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Design of Battery/Ultra Capacitor Hybrid Energy Storage in Solar Powered Electric Vehicles and Energy Management using Genetic Algorithm

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Abstract

This article discusses the development of hybrid energy storage systems for electric vehicles (EVs) powered by solar energy. The research aims to create an ultracapacitor/battery hybrid energy storage system for solar-powered EVs and provide an energy management system to effectively distribute energy from the hybrid system to the vehicle's motor. This article explains that the limited range and high cost of EVs continue to be problems, and that hybrid energy storage systems could increase the efficiency and affordability of EVs. The use of solar power in EVs is also discussed, with increased range being a key advantage. This research highlights the need for more effective and affordable energy storage devices for EVs and discusses the potential benefits of hybrid energy storage systems for addressing these issues. In this study, a discrete time controller is used to control power supplied from Battery and Super capacitor, then the parameters of the system is optimized using Genetic Algorithm to provide maximum battery life by ensuring peak sudden burst of power which is shared by Super Capacitor while battery is being operated within it's safe limit.

Keywords

Electric Vehicle (EV), Energy Management, Battery, Super Capacitor, Hybrid System

1. Introduction

The transportation industry is important to the world economy and is a major source of air pollution and greenhouse gas emissions. The development of alternative transportation options, such as electric vehicles is a result of the growing concern over the environmental effects of transportation (EVs). Compared to conventional gasoline-powered vehicles, EVs provide various environmental advantages, such as fewer energy usage and emissions. Despite EV's having the potential to lessen the environmental impact of transportation, there have been a number of obstacles that have prevented EVs from being widely adopted.

Range anxiety or the worry that the car's battery won't have enough power to get it there, is one of the key problems that EVs face. This worry may restrict the usefulness of EVs and prevent their wide adoption. The high cost of ownership for EVs is another issue, which many consumers may find discouraging for it's ownership. The price of the energy storage system and the requirement for grid-based charging infrastructure are two factors that contribute to the high cost of ownership.

Some of these issues that EVs face could be resolved by solar energy. The incorporation of solar energy into electric vehicles (EVs) can lessen the demand for grid-based charging infrastructure, which can lower ownership costs and provide alternative means for charging the batteries. However, there are a number of obstacles to overcome when integrating solar power into EVs, including the requirement for a high-performance energy storage system and effective energy management.

The low energy density and poor power density, short lifespan of current energy storage technologies for EVs are their main drawbacks. These restrictions may lower performance, increase ownership costs and range anxiety. Furthermore, hybrid energy storage systems are not compatible with the present energy management systems, which might result in performance degradation and inefficiencies [1].

Designing a battery/ultracapacitor hybrid energy storage system for solar-powered EVs and creating an energy management system to effectively distribute energy from the hybrid system to the vehicle's powertrain are the goals of this research, which aims to address these issues. This study aims to decrease the cost of ownership and the environmental impact of transportation while simultaneously enhancing the range and performance of solar-powered electric vehicles (EVs). This study intends to assist the broad use of EVs and the development of sustainable transportation alternatives.

Meta heuristic optimization methods are shown more effective for these kind of optimization as shown by researches [5], [6], [7], [8]. Genetic Algorithm (GA) was specifically chosen for their speed of execution. As calculation of GA objective can be heavily paralleled for computation at once for all population their speed of execution is better than rest. Simulating vehicle drive cycle for almost 45 minutes for each member of population is quite time consuming process. Author's previous familiarity with GA also helped push the case along. Though articles [9] and [10] utilize different optimization technique, thier adopted methodology is quite different than methodology adopted in this work.

2. Hybrid Energy Storage and EV

2.1 Battery, Super Capacitor Hybrid storage system

Energy storage systems that combine batteries with supercapacitors may have a variety of benefits over conventional battery-only systems. By combining the high energy density of batteries with the high power density of supercapacitors, these hybrid systems can deliver increased performance and efficiency for a range of applications, including electric vehicles (EVs) and renewable energy systems.

A hybrid energy storage system's capacity to meet high power and high energy needs is one of its main features. While the batteries can store energy for use during routine driving conditions, supercapacitors can deliver the high power required for acceleration and other high-load scenarios. Moreover, the usage of super capacitors can lessen the strain placed on the batteries, potentially increasing their lifespan and lowering maintenance costs.

