SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

A Review on BLDC Motor Application in Electric Vehicle (EV) using Battery, Supercapacitor and Hybrid Energy Storage System: Efficiency and Future Prospects

Mohd Azri Abd Aziz[1], Mohd Saifizi Saidon[1,*], Muhammad Izuan Fahmi[1], Siti Marhainis Othman[1], Wan Azani Mustafa[1], Mohd Rizal Manan[1], Muhammad Zaid Aihsan[1]

[1] Fakulti Kejuruteraan & Teknologi Elektrik, Universiti Malaysia Perlis (UniMAP), 02600 Arau, Perlis, Malaysia

ARTICLE INFO

Article history:
Received 20 December 2022
Received in revised form 7 March 2023
Accepted 15 March 2023
Available online 4 April 2023

Keywords:
Electric Vehicle (EV); BLDC motor; Battery Energy Storage System (BESS); Supercapacitor Energy Storage System (SESS); Hybrid Energy Storage System (HESS)

ABSTRACT

The automotive industry has rapidly introduced pollution-free vehicles such as Electric Vehicle (EV). The development and improvement of the EV to replace the conventional vehicle become crucial to obtain the customer satisfaction and high technology achievements. The main systems in EV that are improvise to be switch from the conventional engine with a fuel source to an electric type drive system, include the electric motor and the energy/power storage called battery. There are several types of electric motors that suitable for EV and the best solution was Brushless Direct Current (BLDC) motor in terms of power, speed, torque and low maintenance. Meanwhile, the fuel source replacement is the electrical energy/power storage such as batteries. The aims were to study the best Energy Storage System (ESS) in EV which leads to introducing Battery Energy Storage System (BESS), but the drawbacks of the system give the opportunity improvement, in replacement using Supercapacitor Energy storage System (SESS) and Hybrid Energy Storage System (HESS). SESS is a reliable source, but the stand-alone Supercapacitor also has a minimum operation time. With several adjustments in the energy management control strategy, the discharge rate of energy from a supercapacitor can be minimized to prolong its operation.

1. Introduction

The development of the electric vehicle (EV) is an initiative to save the planet from pollution and global warming. There are several ways to recycle the energy and covert it to electrical energy such as using Piezoelectric System [1]. The selection of electric motors is important in EV, where is in this research focusing on Brushless DC motors (BLDCM) due to its high-power density, small size, and simple structure. BLDCM is widely used in industrial control and aerospace [2]. Applications for brushless motors include hand-held power tools, model airplanes, cars, and computer peripherals.

* *Corresponding author.*
E-mail address: saifizi@unimap.edu.my

https://doi.org/10.37934/araset.30.2.4159

Energy storage systems (ESS) is a significant identity in numerous applications, especially in (EV). The introduction of EVs marks the beginning of an evolution in automotive technology, including advancements in transmission systems, braking systems, electric motor systems, and power storage systems.

Previously, ESS consisted of batteries, which were introduced in 1745 by Ewald Georg Jürgen von Kleist of Kammin, known as “Leyden jar batteries” [3]. Supercapacitors (SC) are a new type of energy storage devices that tempt to take the place of batteries as dependable energy sources. Due to its ability to store electrical charge in a surface-electrolyte interface's electric double layer, SC is also known electrically as the electrochemical capacitor (EC). In 1957, General Electric employee H.I. Becker received a patent for the first electrochemical capacitor device. Even though this device used double-layer charge storage, its need to be immersed in an electrolyte solution makes it challenging [4]. A transient may happen at the start of the supercapacitor’s discharging process increasing the peak current to the application and causing damage. According to this aspect, future case studies of supercapacitors' power demands are needed to analyse the different conditions of high load demand, low load demand, stable power demand, and unexpected demand [5]. The behaviour and characteristics of discharging supercapacitors by identification of discharging process [5].

2. Direct Current (DC) Motors for Electric Vehicle (EV) Applications

Brushed motors and brushless motors are the two most popular types of DC motors. DC brushed motors have brushes, as suggested by their names, which are utilised to commutate the motor and make it spin. While, a Brushless DC Motor (BLDCM), also known as the Permanent Magnetic Synchronous Motor (PMSM) [6]. It employs an electronic control that takes the role of the mechanical commutation function. Wound wire coils are used in DC motors to produce a magnetic field. These coils, which make up the "rotor" of a brushed motor, are free to rotate to drive a shaft. The coils are typically wound around an iron core, however there are brushed motors that are "coreless," meaning the winding is sustained by itself. Although they are built somewhat differently, brushless DC motors work on the same magnetic attraction and repulsion theory as brush motors.

The magnetic field of the stator is rotated by employing electronic commutation rather than a mechanical commutator and brushes. There is no mechanical wear issue with the shifting parts because of the removal of the brushes and commutator [7]. Due to BLDCM benefits of better power density, improved performance, cheaper maintenance costs, efficient control, and uncomplicated equipment setup, BLDC motors in particular are widely employed in the automobile industry especially electric vehicle (EV) [6,8]. It may be seen in both domestic appliances and traction applications as well as in industrial solutions like servo drives and actuators. This is caused, in part, by the fact that using permanent magnets makes it possible to miniaturise electronics, which also improves their dependability and energy efficiency [9]. BLDCM involves a variety of components, particularly the motor controller, that should be emphasized.

2.1 Design of Speed Controller

The Speed Controller of BLDC motor are important in wide range of applications as it has a direct impact on the machine's operation and is critical to the work's quality and optimum output [10]. The applications such as home electrical appliances, car appliances and large industrial plants uses different motor rotational speeds must be set for different materials such as drill sizes when drilling, and a conveyor belt must be able to adapt its speed to the workflow [10].

The project developed with Fuzzy Logic Controller since its consistency in solving complex, non-linear issues, adaptability for a variety of challenges, and combine of manipulating approaches, fuzzy continues to be the preferred solution. Fuzzy wants to make decisions based on rules. Under non-linear and unsure parameters and appropriate monitoring capabilities, fuzzy good judgement alter layout to improve dynamic overall performance. When using electromagnetic brakes, fuzzy logic can be applied as well. It provides outstanding overall performance, increased road adaption, and reduced braking distance [11].

However, the fuzzy PID method is the most utilized combination method. Fuzzy PID are considered to have the best operational performance and have many advantages, including reduces overshoot, minimizes step errors, and improves operational accuracy. In this study, the researcher investigated the BLDC motor step operating system using the fuzzy PID method because Fuzzy PID method give best performance overall. The result of simulation was set BLDC motor speed to 650rpm for 1 seconds [11]. Table 1 shows the motor model used in the experiment.

Table 1
BLDC motor model [11]

Parameter	Nilai
Motor Power (Watt)	2 kW
Resistance Equivalent (R)	0.045
Resistance Equivalent (L)	6.85e-3
Constant Voltage (Vp L-L)	65.48
Moment of Intertia (J)	0.0008
Back EMF flat area (derajat)	120
Viscous damping	0.001
Number of Pole	12

The project was developed to create an Adaptative PID Speed Controller for BLDC Motor. The adaptive PID auto-tuner is a hybrid controller that mixes PID and PID auto-tuner functions. This mixed controller can modify to any situation, the increase inside the quantity of input selection changes. Even if the speed of the BLDC Motor are changes, the adaptive PID controller is designed to calculate the manage parameters which can be changed adaptively to supply preferred manage performance. The researchers set the reference speed of the BLDC to 1000 rpm [12]. A basic block diagram of an adaptive PID controller is shown in Figure 1.

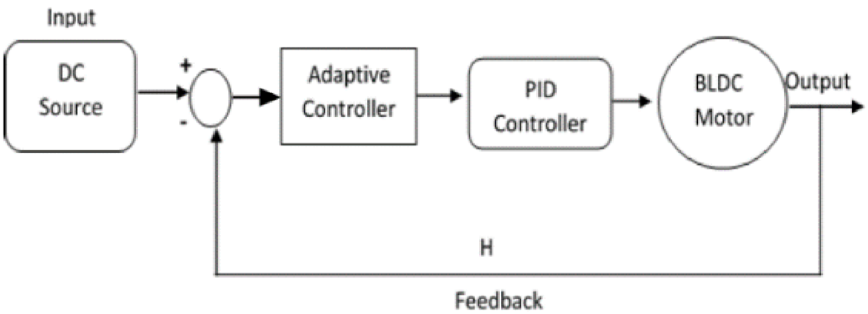

Fig. 1. Basic block diagram of an adaptive PID controller [12]

An Adaptive Neuro Fuzzy Interface System (ANFIS) controller-based speed control for BLDC motor is another type of speed control. It is thought to provide a faster response to speed fluctuations imposed on the BLDC, stabilize the system more dynamically, and reduce steady-state errors. ANFIS Controller was combination between Neural Network and the Fuzzy Inference. The Fuzzy Inference made a variable rule of input and output after Neural Network sense the changes in BLDC Motor. The project was used Photovoltaic source to supply voltage and current to BLDC Motor. The result from Simulink was ANFIS controller is robustness for high performance application [13].

