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Integration of Supercapacitor and Flywheel along with Battery for High-Performance Hybrid Energy Storage System

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Abstract: - Abandoning fossil fuel-based transportation and substituting it with green energy, EVs play a major role in decarbonization. In this paper, a battery, flywheel and supercapacitor-based HESS is designed for EVs which includes electric-based, plug-in type and hybrid vehicles. This HESS combines a supercapacitor, flywheel and battery (Li-ion) along with some converters. The combination of these energy storing and generating devices not only tackle the demand of "high specific power density" and specific energy density, simultaneously needed for better performance of EVs and HEVs, but also reduce the cost of Electric vehicles in long-run. By combining these two-energy storing and generating devices with battery, we can provide the advantages of both the technologies and leads to more efficient ESS (energy storage system). This HESS provide high power and high energy density as the supercapacitor provides high power and fast response times, the flywheel also provides high power density and short duration energy storage and battery provides high energy density and long duration energy storage. This type of hybrid energy storage system is useful in applications where high power and energy density is required.

Keywords: Decarbonization, flywheel, supercapacitor, high power density, high energy density, renewable energy source

I. Introduction

"With the continuous increase in population, the demand for green and renewable energy is also increasing", as the natural resources are limited in number [1]. Every sector is trying to decrease its dependency on natural resources and moving on to other renewable and green energy resources. One such sector is the transportation sector, which causes 14% of the world's total air pollution. The transportation sector uses the internal combustion system which releases carbon dioxide, carbon monoxide, nitrogen oxides, etc. which are the major greenhouse gases [2].

Given all these problems, the demand for Electric Vehicles and Hybrid Electric Vehicles has risen. According to a Fortune Business Insight report, "the Indian EV market has grown up to 3.21 billion USD in 2022 from 1.5 billion USD in 2021 and the further growth is near about 114 billion USD in 2029" [3]. Ministry of Heavy Industries predicted that 0.52 million EVs were registered in the last 3 years in India. This phenomenal rise in the EV market is due to the policies and programs of government, depletion of natural resources, rising fuel prices, increasing population, high emission of greenhouse gases, etc. Moreover, NITI Aayog aims to achieve net zero carbon emissions by 2070[4].

The expected reach of the global electric vehicle market is about 40,000 units by 2030 from 8151 units in 2022. Moreover, the EV's battery price is significantly reducing [5]. In 2010, the price was USD 1100 per kWh, in 2020 the price fell to USD 137 per kWh, and in 2021, it further fell to USD 120 per kWh and is expected to fall to USD 60 per kWh by 2030[6].

In EVs, the ESS (Energy storage system) is the important factor, on which the efficiency, performance, and cost of EVs are dependent. The supply and demand of electrical energy is balanced by ESS in an EV. The process includes storing and converting electrical energy from one form to another energy form and vice-versa. The energy storage conversion can have different forms i.e., it can be thermal, chemical, magnetic, or mechanical. Energy Storage Systems (ESS) allow electricity to be stored when there is less demand in comparison to generation and produced when it is needed. There are different ESSs (Energy storage systems)used in EVs, Mechanical Energy Storage Systems, Electro-Chemical ESS, Fuel ESS, etc.

Due to advances in material engineering and power electronics, Mechanical Energy Storage Systems or Flywheel ESS are suitable for EVs. The flywheel consists of a rotor, a generator/motor, bearings, etc. The flywheel is charged

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with the help of the EV's motor or through the Regenerative Braking System and energy is transferred to the rotor in the form of Kinetic Energy [7]. To utilize this kinetic energy, a flywheel is connected to a generator which converts kinetic energy to electrical energy, which is then used to charge the battery or derive the load. The major issue with FESS is its high self-discharging feature because of friction and winding loss.

The electrochemical energy storage system includes all rechargeable batteries. It will store the energy in Chemical form and release it in electricity form through a process of "electro-chemical reaction". These batteries consist of two electrodes i.e., anode and cathode, electrolyte solution, and a Separator [8]. These batteries have a high specific energy density and constant discharge flow but they do not have a high specific power density that is crucial in applications of high instantaneous power is required. The batteries that are majorly used by the EV industry are lead-acid, lithium-ion, nickel-based (Ni-Cd, Ni-Fe, Ni-Zn), batteries, etc[9].

In Fuel Cell- based ESS, "Chemical Energy of fuel is converted into Electrical Energy". In FC, the anode terminal is fed by hydrogen, and the cathode is fed by oxygen the chemical reaction of these two leads to the production of electricity, and water and heat are released as by-products [10]. Unlike, batteries where fuel and oxidant are integrated with it, these parts are externally supplied to produce electricity. The major problem with Fuel Cell ESS is their limited durability and lifespan i.e., efficiency and performance degrade over time. The fuel efficiency also ranges from 40% to 80% [11].

Now, the problems associated with these ESSs are high power density and energy density are not provided simultaneously, high charging time, short discharging time, short lifespan, and cost. Thus, to manage energy storage and delivery the ESS needs to be optimized by combining two or more ESSs that have complementary characteristics, and hence, the optimal performance of ESSs is ensured [12].

