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Physical Modeling of Battery and Electric Vehicle

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***Abstract*—Electric vehicles are one of the trending and Emerging technologies nowadays. The advent of electric vehicles has called for an improvement in total energy usage and generation. Batteries are applied in many high-power applications and play a vital role in Electric Vehicle Design. Mathematical models are suitable for initial experiments, analyzing, or making significant engineering decisions. Simulation gives us the virtual image of the real-time situation before the actual design. In this paper, Modeling of batteries and Physical Modeling of Electric vehicles were carried out, and the Parameters of the Battery were analyzed through simulation. Thermal Analysis of Li-ion battery is done by COMSOL Software.**

Keywords-Electric Vehicle, simulation, Battery model, Physical Modeling of EV

I. INTRODUCTION

At present, cherishing the earth's limited petroleum resources, protecting the human survival environment, reducing greenhouse gas emissions, and stopping the global warming trend has become the world's common topic. Car, as the product of modern social industry, brings great convenience and comfort to our life. However, there are also disadvantages. Now automotive fuel consumption has become the subject of oil consumption, and the cars release a large scale of off-gas, significantly harming the natural ecological environment. To solve these serious problems, the auto industry must lay its direction of development on environmental protection, clean, and energy saving.

Batteries have been widely applied in many high-power applications, such as electric vehicles (E.V.s) and hybrid electric vehicles. A suitable battery management system (BMS) ensures battery safety and reliability. Improper operations such as over-current, over-voltage, or over-charging/discharging will cause significant safety issues to the batteries, noticeably accelerate the aging process, and even cause fire or explosion [1]. Therefore, the battery management system (BMS) plays a vital role in ensuring the Safety and performance of batteries. A good battery management system design improves battery life and ensures vehicle safety [2]. Here models are used to estimate the battery state of charge (SOC) and simulate the battery system of an E.V.

Actual system realization may be costly and time-consuming; therefore, simulation of any system is an initial step before designing. Simulation gives us a virtual image of the real-time situation. Here the dynamic model of an electric vehicle will be created with MATLAB/Simulink.

An electric vehicle is predicted to be the next disruptive market force for transportation and technology. They have the potential to revolutionize how energy is used, created, and redirected. The electric Vehicle is one solution to the negative environmental impact of conventional vehicles. However, they have also proven to have many more benefits to society. Modeling of Electric Vehicle is done using MATLAB/SIMULINK software.

Modeling is a way to create a virtual representation of a real-world system, including software and hardware. It is valuable for the vehicle designing conditions that might be difficult to reproduce with hardware prototypes alone, especially in the early phase of the design process when hardware may not be available. The physical modeling approach is used to model the electric Vehicle, which is a way of modeling and simulating systems that consist of fundamental physical components. It uses a physical network approach, where simscape blocks correspond to physical elements, such as gears, tires, and motors.

II. BATTERY MODEL OF ELECTRIC VEHICLE

The battery of an electric vehicle is a crucial part of the Vehicle's power system, which is very important for the Vehicle's economy and security. The battery pack consists of various batteries connected in series. We have modeled each battery using an equivalent circuit, a relatively simple electrical circuit containing a voltage source and several resistors and capacitors. Another critical step while sporting a battery is choosing the appropriate parameters of the physical blocks so that it responds as similarly as possible to a biological battery cell. One of the possible ways to determine these parameters is by performing parameter estimation, where we define the design requirements and cost functions to optimize the model parameters.

Electric Vehicles have attracted researchers because electric Vehicle needs electric power to run the motors connected to E.V.s [3]. The Electric power used is generated with the help of batteries.

A. Equivalent Battery Model

The equivalent Battery model (as shown in fig.1) is the most representative of the equivalent circuit model, which is the foundation of another complex comparable circuit model. In the model, the capacitance C_p and resistance R_p (to describe the potential) are in parallel and then connected to the voltage source V_{OC} (to tell open voltage) and resistance R_s (battery resistance). With the battery working conditions and internal state changing.

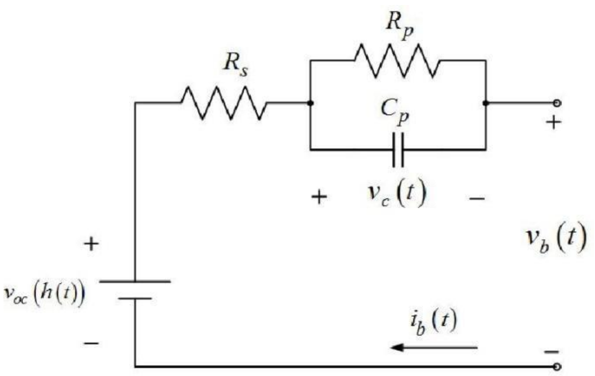

Fig1.Thevenin equivalent circuit model

B. Battery Charger Model and SoC Estimation

A battery charger is a device that stores energy in a battery by running an electric current through it. The charging protocol (how much voltage or current for how long and what to do when charging is complete) depends on the size and the type of the battery being assigned.

