State of Charge Estimation of Lithium-ion Batteries

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***Abstract*—State of charge of a lithium-ion battery is the ratio of amount of charge stored in it to the capacity of the battery. There are various techniques of estimating the state of the charge of the battery but here we explored three most common method to estimate the state of charge they are OCV, Coulomb counting and Kalman filter method. The circuit diagram for getting the open circuit voltage of the lithium-ion battery is simulated in proteus. The coulomb counting method is simulated in the MATLAB and also implemented using the Arduino uno by capturing the discharging current of the lithium-ion battery and integrating it in the Arduino. Kalman filter method is simulated in MATLAB. After performing the simulation, the various methods are compared.**

I. Introduction

Lithium-ion batteries are most commonly used battery nowadays. Many daily life's accessories like Smartphones, Laptops, wireless headphones, and many more electronics equipment use lithium-ion batteries for power storage application. As EV industry in the phase of exponential growth the storage capacity, reliability and protection of the battery becomes more important terms of study[6]. If you see the whole digital revolution, AI revolution and even upcoming quantum revolution, the batteries are the backbone behind everything.

It works basically in two modes. one is charging and another is discharging. In discharging mode the lithium ions move from anode to cathode while in discharging mode lithium ions move from cathode to anode.Now inside battery two more components are present one is Electrolyte and another is Separator. Electrolyte allows lithium ions through it during charging and discharging process. Separator physically separate anode and cathode to avoid short circuiting inside the battery.

In battery the anode is usually made up of graphite while cathodes are lithium metal oxides. The electrolytes are lithium salt in organic solvent and Microporous polymers are used to make separators to prevent the short circuiting inside the battery.

Talking about the performance characteristics of the battery they are generally described by the following terms -

1) Energy Density: Amount of energy stored in a particular size of the battery is known as the energy density of the battery.

2) Power Density: Amount of power that it can deliver quickly is called Power Density of the battery. It is useful for high and quick power applications.

3) Cycle life: Every battery has cycle life that it can operate to certain charge-discharge cycle.

4) Self discharge rate: It is the amount of power losses even when battery is not in use. In lithium ion batteries it is better in most cases.

5) Efficiency: This is the percentage ratio of amount of input energy given and amount of output energy we got

A. Lithium-ion battery types

Following are some most popular batteries used world wide-

1) LCO (Lithium Cobalt Oxide): It can store high amount of energy. It is used in phones and laptops. Typically these have shorter life.

2) LFP (Lithium Iron Phosphate): It is very safe and has long life. It is typically used in EV's and solar systems.

3) NMC (Nickel Manganese Cobalt): It gives Balance performance. It is common to use it in EV's and power tools.

B. Environmental Impact

1) Mining Problems: The lithium is very reactive element. Extracting it is not only difficult process but also harms ecosystem. It leads to air pollution and human right concerns.

2) Recycling Challenges: Lithium-ion batteries are difficult to recycle due to the complex material and need to go through very special process for this.

3) Disposal Hazards and Regulations: Improper disposal leads to many problem like it contaminate the water and soil and some time it also causes some sudden fires. So it need strict regulations for handling and recycling.

C. Safety and protections

As the batteries are used almost in every field now many problems can arise as-

1) Thermal Runaway: When battery heats it triggers internal chemical reactions that generate even more heat. Now this process creates a loop and if not stopped it can lead fire or explosion.

2) Battery Fires: Due to short circuits, overheating or physical damages it is the possibility that battery can blast or fired.

3) Protection Circuits: Now considering the above dangerous possibilities a protection circuit is required that automatically disconnect or limit power to prevent damages and accidents.

D. Advancements and Research trends

As the demand of the batteries are increasing it is also generating the new field of study and research. Some of most profound research fields are-

1) Solid-State Batteries: Now using solid electrolytes may improve many of the security and performance characteristics like it increases the energy density of the battery and also the lifespan of the battery. It is also good for better safety.

