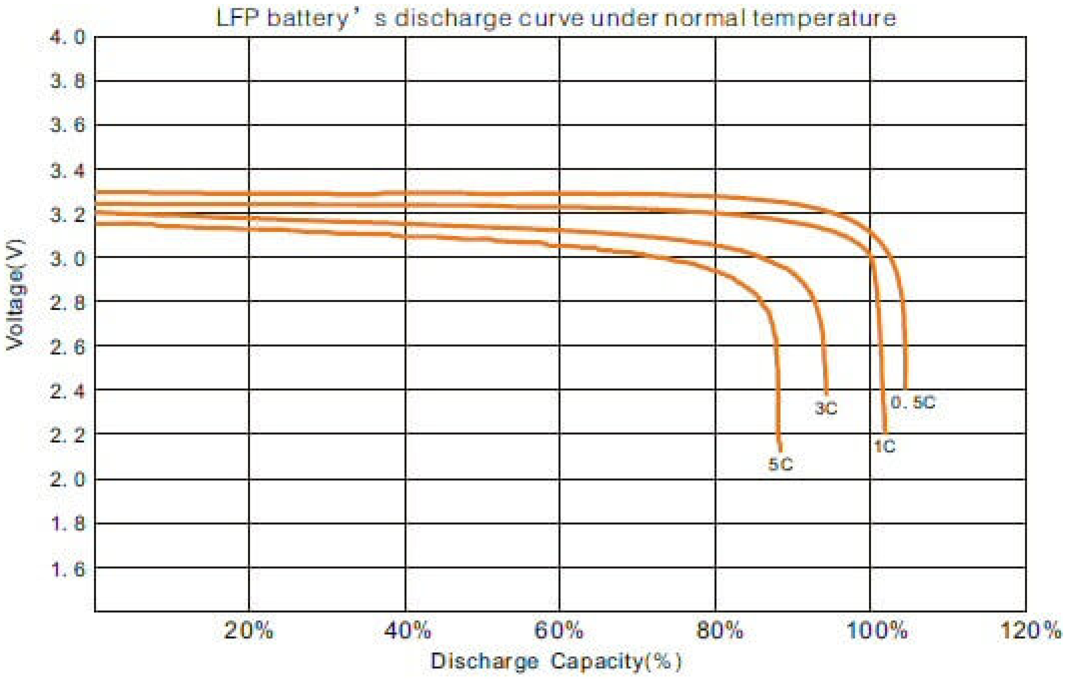


Figure 38: Lithium discharge curve **(25)**

Lithium Ion polymer battery is also similar to the Li-ion battery with the exception of nature of electrolyte. In *Li-ion* battery electrolyte employed is a *polymer matrix* in a gel or plasticised form. Absence of free liquid in electrolyte makes batteries more stable and less prone to issues caused due to overcharging of batteries. Due to this type of electrolyte, power capability of the cell is limited as compared to the *Li-ion* battery. (15)

Comparison of different battery technology cab observed and compared below,

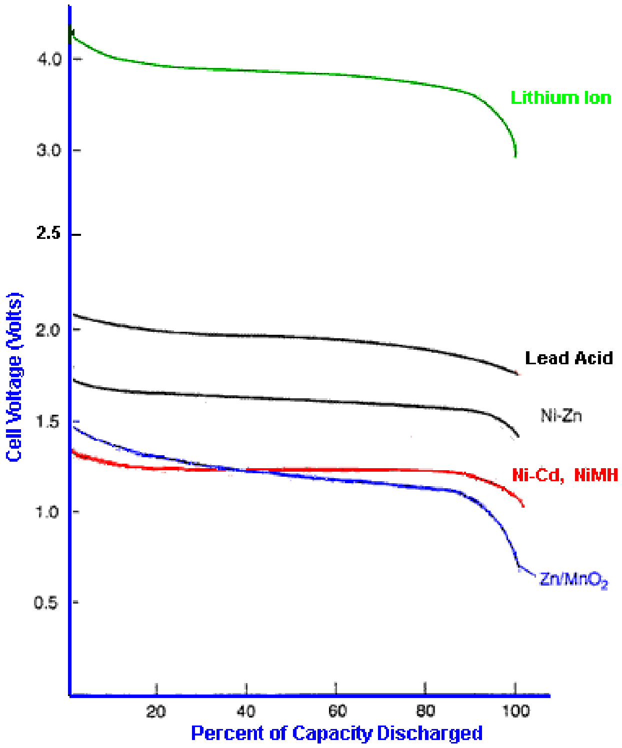


Figure 39:Comparison of different cell's dscharge characteristics **(26)**

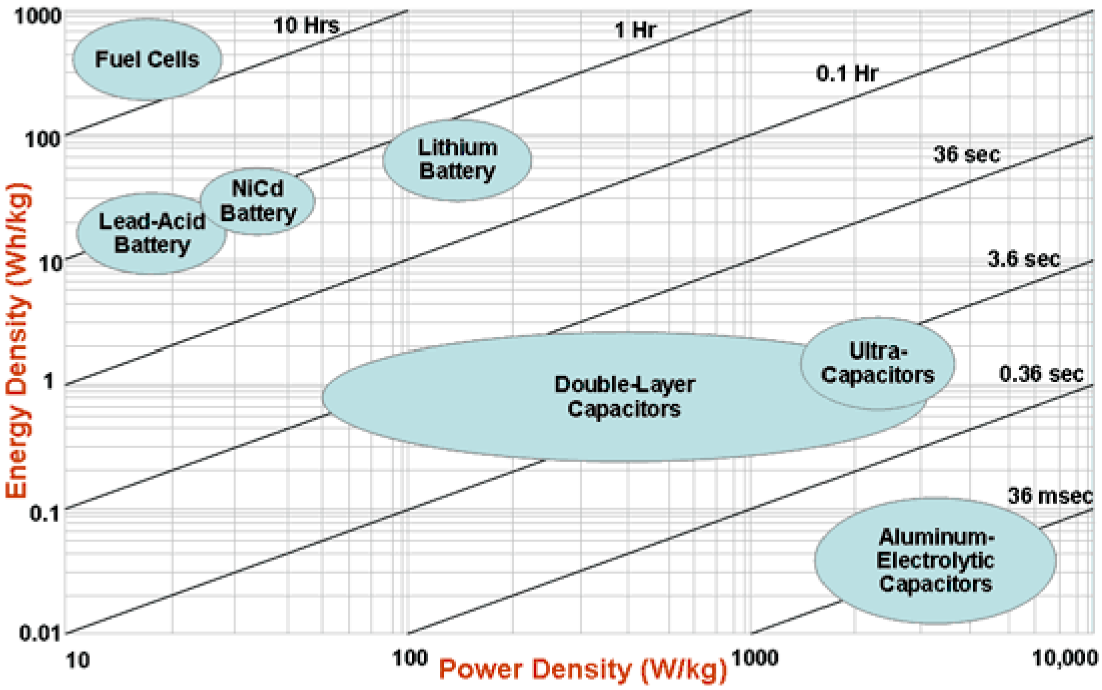


Figure 40: Energy density vs Power density characteristics (26)

3) 5.1.4.3 According to construction: The batteries can be also categorize on the basis of construction, which defines application areas as well. (14)

a) Flooded: Traditional home UPS system , traction battery, which have outlet to replenish distilled water during the lifetime as per need.
b) Sealed: Construction is similar to the flooded with the exception of battery being sealed with sufficient amount of electrolyte for it whole lifetime. Thus eliminating the need of addition to electrolyte.
c) VRLA: *Valve regultaedLead Acid*, also a type of sealed batetry. In this valves are present to provide a safe passage to the gas generated such as Hydrogen and Oxygen during process of charging.
d) AGM: *Absorbed Glass Matte*, a special construction of *valve regulated lead acid*, where electrolyte is suspended close to the active material
e) Gel: It same as *AGM,* just an addition of silica in lectrolyte to demoisturize it resulting into stiff electrolyte. (14)

5.2 Ultracapacitor/ Supercapacitors

Electrochemical batteries as a prime source of propulsion, suffers from limitation when it comes to deliver or receive high power in short interval of time. It is due to the fact that batteries have low power density but high energy density. In order to overcome this limitation, ‘Super Capacitor’ or ‘UltraCapacitors’ are being employed to support propulsion, when current withdrawn from battery via load is higher than *C-rate* or magnitude of current which can lead to fast deterioration of battery. Ultracapacitor are high specific power density system which is able to smooth strong and for few second power solicitations in transportation and stationary applications. (15)

It is also commonly known as *Electrochemical Double Layer Capacitors.* Ultracapacitors are electrochemical capacitors with very high energy density as compared to the common capacitors. IN general, common capacitors are manufactured by sandwiching dielectric material in between electrodes. The charge is accumulated in the dielectric material, opposite to the polarity of voltage applied by the supply. Thus, whenever the load is connected, this electric potential build up inside the capacitor acts as a voltage source to the load. Although, unlike battery , the voltage across the capacitor depreciates with release of the ions or charge carrier accumulated in the dielectric. But in contrast of the common capacitors, *EDLC or Ultracapacitor* does not have any dielectric. (27) (15)

The common construction is being illustrated in the figure below:

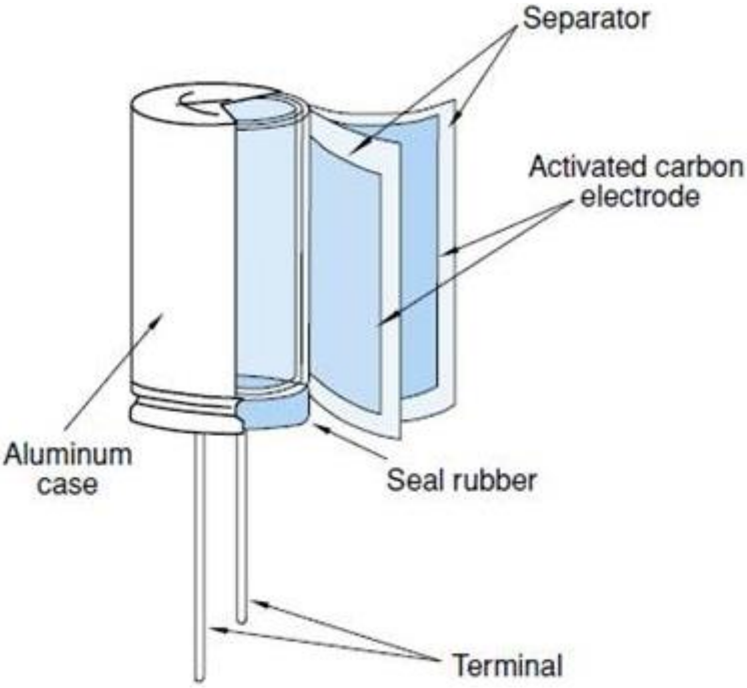


Figure 41:Typical EDLC construction **(27)**

From the figure above, we can see that Ultracapacitor is almost similar to the electrochemical batteries.

Electrodes: Porous Carbon material

Electrolyte: Aqueous or Organic in liquid form

Separator: Same as electrochemical battery (15)

Typically Ultracapacitor exhibits a phenomenon of formation of double layer at the interface of active materials (electrodes) and electrolyte. As there is chemical reaction involved, ultracapacitor can be charge/discharge fast. The energy stored in the ultrcapacitor is same as normal capacitor; proportional to charge stored and potential across the electrodes. The ultracapacitors can have different voltage rating depending upon the type of electrolyte they consist. For aqueous liquid electrolyte, voltage is limited to 1V and for Organic electrolyte, it is 2.7 V. Most of the manufactures, are opting organic electrolyte ultracapacitor, which finds its application in automotive, grid support and renewable energy. Thus, in this work ultrcapacitors mentioned will be of *organic* type electrolyte. (15)

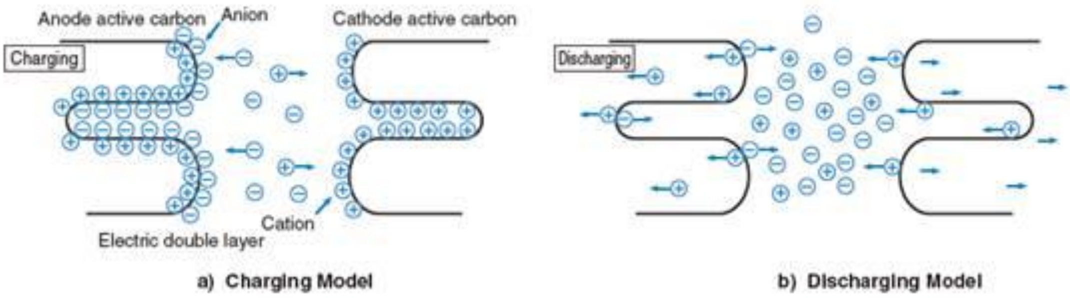


Figure 42: Ionisation in Ultracapacitor **(27)**

As we can see from image above, while charging, charge carriers present in the electrolyte is being attracted and accumulated to the opposite charged electrode. Thus forming an layer at the interface, which is called as double layer. The reason of exhibiting extremely high capacitance is due the two main reasons. One, due to microporous structure of the electrode, surface area is increased to many orders and second, due the really small disctance in between the charges. Thus if we recall mathematical relation of capcitance with area and dsitance, (27)

$$C = \frac{\epsilon A}{d};$$

Where,
A = surface area in contact;

d = distance between charges, (ions).

5.2.1 Circuit representation:

Ultracapacitors has same equivalent circuit as common capacitors as shown in the figure below,

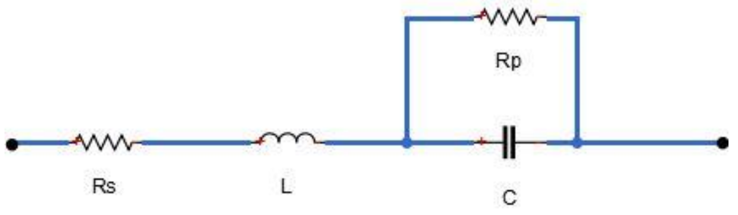


Figure 43: Equivalent circuit of EDLC **(27)**

Where,

R_s = Equivalent series resistance, models the power loss in the ultracapacitor during charging and discharging.

