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Charging and Discharging Control of Li-Ion Battery for Electric Vehicle Applications

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ABSTRACT

This paper presents the detailed simulation and analysis of a battery charging and discharging control for electric vehicle (EV) application using proportional and integral control. A lithium-Ion battery model in MATLAB is considered for this study. The purpose of study is to perform a detailed analysis of the charging and discharging operation and observe the behavior of the key parameters of the battery. To realize these two voltages sources have been used, i.e., one is the battery itself and the other is the DC voltage source. The two different voltage source is feeding to a common load. The DC voltage source feeds the load when the battery is in charging mode. When the battery supply is available then it is discharging to feed the load and its control is designed to generate the reference pulses for DC-DC converter. The two scenarios have been simulated and results are recorded which shows the effective operation of charging and discharging of a battery source.

KEYWORDS: *Battery, Lithium-Ion, MATLAB Simulink, Charging, Dis-charging, PI controller*

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I. INTRODUCTION

The global warming concerns are rising every year and this is a serious issue which needs to be addressed seriously to reduce its cons in near future and for upcoming generations. Thus, the whole world is in race of reducing carbon emission. Transport sector has the highest dependence on fossil fuels which accounts for 37% of CO_2 emissions from end-use sectors [1].

Hence, there is accelerating interest in the electric mobility in recent years and so the importance of battery storage system has increased enormously. The battery plays vital role in EVs operation whether it is a hybrid electric vehicle (HEVs) or plug-in-HEVs. There is need for optimizing the use of battery power and to minimize the fossil fuel consumption to achieve the goal of carbon free environment. This has led industries to think of the battery with higher power density, slow discharge rate when not in use, large number of charge cycle, and economical.

An electric vehicle battery is also called as the traction battery. It is a rechargeable battery that discharges to power the electric motors of a battery electric vehicle (BEV) or hybrid electric vehicles (HEVs) [2]. The lithium-ion batteries are specially designed to store high electric charge which is termed as the charging capacity. Batteries for electric vehicles are characterized by their relatively high power-to-weight ratio, specific energy, and energy density; smaller and lighter batteries are desirable because they reduce the weight of the vehicle and therefore improve its overall performance [3].

The most common battery type in modern electric vehicles are lithium-ion and lithium polymer, because of their high energy density compared to their weight. Other types of rechargeable batteries used in electric vehicles include lead–acid (flooded, deep-cycle, and valve regulated lead acid), nickel-cadmium, nickel–metal hydride, and, less commonly, zinc–air, and sodium nickel chloride (zebra) batteries [4]. The amount of electricity (i.e., electric charge) stored in batteries is measured in ampere hours or in coulombs, with the total energy often measured in kilowatt-hours (kWh).

The charging and discharging phenomenon in battery in significant for its real time operation as well as its durability. The control of charging and discharging play vital role in the EV operation. This paper simulates and analyze the mathematical model of charging and discharging of a lithium-Ion battery. A PI controller has been used to tune the proper reference signals for the DC-DC pulse width modulation block [5], [6]. Based upon the controller response the PWM block generated the pulses to be applied to the switches of DC-DC converter used for battery charging.

To analyze the key parameters i.e., state of charge (SoC %), battery current, Battery voltage associated to it, various scenarios has been considered and simulated to draw suitable conclusions. This study provides the reader the insight of battery charging and discharging and its control especially for electric vehicles (EVs) application. The software tool has been used is MATLAB Simulink version 2020b.

II. Battery properties

A. Types of Energy Storage for EV application

Energy storage systems, usually batteries, are essential for hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and all-electric vehicles (EVs) [8]. The following energy storage systems are used in HEVs, PHEVs, and EVs.

- *Lithium-Ion Batteries:* Lithium-ion batteries as shown in Fig 1 are currently used in most portable consumer electronics such as cell phones and laptops because of their high energy per unit mass relative to other electrical energy storage systems. They also have a high power-to-weight ratio, high energy efficiency, good high-temperature performance, and low self-discharge. Most components of lithium-ion batteries can be recycled, but the cost of material recovery remains a challenge for the industry.

Fig 1 A typical battery pack for EV application

The U.S. Department of Energy is also supporting the Lithium-Ion Battery Recycling Prize to identify solutions for collecting, sorting, storing, and transporting spent and discarded lithium-ion batteries for eventual recycling and materials recovery [9]. Most of today's PHEVs and EVs use lithium-ion batteries, though the exact chemistry often varies from that of consumer electronics batteries. Research and development are ongoing to reduce their relatively high cost, extend their useful life, and address safety concerns regarding overheating.