2) Silicon Anodes: Silicon anodes store more lithium so if we replace the graphite anode with the silicon one it can store more lithium and hence increases the battery capacity.

3) Fast Charging Technologies: Reducing charging time as much as possible without harming the battery life is a key area of research.

4) Cobalt-free Chemistry: Now cobalt used in the lithium ion batteries harms the environment so if we can make battery free of it we can reduce the cost and pollution of environment.

II. Market size of lithium ion battery

A. Global Market Size

The global lithium-ion battery market is experiencing significant growth, with projections indicating a substantial increase in market size. In 2023, the market was valued at around USD 55.4

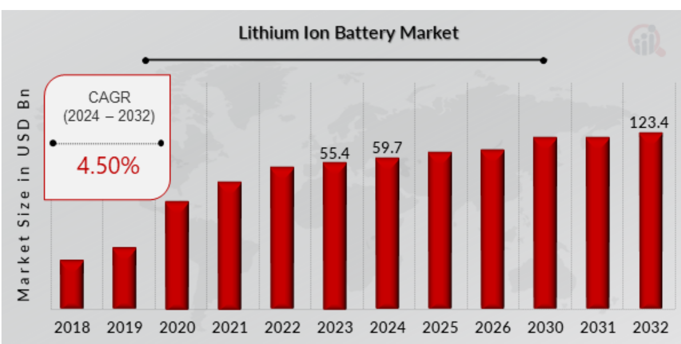

Fig. 1. Global market size of lithium-ion battery https://www.marketresearchfuture.com/reports/lithium-ion-battery-market-979

billion. Forecasts suggest a rise to USD 123.4 billion by 2032, reflecting a compound annual growth rate (CAGR) of 4.72% during the period from 2024 to 2032[1]. Asia-Pacific, particularly China, dominates the market, and growth is driven by increasing demand in the automotive and manufacturing sectors

B. Indian Market Size

The Indian lithium-ion battery market is a large and growing sector, driven by the increasing demand for electric vehicles and renewable energy storage. In 2024, the market was valued at around USD 3.2 billion, with projections estimating it to reach USD 9.56 billion by 2033, exhibiting a CAGR of 12.27% between 2025 and 2033. This growth is fueled by government initiatives like the FAME II scheme and the PLI scheme for Advanced Chemistry Cell (ACC) battery storage, which are incentivizing domestic manufacturing. [2]

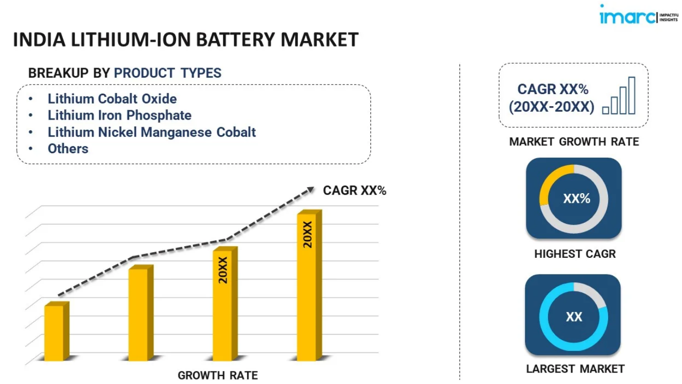

Fig. 2. India lithium-ion Battery Market https://www.imarcgroup.com/india-lithium-ion-battery-market

III. Battery Management System

As the demand of the lithium-ion batteries are growing exponentially it is necessary to make them more reliable and efficient. It is necessary to monitor over them and let the user know the state of charge and health of the battery. BMS monitors the current, voltage and temperature of the battery, optimizes [4]