R_P = models self-discharge of capacitor

C and *L* are very small due to construction of the cell. R_p is generally very high as compared to R_s there it can be neglected. So, now it can be concluded that capacitors have lower self discharge. The more general equivalent ladder circuit are used to model ultrcapacitors, due to the porous structure of the electrode which is been shown below,

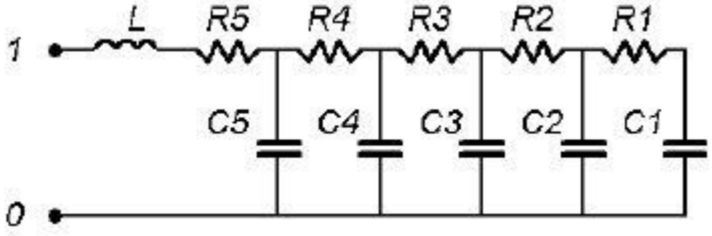


Figure 44:Ultracapacitor's equivalent circuit of 5th order **(28)**

The question arises, why we do need this model when we have a simple 1st order equivalent circuit? Because it can easily combined with various loads and can be used to find analytical or numerical data. Also, it is closer to the experimental observations.

5.2.2 Discharge profile of Ultracapacitor:

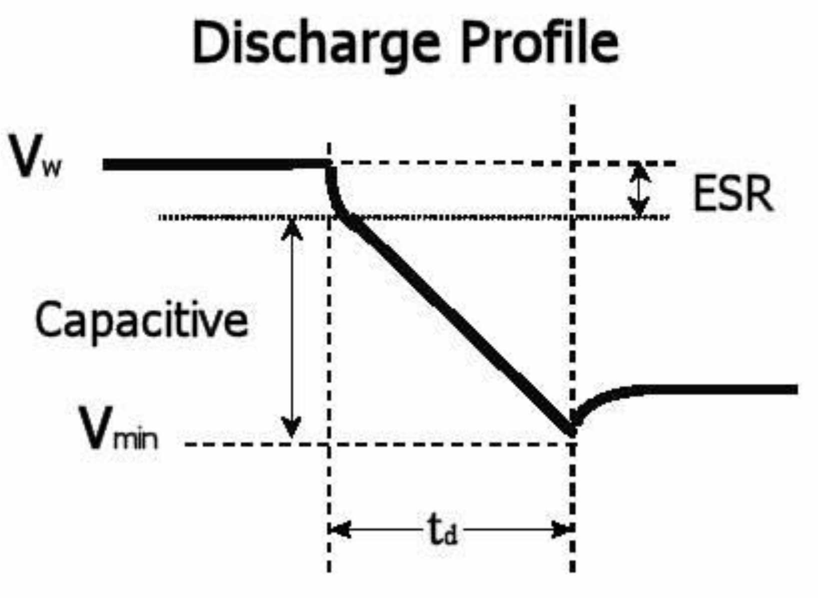


Figure 45 **(27)**

When compared to the battery discharge characteristics, the difference can be seen apparently.

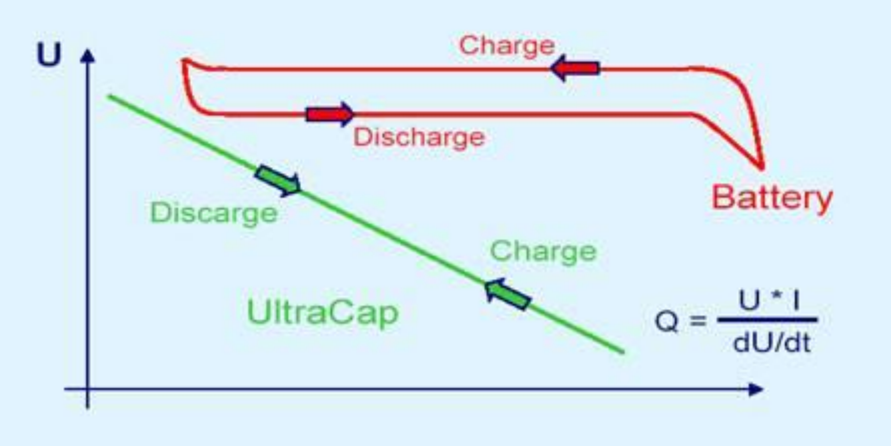


Figure 46 **(27)**

Using hybrid concept of battery and capacitor for active sharing of power is an approach towards saving of battery use, saving money and enhance performance. Ultracapacitors high power density and lower energy density, in contrast with batteries i.e. ultracapacitor is able to provide a really high current due to presence of very low *equivalent series resistance*, but unable to store large amount of energy like batteries. Ultracapacitors can be used to provide high power for a short interval of time, like tens of seconds. Therefore, to employ ultrcapacitors in various applications such as solar energy plants, wind power generating plants, electric mobility, etc. to lower the burden on battery to provide high current, which is not good for the battery health and lifetime.

In addition to the above information, ultrcapacitor can undergo a lot more abuse and can sustain deep discharges even from 100% to 0% *SOC (state of charge)* without sustaining any damage. Also, self-discharge, temperature dependability is much lower as compared to the modern batteries. (28)

Chapter 6

Modelling and Simulation

In this chapter we will discuss and present the *Simulink* modelling of the electric vehicle with different powertrain.

For modelling of simulation vehicle MATLAB and *Simulink*™ (*Simscape*) from MATLAB is being used, due to its wide presence and easy to understand modelling technique. The model being discussed below consists of three major components: Power Sources, Electromechanical device and loads by the virtue of vehicle motion in an open environment. The modelling does have assumptions in order to keep work easy and not complicated to understand for a layman. Due to assumptions, the accuracy of the model is affected, but it will provide base to idea being discussed in this thesis work.

The following assumptions are being taken under consideration

- Vehicle is moving with certain velocity according to standard drive cycle.
- Vehicle's operation weather is constant at all instants during simulation.
- Batteries initially have finite state of charge.
- Using predefined standard drive cycles to assess the results.

With the start of the simulation, we will define some inputs in the *MATLAB Editor*. These values are being considered in accordance to *Nissan Leaf.* This model also allows us to observe range and power it can be taken out of any other vehicle model, once all the parameters are known. Following is the screenshot of the MATLAB editor, with the details mention as the comment in the editor itself due as it is convenient.

The study of the model is in accordance to variation in *velocity-time* profile (drive cycles) and *slope/s*. During drive cycles, the vehicle undergoes transiency due to start, stop, acceleration, braking. Thus, with drawing power and energy from the battery packs in order to overcome the resistance offered by the vehicle. In addition to it, different power electronic converters such as DC/DC bidirectional inverter and DC/AC converters are used in series with electric machine. All these above mentioned converter components come with their own efficiencies. Due to these efficiencies, extra energies have to be extracted from the batteries in addition to required energy to overcome vehicle road load. These efficiencies are also being modelled in this chapter.

6.1 Driving Cycles:

Driving cycles are data point of velocity versus time. It is used to determine performance of vehicle in different ways, such as fuel consumption, emission, etc. There are different standard driving cycles which are subjected on to the vehicle, in order to assess performance of the vehicle. In this thesis, since we are testing drive cycles on the electric vehicle, run on batteries.

Therefor performances is assessed in terms of the battery SOC, power consumed, subjected to different auxiliary power consumption and road gradient. (29)

In this thesis work, standard test cycles employed in Europe and US are being used to demonstrate behaviour of the batteries. Driving cycles being used in the model is being mentioned in further document.

6.1.1 ECE R15: (30) (31) (32)

Also, known as Urban Driving Cycle(UDC), aimed to test vehicle in the busy European cities with the maximum speed of 35 km/h.

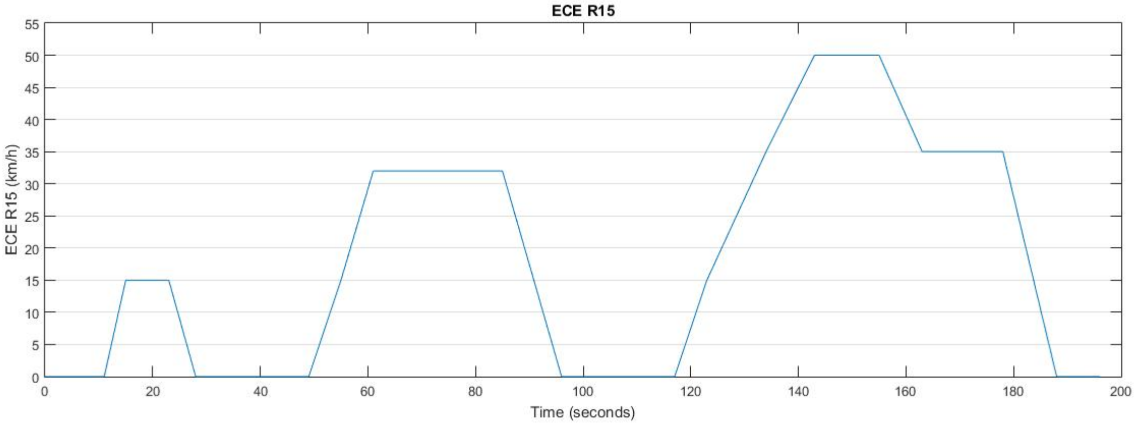


Figure 47: ECE R15 driving cycle **(32)**

6.1.2 EUDC (Extra Urban Driving Cycle) (32)

This cycle is considered more aggressive than ECE R15 with a top speed of 120 km/h.

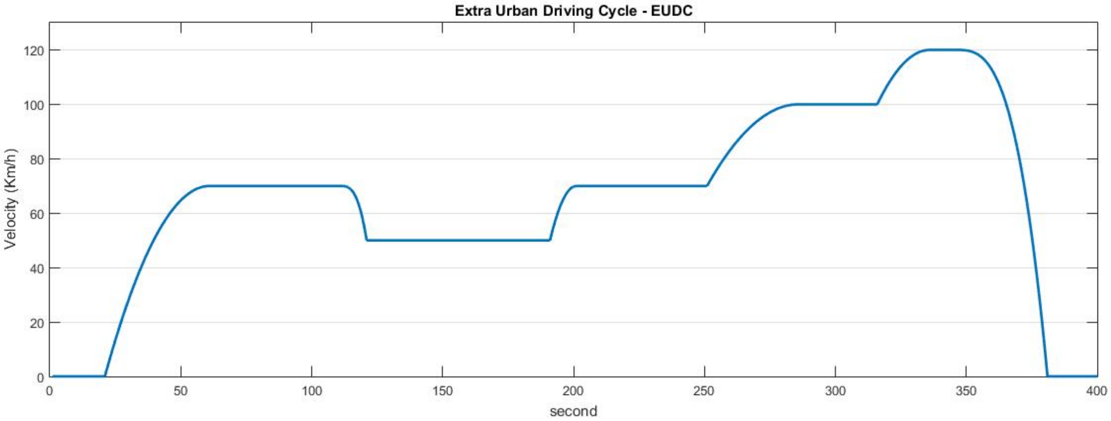


Figure 48: EUDC driving cycle **(32)**

6.1.3 NEDC

Abbreviated as New European Driving Cycle, it consist of four ECE R15 and one EUDC driving cycle. Top speed of the vehicle attained in this driving cycle is about 120 km/h. (32)

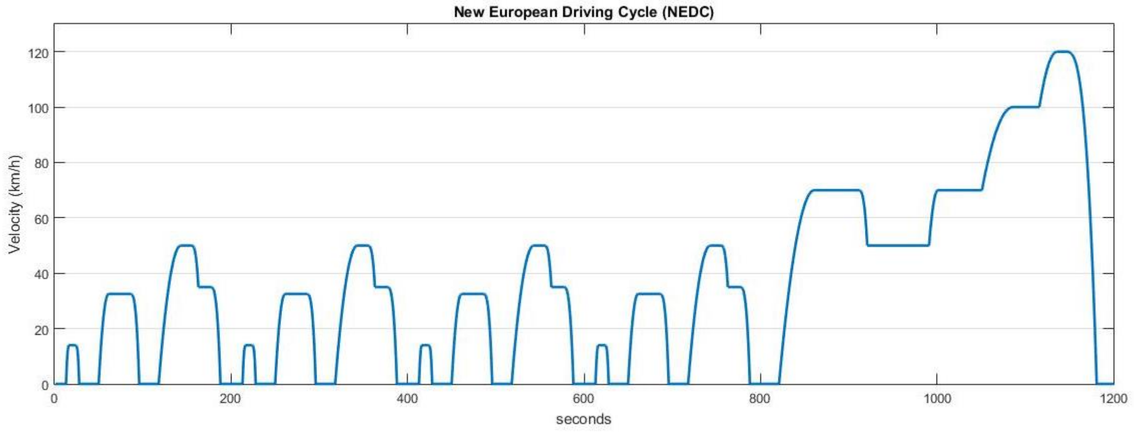


Figure 49: NEDC driving cycle **(32)**

6.1.4 Artemis Cycle:

The driving cycle being developed under the *Artemis* project, a statistical study in Europe. (33). Artemis cycle is being classified in two separate categories, *Artemis Urban Driving Cycle* and *Artemis Rural Driving Cycle*. (32)

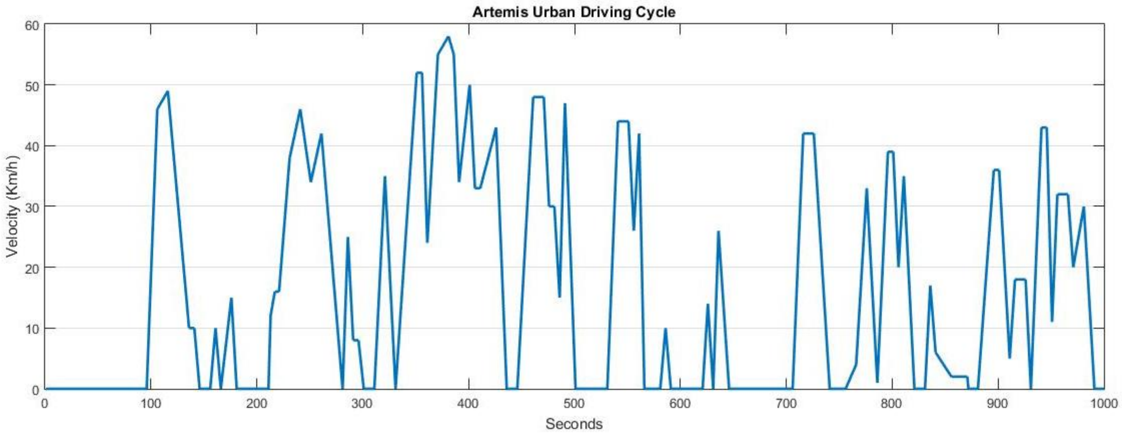


Figure 50: Artemis Urban Driving cycle **(32)**

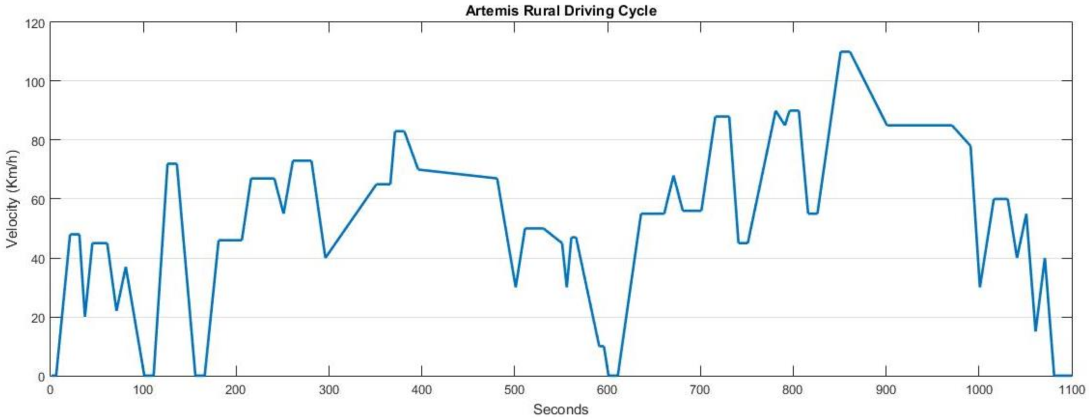


Figure 51: Artemnis Rural Driving Cycle **(32)**

6.1.5 HWFET (Highway Fuel Economy Test Cycle (32)

This drive cycle aim to determine fuel economy rating on the highway. It is being developed and applied in US.

