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Review

Comparative Review of Motor Technologies for Electric Vehicles Powered by a Hybrid Energy Storage System Based on Multi-Criteria Analysis

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Abstract: The modern era of green transportation based on Industry 4.0 is leading the automotive industry to focus on the electrification of all vehicles. This trend is affected by the massive advantages offered by electric vehicles (EV), such as pollution-free, economical and low-maintenance cost operation. The heart of this system is the electric motor powered by lithium-ion batteries; however, due to their many limitations, a hybrid energy storage system (HESS) consisting of batteries and ultracapacitors is currently gaining increased attention. This paper aims to review the distinct motor technologies such as brushless motors, synchronous reluctance and induction motors currently used in EVs. Additionally, through eleven selected criteria, such as regenerative braking efficiency and power density at different load ranges, the motors are classified in terms of their combined ability to operate with a HESS in order to maximize efficiency and sizing. The results show that permanent magnet and induction motors are the best options when all criteria are considered, while synchronous reluctance motor outperforms the induction motor regarding only the main factors affecting the performance of the hybrid storage system.

Keywords: EV; battery; motors; HESS; industry; transportation; e-mobility

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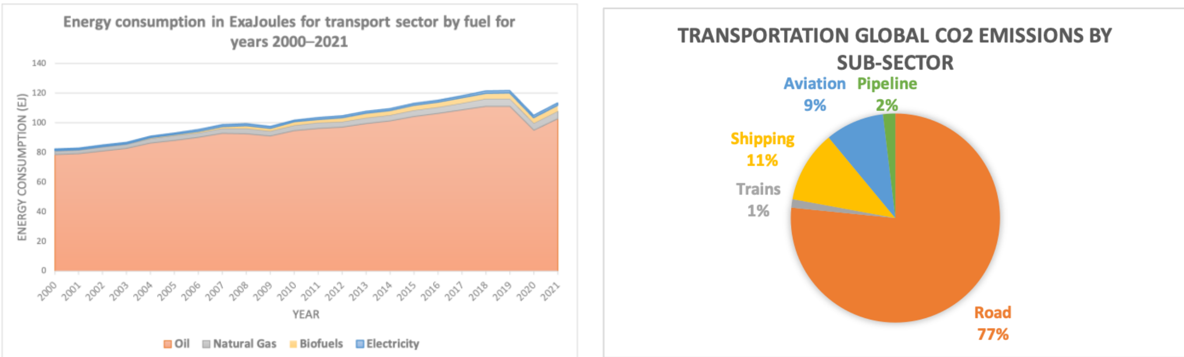
1. Introduction

In recent years, global electricity consumption has been increasing rapidly, mainly due to population increases, economic development and technological advancements. The global electricity demand was 23,000 TWh in 2019, and it is expected to increase by 2.5% annually through 2040, reaching about 39,000 TWh [1]. Since most of the global electricity comes from fossil fuels such as coal and natural gas, greenhouse gas emissions are increasing. Specifically, CO_2 emissions are expected to increase by about 6%, i.e., to 35 Gt in 2050 [1]. Transportation is a major sector that affects global pollution. It was responsible for nearly 7.7 gigatons, or 37% of the carbon dioxide emitted globally by the year 2021, even with the pandemic restrictions [2], and, in particular, passenger cars were the largest source of CO_2 emissions, presenting 41% of the emissions produced in the transportation sector worldwide [3]. It is expected to increase even more unless cleaner and more environmentally friendly modes of transport are adopted, as depicted in Figure 1. Even though emission limits for conventional cars have become highly strict, with the Euro 6 standard forcing manufacturers to minimize greenhouse gases, pollution is still evident with enormous health and economic impacts [4,5].

Following the fourth industrial revolution, or Industry 4.0, modern technology and smart factories are enhancing effective and greener mass production throughout the value chain [6]. In addition, the advanced hardware and adaptive software adopted by modern vehicles allow for a more intelligent vehicle network, where big data analysis utilizing the Internet of Things concept is now achievable (Figure 2). Following the arrival of autonomous vehicles, tracking of each vehicle's position, real-time management of the sensors and faster communication of the network are essential, with the capability for online cloud storage [7]. A digital twin model, a major tool of Industry 4.0, can also be applied to the production line to create a virtual replica of the automobile where every single innovation can be tested via software before being applied to the product [8]. The advantages offered are promising in the implementation of this tool, including the following:

- Engineers can simplify the manufacturing process through simulation;
- Reduced costs as the errors are limited;
- Faster production time;
- Real-time monitoring of the whole process;
- Enhanced quality of the end product;
- Logistics processes are improved.



(**a**) (**b**)

Figure 1. Global energy and CO_2 emissions for the transportation sector (**a**) Energy consumption consumed in the transportation sector in a 21-year scope [1]; (**b**) CO_2 emissions by subsector revealing the influence of road transport on greenhouse gases.

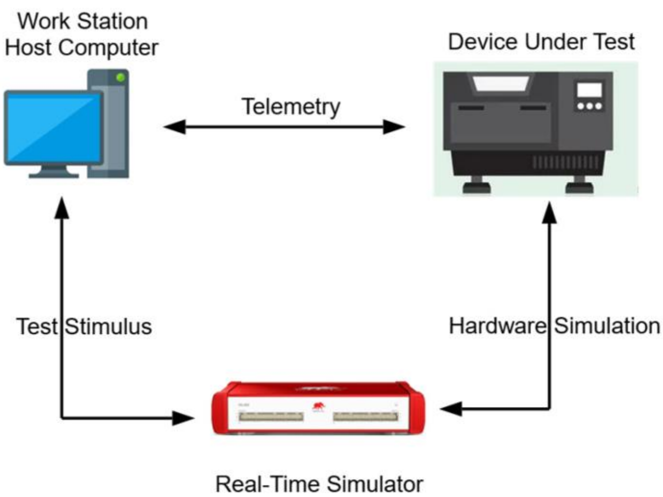


Figure 2. Implementation of the digital twin using hardware in the loop system [7]. Applying unified testing both virtually and physically on the same unit provides faster error tracking and an easier understanding of the process.

