Development of solar supercapacitor by utilizing organic polymer and metal oxides for subsystem of EV

Ataur Rahman1 and Kyaw Myo Aung1,2,∗

1 Department of Mechanical Engineering, International Islamic University Malaysia, 53100, Malaysia
2 Department of Mechanical Engineering, Yangon Technological University, 11011, Myanmar
∗ Author to whom any correspondence should be addressed.
E-mail: kyawmyoaung.22@gmail.com and arat@iium.edu.my

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Abstract
The limitations of the electric vehicles are weight, size, range, charging time and high price tag. Thus, development of a renewable energy-boosting system for EVs is significant. This paper proposes the materials and control system for development of the automotive body panels which are capable to generate electrical energy from solar energy and store the energy not only as structural capacitor but also as solar panel. A solar supercapacitor prototype is developed by utilizing Carbon Fiber Reinforced Polymer, nano Zinc Oxide and Copper Oxide fillers as the positive and negative electrodes and a dielectric layer sandwiched between the electrodes. Different weight percentage compositions of nano CuO/ZnO filled epoxy reinforced Carbon Fiber and different combinations of separators are investigated experimentally. Samples with higher nanoparticle composition can boost both the energy generation and storage performance. Simulation study is conducted on solar supercapacitor concept which is hybrid energy storage system, modelled as the supplementary renewable energy source of electric vehicle. Experiment data from the laboratory scale organic solar supercapacitor are considered as input reference data to design solar supercapacitor HESS in Simulink to generate electricity from solar energy and provide storage. The solar supercapacitor can be considered as the roof panel of EV and simulated at different solar irradiance (200 ∼ 1000 W m⁻²) and different load conditions (200 ∼ 500 W) to reflect the practical conditions. The test results of SSC show potential of energy conversion efficiency (ηec) 17.78%, open-circuit voltage (Voc) 0.79 mV, current density (Jsc) 222.22 A m⁻², capacitance (C) 11.17 μF cm⁻², energy density (Ed) 120 Wh kg⁻¹ and power density (Pd) 29 kW kg⁻¹. Based on Simulink results, fully charged solar supercapacitor system with solar irradiance of 1000 W m⁻² can provide power of 2.3 kWh (18.24 km extra range every hour). Therefore, the system can provide extra 4.56% of conventional EV’s power and range per hour. Solar supercapacitor system integrated with EV battery has the potential to reduce battery size by 10%, weight 7.5%.

1. Introduction
The development of commercialized electric vehicles has yet to be accelerated due to the lack of electrification. EV energy deficit could be supported by integrating different renewable energies through the improvements of the storage devices and the cost reduction of power system. The battery pack is one of the crucial parts of the electric vehicle nowadays. Furthermore, harvesting both electrical and solar energies from a single hybrid system is highly desirable and representing a new trend of all-in-one multiple energy harvesting technology [1, 2]. EV could be made independent by developing panel type composite body with high conductive metal oxides (Graphene Oxide, Copper Oxide, Zinc Oxide etc). The Nano-micro filler epoxy resin could play a crucial role on the clean energy technology by reducing weight and functioning as a battery or capacitor which can store the renewable energy from various systems. The panel type battery has multifunctional characteristics, weight...
saving, energy storing/supplying on demand and protecting vehicle’s body from external heat as an insulator. Based on the investigations, it can be summarized that downsizing of battery pack and capacitor replacement can be made by using light and efficient composite body panel [3, 4]. Since the innovation of electric and hybrid vehicles, researchers have been investigating new technologies to overcome the limitations of electric and hybrid vehicles. One of the potential technologies is the Solar Supercapacitors as body panel in EV. Supercapacitor applications have already been utilized in EV and hybrid vehicle as regenerative braking and power supply for start-stop system etc. Limitations of conventional supercapacitors include expensive cost per Watt-hour and low specific energy (Wh/kg) which is only a fraction of a regular battery. By utilizing solar supercapacitor as body panel of EV, energy density and quick discharging can be improved.