- *Nickel-Metal Hydride Batteries:* Nickel-metal hydride batteries, used routinely in computer and medical equipment, offer reasonable specific energy and specific power capabilities. Nickel-metal hydride batteries have a much longer life cycle than lead-acid batteries and are safe and abuse tolerant. These batteries have been widely used in HEVs. The main challenges with nickel-metal hydride batteries are their high cost, high self-discharge and heat generation at high temperatures, and the need to control hydrogen loss.
- *Lead-Acid Batteries:* Lead-acid batteries can be designed to be high power and are inexpensive, safe, and reliable. However, low specific energy, poor cold-temperature performance, and short calendar and cycle life impede their use. Advanced high-power lead-acid batteries are being developed, but these batteries are only used in commercially available electric-drive vehicles for ancillary loads.
- *Ultra capacitors:* Ultra capacitors store energy in a polarized liquid between an electrode and an electrolyte. Energy storage capacity increases as the liquid's surface area increases. Ultra capacitors can provide vehicles additional power during acceleration and hill climbing and help recover braking energy. They may also be useful as secondary energy-storage devices in electric-drive vehicles because they help electrochemical batteries level load power.

Battery parameters

The key parameters to study the battery operating characteristic and properties are listed below [10]:

A. *Storage Capacity:* It determines for number of hours for which the battery can be discharged at a constant current to a defined cut-off voltage. It is represented by the Coulomb SI unit (Amperes per second) but since this unit is usually very small, the Ampere-hour (Ah) unit is used instead (1 Ah represents 3600 C). The value of this capacity depends on the ambient temperature, the age of the battery, and the discharge rate. The higher the discharge rate, the lower the capacity, although it affects each battery technology differently. Additional to the Ampere-hour unit, the storage capacity can also be defined in Watt-hours (Wh=V x Ah), where 1 Wh represents 3600 J.

B. *Energy Density:* The energy density is the amount of energy that can be stored, per cubic meter of battery volume, expressed in Watt-hour per cubic meter (Wh/m3). This is a very important parameter to select a specific battery technology for transportation applications, where space availability is critical.

C. *Specific Power:* This parameter is defined as the power capacity per kilogram of battery, in W/kg. Some battery technologies offer high energy density but low specific power, which means that even though they can store a large amount of energy, they can only supply a small amount of power instantly. In transportation terms, this would mean that a vehicle could run for a long distance, at low speed. On the contrary, batteries with high specific power usually have low energy density, because high discharge currents usually reduce the available energy rapidly (e.g., high acceleration).

D. *Cell Voltage:* The cell voltage is determined by the equilibrium thermodynamic reactions that take place inside the cell; however, this value is often difficult to measure and therefore, the open circuit voltage (OCV) measured between the anode and cathode terminals is used instead. For some battery technologies (e.g., lead-acid), the OCV can be used as a basic estimate of the state of charge (SoC). Another measure often used is the closed-circuit voltage (CCV), which depends on the load current, state of charge, and cell's usage history. Finally, battery manufacturers provide the nominal voltage value, from the cell's characterization and therefore, cannot be experimentally verified.

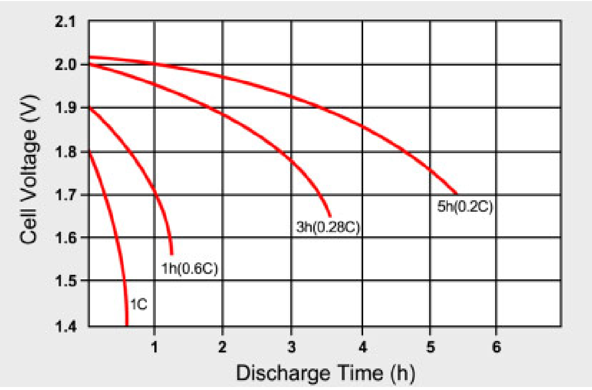


Fig 2 Typical discharge curves of lead acid as a function of C-rate

E. *Charge and Discharge Current:* During the discharging process in a battery, electrons flow from the anode to the cathode through the load, to provide with the required current and the circuit is completed in the electrolyte. During the charging process, an external source supplies with the charging current and the oxidation takes place at the positive electrode while the reduction takes place at the negative electrode. For practical purposes, the term C-rate is used to express the charge or discharge current relative to the rated capacity. For example, a discharge rate of 1 C means that the battery will be fully discharged in 1 h. Charge and discharge rates of a battery are governed by C-rates.