Now, our proposed HESS combines the characteristic and output power of the battery, supercapacitors, and flywheel. This HESS will provide a higher energy density for long vehicle range, and higher power density for better efficiency, Due to reduced stress on the battery during high power demand the battery lifespan will increase, cost of the vehicle will reduce in the long run, and the discharging time of the battery will increase and hence the overall performance of EVs will enhance [13].

The applications of this combination of battery along with supercapacitor and flywheel are not only limited to EVs but also have uses in the manufacturing and industrial sector, telecommunication and data centers, renewable energy industries, etc.

II. METHODOLOGY

A. FESS

FESS i.e., Flywheel energy storage system is a mechanical system in which the rotating mass i.e., flywheel, stores the mechanical energy and, with the help of an electrical machine, it converts that stored energy into electrical-energy & vice-versa. The kinetic energy E can be derived as:

$E = 1/2 I\omega^2$

I = moment of inertia,

ω = Rotational velocity,

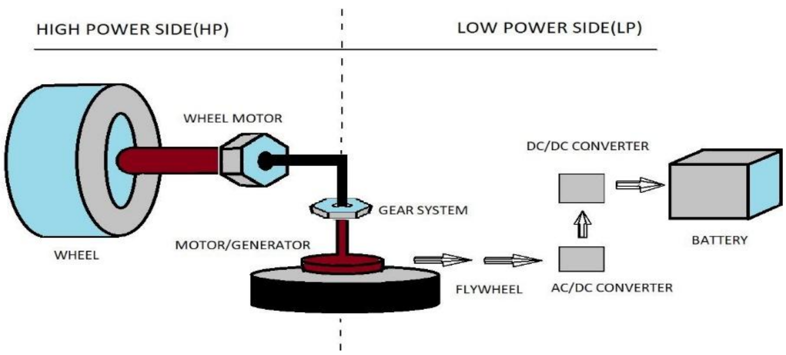

Figure 1. Flywheel Energy Storge System

$I = \int r^2\, dm = cmr^2$

where c (constant).

Thus,

$E = 1/2cmr^2\omega^2$

Power transfers from and to the flywheel in different energy forms and since it is a reversible process, the fly wheel acts like a battery. The conversion to DC electrical-energy from AC electrical-energy at mechanical frequency & vice-versa is done with a bidirectional converter [14]. Fig.1 shows the Flywheel Energy Storage System.

B. Components of Flywheel Energy Storage System (FESS)

The typical FESS consists of:

Flywheel: It is the central part of the FESS. It is composed of a durable material, with low friction and high strength to maintain its structural integrity during operation.

Electric Motor/Generator: It is in combination with the flywheel. During the charging state, the motor will act as a generator as it gives mechanical energy from electrical energy and accelerates the flywheel to a high speed during the system discharging period motor works like a generator and transforms the Rotational Energy of the flywheel back into Electrical Energy [15].

Magnetic Bearings: It is used to reduce friction and energy losses. As we know, normal mechanical bearings can cause energy losses and require periodic maintenance and lubrication. To overcome the problem, FESS uses magnetic bearings, here because of repulsive magnetic forces the shaft levitates. In magnetic bearings, there is no requirement for lubricant and hence, results in vacuum confinement.

Power Converter: The FESS consists of a bidirectional DC/AC converter, used to connect an electric machine to a DC link. They are 3-ϕ bridges of semiconductor switches that works like VSI and are controlled by PWM. The inverter is responsible for the machine behaving as a motor or generator, according to need. To vary the torque the electrical machine is controlled, as required for constant voltage [16].

1) Working

The rotor of the flying wheel, which stores kinetic energy, is connected to an electric motor-generator. The rotational speed increases when electricity is fed into the storage system. When the electricity supply is cut off, the rotor mass keeps spinning in a low-friction environment (i.e., vacuum, magnetic, or low-loss roller bearings) and maintains its speed with only a slight decrease over time. When electricity is needed, the electric machine is switched to generator mode and the inertia of the spinning mass provides the torque to power the generator. The maximum stored energy in a flywheel is limited by centripetal forces.

The flywheel's stored energy depends on the material of the flywheel, if we are using 31 kg of high-strength carbon fibers (T1000G) and high-strength steel, carbon fiber would store more energy as compared to the high-strength steel [17][18].

The basic purpose of this connection between the flywheel and the HEV/EV battery is to enhance the ESS by leveraging the strength of the two components.

The flywheel has a large power density & fast response time and the battery has a high energy density. By integrating these two technologies, the circuit can provide a more stable and consistent power output, minimizing fluctuations in the energy supply from the o/p of the generator to the battery with the help of an AC/DC converter [19].

“For high speeds, fly-wheel o/p voltage is large during charging and to control the constant current into the battery, a buck DC/DC converter is required” [20]. In the case of high o/p voltage of the flywheel, a buck converter should be used. In case of lower flywheel output voltage, to keep the current constant a DC/DC converter must be used [21][22]. Fig. 2 shows the MATLAB circuit of the flywheel with AC/DC converter.

