



Performance Investigation Of Triple Energy Storage System For Ev Applications

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Abstract: The integration of multiple energy sources in a DC microgrid enhances reliability, efficiency, and sustainability. This study explores the hybridization of solar photovoltaic (PV), battery, and supercapacitor systems to ensure a stable and continuous power supply. The solar PV serves as the primary energy source, while the battery acts as a backup to compensate for solar intermittency. The supercapacitor is incorporated to handle transient power demands and improve system dynamics by providing fast response during load variations. A power management strategy is implemented to optimize energy distribution among the sources and maintain stable DC bus voltage. The system is modeled and simulated in MATLAB/Simulink, with performance evaluation conducted under varying load and environmental conditions. The results demonstrate improved power quality, enhanced voltage regulation, and increased efficiency in the hybrid microgrid. This research contributes to the development of resilient and energy-efficient microgrid solutions for sustainable power applications. Adaptive Neuro-Fuzzy Inference System (ANFIS) combines the learning capability of artificial neural networks (ANN) with the reasoning ability of fuzzy logic. When applied to the hybridization of solar, battery, and super-capacitor systems.

Index Terms- pv system, supercapacitor, (li-ion) battery, controller (ANFIS), converter).

I. INTRODUCTION

The growing demand for efficient reliable, and sustainable energy storage solutions has led to the development of innovative hybrid systems. A Triple Energy Storage System (TESS), which integrates batteries, super capacitors, and solar cells, offers a promising approach to addressing the challenges of energy storage and management. This system leverages the complementary strengths of each technology: batteries for long-duration energy storage, supercapacitors for rapid charge and discharge to manage short-term fluctuations, and solar cells for harnessing renewable energy from sunlight. By combining these components, TESS optimizes the storage and distribution of energy, ensuring both quick-response power for immediate needs and sustained energy for longer durations. The system is particularly beneficial in

applications such as renewable energy integration ,offgrid power solutions ,and electric vehicles, where variability in energy demand and supply is common. TESS contributes to improving the efficiency, flexibility, and sustainability of energy systems, helping reduce reliance on conventional fossil fuels senvironmentally friendly energy management.

II. PROPOSED SYSTEM:

Energy storage system(ESS):

Energy storage systems (ESS's) are becoming essential in power markets to increase the use of renewable energy ,reduce CO2emission,and define the smart grid technology concept ESS has an important effect on overall electric systems.

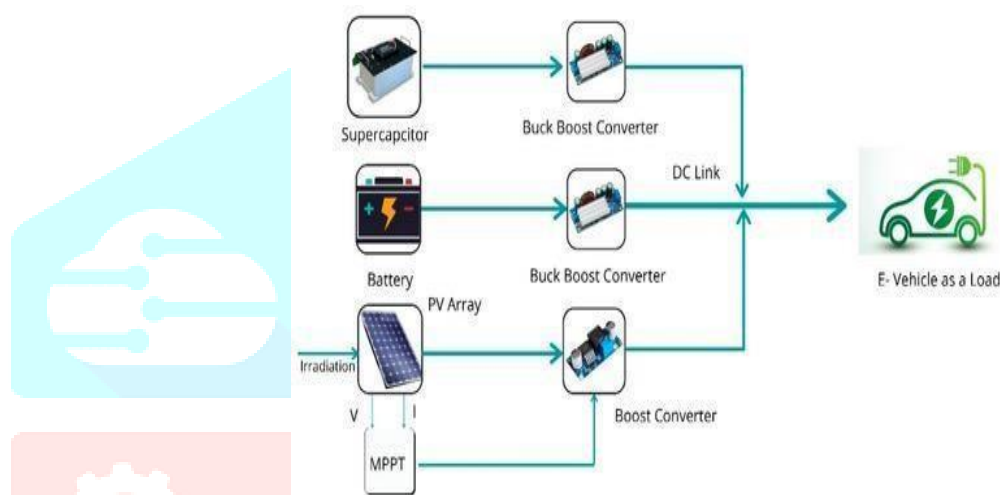


Figure.1.1
(Energy storage system)

It provides continuous and flexible power supply to maintain and to enhance power as a result of congestion and interruption of transmission line for excessive demand. In addition, an ESS ensures reliable services for consumers. ESS system sis determined with the use of energy in a specific form. ESS is classified into mechanical, electrochemical, chemical, electrical, thermal, and hybrid [30]. These systems are classified into various types according to their formations and composition materials .presents the classification of ESS in

Detail ,where the common ESS's for EV

Application are boxed in gray.