Proportional Integral (PI) Controller to control the torque and speed to maintain the desired performance. The PI controller is specifically made up of two circuit blocks: proportional and integral. The speed controller compares between the actual speed and reference speed, so the controller will control the voltage incoming. The torque controls have four main stages, which is reference maximum current quality, back electromagnetic field (emf), current regulator will compare between set torque and actual torque and the switching controller need a specified value in reference. The result of the PI controller had better performance than the BLDC without a controller. The current response to the torque is quickly and the voltage response to the speed also quickly [14].

Proportional Integral Derivation (PID) Controller demonstrate the dynamic reaction to the suggested modified PID controller's quick tuning results, it can assist in managing the motor's speed and maintaining steady speed during load variations PID controllers can aid in improving the performance of BLDC motors. The PID controller is specifically made up of three circuit blocks: proportional, integral, and derivative [12]. The PID controller is used for the response in overshoot, steady-state error, response time and settling time. The researchers also compared the PI controller, Fuzzy Controller and PID Controller but PID controller had better performance than the other two controllers [15,16].

Moreover, Multiple Controller (MC) was developed to create a BLDC Motor Speed Controller. There are 3 types of controllers have been used in this project, which is Fuzzy Logic Controller, Artificial Neural Network and PID controller were combined made it 7 controller combination. This project aimed to compare the performance of 7 controller performances and the combination multiple controllers will give a better response for BLDC, but not all combination controllers work better than a single controller. According to the journal, multiple combinations of controllers will improve the performance of BLDC than single controller-like Fuzzy + PID, Fuzzy + Artificial Neural Network + PID and Fuzzy + Artificial Neural Network [17]. Figure 2 propose a technique for multi-controller schematic.

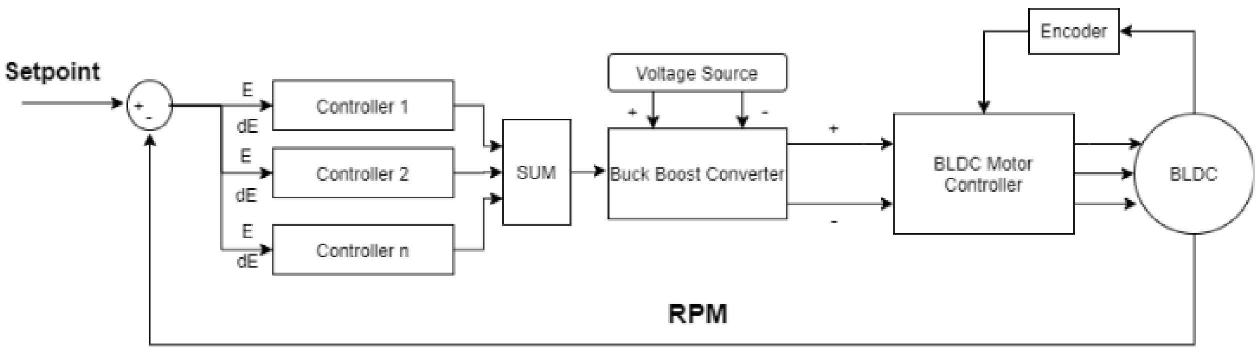

Fig. 2. Multi-Controller Schematic (Proposed Technique) [17]

3. Battery as Energy Storage System (BESS)

As the issue of ongoing and predictable energy scarcity continues and global concerns for the environment persist, the implementation of clean energy sources that rely on renewable resources and battery storage system could be an innovative and environmentally sustainable solution. BESS is foundation energy storage, which has a quick response time, a high level of dependability, and a low self-discharge rate [18]. A battery is known as a device that stores chemical energy and converts the energy to electrical energy when connected through the load with the application of electron transfer. Electrochemical reactions in batteries are accompanied by a spontaneous drop in the Gibbs free energy due to variations in the reactant and product lattice cohesive energies and ionization free energies (in water), as quantified for numerous metal combinations [19].

3.1 Battery Energy Storage System (BESS) Powered BLDC Motor

BESS is excellent in storing voltage and current for long term application. Moreover, the costing also cheaper and can stand for a long period as the self-discharge rate is small. Driving a BLDC motor using BESS as energy storage acquires energy from solar Photo Voltaic (PV) [20].

3.1.1 Lead-acid technology

Understanding how batteries behave in various working environments is crucial. The market for electrochemical storage devices is currently dominated by applications of established lead-acid technology. Despite the fact that the fundamentals of the system have been known for more than a century, operational details, such as the condition of deep discharge, remain poorly understood. This condition operation has been further researched and included in a semi-empirical battery ageing model to facilitate the effective integration and exploitation of big BESS with hundreds of lead-acid cells [21].

The main motivation for its continued usage is the low price. Nevertheless, although there are a few projects in development, lead-acid batteries are not yet a common component of consumer electric vehicles. This type of battery is mostly utilised as a supplementary storage system for commercial vehicles. An additional benefit is the ability to be recycled although the life span is only three years [22]. Both the mobile and stationary applications employ lead acid battery systems. Emergency power supply systems, standalone PV systems, battery systems for reducing output swings from wind power, and starting batteries for cars are some of their frequent applications [23]. However, one of the major disadvantages of this technology is that it ages, both calendar and cycle, which makes long-term operation and performance difficult [24].

3.1.2 Lithium-ion technology

Other than lead-acid cells, lithium-ion cell are commonly used in EV [25] . The power density of a lithium-ion battery is generally less than its energy density [26]. An energy storage system is necessary during vehicle configuration to satisfy both the power and energy demands. As its extremely high power-to-weight ratio, vehicles are very energy efficient. At high temperatures, the battery works better than others because of its energy to weight ratio, a key element in electric car batteries. Furthermore, it can maintain its charge because it has a low self-discharge level [22]. Li-Ion batteries currently make up the largest market category for electric car equipment. Li-Ion batteries are the best option in this category because to their low weight, large energy storage capability, moderate energy consumption (14.7 kWh/100 km), constant cost price reduction, advanced production technology, increased cycle life, and moderate energy consumption [27].

The construction of a circuit model based on the demand of vehicle battery pack, which to identify the parameters, a joint experiment of intermittent discharge and hybrid power pulse characterization is established on the basis of the model's parameter identification needs. The results of the study reveal that it is capable of determining the parameters. Second, MATLAB/Simulink was used to simulate the splice equivalent circuit model of a vehicle battery pack, demonstrating that the model is capable of describing the vehicle battery pack [28]. The power arrangement is insufficient while considering the power density features. Due to the battery's high discharging current, the capacity degradation rate is accelerated. In simple, the high discharge current speeds up the degradation [26].

4. Hybrid Energy Storage System (HESS)

Hybrid Energy Storage System is a combination of two or more energy source as the supply to the system. sometime one acts as the main energy sources and others as a backup or supportive energy source to the system. In some cases, the SC can be used by HESU to store regenerative energy from the BLDCM during braking and help the battery power the motor during acceleration [29].

4.1 Hybrid System in Pure Electric Car (EV)

In pure EV, hybrid system means a combination of a battery and supercapacitor to form an energy storage system. A hybrid battery-supercapacitor is also known for its benefits to the latest devices nowadays. It is crucial to design and manufacture electrochemical energy storage devices that have high power and energy densities as well as lengthy cycling lives. Battery-Supercapacitor Hybrid device (BSH), which is one of these systems and is typically built with a high-capacity battery-type electrode and a high-rate capacitive electrode, has drawn a lot of interest due to its potential uses in future electric vehicles, smart electric grids, and even miniature electronic and optoelectronic devices, among other things [30].