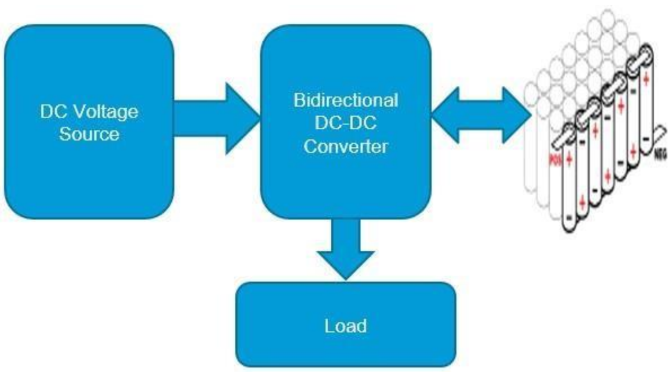

Fig2.Battery Charger model

Battery SoC is the fraction of the total energy or battery capacity that has been used over the total available from the battery. It shows the remaining capacity of the battery while in use. The state of health measures a battery's ability to store and deliver electrical energy. A C-rate measures the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means the discharge current will release the entire battery in one hour. These all are the parameters related to the battery. In batteries, battery capacity changes can be monitored by tracking the number of electrical charges going in/out.

$$q(t) = q_o + \int I(t).\,dt$$

$$SoC(t) = \frac{1}{C}\int I(t).\,dt$$

$$SoC(t) = SoC(t-1) + \frac{1}{C}\int I(t).\,dt$$

Where;
q(t)- charge w.r.t time I(t)-
Battery Current time at Instant
SoC-State of charge
SoC(t-1)- Initial SoC
dt-Step Time
C- Nominal capacity of the Battery in Ah
1/C- Total capacity of the battery

This method measures the battery charge starting at a well-defined initial point, e.g., the state of total payment. The charge value resulting from this process is relative to this reference point. Since demand cannot directly be measured, we have to calculate it by measuring the current and integrating it over time.

C. Battery Management System

Battery management systems (BMSs) are real-time systems controlling many functions essential to the correct and safe operation of E.V.s' electrical energy storage system. This includes monitoring temperatures, voltages, currents, maintenance scheduling, battery performance optimization, failure prediction or prevention, and battery data collection/analysis [4].

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Fig3.Battery Management System(BMS)

All lithium-ion (Li-ion) batteries require a BMS. All Li-ion batteries will fail if overcharged, wholly discharged, or operated outside their safe temperature window. The lithium ion batteries can be used only under specified conditions, and therefore battery management system (BMS) is required to monitor the battery state and ensure the Safety of operation. Each Li-ion cell type has its safe operating area, making it necessary to program the BMS accordingly. The different BMS structures can be compared, and their advantages can be noted depending on battery system size. Moreover, typical functions of BMS have been described with particular attention to the state of charge (SoC) estimation.

D. Cell Balancing

In a multicellular battery (serial connection), slight differences in capacity among cells appear due to production tolerances or operating conditions and tend to increase with each charging cycle. Moreover, self-discharge processes lose some cell capacity over time (typically 2–10% depending on temperature and SoC) [5]. If the temperature distribution in the pack is not equal, hotter cells tend to have higher capacity losses, eventually leading to an imbalance.

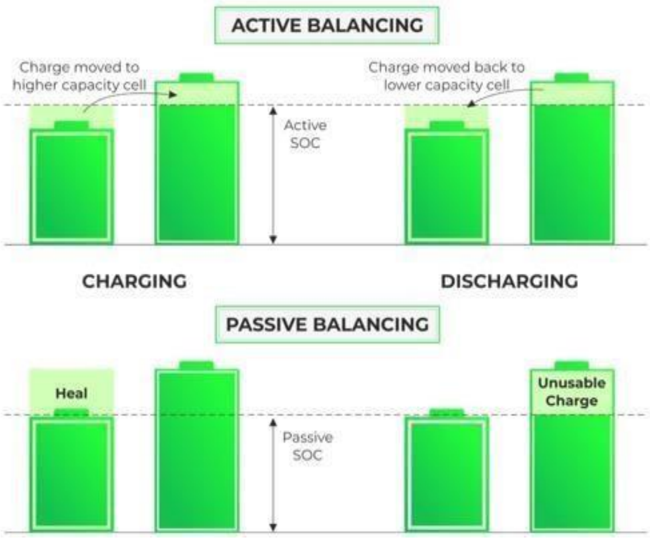
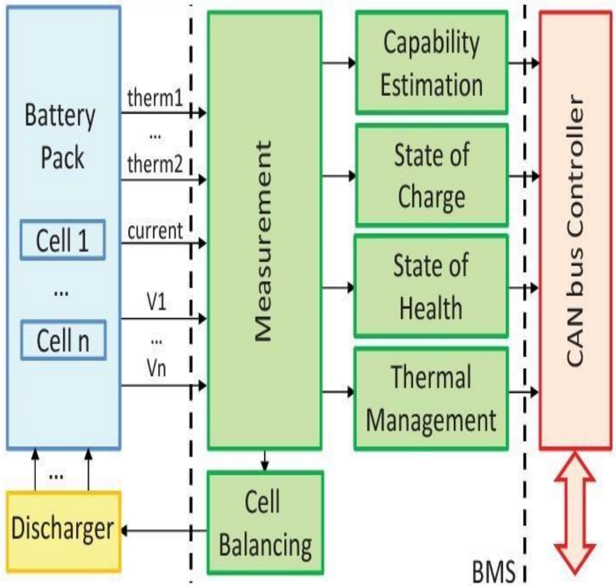