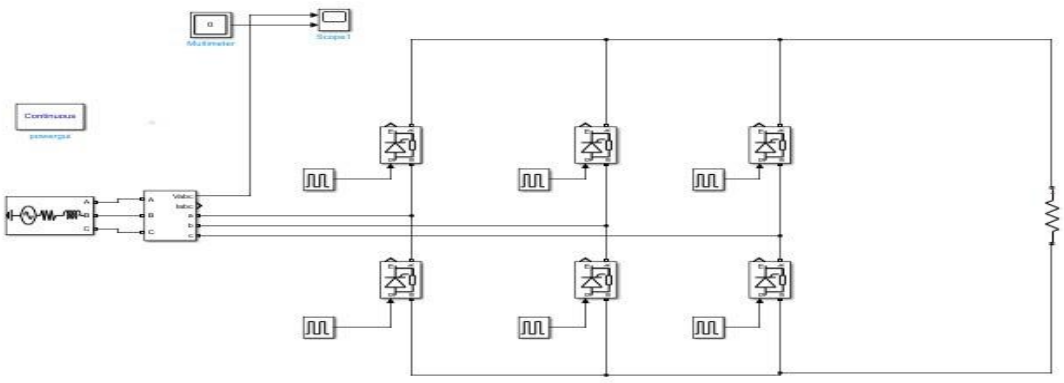

Figure 2. MATLAB circuit of Flywheel with AC/DC converter

C. Supercapacitor

A supercapacitor, which is also called a double-layer capacitor or an ultra-capacitor [23], is an electrochemical energy storage device whose voltage limits are low, but capacitance value is high and has a higher energy density than a conventional capacitor, but lower than a battery. Its energy storing capacity per unit mass and volume is usually higher than electrolytic capacitors store i.e.,10 to 100 times more, and allows the movement of charges at a faster rate than batteries [24].

Supercapacitors store and release energy through the movement of ions within the electrolyte while batteries use chemical reactions for this purpose [25]. This makes them capable of charging and discharging much faster than batteries, with a lifespan usually > 100,000 cycles, which is way longer than the lifecycle of conventional capacitors.

The construction of a supercapacitor is similar to an electrolytic capacitor. Supercapacitors are constructed from two electrodes (made of graphene or activated carbon material), an electrolyte solution (usually Potassium Hydroxide Sulphuric Acid), and a separator (made of Kapton). As compared to normal capacitors, the supercapacitor has a large surface-area of conduction plates & small distance b/w plates [26]. Fig. 3 shows the basic structure of the supercapacitor.

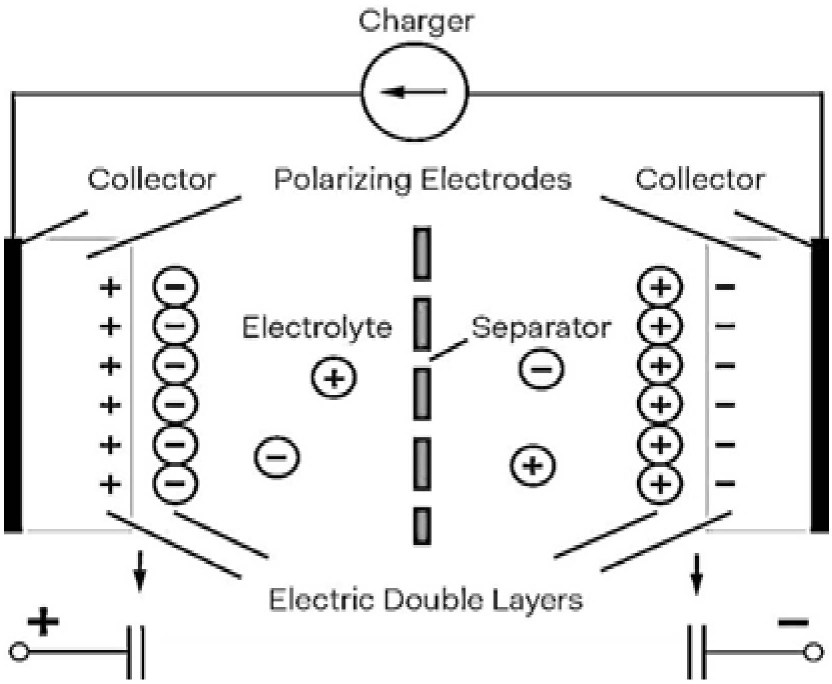

Figure 3. Construction of Supercapacitor

With the application of voltage, the plates are charged accordingly. This leads to the movement of ions present in electrolyte solution i.e., the positively charged ions will move to the (-)ive charged plate and negative ions will move to the +ive charged plate. Due to the movement of ions, there is deposition of ions on the inner side of both plates. This forms an electrostatic double layer like two capacitors connected in series. The two capacitors have a high value of capacitance due to the small distance between the charge layers of the capacitors. The capacitance of the supercapacitor is given by (C1 x C2)/ (C1 + C2) formula [27].