Electric vehicles (EVs) powered by electric motors are considered a key factor for the new generation of transportation [9]. EVs inherit a variety of benefits over traditional internal combustion engines (ICE), such as (i) higher efficiency as EVs can convert up to 90% of the energy they consume into useful work, whereas ICE are typically less than 50% efficient, (ii) instant torque at different loads, especially in urban driving, (iii) less maintenance required as there is no need for oil changes and (iv) they have the ability to recover power through braking [10]. As there are not many moving parts, compared to a conventional car with ICE, the sizing can be improved to reduce the overall weight [11] while wear is limited, and hence maintenance costs are even lower. In addition, EVs are environmentally friendly as they produce no emissions or pollution at the point of use.

It is crucial to keep the total mass at minimum levels to decrease energy consumption and, at the same time, improve the drivability and longevity of the car. Moreover, as the different subsystems and control modules, such as the body control unit, become more advanced and intelligent, driver safety and vehicle handling are ensured [12]. Currently, there are almost 2000 patents by the major players in the EV industry (Toyota, Honda and Panasonic) for the power electronics field and about 20,000 patents for the electric motor, presented in Figure 3 [13]. It is obvious that most patents refer to two domains, "electric motor" and "energy storage". This is logical as the electric propulsion system of an EV is the combination of the electric motor, controller and storage devices. It can be concluded that all manufacturers are already planning ahead for the next big step.

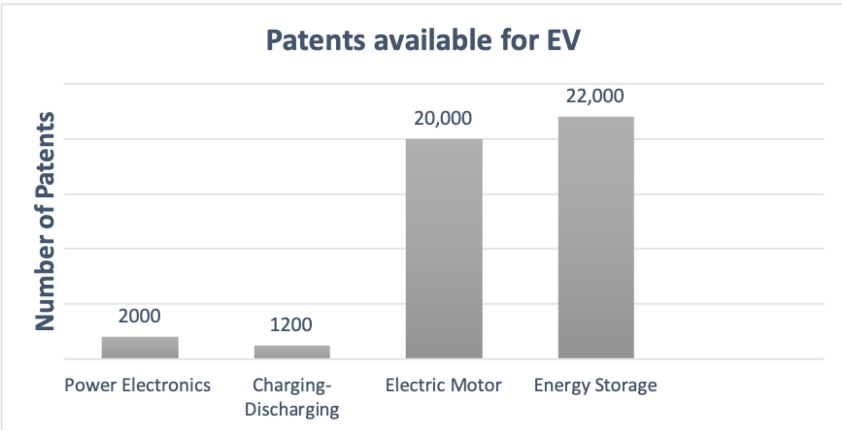


Figure 3. Patents at each component of EV, reveal the research and development focus of manufacturers for mass adoption of EVs [13].

EVs are highly dependent on the available energy storage technologies (EST) since EST determines the vehicle's driving range, performance and overall efficiency [14]. The four types of EST for EVs are fuel cells, ultracapacitors, electrochemical batteries and hybrid energy storage systems.

The required specifications of energy storage systems for various types of EVs are presented in Table 1.

Table 1. Energy storage specifications for EVs [15,16].

EV	System Voltage (V)	Fuel Cell (kWh)	Ultracapacitors (kWh)	Electrochemical Batteries (kWh)
Micro-hybrid	12–42	-	0.03	0.02–0.05
Mild-hybrid	150–200	-	0.1–0.15	0.1–1.3
Full-hybrid	200–250	-	0.1–0.2	1.4–4
Plug in hybrid	250–500	-	0.1–0.2	5–20
All EVs	300–500	150–200	0.3	20–40

Most of the used EST incorporated in EVs are based on electrochemical batteries. The suitable batteries for an electric propulsion system of an EV are the lead–acid batteries, nickel-based batteries and lithium-based batteries [17]. The lead–acid batteries have a high energy density, but clean-up and adding water are the main disadvantages, and that is why they were replaced by nickel-based batteries [18]. Nickel-metal hydride batteries are very robust with a very long life span; in particular, they can last for more than 20 years, but their self-discharge rate is high and their performance in cold weather is poor, resulting in reduced charging and discharging efficiency [19]. Lithium-ion batteries have a high energy density, fast charge and are lightweight and also are cost economic [18]. This is why most of the patents on energy storage refer to this type of battery [12]. The typical characteristics of EV batteries are presented in Table 2. In addition, according to the literature [20,21], the hybridization of the energy storage systems for EVs can provide higher power and energy densities, response time balancing, efficiency balancing, and life cycle increase.

Table 2. Typical characteristics of EV batteries [14,22–25].

Battery Type	Energy * (Wh/kg)	Energy Density * (Wh/L)	Specific Power ** (W/kg)	Efficiency (%)	No. of Cycles	Operating Temperature (°C)
Lead–acid	30–50	60–100	200–400	70–90	2000–4500	−15–50
Nickel-metal hydride	30–70	60–170	25–350	50–90	500–3000	−40–60
Lithium-ion	120–180	200–400	200–400	70–85	1500–4500	−60–70

* At 80% depth-of-discharge. ** At 3-h discharge rate.