One of well-known applications for hybrid battery-supercapacitor is Electric Vehicle (EVs) which is being developed. Both the advancement of battery technology and electric cars (EVs) have received a lot of attention recently. Although battery technology has made considerable strides, the current battery supply still falls short of the energy needs of EV power consumption. One of the main problems is non-monotonic energy consumption followed by rapid variations as the battery is being discharged [31]. New technology development in supplying energy to devices and machines are widely researched for benefits of consumer nowadays. Many factors are being considered, such as costing, environment and needs. In researching of establish a hybrid system, HESU parameter matching approach is suggested for EV. This technique can match parameters while meeting the performance indicators of the EV in terms of power and energy. The outcome demonstrates that by lowering the weight and cost, optimum parameter matching is accomplished [32].

The hybrid system BSH, however is more complex than simply joining two electrochemical power sources. By consideration of establish an integer power source, the complete electrical system needs to be subtly matched, in addition to the individual cell layouts. Choosing when and how each electrochemical cell should be charged or discharged is crucial [31]. Electric double layer capacitive (EDLC) materials and pseudocapacitive materials can be used as SC electrode materials, respectively [30]. Figure 3 shows power density verses energy density of several electrochemical energy storage.

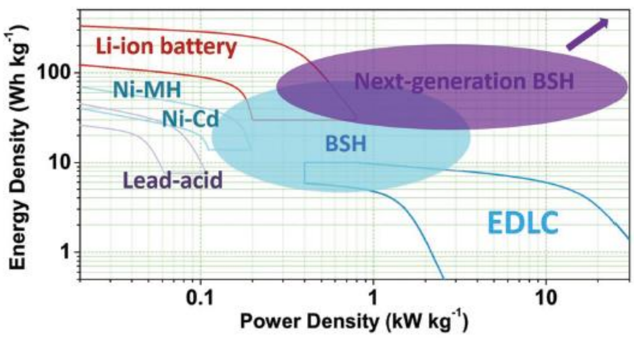

Fig. 3. Comparison of electrochemical energy storage

4.2 Hybrid System in Other Hybrid Car

Automotive Industry supply a hybrid car combining an electric motor and petrol or diesel engine, and the two energy sources work together to drive the vehicle. Due to these situations, the car can consume less gasoline and achieve more fuel efficiency than a conventional engine. The engine was given a performance boost thanks to electric power. Except for plug-in hybrids, hybrid vehicles do not require recharging because they charge their batteries internally [33]. The reason that plug-in hybrid electric vehicles (PHEVs) have a longer driving range than pure electric vehicles is that the engine can keep the vehicle running for an additional driving range that is comparable to that of a conventional vehicle only when the battery's state of charge (SoC) is low [34].

Others are the project offers a supercapacitor/battery hybrid PEM fuel cell excavator energy management approach. The energy storage device, using fuel cell as the primary power source for the majority of the excavator workload while battery or SC, which provides additional necessary power and recovers energy [35].

4.3 Hybrid Energy Storage System (HESS) Powered BLDC Motor

The hybrid system is practically used in pure EV nowadays. The special characteristics of a SC can help the battery pack meet peak power requirements, extending battery life and enhancing vehicle acceleration [36]. The design calculations in [37] are based on theories related to the chosen vehicle. As mention, a single energy storage device cannot satisfy all necessary requirements, hence this article also discusses power management between two separate energy storage devices, which are dual energy devices employing a converter (HESS). Figure 4 illustrates the differences between lead-acid batteries and SC that complementing characteristics can be employed [38].

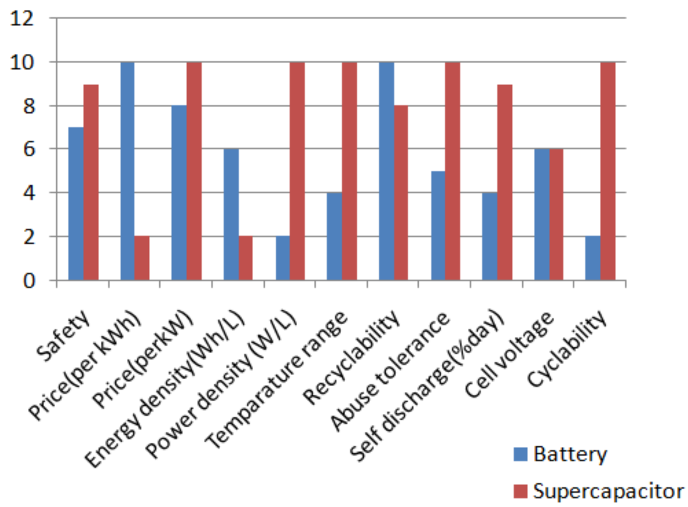

Fig. 4. Comparison between battery and SC [38]

HESS so called hybrid powered BLDC motor system is equipped with two power sources (SC and battery) allowing high voltage can be achieved. It is possible to get the high voltage required by the BLDC motor during the commutation period by properly stacking the voltages of these two power sources [29]. Figure 5 shows Control strategy of BLDC motor powered by Hybrid Energy Storage Unit (HESU). The advantage of HESU is an alternative to prolong the battery life in EV is to use HESS, which include a battery and SC [39]. In fact, while SCs have a lifetime of over 500,000 cycles, existing battery technologies only allow not more than 10,000 of cycles of charge-discharge [40,41].

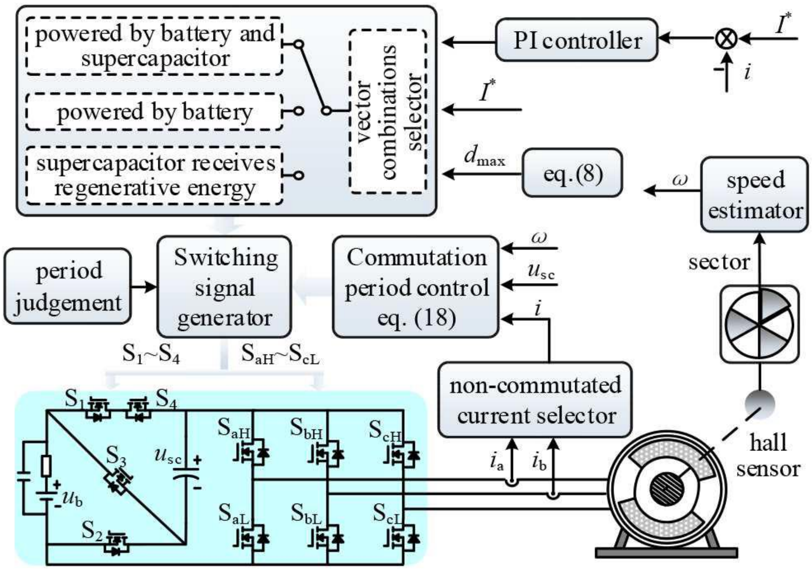

Fig. 5. Control strategy of BLDC motor powered by HESU [29]

The schematic view in Figure 6 illustrates the modeling of the HESS EV system proposed in [42]. Batteries, SC, three-phase inverters, BLDC motors, and motor drivers (speed control) serve as speed regulators and provide regenerative braking as part of the EV system.

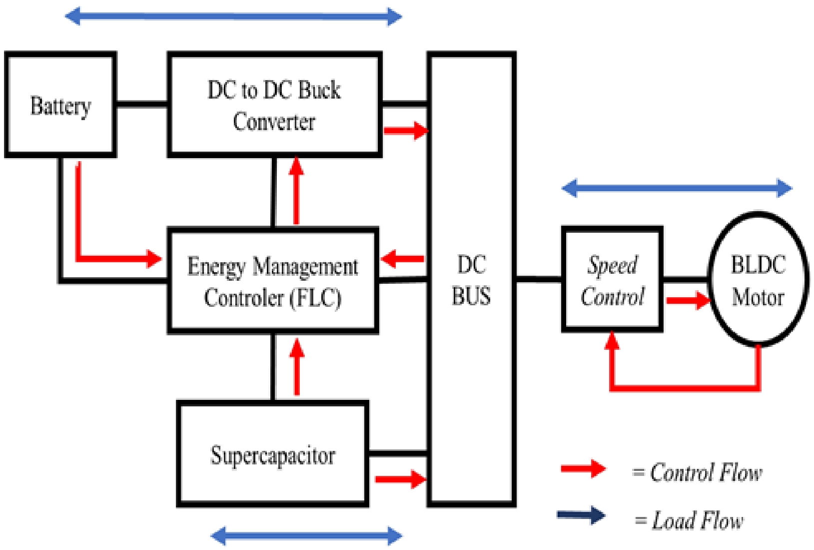

Fig. 6. EV System Block Diagram [42]

Another advantage of control strategies using HESS is the ability to clearly reduce the peak current of the battery while maintaining that the voltage of the supercapacitor fluctuates within a specific desirable range. A platform with a 30-kW rated power was built, and the power flow between the battery and the supercapacitor was controlled by dc/dc converter [43]. Then, some HESS using input of speed and changing in speed as input to the controller. The regulated voltage source receives the output from the controller and feeds the inverter circuit [44]. The fluctuation in current and voltage of SC during PI control operation in can be solve using Fuzzy Logic Controller [44]. Most HESS employ the battery as the primary source and the SC as a backup to offset any shortcomings in the battery and enable the system to function at its optimum.