Table 1.Comparison of different properties of Battery and Supercapacitor

Functions	**Supercapacitor**	**Battery (Li-ion)**
Specific-Power(W/kg)	<=10,000	1,500 to 3,000
Specific-Energy (Wh/kg)	5	110-200
Charge Time	10 seconds to few minutes	10 to 60 minutes
Cell-Voltage	2.30-2.75v	3.60-3.70v
Service life	10-15 years	5-10 years

Supercapacitors have a long cycling time, with a high cycle efficiency (84-97%) and have a cycle life of 1 million or 30,000H, capacitance ranging from 1mF to >10kF, and have a specific-energy density of 5 to 10 wh/kg [26]. Supercapacitors have a very large specific power i.e., 10,000 w/kg, cell voltage of about 2.3v to 2.75v[28]. The charge time of a supercapacitor is about 10sec to a few minutes and supercapacitors are environment friendly as no heavy metals are used in their development. The service life of supercapacitors is usually about 10-15 years [29].

D. Combination of Battery along with Supercapacitor

Batteries have high specific energy density and can store more energy per unit weight or volume and are suitable, where continuous energy is required for a longer duration of time [30].

Supercapacitors have high specific power density and rapid charging. They are useful when a short burst of energy. Supercapacitors have high costs during the initial phase, but in terms of the long run, they are cost-efficient [31].

So, the integration of battery along with supercapacitor can provide us the high specific energy as well as high specific power, which will ultimately lead to high performance of HEV [32]

"The supercapacitor is parallelly connected to the battery and the battery is linked to a bi-directional Dc/Dc converter (consists of MOSFET, inductor, diode, and capacitor) and the supercapacitor is connected to the battery in parallel along with bidirectional DC/DC converter".

This connection allows proper power management between the Battery and Supercapacitor. When there is a need for sudden high power, then the power is delivered by supercapacitor and when we need average speed, then power is supplied by battery. The bi-directional DC/DC converter works as a Buck-Converter in case of charging and works as a Boost-Converter in case of discharging. Supercapacitors reduce the additional load on batteries during acceleration or hill climbing [33]. Fig. 4 shows the MATLAB circuit for a combination of battery and supercapacitor along with a dc/dc converter.

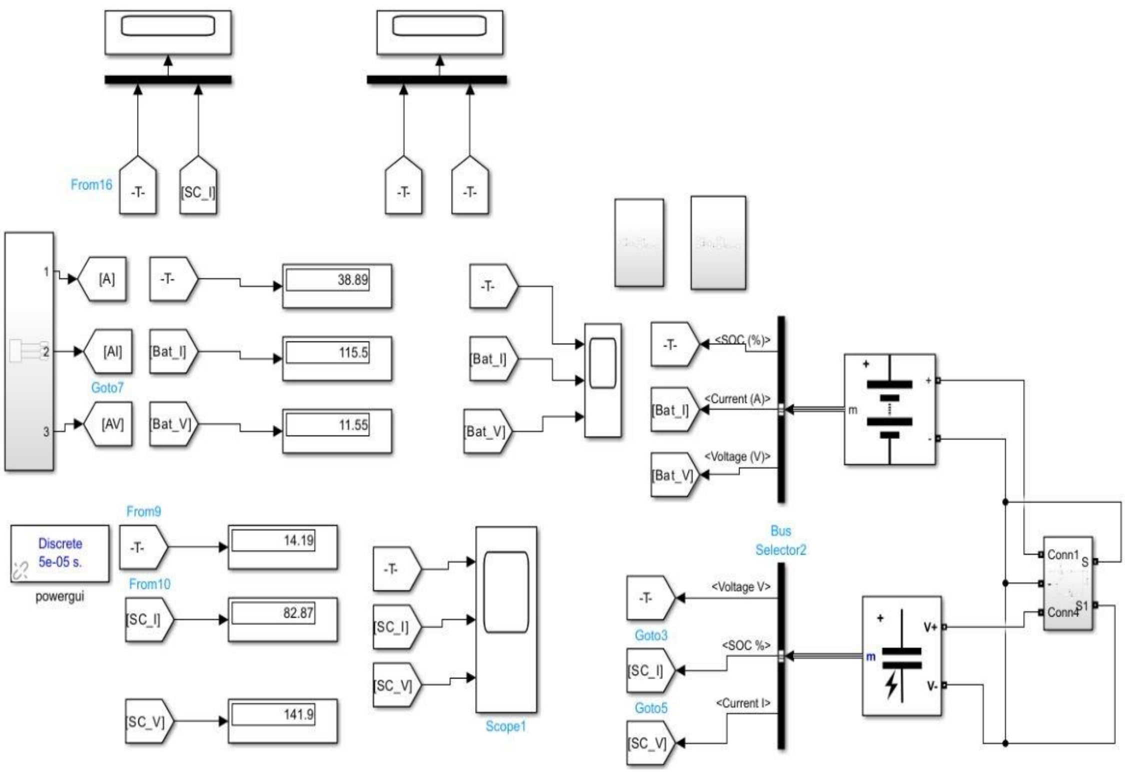

Figure 4. MATLAB circuit of Supercapacitor with Battery along with dc/dc converter

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III. HESS CIRCUIT USING SUPERCAPACITOR, FLYWHEEL AND BATTERY

Before This HESS will provide large power and large energy density as the supercapacitor will provide high power and fast response times, the flywheel will provide high power and short-duration energy storage and the battery will provide high energy density and long duration energy storage.

