VIVEK KUMAR YADAV[1,*], KULDEEP SAHAY[2],*, ADEEB UDDIN AHMAD[3],*

J. Electrical Systems 18-2 (2022): 233-245

Regular paper

Performance Improvement of Hybrid Electric Vehicle Using Supercapacitors Energy Storage System

Journal of Electrical Systems

Globally, Internal combustion (IC) engine-based vehicles are being replaced by electric vehicles to decrease fossil fuel depletion, pollution, and the effects of global warming. But in electric vehicles, the primary concerns are battery power consumption and battery life, which affects the range of the electric vehicle (EV). In this paper, a hybrid storage system comprising a battery and a supercapacitor is simulated in MATLAB software to enhance the range, duration, and performance of the EV by controlling the charging and discharging of the supercapacitor and battery and control logic is used to integrate a li-ion battery with a supercapacitor based on the state of charging of the battery and supercapacitor. with the use of a hybrid energy storage system, the range and performance of EVs has improved.

Keywords:Electric Vehicle, State of Charge, Battery, Supercapacitor, Hybrid Energy Storage System, Charging, Discharging, Regenerative Braking, IC Engine.

1. Introduction

Electric vehicle utilization is gradually rising as a result of its cost-effectiveness and environmental benefits. The energy storage system (ESS) employed in the EV determines the efficiency of any EV technology. Mainly batteries were utilized as the storage system in EVs before 2012, but due to the EV's inconsistent loading profile, the life and performance of the batteries were decreased, because only batteries had to deliver the power in the conditions of peak load demand and average load demand. The optimization of the ESS has become critical since in the event of peak demand [1]-[3], therefore hybrid energy storage systems (HESSs) based on battery/ super-capacitor have been applied in electric vehicles (EVs) because this type of hybridization may satisfy EV criteria like as high energy/power density and extended battery life [6], [7]. In this paper, A HESS consisting of a battery and a super-capacitor (SC) is used. where the SC serves as the main source of power when the vehicle is started and the battery serves as the main source [14] when the SOC of SC decreases to 40%. Because SC's have high power density [17], they can supply enough current to the starter without affecting the battery's state of charge, and the remaining power may be utilized to charge the battery's low SOC while the vehicle is running [8]. The concept of charging in electric vehicles through regenerative braking helps to convert the wasted energy during braking to useful energy, which helps to improve the vehicle driving range approximately 5-20% [5] because in regenerative braking mode motor act as a generator [4] that supplies power back to the supply system and this power is utilized in the charging of SC and battery with the help of control circuit, so the performance of the developed HESS is heavily dependent on, how the power flow between the Li-ion battery and super-capacitor pack is controlled [9].

* Corresponding authors: 1.Vivek Kumar YadavDepartment of Electrical Engineering Institute of Engineering & TechnologyLucknow, India, E-mail: 1900520885013@ietlucknow.ac.in
2. Prof. Kuldeep Sahay,Department of Electrical Engineering, Institute of Engineering & TechnologyLucknow, India, E-mail: kuldeep.sahay@ietlucknow.ac.in

2. Abbreviations

The abbreviations used throughout the paper is stated below.

EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
SOC	State of Charging
HESS	Hybrid Energy Storage System
EMS	Energy Management System
ESS	Energy Storage System
SC	Supercapacitor
IC	Internal Combustion

3. Concept of supercapacitor

Supercapacitors are used as an energystorage system, itis an alternative to conventionalelectrochemical batteries, particularly lithium-ion batteries, which are frequentlyused. Supercapacitors are closer to batteries thancapacitors in terms of physicalmechanism and operating concept. They have characteristicsthat are midwaybetween batteries and capacitors, Fast charge-discharge rates, longer life cycles, high power, and high energydensitydifferentiatesupercapacitors or supercapacitorsfromconventionalcapacitors and itplays an important role in power engineering research and development as a modern energystoragetechnology [10], [11]. Supercapacitors are utilized in the proposed HESS to mitigatebattery life-cycle degradationcaused by continuousacceleration and de-accelerationproduced by the high current due to regenerativebraking mode [8]. SC are not as much of weightythanthat of a battery for the sameenergystoragecapacity, ittakeslesscharging time thana battery, and the discharge/charge cycle is more thanbatteryapproximately 106 times [12].The voltage provided by a single SC isverylessapproximately 2.5 volts to 3 volts, whichisveryless as compared to the battery, but by making a package of series-parallelcombinations of thesesmall rating supercapacitors, wecanreducethisdisadvantage of SC [13].

4. Battery and SC Hybridization

The supercapacitor/battery hybrid power system combines its advantages and can [15] fulfill both energy and peak power demands in electric vehicle acceleration and regenerative braking. The basic block diagram of HEV is given in Fig. 1.