5. Supercapacitor as Energy Storage System (SESS)

Supercapacitors (SCs) are energy storage devices with extremely high capacitance, great reliability, and high power. They are made with an electrochemical double layer capacitor (EDLC) structure and proprietary materials and processes. This convergence of state-of-the-art technology enables SC solutions tailored for applications of backup power, pulse power, and hybrid power systems. They can be used either alone or in conjunction with batteries to maximize cost, lifespan, and runtime. A system may require anything from microamps to megawatts, depending on its requirements.

SCs can be utilized in electric vehicles (EVs) due to their unique properties such as high-power output, rapid charging and discharging, long lifespan, and high-power density [45]. The SC also contain more energy while retaining power under discharging conditions. However, the SCs and electrolyte capacitors vary significantly from the viewpoints of construction and functioning.

Figure 7 shows the SC's supported the existence. It is composed of an electrolyte, a separator, and positive and negative electrodes (current collectors). The SC is built much the same as electrochemical batteries, with both electrodes submerged in the electrolyte solution and separated by a layer known as a separator. The electrodes are protected by a membrane in the separator, which protects only the mobility of ions and just not their electrical connection [46].

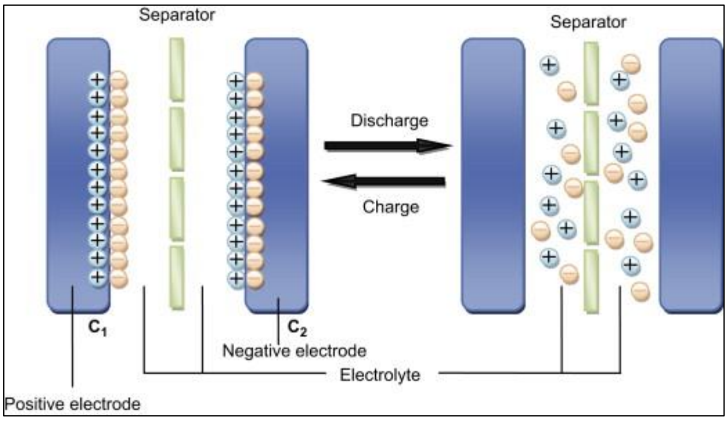

Fig. 7. Structure of the Supercapacitor [46]

The energy will be stored through the construction of the so-called double-layer structure (also known as the Helmholtz layer) between the electrolyte and the electrode interfaces. The cations and the anions of the electrolyte solution will be respectively attracted by the negative and positive electrodes forming thin double layers without the need for charge transfer. As a result, energy storage involves no electrochemical phase or composition changes, making the entire process very reversible, allowing the charge or discharge operation to be performed repeatedly and preferably without constraint. As a result, SCs have a far longer life cycle than electrochemical batteries. SCs have an advantage over regular capacitors; hence, they are current market trend. The SC is used in the research to reduce peak current. This type of SC is used in ES to supply and store peak power during discharging and charging. SCs outperform regular capacitors in terms of results and stability.

In Table 2, the comparisons of capacitor and SC are shown [47].

Table 2
Comparisons of Capacitor and Supercapacitor [47]

Capacitor	Supercapacitor
Low breakdown voltage rating	High breakdown voltage rating
Slow charging and discharging	Fast charging and discharging
Low energy density	High energy density
Long life cycle	Longer life cycle
-	Higher superior efficiency

5.1 Supercapacitor Energy Storages in Motor Applications

The Supercapacitor bank can deliver electrical energy for starting, and in the event of electric braking, the energy can be immediately recovered into the Supercapacitor bank. The outcomes attest to the efficiency increase in energy usage and the efficacy of this control approach [48]. Figure 8 shows the system combination of supercapacitor bank through the motor drive unit.

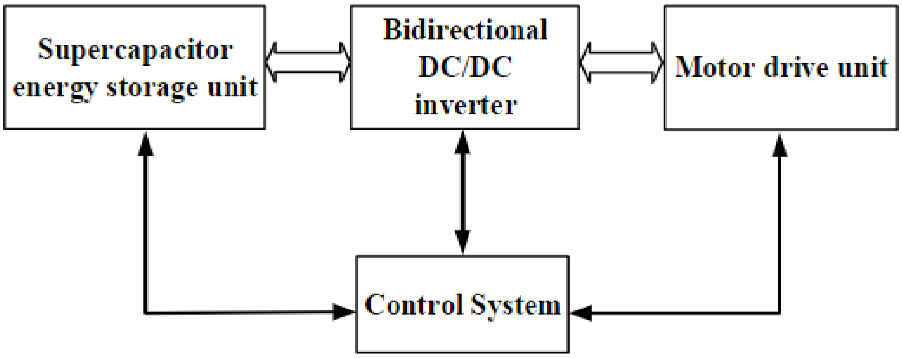

Fig. 8. Block diagram of supercapacitor – motor drive system [48]

Its internal characteristics are changed to achieve the same SC characteristic as the battery. The findings indicate that a super-capacitor can perform battery-like functions for 1000 seconds [49]. SC discharging time becomes slower when series resistor within capacitors affects the discharging characteristic. As a result, the series capacitor's capacitance is higher [49]. The electrolyte might be either organic or aqueous in character. The SC's energy storage output is displayed in microfarads, nano-farads, or even picofarads for lower amounts. SCs are mostly employed in practice to filter pulsed load currents, standby power, and memory backup devices, and to replace electrochemical batteries.

5.2 Comparison Between Supercapacitor and Lead Acid Battery

Traditionally, batteries and supercapacitors operated as symbiotic devices. The SC readily transferred energy, while the storage capacity of a rechargeable battery filled the needs of a power bank. These devices seem to be unrivaled in their respective fields. The SC exhibited unprecedented power density, while the battery offered superior energy density. Recently advanced SCs have come to market that break down that barrier [50].

When SC and lead acid batteries are considered, it is commonly accepted that the first devices can deliver more specific powers, while the latter have their main advantage in the higher specific energy they can deliver. Therefore, a previous paper aimed to compare supercapacitors (SCs) and lead-acid batteries and evaluate their performance based on common comparison criteria such as specific power and energy, cycle efficiency, and simulation results obtained from two different energy storage systems. The objective of this work is to present an up-to-date comparison between the two technologies [51]. Figure 9 shows the comparison of SCs versus lead-acid batteries in terms of quality.

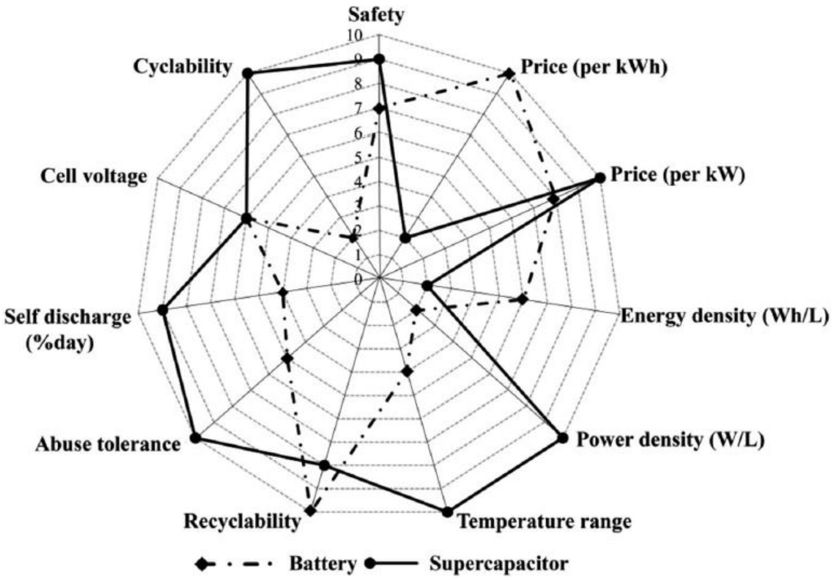

Fig. 9. Qualitative comparison of the Lead–Acid battery and SC [36]

In comparison with batteries, SC achieve higher power density but lower energy density. The difference stems from a different mechanism of energy storage. Batteries store energy by redox reactions in the bulk electrode, leading to high energy density but slow kinetics. The higher rate capability of SC comes from the electrostatic storage of charge at the electrode surface. The transport of ions in the solution to the electrode surface is rapid, leading to fast charge and discharge capability [52]. In contrast to batteries, no electron transfer takes place across the interface. SC can be fully charged or discharged within a few seconds without damaging the cell and thus are well suited for use in power-assist applications in vehicle propulsion. The charging and discharging processes are highly reversible and do not require phase changes in the electrodes. This should lead to increased cycle life, compared to batteries [53].