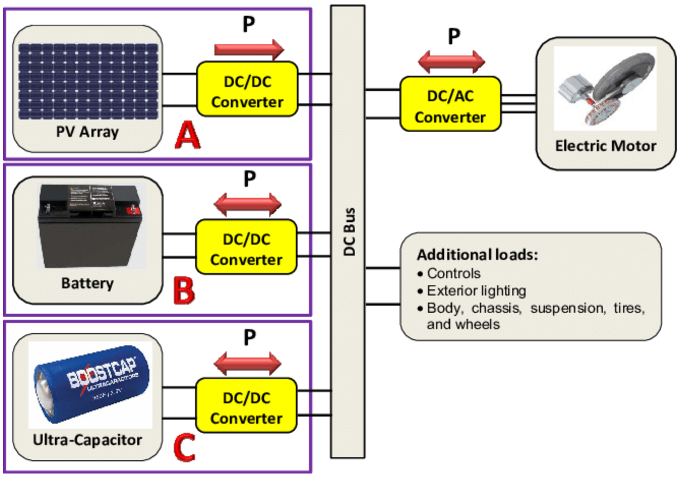

Figure 1: Block Diagram of Solar Powered Car with battery and UC [4].

With these hybrid systems, DC-DC converters are crucial because they control the energy flow between the battery and super capacitor components. To guarantee that the energy is distributed properly and effectively, these converters can be utilized to control the voltage and current levels. In some circumstances, numerous converters may be utilized to manage separate components of the system, such as the charging and discharging of the super capacitors. Performance may be optimized, component lifespan can be increased, and system costs can be decreased by carefully managing the energy flow in the hybrid energy storage system.

Overall, hybrid energy storage systems that combine batteries with super capacitors present a promising answer for a number of applications. As comparison to conventional battery-only systems, these systems can offer better efficiency, performance, and lifespan with the correct design and control systems. Hybrid energy storage systems are projected to become more crucial in supplying our energy demands as the demand for sustainable energy solutions rises.

2.2 EV

The foundation of an electric vehicle (EV) is its electrical system, and the effectiveness and range of the system depends greatly on its design and performance. The battery or energy storage system, the power electronics and the electric drivetrain are all parts of the electrical system. The primary power source for EVs is a battery or energy storage system, which also affects the car's performance and range. Lithium-ion batter- ies, nickel-metal hydride batteries, lead-acid batteries, and other types of batteries are among the many types of batteries used in EVs. The selection of a battery is influenced by a number of variables, including cost, cycle life, energy density and power density. Due to their high energy density, lengthy cycle life, and relatively low cost, lithium-ion batteries are the most popular type of battery used in EVs. However, lithium-ion battery manufacturing is an environmental concern since it uses a lot of energy and produces a lot of greenhouse emissions. An EV's electrical system depends heavily on power electronics. They are in charge of controlling the energy flow between the electrical grid, the electric drivetrain and the battery or energy storage system. Electricity electronics transform the battery's high- voltage DC power into low-voltage AC power, which powers the electric motor. The maximum power point tracking (MPPT) controller, another component of the power electronics, enhances the performance of the solar panels by shifting the operating point to the maximum power point. The power output of solar panels varies with variations in sun irradiation, temperature and other conditions, necessitating the usage of MPPT controllers. The component of an electric vehicle (EV) that transforms electrical energy from a battery or other energy storage device into mechanical energy to turn the wheels is called the electric drivetrain. The electric motor, gearbox and drive shaft are all com- ponents of the electric drivetrain. The primary element of an electric powertrain, the electric motor is in charge of transforming electrical energy into mechanical energy. The choice of machine such as power density, efficiency and cost, determines whether the electric motor is normally an AC or DC machine. The drive shaft and gearbox transfer the electric motor's mechanical energy to the wheels. The effectiveness of the vehicle's electric drivetrain, both in terms of design and efficiency is critical.