Energy storage systems play a vital role in enhancing the flexibility, reliability, and sustainability of modern power systems. With the growing adoption of renewable energy sources and the increasing demand for electric vehicles and energy independence, ESS's are poised to become even more important in shaping the future of energy. Advancements in energy storage technologies ,such as solid-state batteries, hydrogen storage, and grid-scale storage solutions, hold great potential for Improving energy efficiency ,reducing costs ,and addressing the challenges of climate change.

Photovoltaic(PV):

The most common use of PV systems in EV's is to charge the vehicle's battery using solar energy. PV panels can be installed on the roof of the vehicle or in charging stations to capture sunlight and convert it into electricity.

This electricity is then used to charge the EV's battery ,which helps reduce the depend encyon grid-based electricity and fossil fuels. PV panels integrated into the roof, hood, or other surface so fan EV can contribute to the vehicle's range by directly converting sunlight into power.

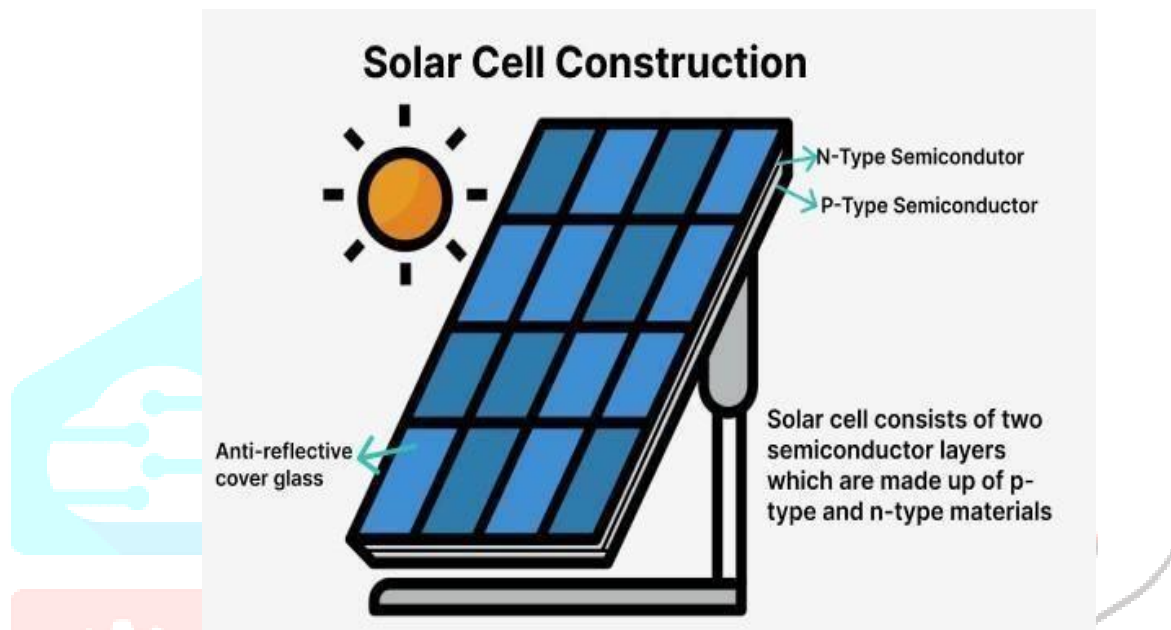


Figure.1.2
(solar cell)

While the amount of energy generated is not enough for a complete charge, it can provide enough energy to power auxiliary systems such as air conditioning,

Lighting ,and infotainment, reducing the load on the EV's main battery and effectively extending the range.

Benefits of PV Systems in EV's:

Extended driving range due to the energy contribution from solar panels.Sustainability and lower carbon footprint as solar energy is a clean, renewable resource panel. Reduced Dependence on-grid electricity in are as with high sunlight exposure.

Challenges and Limitations:

Energy Generation Capacity :The amount of Energy generated by the solar panels on EV's is still relatively small compared to the total energy needed for full charging. It may not be sufficient for long-

distance travel but can be useful for auxiliary functions and partial charging .Weather Dependency: The effectiveness of PV systems in EVs is highly dependent on the weather and geographical location. Cloudy or rainy days will significantly reduce energy generation from the panels.

Cost of Integration :The addition of PV panels to EVs may increase the initial cost of the vehicle, though the long-term savings can offset the upfront cost. Photovoltaic systems in EV's offer exciting possibilities for sustainable transportation. While they are not yet a complete solution for fully powering an electric vehicle, they can significantly extend range, reduce energy costs, and contribute to a more sustainable, clean energy ecosystem. As solar technology advances and becomes more efficient, the integration of PV systems into electric vehicles will likely become more widespread.