5.3 Methods of Simulating and Modelling SC

Simulation and modelling of supercapacitors (SCs) can be performed using various techniques, each with its own advantages and disadvantages based on the behaviours and charge/discharge conditions of the SCs. Many simulation techniques have their own algorithms that show they can be used to simulate SC.

Piecewise Linear Electrical Circuit Simulation (PLECS), LabVIEW, MATLAB Simulink, and PSCAD (Power System Computer Aided Design) approaches are a few of the simulation tools researched and are grouped [54]. Table 3 compares simulations base on several references, shows that MATLAB increases efficiency when modelling SC behaviour. Regarding the viability of the simulation program, MATLAB performs better. Data collection was performed in charging and discharging simulations using MATLAB Simulink. Resistance has been shown to be the best component to use in a circuit. Therefore, SC voltage should be measured accurately [54].

In contrast to model-based methods, data-based approaches do not require expensive mathematical models to simulate the internal aging process of SC. Fuzzy logic and Artificial Neural Networks (ANN) are two examples of approaches to anticipate the trends of device parameters during the aging process that are mostly based on historical data of the aging process of SCs and state data [55]. Zhou *et al.,* [56] proposed a hybrid genetic algorithm based on a long short-term memory neural network. The exit probability and the number of hidden layer units are used as a local search operator of the genetic algorithm, which improves its global search capability and enables it to quickly search for the local optimal solution. This method predicts future the remaining lifetime of supercapacitors in steady-state charging mode, and it also works for supercapacitors with dynamic operating cycles.

The study by Liu *et al.,* [57] uses a stacked bidirectional long- term and short-term Memory Recurrent Neural Network model that adds a reverse recurrent layer in the input sequence with t-time and subsequent time values to the traditional long- and short-term memory recurrent neural network. Among those, the stacked network can provide adequate capacity space. To validate the findings, the forward chain approach is developed, which is superior to the cross-validation method in machine learning, which ignores the time-series features of the time-series data. The messenger running time is only around 20% of the running time, and the prediction accuracy is better.

Moreover, Haris *et al.,* [58] deep belief network (DBN) paired with Bayesian Optimization and Hyper Band (BOHB) was presented as a new deep learning approach for forecasting RUL at the early stage of SC deterioration. When compared with earlier research, the RUL prediction model development time was reduced by 54%, significantly reducing the time necessary to collect and test SC cycle data, and the suggested model has high accuracy and resilience.

Table 3
Comparison of Simulation Software for Supercapacitor Energy Management

Software	Advantages	Disadvantages	Reference
MATLAB with Simulink Fuzzy Logic	Accurate mathematical model while applying to non-linear system	Hard to withstand high power if connects with hardware (In real time)	[55]
LabVIEW	Good for development and debugging Readily build graphical user interface (GUI) for data reading	Graphical programming is totally different compared to text-based programming	[59]
MATLAB Simulink	Large user base Easier implementation of control algorithms	Only mathematical modelling	[60]
PLECS (Piecewise) Linear Electrical Circuit Simulation)	Access to MATLAB directly Has modelling simulation	Different functions as MATLAB to simulate results Not user friendly	[54]
PSCAD (Power System Computer Aided Design)	Good at editing schematic	Information is not complete Not suitable to create models	[61]

5.4 Supercapacitor Energy Storage System (SESS) Powered BLDC Motor

The primary research question is whether SCs alone can replace batteries in electric vehicles (EVs) as BLDC motor drivetrain operation. The reason is that SCs have advantages over batteries, but they also have significant drawbacks that must be rectified for promising future. Due to their superior power density and cycling properties, SCs are being examined; however, their performance under regenerative braking situations has not been well explored [62]. The fast-charging capabilities of the SC enhance the regenerative breaking performance. Particularly in rapid and frequent start-and-stop driving cycles, the usage of SC can maximize the alternator's performance to absorb a more kinetic energy during braking [63].

The biggest barrier to overcome in SC development is to enhance their energy density. Doing so will enable the devices to expand their range of potential applications and could lead the way for employing of entirely super-capacitive systems for transportation and energy storage [64]. Using standalone-produced module called a commercial Maxwell SC, data on SC self-discharge and supercapacitor E-bike features such motor current, driving range, and energy consumption under various loads and speeds have been gathered [65]. In Table 4 is a synopsis of the proposed SC as a main energy source. In short, SC adjustment of critical factors can prolong the capability of SC to replace batteries in the future.

Table 4
Proposed SC as a main energy source

SC problem	Solution Method	Result/Finding	Reference
The state of charge (SOC) accuracy estimation needs to be highly kept to ensure the SC working properly	Utilising the Adaptive Neuro-Fuzzy Inference System (ANFIS)	The results of the simulation show the mean absolute percentage error (MAPE) for the SOC estimation is 0.70% for charging and 0.83% for discharging.	[66]
A constant current load, a constant resistance load, or a constant power load are the three fundamental discharge modes.	The voltage, current, power, and energy expressions of SC discharges are derived to maintains their constancies and performance	Fractional-order expressions for Constant current discharge, constant power discharge and constant resistance discharge	[67]
Researchers suggest the usage of an electric two-wheeler for travelling short distance. In order to overcome the limitations of batteries, an ultracapacitor bank will power the vehicle.	Calculations for determine the vehicle's energy requirements, mathematical modelling of the vehicle, justification for BLDC motor, system-simulation, and verification of the SC bank's ability to power such a vehicle over short distances.	Test 1: speed 25 km/h, 1.5km in 216 seconds energy required = 49.9 kJ discharge 43.3v to 32v in 240sec load 5 Ω conclusion: 1.4km in 4 minutes speed of 17 km/h	[68]

6. Conclusion

In application of EV, there are advantages of a brushless motor over a brushed motor, which are a high power-to-weight ratio, high speed, almost comes about as a result of speed (rpm) and torque, high efficiency, and low maintenance. Brushless DC motors have made it possible to replace rubber belts and gearboxes in current washing machines with a direct-drive design. In short, BLDC motors are preferable compared to others in the experimental setup. Table 5 shows comparison between types of motor [49].

Table 5
Comparison of BLDCM with Other Motor [49]

Feature	Brushless DC Motor	Brushed DC Motor	Induction Motor
Mechanical Structure	Field magnets on the stator and stator are made of permanent magnets	Field magnets on the rotor and stator are made of permanent magnets or electromagnets	Both the rotor and stator have windings, but the AC lines are connected to the stator
Maintenance	Low or no maintenance	Periodic maintenance because of brushes	Low maintenance
Speed-Torque characteristics	Flat - Operation at all speed with rated load	Moderate – loss in torque at high speeds because of losses in brushes	Non - linear
Efficiency	High – Because the stator is on the outside, there are no losses in the brushes, allowing it to dissipate more heat and generate greater torque.	Moderate – Losses in the brushes; Rotor is on the inner periphery	Low – Both the rotor and the stator suffer from heat and current losses; high efficiency induction motors are also available (higher cost)
Commutation method	Using solid state switches	Mechanical contacts between brushes and commutator	Special starting circuit is required
Speed range	High – No losses in brushed	Moderate - Loses in brushed	Low – Determined by the AC line frequency; Increases in load further reduces speed
Electrical noises	Low	High – Because of the brushes	Low
Detecting method of rotor's position	Hall sensors, optical encoders, etc.	Automatically detected by brushes and commutator	NA
Direction reversal	Reversing the switching sequence	Reversing the terminal voltage	By changing the two phases of the motor input
Control requirements	A controller is always required to control the commutation sequence	No controller is required for a fixed speed; controller required for variable speed	No controller is required for a fixed speed; controller required for variable speed
System cost	High – Due to external controller requirement	Low	Low

6.1 Efficiency and Future Prospect of Supercapacitor (SC) in Energy Storage System (ESS)

The study on using SC as main source of energy supply because of its benefits, including their high-power density, quick charging and discharging speeds, and wide operating temperature range, SC are widely employed in a variety of industries. SC have much greater longevity than conventional batteries, with commercial devices frequently claiming hundreds of thousands of cycles with negligible degradation [64].