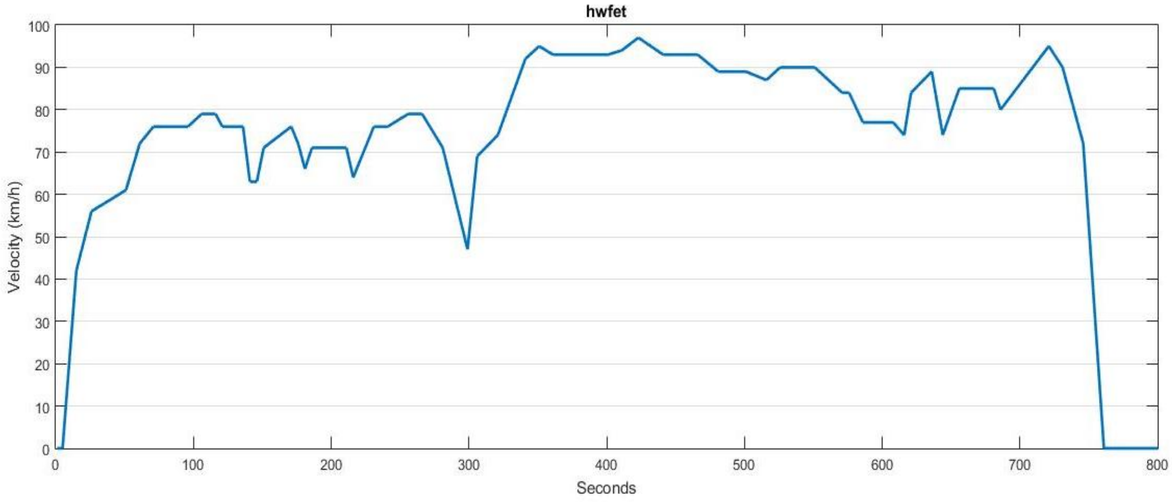


Figure 52: HWFET Driving Cycle **(32)**

6.1.6 SFUDS (Simplified Urban Driving Schedule) (34)

This drive cycle is also being developed in US.

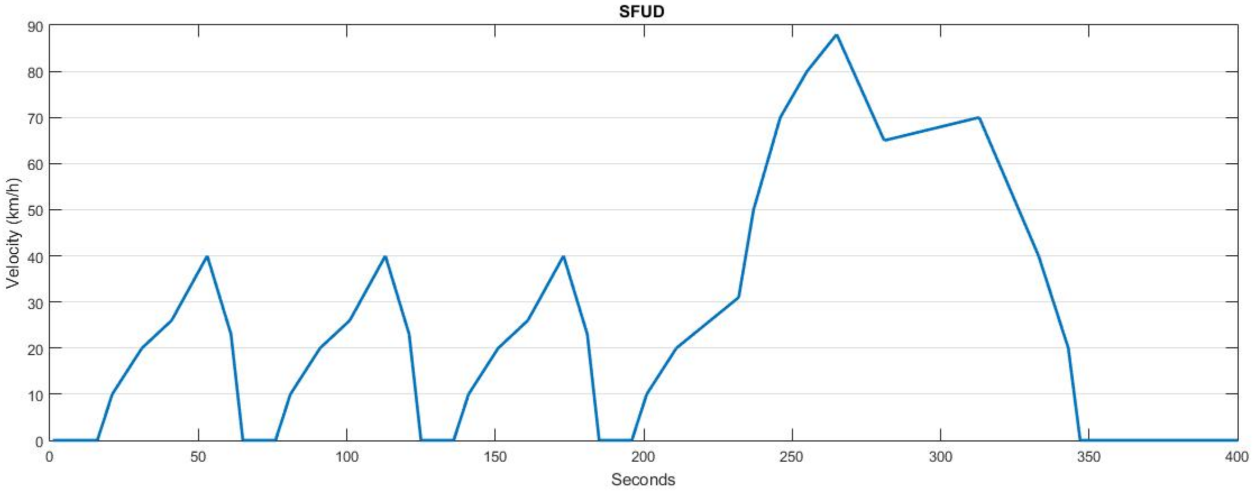


Figure 53: SFUD Driving Cycle **(32)**

Custom Driving Cycle:

I have created this drive cycle, demonstrating one cycle of start, accelerate, braking and hard stop. In this vehicle supposed to accelerate quickly and come to rest quicker. It can be sought as a driving cycle in traffic where fast acceleration and stop is required, e.g. traffic during afternoon, fast acceleration due to light traffic and stop due to traffic signals.

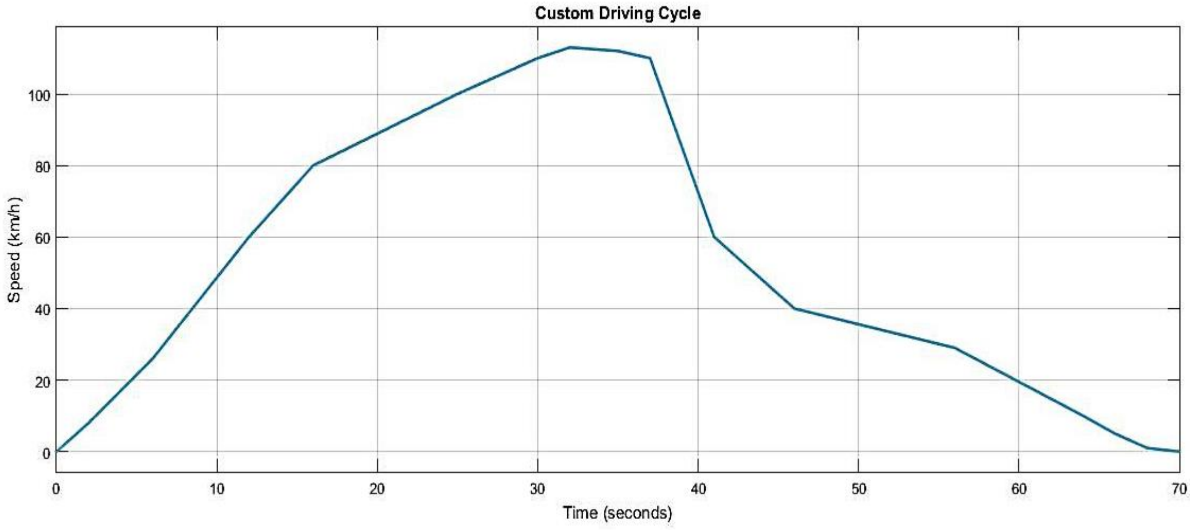


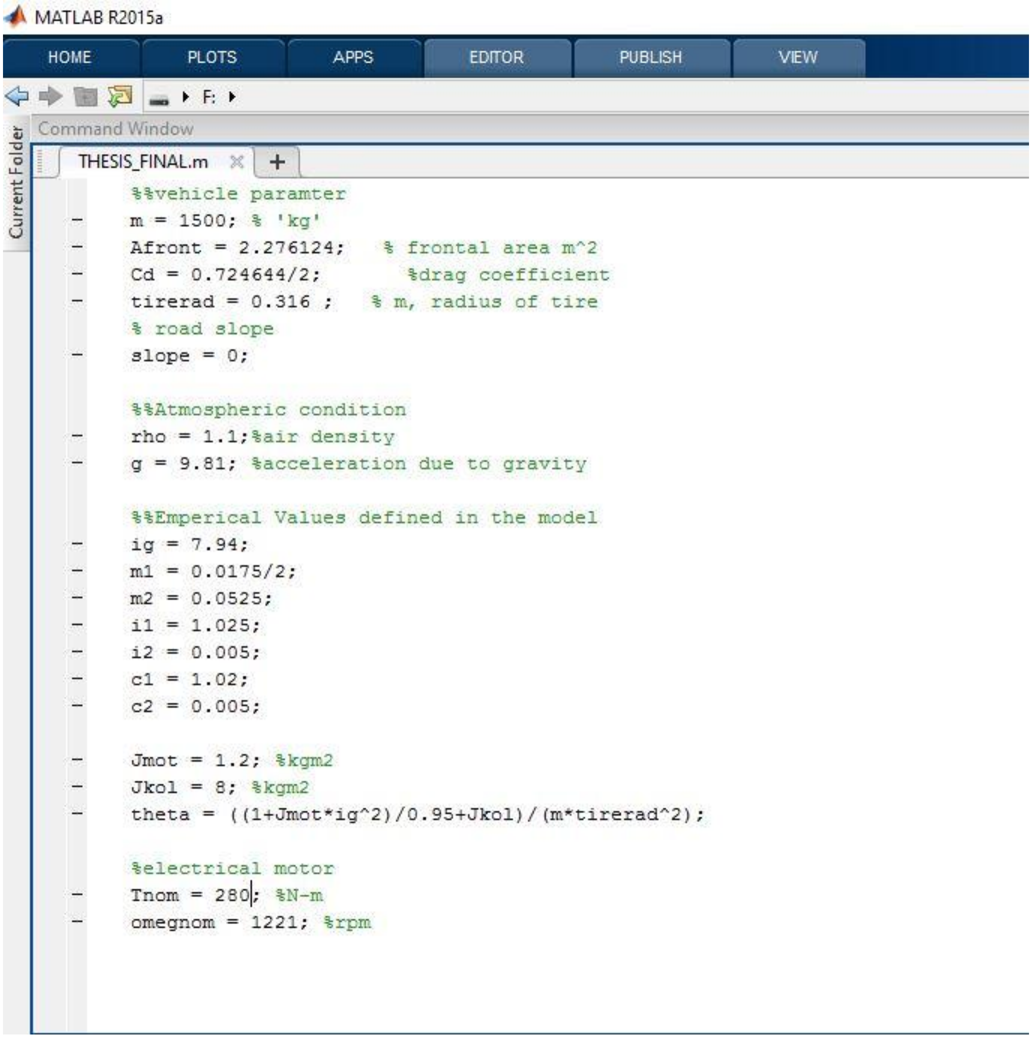
Figure 54: Custom Driving Cycle

6.2 Simulink *Modelling:*

This section will deal with the mathematical modelling on the MATLAB *Simulink*, 2015a version. This model includes use of all three main components of MATLAB *Simulink*, i.e. MATLAB, *Simulink*, and *Simscape*. While *Simulink* is based on the representation and modelling in terms of blocks and their meaningful arrangement, *Simscape* takes physical modelling into the account, thus is connected physically unlike *Simulink*, whose connection is represented by signals with mention direction of flow. Battery block and Controlled current source is being modelled via *Simscape* and rest of the model is being modelled via *Simulink*. The inputs of the data are either being done directly in the *Simscape* environment or in *MATLAB editor*. The screenshot below is shows the *MATLAB editor* and the input defined in the modelled in addition to the table below which tabularise electrical specifications of light weight EV. This data is being inspired by *Nissan leaf* (model : 2013), but model can be modified with change in specific values. (35) (36)

Specification Used	
Machine power rating(kW)	80
Nominal speed (radian/ s)	1221
Nominal torque(Nm)	280
Battery type	Li-ion
Battery pack nominal voltage	330
Battery pack energy(kWh)	24.0
Capacity(Ah)	66.2
Gear ratio (i_g)	7.94

Table 3: Used data as input in model



```
%%vehicle paramter
m = 1500; % 'kg'
Afront = 2.276124;   % frontal area m^2
Cd = 0.724644/2;       %drag coefficient
tirerad = 0.316 ;   % m, radius of tire
% road slope
slope = 0;

%%Atmospheric condition
rho = 1.1;%air density
g = 9.81; %acceleration due to gravity

%%Emperical Values defined in the model
ig = 7.94;
m1 = 0.0175/2;
m2 = 0.0525;
i1 = 1.025;
i2 = 0.005;
c1 = 1.02;
c2 = 0.005;

Jmot = 1.2; %kgm2
Jkol = 8; %kgm2
theta = ((1+Jmot*ig^2)/0.95+Jkol)/(m*tirerad^2);

%electrical motor
Tnom = 280; %N-m
omegnom = 1221; %rpm
```

Figure 55: Input to *MATLAB editor*

6.2.1 Energy required by the Propulsion:

Energy required by the vehicle to overcome inertia, and accelerate is being modelled in the *Simulink* environment by the help of predefined blocks already given in the *MATLAB Simulink*. according to equation 4.1 from chapter 4 of this work.