Battery(Li-Ion):

Lithium-ion (Li-ion) batteries are a type of rechargeable battery that has become the preferred power source for many portable devices ,electric vehicles(EV's),and energy storage systems due to their high energy

Density ,long cycle life, and relatively low self- discharge rate. A lithium-ion battery works by moving lithium ions between the positive electrode (cathode) and negative electrode (anode) through an electrolyte. During discharge ,lithium-ions move from the anode to the cathode, producing electricity .When charging, lithium ions move back from the cathode to the anode.

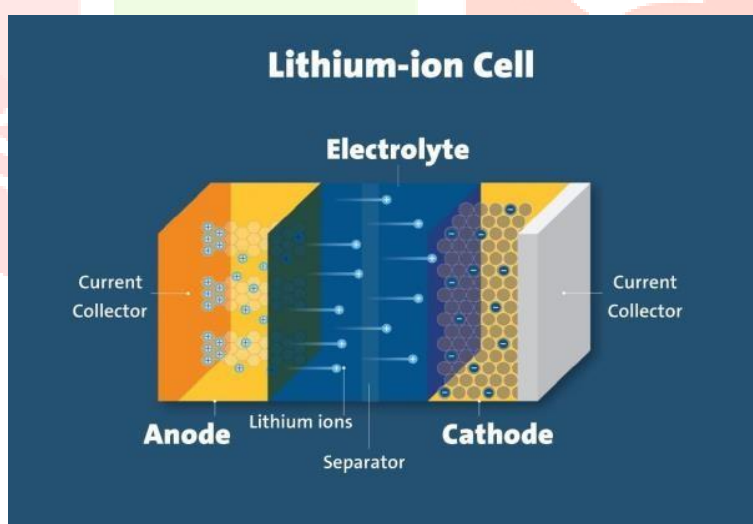


Figure.1.3
(li-ion battery cell)

Advantages of Li-Ion Batteries:

High Energy Density :Li-ion batteries can store more energy in a smaller and lighter package compared to other battery types, making them ideal for applications where space and weight are important (e.g., smart phones, electric vehicles). **Long Cycle Life:** Li-ion batteries can last for many

charge and discharge cycles, making them more durable over time than other rechargeable batteries.

Low Self- Discharge Rate: Li-ion batteries lose charge slowly when not in use, meaning they maintain their power longer than other types of rechargeable batteries.

Disadvantages of Li-Ion Batteries:

Cost: Li-ion batteries are more expensive to manufacture than other battery types, though their cost has been steadily decreasing with advances in technology. **Safety Concerns:** If overcharged, punctured, or exposed to high temperatures, Li-ion batteries can catch fire or explode, leading to safety concerns.

Degradation Over Time: Li-ion batteries degrade overtime, even if not used, leading to a gradual decrease in capacity and performance.

Li-ion batteries are the backbone of many modern technologies, especially in areas requiring portable energy storage. As the demand for electric vehicles, renewable energy, and portable electronics continues to grow, the role of Li-ion batteries will remain crucial.

However, ongoing research is focusing on improving the efficiency, safety, cost- effectiveness, and environmental impact of these batteries to meet future energy needs.

Supercapacitor:

Super capacitors, also known as ultra capacitors or electric double-layer capacitors (EDLCs), are a key energy storage technology for electric vehicles (EVs), particularly in applications requiring rapid charge and discharge cycles. These devices offer high power density, long cycle life, and excellent efficiency, making them ideal for complementing batteries in hybrid energy storage systems.[a]Currently, electric double- layer capacitors (EDLC), pseudo capacitors, and hybrid capacitors are the three types of SC technologies employed in electric vehicles.

Supercapacitors offer several advantages in electric vehicle applications, including high power density, fast charging and discharging capabilities, and long cycle life.



Figure.1.4
(super capacitor)

They are often used in conjunction with batteries in hybrid energy storage systems to handle high power demands, such as during acceleration or regenerative braking, while the battery handles energy storage for longer durations.

Electrification is an important means of decreasing greenhouse gas emissions in the transportation sector. The global electric car fleet has now exceeded 5 million and will continue to increase in future. The energy storage system is a critical part of the electric vehicle. The storage system has to be cost-effective, light, efficient, safe, reliable, occupy less space and have a long life. It should also be produced and disposed of in an eco-friendly way. Interestingly, electric vehicles can be used as back-up storage during periods of grid failure or spikes in demand. Elverlingsen in Germany collects almost 2,000 batteries from Mercedes Benz EVs to create a stationary grid-sized battery that can hold 9 MW of energy. The lithium-ion (Li-ion) battery technology plays a major role in EVs due to its power and energy density. Supercapacitors (SC) possess extremely high power density, high cycle time, cycling efficiency and low energy density. Connecting battery pack with supercapacitors is considered to be an effective method to provide energy and power for EVs and Hybrid Electric Vehicles (HEVs) as it results in both high power and high energy capability.