Besides the other advantages that EVs offer, the ease of control is definitely worth mentioning. Since the powerhouse and the energy source of the vehicle are electrical, management of the power output and supervision of the main processing unit is more adaptive to optimization. Torque techniques are easier to adjust, regardless of the motor used, and are more robust and reliable for the end user [26]. This pattern also affects the driving range and the capability of the user to embrace an eco-driving behavior [27]. Driving on an urban cycle becomes simpler than a conventional car due to the following:

- No operation status of the engine at traffic lights contrary to an ICE;
- Imminent acceleration at low speeds so full throttle is not required;
- Additional energy harvesting through braking;
- No need for transmission, so less weight.

Considering these facts, an individual can be trained to drive in a more environmentally friendly and ecological way, with mild acceleration, thus protecting the batteries from thermal stress [28]. In general, the core operation and simplicity of an EV allow for a comfortable and enjoyable driving experience thanks to the intelligent energy and power management controller, which handles all processes. However, there are the following four major factors that are currently being examined thoroughly, presented in Figure 3 [29]:

1. High purchase price;
2. Charging speed, type and time required;
3. Limited range;
4. High space and weight required for energy storage.

The increased price compared to fossil fuel vehicles is expected to be reduced adequately on account of massive production, battery availability and state diversities. The global stock will reach 250 million units by 2030, while sales are expected to double almost every 2 years [29]. Charging is still a serious drawback, as the time needed for a full charge extends the 1-h limit at a charging station for a quick stop. DC super or fast charging is still the way to go on this occasion, but with low power (up to 20A) and slows overnight single-phase AC method is preferred for battery longevity and protection [30]. Specific infrastructure for level 1 charging protocol at home is required with a negligible cost (800–1200 €), as the need to charge at a public station is quite costly, and there is always a possibility for a lack of a free spot. Therefore, proper hourly charging scenarios are essential, while the protection of instability and potential aging induced in the grid is crucial [31].

Likewise, the limited range parameter is mainly affected by vehicle speed, traffic and partially the exploitation of regenerative braking [32]. While traffic is not the key factor of heavy power usage like with a conventional car, the energy needed for stop-and-go acceleration is still high, and there is not a free path for coasting mode. Cruising or coasting is defined as the low to no press of the acceleration pedal without loss of speed, leading to minimal consumption that implied with energy accustomed by braking, increasing the useful range [33]. The main impact depends on the weight of the battery pack, as more batteries required to raise the capacity result in reduced total efficiency. It is suggested that an EV with a smaller capacity is far more efficient in the same distance, a verity that, in combination with the driving mode (cruising or aggressive acceleration) and the proper motor technology, significantly affects the effective range. All those factors, along with their stated solutions and feasible gains, are summarized in Table 3.

Table 3. Factors concerning EV adoption and their solution [30–32].

Factor	Solution	Gains
Purchase price	Diversities, massive production	Up to 50% savings
Slow charging	Rapid charging	75% less time required
Moderate range	Regenerative braking	Up to 25%
Weight	Smaller batteries	10% *

* Theoretical approach based on combined factor exploitation.

The purpose of this work is to review the current motor technologies available in the market and their evolution through the decades. Additionally, via selected criteria gathered from the literature, a direct comparison of those motors based on selected criteria will take place in order to justify the ideal motor for EV applications in terms of costs, weight and durability.

The manuscript is structured into four main sections. The motor technologies paragraph describes the different motor types available and their characteristics, along with the selected motors that current manufacturers prefer. In the third main section, the comparison based on selected criteria, there is an extensive comparison of the different motors based on certain criteria selected to cover immersive daily needs based on the utilization of a hybrid energy storage system. In the last section, conclusions about the comparison and the classification of motors are provided.

2. Motor Technologies and Transmission

2.1. Motor Types

There are the following seven different technologies currently available for EV propulsion [34–38]:

i. DC brushed motor;
ii. DC brushless motor (BLDC);
iii. Induction motor (IM);
iv. Synchronous reluctance motor (SynRM);
v. Switched reluctance motor (SRM);
vi. Permanent magnet motor (PMSM);
vii. Flux reversal motors.

Brushed DC is a classic traction device, particularly known for powering small and remote-controlled toys [34]. It is accepted to be one of the first motors used in EVs because of its high torque at low speed and adequate management. It is based on series or shunt field orientation operation depending on the output power needed. Because of the many drawbacks it inherits, such as high maintenance, low efficiency and speed but mainly bulky construction, as both brushes and commutator need replacement due to aging by friction, it is no longer a serious candidate for an EV powertrain [35].

Brushless DC is one of the most popular and widely applicable motors for different systems (vehicles, boats and home accessories) due to its small size and need for maintenance while achieving high efficiency plus controllability [36,37]. It is manufactured with a permanent magnet rotor with differentiations in pole count and wire wounded stator to form an unvarying flux density, as shown in Figure 4. The stator coils, driven by DC voltage and controlled by hall sensors, provide high efficiency and power density with minimum noise [38,39]. Further enhancement of this model is available with the minimization of iron losses, stress and ripple via a sensorless predictive design [40].