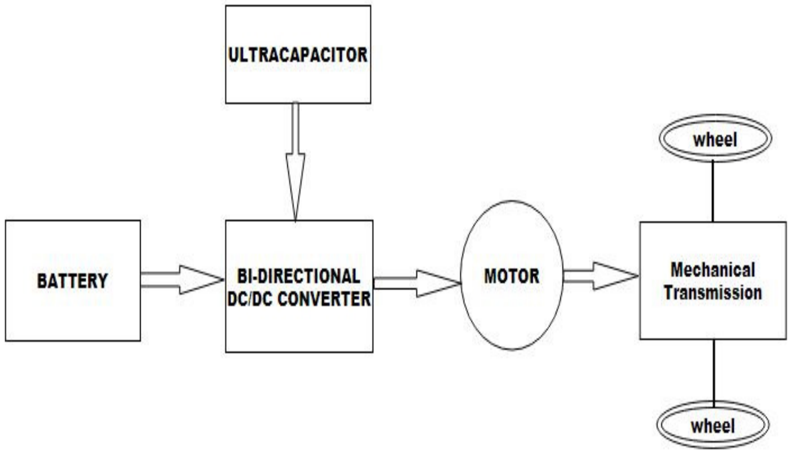


Fig. 1. block diagram of the hybrid electric vehicle based on battery and Supercapacitor.

The goal of a hybrid power system is to combine the high special power and high special energy components into a uniform power system, in which the battery provides long-distance energy and the ultra-capacitor gives peak acceleration power and absorbs brake recovery energy [15].

The performance of the developed HESS is highly reliant on how the power flow between the Li-ion battery and super-capacitor pack is controlled [16], thus A control logic is used to Integrate a Li-ion battery with a supercapacitor based on the SOC of the battery and supercapacitor, this control logic is the key component, which controls the flow of energy between the battery and supercapacitor. The proposed study emphasis how a HESS, which combines the benefits of a battery pack and a supercapacitor to create high-performance EVs or HEVs, works [16]. The specifications of single unit li-ion battery & its banks are given in Table 1 & Table 2 respectively, while specifications of single unit supercapacitor& its banks are given in Table 3 & Table 4 respectively.

Table 1: Single unit Li-Ion Battery specifications:

Rated voltage	24 V
Ratedcapacity	22Ah
Internalresistance	0.01 ohm

Table 2: Li-Ion Battery Bank specifications:

Rated voltage	240 V
Number of batteries in series	10
Ratedcapacity	220Ah
Internalresistance	0.1ohm

Table 3: Supercapacitor Bank specifications:

Rated capacitance	2000 F
Equivalent DC seriesresistance	0.8 ohm
Rated voltage	240 V
The nominal voltage of a single supercapacitor	3 V
Number of seriescapacitors	80
Operating temperature	25°C

Table 4:Single unit Supercapacitorspecifications:

The nominal voltage of supercapacitor	3 V
Equivalent DC seriesresistance	0.01
Operating temperature	25°C

5. Simulation model of HESS

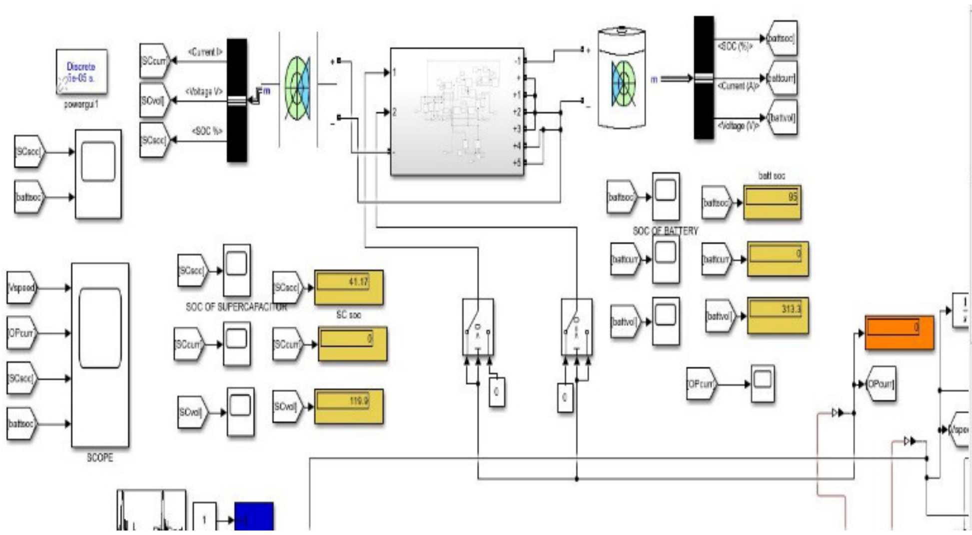


Fig. 2. Simulation model of the hybridenergystorage system.

The simulated model of HESS isgiven in Figure 2, In this model, the control logicisused to develop a hybrid model based on battery&supercapacitor, whichworks as an energy management system. It manages the charging&discharging of the battery&supercapacitor and alsoprotects the batteryfrom high currentduringregenerativebraking.
Control logicworksbased on the followingcases :

CASE 1:Discharging Mode

In discharging mode, the output currentflowsfrom source (battery or ultra-capacitor) to load (motor), so in this case, the obtained output currentis Positive.

- When the SOC of SC is > 40% then SC will be Discharged.
- When the SOC of SC is < or = 40% then the battery will discharge until the SOC of the battery becomes 20%, after this the remaining 40% SOC of SC will discharge.