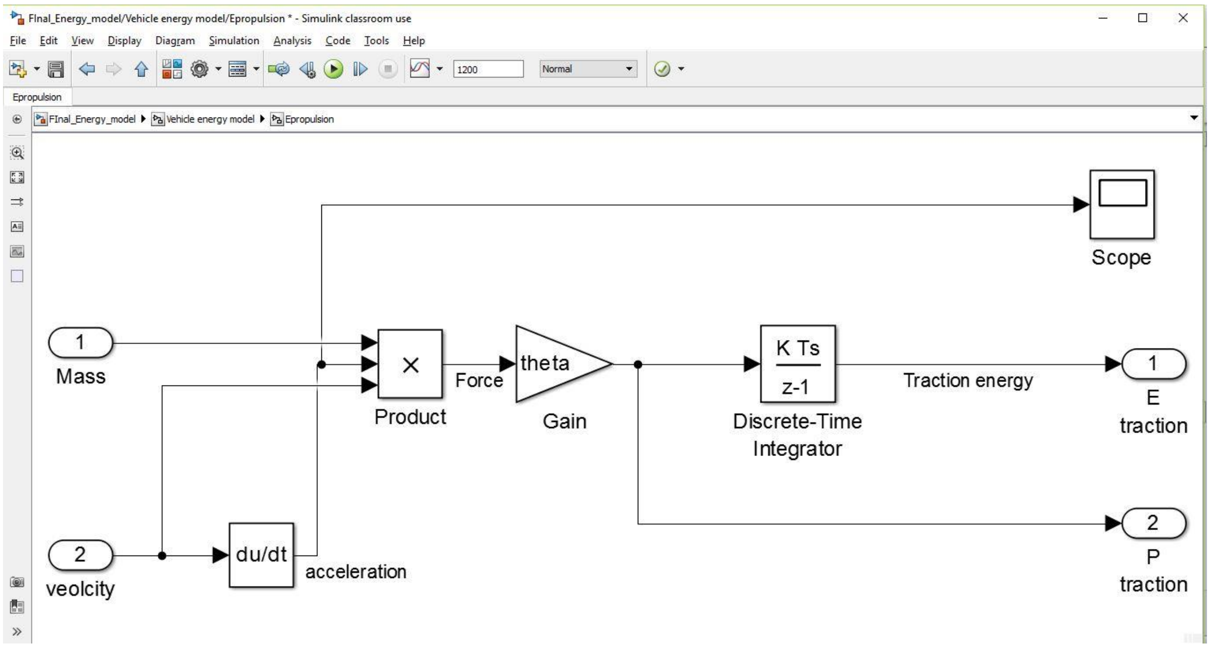


Figure 56: propulsion energy model

6.2.2 Energy consumed due to Aerodynamic Drag

The screenshot mentioned below is from the *Simulink* window. This model calculates energy loss due aerodynamic resistance, which is primarily due to the movement of the vehicle as being explained before in previous chapter. This model is based on the mathematical equation no. 4.12 as mentioned in the respective chapter.

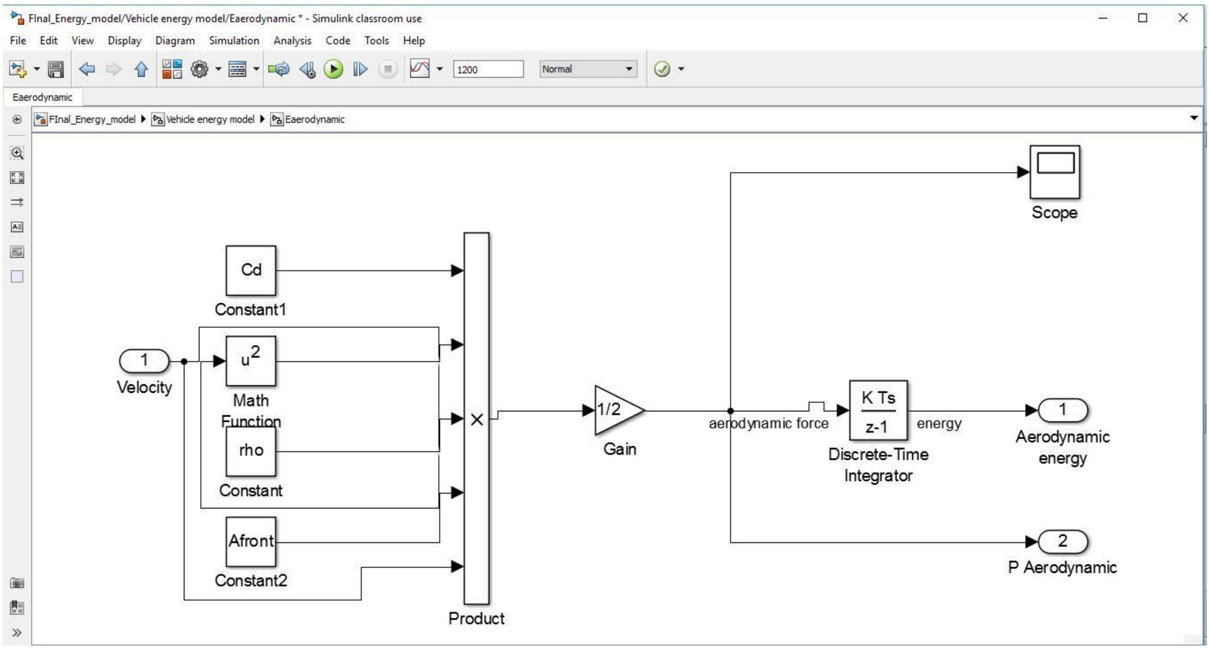


Figure 57: model to estimate resistance force due to Aerodynamic drag

6.2.3 Energy consumption due to slope:

The following figure is the screenshot of *Simulink* model which represents energy consumed by vehicle due to subjected slope profile. Modelling is being based on the mathematical relation according to equation number 4.11.

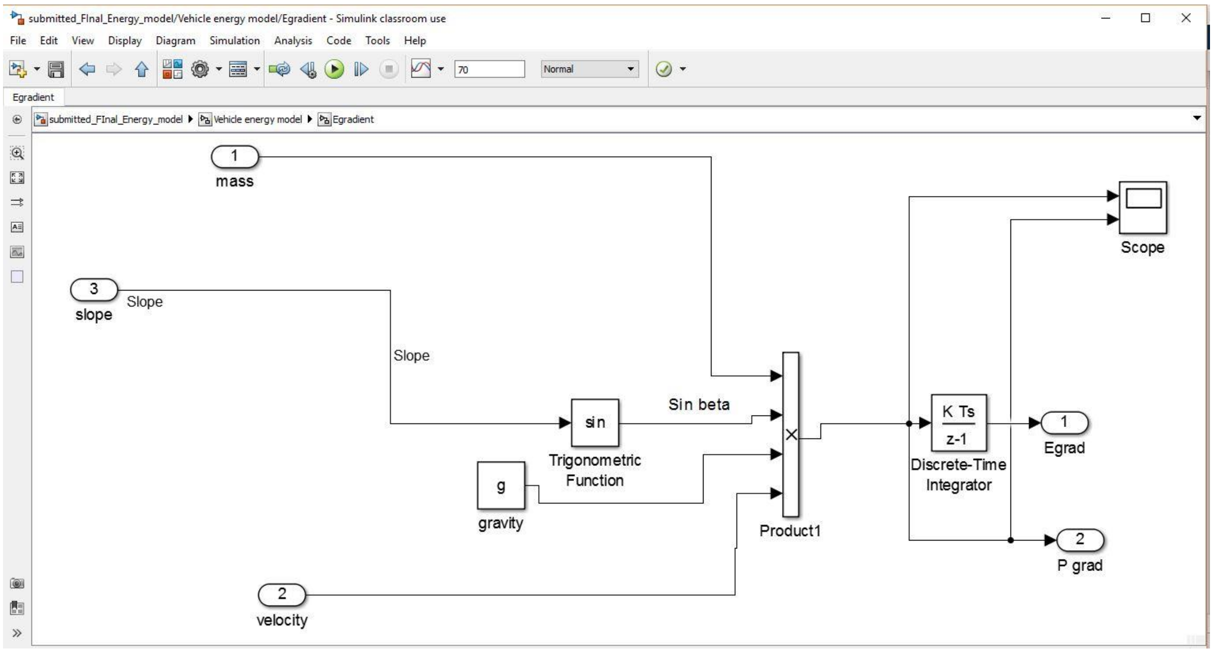


Figure 58: model to estimate resistance force due to gravity (Slope)

6.2.4 Energy consumed by the vehicle due to the rolling resistance

Rolling resistance being modelled in the screenshot below is being modelled upon equation no. 4.11

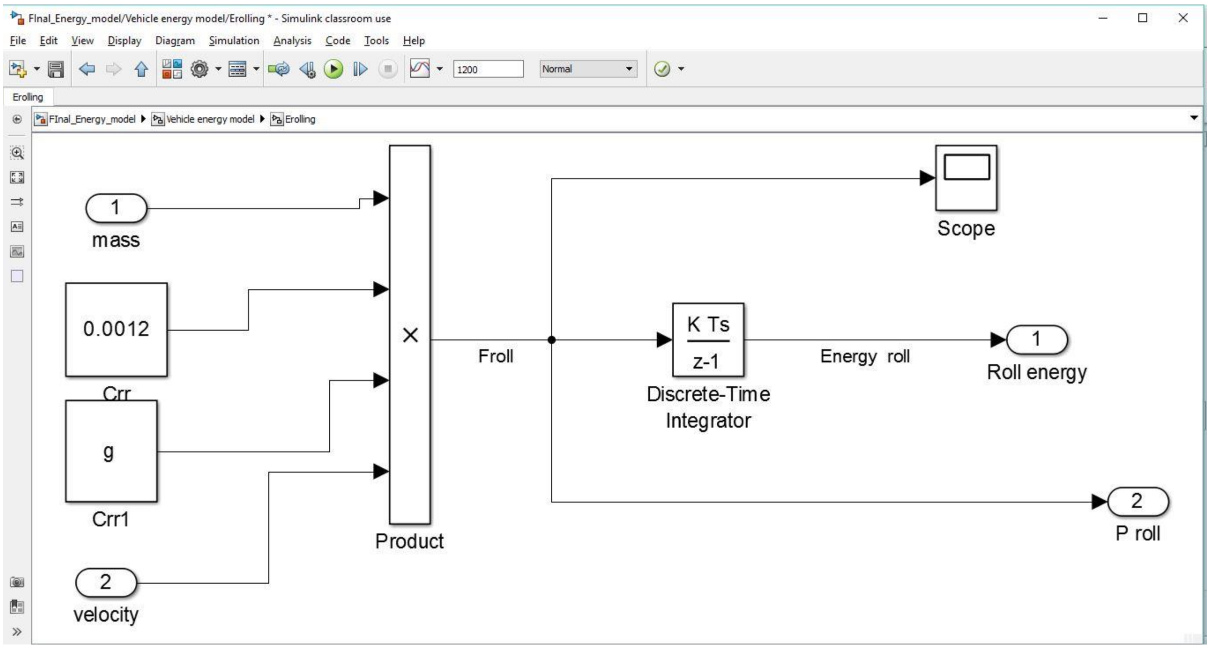


Figure 59: Rolling resistance model

6.2.5 Overall energy model of the electric vehicle:

With respect to following screenshot given below, the energy consumption of the vehicle from each of the individual energy consumption mentioned previous in the chapter is being added in order to give a output in the terms of the power required by the vehicle to complete different driving cycles our vehicle would be subjected to. Please note that this power consumption is just the result of the vehicle dynamics and not include *auxiliary* power consumptions, such as heating, air conditioning, and other amenities.

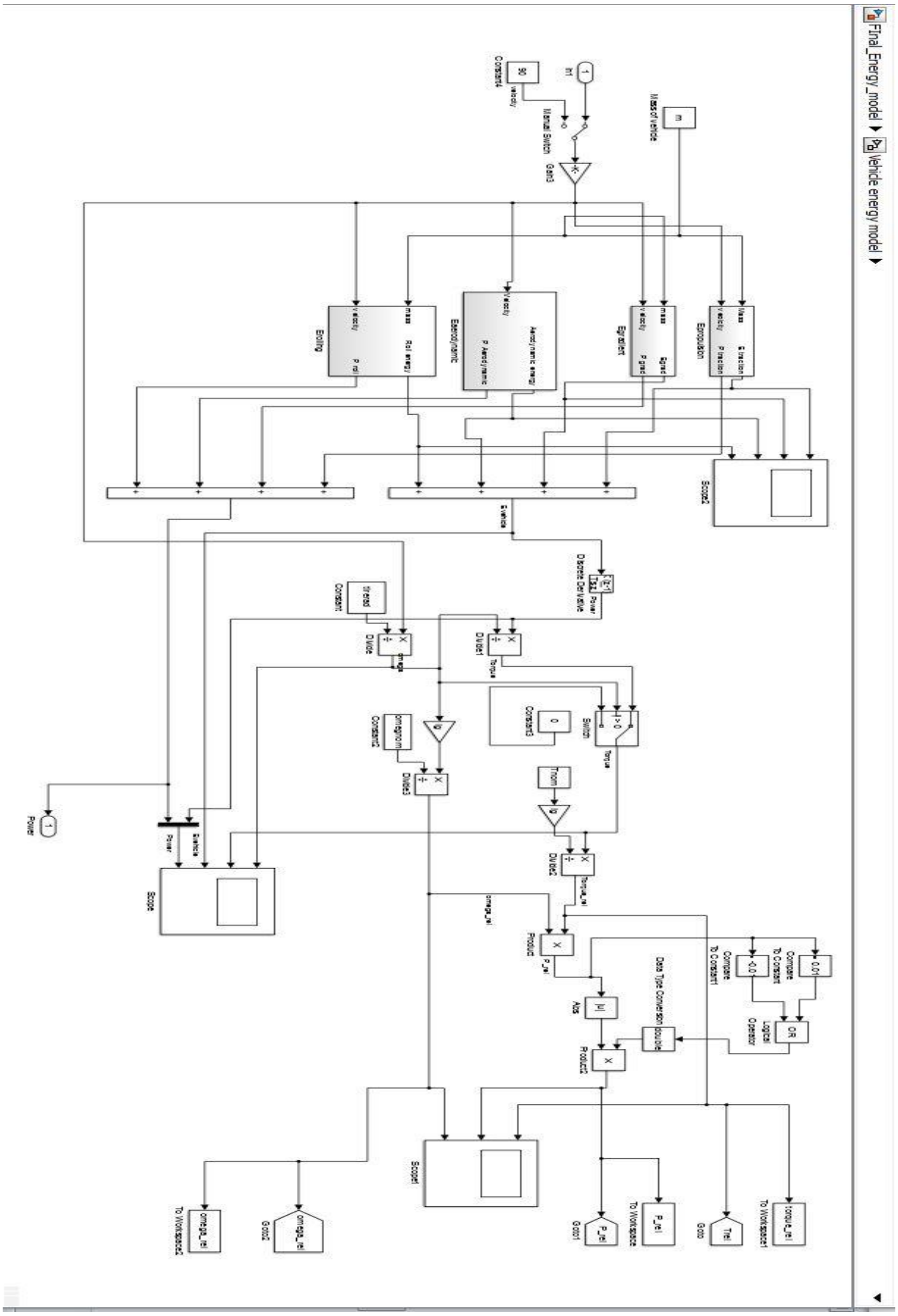


Figure 60: Complete energy model

6.2.6 Efficiency Modelling:

This section of current chapter will bring some light on the modelling of different components incorporated in the drive train. These components facilitate power flow from the source, i.e. Electro-chemical batteries to the load, i.e. due to vehicle dynamics and auxiliary power consumptions.