In recent years, many automobile manufacturers have invested in transforming the conventional vehicle into an EV that can provide renewable and green solution. EV demand is rising in terms of market share [5]. With advanced innovations and competitive price compared to commercial petrol vehicle, EV is a better choice not only for the users but also for the environment. Substantial research and innovation is required to enhance the range of EVs to overtake the vehicle market in the future [6]. The choice of the appropriate design parameters requires deep understanding of vehicle use purposes, study of driving cycles, vehicle size and weight, desired performance and type of application. Once the design parameters have been selected, the second step is the design of an energy management control strategy which is an essential key for an efficient electric vehicle [7].

Supercapacitors have several advantages over electrochemical batteries and fuel cells, including higher power density, shorter charging times, and longer cycle life and shelf life [8–10]. The first group of materials, which is most frequently used in commercial supercapacitor electrodes, is carbon. Carbon has gained considerable interest due to its various properties including the existence of different allotropes, accessibility, low cost, high surface area, high conductivity, superior corrosion inhibition property, high temperature stability and environmental friendliness. So far the forms of carbon, which are well recognized in the use of the supercapacitor electrodes, are activated carbon, carbon aerogels, carbon nanotubes (CNTs), carbon fibres and graphene [11]. Another attractive material for supercapacitor electrodes is carbon fibre. Carbon fibre has superior charge transportation property due to one dimensionality. It provides high adsorption capacities to ions due to the existence of large number of pores at the surface of the fibre and proves to be the best candidate for electric double-layer capacitor (EDLC) electrodes [12].

Many researchers have investigated conducting polymer in detail as a new choice for supercapacitor electrodes. Conducting polymers are different from carbon and metal oxides in terms of low cost, large scale, easy to process, fast redox reactions, substrate independent and have high conductivity [13]. The main drawback of the conducting polymers is the weak mechanical stability. Since recycling polymers undergo a series of physical changes e.g., swelling, shrinkage, doping and undoping which degrades the performance of the material over time. Therefore, in order to enhance the mechanical property of the conducting polymer, synthesis of polymer and metal oxides such as ZnO/CuO is the proposed idea. Researchers are experimenting with many different types of polymers to advance medicine development and synthesize products such as carbon polymers for the automotive industry.

Copper (II) oxide (CuO) is another metal oxide semiconductor having narrow band gap ~1.2 eV in bulk. It is intrinsically p-type semiconductor. CuO draw much attention since the starting growth material is inexpensive and easy to get, and the methods to prepare these materials are of low cost [14]. CuO nano-structures have...
stimulated intensive research due to their high surface area to volume ratio. CuO nanoparticles are a good candidate for sensing owing to its exceptional electrochemical activity and the possibility of promoting electron transfer at low potentials [15]. Due to the photoconductive and photochemical properties, CuO nano-structures are also promising materials for the fabrication of solar cells [16, 17].

Zinc oxide is a wide band gap semiconductor with an energy gap of 3.37 eV at room temperature. It has been used considerably for its catalytic, electrical, optoelectronic, and photochemical properties. ZnO nanostructures have a great advantage to apply to a catalytic reaction process due to their large surface area and high catalytic activity [18]. Furthermore, the remarkable properties of ZnO such as being bio-safe, bio-compatible, having high-electron transfer rates and enhanced analytical performance are suitable for cellular sensing applications. In order to exploit the full advantages of metal oxides and the composite materials as solar supercapacitor electrodes, researches need to be conducted for enhancing the performance of supercapacitor. Several methods can synthesize nanoparticles: giving them specific properties. Depending on the desired conditions and desired application of the nanoparticles, a particular process of synthesizing nanoparticles can be chosen. Table 1 summarizes the main advantages and disadvantages of obtaining nano-materials using some physical and chemical methods of synthesis by various researchers [19–23].

Maximizing the surface area between the electrodes and the dielectric material is one of the key factors to achieve higher capacitance. Sol–Gel method produces pure and very fine powdered product at low temperatures (room temperature). The process is also fairly simple and can be easily carried out. Researchers [21] investigated the synthesis of nano-crystalline ZnO powder via Sol–Gel process and their research found out that the diameter of crystallite size of obtained ZnO particles was varying from 6 to 14 nm, smallest among the other nanoparticle synthesis processes such as sonicating.

