Enhancing Electric Vehicle Performance: A Comparative Study of Full Active and Passive Hybrid Energy Storage Systems via MATLAB Simulink

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Abstract

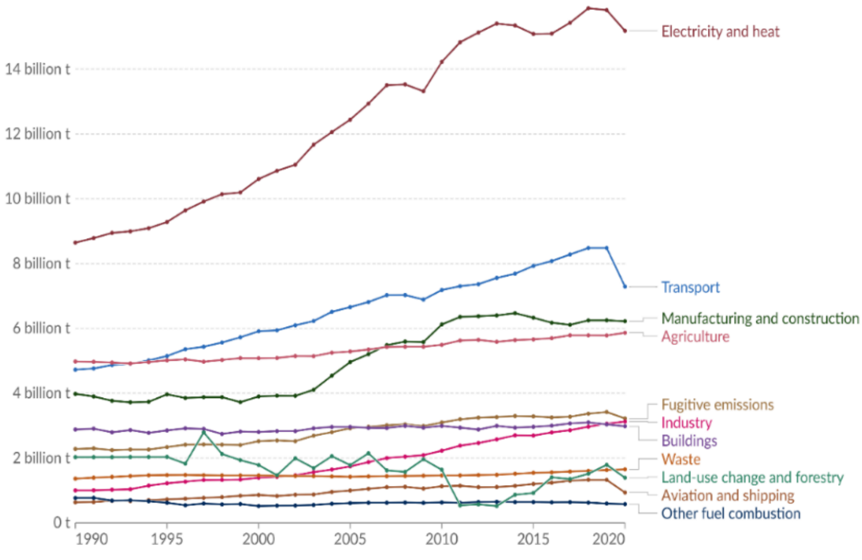
In this study, a comprehensive examination of battery and supercapacitor-based hybrid energy storage systems (HESS) is conducted to enhance the performance of electric vehicles. By utilizing MATLAB Simulink as the primary analytical tool, we compare the efficiencies of fully active and passive hybrid energy storage systems. The primary objective is to integrate the power density of supercapacitors with the energy density of batteries, aiming to achieve superior performance metrics for electric cars. Our findings reveal that the fully active hybrid energy storage system demonstrates a more efficient power management capability, outperforming the passive system by generating over 41% more power under identical load conditions. This research not only underscores the potential of full-active HESS in electric vehicles but also sets a foundational base for future investigative endeavors in this rapidly evolving field.

Keywords: Electric Vehicles, Hybrid Energy Storage Systems, MATLAB Simulink, Performance Enhancement, Supercapacitors

1.INTRODUCTION

The gasoline vehicles are an integral part of this world as they provide convenience and mobility to almost everyone. However, this convenience leads to pollution and an increase in greenhouse gas (GHG) emissions due to the combustion of gasoline. There have been many studies that indicate that the environment is negatively affected by gasoline vehicles as far as air contamination and release of greenhouse gases are concerned [1]. Carbon dioxide (CO_2) emissions, mainly from fossil fuel combustion, have increased significantly since the beginning of the industrial revolution. CO_2 is one of the gases contributing to greenhouse effects and, subsequently, climate change. Currently, transportation is responsible for over 20 % of worldwide CO_2 emissions resulting from the combustion of fossil fuels [2]. To reduce concentration levels of air pollutants like CO_2 and other greenhouse gases, governments of quite a few developed countries have been promoting the use of electric vehicles (EVs) [3].

Energy storage systems (ESS) in electric vehicles (EVs) have an equivalent fuel consumption cost of \$0.04 per mile compared to \$0.10 per mile of internal combustion engine vehicles (ICEVs) [4].



Data source: Climate Watch (2023) OurWorldInData.org/co2-and-greenhouse-gas-emissions | CC BY

Figure 1: GHG emissions (as per "Our World Data")[5]

Most of the produced oil is used in the transportation industry. An electric vehicle addresses the issues of not relying on fuel supplies, being a zero-emission vehicle, and operating silently, which lowers noise and air pollution owing to its onboard energy storage system [6].

The primary energy storage component of an electric car is its batteries. The success of an electric vehicle is determined by its batteries. Rechargeable batteries provide power to the controller, which in turn powers the electric motor. The electric/current principle governs the operation of an electric vehicle runs. It powers an electric motor with a battery pack or a battery. The motor then rotates the gearbox, which turns the wheels using the power (voltage) from the batteries [7]. Although Different types of batteries have been used in electric vehicles, lithium-ion (Li-ion) batteries show the greatest promise and are currently being used [8].