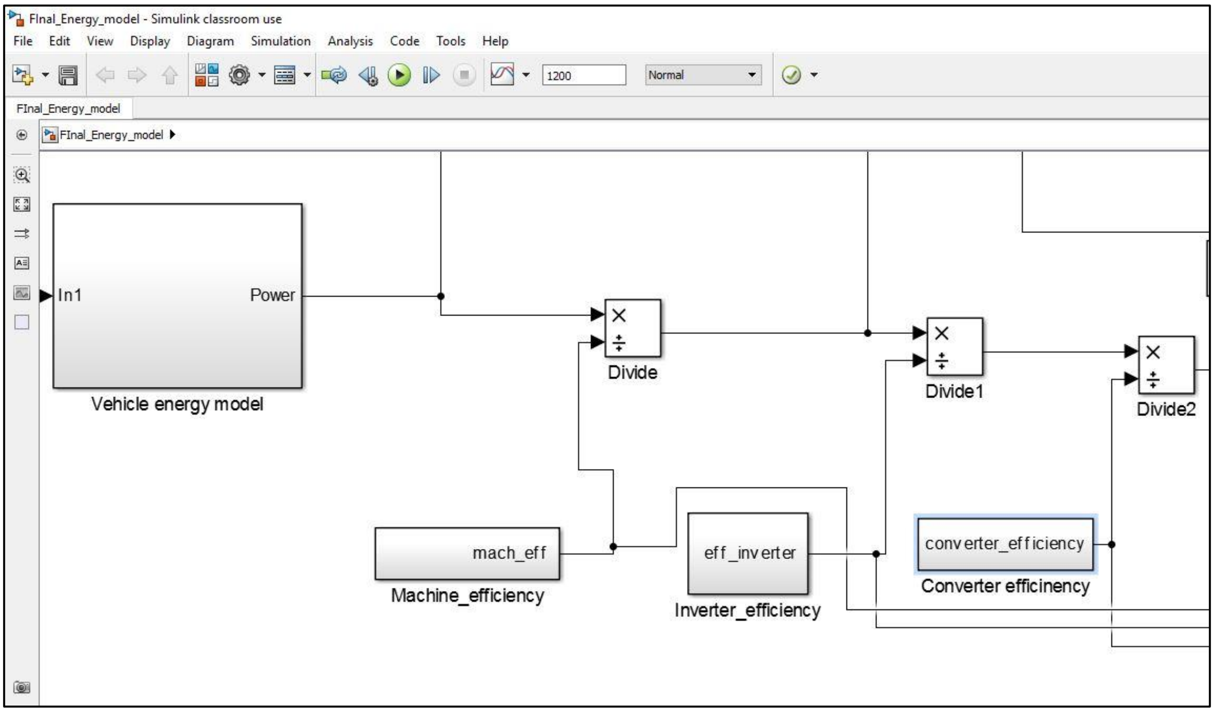


Figure 61: Model to estimate aggregate energy required

6.2.6.1 Machine Efficiency

Machines are electromechanical device, which are meant to provide interface between mechanical and electrical parameters. Mechanical input can be torque, force, speed and the output can be current, power, and vice versa. Ideally machines have no losses, but in real case, there are different power losses due to different factors such as mechanical and electrical. Thus this loss can be measured by the mathematical relation in between machine's output over input. (37)

$$\eta_{machine} = \frac{P_{rel}}{P_{rel} + m_1 * M^2{}_{rel} + m_2 * \omega^{1.8}{}_{rel}} \qquad (6.1)$$

Where,

$$P_{rel} = M_{rel} * \omega_{rel} \qquad (6.2)$$

$M_{rel} = \frac{M_{instant}}{M_{nominal} * i_g}$; Relative torque in Nm

$\omega_{rel} = \frac{\omega_{instant} * i_g}{\omega_{nominal}}$; Relative angular speed in rad/s

$M_{instant}$ = Instantaneous torque during driving cycle,

$M_{nominal}$ = Rated torque of electrical machine,

$\omega_{nominal}$ = rated angular speed of machine in

$\omega_{instant}$ = instantaneous angular speed of machine during driving cycle. (37)

Here,

i_g = (7.2) (gear ratio of *Nissan Leaf*)

$m_1 = 0.0175$, (empirical constants)

$m_2 = 0.0525$, (empirical constants) (37)

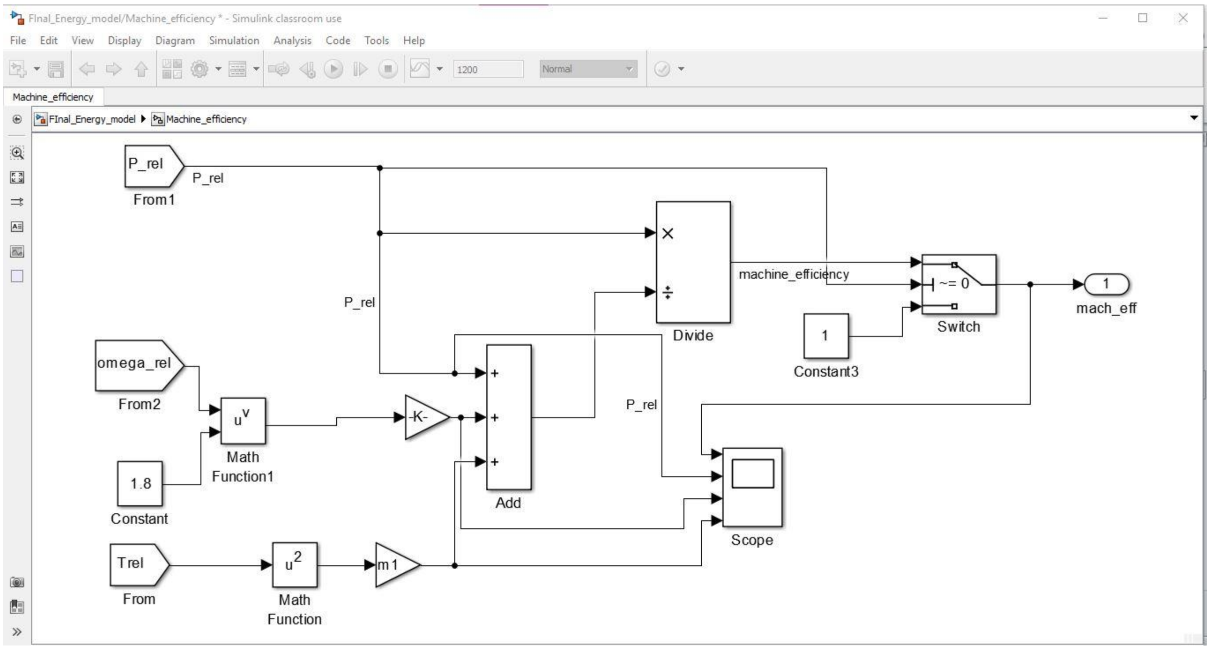


Figure 62: Machine's efficiency model

6.2.6.2 Inverter Efficiency:

One of two primary types of power electronic device's application used in this model is inverter. Inverters are the devices which are responsible for conversion of direct current supply to three phase current or vice versa by the means of intelligent switching of power electronic devices. There are different topologies and different scheme of switching schemes of inverters. Topologies and switching schemes are vast and requires whole discussion over that, thus we are limiting the work to calculate the efficiency of the inverters being used, in general. Since, this modelling is to demonstrate energy consumption and comparison for different parametric changes in the vehicle loads, therefore, I am using a general mathematical relation for efficiency being mentioned during lectures. It greatly simplifies the model itself and easy to understand. (37)

$$\eta_{inverter} = \frac{P_{rel}}{i_1 * P_{rel} + i_2} \qquad (6.3)$$

Where,

$\eta_{inverter}$ = Efficiency of inverter,

i_1 = 1.025, (empirical constant)

i_2 = 0.005, (empirical constant) (37)

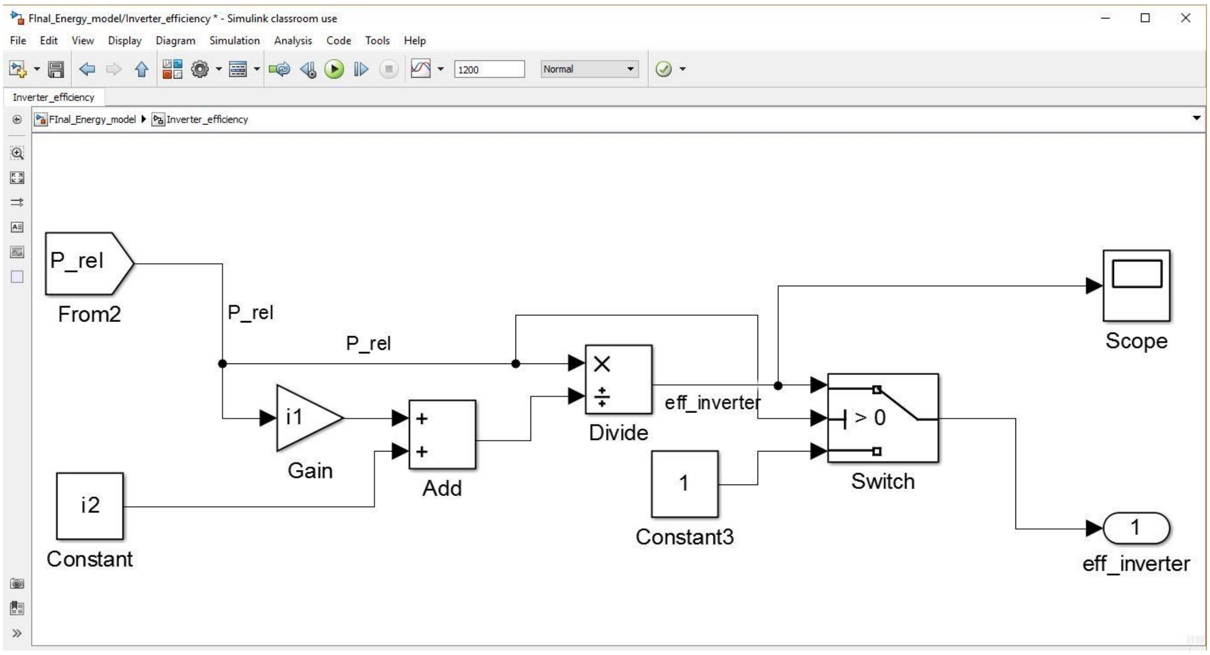


Figure 63: Inverter's efficiency model

6.2.6.3 Converter efficiency:

Converter or DC/DC converter is a device which alters the voltage level into different output. Usually rated voltage of electrical machine is different from that of battery terminal voltage. Also, ideal battery source experiences drop of voltage, depending on different parameters such as Battery's State of Health (SOH), lifetime, SOC, etc. (37)These effects have already been discussed during previous chapters in this work. *Simulink* model of converter efficiency is being shown in following screenshot.

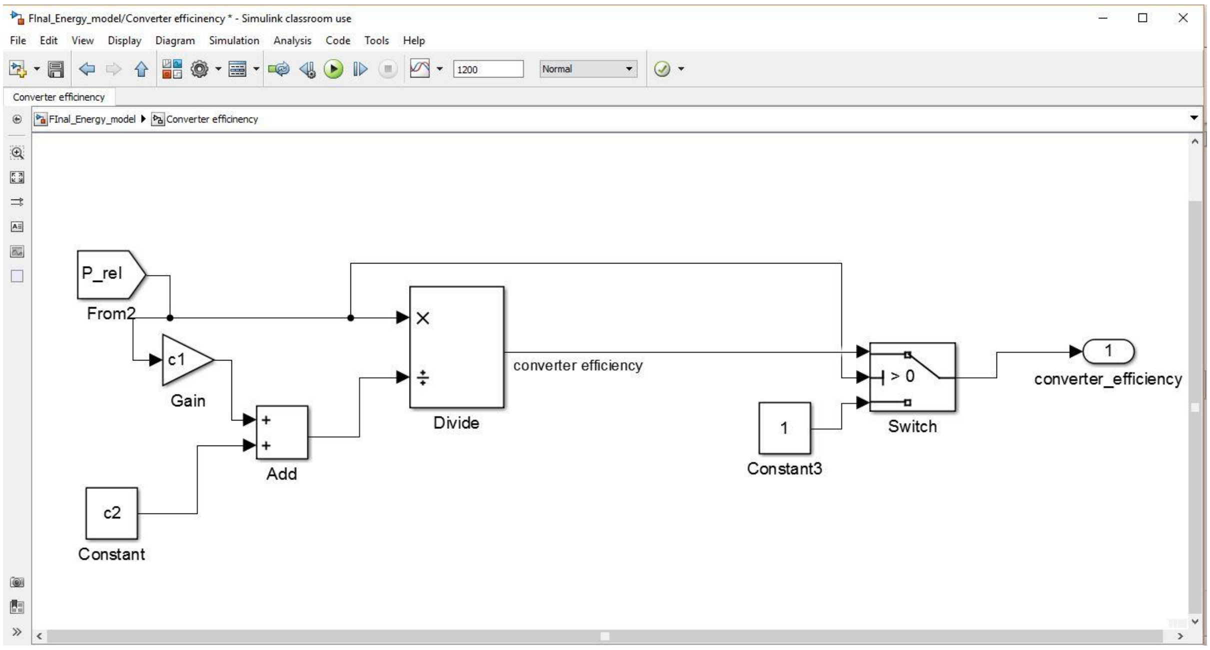


Figure 64: Converter's efficiency model

The mathematical model used for the *Simulink* model is as follows,

$$\eta_{converter} = \frac{P_{rel}}{c_1 * P_{rel} + c_2} \tag{6.4}$$

Where, $\eta_{converter}$ = efficiency of DC/DC converter
$C_1 = 1.02$ (empirical value)
$C_2 = 0.005$ (empirical value) (37)

Once we get the efficiency from each component as above, we can calculate the actual energy (current) withdrawn from the battery source and thus we can know the actual SOC of the vehicle model.