This HESS is useful in the case of large specific energy & large specific power density, such as in renewable energy systems, grid-stabilization, and EVs. The supercapacitor and flywheel can handle the high-power demands of these applications, while the battery can provide the energy needed to drive the vehicle for longer periods of time.

The supercapacitor not only charges the battery but also provides the power to motor during high power demand, there is less stress on the battery and the battery supplies the energy during normal or static operation of the vehicle. The supercapacitor is charged by a regenerative braking system and flywheel. The flywheel provides the DC power to the supercapacitor through an AC/DC converter as the flywheel output is AC [34]. The flywheel generates power during the de-acceleration of the vehicle. The work of the AC/DC converter is to change the AC power, produced by flywheel into DC power.

A. Circuit

In this HESS, the battery is parallelly linked to the supercapacitor along with the DC/DC converter and then connected to the motor. The flywheel is connected to a supercapacitor along with ac/dc converter and is connected to the motor through the gear box. Fig. 5 shows the basic layout of the Hybrid Energy Storage System using supercapacitor, flywheel, and battery.

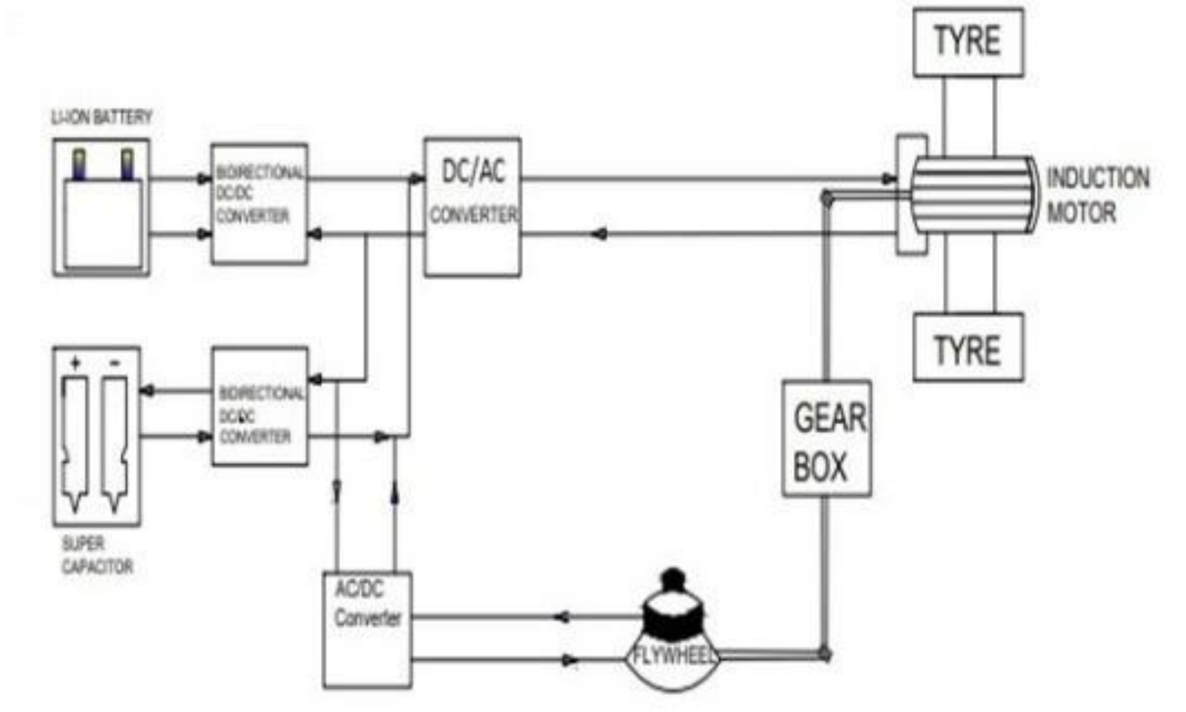


Figure 5. Layout of Hybrid Energy Storage System using Supercapacitor, Flywheel and Battery