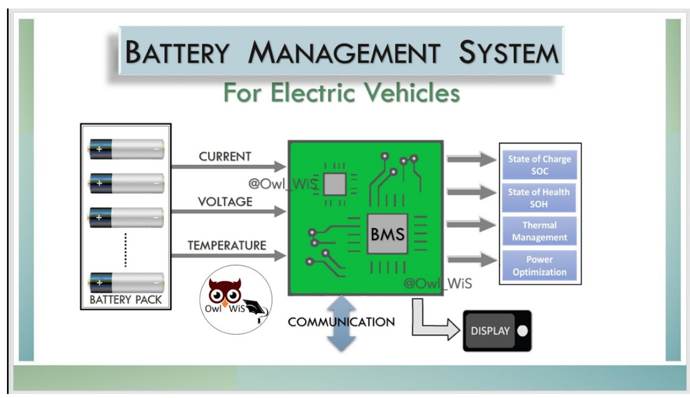

Fig. 3. Function of BMS source : Owl wis

performance and manage the heat production and ejection to the environment of the battery. It also calculates the state of charge and state of the health of the battery.

A. Need of Battery Management System

1) Safety: A proper battery management system is needed to avoid overcharging, overheating and deep dischargings.

2) Performance: For increasing the efficiency of the battery and regulate the charging and discharging of the battery battery management system is required.

3) Reliability: To make battery more reliable we need to detect the faults and turn of the power supply these all are done by the BMS.

4) Battery Life: BMS improves the life of the battery by managing each cells properly. It make balance b/w the charging level of the each cell of the battery and operate them well.

B. Types of Battery Management Systems

1) Centralized Battery Management System: In this kind of the battery management system a we use a single control unit that manages all battery cells present. This kind of topology is simple to use but is less scalable due to increase in complexity while using only one control unit.

2) Modular Battery management system: In this kind of topology we use Multiple Battery Management system unit to control the separate cell groups. This offers a good scalability and easy to maintain.

3) Distributed Battery Management System: Now in this topology each and every cell has it's own BMS module. This topology is good for large and scalable systems like EVs.

C. Future of Battery Management system

With increasing demand of the Batteries the demand of bms are also increasing and it is acquiring new technologies continuously some of them are -

1) Cloud - Connected Battery Management System: Cloud technology is used to diagnose and monitor the battery remotely. It also enables real time update of the battery data.

2) Integration with Smart grids: Integration of battery management system with smart grids allows smooth communication b/w system and grid. Also, in renewable systems.

3) Wireless Battery Management System: Normal Battery management system uses a lot of circuit that make design to complex. Using Wireless BMS architecture reduces the complexity of the circuit.

4) AI-driven Battery Management System: Machine learning is a tool that gets the insight of the data using mathematical model and try to predict the data based on the pattern that it got from training data. Now in Battery Management system getting the State of Charge of the battery and State of Health of Battery are data based estimation that can be accurately done by ML algorithms.

IV. State of Charge

This is the ratio of the useful charge available in the battery to the charge capacity of the battery.

soc= $\frac{(useful\, charge\,(AH))}{(capacity\, of\, the\, battery(AH))}$

A. Importance of State of Charge

1) Battery Management: By knowing the State of charge accurately we can prevent overcharging and over discharging of the battery and hence the life of the battery is increased because these damages the battery.

2) Efficiency: By knowing the State of the charge of the battery we utilizes our battery more efficiently and thus it increases the overall efficiency of the battery.

3) Safety: Now proper State of charge also ensures that battery is operating within safe voltage and current ranges. That can also prevent Thermal runaway and failure of battery management system. Estimating the state of charge(SOC) in lithium-ion batteries is crucial for effective battery management, ensuring both optimal performance and extended lifespan. Several techniques are employed to accurately determine SOC. [3]

B. Ways to improve State of charge of the battery

For proper working and long life of the Battery it is necessary to improve the SOC performance of the battery. Some of most common ways are-

1) Battery Balancing: For proper working of the battery it is necessary to regularly balance the cells of the battery so that it charge and discharge battery uniformly and improving overall accuracy.