Table 6 shows are the advantages and disadvantages of supercapacitors [69]. For the development of next-generation energy systems, SC are acknowledged as a new class of potential electrochemical energy storage devices [70]. Since the SCs storage system are made up numerous of basic components, the unreliable specifications of each component, the uneven charging voltage, and the variation in internal temperature in large-scale applications will cause the devices to age and perform worse over time [71]. In making these possibilities, the help from the battery is also needed as a check and balance for the system to operate successfully. Supercapacitors are widely used in many fields alongside with batteries, making the system more reliable. Supercapacitor batteries that can be operates independently are nearly a reality. In comparison to lithium-ion cells, a prototype supercapacitor battery developed by researchers at the University of Central Florida charges faster and can be recharged 30,000 times without losing any performance [72]. Supercapacitors are the most efficient technologies for delivering electrical energy instantaneously and in situations where a long shelf life is required. As a result, there are significant market demands for the growth of supercapacitors, and long-term advancement is required for their effective development and commercialization [73].

Table 6
Advantages and Disadvantages of Supercapacitor [69]

Advantages	Disadvantages
It offers high energy density and high-power density compared to common capacitor	Low energy density; usually holds 1/5-1/10 of a battery
It offers high capacitance (From 1 mF to >10,000F)	Cannot use the full energy spectrum for some applications
It offers fast charging ability	High self-discharge as compared to electrochemical batteries
It offers superior low temperature performance (from -40oC to 70oC)	Low voltage cells: to get higher voltages, serial connections are required
It reduces size of the battery, its weight and consecutively cost	-
Supercapacitors meet environmental standards. Hence, they are eco-friendly	-

Acknowledgement
This research was conducted in Centre of Excellence Renewable Energy, Faculty of Electrical Engineering & Technology, Universiti Malaysia Perlis (UniMAP).

References
[1] Nordin, Nur Fatihah, Kee Quen Lee, and Hooi Siang Kang. "Energy Harvesting of Daily Human Life Activities using a Self-Made Piezoelectric System." *Progress in Energy and Environment* 10 (2019): 1-5.
[2] Li, Haitao, Wenzhuo Li, and Hongliang Ren. "Fault-tolerant inverter for high-speed low-inductance BLDC drives in aerospace applications." *IEEE Transactions on Power Electronics* 32, no. 3 (2016): 2452-2463. https://doi.org/10.1109/TPEL.2016.2569611
[3] Allerhand, Adam. "Who invented the earliest capacitor bank ("battery" of leyden jars)? it's complicated [scanning our past]." *Proceedings of the IEEE* 106, no. 3 (2018): 496-503. https://doi.org/10.1109/JPROC.2018.2795846
[4] Conway, Brian E. "Electrochemistry Encyclopedia: Electrochemical Capacitors: Their Nature, Function, and Applications." *Chemistry Department, University of Ottawa* (2003).
[5] Naseri, F., S. Karimi, E. Farjah, and E. Schaltz. "Supercapacitor management system: A comprehensive review of modeling, estimation, balancing, and protection techniques." *Renewable and Sustainable Energy Reviews* 155 (2022): 111913. https://doi.org/10.1016/j.rser.2021.111913
[6] Dasari, Murali, A. Srinivasula Reddy, and M. Vijaya Kumar. "A comparative analysis of converters performance using various control techniques to minimize the torque ripple in BLDC drive system." *Sustainable Computing: Informatics and Systems* 33 (2022): 100648. https://doi.org/10.1016/j.suscom.2021.100648
[7] MohanaPriya, C., N. Prasidha Devi, C. Suruthy, and D. Murugesan. "PERFORMANCE ANALYSIS OF BLDC MOTOR USING INTELLIGENT CONTROLLER."
[8] Bharathidasan, Mohan, V. Indragandhi, Vishnu Suresh, Michał Jasiński, and Zbigniew Leonowicz. "A review on electric vehicle: Technologies, energy trading, and cyber security." *Energy Reports* 8 (2022): 9662-9685. https://doi.org/10.1016/j.egyr.2022.07.145
[9] Czerwinski, Dariusz, Jakub Gęca, and Krzysztof Kolano. "Machine learning for sensorless temperature estimation of a BLDC motor." *Sensors* 21, no. 14 (2021): 4655. https://doi.org/10.3390/s21144655
[10] MadhusudhanaRao, G., B. V. SankerRam, B. Smapath Kumar, and K. Vijay Kumar. "Speed control of BLDC motor using DSP." *International Journal of Engineering Science and Technology* 2, no. 3 (2010): 143-147.

[11] Apribowo, Chico Hermanu Brillianto, and Hari Maghfiroh. "Fuzzy Logic Controller and Its Application in Brushless DC Motor (BLDC) in Electric Vehicle-A Review." *Journal of Electrical, Electronic, Information, and Communication Technology* 3, no. 1 (2021): 35-43. https://doi.org/10.20961/jeeict.3.1.50651

[12] Mahmud, Md, S. M. A. Motakabber, AHM Zahirul Alam, Anis Nurashikin Nordin, and AKM Ahasan Habib. "Modeling and performance analysis of an adaptive PID speed controller for the BLDC motor." *International Journal of Advanced Computer Science and Applications* 11, no. 7 (2020).

[13] Hemanth, D. J. "ANFIS controller based speed control of high-speed BLDC motor drive." *Intelligent Systems and Computer Technology* 37 (2020): 341.

[14] Hasan, Mohammed S., Almakhturi F. Sharaf, Mohammed D. Albakhait, and Ahmed I. Jaber. "High performance rectifier/multilevel inverter based BLDC motor drive with PI controller." In *IOP Conference Series: Materials Science and Engineering*, vol. 745, no. 1, p. 012005. IOP Publishing, 2020. https://doi.org/10.1088/1757-899X/745/1/012005

[15] Mahmud, Md, S. M. A. Motakabber, AHM Zahirul Alam, and Anis Nurashikin Nordin. "Control BLDC motor speed using PID controller." *International Journal of Advanced Computer Science and Applications* 11, no. 3 (2020). https://doi.org/10.14569/IJACSA.2020.0110359

[16] Linggarjati, Jimmy. "Learning PID digital motor control using launchpad C2000 ecosystem from Texas-instruments." In *IOP Conference Series: Earth and Environmental Science*, vol. 195, no. 1, p. 012062. IOP Publishing, 2018. https://doi.org/10.1088/1755-1315/195/1/012062

[17] Avian, Cries, Setya Widyawan Prakosa, and Bayu Rudiyanto. "Performance improvement on motor BLDC speed controller by using multi controller with summation technique." *Journal of Applied Engineering Science* 19, no. 4 (2021): 902-909. https://doi.org/10.5937/jaes0-30440

[18] Hannan, M. A., S. B. Wali, P. J. Ker, M. S. Abd Rahman, M. Mansor, V. K. Ramachandaramurthy, K. M. Muttaqi, T. M. I. Mahlia, and Z. Y. Dong. "Battery energy-storage system: A review of technologies, optimization objectives, constraints, approaches, and outstanding issues." *Journal of Energy Storage* 42 (2021): 103023. https://doi.org/10.1016/j.est.2021.103023

[19] Schmidt-Rohr, Klaus. "How batteries store and release energy: Explaining basic electrochemistry." *Journal of chemical education* 95, no. 10 (2018): 1801-1810. https://doi.org/10.1021/acs.jchemed.8b00479

[20] Alphonse, Immanuel, Hosimin Thilagar, and F. Bright Singh. "Design of solar powered BLDC motor driven electric vehicle." *International Journal Of Renewable Energy Research* 2, no. 3 (2012): 456-462.