Fig4. Cell Balancing

Such weaker cells also become overstressed during charging. This continuing imbalance causes a drift in capacity until the most invalid cell eventually fails. Cell balancing is a way of equalizing the charge of all cells in the chain. Many different balancing methods exist.

A primary classification is done by dividing balancing methods into active and passive ones. In the case of dynamic balancing, the energy is transferred between adjacent cells. Passive balancing methods usually use a



switching resistor that is switched on for the most charged cell in a battery string. The cell is discharged, and energy is dissipated as heat [6,7].

E. Vehicle Parameters

S.no	Parameters	Value	Unit
1	Rated Power	350 / 0.47	Watts/Hp
2	Rated Voltage	24V	Volts
3	Rated Current	19A	Amps
4	Rated Speed	1500	RPM
5	Load Torque	2	Nm

F. Battery Calculations

Battery Parameters	Value
Nominal Voltage	24V
Current Consumption by Motor	14.5A
Watt-Hour Rating (Assuming 20% more than source energy)	420 Wt-hr
Ampere Hour Rating	17.5 Ah
Battery Rating	**24V,17.5Ah**

III. PHYSICAL MODELLING OF ELECTRIC VEHICLE

The electric vehicle (E.V.) market continues to grow, with over seven million E.V.s worldwide [8]. The International Energy Agency (IEA) forecasts that these numbers will exceed 125 million by 2030[9]. Electric Vehicles have attracted researchers because electric Vehicle needs electric power to run the motors connected to E.V.s [10].

Vehicle modeling occurs in different forms, such as mathematical models, steady-state models, multi-physics domain physical modeling, dynamics, and transient modeling [11]. With significant advancements in recent years, MATLAB/Simulink software is a tool capable of modeling complete E.V.s of different levels of fidelity and detail and has become an invaluable modeling platform.

Kerem, as electric vehicle technology in the world develops, interest in electric vehicles will increase. Fossil fuel is the leading energy resource for these vehicles. In the 21st century, oil production reached a peak. Estimates indicate that petroleum and natural gas will run out by 2042 (Shafiee and Topal, 2009). This shows that environmental pollution and petrol dependence will decrease [12].

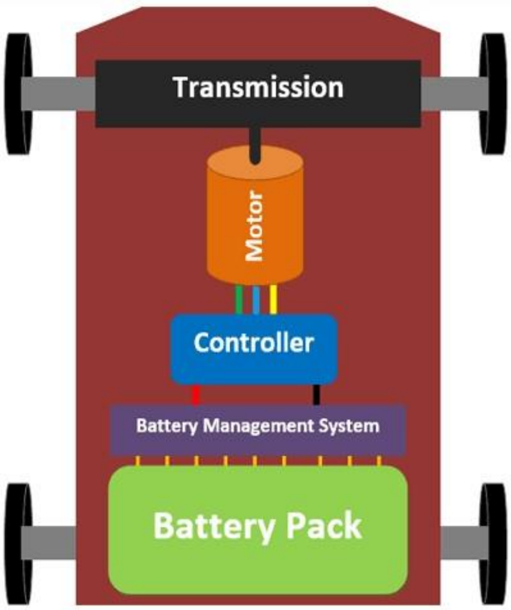
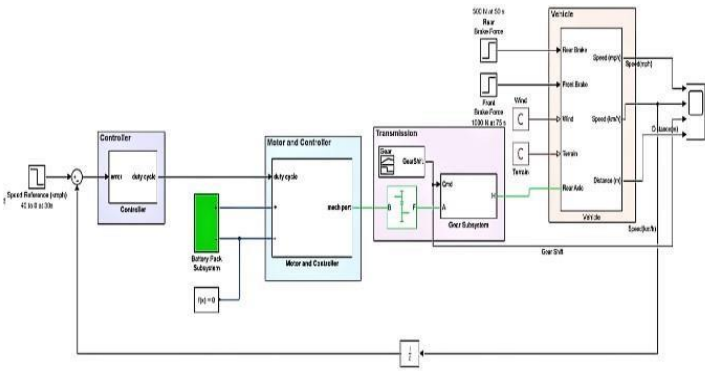


Fig5. Block Diagram of Electric vehicle

This software features a variety of shipped sample models for simulation of pure battery-electric and hybrid electric vehicles of different configurations and types [13-14].