CASE 2:Charging Mode

In charging mode, the output currentflowsfrom the load (motor) to the source (battery or super-capacitor), so in this case, obtaining output currentisNegative.

CASE (a) When output currentis> -20Amp then SC will charge.

CASE (b) When output currentis< or = -20 Ampthenfollowing cases willfollow.

- When the SOC of SC is > 80% then the battery will charge to 100%.
- When SOC of SC is < or = 80% then SC will charge.

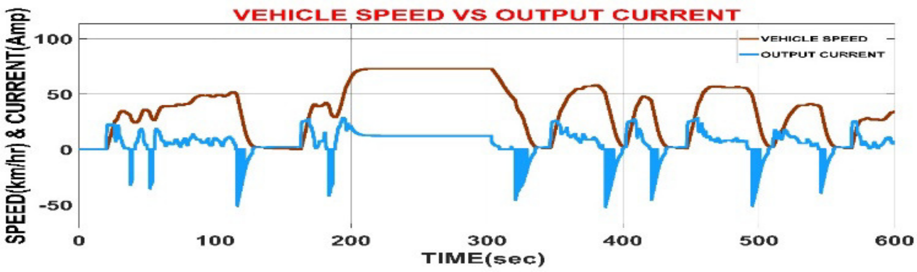
From the above cases, it is clear that Control logic not only works as EMS (energy management system) but also provides protection to the battery from high current during regenerative braking because when charging current becomes higher than -20 Amp then this charging current charges the only supercapacitor.

6.Simulation results & case study

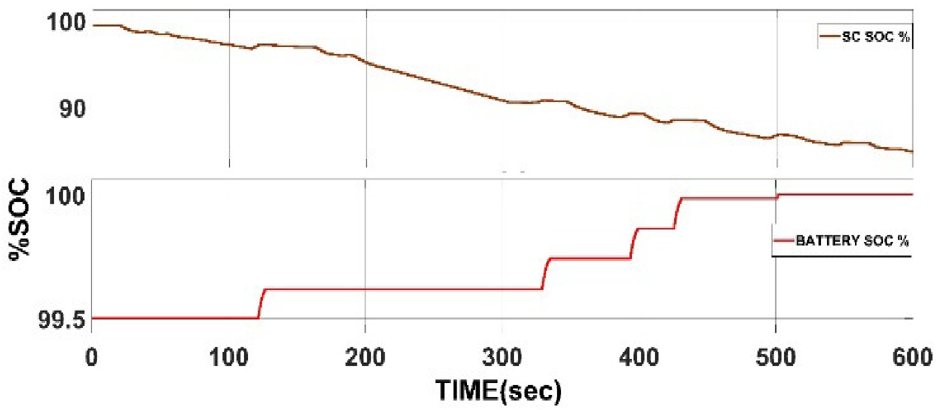
The results of the simulated hybrid energy storage system are divided into four different cases, to see that, which source will act as a primary source of supply to the vehicle based on cases used in the control logic, these results show the discharging and charging profile of the hybrid energy storage system for these four cases based on their SOC. in the first case, it is assumed that the SOC of battery is 99.5% and SOC of SC is 100% in this case positive current from source to load will discharge SC and negative current through regenerative braking will charge the battery. After discharging sometime when supercapacitor SOC reaches 83% and battery SOC reaches 100% Fig. 3(b) because of the charging of the battery with the regenerative current. In the second case, it is assumed that the SOC of the battery is 99.5% and the SOC of SC is 83% Fig. 4(b). in this case positive current from source to load will discharge the SC till 40% and negative current through regenerative braking will charge the battery only when SOC of the supercapacitor is above 80% otherwise this negative current will charge SC when its SOC is below 80% after some time in case 3 when SOC of Supercapacitor reaches 40% and the SOC of the battery reaches at 99.65% Fig. 4(b). in this case, the positive current from source to load will discharge the battery and the negative current through regenerative braking will charge SC, after some time when SOC of the battery reaches 20% and SOC of supercapacitor reaches around 40% Fig.6(b), in this case, since the battery discharges up to its minimum limit of 20% and SC is still 40% remain to discharge so the remaining stored energy in SC starts discharging up to its minimum limit 10%. Now the vehicle has stopped running because the energy sources are fully discharged to their lower limit.

CASE 1:Whenbattery SOC is 99.5% and Supercapacitor SOC is 100%.