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Advantages of Supercapacitors in EV Applications:

Rapid Charging and Discharging: Supercapacitors can quickly absorb and release energy, making them ideal for applications requiring rapid power delivery. **High Power Density:** They can deliver high bursts of power, which is beneficial for acceleration and other dynamic driving conditions. **Extended Lifespan:** Supercapacitors endure a high number of charge and discharge cycles without significant degradation, contributing to the longevity of the vehicle's energy storage system.

Considerations:

Energy Density: Supercapacitors have lower energy density compared to batteries, meaning they store less energy for the same weight. This limits their use as the sole energy source for long-distance travel. However, their role is typically complementary to batteries, addressing specific needs that batteries alone may not efficiently fulfill.

III. BLOCK DIAGRAM :

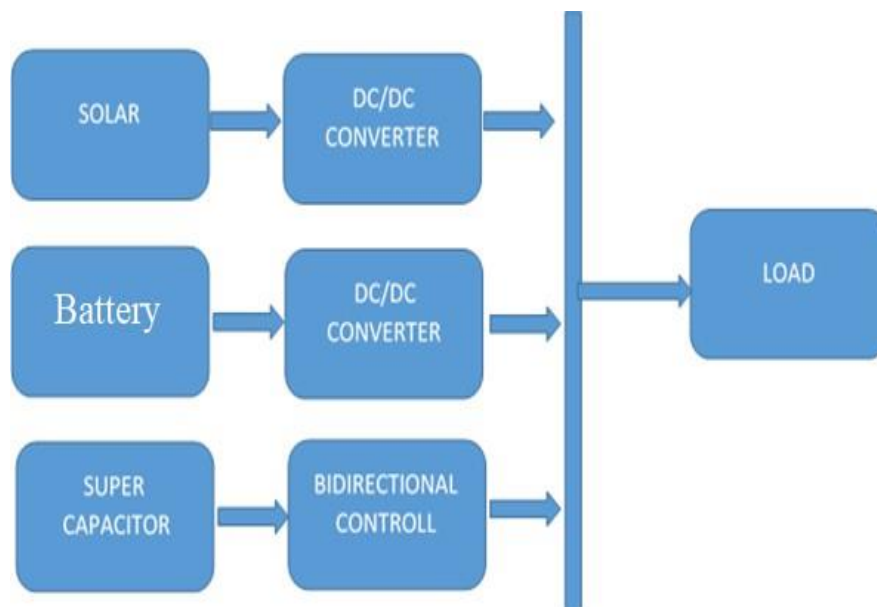


Figure.1.5

(block diagram of triple energy storage system)

ANFIS controller:

Process control systems are often non-linear and difficult to control accurately. Their dynamic models are more difficult to derive than those used in aerospace or robotic control, and they tend to change in an unpredictable way. The conventional PID controllers, in various combinations have been widely used for industrial processes due to their simplicity and effectiveness for linear systems, especially for first and second order systems.

Features of ANFIS:

Hybrid Learning: Combines the learning capabilities of neural networks with the reasoning approach of fuzzy logic. **Fuzzy Rule- Based System:** Utilizes fuzzy IFTHEN rules for decision-making processes.

Adaptive Learning: Adjusts membership functions and rules based on input-output data pairs.

Architecture Overview:

Input Layer (Fuzzification): Determines the degree to which inputs belong to fuzzy sets using membership functions. **Rule Layer:** Generates firing strengths for each rule based on input membership values. **Normalization Layer:** Normalizes firing strengths to ensure they sum to one. **Defuzzification Layer:** Computes outputs by combining normalized firing strengths with corresponding rule consequences. **Output Layer:** Produces the final crisp output after defuzzification. ANFIS controller to achieve coordinated power exchange between battery storage and the AC electrical grid through different mediators and controllers. A bidirectional power flow between the PEV and AC power grid is accomplished with the help of two ANFIS controllers and a proposed control strategy. The same scheme

was carried out with PI controllers by replacing the two ANFIS controllers. Several technical issues were found in the second case while using PI controllers for the power management of PEVs' batteries. This was illustrated by the different Characteristic curves of PEV's battery.

SIMULATION RESULTS AND DISCUSSION:

the proposed system is developed in MATLAB software that allows you to do data manipulation and visualization, calculations, math and programming. It can be used to do very simple as well as very sophisticated tasks. We will start very simple.