2) Regular Calibration: We need to calibrate the Battery Management system periodically to ensure that State of charge reading are accurate.

3) Energy Efficiency: Also, load connected to the battery should be managed properly for prolong use and proper efficiency of the battery and hence better state of charge level.

4) Temperature Control: Now, maintaining the proper temperature level helps to prevent the level of soc good and avoid capacity losses.

5) Proper Charging: We should use controlled charging method like constant current-constant voltage so that we can prevent overcharging and over discharging of the battery.

Now soc is not something to measure it directly by any sensor but we have to go through certain processes to measure it. Most popular methods to measure the soc of battery are the following –

V. Open Circuit Voltage method

Every battery has its voltage vs soc characteristics so we can measure the voltage and determine the soc of the battery. Polynomial fitting provides a smooth, continuous function that can accurately describe the OCV vs SOC relationship. Polynomial equations are straightforward to implement in software for real-time SOC estimation.

A. Problem with this approach

(i) Aging is a problem that make this method unreliable. Because with aging the OCV vs SOC characteristics of the battery changes and that need to be modified regularly.
(ii) Open circuit voltage is also temperature dependent thus getting the soc at various temperature level via this approach is not feasible.
(iii) Now due to hysteresis effect voltage may differ during charging and discharging at same soc level.
(iv) It can't be used effectively during the operation time of the battery actively.
(v) Just at starting of the battery the OCV of the battery takes some time to reach stable level this is also known as the rest time, in this time we can't measure the soc via this method accurately.

B. Ways to improve SOC estimation via OCV method

1) Hybrid Method: We can combine the OCV method with other method like coulomb counting or Kalman filter method for getting the better accuracy.

2) Temperature Compensation: We can have different-different SOC-OCV curves at different-different temperatures.

3) Machine Learning Models: We can train Machine Learing models to predict the soc at varios temperature data.

VI. Coulomb Counting Method

If we know the soc of the battery initially then by knowing the current that it releases we can count the charge of the battery and hence soc. Coulomb counting is easy to implement with minimal computational requirements. The formula for the coulomb counting method are below-

$$\text{soc(t)=soc(t0)+ } \int_0^t I(battery)\, dt \frac{}{C(rated)}$$

A. Problems with this approach

1) Initialization: This requires the value of the soc(t0) should be known previously and if it not so good then do not converges to real one readily.

2) Error accumulation: Also, it accumulates the measurement noises and errors in the sensor that causes a large inaccuracy in the system.

3) Temperature Effect: Accuracy of the current sensor changes with respect to time and hence at varying temperature getting accurate soc via this method becomes a challenging task.

4) Self-Discharge: In this approach the self discharge of the battery is not accounted that is the amount of energy lost when the cell was not working.

5) Capacity Changes: The capacity of the battery also decreases with the age and hence it affects the accuracy of the SOC.

B. Ways to improve the Coulomb Counting method

1) Sensor Calibration: The current sensor with very high accuracy and precision should be used and it need to be calibrated regularly.

2) Hybrid techniques: For initialization we can use OCV method to get proper accuracy.

3) Real time capacity estimation: We should be regularly updating the capacity of the battery to the measurement unit so that we get accurate soc value.

VII. Extended Kalman Filter Method

Kalman filter method – Kalman filter is a state observer that is to predict the state and update the state based on the errors (feedback)[5]. It works in following three stages –

1) Initialization: We initialize the soc of battery any random value and later on it converges to real value.

2) Prediction: The based on the initialized value of the soc we predict the new value of soc.

3) Update: Now we measure error b/w the measured and predicted data and then update it according to the error.

A. Advantages of Extended Kalman filter method for State of charge estimation

1) Handle Non-linearity: As we know that battery soc behavior with respect to current of the battery is non linear but EKF handles it well.

2) Noise Filtering: Kalman filter is well known for its noise filtering ability and hence the noises present due to measurement from the sensors don't affect much to the accuracy of measurement.