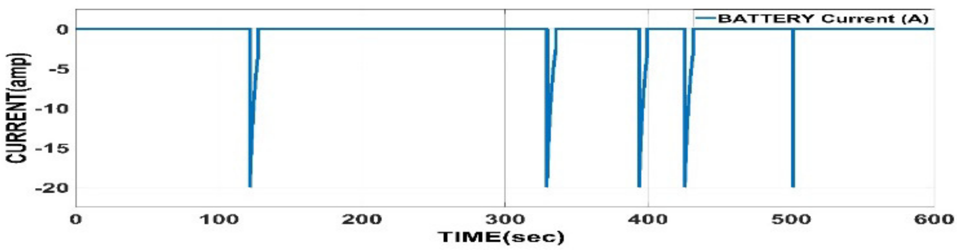
In this case, itisassumedthat the SOC of the batteryis 99.5% and the SOC of SC is 100%. In this case with the help of control logic, the positive current (source to load) willdischarge SC and the negativecurrentthroughregenerativebrakingwill charge the battery. According to the drive cycle, the vehiclestarts and accelerates for 120 seconds Fig. 3(a). Since the SOC of the supercapacitoris more than 40% sosupercapacitorstartsdischarging, at 120 seconds Fig. 3(b), now the SOC of the supercapacitoris 96 % Fig. 3(b). when the vehiclestartsdeacceleratingsince the SOC of the supercapacitorisstill more than 80% so the batterystartschargingwith a current of lessthan -20-amp Fig. 3(c). But whencurrentbecome more than -20 ampthen SC startedchargingdespitebeingcharged more than 80% Fig. 3(d). Afterdeceleration of 10 -12 seconds [Fig. 3(a)] vehicleagainstartsaccelerating, soagainsince SOC of the supercapacitoris more than 40% sosupercapacitorstartsdischarging and thisprocess of discharging SC and charging of the batterywithlessthan -20 ampchargingcurrent, iscontinued and SC stops dischargingwhenits SOC reaches 40%.



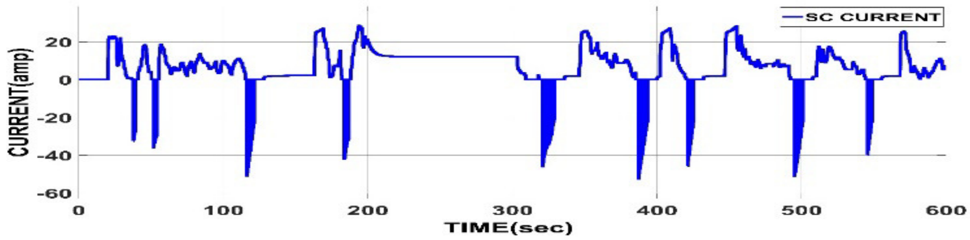
(a)



(b)



(c)

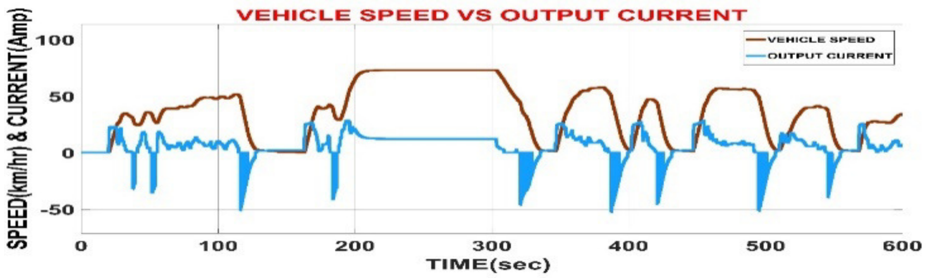


(d)

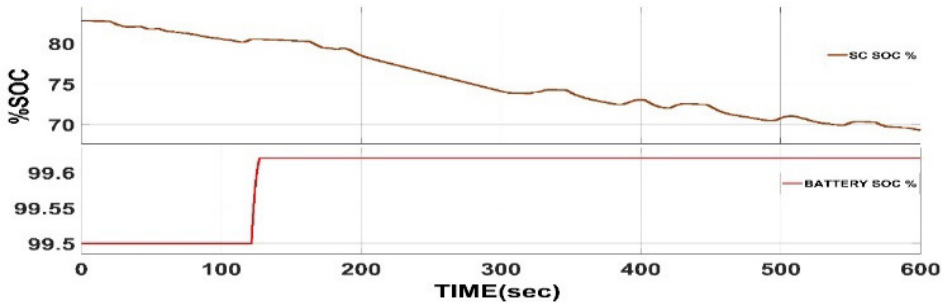
Fig. 3. Case 1 output parameters

CASE 2:Whenbattery SOC is 99.5% and SOC of SC is 83%.

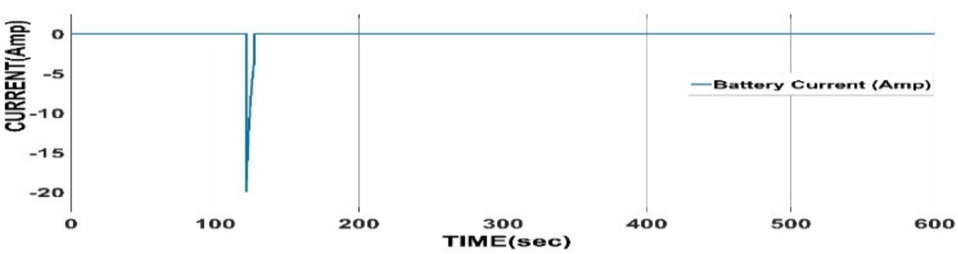
In this case,itisassumedthat the SOC of the batteryis 99.5% and the SOC of SCis 83%. According to the drive cycle, the vehiclestarts and accelerate for 120 seconds Fig. 4(a)Since SOC of the supercapacitoris more than 40% Fig. 4(b)sosupercapacitorstartsdischarging, at 120 seconds Fig. 4(a), when SOC of the supercapacitoris 78%. nowafter 120 secondsvehiclestartdeaccelerating Fig. 4(a)sincethe SOC of the supercapacitoris 78% whichislessthan 80% sothe supercapacitorstartscharging Fig. 4(b) with a negativecurrent Fig. 4(d), in thischargingprocess, if the SOC of the supercapacitorreaches 80% then the batterywillstartchargingwitha chargingcurrentlessthan -20-amp Fig. 4(c). Afterdeceleration of 10 -12 second vehicleagainstartsaccelerating Fig. 4(a), soagainsince SOC of the supercapacitoris more than 40% sosupercapacitorstartsdischarging and thisprocess of dischargingsupercapacitor and charging of supercapacitoriscontinued.