The capacity of a battery is commonly rated at 1C, meaning that a fully charged battery rated at 1Ah should provide 1A for one hour. The same battery discharging at 0.5C should provide 500mA for two hours, and at 2C it delivers 2A for 30 minutes. Losses at fast discharges reduce the discharge time and these losses also affect charge times. Fig 2 illustrates the discharge times of a lead acid battery at various loads expressed in C-rate.

F. *A C-rate:* The C-rate of 1C is also known as a one-hour discharge; 0.5C or C/2 is a two-hour discharge and 0.2C or C/5 is a 5-hour discharge. Some high-performance batteries can be charged and discharged above 1C with moderate stress. Table 1 illustrates typical times at various C-rates.

G. *State of Charge:* The state of charge (SoC) defines the amount of stored energy relative to the total energy storage capacity of the battery. Depending on the battery technology, different methods are used to estimate this value.

H. *Depth of Discharge:* Often referred to as DoD (in %), this parameter expresses the battery capacity that has been discharged relative to the maximum capacity. Each battery technology supports different maximum recommended levels of DoD to minimize its impact on the overall cycle life.

I. *Cycle Life:* The cycle life determines the number of charge/discharge cycles that the battery can experience before it reaches a predetermined energy capacity or other performance criteria. The current rate at which the battery is charged/discharged as well as environmental conditions (e.g., temperature and humidity) and the DoD can affect this number, since it is originally calculated by the manufacturer based on specific charge and discharge conditions.

J. *Self-discharge:* This parameter defines the reduction in energy capacity of the battery under no-load conditions (e.g., open circuit), because of internal short-circuits and chemical reactions. This parameter can be affected by environmental conditions such as temperature and humidity, as well as the DoD and the battery's charge/discharge history. Additionally, this parameter is particularly important for long-term shelf storage of batteries.

K. *Round-Trip Efficiency:* Due to internal losses and material degradation, not all the energy supplied to the battery during charging can be recovered during discharge. The amount of energy that can be taken from the battery during the discharging process over the energy supplied determines the round-trip efficiency. This efficiency is sensitive to the charging and discharging currents. At higher currents, thermal losses increase and therefore the efficiency is reduced

III. Battery parameters

Before Objective behind this study is to understand the concept of power flow and control in a typical battery. For this purpose, a Simulink model of battery charging, and discharging has been developed in MATLB Simulink using SimPowerSystem library. The mathematical simulation models of various component from Simulink are utilized to develop the model and study the various dynamics during battery operations such as charging/discharging. Following models have been imported from Simulink library to make the circuit shown in Fig 3.

- Battery (Li-Ion)
- DC voltage Source
- Bi-directional DC-DC converter
- Common Loads for two different sources

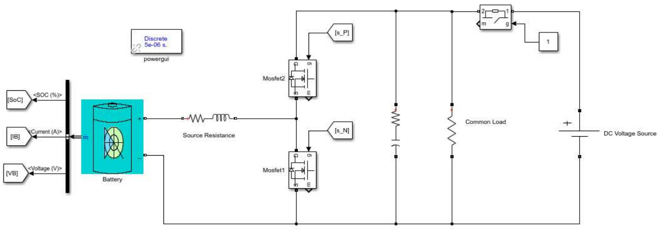
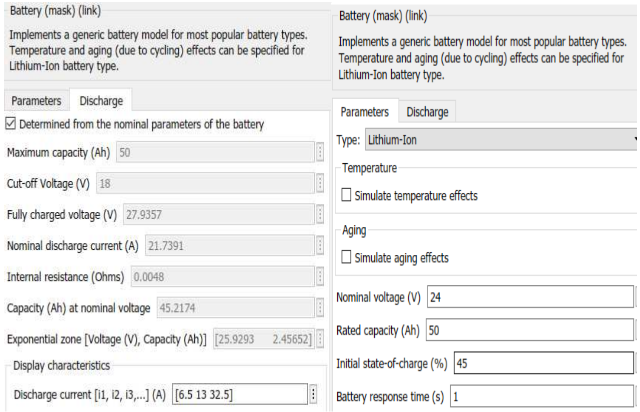


Fig 3 Circuit diagram for power flow control between battery and applied DC voltage source

Simulink model in Fig. 3 implements a generic battery model for most popular battery types. Temperature and aging (due to cycling) effects can be specified for Lithium-Ion battery type. Fig. 4 shows the battery parameter assumed in MATLAB Simulink.