3) Real-time Estimation: It works accurately in both the cases while battery is charging or discharging.

4) Adaptive: It is Adaptive means that it updates soc and it's parameters every time the new data comes.

B. Challenges in EKF method

1) Model Accuracy: The prediction via EKF is heavily dependent on the model of the battery and it is too much complex to model the battery accurately.

2) complex Implementation: It requires more and heavy computation that increases the computation cost.

3) Parameter Tuning: We need to carefully tune the system and measurement noise matrices o/w it gives unstable or inaccurate soc estimate.

4) Aging: Charging and discharging the battery multiple time leads to change in the parameter and model of the battery and hence if model is not updated it gives inaccurate result overtime.

C. Ways to improve Extended Kalman Filter Based Estimation

1) Better Battery Models: We should regularly update the battery model this prevent the problem of aging and we get the accurate charge and discharge data over time,

2) Hybrid Approach: We can combine EKF with other methods like OCV or Coulomb Counting for initial calibration.

3) Integrating with ML: We can use Machine Learning to assist the extended Kalman filter method because ML can detect the complex patterns that comes from aging or temperature.

VIII. OCV circuit implementation in Proteus

A. Components that are used in this method

1) Arduino UNO: Arduino is a very popular Microcontroller that I used to generate PWMs to control the relays and to capture the value of open circuit voltage and discharge current.

2) Relay: Two relays are used to switches b/w the OCV measurement once and discharging current once. The relay used requires 12 V to switching.

3) Transistors: Two transistor are used in the circuit to operate two relays. Basically here they are used as level shifter of the Pulse width modulations generated by the arduino.

4) Diodes: Two diodes are used for freewheeling in parallel of the relays.

B. Process

For capturing the open circuit voltage of the lithium ion battery the setup that is required is simulated in the Proteus. Here I used Arduino UNO R3 to capture the open circuit voltage. I used two relays to once open circuit the system to take OCV and another to discharge the battery. Both the relays are operated and inverted PWM's only one of the turns on for the same time. The relay 2 when turns on we measure the OCV of the battery and when the relay one turns on we measure the discharge current of the battery. The two transistors are used as a level shifter to turn on the relays as they turn on at 12 V.

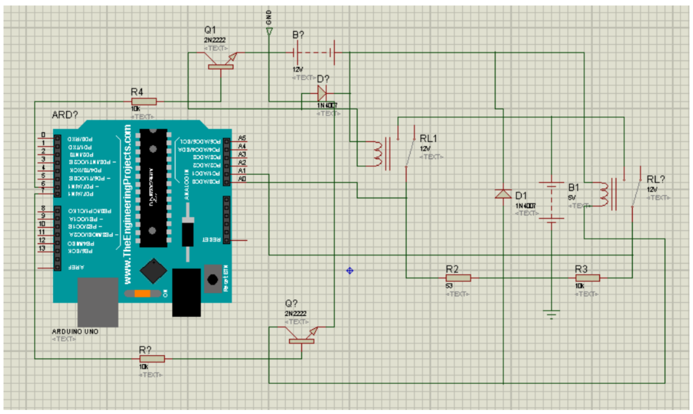

Fig. 4. Simulation of circuit for getting open circuit voltage in Proteus

IX. Coulomb Counting simulation in MATLAB

A. Components used in this method

1) Current Sensor: Current sensor is used to capture the discharge current of the battery.

2) Adder: Adder block is used to add some measurement noises that can come from the sensor. The second adder block is used to subtract the charge consumed from 100%.

3) Integrator: Integrator block is used to integrate the current signal with respect to time.

4) Scope: Scope is used to observe the waveform of real and estimated soc value.