As you can see, the Battery Pack, Battery Management System (BMS) Controller, Motor, and the Transmission unit form the significant components of an E.V. An electrical motor replaces the Engine of a conventional I.C. engine, and the Battery Pack replaces the fuel tank. Of all the features, only the Battery Pack and Motor alone contribute to more than 50% of the total Vehicle's weight and price**.**

In the battery model, it is necessary to estimate the battery state of charge (SOC) and simulate the battery management system of an E.V. Still, it is challenging to model and affect the battery management process [15]. Every BMS measures only three vital parameters of the battery: The Voltage, current, and Temperate of the cell. It constantly compares these values with safety limits and disconnects the load if they exceed the threshold values. Apart from safety purposes, th**e** BMS is also used for computational purposes, like measuring the SOC and SOH of a battery.



Here Physical modeling of an Electric Vehicle consists of a battery pack with 24 cells of 4.2V each. This model has an electric motor that provides the power input instead of a combustion engine; a closed-loop controller has also been developed so that the motor senses and reacts to the Vehicle's speed. DC motor converts the electrical energy into rotational mechanical energy [16]. Implementation of a DC motor drive mechanism with PWM pulse width modulation actuation is discussed, along with performance considerations.

Controlling the speed of the DC motor is a critical problem. One approach to managing the DC motor speed would be adding a potentiometer to the line between the battery and the DC motor; however, this would lead to a rapid drain on the battery. Instead of a pulse width modulation, a PWM controller is used. The PWM system receives various duty cycle values as input and then modulates the battery voltage as pulses to a load.

Next is the transmission system, which consists of three main components, i.e., the Actuator block that converts the gear shift signal to clutch plate pressure and outputs the force required to engage the clutch. Disk friction clutch restricts torque transmission between the driving and driven shafts.

Then, the Gears are used to build a 3-speed transmission system. Simple Gear blocks are used with two different gear ratios to create high and low gears.

Eventually, the Vehicle system is modeled using the physical blocks from the Simscape Driveline, consisting of the following subsystems, i.e., the Brake system applied at the rear and front wheels. It has been modeled using the Loaded Contact Rotational Friction block that transmits torque between two rotating surfaces.

A Vehicle Body block is used in conjunction with a set of Tire blocks to model the vehicle system of a two-axle vehicle body in longitudinal motion. The later Sensor system is modeled using The Ideal Translational Motion Sensor block, which measures the vehicle velocity and the distance traveled[16].

Finally, these subsystems are connected through physical connections to build a closed-loop simulation model. Additionally, the reference speed that has to be tracked is added, and a P.I. controller to output the required duty cycle control signal is also used.
Some researchers have already designed the E.V., like E. Schultz, who designed and modeled an electric vehicle. This Vehicle consumes 148.3 Wh/km of energy. Also, explain that a large part of the energy loss is caused by the auxiliary loads, the lighting system, the security systems, the comfort systems, and the Battery [17]. X. D. Xue tried to determine the appropriate electric motor for electric vehicles. Electric motors were compared according to efficiency, cost, Safety, and weight criteria [18]. Similarly, many works are going on concerning Electric vehicles. Therefore, modeling Electric vehicles is one of the important accepts to work on to determine or increase the performance, Efficiency, Speed, etc.

G. Vehicle Design Parameters

Sl.no	Vehicle Parameters	Value	Unit
1	Rider Mass	80	Kg
2	Vehicle Mass	237	Kg
3	CG Height	254	mm
4	Drag Coefficient	1.2	-
5	Front Axle	1520	mm
6	Rear Axle	1400	mm
7	Front Area	1.33	m2
8	Tire Inertia	1e-3	in
9	Rolling Resistance	0.005	-

IV. THERMAL ANALYSIS OF Li-ION BATTERY

COMSOL is mathematical modeling software that drives breakthroughs in physics and engineering. COMSOL
Multi physics is a cross-platform finite element aanalysis, solver, and multiphasic simulation software. It allows conventional physics-based user interfaces and coupled partial differential equations (PDEs) systems. COMSOL provides an IDE and unified workflow for electrical, mechanical, fluid, acoustics, and chemical applications.