3. Problem Formulation

The ultimate reason for using hybrid energy storage system in EV is to prolong life of Lithium batteries. To actually have economic benefit from using hybrid system we must carefully select capacitor size as well as power sharing strategy such that combined costs of system (Initial investment, Operating costs, energy costs and Losses) are kept at minimum. Lithium battery gets degraded over time and it's capacity loss after a operation is given by equation 1 [1].

$$Q_{loss} = Ae^{-\frac{E_a + B*C_{rate}}{zR(|T_b - T_{bat}| + T_c)}} (A_h)^z \tag{1}$$

where,

Q_{loss} is normalized battery capacity loss
A is pre-exponential factor
E_a Activation energy(J)
R Gas constant (J/mol.K)
A_h Battery Cpacity

C_{rate} Battery disch
arge Rate
B is compensation factor of C_{rate}
z is Time Factor
T_b baseline temperature of battery
T_{bat} Battery operating temperature
T_c Compensation Temperature
The experimental work of [2] have shown these equations to be simplified into:

$$Q_{loss} = 0.0032e^{-\frac{15162+1516*C_{rate}}{R(|285.75-T_{bat}|+265)}}(A_h)^{0.849} \quad (2)$$

The global optimization problem is expressed as [1].

$$Minimize\left(\sum_{k=1}^{k=k_{max}}\frac{Cost_{bat,loss}(k)+Cost_{elec}(k)}{L_c}\right) \quad (3)$$

where,

$$Cost_{bat,loss} = \frac{C_{bat}V_{bat}Price_{bat}}{0.2x1000}[9.78x10^{-4}\frac{|I_{bat}(k)|T_s}{3600M_{bat}} e^{-\frac{15162-1516C_{rate}}{0.849R(|285.75-T_{bat}(k)|+265)}}Q_{loss}(k-1)^{-0.1779}] \quad (4)$$

$$Cost_{elec}(k) = \frac{Price_{elec}*T_s}{3600}[P_{sc}(k)+P_{bat}(k)] \quad (5)$$

T_S is simulation time step (1S)
$Cost_{bat,loss}$ battery degradation cost of time k
$Price_{bat}$ battery Price
$Price_{elec}$ Electricity Price
C_{bat} Battery pack capacity
V_{bat} Battery Pack voltage
M_{bat} no of parallel strings in battery pack
$Cost_{elec}(k)$ electricity Costs
$I_{bat}(k)$ battery Current
$Q_{loss}(k-1)$ cumulative battery degradation at instant k-1

Additional to these, following constraints also apply.

$$P_{demand} = P_{solar}+P_{bat}+P_{sc} \quad (6)$$

$$P_{es} = P_{bat}+P_{sc} = P_{demand}+P_{sc_{soc}}-P_{solar} \quad (7)$$

Where,
P_{es} is total power to be supplied from energy storage system.
$P_{sc_{soc}}$ is power reference for maintaining super capacitor SOC.

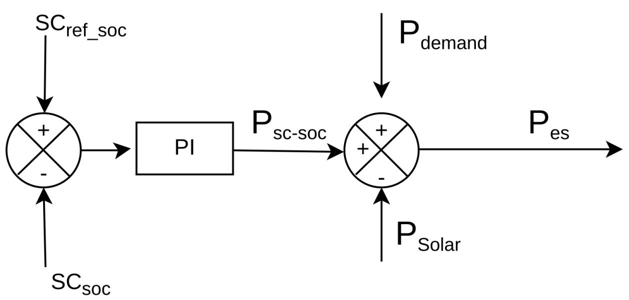

Figure 2: Control algorithm for maintaining Super Capacitor SOC

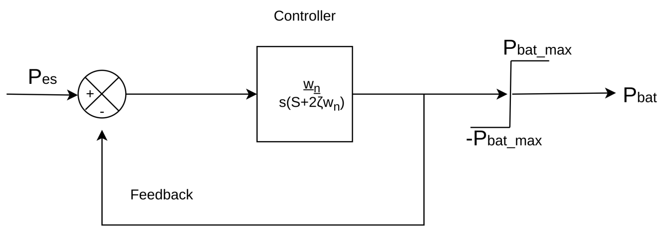

Figure 3: Reference Power for battery Generation

Power required from energy storage system is fed into a discrete time control system which then gives out the amount of power required to be supplied by Battery. Rest power is supplied by super capacitor.

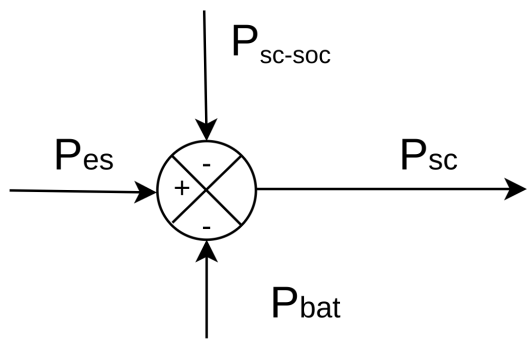

Figure 4: Reference Power for Super Capacitor Generation

A discrete time 2nd order control system is given by:

$$\frac{C_s}{R_s} = \frac{\omega_n^2}{s^2+2\zeta\omega_n+\omega_n^2} \quad (8)$$

Where,
ω_n is natural frequency of System.
ζ is damping ratio of the system.
Equation 8 doesn't have any zeros as second order system with zeros act as either high pass or bandpass filters. Our specific requirement is more similar to low pass filter than either of those.