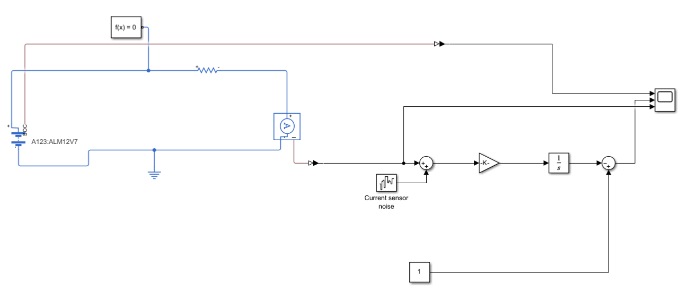

Fig. 5. Simulation of Coulomb counting method in Simulink

B. Working of the circuit

The above circuit is used to simulate the coulomb counting method of soc estimation. Here I used a table battery of MATLAB and discharged this battery via a resistor and by using a current sensor now I added some current sensor noise to the sensor signal then integrated the current with respect to small time intervals and subtract this from my initial assumptions of SOC.
For the correct initialization the circuit performed very well but as time passes the sensor noise gets added and the error increases.

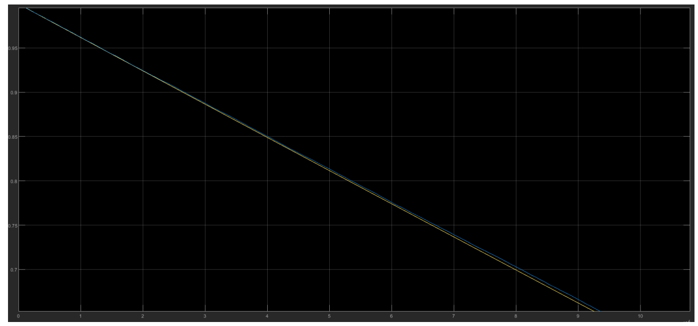

Fig. 6. Simulation result of Coulomb counting method in Simulink

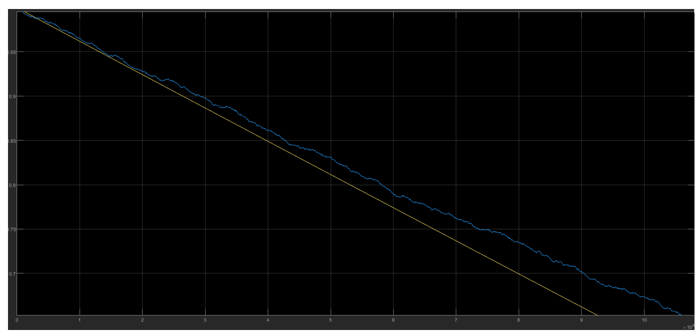

Fig. 7. Simulation result of Coulomb counting method in Simulink with high sensor noise

X. Extended Kalman Filter

A. Component used in the circuit

1) Temperature sensor: Temperature sensor is used to get the temperature data of the battery.

2) Voltage Sensor: Voltage sensor is used to get the voltage data across the battery.

3) Current sensor: Current sensor is used to get the current data through the battery.

4) Measurement Noises: Measurement noises are added to show actual behavior of the sensors.

5) SOC estimator Kalman filter: In built Kalman filter soc estimator are used that takes the current, voltage and temperature as input and output the soc.

6) Scope: Scope is used to show the plot of actual and estimated soc.

B. Working of the circuit

Now using the Kalman filter algorithm to estimate the soc of battery is little bit complex. It requires the very accurate mathematical modeling of the lithium-ion battery. I used inbuilt MATLAB example to simulate the Kalman filter method. As you can see, we take the current, voltage and temperature data of the battery via various sensors and also, we input initial value of guessed soc. Now we can observe