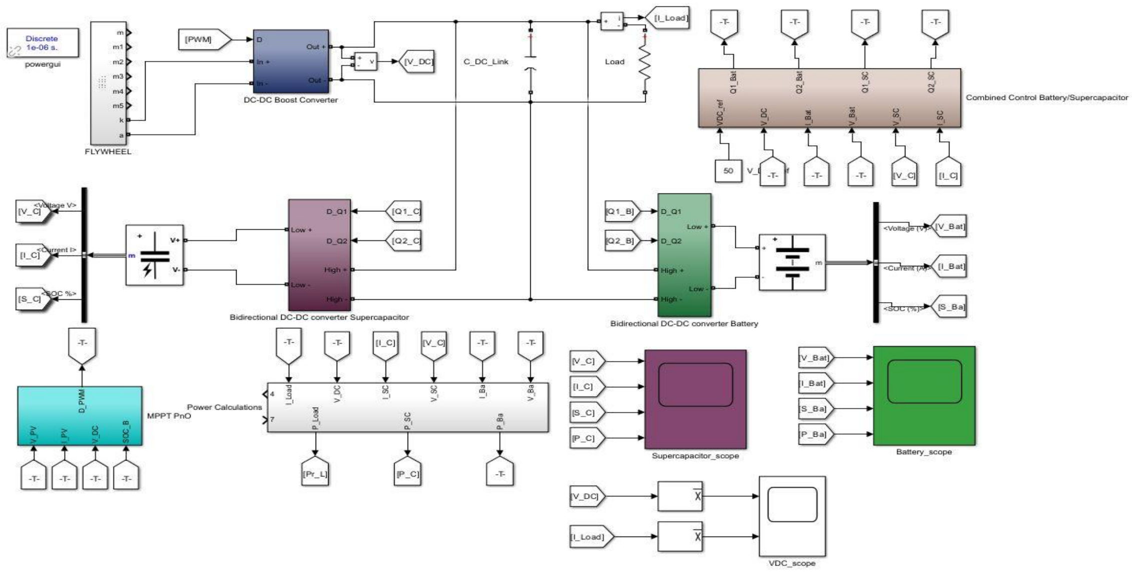


Figure 6. Matlab circuit of HESS using Supercapacitor, Flywheel, and Battery

IV. RESULT

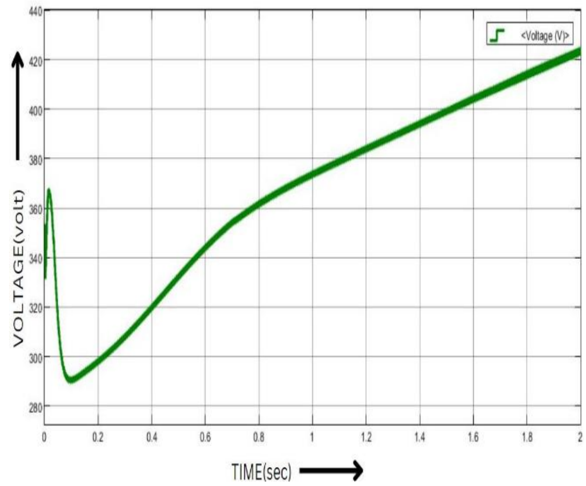
"5 Li-Ion batteries of 3.6V, 600mAh were taken along with a supercapacitor of 600mF which is parallelly connected to battery. Batteries were charged to 4.20V respectively and then discharged to 3.1V when the current is 2.1A, the duty cycle is 12.50% & the period is 4.60ms" [35].

As a result, the battery alone lasts for 2.21 hours, and when combined with a supercapacitor it lasts for 2.53 hours, a net increase of 14% [35]. The transients were reduced significantly. If the threshold had been 3.3V then there would have been a total of 33% extension. Likewise, an increase of 305% would have been recorded for the threshold of 3.5V [35].

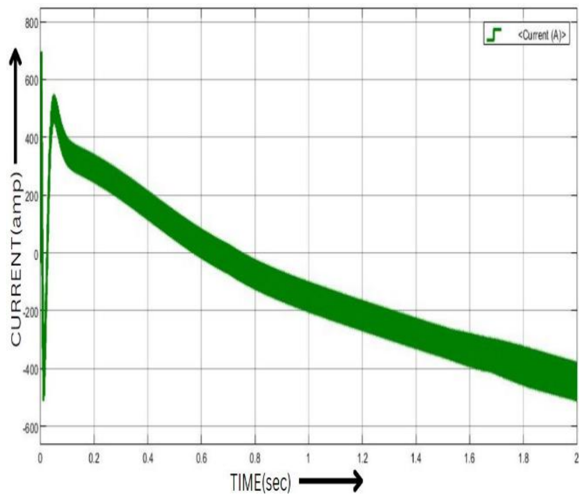
The battery impedances are usually hundreds of milli-Ω, but a parallelly connected supercapacitor would effectively reduce the impedance to a few milli-Ω& further lead to a reduction in transients.

Results show the average runtime as 2.3 hours in the case of no supercapacitor, along with 0.16 standard deviation, while it was 2.5 hours in the case of a supercapacitor with 0.08 standard deviation, which results in an advancement of 9%. The best improvement which was recorded was 23% and the worst was 1.2% [35].

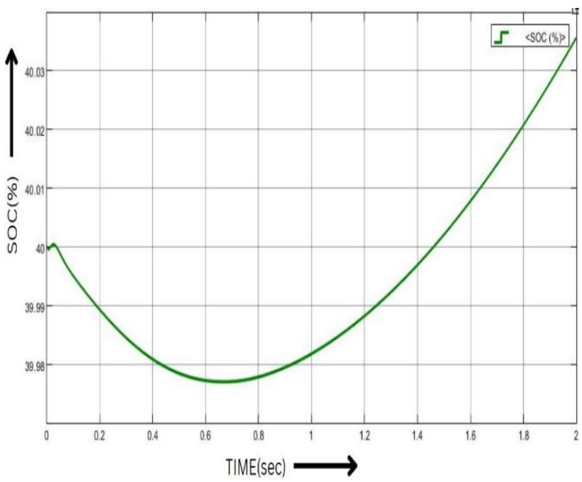
The circuit simulation of the following proposed HESS is done on MATLAB and the graphs for the same are attached below. Fig. 6 shows the MATLAB circuit of HESS.