Table 1: Comparison of various battery types used in EVs[8]

Battery Type	***Specific Power (W/kg)***	***Specific Energy (Wh/kg)***	***Life (Years)***	***Cycles***	***Efficiency (%)***	***Cost ($/kWh)***
Lead-Acid	50-180	30-50	3-15	500-4.5k	70-90	50-200
Ni-Based	50-1000	30-70	15-20	100-40k	50-90	150-2400
Li-Based	250-400	90-190	~15	500-18k	80-95	100-2000

Batteries face several key limitations. They struggle to meet peak power demands, which is a major drawback. Additionally, the frequent charge and discharge cycles required in applications needing instant power input and output negatively impact battery life. Thermal management also poses a challenge, making it difficult for batteries to operate safely under high-power loads [9]. This involves not only warming the battery to cold temperatures to reach the desired power limits but also cooling it down. Balancing the cells in a battery system is another problem that affects the battery life. The voltages of the individual cells eventually drifted apart in the absence of a balancing system. When a battery is used for high-rate charging and discharging, this condition worsens [10]. On the other hand, supercapacitors (SC) have a long-life cycle, high specific capacitance, high power density, high power rates, and minimal maintenance requirements. The fact that supercapacitors can be charged and discharged quickly is one of their main selling points [11].

In this study, we will study the battery and supercapacitor-based hybrid energy storage system (HESS) combining power density with energy density to offer the best possible performances for Electric Cars by using MATLAB simulink.

The study also presents various HESS topologies and a MATLAB comparison between full-active and passive configurations. It was found that Full-Active HESS demonstrates better power management compared to Passive HESS, as FA-HESS generates more than 41% of the power Passive HESS generates for the same load. It was also found that FA-HESS was approximately 2% more efficient than Passive HESS, which makes it better for high-performance applications.

1.1. HYBRID ENERGY STORAGE SYSTEM

In an energy storage system where both supercapacitors and batteries are used as a single storage system, where we can exploit the advantages of batteries and supercapacitors and mitigate their disadvantages, we call it a hybrid energy storage system (HESS). It combines the benefits of multiple energy storage systems by combining high-energy-capacity devices with high-power-capability devices [12]. HESS's aim is to balance short-term power peaks with long-term energy requirements, with high-energy storage devices acting as the primary storage and high-power energy storage devices as the secondary storage [13].

The various benefits of sharing power in a HESS are as follows:

- A higher power limit can be attained by incorporating an external power delivery device that surpasses the capacity of a single energy-storage device [12].
- The lifespan of a battery can be prolonged by producing a lower instantaneous power output, which consequently ensures that the temperature of the battery remains within safe parameters, as the supercapacitor assumes responsibility for delivering the required power [14].
- The more effectively a battery is utilized by reducing the power or current drawn from it, the greater the efficiency with which power may be extracted from it [14].

1.2. HESS Topology

Generally, HESS topologies can be divided into three categories: passive, semi-active, and fully active topologies [15]. In the passive HESS topology shown in Fig (3a), Supercapacitors (SCs) and batteries are arranged in a parallel configuration and are directly connected to the load. Although the topology is straightforward and inexpensive, the contribution of the SCs is small. A superconductor provides energy only when its terminal voltage changes. Consequently, when the SC is connected in parallel to the battery, it restricts voltage fluctuations, thereby limiting its contribution [16]. The Semi-active HESS enables the DC/DC converter to regulate one of the energy storage devices, either the battery or the SC stack, while the other storage device remains linked to the load without any regulation. It is further divided into battery semi-active (bSA) HESS and capacitor semi-active (cSA) HESS.

In cSA HESS, a battery is combined with a supercapacitor, and then they are linked to the load by a DC-DC converter Fig (3b). The system is regulated in a manner where the battery provides a relatively steady current, which is equivalent to the average load current, while the supercapacitor provides the fluctuating portion of the load current. By positioning the DC-DC converter on the supercapacitor instead of the battery, the voltage of the ultracapacitor is separated from the voltage of the battery and the load [17]. In bSA HESS, the battery is controlled by DC-DC converters Fig (3c). SCs respond quickly because they are directly linked to the motor drives. Regardless of the load profile, the battery's current may be managed to maintain the SC charge and allow for a smooth discharge profile, which keeps the battery safe [18].