[21] Blank, Tobias, Julia Badeda, Julia Kowal, and Dirk Uwe Sauer. "Deep discharge behavior of lead-acid batteries and modeling of stationary battery energy storage systems." In *Intelec 2012*, pp. 1-4. IEEE, 2012. https://doi.org/10.1109/INTLEC.2012.6374527

[22] Carandbike Team, "Types Of Batteries Used In Electric Vehicles & Their Parameters," *28-Feb-22 11:42 AM IST*, Feb. 22, 2022. https://www.carandbike.com/news/types-of-batteries-used-in-electric-vehicles-their-parameters-2754393

[23] KITARONKA, Sefu "Lead-Acid Battery," Siirt University, Siirt University ,Kezer Yerleşkesi Veysel Karani , 2022. https://doi.org/10.6084/m9.figshare.19115057

[24] Todeschini, Fabio, Simona Onori, and Giorgio Rizzoni. "An experimentally validated capacity degradation model for Li-ion batteries in PHEVs applications." *IFAC Proceedings Volumes* 45, no. 20 (2012): 456-461. https://doi.org/10.3182/20120829-3-MX-2028.00173

[25] Center, Alternative Fuels Data. "Batteries for Electric Vehicles."

[26] Zhang, Cong, Dai Wang, Bin Wang, and Fan Tong. "Battery degradation minimization-oriented hybrid energy storage system for electric vehicles." *Energies* 13, no. 1 (2020): 246. https://doi.org/10.3390/en13010246

[27] Iclodean, Calin, Bogdan Varga, Nicolae Burnete, Denisa Cimerdean, and B. Jurchiş. "Comparison of different battery types for electric vehicles." In *IOP conference series: materials science and engineering*, vol. 252, no. 1, p. 012058. IOP Publishing, 2017. https://doi.org/10.1088/1757-899X/252/1/012058

[28] Su, Jie, Maosong Lin, Shunli Wang, Jin Li, James Coffie-Ken, and Fei Xie. "An equivalent circuit model analysis for the lithium-ion battery pack in pure electric vehicles." *Measurement and Control* 52, no. 3-4 (2019): 193-201. https://doi.org/10.1177/0020294019827338

[29] Shi, Tingna, Haitian Lu, Yanfei Cao, Xinmin Li, and Changliang Xia. "Supercapacitor/battery hybrid energy storage unit for brushless DC motor operation." *IET Electric Power Applications* 14, no. 4 (2020): 597-604. https://doi.org/10.1049/iet-epa.2019.0682

[30] Zuo, Wenhua, Ruizhi Li, Cheng Zhou, Yuanyuan Li, Jianlong Xia, and Jinping Liu. "Battery-supercapacitor hybrid devices: recent progress and future prospects." *Advanced science* 4, no. 7 (2017): 1600539. https://doi.org/10.1002/advs.201600539

[31] Kouchachvili, Lia, Wahiba Yaïci, and Evgueniy Entchev. "Hybrid battery/supercapacitor energy storage system for the electric vehicles." *Journal of Power Sources* 374 (2018): 237-248. https://doi.org/10.1016/j.jpowsour.2017.11.040

[32] Liu, Fengchen, Chun Wang, and Yunrong Luo. "Parameter Matching Method of a Battery-Supercapacitor Hybrid Energy Storage System for Electric Vehicles." *World Electric Vehicle Journal* 12, no. 4 (2021): 253. https://doi.org/10.3390/wevj12040253

[33] "What is a hybrid car? | Kia Mauritius." https://www.kia.com/mu/discover-kia/ask/what-is-a-hybrid-car.html

[34] Zhang, Shuo, Rui Xiong, and Fengchun Sun. "Model predictive control for power management in a plug-in hybrid electric vehicle with a hybrid energy storage system." *Applied energy* 185 (2017): 1654-1662. https://doi.org/10.1016/j.apenergy.2015.12.035

[35] Do, Tri Cuong, Hoai Vu Anh Truong, Hoang Vu Dao, Cong Minh Ho, Xuan Dinh To, Tri Dung Dang, and Kyoung Kwan Ahn. "Energy management strategy of a PEM fuel cell excavator with a supercapacitor/battery hybrid power source." *Energies* 12, no. 22 (2019): 4362. https://doi.org/10.3390/en12224362

[36] Naseri, Farshid, Ebrahim Farjah, and Teymoor Ghanbari. "An efficient regenerative braking system based on battery/supercapacitor for electric, hybrid, and plug-in hybrid electric vehicles with BLDC motor." *IEEE Transactions on Vehicular Technology* 66, no. 5 (2016): 3724-3738. https://doi.org/10.1109/TVT.2016.2611655

[37] Rade, Minal R. "Design and development of hybrid energy storage system for electric vehicle." In *2018 International Conference on Information, Communication, Engineering and Technology (ICICET)*, pp. 1-5. IEEE, 2018. https://doi.org/10.1109/ICICET.2018.8533757

[38] Hamid, Jinsy, R. Sheeba, and S. Sofiya. "Energy harvesting through regenerative braking using hybrid storage system in electric vehicles." In *2019 IEEE International Conference on Intelligent Techniques in Control, Optimization and Signal Processing (INCOS)*, pp. 1-6. IEEE, 2019. https://doi.org/10.1109/INCOS45849.2019.8951323

[39] Castaings, Ali, Walter Lhomme, Rochdi Trigui, and Alain Bouscayrol. "Comparison of energy management strategies of a battery/supercapacitors system for electric vehicle under real-time constraints." *Applied Energy* 163 (2016): 190-200. https://doi.org/10.1016/j.apenergy.2015.11.020

[40] Song, Ziyou, Heath Hofmann, Jianqiu Li, Xuebing Han, Xiaowu Zhang, and Minggao Ouyang. "A comparison study of different semi-active hybrid energy storage system topologies for electric vehicles." *Journal of Power Sources* 274 (2015): 400-411. https://doi.org/10.1016/j.jpowsour.2014.10.061

[41] Khaligh, Alireza, and Zhihao Li. "Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles: State of the art." *IEEE transactions on Vehicular Technology* 59, no. 6 (2010): 2806-2814. https://doi.org/10.1109/TVT.2010.2047877

[42] Brafianto, Dary Rafi, Wijono Wijono, and Tri Nurwati. "Energy Management Applications in Battery And Supercapacitor Hybrid Electric Vehicles Using Fuzzy Logic." In *2022 11th Electrical Power, Electronics, Communications, Controls and Informatics Seminar (EECCIS)*, pp. 76-81. IEEE, 2022. https://doi.org/10.1109/EECCIS54468.2022.9902944

[43] Zhang, Qiao, and Gang Li. "Experimental study on a semi-active battery-supercapacitor hybrid energy storage system for electric vehicle application." *IEEE Transactions on Power Electronics* 35, no. 1 (2019): 1014-1021. https://doi.org/10.1109/TPEL.2019.2912425

[44] Nayanar, Vaishakh M., and Keerti S. Nair. "Fuzzy & pi controller based energy management strategy of battery/ultracapacitor for electric vehicle." In *2019 2nd International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT)*, vol. 1, pp. 572-577. IEEE, 2019. https://doi.org/10.1109/ICICICT46008.2019.8993374

[45] Fenol, Sheryl Dinglasan, Felicito S. Caluyo, and Jhunlyn L. Lorenzo. "Simulation and modeling of charging and discharging of supercapacitors." In *2017 International Conference on Circuits, System and Simulation (ICCSS)*, pp. 14-17. IEEE, 2017. https://doi.org/10.1109/CIRSYSSIM.2017.8023172

[46] Zhang, Deyi, Binbin Yang, Wenna She, Shiyao Gao, Jingruo Wang, Yi Wang, Kunjie Wang, Hongxia Li, and Lele Han. "Simultaneously achieving high energy and power density for ultrafast-charging supercapacitor built by a semi-graphitic hierarchical porous carbon nanosheet and a high-voltage alkaline aqueous electrolyte." *Journal of Power Sources* 506 (2021): 230103. https://doi.org/10.1016/j.jpowsour.2021.230103

[47] Naseri, F., S. Karimi, E. Farjah, and E. Schaltz. "Supercapacitor management system: A comprehensive review of modeling, estimation, balancing, and protection techniques." *Renewable and Sustainable Energy Reviews* 155 (2022): 111913. https://doi.org/10.1016/j.rser.2021.111913