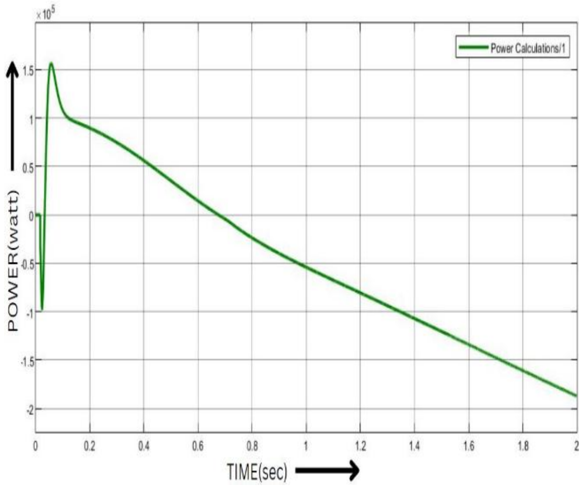
7(a) Voltage vs time graph of battery



7(b) Current vs time graph of battery

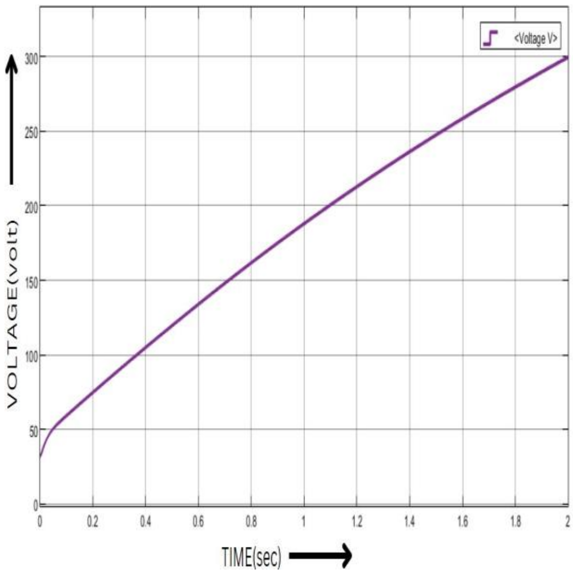


7(c) SOC (%) vs time graph of battery

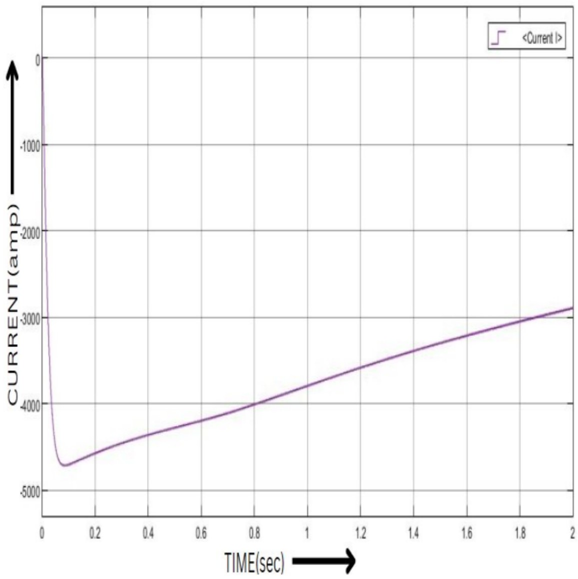


7(d) Power vs time graph of battery

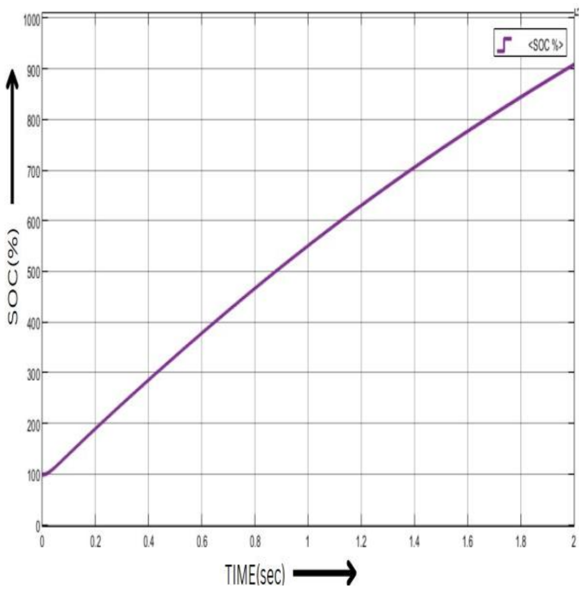
The above-mentioned figure shows the battery charging and discharging process. Initially, the SoC decreases in fig 7(c), which shows the discharge of the battery and during the discharging of the battery, the voltage decreases as shown in Fig 7(a). Then SoC increases, which shows the charging of a battery and during the charging of the battery voltage increases, and this is clearly depicted in Fig 7(a). Fig 7(d) initially shows the power hike because the battery was discharging i.e., power is being supplied to load and then it shows the decrease because the battery is now charging i.e., power is not being supplied to load. Fig 7(b) shows the current discharge of a battery.