SOLAR PV SIMULATION DIAGRAM:

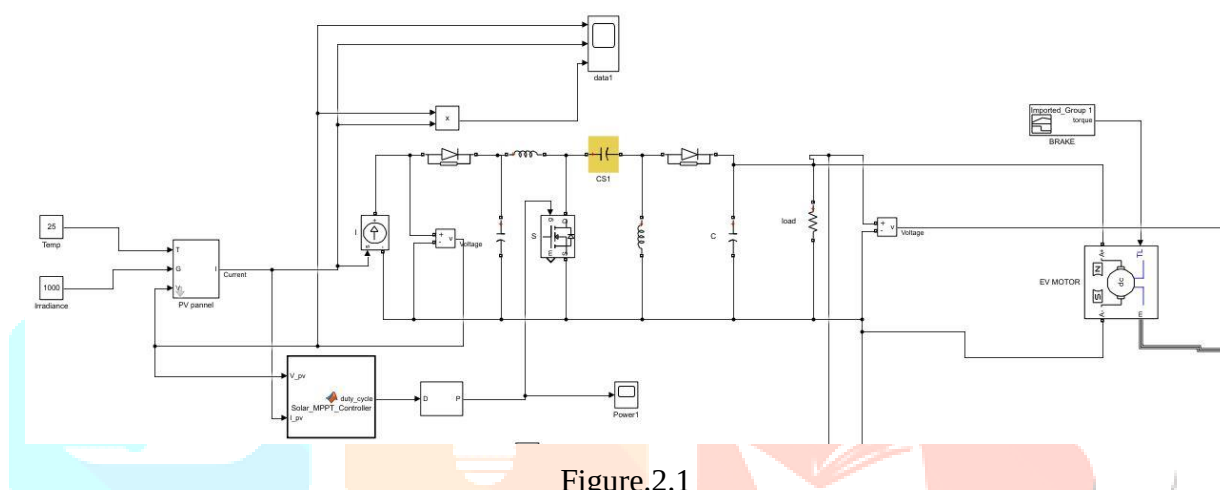


Figure.2.1

(simulation fig of solar pv)

In this simulation, a solar photovoltaic (PV) system is connected to a DC-DC converter to regulate the output voltage and enhance power transfer efficiency. The PV module generates a variable DC voltage depending on solar irradiance and temperature, which is then stabilized by the DC-DC converter—typically a boost or buck-boost type.

OUTPUT:

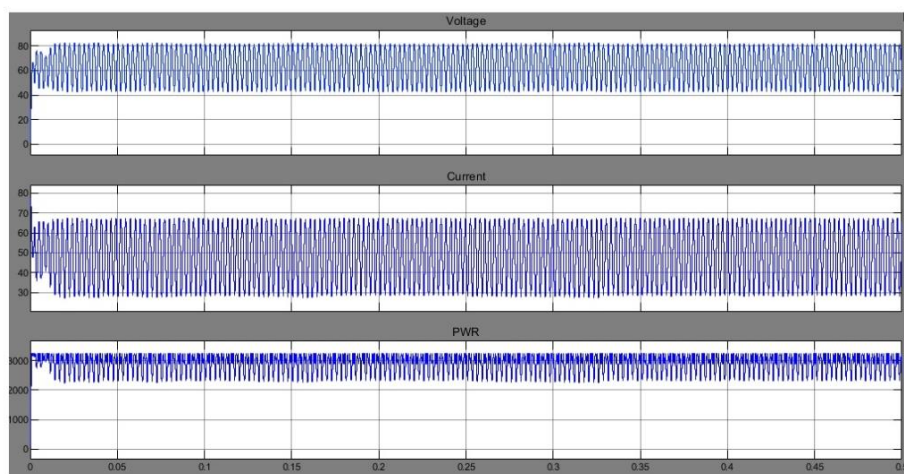


Figure.2.2

(Solar Pv system output)

The simulation results demonstrate the effective operation of the solar PV system integrated with a DC-DC converter. Under standard test conditions, the PV module generates a variable DC voltage, which is successfully regulated by the converter

OUTPUT FOR SOLAR SIDE CONVERTOR:

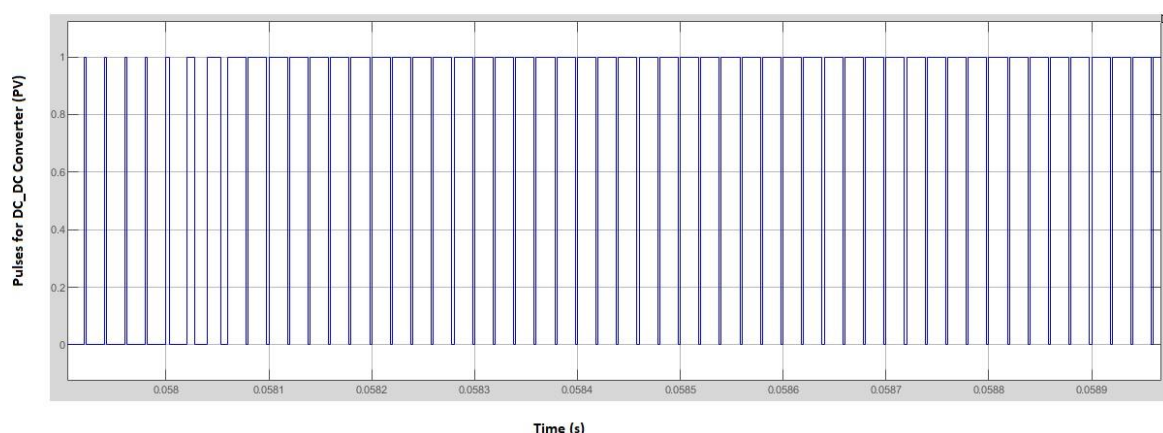


Figure.2.3

(PWM pulse for solar side convertor)

The simulation of the DC-DC converter, interfaced with the solar PV module, shows effective voltage regulation and dynamic response. As the input voltage from the PV array varies with irradiance, the converter adjusts its duty cycle to maintain a constant output voltage. For instance, when the PV voltage drops due to lower sunlight, the converter compensates by increasing the duty cycle to boost the output voltage.

The results confirm that the converter effectively smooths voltage fluctuations and contributes to efficient power conditioning in the PV system.

SUPERCAPACITOR AND BATTERY SIMULATION DIAGRAM:

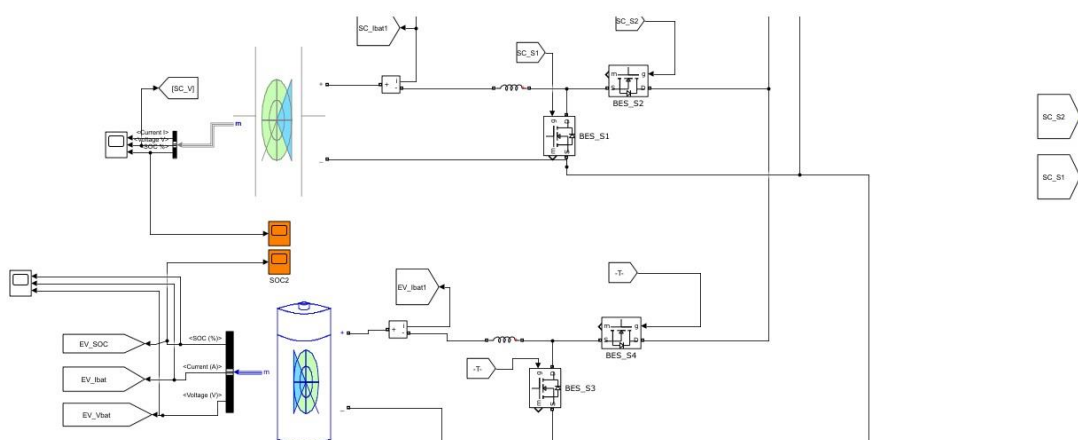


Figure .2.4

(simulation figure of supercapacitor and battery)

The simulation integrates both a battery and a supercapacitor to evaluate their combined performance in energy storage and power management. The battery serves as the primary energy storage unit, supplying steady power over extended periods, while the supercapacitor handles rapid charge/discharge cycles and compensates for sudden load variations.

The simulation demonstrates how the supercapacitor supports transient demands, reducing stress on the battery and enhancing system lifespan. This hybrid energy storage approach ensures improved response to dynamic load conditions and efficient energy balancing, particularly in applications requiring both high energy and high power density.

SOC FOR SUPERCAPACITOR:

The simulation monitors the state of charge (SoC) of the supercapacitor to evaluate its performance in dynamic energy support.