This paper proposes modelling and developing of solar structural supercapacitor as EV body panel. The ultimate goal of this paper is to develop a solar supercapacitor system which will serve as a photovoltaic energy generator and store the renewable energy from the Sun and provide accurate power to EV’s Load (Accessories) and Auxiliary Battery. SSC model will be developed by referencing experimental data from solar supercapacitor samples which are developed by sandwiching the CuO/ZnO and filler epoxy Resin (ER) with CF sheets. Simulation study is conducted to determine the performance of the SSC and Power Management System (PMS).

### 2. Methodology

#### 2.1. Experiment

The proposed prototype of body panel consisting of ZnO/CuO ER and paper film acting as dielectric material sandwiched between Carbon Fibre layers as shown in figures 1 and 2. The composite body panel can also act as a protection layer from external heat as insulator. CuO can enhance higher electron transfer along their surfaces. ZnO nanostructures can have a great advantage for catalytic reaction process due to their large surface area and high catalytic activity. Therefore synthesized ZnO/CuO material will result to faster charging time. Presence of

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**Table 1. Comparison between different nanoparticle synthesis processes.**

| Method      | Advantages                  | Disadvantages                  |
|-------------|----------------------------|--------------------------------|
| CVD         | High deposition rate        | High vapor pressure            |
| PVD         | No chemical substances      | Low deposition rate            |
| Mechanical grinding | Any metal                | High impurities               |
| Arc-discharge | High crystallinity          | Broad distribution size        |

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Figure 2. Prototype of ZnO/CuO ER body panel (AutoCAD 2015).
ER makes the nanostructures of ZnO/CuO compact, thus storing the charge longer without discharging too fast as a conventional capacitor. Due to the presence of the conducting polymer, the panel can also harness solar energy and convert it to electricity. Hybrid photovoltaic systems of inorganic semiconductors and organic conducting polymers need to be investigated. The proper synthesizing of the nano-filler hybrid materials with conducting polymer (ER) can be one of the approaches to achieving this target. Therefore, the composite body can serve not only as supercapacitor but also as hybrid solar renewable energy body panel. Supercapacitors are governed by the same fundamental equations as conventional capacitors but utilize higher surface area electrodes and thinner dielectrics to achieve greater capacitances. This allows for energy densities greater than those of conventional capacitors and power densities greater than those of batteries.

The organic SSC was developed utilizing separator/Na2SO4 electrolyte, zinc oxide (ZnO), copper oxide (CuO), conductive polymer (ER) and carbon fibre (CF). The main objective is to improve solar efficiency and to minimize losses in transfer of electrons during the process of converting solar energy to electrical energy. The efficiency of organic solar cells is improved by increasing the effect of exciton generation in quantum dots, energy band gap, producing specific optical effects and enhancing the transportation and collection of electrons. CuO doped polymer with CF reinforced is utilized to improve the concentration of electrons. CF Embedded N-type SC was made of CF-ZnO, which has the properties of donating (emitting) electrons in the presence of a solar heat photon, while CF Embedded P-type SC has properties of accepting electrons (electron-hole).

Unlike a ceramic capacitor or aluminum electrolytic capacitor, the Na2SO4 electrolyte is filled between two CF electrodes. In proposed SSC sample, electrical double layer is formed between the ZnO/CuO CF electrodes and Na2SO4 electrolyte which works as the dielectric. Capacitance is proportional to the surface area of the electrical double layer. Therefore, using activated carbon fibre, which has large surface area for electrodes, enables EDLC to have high capacitance. The mechanism of ion absorption and desorption is the main mechanism for the charge and discharge of SSC. During charging, ions are drawn to the surface of the electrical double layer by applying voltage to the facing electrodes. During discharging, ions move away from the facing electrodes. The dielectric paper film prevents facing electrodes from contacting each other.

Capacitance can be defined as the ratio of stored (positive) charge Q to the applied voltage V:

\[
C = \frac{Q}{V}
\]

For a conventional capacitor, C is directly proportional to the surface area A of each electrode and inversely proportional to the distance D between the electrodes as shown in equation 2.2:

\[
C = \varepsilon_0\varepsilon_r \frac{C}{D}
\]

The two primary attributes of a capacitor are its energy density and power density. The density can be calculated as a quantity per unit mass or per unit volume. The energy E stored in a capacitor is directly proportional to its capacitance and can be calculated as:

\[
E = \frac{1}{2}CV^2
\]