Full-active HESS (FA-HESS) (Fig (3d)) solves the disadvantages of both semi-active HESSs. Both the battery and the supercapacitor are controlled by DC-DC converters, which are connected to the DC link, which is connected to the load. The supercapacitor effectively utilizes its whole operating voltage range, eliminating the need for high-power pulses from the battery. This is achieved by efficiently managing its current and correctly adjusting the DC-link voltage via the use of DC/DC converters. Nevertheless, the system is somewhat intricate, and its effectiveness is expected to be subpar due to the transfer of power via DC/DC converters [19].

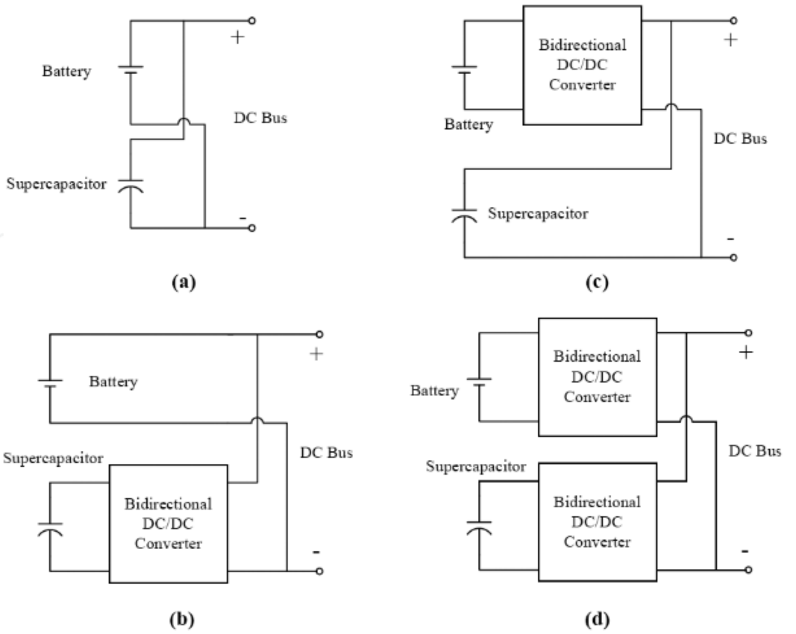


Figure 2: (a)Passive HESS (b) cSA HESS (c) bSA HESS (d) Full-Active HESS[20]

2. MODELLİNG AND SIMULATION:

MATLAB Simulink was used to simulate the full-active and passive HESS. Battery and supercapacitor models from Simscape were used to model the FA-HESS and Passive HESS, respectively. DC-DC converters for the fully active HESS were modeled separately, and a controller was designed for the FA-HESS, which allowed us to have complete control over the FA hybrid system.

The parameters for the battery and supercapacitor for both FA-HESS and Passive were kept the same, and they are listed in tables (2) and (3), respectively.

Table 2: Parameters of Battery in Active and Passive HESS

Parameters	**Specifications**
Battery Type	Li-Ion Battery
Nominal Voltage	40 V
Rated Voltage	20 Ah
SoC (%)	100

Table 3: Parameters of Supercapacitor for Active and Passive HESS

Parameters	**Specifications**
Rated Capacitance	400 F
Rated Voltage	40 V
Equivalent DC Series Resistance	0.0001
Operating Temperature	25°C

2.1. Modelling of DC-DC converters:

A DC-DC converter is a device that uses DC as an input and output. They use semiconductor devices as switches, and switching occurs at very high frequencies [21]. In our model, the switching frequency was set as 15000 KHz.

Fig (3) shows the MATLAB model of the boost DC-DC converter for supercapacitors and batteries. It comprises an inductor, capacitor, and IGBT switch.