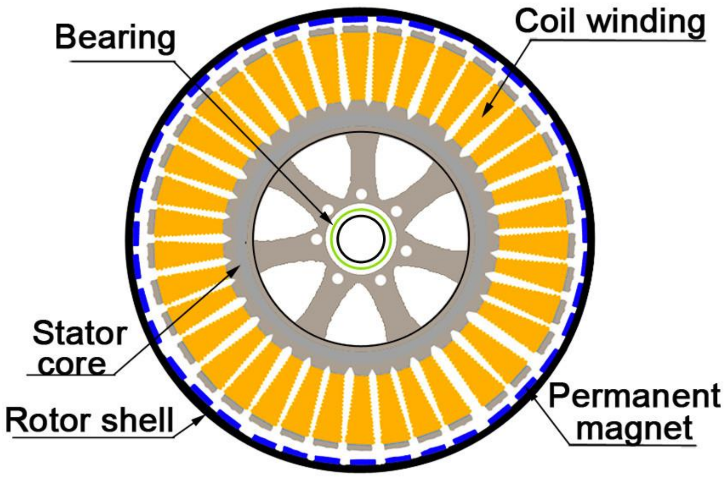
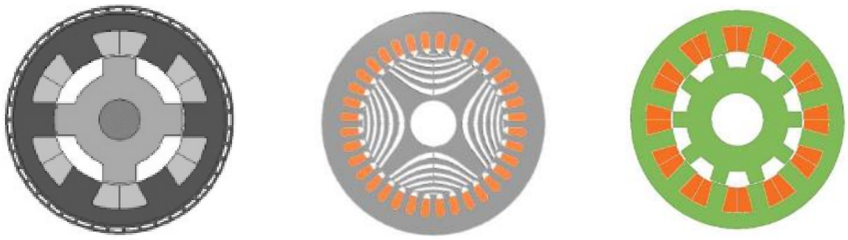


Figure 4. Brushless motor inner design by [37].

The induction motor, invented by Nicola Tesla in 1890, continues to account for the most admired and mature powertrain found in various applications such as industries, university labs and public elevators. It consists of a rotor, commonly a squirrel cage formed by conductive bars inserted through slots to two cylindrical laminations. [41,42]. Due to production simplicity, advantages such as low price, high toughness and efficiency led it to be the preferred traction motor by all manufacturers until recently, where PMSM has gradually replaced it in a high percentage [43]. Another benefit is that it can be driven via an inverter, as adjusting the output frequency can easily modify the vehicle speed with minimum errors and zero maintenance [44,45].

Synchronous reluctance or SynRm motor is very promising in traction motors as it is rated for the high torque, speed and power-to-weight ratio [46]. The technology has been available for over a century, but the absence of superior power electronics made it neglected until 1980 [47]. The principle of its operation is very simple, as follows: as the rotor tends to align with the core of the stator, the coil is powered by magnetic reluctance minimization, called reluctance torque. When the rotor and stator poles are lined up, the rotor claims a minimum reluctance position hence the magnetic reluctance is lower. Conversely, if the stator pole lines up to the rotor slots, thus reaching the maximum reluctance position, so both windings are unaligned. Since the rotor tends to avoid reluctance, torque is always produced, causing rotation at synchronous speed. This is where power electronics come in handy to manage this operation, for maximum efficiency, over 88% even at high slopes, with limited core losses, torque ripple and low manufacturing costs [48,49]. This aspect designates this motor as ideal for regular driving styles and complex powered vehicles such as fuel cell electric and plug-in hybrids [30,48]. However, the low power factor is still a great concern.

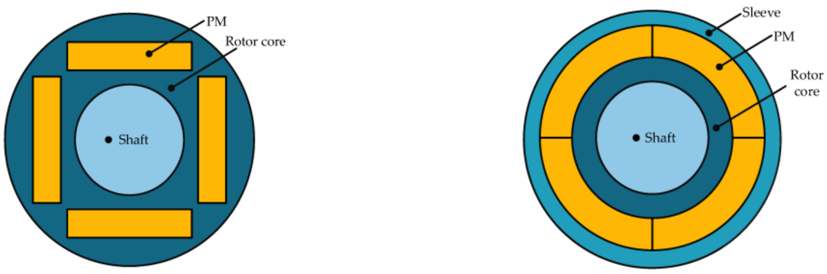
Switched reluctance motor, or SRM, was the primary motor applied in the first EV prototypes over two centuries ago on account of its low cost and durability, as no magnets are needed with no evident risk of demagnetization [50]. Operation is similar to SynRM, and it is characterized by low torque ripple, vibration and noise, both in conventional or segmented rotor construction [51]. On the other hand, its main drawback remains the complexity of the drive and control methods it requires, along with low power density and high noise [52]. A soft switch converter can be applied to overcome this downside, effectively optimizing the flux linkage and adding extra capabilities, such as the collaboration with a hybrid storage system. Thus, it can be the ideal propulsion system, mainly for a small EV, as the maximum motor speed is low—up to 4.6 k rounds per minute [53]. All three previously mentioned technologies are enlisted in Figure 5 below, as follows:



(**a**) (**b**) (**c**)

Figure 5. Cross-section of different motor cores: (**a**) induction; (**b**) synchronous reluctance; (**c**) switched reluctance [39,47].

Permanent magnet motors (PMSM) can be found on the majority of pure and hybrid electric vehicles due to their great efficiency at variable speeds and compact sizing [39,54–56]. It belongs to the AC synchronous motor category. When the stator windings are supplied with three-phase AC, a rotating magnetic field is generated, reacting to the constant magnetic field of the rotor, causing swirling [57]. However, these motors cannot self-start, so a variable frequency supply is necessary. Depending on the magnet location, there are the following two main types of PMSM, as shown in Figure 6: surface or interior (IPMSMs) [58]. Finally, constant monitoring is essential for undisrupted operation, as issues such as noise, harmonics and partial vibrations affect driving comfort [59–61]. Because of their easy installation, reliability and torque, manufacturers prefer them as powertrains [62,63].