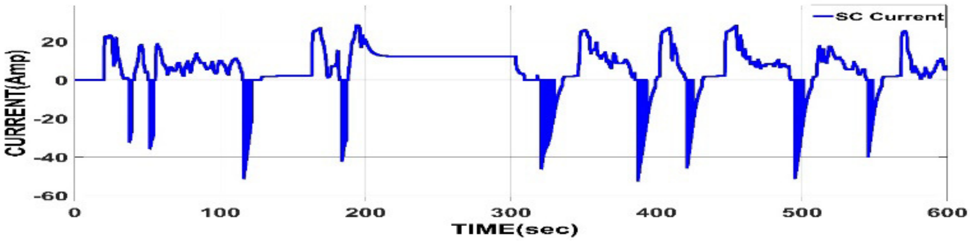
(a)



(b)



(c)



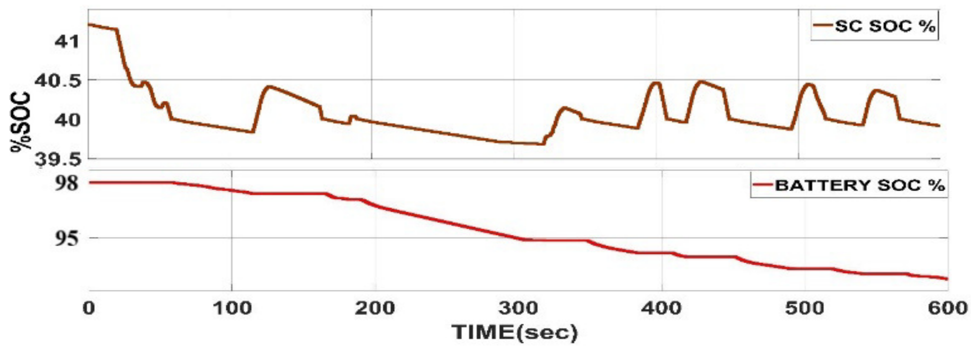
(d)

Fig. 4. Case 2 output parameters

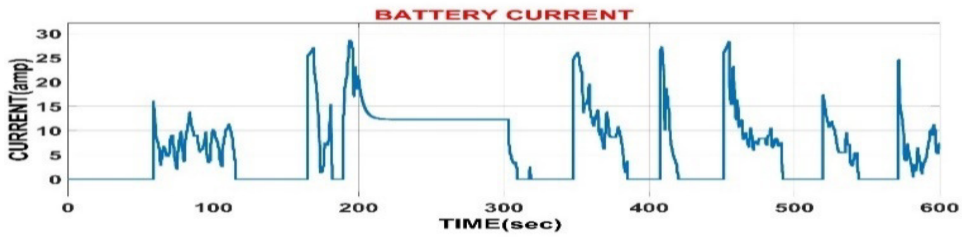
Case 3:When SOC of batteryis 100% and SOC of SC is 41%

In this case,itisassumedthat the SOC of the batteryis 100% and the SOC of SCis 41%. According to the drive cycle, the vehiclestarts and accelerates for 120 seconds Fig. 5(a). Since the SOC of the supercapacitoris more than 40% sosupercapacitorstartsdischarging, but when the SOC of the supercapacitorreacheslessthan 40% Fig. 5(b)then the batterystartsdischarging, at 120 seconds Fig. 5(a), since the SOC of the supercapacitorisapproximately 40%. nowthe vehiclestartdeaccelerating, sincethe SOC of the supercapacitorisapproximately 40% whichislessthan 80% so SC startscharging Fig. 5(b) with a negativecurrent Fig. 5(d), afterdeceleration of 10 -12 second vehicleagainstartsaccelerating Fig. 5(a), soagainsince SOC of the supercapacitoris more than 40% sosupercapacitorstartsdischarging till 40% afterthatagain the batterywillstartdischarging Fig. 5(b). This process of dischargingsupercapacitor /battery and charging of supercapacitoriscontinued.