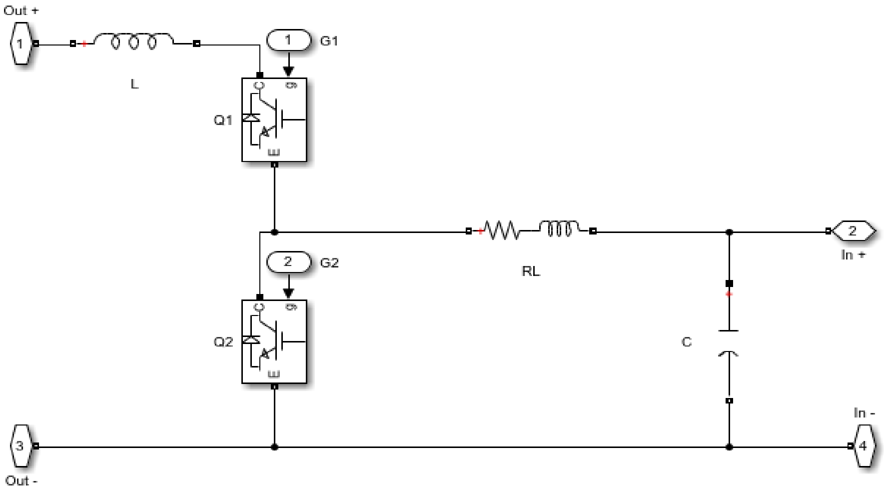


Figure 3: DC-DC Boost converter

2.2. Modelling of the Full-Active HESS

Fig (4) shows the MATLAB model of FA-HESS. As shown, the supercapacitor and battery have individual converters connected to them, which are subsequently connected to the load.

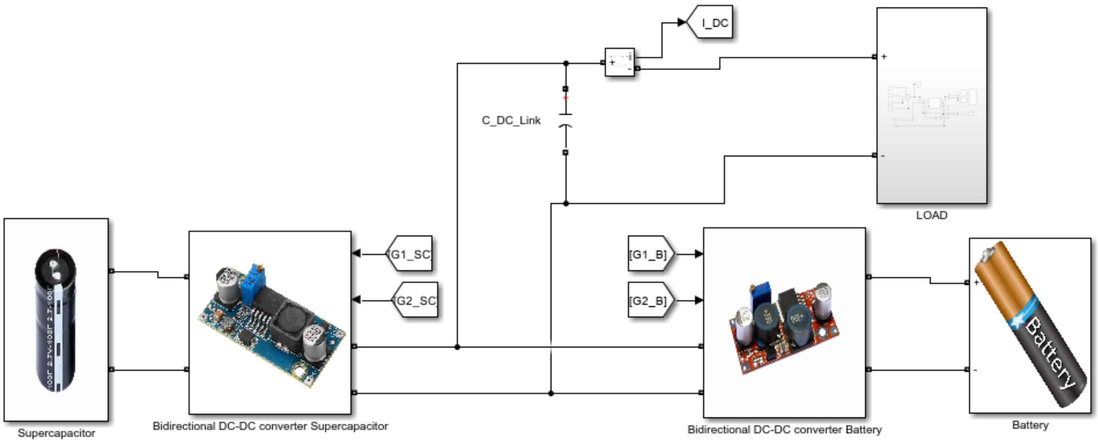


Figure 4: MATLAB model of Full-active HESS

2.4. Modelling of the controller for FA-HESS

The figure (5) shows the controller used for FA-HESS. It's based on the work by [22]. For the battery, the actual voltage (V_DC) is compared with the reference voltage (V_ref), and the resulting error signal is fed into the PI controller. In order to reduce the error, the PI signal generates the I_ref needed from the HESS. In order to avoid high charge/discharge rates, a rate limiter is present in the controller. The rate limiter's output is sent to the battery converter as a reference current signal. This reference current is now compared with the battery current, and the resulting error is sent to the PI controller, which generates Ib_er, and it is then sent to the PWM generator, which generates pulses for the battery converter switches (G1_Bat, G2_Bat).

For the SC, the process is the same. The only difference is the lack of a rate limiter since it produces high charge/discharge rates for the system. G1_SC and G2_SC are the pulses generated by the PWM generator.