Values of both ω_n and ζ are initialized by genetic algorithm and then P_{bat} and P_{sc} is calculated. Equation 3 is then used as objective function for GA to calculate fitness score. Then new generation are created by genetic operations (crossover, mutation) to produce new more fit individual. This process is repeated untill best solution is reached.

4. Simulation Setup and Results

A Matlab/Simulink model was built for Hybrid EV with vehicle body, drive train, Battery, Solar Panels, Super Capacitor, DC DC Converters and Controller for energy management. A standard FTP75 drive cycle is fed into EV as input drive cycle.The U.S. Environ- mental Protection Agency (EPA) uses the Federal Test Procedure 75, also known as the standardized driving cycle, to assess the fuel efficiency and emissions of automobiles. The FTP75 cycle features a combination of acceleration, deceleration and steady-speed driving to imitate both city and highway driving conditions. A simple discrete low pass filter was as controller for power sharing between battery and ultra capacitor initially before optimization.

The vehicle model built in Simulink uses parameters as shown in table 1.

Parameters	Value
Mass	1490 KG
Wheels Per axle	2
Front axle to CG	1.2 m
Rear axle to CG	1.2 m
CG Above Ground	.7 m
Battery Size	60 KWhr
Solar Size	1.5 KW
Super Capacitor Size	99 F

Table 1: Vehicle Model Parameters for EV

The above parameters are taken from real world EV Light year One Manufactured by company Lightyear in Netherland. Super capacitor size is taken to be 99F before optimization. In addition to that, road grade is taken to be 0.2 rad from [3].

All the simulation models have been modeled using Matlab Simulink. The initial simulation is ran for FTP75 Drive cycle lasting 2474 Seconds. The input drive cycle is shown in figure 5.

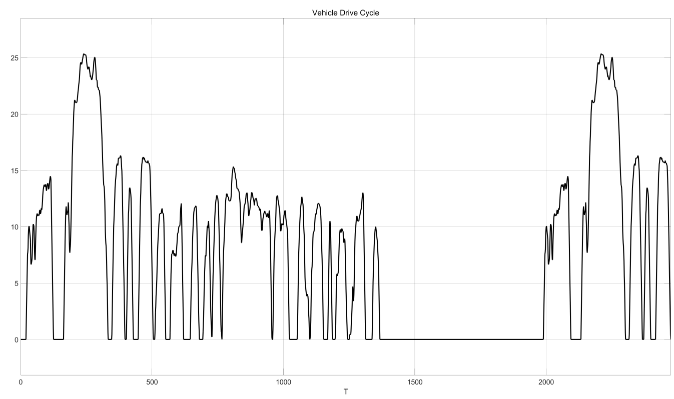

Figure 5: Vehicle drive cycle input(Velocity(m/s) vs Time(s))

The drive cycle consisted acceleration, deceleration, cruising and parking conditions. In Ev this results in high power demand in acceleration, regenerative braking releases power in deceleration, cruising and parking conditions require minimum power output. Simulating built vehicle model with above drive cycle, Power demand for vehicle in whole journey was calculated, which is shown in figure 6.

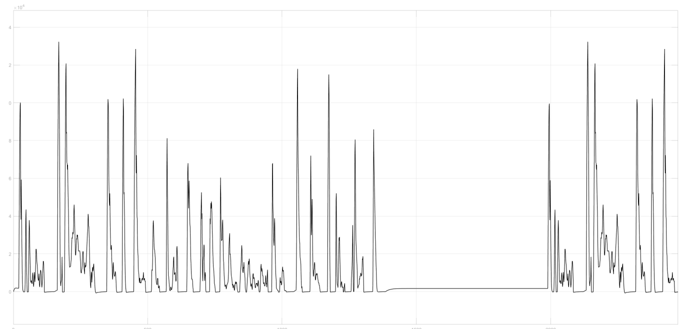

Figure 6: Vehicle Power demand according to given drive cycle (power vs time)