Battery (mask) (link)

Implements a generic battery model for most popular battery types. Temperature and aging (due to cycling) effects can be specified for Lithium-Ion battery type.

Parameters | Discharge

☑ Determined from the nominal parameters of the battery

Maximum capacity (Ah) 50

Cut-off Voltage (V) 18

Fully charged voltage (V) 27.9357

Nominal discharge current (A) 21.7391

Internal resistance (Ohms) 0.0048

Capacity (Ah) at nominal voltage 45.2174

Exponential zone [Voltage (V), Capacity (Ah)] [25.9293 2.45652]

Display characteristics

Discharge current [i1, i2, i3,...] (A) [6.5 13 32.5]

Battery (mask) (link)

Implements a generic battery model for most popular battery types. Temperature and aging (due to cycling) effects can be specified for Lithium-Ion battery type.

Parameters | Discharge

Type: Lithium-Ion

Temperature

☐ Simulate temperature effects

Aging

☐ Simulate aging effects

Nominal voltage (V) 24

Rated capacity (Ah) 50

Initial state-of-charge (%) 45

Battery response time (s) 1

Fig. 4 (a) Discharge parameters (Left) (b) Nominal parameters (right)

The characteristics of the battery considered for this purpose is shown in Fig. 5. This includes the discharging characteristics, volt-Ampere-hour characteristics below and above rated current ratings. It has been plotted using MATLAB tool and considering various characteristics.

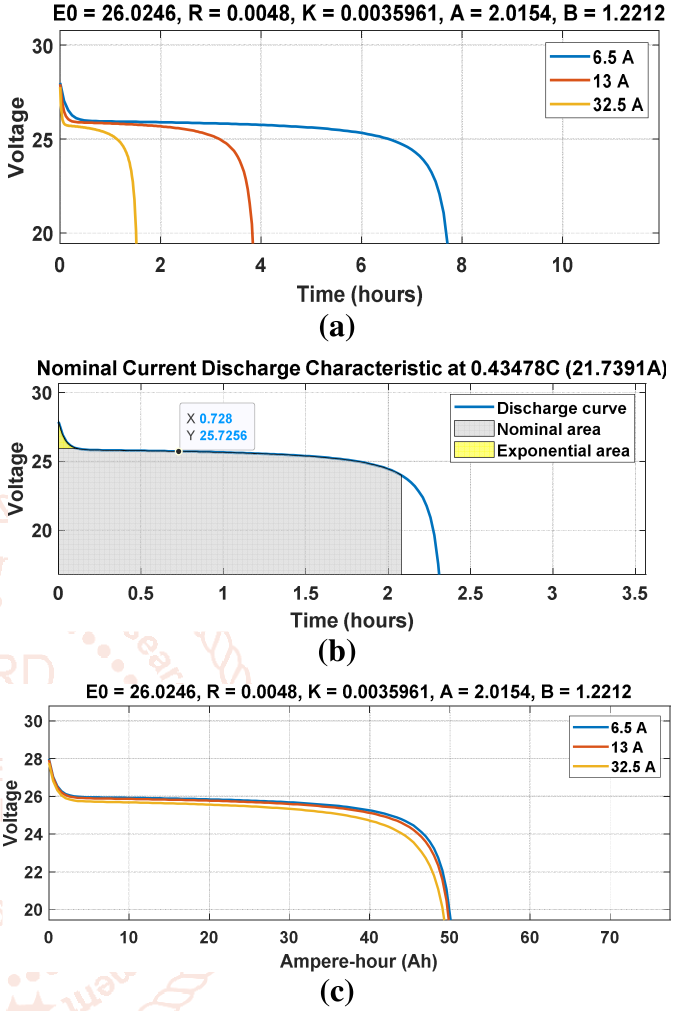


Fig. 5 Characteristics of Li-Ion battery (a) Discharge characteristics with Nominal Currents (b) Discharge characteristics for above and below to the nominal amperes (c) Volt-Ampere characteristics for above and below to the nominal amperes

IV. Battery charge control

The charging of battery takes place in two different modes: Constant Current (CC) Mode and Constant Voltage (CV) Mode

A. Constant Current (CC) Mode

In this mode of operation there are two methods to generate the reference current and PWM control signal i.e., Current based control and Voltage based control described below.