6.3.7 SIMSCAPE(Battery and controlled current source)

In this chapter, a model has been worked out which includes the electrochemical battery source block from the *Simpowersystem*. We can choose any battery predefined in the block, such as Lead Acid, Ni-based batteries, Lithium-ion batteries (38). In this model, I have considered Lithium-ion battery model (used in Chevrolet Leaf), due to its scope in modern applications in terms of energy density, lifetime and flat profile of discharge. The *controlled current source* block is being used here to account the variation of load. This is being controlled by the current input. In this case, our input current is the result of the varying power requirement by the vehicle during different driving cycles. The screenshot of the *Simscape* model is mentioned down below,

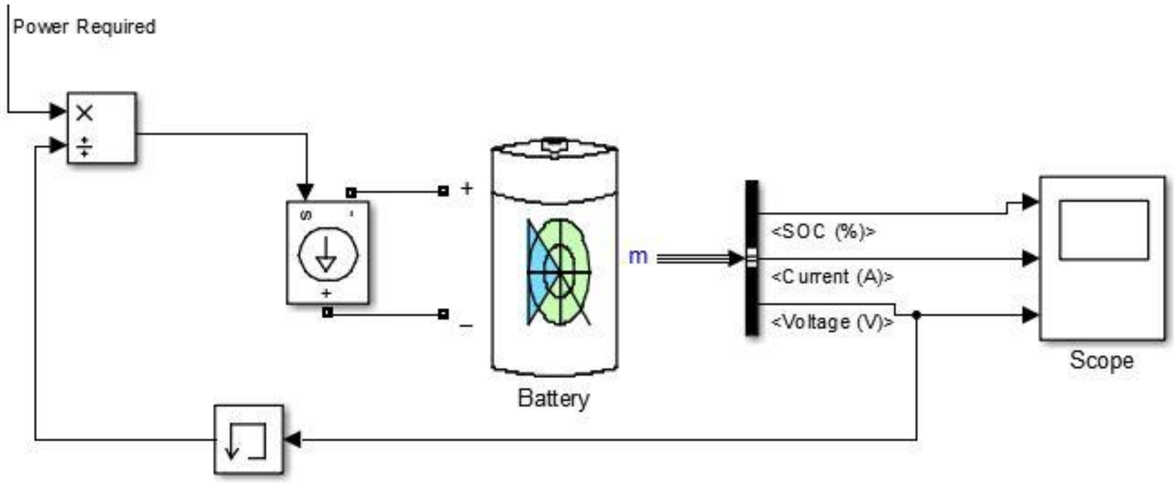
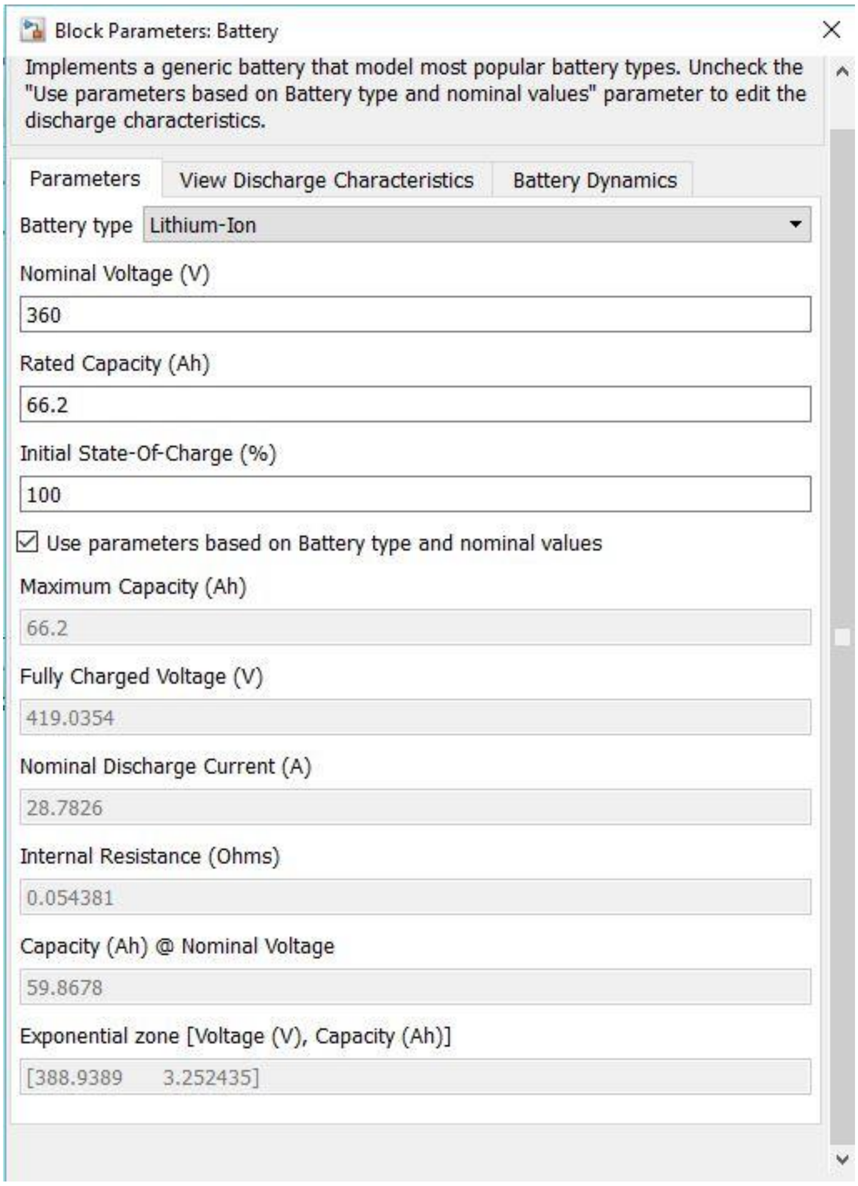


Figure 65: SIMSCAPE battery and Controlled Current source block



Block Parameters: Battery

Implements a generic battery that model most popular battery types. Uncheck the "Use parameters based on Battery type and nominal values" parameter to edit the discharge characteristics.

Battery type: Lithium-Ion

Nominal Voltage (V): 360

Rated Capacity (Ah): 66.2

Initial State-Of-Charge (%): 100

☑ Use parameters based on Battery type and nominal values

Maximum Capacity (Ah): 66.2

Fully Charged Voltage (V): 419.0354

Nominal Discharge Current (A): 28.7826

Internal Resistance (Ohms): 0.054381

Capacity (Ah) @ Nominal Voltage: 59.8678

Exponential zone [Voltage (V), Capacity (Ah)]: [388.9389 3.252435]

Figure 66: Battery parameters in accordance to light electric vehicle (Leaf)

6.4 Observations

In this section we will observe, energy consumed by the vehicle, State of Charge (SOC) remaining, and their comparison. With these observations we can observe how energy requirement varies with different profile of driving cycle along with the slope variation. We can also observe depletion of the battery during the standard and custom driving cycles, in the terms of SOC remaining at the end of each driving cycle.

6.4.1 Total Energy Consumed

The scope’s graphs shown below are the total energy consumed by the vehicle model during the different driving cycles. We can notice different curves in graphs, they belong to different subjected slopes on the vehicle.

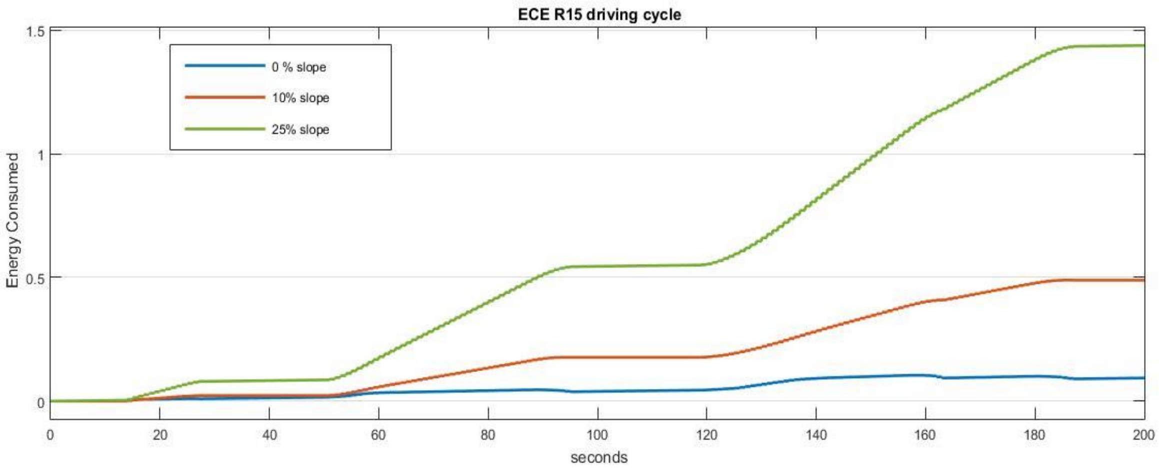


Figure 67: Energy consumed during ECE R15

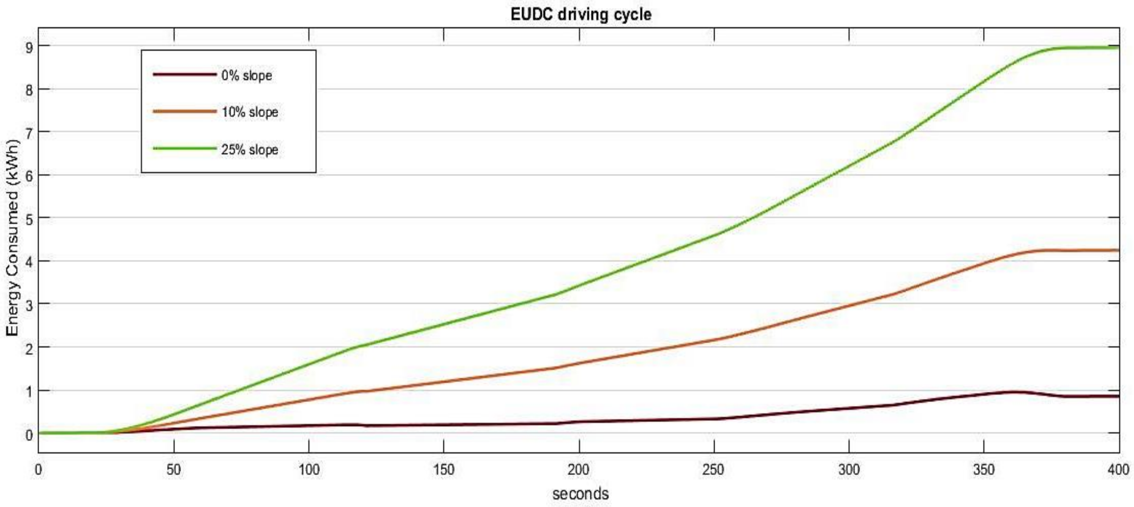


Figure 68: Energy consumed during EUDC

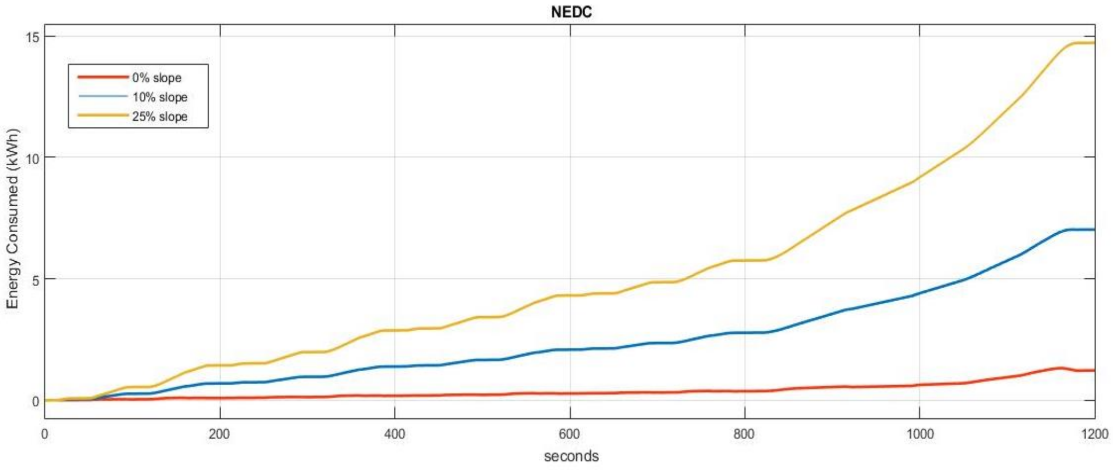


Figure 69: Energy consumed during NEDC

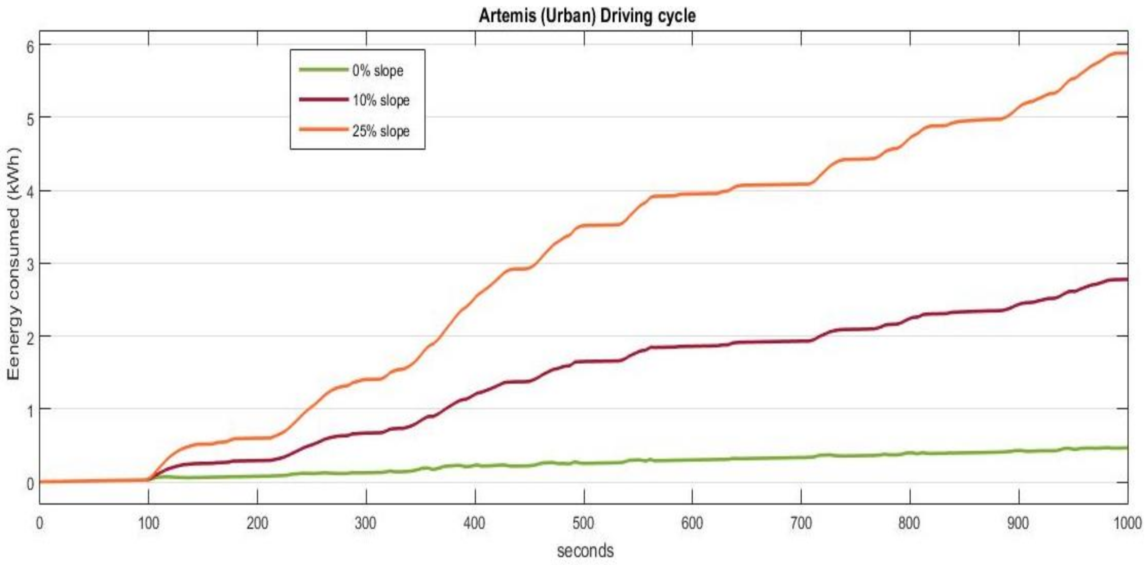


Figure 70: Energy consumed during Artemis (Urban)