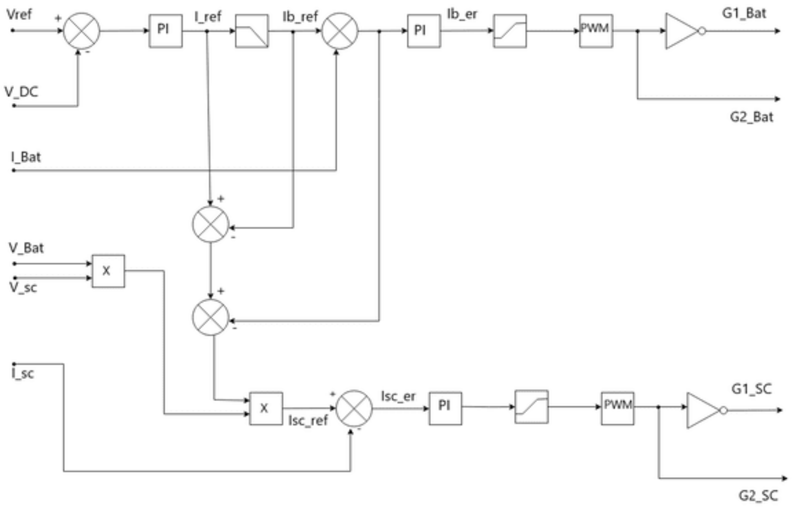


Figure 5: Controller for FA-HESS

2.3. Modelling of the Passive HESS

Fig (6) shows the MATLAB model of the passive HESS. The battery and supercapacitor were connected to the load without any converters.

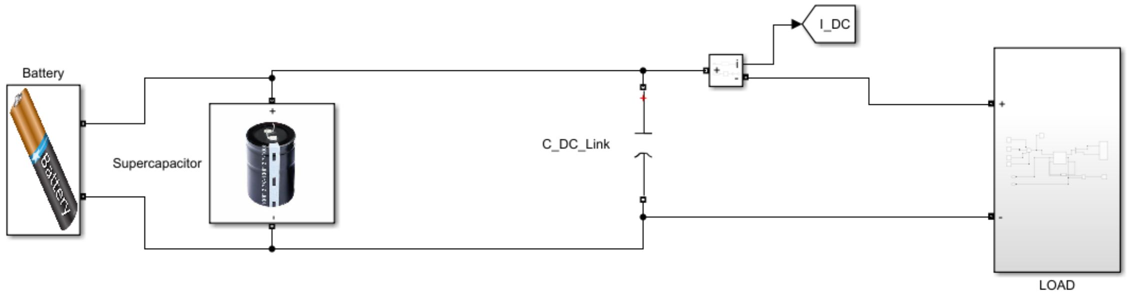


Figure 6: MATLAB model of Passive HESS

3. Experimental Studies

3.1. Power Comparison

Figure (7) shows us the graph of load power vs total power of the passive HESS system. The load power is almost the same as that of the total power because there is a direct connection between the battery and supercapacitor to the load as there are no active power electronics (DC-DC converter) in the circuit, which means there are no additional power losses. Contrary to this, in FA-HESS, the graph **(Figure 8)** of load power vs total power shows that the total power of the system is more than that of the load. One of the reasons for that is the DC-DC converters which control the power flow from the battery and SC and supply that to the load. We compared the graphs, and we discovered that the passive HESS generated a peak power of *approximately **1700 watts***, while the FA-HESS generated a peak power of *approximately **2400 watts***. This means that even though there are some power losses associated with the FA-HESS, the power dissipated by the FA-HESS to the system is around 41% more than that of the passive HESS.

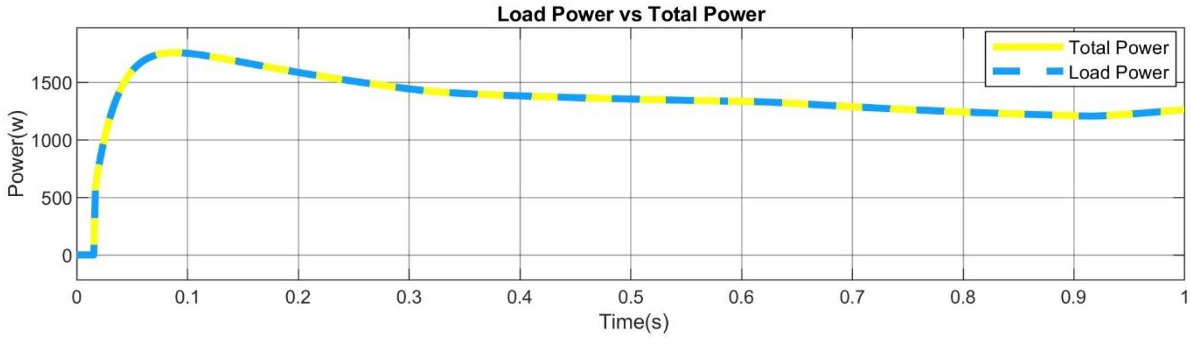


Figure 7: Load Power vs Total Power (Passive HESS)