The internal components of the capacitor also contribute to the resistance, which is measured in aggregate by a quantity known as the equivalent series resistance (ESR). The voltage during discharge is determined by these resistances. When measured at matched impedance \( R = ESR \), the maximum power \( P_{max} \) for a capacitor can be calculated by the following equation:

\[
P_{max} = \frac{V^2}{4 \times ESR}
\]

Graphite derived Carbon fiber weaves of 0.25 mm thickness and 240 g m\(^{-2}\) are used for the electrodes of the capacitors. They will also act as the electrodes for the solar performance. To increase the specific surface area of carbon fiber electrodes, they should be activated by etching in HNO\(_3\) at 90 °C for about 2 h on the side that is to be in contact with the dielectric [15]. Epoxy resin and hardener were selected based on their compatibility with carbon fibers. Transparent epoxy resin and hardener has a recommended mixing ration of 2:1 for hard sample (1:1 for soft sample) and a full cure time of 24 h at 25 °C to 30 °C, supplied by Pi Carbon.

The CFRP electrodes were reinforced with nano ZnO filled epoxy for the negative electrode to facilitate high electron mobility as it is n-type semiconductor with a band gap energy of 3.2 eV to 3.4 eV and nano CuO filled epoxy for the positive electrode to facilitate hole/positive charge movement since it is a p-type semiconductor with a band gap of 1.2 eV to 1.8 eV when light falls on the surface. By incorporating these nano-particles on the opposite electrodes, they both increase the conductivity of the electrodes as well as increase the surface area of the electrodes. The particle sizes are in the range of 10 nm to 30 nm. Premium grade ZnO is called Platinum Seal which has purity level of 99.9% with bulk density of 0.46 ~ 0.55 g cm\(^{-3}\) and is used in various applications and industries that need high purity zinc oxide [24]. Copper (II) Oxide (CuO) nano-particles were from...
Sigma-Aldrich which states a maximum size of 50 nm as shown in table 2. High physical and chemical stability of metal oxide nanoparticles renders them extremely useful in catalytic applications. Cu$_2$O has been used in coating Cu nanoparticles (Cu$_2$O NPs). Copper oxide nanoparticles have been reported to be used as an anode material for lithium ion cells and as gas sensors on account of it high surface reactivity.

Separator materials used in the experiment are as follows:

- 70 g m$^{-2}$ paper, 0.07 mm thickness
- 20 g m$^{-2}$ paper, 0.05 mm thickness (soaked in Na$_2$SO$_4$ electrolyte)

### 2.2. Simulation

Simulation study is conducted to investigate the full potential of SSC system integrated with EV auxiliary battery. Full-sized SSC system will have 2.4 m$^2$ of roof area and be able to provide power to auxiliary loads of EV and charge EV main traction battery. Efficiency of the SSC from experiment will be used as reference for the simulations of full solar supercapacitor system with DC-DC converters and EV auxiliary load. The system is designed as solar panel block, supercapacitor block, Li-ion battery block and voltage converters as show in figure 3. EV accessories load will be supported by combination of Solar+Supercapacitor (Structural Capacitor) and battery. Bi-directional converters, table 3 are used to boost and buck the input voltage to required system voltage. Conventional capacitor is used as a DC-link between the supply side and load side. Battery is defined as 12 V and 100Ah to represent the auxiliary battery of the EV which is charged by solar energy and to provide power to electronic accessories.

![Figure 3. Solar supercapacitor system in Simulink.](image)

**Table 2. Properties of CuO.**

| Form       | Nano-powder |
|------------|-------------|
| Particle size | <50 nm     |
| Surface Area   | 29 m$^2$ g$^{-1}$ |
| Featured Industry | Battery Manufacturing |

**Table 3. Parameters of battery PMS.**

| Switching Frequency | 1 kHz |
|---------------------|-------|
| Converter Inductance | 0.75 mH |
| Converter Capacitance | 2000 µF |
| Mosfet/Diode Resistance | 1 mOhm |
| PI Controller Parameters | $K_p = 0.0005, K_i = 1.5$ |
Fill factor (FF) is another defining term in the overall behaviour of a solar cell. The quality of a solar cell is measured by this factor. Fill factor is defined as:

\[
FF = \frac{P_m}{V_{OC} \times I_{SC}} = \frac{\eta \times A_c \times G}{V_{OC} \times I_{SC}}
\]

Where, FF is fill factor, \(P_m\) is maximum power (W), \(V_{OC}\) is open-circuit voltage, \(I_{SC}\) is short-circuit current (A), \(\eta\) is efficiency of solar panel, \(A_c\) is area of solar panel (m²) and \(G\) is solar irradiance (W m⁻²).