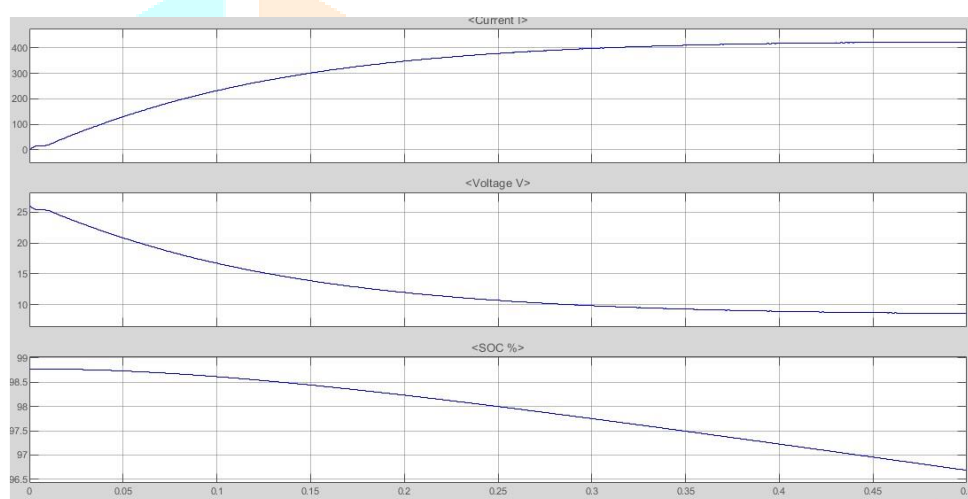


Figure.2.5
(supercapacitor's SOC)
OUTPUT:PULSE(SUPER CAPACITOR)

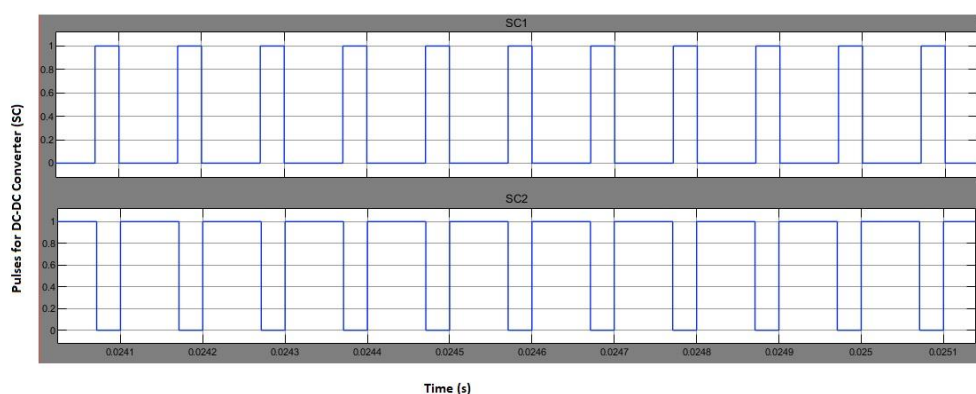


Figure.5.6
(pulses for supercapacitor)

The simulation shows that the supercapacitor delivers sharp output pulses in response to sudden load demands or power fluctuations. These high-power pulses are characterized by

rapid discharge followed by quick recovery during low-demand periods. The output pulse profile indicates the supercapacitor's ability to respond almost instantaneously, providing short bursts of energy to stabilize voltage and support the system during transients. This fast pulse behavior ensures minimal voltage dips and protects other energy storage components, like the battery, from high-stress conditions.

OUTPUT:BATTERY

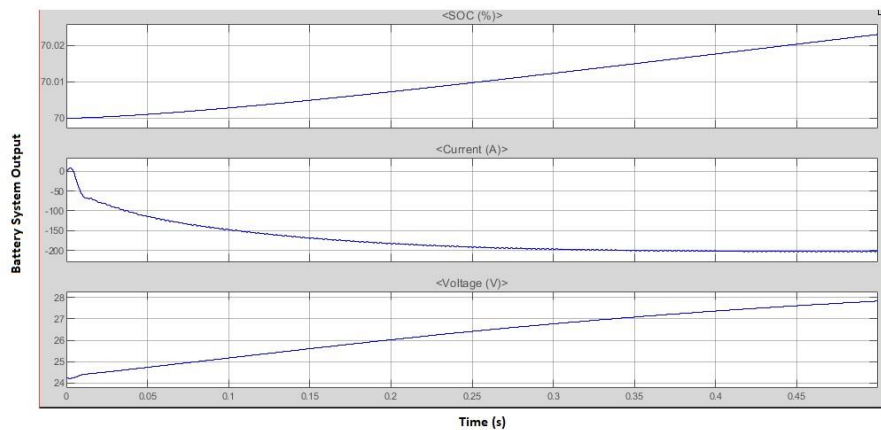


Figure.2.7
(output for battery)

The simulation of the Li-ion battery shows a stable and consistent output, supplying energy during sustained load conditions.