(**a**) (**b**)

Figure 6. Schematic representation of permanent magnet synchronous motor structure with (**a**) interior rotor; (**b**) exterior or surface rotor layout; with windings and air gaps, replicated from [58].

Lastly, a new motor technology has been unveiled recently called Flux-Reversal Motor. It involves a reluctance rotor fitted for high-speed rotation with the field windings integrated on the stator teeth alongside permanent magnets, portrayed in Figure 7 [64]. They can achieve high efficiency and torque density but with low, up to 0.7, power factor [51]. Increased performance can be achieved with larger magnets and the addition of slots between teeth, but this approach may lead to demagnetization and a non-compact design, whereas auxiliary teeth do not comprehend those disadvantages [65].

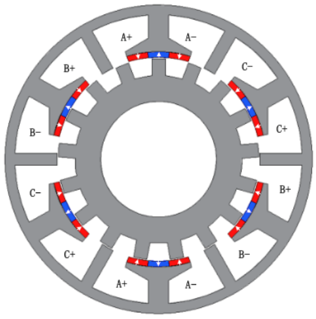


Figure 7. Topology of flux reversal motor with three-phase supply [64]. A, B and C represent the three-phase windings of the motor installed in an X configuration.

Figure 8 outlines the main the following motor technologies for electric vehicles described above:

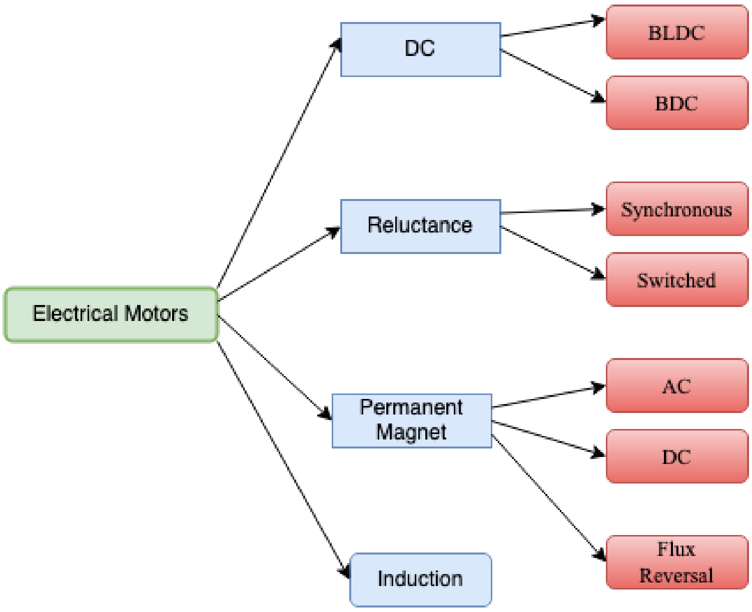


Figure 8. Main electric motor technologies currently available for EVs [34–39].

2.2. Multiple Rotors and Transmission

Besides the need to select the proper motor, research has focused on the dependence of transmission on total power, reliability and efficiency [66]. Two motors and multiple gears have been tested at [67–69] at both axles to decide if the powertrain size and energy consumption can be reduced with improvements of 5% to energy consumption and 10% efficiency compared to a single motor. Additionally, multiple motors and gear ratios offer the following:

- Regenerative braking enhanced exploitation, about 22% [70];
- Over 30% increased rate of acceleration [71];
- Minimization of power losses and battery aging [72,73];
- Escalated range, up to 5% and top speed [74].

Additionally, constant variable transmission (CVT), already equipped on all the small scooters and Toyota hybrid electric vehicles currently manufactured, has gained great attention and is already being implemented in pure electric vehicles [75,76]. CVT is very simple in its operation as two pulleys with variable diameters connected via a timing belt. Both pulleys are constantly adjusting, and the ratio between the drive and driven pulley determines the gear ratio, as illustrated in Figure 9. As both pulleys are embraced in lubricant and auto-regulated, there is no need for maintenance except a typical oil change and a belt replacement every 3–4 years [76].

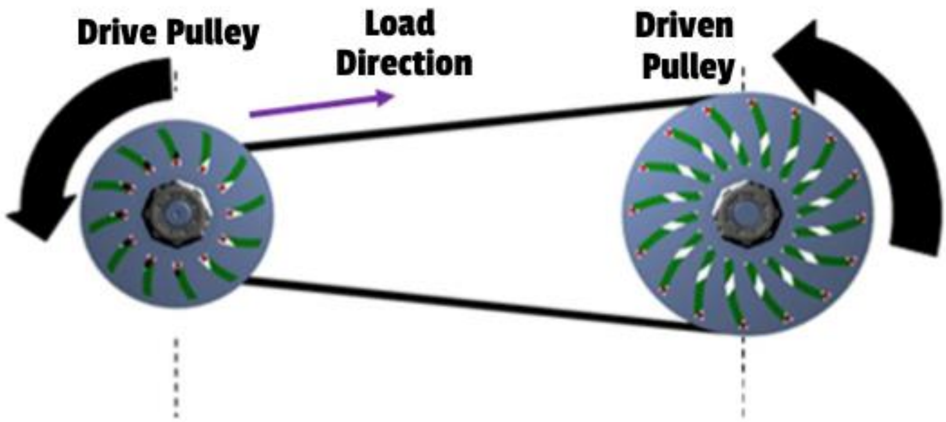


Figure 9. CVT operation principle, currently implemented at most hybrid or battery electric vehicles and electric scooters [76].