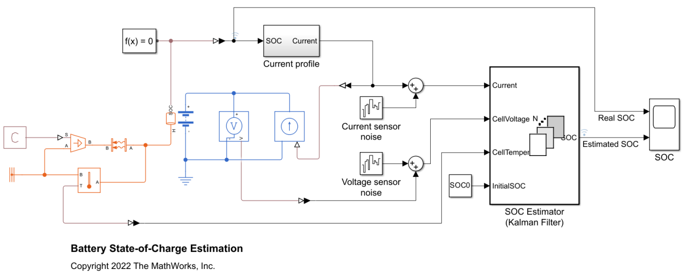

Fig. 8. Simulation of Extended Kalman Filter method in Simulink

the waveform that whatever value we initialize the our initial soc value it very quickly converges to real value of the soc. Also we observe that adding the sensor noise also does not accumulate and give error over a long period of the time

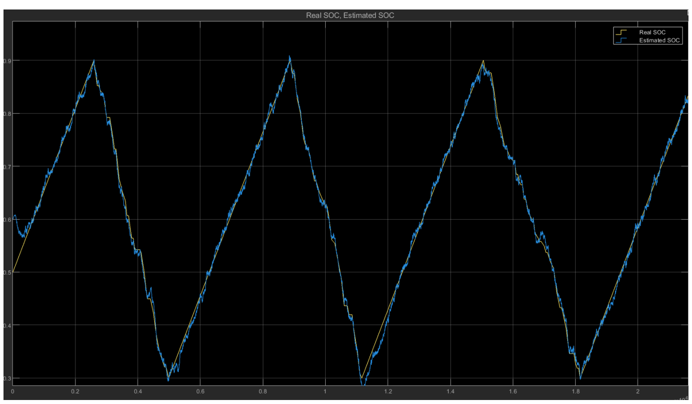

Fig. 9. Simulation result of Extended Kalman Filter method in Simulink

XI. Conclusion

I did the simulation of three methods for estimating the state of the charge of the battery. The OCV method has measure drawback of the aging of the battery and Coulomb counting performs very smooth but it adds some sensor noise that accumulate over time and also, we need to give a proper initialization of soc value. The Kalman filter method is very reliable and popular but it is difficult to model the battery very accurately. The field of battery is very vast and need more research more accurate and protective models. The EV industry is exploding similarly the use of digital equipments are also increasing exponentially all of them are required to store the energy for long time, for better performance and for more security. That make the field of study of lithium ion batteries more vast. The very new topics of research

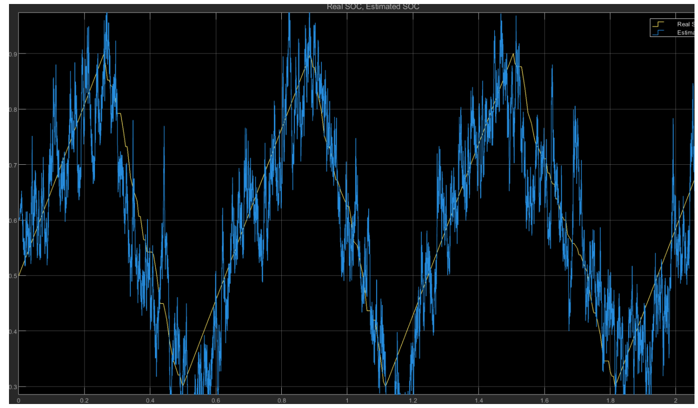

Fig. 10. Simulation result of Extended Kalman Filter method in simulink with high sensor noise

are to make battery more sustainable, to make them easily recyclable, to make them more reliable and to make them more efficient. Addressing all these concern researchers are working overnight. The new technologies like machine learning, deep learning and quantum computing are also being used in this field that is making the Energy storage more and much possible for all section of the people.

Acknowledgment

The topic was initially unknown to me thanks to Dr. N.K. Swami Naidu Sir, Who supported and guided me throughout the semester. He was in contact throughout the the semester and was ready to address any kind of concern related to it. I would also like to thank Dr. Sandip Ghosh sir who addressed some of my doubts in this topic. I would also like to thank Shilpi Shivangi ma'am who gave me the overview of the battery modeling. Finally I would thank Shiva sir who helped in machines lab for hardware implementation.

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