[48] Cao, Biao, Chao Bi, and Zhen Peng. "Energy Recovery Control Strategy of Motor with Supercapacitor." In *2019 22nd International Conference on Electrical Machines and Systems (ICEMS)*, pp. 1-5. IEEE, 2019. https://doi.org/10.1109/ICEMS.2019.8921530

[49] Sani, Arman, S. Siahaan, and Naemah Mubarakah. "Supercapacitor performance evaluation in replacing battery based on charging and discharging current characteristics." In *IOP Conference Series: Materials Science and Engineering*, vol. 309, no. 1, p. 012078. IOP Publishing, 2018. https://doi.org/10.1088/1757-899X/309/1/012078

[50] Tomaszewska, Anna, Zhengyu Chu, Xuning Feng, Simon O'kane, Xinhua Liu, Jingyi Chen, Chenzhen Ji et al. "Lithium-ion battery fast charging: A review." *ETransportation* 1 (2019): 100011. https://doi.org/10.1016/j.etran.2019.100011

[51] Rufer, Alfred, David Hotellier, and Philippe Barrade. "A supercapacitor-based energy storage substation for voltage compensation in weak transportation networks." *IEEE Transactions on power delivery* 19, no. 2 (2004): 629-636. https://doi.org/10.1109/TPWRD.2004.824408

[52] Choi, Christopher, David S. Ashby, Danielle M. Butts, Ryan H. DeBlock, Qiulong Wei, Jonathan Lau, and Bruce Dunn. "Achieving high energy density and high power density with pseudocapacitive materials." *Nature Reviews Materials* 5, no. 1 (2020): 5-19. https://doi.org/10.1038/s41578-019-0142-z

[53] Weiss, Manuel, Raffael Ruess, Johannes Kasnatscheew, Yehonatan Levartovsky, Natasha Ronith Levy, Philip Minnmann, Lukas Stolz et al. "Fast charging of lithium-ion batteries: a review of materials aspects." *Advanced Energy Materials* 11, no. 33 (2021): 2101126. https://doi.org/10.1002/aenm.202101126

[54] Noh, Sejin, Jaeho Choi, Hyung-Cheol Kim, and Eun-Kyu Lee. "PSiM based electric modeling of supercapacitors for line voltage regulation of electric train system." In *2008 IEEE 2nd International Power and Energy Conference*, pp. 855-859. IEEE, 2008.

[55] Khan, Muhammad Adil, Kamran Zeb, P. Sathishkumar, Muhammad Umair Ali, Waqar Uddin, S. Hussain, M. Ishfaq, Imran Khan, Hwan-Gue Cho, and Hee-Je Kim. "A novel supercapacitor/lithium-ion hybrid energy system with a fuzzy logic-controlled fast charging and intelligent energy management system." *Electronics* 7, no. 5 (2018): 63. https://doi.org/10.3390/electronics7050063

[56] Zhou, Yanting, Yanan Wang, Kai Wang, Le Kang, Fei Peng, Licheng Wang, and Jinbo Pang. "Hybrid genetic algorithm method for efficient and robust evaluation of remaining useful life of supercapacitors." *Applied Energy* 260 (2020): 114169. https://doi.org/10.1016/j.apenergy.2019.114169

[57] Liu, Chunli, Yang Zhang, Jianrui Sun, Zhenhua Cui, and Kai Wang. "Stacked bidirectional LSTM RNN to evaluate the remaining useful life of supercapacitor." *International Journal of Energy Research* 46, no. 3 (2022): 3034-3043. https://doi.org/10.1002/er.7360

[58] Haris, Muhammad, Muhammad Noman Hasan, and Shiyin Qin. "Early and robust remaining useful life prediction of supercapacitors using BOHB optimized Deep Belief Network." *Applied Energy* 286 (2021): 116541. https://doi.org/10.1016/j.apenergy.2021.116541

[59] Khan, MD Adnan Shahrukh, R. K. Rajkumar, C. V. Aravind, Y. W. Wong, and M. I. F. Bin Romli. "A LabVIEW-based real-time GUI for switched controlled energy harvesting circuit for low voltage application." *IETE Journal of Research* 66, no. 5 (2020): 720-730. https://doi.org/10.1080/03772063.2018.1510747

[60] Şahin, Mustafa Ergin, and Frede Blaabjerg. "A hybrid PV-battery/supercapacitor system and a basic active power control proposal in MATLAB/simulink." *Electronics* 9, no. 1 (2020): 129. https://doi.org/10.3390/electronics9010129

[61] Li, Xiao, Changsheng Hu, Changjin Liu, and Dehong Xu. "Modeling and control of aggregated super-capacitor energy storage system for wind power generation." In *2008 34th Annual Conference of IEEE Industrial Electronics*, pp. 3370-3375. IEEE, 2008. https://doi.org/10.1109/IECON.2008.4758501

[62] Partridge, Julius, and Dina Ibrahim Abouelamaimen. "The role of supercapacitors in regenerative braking systems." *Energies* 12, no. 14 (2019): 2683. https://doi.org/10.3390/en12142683

[63] Wei, Qing Sheng, Xia Zhang, Byeong-Heon Kim, and Byeong Soo Oh. "Experimental investigation of supercapacitor based regenerative energy storage for a fuel cell vehicle equipped with an alternator." *International Journal of Hydrogen Energy* 47, no. 3 (2022): 1954-1964. https://doi.org/10.1016/j.ijhydene.2021.10.102

[64] Horn, Michael, Jennifer MacLeod, Meinan Liu, Jeremy Webb, and Nunzio Motta. "Supercapacitors: A new source of power for electric cars?." *Economic Analysis and Policy* 61 (2019): 93-103. https://doi.org/10.1016/j.eap.2018.08.003

[65] Bharathi Sankar Ammaiyappan, A., and Seyezhai Ramalingam. "Design and Development of Power Electronic Booster to Extend the Range of Supercapacitor-Powered Electric Bicycles." In *Recent Advances in Energy Technologies: Select Proceedings of ICEMT 2021*, pp. 409-418. Singapore: Springer Nature Singapore, 2022. https://doi.org/10.1007/978-981-19-3467-4_25

[66] Nurdiansyah, Rizal, Novie Ayub Windarko, Renny Rakhmawati, and Muhammad Abdul Haq. "State of charge estimation of ultracapacitor based on equivalent circuit model using adaptive neuro-fuzzy inference system." *Journal of Mechatronics, Electrical Power, and Vehicular Technology* 13, no. 1 (2022): 60-71. https://doi.org/10.14203/j.mev.2022.v13.60-71

[67] Fouda, Mohammed E., Anis Allagui, Ahmed S. Elwakil, Ahmed Eltawil, and Fadi Kurdahi. "Supercapacitor discharge under constant resistance, constant current and constant power loads." *Journal of Power Sources* 435 (2019): 226829. https://doi.org/10.1016/j.jpowsour.2019.226829

[68] Sinha, Mayank, Dheeraj Kapur, and Vivek Agarwal. "An ultracapacitor driven short-distance electric vehicle." In *2012 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, pp. 1-6. IEEE, 2012. https://doi.org/10.1109/PEDES.2012.6484366

[69] Tarigan, Kerista, Syahrul Humaidi, and Kurnia Brahmana. "Effect of capacitance of graphene coated electrodes on supercapacitor by charging and discharging method." In *AIP Conference Proceedings*, vol. 2221, no. 1, p. 110031. AIP Publishing LLC, 2020. https://doi.org/10.1063/5.0003130

[70] Nahirniak, Svitlana, Apurba Ray, and Bilge Saruhan. "Challenges and Future Prospects of the MXene-Based Materials for Energy Storage Applications." *Batteries* 9, no. 2 (2023): 126. https://doi.org/10.3390/batteries9020126

[71] Yi, Zhenxiao, Kun Zhao, Jianrui Sun, Licheng Wang, Kai Wang, and Yongzhi Ma. "Prediction of the remaining useful life of supercapacitors." *Mathematical Problems in Engineering* 2022 (2022): 1-8. https://doi.org/10.1155/2022/7620382

[72] Cabe Atwell, "Supercapacitors: Past, Present, and Future | Electronic Design," Mar. 17, 2018. https://www.electronicdesign.com/technologies/power/alternative-energy/article/21199519/supercapacitors-past-present-and-future

[73] Huang, Shifei, Xianglin Zhu, Samrat Sarkar, and Yufeng Zhao. "Challenges and opportunities for supercapacitors." *APL Materials* 7, no. 10 (2019): 100901. https://doi.org/10.1063/1.5116146