The narrow spike width compared to drive cycle in power demand shows, power demand is only high when vehicle is accelerating, once it reaaches constant speed, power is only used to overcome frictional losses and air drag. As our main requirement is to fulfill this power requirement of vehicle from combination of Solar, Super Capacitor and Battery, the requirement is fed to control block. The first priority for power fulfillment is given to Solar. After subtracting Solar Generation from Vehicle demand, the remaining demand or surplus is fed to control block. this block outputs power split for Battery (as shown in figure 7), the rest is handled by Super Capacitor. A saturation block is also used so battery doesn't exceeds maximum power constraints. Depending on weather Solar Generation is greater than vehicle demand, battery and super capacitor charge or discharge.

Feeding these data into GA based on optimization model described by equation 3 we get our control system as

$$\frac{0.2391}{s^2+1.72s+0.2391}$$

Then equivalent power demand as described by equation 7 and shown in figure 2, P_{es}, was calculated. This power was fed into controller model shown in figure 3. The output passed through a band pass limiter that limited maximum battery power to safe value ($\pm$ $60KW$) to get reference power for battery. Deficit power was supplied by super capacitor.

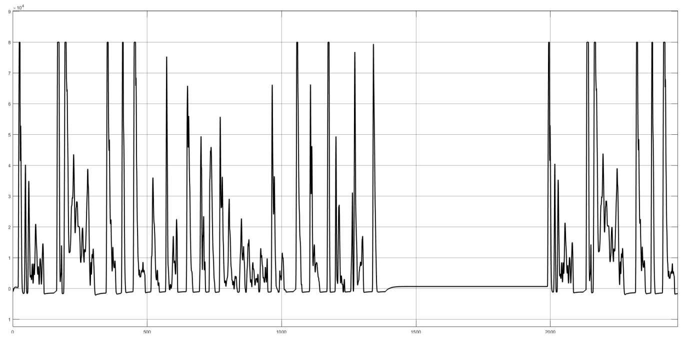

Figure 7: Power Split for Battery (-ve Charging and +ve Discharging)

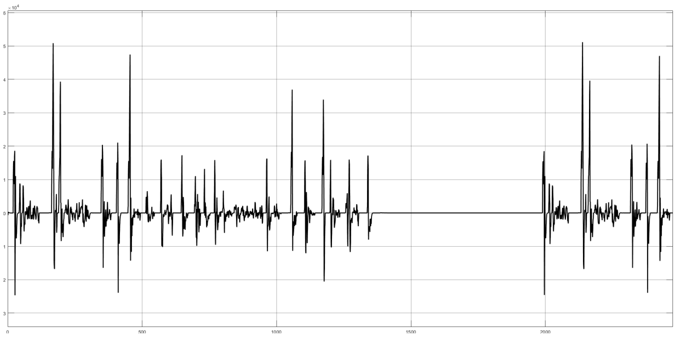

Figure 8: Power Split for Super Capacitor (-ve Charging and +ve Discharging)

Figure 8 shows both charging and discharging of Super capacitor. As described earlier once super capacitor discharges below 70% of usable SOC, a control block allocates an additional demand for charging of super Capacitor.

The power split for battery is fed as reference power to Bi-Directional DC-DC Converter of Battery, which will then control power flow direction (Charge/Discharge) as well as magnitude. The resulting variation in SOC is shown in figure 9.

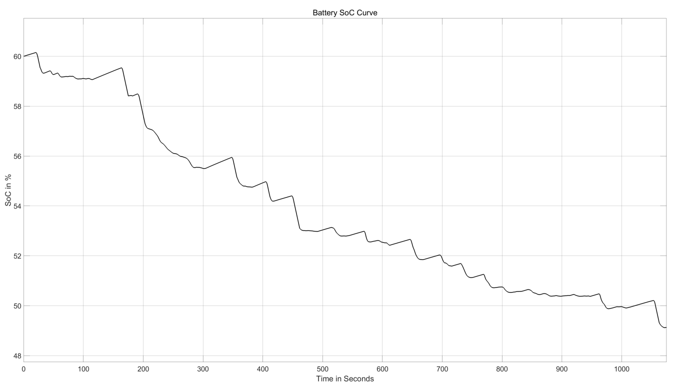

Figure 9: Battery SOC

Similarly power split for SC is fed as reference power to Bi-Directional DC-DC Converter of Supercapacitor, which again will then control power flow direction (Charging/Discharging) as well as magnitude of power flow. The resulting variation in SOC of SC is shown in figure 10.