(a) *Current based Control:* To study the dynamics of battery charging the circuit of Fig. 3 is built in MATLAB Simulink and simulated to observe the three parameters i.e., SoC (State of Charge), Voltage and Charging Current. A common load is assumed which is supplied by two voltage sources i.e., a battery (Li-Ion) and a DC voltage source. To demonstrate the charging of the battery, the battery operating current is assumed to be negligible since it is under charging mode.

In this mode a reference current is provided which is further utilized as a reference to the PI controller. The output response of the PI controller is utilized by DC-DC pulse width modulation (PWM) block to generate the switching signals for switches (MOSFETs). The PWM signal pulse width is 5 micro-seconds and frequency is 10 kHz. Fig. 6 shows the Simulink blocks for the PI controller and PWM signal generator.

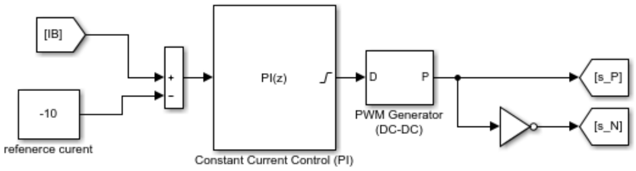


Fig 6. Proportional Integral Controller and current based control

The Fig. 7 shows the charging characteristics for current based control. The Charging current is the reference current, and it can be clearly observed from the figure that SoC % is increasing for the constant reference current.

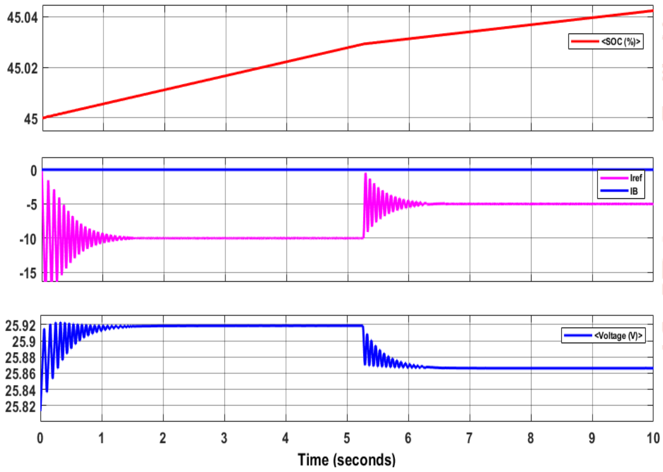


Fig. 7 Characteristics during battery charging in constant current mode (a) SOC% (top), (b) Reference current (middle) and (c) Voltage of the battery (bottom).

From Fig. 7 it can be inferred that the voltage of the battery is also increasing while charging. There are two reference current applied as input at different time instants, firstly 8A and after that 10 A. As the reference current increases the SoC% increases and so the voltage across the battery also increases. Here the reference current is applied externally and not generated internally just to demonstrate the charging of the battery. The permissible maximum current is 22A. The pulse width modulation (PWM) method is used to generate the switching signals for the two MOSFETS. The two signals are complementary to each other as shown in Fig. 8.

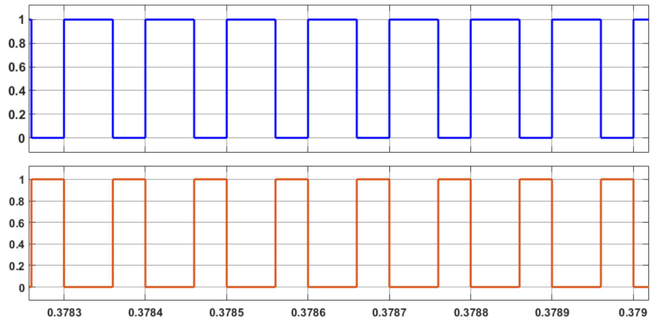


Fig. 8 The waveform of the PWM switching signals to MOSFETS

While charging the battery up to 80% SoC there is hardly any significant difference in modes (CC or CV), while after this point i.e., the mode of charging matters. Now the constant current and constant voltage modes can be observed separately.