The fill factor is directly affected by the values of the cell’s series, shunt resistances and diodes losses. Increasing the shunt resistance \(R_{sh}\) and decreasing the series resistance \(R_s\) lead to a higher fill factor, thus resulting in greater efficiency, and bringing the cell’s output power closer to its theoretical maximum. Typical fill factors range from 50% to 82%. The fill factor for a normal silicon PV cell is 80%. Parameters from the experiment (table 4) is used as reference to construct the model of Solar Supercapacitor for optimal roof area of EV (2.4 m²) in Simulink. Simulink solver setting is as shown in figure 4.

The combination of two or more electrical storage devices with different and complementary characteristics is the focus of Hybrid Energy Storage System (HESS) technology. The batteries used in electric cars are the main energy storage components to meet load demand alone. In practice, this can make the required battery capacity too large. In addition, the process of decreasing the ability of the battery during the charge/discharge process can reduce battery life. Supercapacitors emerge as complementary components of the storage device to cover the deficiencies of the battery [25]. A hybrid arrangement, with a parallel combination of solar, auxiliary battery and supercapacitor, can be investigated using MATLAB/Simulink program. It is found that the P&O technique is straightforward, accurate, and easy to implement for solar cells. Furthermore, battery life can be improved due to decrease in the output current. A hybrid energy storage arrangement as shown in figure 5 enhances the overall energy management system.

3. Results and discussion

Performance parameters of the SSC such as open circuit voltage \(V_{oc}\), current density \(I_{ac}\), capacitance (C), power density and energy density are measured and calculated for two different samples (i) paper film dielectric; (ii) Na₂SO₄ aqueous soaked paper film. The parameters of the samples are as shown in table 5.

The optimal capacitance readings of different samples are summarized in table 6. The results show that increase in ZnO/CuO % promotes the capacitance performance of both types of SC. Moreover, SC with 20gsm paper soaked in Na₂SO₄ electrolyte has greater capacitance compared to dielectric SC. The presence of the Na₂SO₄ electrolyte boosts the capacitance of SC exponentially up to 522 \(\mu\)F.
The voltage readings from the best 4 samples with 70gsm paper dielectric are summarized as shown in figure 6(a). The voltage readings from the best 4 samples with 20gsm paper soaked in Na2SO4 electrolyte are summarized in figure 5(b). The voltage profiles are similar but SC with two layers of dielectric paper can hold the higher voltage for longer duration compared to dielectric SC. Voltage readings of 70gsm paper sample show that 30% of ZnO/CuO & 6% of C composition has the highest voltage and voltage drop respect to time is the lowest compared to other composition.
Solar energy readings were taken at Malaysia ambient temperature of 33 °C (Afternoon Sun). Since it is sunny, the intensity of the Sun is strong and solar irradiance is about 1000 W m$^{-2}$. The SSC samples were fully discharged before testing for solar energy conversion. Not all the samples are able to produce electricity under sunlight. Therefore, the best samples from two types of dielectric paper are investigated. The open circuit voltage changes significantly with increasing temperature, figure 7. Mathematically $V_{OC}$ can be defined using the equation;

$$V_{OC} = \frac{E_g}{q} - \frac{kT}{q} \ln \left( \frac{N_n + N_p}{n p} \right)$$

(6)

Where, $q$ is the charge, $E_g$ is the energy gap, $k$ is Boltzmann constant, $T$ is temperature $N_n$ ($N_p$) is the effective conduction band (valence band) density-of-states, ($n$) ($p$) is the free electron (hole) concentration.

The solar voltage profile of different SSC samples is shown in figure 7. Na$_2$SO$_4$ sample has higher solar $V_{OC}$ compared to dielectric paper samples due to different material composition and preparation procedure. Small sample [45 cm$^2$] with no primary photovoltaic cells showing this voltage profile means that it has great potential as full size solar supercapacitor for various applications.