By utilization of multi-gear or CVT, battery aging is limited, with a better energy rate and less electricity consumed, as shown in Table 4 below. The savings of the battery pack is 16% or 4000 € less, while CVT integration doubles the overall payoff. Sizing, up to 50%, is also achieved at private and heavy-duty trucks as well [77].

Table 4. Improvements on battery and costs by exploitation of multi-geared or CV transmission types [75].

Improvements	2-Speed	3-Speed	4-Speed	CVT
Battery aging	16.2%	16.3%	17.1%	18%
Capacity needed for 200 km range	18%	18%	19%	23%
Consumed electricity improvement *	15%	15%	22%	31%
Energy rate	9.6%	9.0%	16%	24%
Battery cost **	16%	16%	17%	32%
Total cost (€)	5100 €	5300 €	5150 €	11,000 €

* Combined cycle. ** Assuming standard nominal capacity.

2.3. Protection and Cooling

Integration of multiple gears, complex components such as super-efficient and premium power converters, plus the need for increased power density and efficiency of the motor, causes a lot of stress for the moving parts and electronics. Temperatures rise, and a possible error is evident either on the powertrain (motor and transmission) or any part of the controller or the charging array. Therefore, manufacturers install high-accuracy sensors on each part to assure temperature stability and through constant monitoring and diagnosis [78,79]. Air cooling is not sufficient; thus, more advanced ways are researched for heat dissipation.

Oil spray cooling is considered the easiest and safest method to cool the motor parts, such as the rotor, windings and stator [80]. Oil, mainly automatic transmission fluid (ATF), is injected through sealed channels at the component cores to remove heat and transfer it back to the sump, where it is cooled, as shown in Figure 10 [78]. A major difference, however, is that at low RPM and normal road incline, where the load is not high, there is no oil flow, but as vehicle speed is increased, the spray runs as MultiJet to cover the required escalated heat exchange [81]. However, stagnant oil cannot be present, as it contributes to the rise of core temperature.

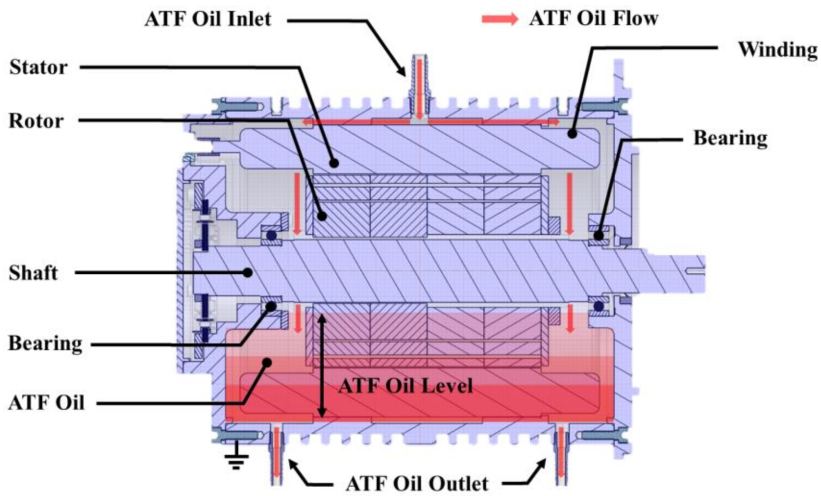


Figure 10. Flow channel for oil spray cooling method by [78].

Hairpin winding is lately utilized for cooling at small and efficient motors. A study at a Chevrolet Bolt suggested that mixing oil with forced air cooling is the ideal approach with specific parameters—60 °C and 0.140 kg per second flow rate [82]. Hence a faultless prediction of the temperature distribution of all motor areas can be achieved to avoid possible faults while straining the motor.

Jacket cooling, taking place around the perimeter of the stator and rotor, is also preferred by different manufacturers, such as Tesla, due to its simplicity and cost [83]. It is similar to the conventional vehicle cooling procedure with known characteristics. A comparison of all techniques revealed a great temperature decrease, almost 30 degrees at direct winding heat exchanging at electro-magnetic performance. Table 5 below includes all the different cooling techniques EV industries use the following [84]:

Table 5. Cooling methods employed by different manufacturers [84].

Model	Motor Specs	Cooling
Toyota Prius 2010	I-PMSM	Jacket
Toyota Sonata 2011	PMSM	Jacket
Tesla Roadster 2012	IM	Forced Air
Nissan Leaf 2012	I-PMSM	Jacket
Tesla S60	IM	Jacket + Shaft
BMW i3	I-PMSM	Jacket

2.4. Motors Utilized by Manufacturers

As mentioned before, each motor inherits its own pros and cons, so each manufacturer chooses the proper type according to the specifications required. For example, Tesla Inc. used an induction motor until 2015–2016 but has now swapped it to a synchronous reluctance powertrain manufactured in-house, or a dual motor layout, one motor at each axle [85,86]. Other renowned industries such as Porsche, Hyundai and BMW have moved to permanent magnet synchronous motors for over a decade, accepting its many advantages, while Audi and Mercedes prefer the more controllable, cheap and quiet induction motors [87,88]. Brushless motor is not found in almost any car due to the parameters mentioned in previous chapters, but it is favored for electric scooters and motorbikes combined with CVT due to their particularity. It is obvious that permanent magnets have dominated the EV powertrain field, with SynRM being a big competitor. Table 6 summarizes the motor technologies utilized by each manufacturer over the years.

Table 6. Different motor technologies currently applied by EVs industries [85–88].