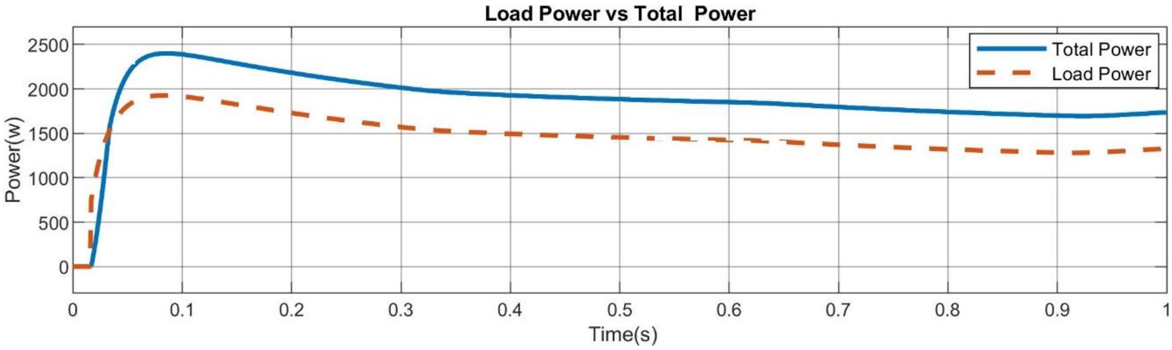


Figure 8: Load Power vs Total Power scope (FA-HESS)

3.2. Efficiency Comparison

To calculate the efficiency of the load (DC Machine), we first need to calculate its input power and output power.

3.2.1. Calculating the Input Power:

For calculating the input power of the load, we need first to calculate the power of the armature circuit and the power of the field circuit, and then we have to find their sum as shown in equation (1).

$$P_{in} = P_{ar} + P_{f} \tag{1}$$

Where **P_{in}** = Input Power, **P_{ar}** = Power of the armature circuit, and **P_f** = Power of the field circuit.

Equations (2) and (3) show the equations for calculating Power for the armature circuit and the field circuit.

The power of the armature circuit can be calculated by:

$$P_{ar} = V_{ar} + I_{ar} \tag{2}$$

Where **V_{ar}** = Voltage of armature circuit, and **I_{ar}** = Current of armature circuit

The power of Field circuit can be calculated by:

$$P_{f} = V_{f} + I_{f} \tag{3}$$

Where, **V_f** = Voltage of field circuit and **I_f** = Current of field circuit

3.2.2. Calculating the Output Power

Output power is calculated using equation (4).

$$P_{out} = \tau * N \tag{4}$$

Where $\mathbf{P_{out}}$ = Output Power, **Ʈ** = Torque applied on the machine, and **N** = Speed of the DC Machine.

3.2.2. Efficiency of the load (η)

The efficiency of the load is calculated using equation (5).

$$\eta = \frac{P_{in}}{P_{out}} * 100 \tag{5}$$

The efficiency of passive HESS and FA-HESS was calculated using the above equations, and we found that passive HESS had a 70.34% efficiency and FA-HESS had a 72.52% efficiency.

4. Conclusion

In this paper, the effect of supercapacitors and battery combinations for energy storage systems was studied; we claimed that it is prominent to use hybrid energy storage systems for electric vehicles. We have elucidated the operation of an electric vehicle and the necessity of combining supercapacitors with batteries to create a hybrid energy storage system (HES), as this system could offer a sustainable alternative to gasoline-powered vehicles, which significantly contribute to greenhouse gas emissions. In electric and hybrid cars, the battery and supercapacitor-based HESS combine power density with energy density to offer the best possible performance.

The paper also presents various HESS topologies, as well as a MATLAB comparison between full-active and passive configurations. It was found that Full-Active HESS demonstrates better power management compared to Passive HESS as FA-HESS generates more than 41% of the power Passive HESS generates for the same load, and it was also found that FA-HESS was approximately 2% more efficient than Passive HESS, which makes it better for high-performance applications.

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