(a)



(b)



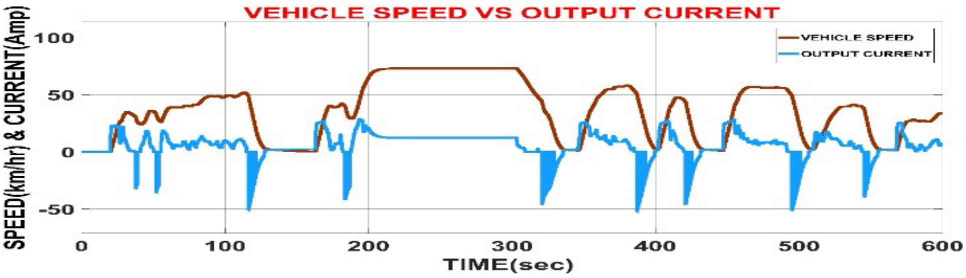
(c)

(d)

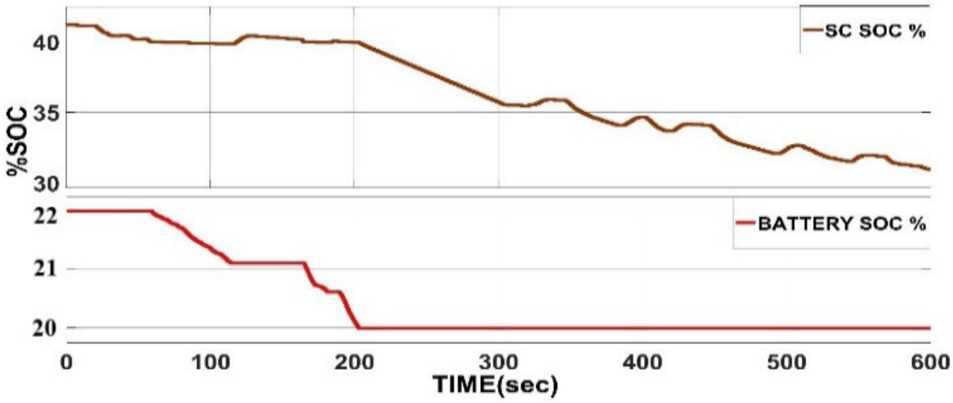
Fig. 5. Case 3 output parameters

Case 4:When SOC of batteryis 22% and SOC of SC is 41%

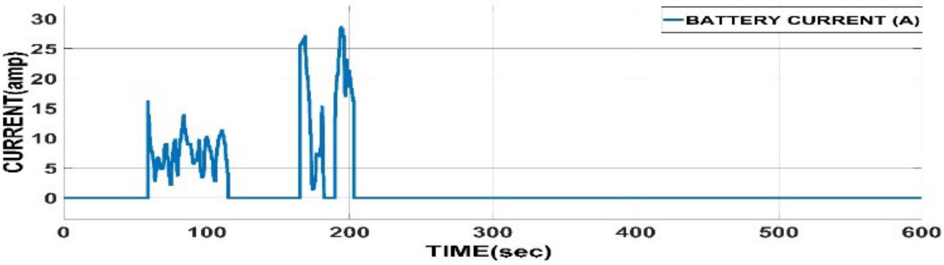
In this case, itisassumedthat the SOC of the batteryis 99.5% and the SOC of SCis 100%. According to the drive cycle, the vehiclestarts and accelerates for 120 seconds Fig. 6(a). Since SOC of the supercapacitorislessthan 40% after 50 seconds Fig. 6(b)sobatterystartsdischargingwhen SOC of the batteryreaches up to 20%then the batterystoppeddischarging Fig. 6(c),nowsupercapacitorstartdischargingbelow 40% Fig. 6(b), at 120 seconds, whenvehiclestartdeaccelerating Fig. 6(a), since the SOC of the supercapacitorisbelow 40% whichislessthan 80% sosupercapacitorstartscharging Fig. 6(b) with a negativecurrent Fig. 6(d), afterdeceleration of 10 -12 second vehicleagainstartsaccelerating Fig. 6(a), soagainsupercapacitorstartsdischargingbecause SOC of the batteryreaches to itslowerlimit of discharge. This process of discharging/charging of supercapacitoriscontinued till the SOC of the supercapacitorreachesitslowerlimitof 10% and the vehicleisfullystopped due to fullydischarged.



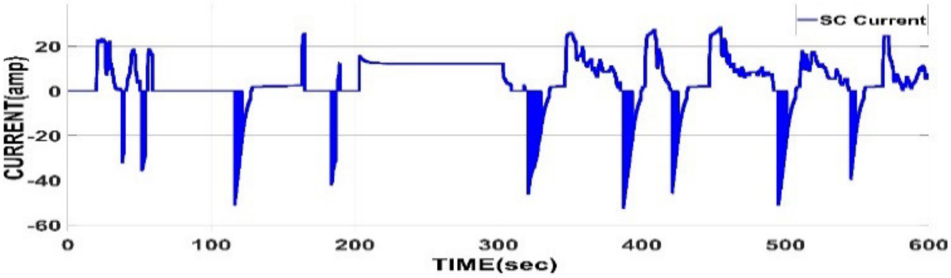
(a)



(b)



(c)



(d)