Model Name	Year	Motor Type
BMW iX	2022	PMSM
Tesla Model X	2021	SynRM
Tesla Model Y	2021	SynRM
Tesla Model 3	2021	SynRM
Volvo XC40	2021	PMSM
Tesla Model S	2020	SynRM
Renault Zoe	2020	PMSM
Porsche Taycan	2020	PMSM
Hyundai Kona E	2020	PMSM
Mercedes Benz EQ	2020	IM
Skoda Citigo-e IV	2020	PMSM
Mini Cooper SE	2020	PMSM
Kia e-Niro	2020	PMSM
Nio EC6	2020	PMSM
Nissan Leaf	2019	PMSM
Jaguat i-Pace	2019	PMSM
Volkswagen E-Up	2019	PMSM
Audi E-Tron Q	2019	IM
Xpeng G3	2019	PMSM
Chevrolet Bolt	2017	PMSM
Toyota Prius Hybrid	2017	SynRM
Mahindra Everito	2016	IM
Tesla Model X	2015	IM
Land Rover 110 Defender	2013	SRM
Ford Focus Electric	2011	IM
Tata EV	2011	PMSM
Reva NXR	2011	IM
Fiat Doblo	2011	IM
Toyota Camry	2006	PMSM
Peugeot Partner	1999	BLDC
Honda EV plus	1997	BLDC
Nissan Altra	1997	PMSM
Ford Ecostar	1992	IM
City EI	1987	BDC
Citicar	1974	BDC
Enfield 8000	1969	BDC

Small PMSM, similar to BLDC.

3. Comparison Based on Selected Criteria

After studying the motors currently available and utilized on battery electric vehicles (BEV), an approach for selecting the proper powertrain with a hybrid energy storage system (HESS) is the next step of this paper. There are many types of hybrid storage systems, but the main focus is centered on a lithium-ion battery and an ultracapacitor array. This type of EV faces certain issues [89,90], such as the following:

- Major thermal stress by fast charging and peak loads;
- Inability to fully capitalize on regenerative braking;
- Aging due to limited range of safe charging and life cycles;
- Lithium deposition on the cathode.

Specifically, fast charging produces a high temperature, causing stress on the battery [91]. Even though it is convenient for the owner and modern life necessities, high temperature can cause the breakdown of the battery as heat stretches the internal structure of the cells, where a possible minor leak may lead to an explosion due to the toxicity of lithium. Peak loads, including rapid acceleration or deceleration or highly inclined roads, require high power from the powertrain and since the battery pack is required to supply that power, the increased temperature substantially induced, along with a major voltage drop, will provide a similar outcome.

Since the battery cycle is a closed loop where lithium ions are transferred from the anode to the cathode and vice versa, elevated temperature violates this loop, leaving lithium deposits on the cathode side [92]. So as there are fewer available lithium ions to travel, the maximum capacity is reduced. Further damage occurs when the cell's voltage is dropped outside of the safe zone, avoiding boundary charging states such as fully or non-charged conditions. As the current state of charge is constantly left at 100 or 2% level, the electrolyte and the separator are stressed, producing solid blocks and minimizing nominal capacity. As life cycles rise, it is natural for the battery to age and depletes, although these measures are taken as a precaution and safety operation guide to preserve and highly enhance the cell's expected lifetime [93].

To overcome those challenges, ultracapacitors or supercapacitors are implemented in a hybrid system to cover peak loads and high-frequency currents and generally handle all the stressful and dangerous conditions that the battery may confront. It can endure over a million operation cycles with constant charging/discharging without losing storage capabilities compared to lithium batteries, where the expected lifetime and cycle count are minimum. Unlike common capacitors, the typical electric double layer capacitors (ELDC) technology, widely used by various manufacturers, have very high capacitance high, allowing them to achieve excessive power density and high efficiency and operating temperature [29,94,95]. Additionally, due to their small internal resistance equivalent, the leakage current is low, so ELDCs can maintain their charge for longer periods, unlike ceramic capacitors or lithium batteries. However, due to their low energy density, they cannot provide sufficient energy to the various loads of the vehicle, such as the motor or the climate control system, and this is the main reason why they cannot be used as the sole energy source of any EV. Hybrid or lithium-ion supercapacitors, which combine characteristics and advantages, such as longer lifespan and higher operating voltage, from both sources, do not suffer from this constraint, but they are still very expensive. In Table 7 below, the specifications of the two components of technology are summarized.

Table 7. Comparison of characteristics for battery and ultracapacitors [16,94,95].

Characteristic	EDLC	Lithium Battery
Nominal cycles	50 k to 1.1 mil	3000
Nominal voltage (V)	2.7–3	3.7
Charge time (s) *	<60	3600–18,000
Discharge time (s)	<1800	<10,800
Energy density (Wh/kg)	4–10	Up to 250
Power density (W/kg)	800–2000	<3000
Operating temperature (°C)	40–70	20–60
Lifetime expectancy (Years)	>25	5–20
Series equivalent resistance range	milliOhms	Ohms
Endurance at heavy conditions	High	Low

* Depending on the available capacity and charger power output.

The sizing of a hybrid energy storage system is an important issue for the overall cost of an EV [96,97]. The power source of an EV is subject to various volume and weight constraints. Maximum utilization of supercapacitors is not the optimal choice as it will affect the charging efficiency and minimize the expected range. While lower reference power may result in current shavings of the battery, increasing the ultracapacitor pack is in trade-off with the HESS weight. In addition, typical management of charging strategies does not allow for charge exchange between the battery pack and the ultracapacitors. Each module has to be charged separately through the DC link and the converter for maximum control and safety. The most common hybrid storage system topology is depicted in Figure 11. Due to the apparent asymmetry of driving conditions, such as accelerations and decelerations, the monitoring of the state of charge for both power sources remain critical [21].