The Lithium-ion (Li-ion) battery is considered the first–choice candidate for a power source for E.V.s due to its many advantages, such as low self-discharge rate, high efficiency, and high power-to-weight and energy-to-weight ratios [19]. Mainly, we investigate the temperature distribution and the heat generation characteristics of a cylindrical Li-ion battery module. Adverse effects of uneven temperature, including thermal runaway, low-temperature performance, and performance degradation, are described.

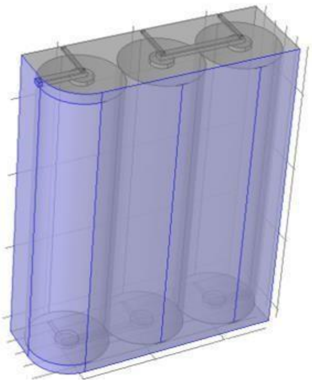


Fig7. .3D Battery Model

The energy balance equation for a cylindrical Li-ion battery cell is developed by considering the energy conservation law, and the equation can be expressed as follows:

$$\rho C_p \frac{\delta T}{\delta t} = \frac{1}{r}\frac{\delta}{\delta r}\left(k_r r \frac{\delta T}{\delta r}\right) + \frac{1}{r^2}\frac{\delta}{\delta \Psi}\left(k_a \frac{\delta T}{\delta r}\right) + \frac{\delta}{\delta z}\left(k_z \frac{\delta T}{\delta z}\right) + \dot{Q}$$

Þ is the density of active battery material (kg/m^3), and C_p is for specific heat capacity (J/kgK). T denotes the absolute temperature (K), and r represents the radius of the battery cell (m).k_r, k_a, kHz and denote the thermal conductivity for radial-axial and z directions, respectively (W/mK). Furthermore, Q represents the volumetric heat generation rate for the battery cell(W) [20].

Later lumped model for the Li-ion battery is applied for heat transfer, and the equation can be simplified as follows:

$$\rho C_p \frac{\delta T}{\delta t} = hA(T - T_{amb}) + \dot{Q}$$

Where T_{amb} is the absolute temperature at the ambient condition (K).

In 1995, John Newman and Caroline [21] published the first equation related to the heat transfer in a single Li-ion battery cell. The above equation confirms Newman's equation of heat transferring for a Li-ion battery cell.

The 3D simulation model for the Li-ion battery cell was developed as a model by using COMSOL Multi physics 5.5 software [22]. The 3D model is used to model the temperature profile of he battery cell.

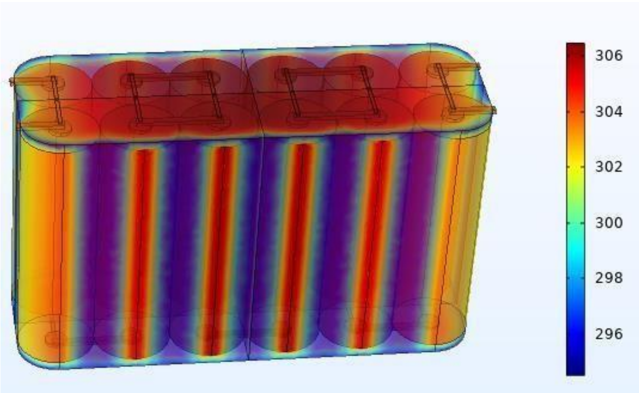
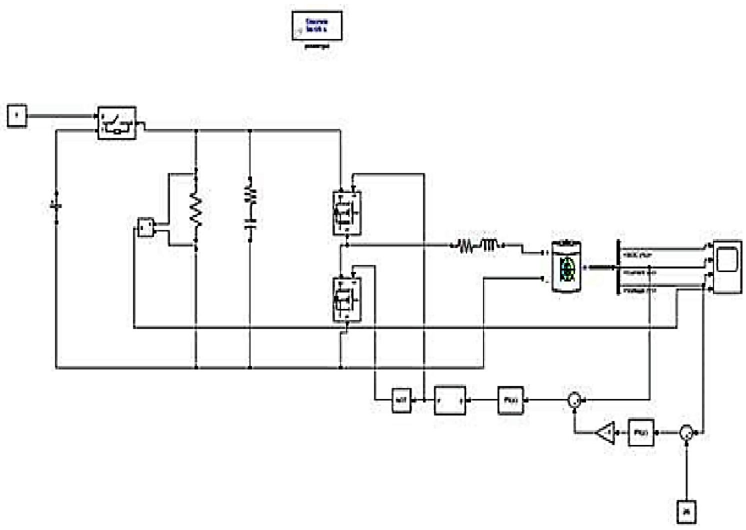
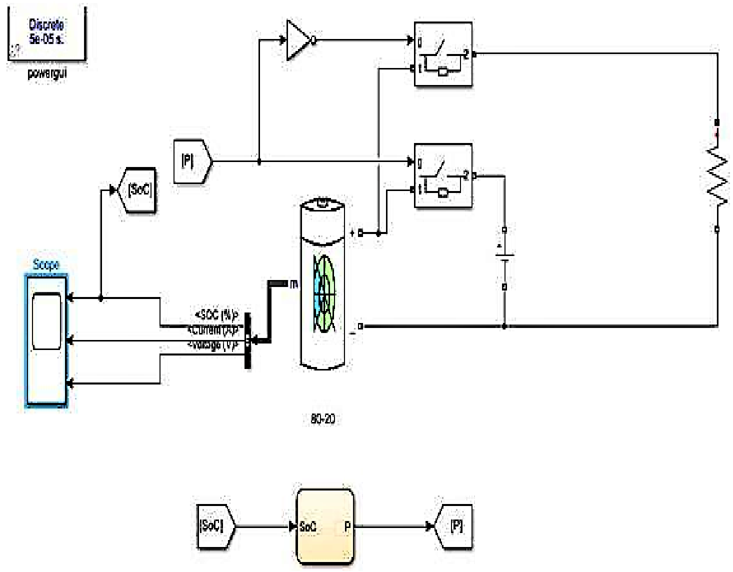