The current density level at 0 s indicates maximum $J_{SC}$ of the SSC. SC with 6% activated carbon has highest $J_{SC}$ with 222.22 A m$^{-2}$, figure 8. It discharges over time until 100 s. The current density drop was very high at time interval 0–10 s which is the characteristic of a supercapacitor. The average power conversion efficiency of 11 samples with different composition was found 11.5%. When filling factor drops, it leads to the reduction of $J_{SC}$, $V_{OC}$ and conversion efficiency. The solar energy conversion from the Sunlight is measured by the efficiency of energy conversion, $\eta_{SC}$. It is directly compared with the power density of the Sunlight which is 1000 W m$^{-2}$.

$$J_{SC} = 0.0222 \text{ A cm}^{-2} = 222.22 \text{ A m}^{-2}$$

$$P_{solar} = V_{OC} \times J_{SC} = (0.8)222.22 = 177.78 \text{ W m}^{-2}$$

(7)
Where, $P_{\text{solar}}$ is solar power, $V_{\text{SC}}$ is voltage of supercapacitor, $J_{\text{SC}}$ is current density of supercapacitor and $\eta_{\text{SC}}$ is solar conversion efficiency of supercapacitor.

Solar power of the best sample gives 177.78 W m$^{-2}$. The solar energy conversion efficiency, $\eta_{\text{SC}}$, of optimal supercapacitor is 17.78%. With optimal experiment procedures and better nanoparticles synthesis, solar supercapacitor can have solar energy conversion efficiency about 19%–22%, power generation of 2800 W/day, 29 kW kg$^{-1}$ power density, 120 Wh kg$^{-1}$ energy density and 11.17 μF cm$^{-2}$ capacitance. The 40% nano-particle epoxy mixture is too thick for sample development because 40 wt% of powder is beyond the saturation point of the epoxy resin. Overall, the optimal % composition is 30% ZnO in the negative electrode and 30%CuO in the positive electrode as summarized in table 7.

Mixture 4, figure 9(a), sample operates well as a capacitor but does not perform as a solar panel. Mixture 5, figure 9(b), samples does not operate as solar photo-voltaic but retained good structural properties. To maintain high mechanical performance as well as electrical conductivity, the best material for the electrodes of the capacitor is found to be carbon fiber. Synthesizing carbon fiber with ordinary epoxy resin reduces its conductivity. Therefore, to maximize the mechanical strength and conductivity of the carbon fiber electrodes, nano ZnO filled epoxy was used for the negative electrode and nano CuO filled epoxy was used for the positive electrode. The results show that a higher percentage of nano-particles improves the performance of the carbon fiber electrodes in terms of both capacitance and solar voltage but reduces mechanical strength by a small amount. Due to the saturation point of mixing nano-particles with epoxy, the mixture becomes too saturated to operate its function.

The performance of solar supercapacitor power management system is investigated at various irradiance settings and various load conditions as shown in figures 10 and 11. At 1000 W m$^{-2}$, the solar supercapacitor system is charging the battery at −28 A while supplying 500 W to the EV load. At 500 W m$^{-2}$, the solar power alone is not enough to supply 500 W to EV load. Therefore, the auxiliary battery supplies 5 A to EV load. At 200 W m$^{-2}$, the auxiliary battery needs to supply more power to EV load at 28 A. At 800 W load, the solar supercapacitor system is charging the battery only at 8 A. At 300 W load, the solar supercapacitor system is charging the battery at 48 A. At 100 W load, the solar supercapacitor system is charging the battery at 70 A. Power management system is operating efficiently to provide correct signals to the converter system.

The performance of the solar panel at different irradiance settings is as shown in table 8. The output voltage of solar panel varies with different input irradiance. When the irradiance drops to 500 W m$^{-2}$, the voltage also

![Figure 9. (a) Mixture type 4 sample (b) mixture type 5 sample.](image)

| CF electrodes | Mixture 1 (wt%) | Mixture 2 (wt%) | Mixture 3 (wt%) | Mixture 4 (wt%) | Mixture 5 (wt%) |
|---------------|----------------|----------------|----------------|----------------|----------------|
| Epoxy+hardener | 95             | 90             | 70             | 64             | 60             |
| ZnO/CuO       | 5              | 10             | 30             | 30             | 40             |
| Activated Carbon | 0              | 0              | 0              | 6              | 0              |
| Result        | Poor performance | Average | Best performance | Average | Did not work |

$$\eta_{\text{SC}} = \frac{P_{\text{solar}}}{1000}$$

(8)
Figure 10. Current profile of battery at different irradiance setting.