PI controller gains

Reference Current generation method	Kp	Ki
Current Based	0.005	10
Voltage Based	40	2000

Firstly, the open circuit voltage (OCV) at 80% SoC level has been recorded. To get this open circuit the battery and set the SoC % to 80%. The OCV is found to be 25.98 Volts at this SoC level. Table I shows the proportional (Kp) and integral gains (Ki) for generating the reference current based upon the current based and voltage-based control.

(b) *Current based Control:* In this mode the battery voltage is compared to the OCV i.e., 25.98 and the difference is sent to PI controller to generate the reference current. Fig. 9 shows the schematic of the control for reference current generation and PWM switching according to this current.

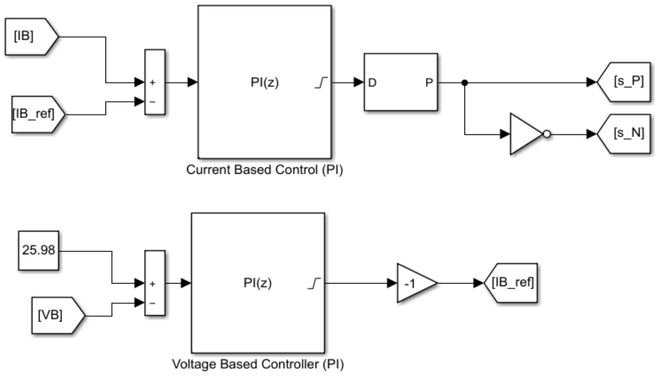


Fig. 9 Reference current generation using battery voltage

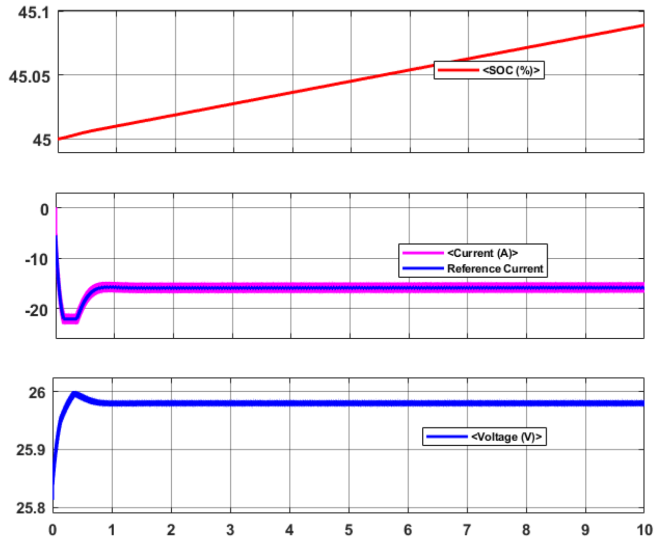


Fig 10. Reference current, voltage, and state of charge for voltage-based control

B. Constant Voltage Mode

When the battery gets charged up to 80% of SoC the voltage becomes constant, and the charging enters into constant voltage mode.

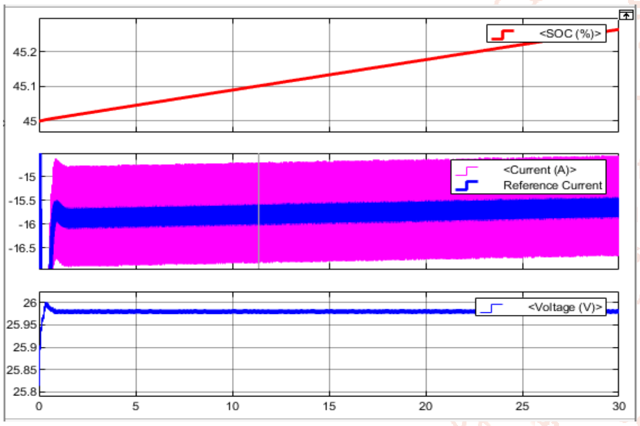


Fig. 11 Constant voltage mode showing the reference current decreasing as the time increases

Due to this the reference current and the battery current starts decreasing as shown in the Fig. 11 while the voltage remains constant.

C. Discharge characteristics of the Battery

The above circuitry of Fig. 3 is modified to realize the discharging characteristics of the battery and dynamic parameters are recorded for analysis. Fig. 12 shows the dynamic parameters of a battery while discharging. It includes, the SoC%, Voltage of the battery, current of the battery, and power for source, load, and battery.