Unlike the supercapacitor, the battery responds more gradually and is primarily responsible for delivering continuous power over longer durations. The output voltage remains within the expected range, while the current varies depending on the load demand.

The battery complements the supercapacitor by handling the bulk of the energy supply, and its controlled discharge pattern ensures longevity and efficiency in the overall energy management system.

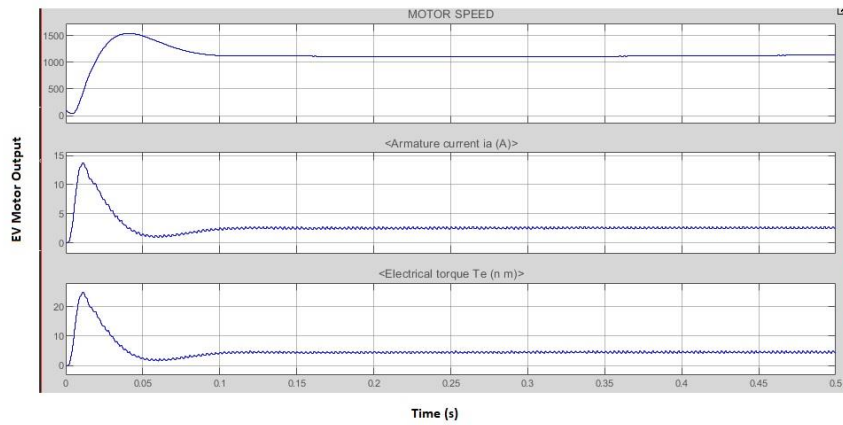
LOAD /EV / MOTOR:

Figure. 2.8

(output for LOAD/EV/MOTOR)

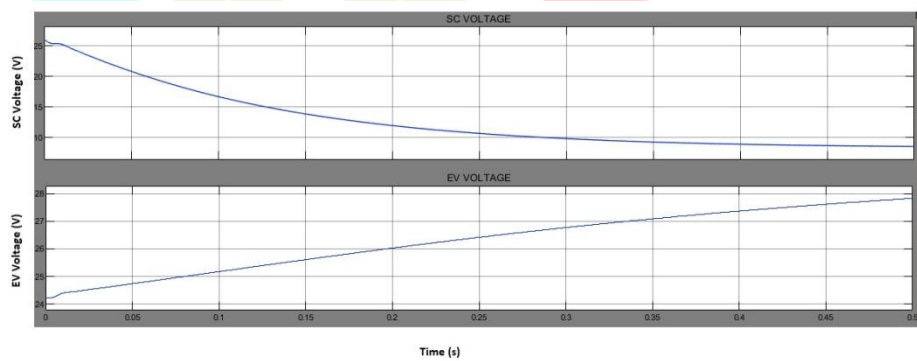
EV AND SUPERCAPACITOR SOC:

Figure.2.9

(SOC of supercacitor and EV)

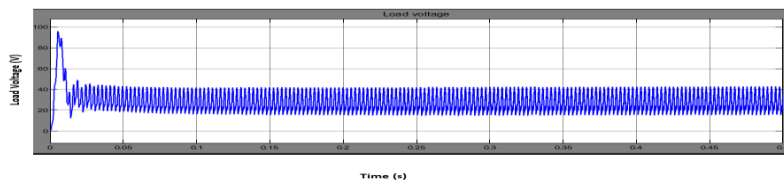
LOAD VOLTAGE:

Figure.2.10

(output of load voltage)

The simulation of load voltage demonstrates the system's ability to maintain a stable output despite variations in load conditions.

IV. CONCLUSION:

The integration of solar, battery, and ultra- capacitor energy sources using an Adaptive Neuro-Fuzzy Inference System(ANFIS) presents a highly efficient and intelligent approach to hybrid energy management. By leveraging the learning capability of artificial neural networks (ANNs) and the reasoning ability of fuzzy logic, ANFIS dynamically optimizes power distribution among the three energy sources, ensuring stable voltage, improved efficiency, and real- time adaptability. The system effectively addresses key challenges such as solar intermittency and transient load variations by intelligently balancing power flow.

Simulation results demonstrate that the ANFIS- controlled hybrid system significantly enhances power stability, load adaptability, and overall energy utilization, making it suitable for applications such as smart-grids, electric vehicle charging, and micro-grid systems. Compared to conventional controllers, ANFIS reduces energy wastage, improves response time, and adapts to changing load conditions more efficiently.

Future work can focus on hardware implementation, IoT integration for remote monitoring, and advanced AI techniques to further optimize energy management. The ANFIS-based approach holds great potential for transforming renewable energy systems into highly autonomous ,intelligent ,and sustainable solutions for modern power applications.

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