Figure 11. Current profile of battery at different load setting.

### Table 8. Solar power (Simulink Result).

| Irradiance (W m\(^{-2}\)) | Ideal Power Solar (W) | Simulink Data (W) |
|---------------------------|------------------------|--------------------|
| 1000                      | 976                    | 957.1              |
| 600                       | 584                    | 584.5              |
| 200                       | 192                    | 180.8              |

| Load (W)    | Ideal Power Battery (W) | Simulink (W) |
|-------------|--------------------------|--------------|
| 500         | −397.17                  | −375.6       |
| 300         | −564.03                  | −525.4       |
| 100         | −730.85                  | −705.3       |
drops to 13.5 V. When the irradiance drops to minimum requirement of 200 W m\(^{-2}\), the output voltage is only 5 V.

For system validation of Simulink, the input values are set as constant throughout particular simulation. For real-life application of solar supercapacitor, input irradiance will vary with respect to the geographical location of the application. Figure 12 shows the solar irradiance profile of Malaysia on 25 Jan 2021 from solarcast.com. It can be seen that even in one country, the solar irradiance profile is different for each districts. Therefore, solar irradiance profile set as 1000 W m\(^{-2}\) for 30% of total time, 600 W m\(^{-2}\) for 30% of total day time, 200 W m\(^{-2}\) for 30% of total day time and 0 W m\(^{-2}\) (No sunlight) for 10% of total day time. With practical solar irradiance profile, the output of the solar supercapacitor is as shown in figure 13. Signal statistics from Simulink show that mean solar power over one specific period is 495.4 W.

The potential performance of solar supercapacitor system is estimated by the following equation and calculation;

\[
P_{\text{system}} = P_{\text{Solar}} + P_{\text{SC}} + P_{\text{Batt}} = 976 + 45 + (12.8 \times 100 \times 11) = 2.3 \text{ kWh}
\]  

(11)

The battery specifications of Tesla Model 3 are 50kWh with 400 km range. Fully charged solar supercapacitor system with solar irradiance of 1000 W m\(^{-2}\) can provide power of 2.3kWh (18.24 km extra range every hour). Therefore, the system can provide up to 4.56% of conventional EV's power and range per hour.

4. Conclusion

ZnO/CuO promotes the conductivity and performance of solar supercapacitor samples. Moreover, samples with 20gsm paper soaked in Na\(_2\)SO\(_4\) electrolyte has greater capacitance compared to dielectric paper samples. Presence of carbon fiber is essential for mechanical stability as well as conductivity of the electrodes. Synthesizing carbon fiber with ordinary epoxy resin reduces its conductivity. Higher percentage of metal oxides improves the performance of the carbon fiber electrodes in terms of both capacitance and solar voltage. The optimal weight % composition is 30% ZnO in the negative electrode and 30%CuO in the positive electrode. With ideal experiment
procedures and better nanoparticles synthesis, solar supercapacitor can have much better performance and efficiency for commercialization in the near future.

The proposed hybrid energy storage system (HESS) meets the power and energy requirements of the EV accessories load and accurate power distribution between multiple storage systems. The addition of solar supercapacitor system has the potential to reduce the EV battery size by 10% and weight about 7.5%. The performance of solar supercapacitor system heavily depends upon the development of supervisory control logic and power efficiency of converters. Moreover, the solar supercapacitor system can increase battery life due to usage of renewable energy. The cost of the system can be reduced by utilizing light-weight and efficient materials for product development.

For future studies, full size solar supercapacitor should be developed to investigate the performance of hybrid energy storage system. DC-AC converters should also be investigated for the voltage conversion between main traction battery (AC output) and auxiliary battery (DC output) of EV. Real world driving scenarios and testing conditions can better investigate the performance of the system. Ultimately, the system should be integrated with a commercial EV model in the near future.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Declaration of competing interest

The authors declare that they have no competing, personal and financial interests in this manuscript.

ORCID iDs

Kyaw Myo Aung https://orcid.org/0000-0002-1904-9432

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