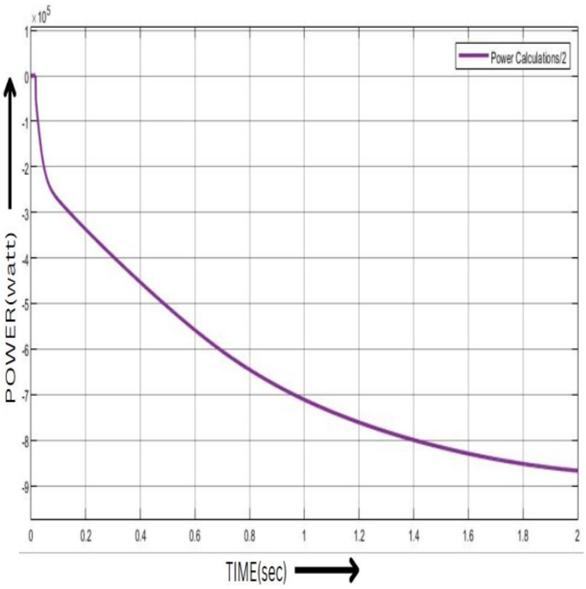
8(a) Voltage vs time graph of supercapacitor



8(b) Current vs time graph of supercapacitor

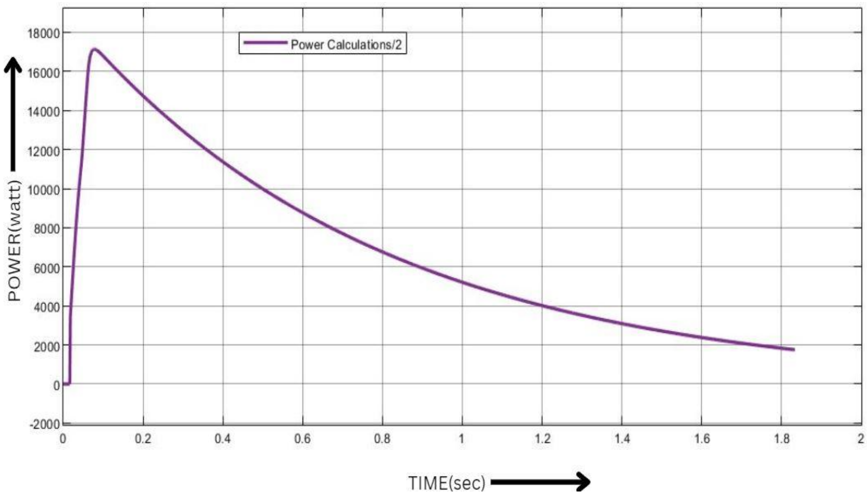


8(c) SOC (%) vs time graph of supercapacitor

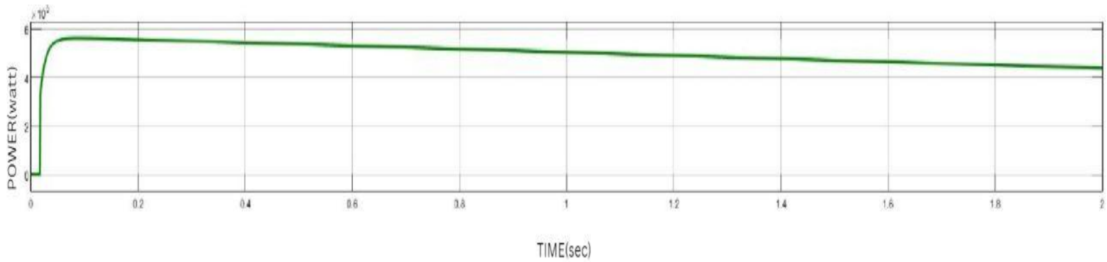


8(d) Power vs time graph of supercapacitor

The above-mentioned figure shows the response of the supercapacitor when connected in combination with battery and flywheel. Fig 8(c) shows the linearly increasing SOC (%) of supercapacitors. The increasing SOC (%) shows the charging of the supercapacitor and during charging, the supercapacitor voltage increases which is shown in Fig 8(a). Fig 8(b) shows the current vs. time graph during the charging of supercapacitor. The power is decreasing in fig 8(d), which shows that the supercapacitor is not supplying any power to load.



9(a) Power delivered vs time graph of supercapacitor



9(b) Power delivered vs time graph of battery

The above-mentioned figure shows the comparison of power supplied to load by supercapacitor and battery. During starting condition, high and sudden power is required which is supplied by the supercapacitor fig 9(a), and when the vehicle comes into normal operating condition the power supplied by the supercapacitor decreases, and the power supply from the battery increases, as shown in the fig 9(b). This power supply by supercapacitor during high power demand increases the lifespan of the battery and increases the efficiency of the battery.

V. CONCLUSION

The integration of supercapacitors, flywheels, and battery assembly provides mixed power generation and storage capacity. The supercapacitor and flywheel both have high power density, moreover, the flywheel can also provide high energy density. By integrating these two technologies with batteries, the resulting system can provide high power and high energy density simultaneously, which improves the efficiency, reliability, and range of electric vehicles. In total, the supercapacitor, flywheel, and battery integrated into the mixed power generation system have exhibited high vehicle performance and efficiency and same is evident from the results.

ACKNOWLEDGMENT

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