Fig. 6. Case 4 output parameters

- **SOC of batterywithoutSupercapacitor**

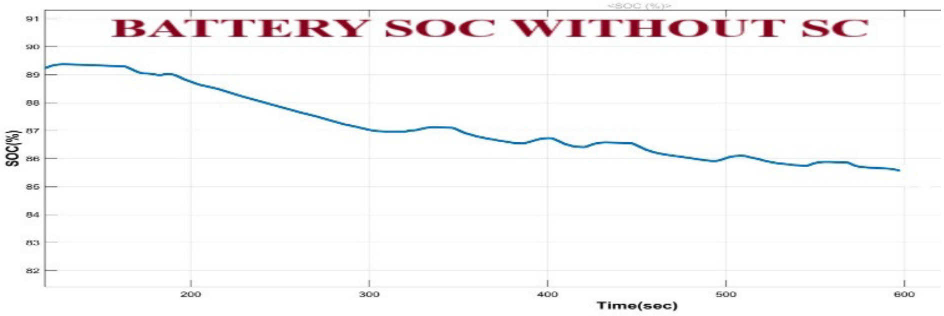


Fig. 7**.** SOC of battery without supercapacitor

- **SOC of Hybrid energy storage system**

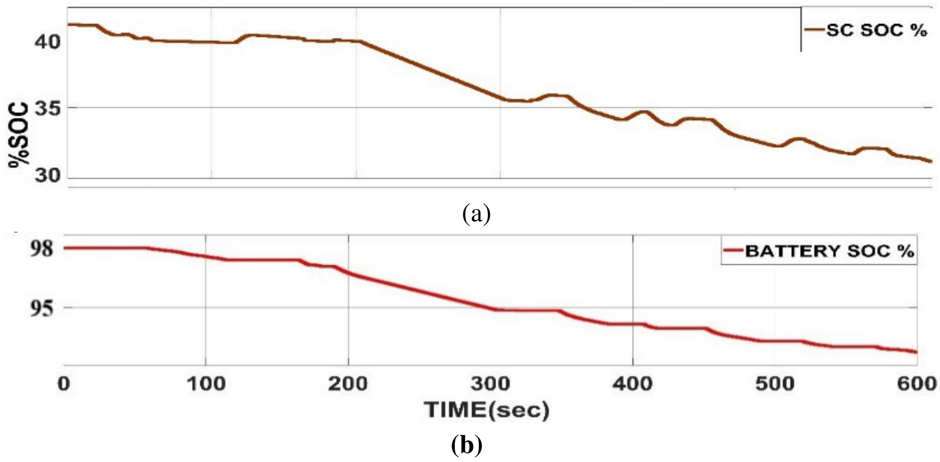


Figure 8. SOC of supercapacitor (a) and Battery (b)

- **Distance travelled by vehicle in 600 seconds:**

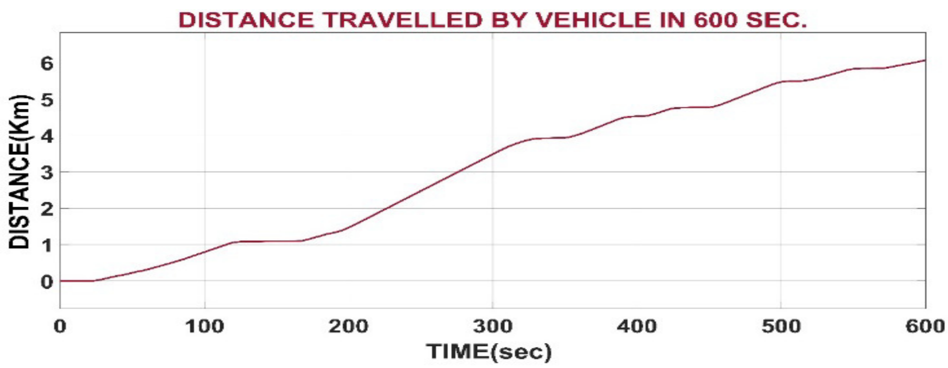


Fig. 9. Distance travelled by vehicle in 600 sec.

- **Range of the vehicle without supercapacitor:**

  When the vehicle is running without a supercapacitor then the only battery is used as a supply system. The Capacity of the battery bank is 286 Ah. In this case, the battery discharges at the rate of 3.4% in 10 minutes for a specific drive cycle (Fig. 7). The distance travelled by the vehicle is 6.02 km in 10 minutes (Fig. 9), so for 90% discharged, the vehicle covers a distance of 159.34 km. Fig. 7 show the rate of discharging/ charging of battery without supercapacitor.

- **Range of the vehicle with HESS:**

  When the combination of battery and supercapacitor is used as a hybrid energy storage system for the electric vehicles in this case the battery capacity is 220 Ah only and supercapacitor capacity is 66 Ah. When Supercapacitor supplies power to the vehicle then it discharges at a rate of 9% in 10 minutes Fig. 8(a) and the battery discharges at a rate of 4.8 % in 10 minutes Fig. 8(b). For 90% discharging of the supercapacitor,the vehicle covers a distance of 60.19 km and for 90% discharging of battery vehicle covers a distance of 112.87 km. So the overall distance covered by the vehicle in presence of battery and supercapacitor is 173.06 km. It can be observed that the range of the vehicle when it is integrated into battery and supercapacitor is increased by 8.61 % for the same drive cycle.