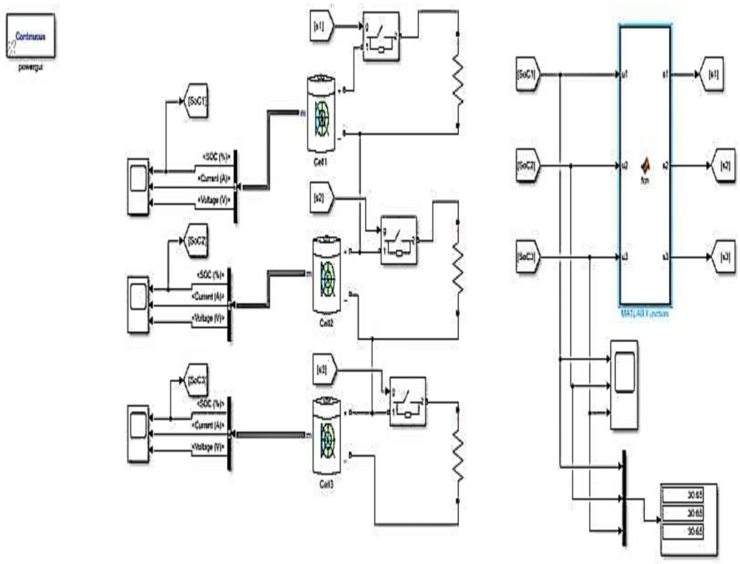
Fig8. Temperature Distribution Results

V. SIMULATION AND RESULTS

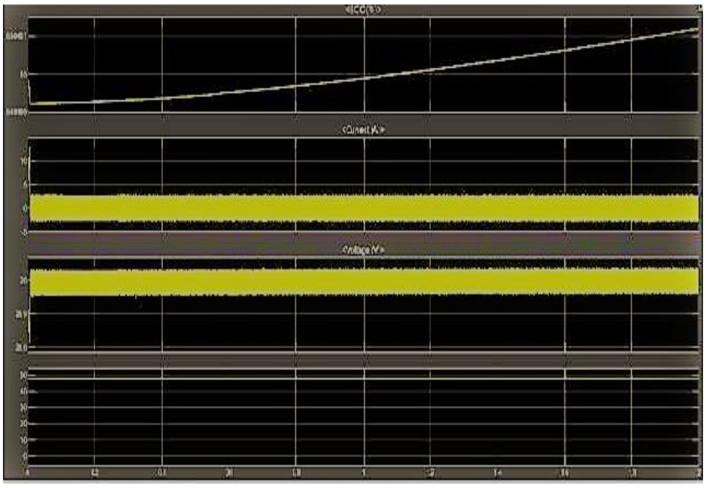
Simulations are carried out for the above models, i.e., Battery modeling and physical modeling of electric Vehicle is done per the parameters mentioned above in MATLAB. Thermal analysis of Li-Ion is carried out in COMSOL Software, and the results are shown below.