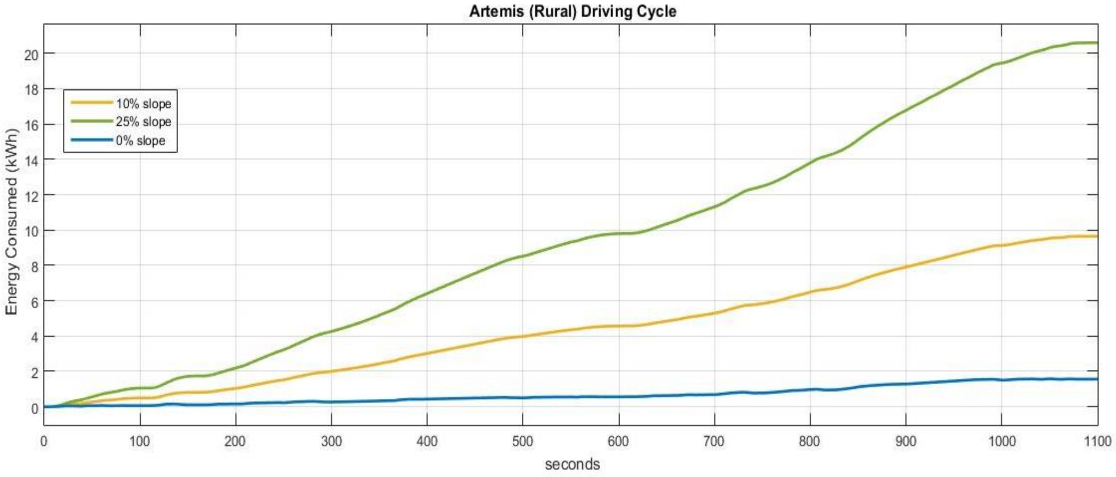


Figure 71: Energy consumed during Artemis (Rural)

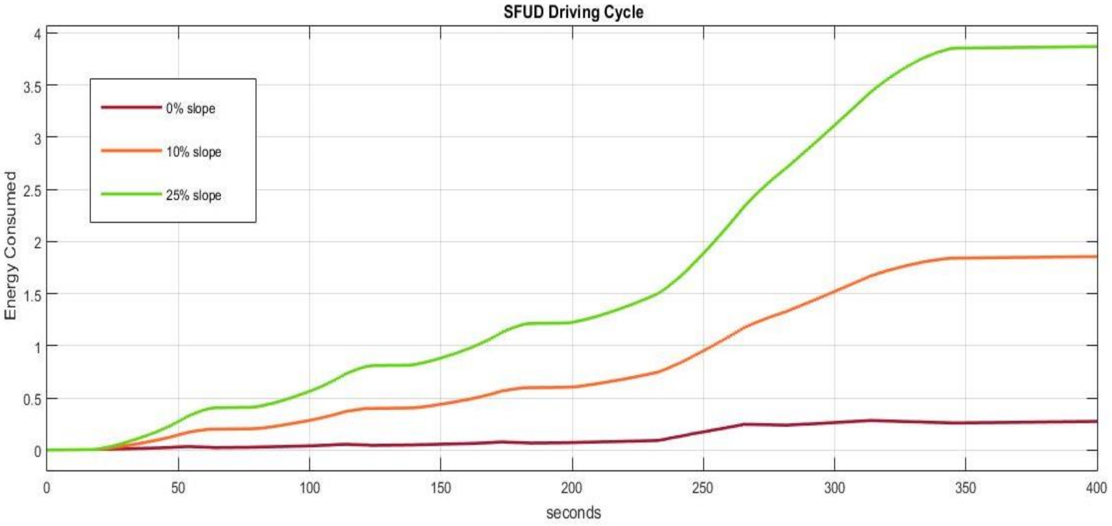


Figure 72: Energy consumption during SFUD

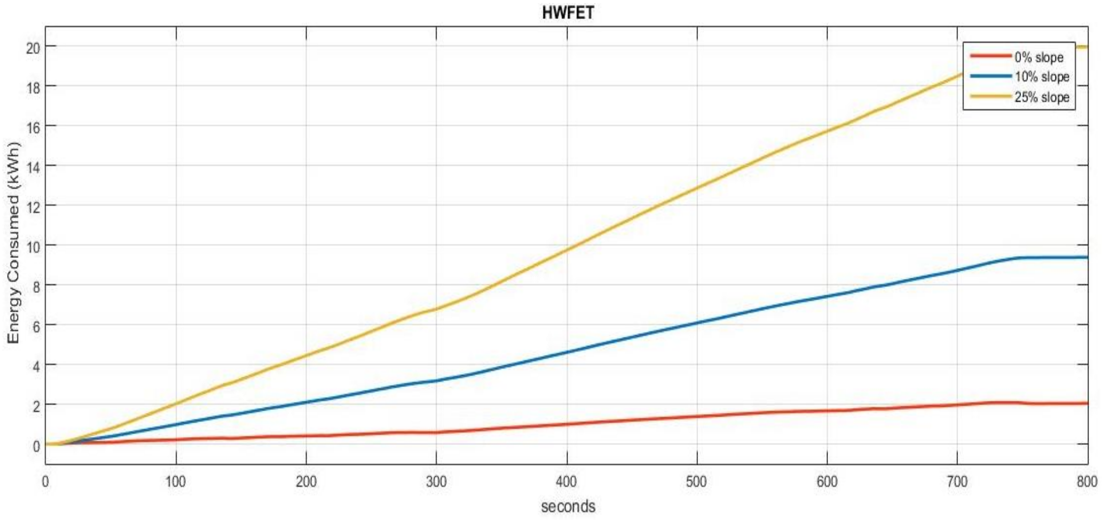


Figure 73: Energy consumed during HWFET

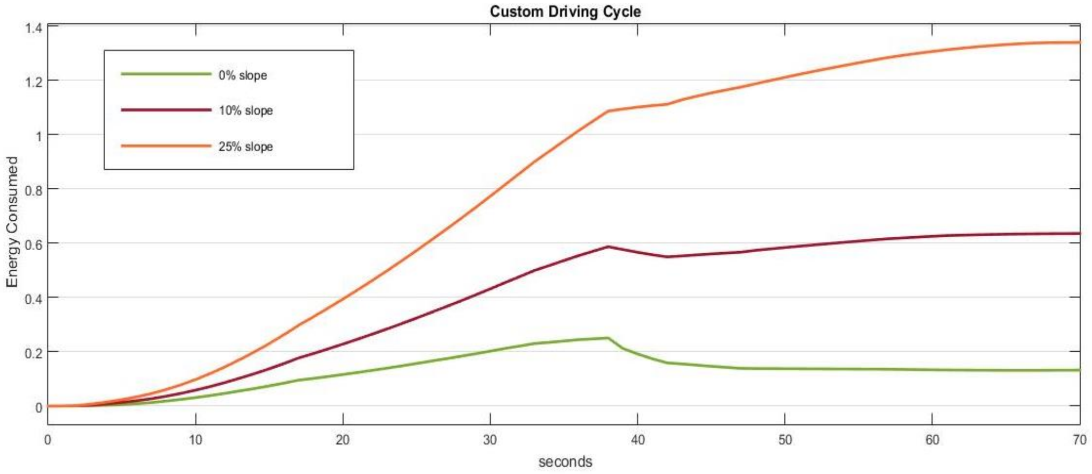


Figure 74: Energy consumed during Custom driving cycle

6.4.2 State of Charges (SOCs) for different drive cycle for different slopes

In this section we can see, SOCs left after each standard driving cycle and custom cycle. Each graph contains three different curves, which represents as different slopes. We can observe with the help of these graphs, we can conclude that slopes and velocity profile plays a major role in the variation of SOC of the electrochemical source.