5. Conclusion

The proposed model and results show the maximum utilization of supercapacitor energy to run the vehicle because a high current through regenerative breaking can charge SC faster than the battery, that's why most of the time only supercapacitors are being used for charging and discharging when its SOC is between 40% to 80% so this reduces the stress on the battery and battery energy are less utilized when SOC of the supercapacitor is above 40%. The battery starts discharging when the SOC of the supercapacitor reaches 40% or below.

When the vehicle is running without a supercapacitor then the only battery is used as a supply system. In this case, the battery discharges at the rate of 3.4% in 10 minutes for a specific drive cycle. And the distance travelled by the vehicle is 6.02 km in 10 minutes, so for 90% discharged, the vehicle covers a distance of 159.34 km.

When the combination of battery and supercapacitor is used as a hybrid energy storage system for electric vehicles, the overall distance covered by the vehicle in presence of battery and supercapacitor is 173.06 km. It is also observed that the range of the vehicle when with battery and supercapacitor increased by 8.61 % for the same drive cycle.

When a hybrid energy storage system is being used, the size of the battery also gets reduced which indirectly affect the overall weight of the EV that leading to improved range and efficiency of EV. The supercapacitor and battery-based hybrid energy storage system with the control logic, not only helps to improve the battery life, vehicle range but also provides better energy management and protection to the battery from high discharging current during regenerative braking.

References

[1] R. Karangia, M. Jadeja, C. Upadhyay and H. Chandwani, "Battery-supercapacitor hybrid energy storage system used in Electric Vehicle," *2013 International Conference on Energy Efficient Technologies for Sustainability*, 2013.

[2] Jian Cao & Ali Emadi, "A New Battery / Supercapacitor Hybrid Energy Storage System for Electric, Hybrid, and Plug-In Hybrid EVs," IEEE Transactions on Power Electronics, vol. 27, no. 1, january 2012.

[3] AlirezaKhaligh, Zhihao Li, "Battery, Supercapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric, Hybrid Electric, Fuel Cell, and Plug-In Hybrid EVs: State of the Art," IEEE Transactions on Vehicular Technology, Vol. 59, No. 6, July 2010.

[4] M. K. Yoong et al., "Studies of regenerative braking in electric vehicle," 2010 IEEE Conference on Sustainable Utilization and Development in Engineering and Technology, 2010.

[5] Cao Binggang, Zhang Chuanwei, BaiZhifeng, Trend of Development of Technology for Electric Vehicles. Journal of Xi'an Jiaotong University,2004.

[6] F. Akar, Y. Tavlasoglu and B. Vural, "An Energy Management Strategy for a Concept Battery/Ultracapacitor Electric Vehicle With Improved Battery Life," in IEEE Transactions on Transportation Electrification, March 2017.

[7] O. C. Onar and A. Khaligh, "A novel integrated magnetic structure based DC/DC converter for hybrid battery/ultracapacitor energy storage systems," Smart Grid, IEEE Transactions, 2012.

[8] G. Subramanian and J. Peter, "Integrated Li-Ion Battery and Super Capacitor based Hybrid Energy Storage System for Electric Vehicles," 2020 IEEE International Conference on Electronics, Computing and Communication Technologies, 2020.

[9] Lia Kouchachvili, WahibaYaïci, EvgueniyEntchev "Hybrid battery/supercapacitor energy storage system for the electric vehicles". Journal of Power Sources journal 374(2018)237-248.

[10] Zhifeng Bai, Yaojie Sun, Yandan Lin, Guorong Chen and Binggang Cao, "Research on Ultracapacitor-Battery Hybrid Power System," 2011 International Conference on Materials for Renewable Energy & Environment, 2011.

[11] S. Pay, Y. Baghzouz, "Effectiveness of battery &supercapacitor combination in electric vehicles," Power Tech. Conference Proceedings, 2003 IEEE Bologna.

[12] K. Sahay, B. Dwivedi, An overview on Supercapacitors Energy Storage System for Power Quality Improvement, JES 2009

[13] Zhang Enhui, Qi Zhiping, Wei Tongzhen. "Research on combination of series and parallel with Supercapacitor Module," 2010 2nd IEEE International Symposium on Power Electronics for Distributed Generation Systems.

[14] N. Schofield, H. T. Yap, and C. M. Bingham, "Hybrid energy sources for electric and fuel cell vehicle propulsion," IEEE Vehicle Power and Propulsion Conference, VPPC, 2005.

[15] Ying Wu, Hongwei Gao, "Optimization of Fuel Cell and Supercapacitor for Fuel-Cell EVs," IEEE Transactions on Vehicular Technology, November 2006.

[16] HyunjaeYoo, Student Member, IEEE, Seung-Ki Sul, Fellow, IEEE, Yongho Park, and JongchanJeong, "System Integration and Power-Flow Management for a Series Hybrid Electric Vehicle Using Supercapacitors and Batteries" in IEEE Transactions on Industry Applications, January/February 2008

[17] H. Kumar, S. K. Yadav, K. Sahay and S. S. Kumar, "Investigation on Recuperation of Regenerative Braking Energy using ESS in (Urban) Rail Transit System," 2019 International Conference on Electrical, Electronics and Computer Engineering (UPCON), 2019, pp. 1-6, doi: 10.1109/UPCON47278.2019.8980241.