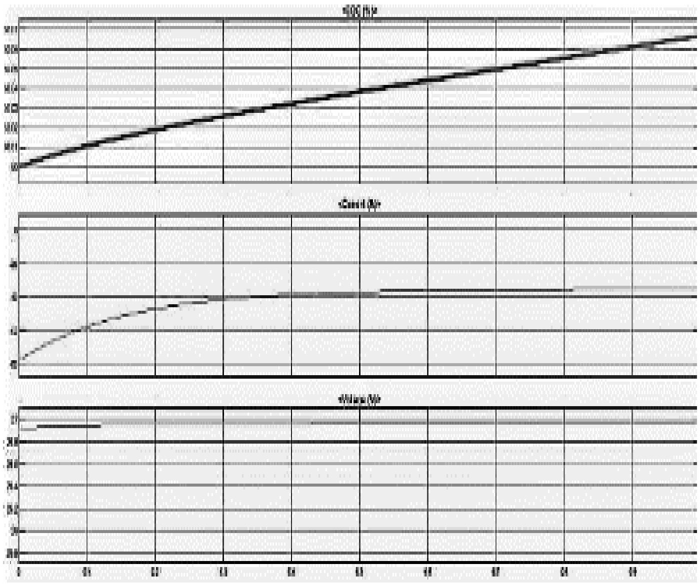


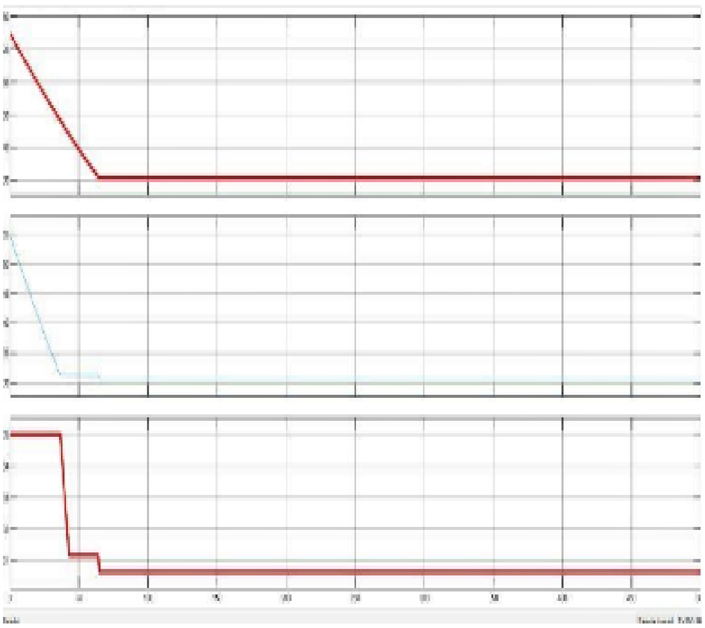


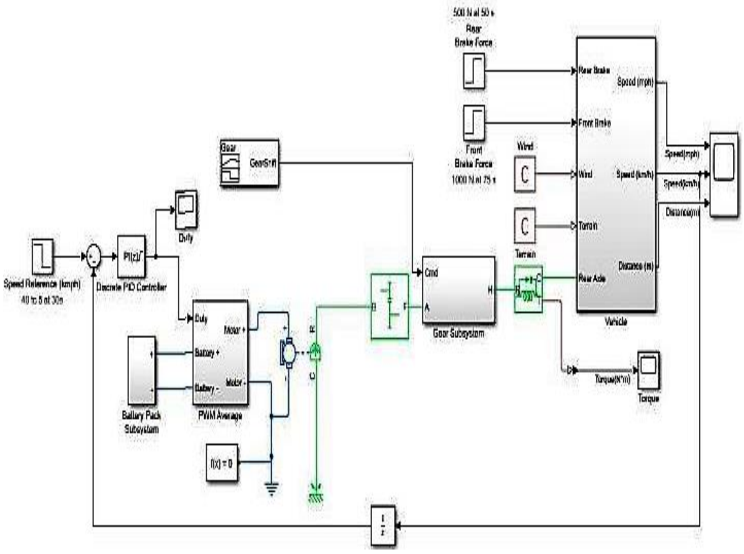


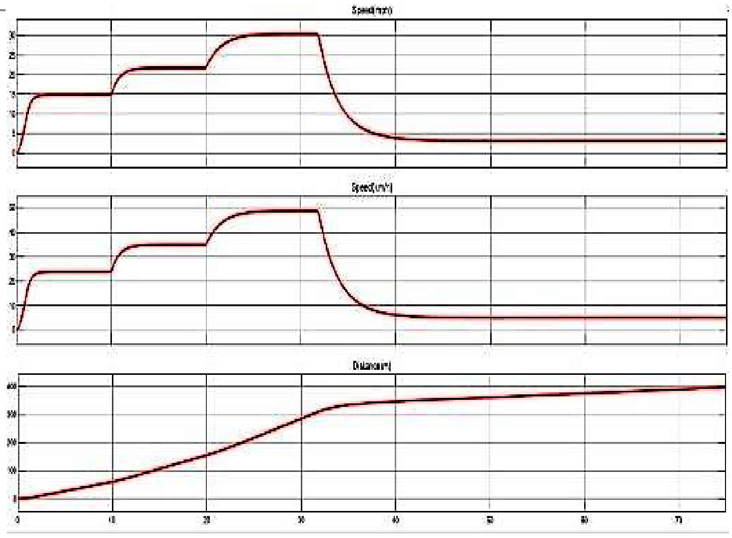
Battery Charger
BMS



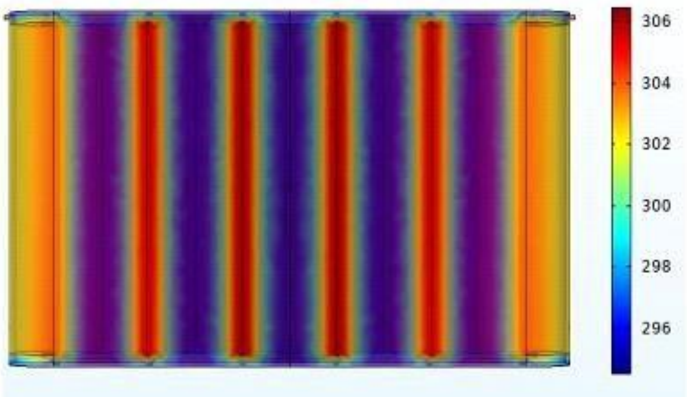


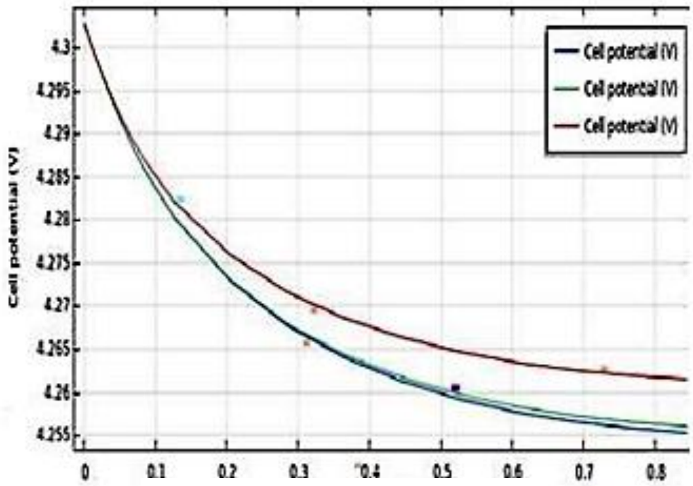




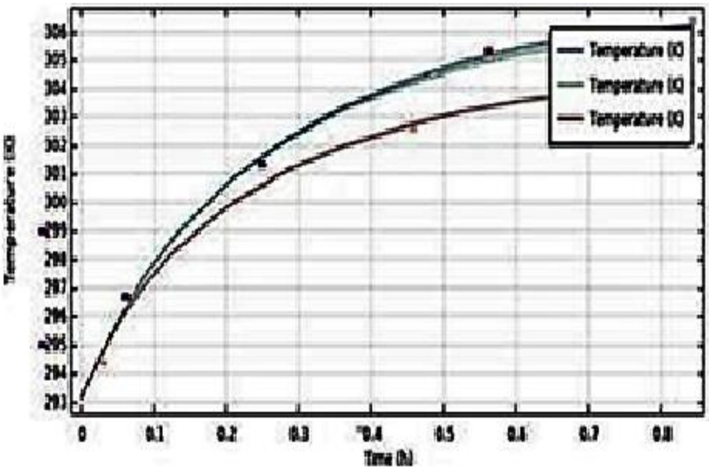


Physical Modeling of Electric Vehicle





Time (h)	Temperature (K)
3.0846E-4	293.17
6.1691E-4	293.19
0.0012338	293.23
0.0024677	293.30
0.0049353	293.45
0.0074030	293.59
0.012338	293.88
0.017274	294.15
0.027144	294.68
0.037015	295.19
0.046885	295.67
0.066627	296.55
0.086368	297.37
0.12585	298.74
0.20482	300.76
0.28482	302.26
0.36482	303.38
0.44482	304.23
0.52482	304.90



Temperature Distribution Result

VI. CONCLUSION

BMS of E.V. has been considered, especially in battery modeling, state estimation, and battery charging. Physical modeling of electric vehicles and simulating the system consists of fundamental physical components (gear tires and motors). Once we run the simulation, it is evident that the controller can reach the reference velocity of 40 km/h and drop to zero after 30 seconds. The sudden change in the vehicle speed accounts for the gear shift. Analyzing the output concerning the gears and brakes has been done. The thermal performance of the Li-ion battery module is discussed by considering simulation methods. Simulation is conducted, and the corresponding temperature and cell potential plots are observed.

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