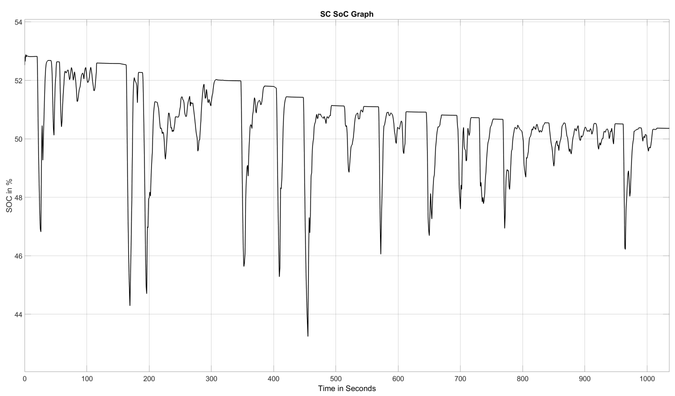

Figure 10: Super Capacitor SOC

The power tracking capability of DC DC Converter is illustrated below.

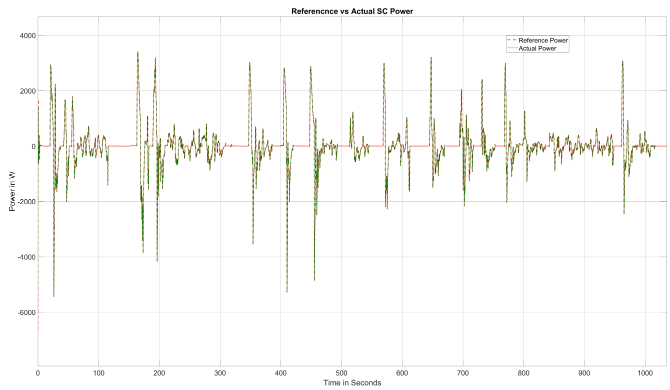

Figure 11: Super Capacitor Reference Power vs Actual power transmitted from DC DC Converter

The overall distribution of Power is illustrated in figure 12

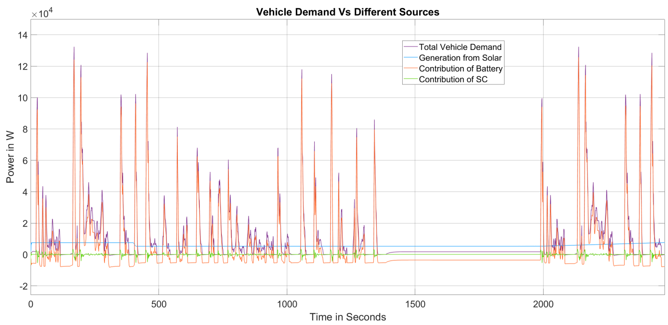

Figure 12: Power contribution from different sources and total demand

Without SC	With SC
345 A	311 A

Table 2: RMS Current supplied from battery through out drive cycle

The above table shows 9.8% improvement in rms current supplied by battery through out drive cycle. RMS currecnt is considered single main contributor to battery health. Based on equation 1 the no of cycles required for battery replacement (battery replaced at 60% of original capacity) increased from 2759 cycles (Assumed battery charges after it reaches 10% of usable SOC and resumes operation once it exceeds 95%) to 3030 cycles. This is 9.5% increase in life in terms of drive cycles.

Without SC	With SC
0.0145%	0.0132%

Table 3: Average Battery Capacity Loss per Drive cycle

5. Conclusions

In conclusion, the proposed battery capacitor hybrid storage scheme with a power sharing algorithm for EV applications is a promising solution to increase the efficiency of electric vehicles while reducing the cost and environmental impact of transportation. The use of solar power, super capacitors, and batteries in combination with a DC DC converter and a control system for power management can significantly improve the performance and range of EV's Battery. The implementation of Genetic Algorithm as an optimization tool for finding proper control system parameters can also help to minimize the total cost and enhance the efficiency of the system. The simulation results showed that this control strategy can increase the battery life by almost 10% while reducing peak currents to the battery, which is a significant improvement. Overall, the proposed scheme has the potential to revolutionize the EV industry and contribute to the development of sustainable transportation alternatives.

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