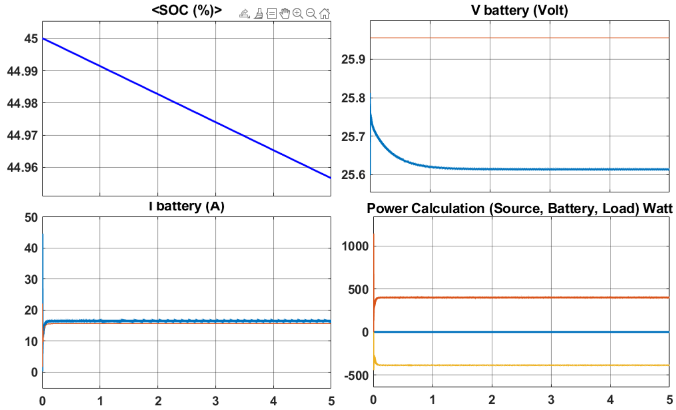


Fig. 12. Discharge characteristics of a battery with dynamic parameters

D. Combined Operation of charging & discharging

The charging and discharging mode are combined to analyse the results. Fig. 13 shows the dynamic parameters for different mode of charging and Fig. 14 is trend of the key parameters such as SoC%, voltage, reference current during charging and discharging.

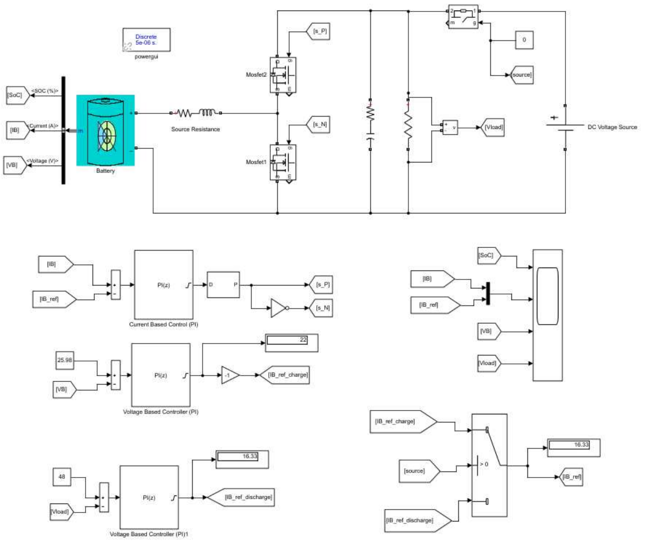


Fig 13 Simulink Diagram for charging/discharging combined mode of operation

The charging and discharging operation are controlled together in this scenario. A logical selector switch is used which compares the signal coming from the source. If this signal is greater than zero, then charging operation is performed else discharging operation executes.

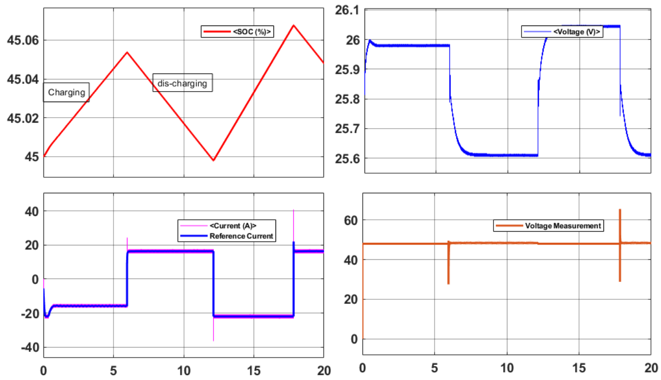


Fig 14 Dynamic parameters for charging/discharging combined mode of operation

From Fig. 14 it can be observed that when a charging command is received then the SoC starts increasing and therefore the voltage of the battery increases while when a discharging command is received then the voltage across the battery begins to fall and the SoC % starts decreasing, keeping the voltage across the load at constant level.

Cconclusion

The battery mathematical model is utilized to study the dynamic behavior of charging and discharging especially for EV applications. The main components involved in this operation are DC-DC switched converter, a load, a DC source, and a Li-Ion battery. The battery characteristics has been summarized and further analyzed while considering different scenarios. The two modes of charging i.e., constant current and constant voltage has been studied. In constant current mode, the reference current generation has been done by two different methods i.e., current based and voltage based. Three scenarios have been simulated and recorded as per the objective i.e., charging alone, discharging and both together considering a command signal. The effective study of charging and discharging of Li-Ion battery is carried out which will provide the readers an in depth insight of the technology.

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