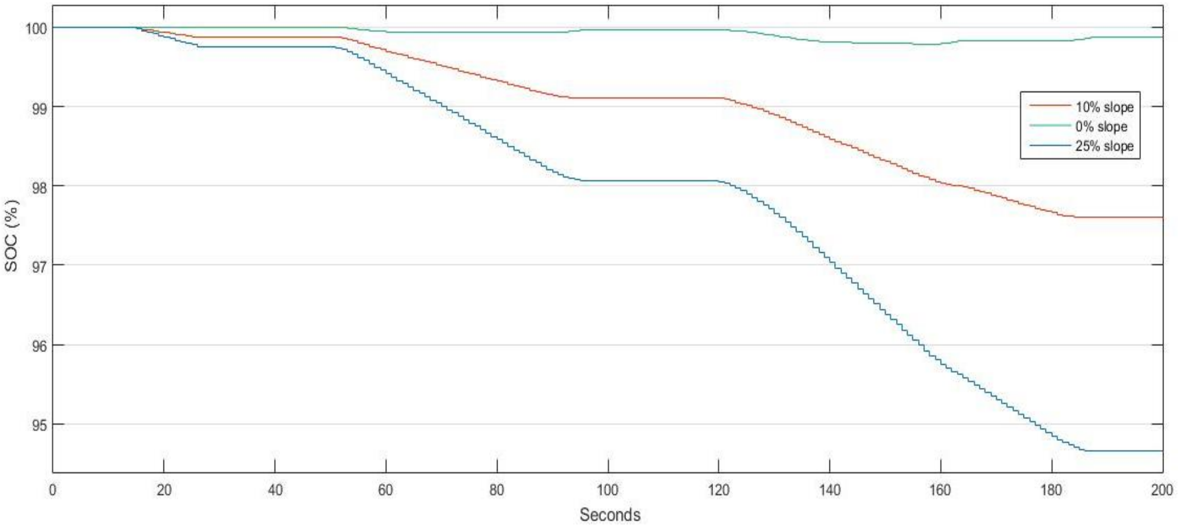


Figure 75: SOC for different slopes for ECE R15 driving cycle

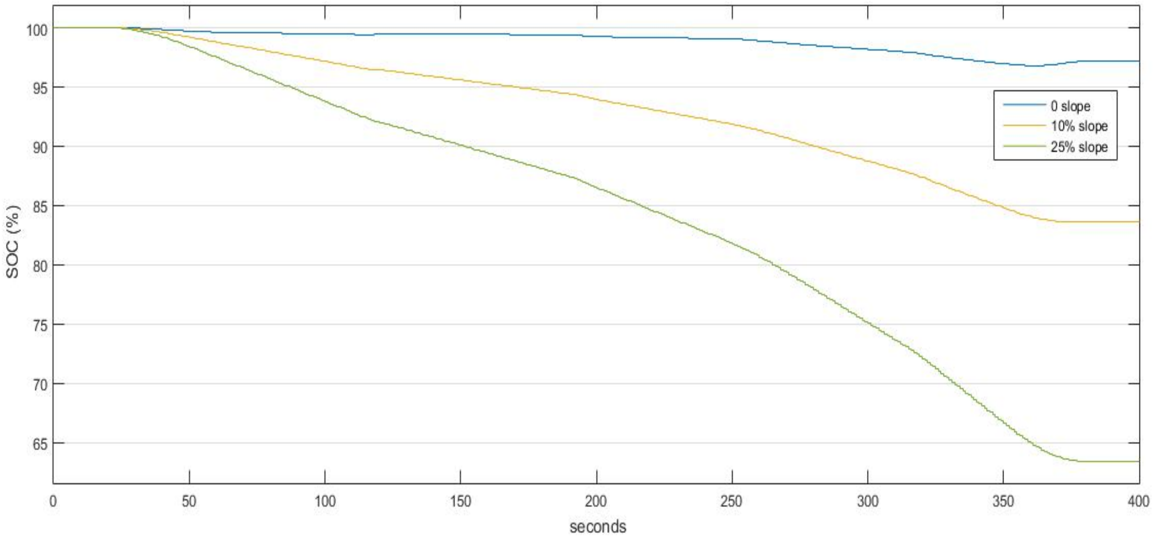


Figure 76: SOC for EUDC driving cycle

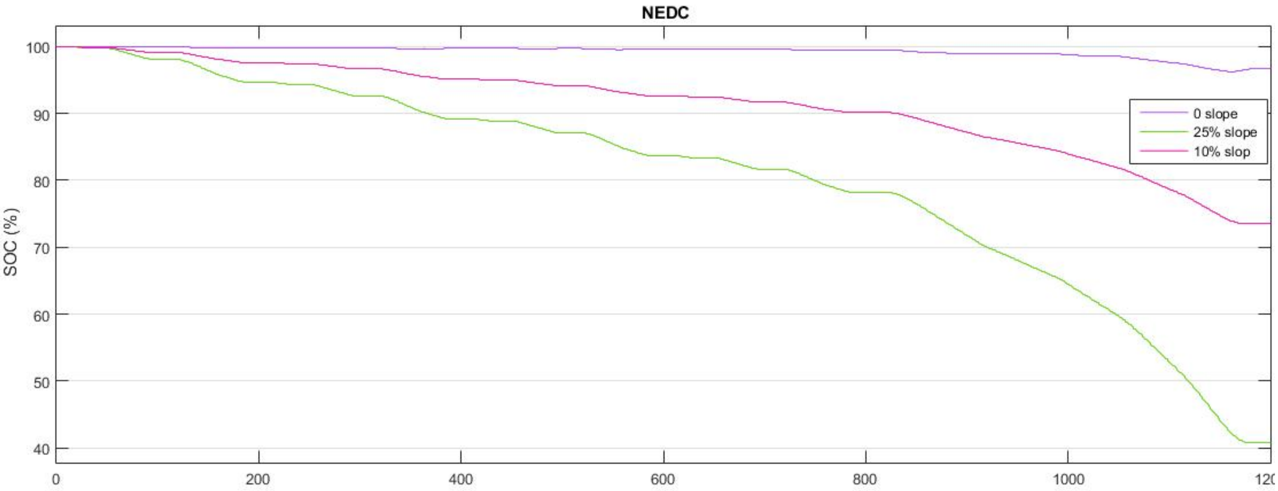


Figure 77: SOC for NEDC driving cycle

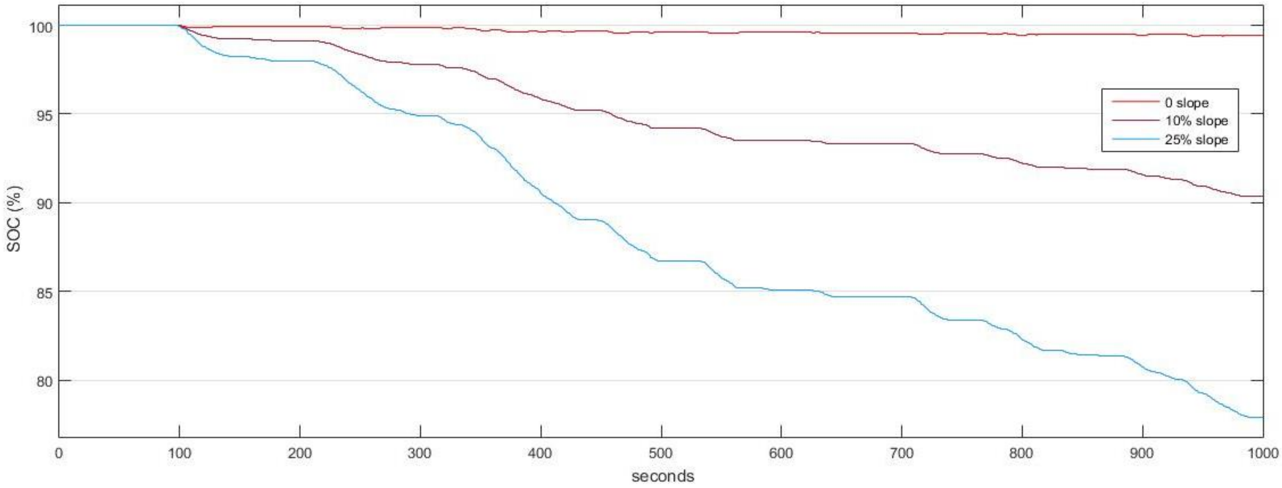


Figure 78: SOC for Artemis (Urban) driving cycle

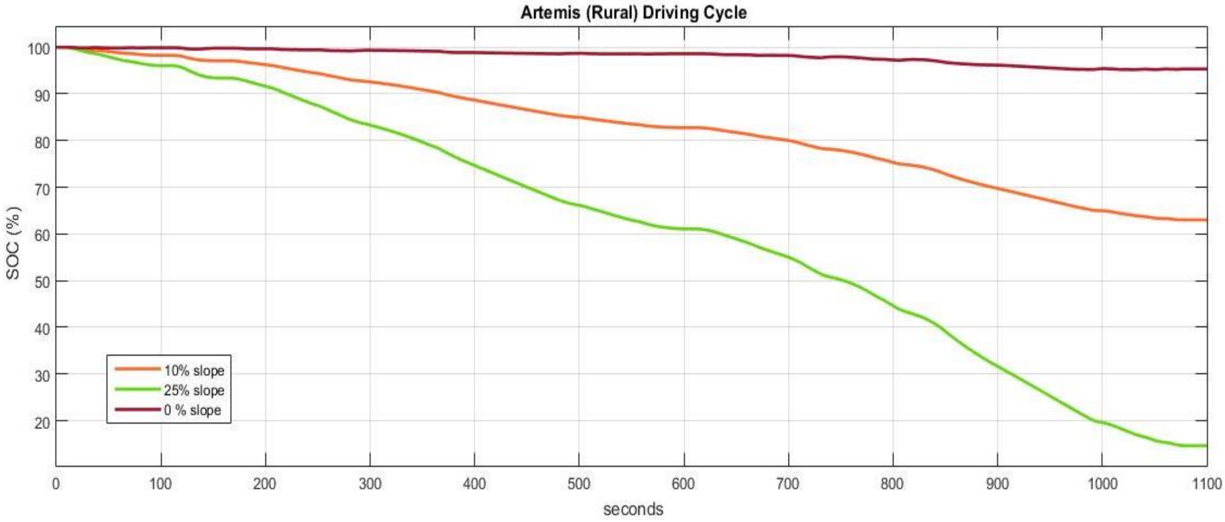


Figure 79: SOC for Artemis (Rural) Driving Cycle

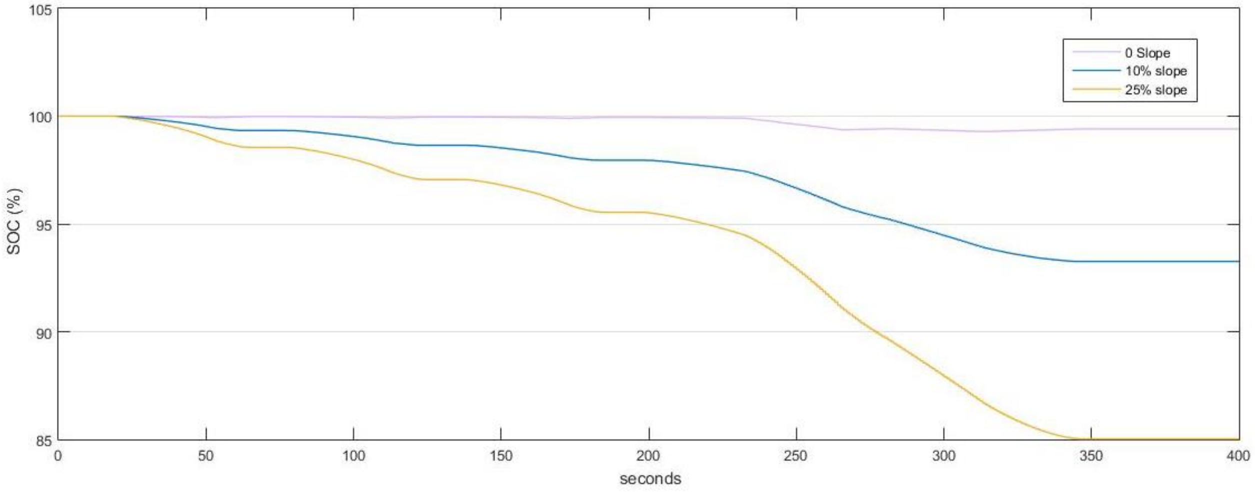


Figure 80: SOCs for SFUDS Driving Cycle

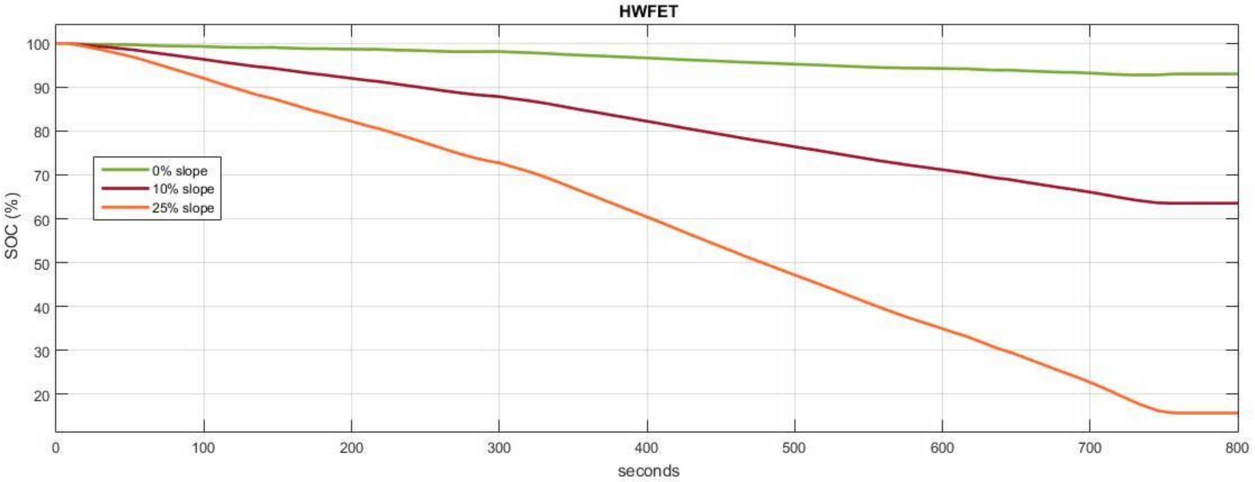


Figure 81: SOCs for HWFET Driving Cycle

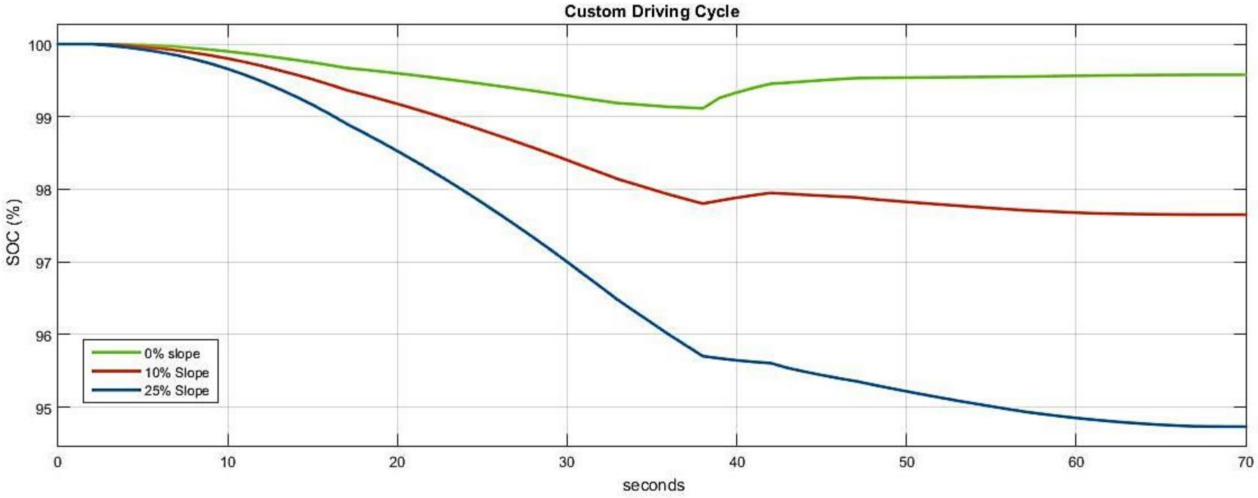


Figure 82: SOC at different slopes for Custom Driving Cycle

Driving Cycle	Distance	Avg. Speed	Avg. Power (kW)	Time(s)	Max.Power	Slope pu	Auxiliary (kWh)	Final SOC (%)
NEDC	11.84	35.53	2.689	1200	26.06	0	0	96.64
NEDC	11.84	35.53	3.689	1200	26.06	0	1	69.64
NEDC	11.84	35.53	44.12	1200	143.43	0.25	1	40.80
NEDC	11.84	35.53	21.8	1200	71.73	0.1	1	73.58
ECE 15	1.12	20.27	12.51	200	24.20	0.1	1	97.61
ECE 15	1.12	20.27	1.686	200	6.17	0	1	99.87
ECE 15	1.12	20.27	25.89	200	54.22	0.25	1	94.66
EUDC	7.37	66.04	7.695	400	26.06	0	1	97.19
EUDC	7.37	66.04	38.21	400	71.73	0.1	1	83.60
EUDC	7.37	66.04	80.6	400	143.43	0.25	1	63.40

Table 4: Power and SOC at the end of driving cycles

Driving Cycle	Distance	Avg. Speed	Avg. Power (kW)	Time(s)	Max.Power	Slope pu	Auxiliary (kWh)	Final SOC (%)
Artemis(Urban)	4.46	16.06	1.68	1000	22.16	0	1	99.43
Artemis(Urban)	4.46	16.06	10	1000	41.74	0.1	1	90.30
Artemis(Urban)	4.46	16.06	21.19	1000	71.05	0.25	1	77.90
Artemis(Rural)	16.02	55.5	5.12	1100	30.93	0	1	95.30
Artemis(Rural)	16.02	55.5	31.58	1100	76.16	0.1	1	63.01
Artemis(Rural)	16.02	55.5	67.41	1100	143.36	0.25	1	14.60
SUFD	3.08	27.72	2.47	400	14.75	0	1	99.41
SUFD	3.08	27.72	16.70	400	45.55	0.1	1	93.30
SUFD	3.08	27.72	34.82	400	102.42	0.25	1	85.00
HWFET	16.52	74.36	9.20	800	18.80	0	1	93.00
HWFET	16.52	74.36	42.25	800	52.75	0.1	1	63.50
HWFET	16.52	74.36	89.86	800	110.71	0.25	1	15.60
Custom	1.07	54.92	6.808	70	33.38	0	1	99.58
Custom	1.07	54.92	32.68	70	74.58	0.1	1	97.60
Custom	1.07	54.92	68.87	70	145.49	0.25	1	94.73

Table 5:Power and SOC at the end of driving cycles

Conclusion:

In this work, I have covered introductory information of Electric Vehicles, with market survey. In addition to it, one can find sufficient information of the resistive forces acting on the vehicle while subject to different driving conditions, which in this work is being represented by standard and custom driving cycles.

The model created in this work is quite simple to understand and gives a fine idea of different forces acting on the vehicle while in motion, and against the slope (gravitational pull). When going through observations obtained via simulations at different slope and at different driving cycles, we can see that battery’s state of charge depends on speed, acceleration, deceleration and slope on which vehicle is subjected. The variations of slope although is quite prominent and also plays a significant role in determining the SOC of battery, therefore range of the vehicle.

Created model offers a path for more work in the terms of batteries. This model can be further studied with different power sources and energy storage devices, such as Ultracapacitors, Fuel cells, Flywheels and more. Thermal modelling for batteries with the effect of ambient temperature can also be included for further work. This model is flexible and easy to modify with the basic knowledge of *MATLAB and Simulink*. One can change data inputs from the specification sheets obtained from manufacturer.

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