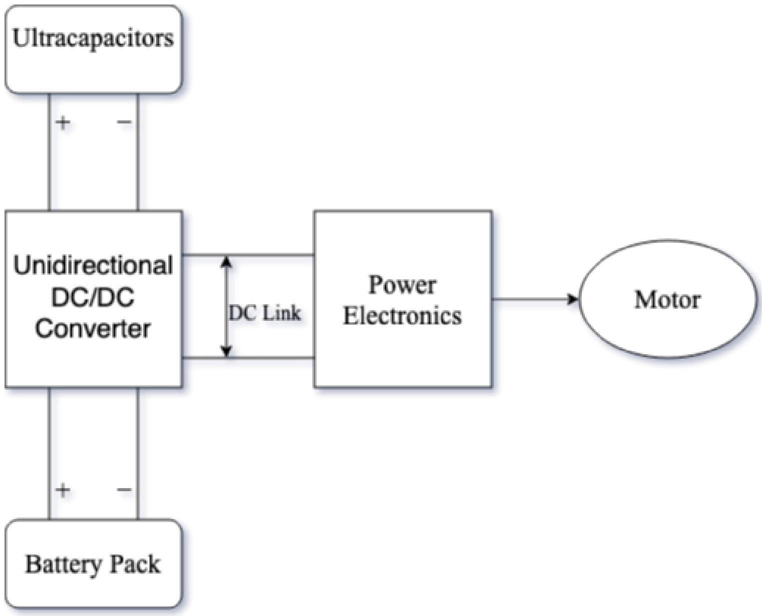


Figure 11. Common topology for the hybrid energy system consisting of batteries and ultracapacitors.

Lithium batteries should be maintained at a medium capacity level, avoiding stressful conditions such as very low or fully charged states. Similarly, supercapacitors cannot be kept charged to 100% so that when the car decelerates, regenerative braking can be fully utilized. Thus, the high-frequency current produced by the magnetic brakes will not damage the battery or be lost as heat but will be fully absorbed by the supercapacitor array, keeping it continuously charged in a manageable manner [91]. On the other hand, if the capacitors are depleted, they cannot provide their high-power density; therefore, the battery pack will be stressed as well, causing lithium deposition during the discharge cycle and reducing its maximum capacity. Both sources, however, have a certain lower voltage limit that can be reached as the power converter will not operate at all if the input is below this threshold. Thus, the process of handling and constantly regulating their state of charge is very demanding and requires a complex and precise energy management system.

Cold starting is a typical example of how ultracapacitors save sources when the battery bank is still cold and uses a sufficient amount of energy to preheat. Acceleration should be gentle, as excessive energy consumption can cause damage and severe breakdown. The ultracapacitors can drive the motor quite easily providing maximum power, and then the battery, being warmed up, covers the energy demand, and the motor recharges the ultracapacitor array thereafter. The use of different types of chargers for local charging at home or a public station cannot directly affect the ultracapacitor condition, as fast charging does not promote aging or risk of breakdown as in a lithium-ion battery, where many of the previously mentioned requirements must be met, especially temperature [98].

Slow charging and minimizing the depth of discharge factor remain the main prerequisites τo effectively protect battery operation, enhance optimal battery life and meet safety standards. Depth of discharge resembles the discharge rate of the energy source, and lithium batteries have drawn great attention recently. Even though charge cycles (from 0 to 50% charging is considered a half cycle) remain an important parameter for the cells indicating durability and expected lifespan by manufacturers, nonlinear discharging plays a significant role in the battery life and has to be handled properly. There are the following three main types of charging methods [9,29]:

- Battery exchange;
- Conductive charging;

- Wireless power transfer (WPT).

Battery exchange is, without a doubt, the easiest and less time-consuming method. At specific stations, EV owners can swap their discharged or aged battery for a new or a used unit, in excellent condition for a specified fee, within minutes. At the same time, these stations use renewable energy sources, as well as the batteries stored for exchange to provide additional power to the grid when needed. However, not all batteries are standardized, and certain manufacturers build their battery packs inside the vehicle chassis for better weight distribution, making swapping practically impossible [9]. In addition, the rental fees charged to the EV user are still high, so this tactic seems unfeasible, whereas the time needed to inherit this method requires strategic decisions due to the number of requirements it has to meet to be fully implemented and safe to use.

Conductive charging is the most common and applied method currently available. It simply requires a normal connector plugged into a domestic socket for slow charging or an EV park for rapid charging. The majority of charging sessions include this pattern as it is the easiest, and most typical process, so it has become standardized in the following different components: connectors, plugs and charging speeds. Despite the previous aspects, its main advantages include voltage and current regulation, utilization of renewables and reliability and simplicity. However, due to fast charging associated with highly discharged cells, battery aging can be severe, while the energy absorption can cause grid overload and power delivery discontinuities.

Wireless power transfer or inductive charging substitutes the usual direct cable connection with a wireless one. Therefore, there is no need to plug in any connectors or stop at a charging station. Any EV can be charged wirelessly (typically 20 cm to 1 m gap) while in motion via a standard two inductors coupling, an external one transmitting power to the receiver located inside the car. The components applied must be constantly monitored for overcharging, overvoltage and temperature regulation to avoid unsafe conditions. The difficulties to establish this method are still a burden, although research has taken a leap forward as range, which is regarded as the most important factor impeding electric vehicle adoption, is no longer considered restrictive, assuming installation at motorways. Although this approach seems ideal, the power transfer is weak, with losses through eddy currents, in addition to the communication delay of the controllers. All three methods are shown in Figure 12 below.

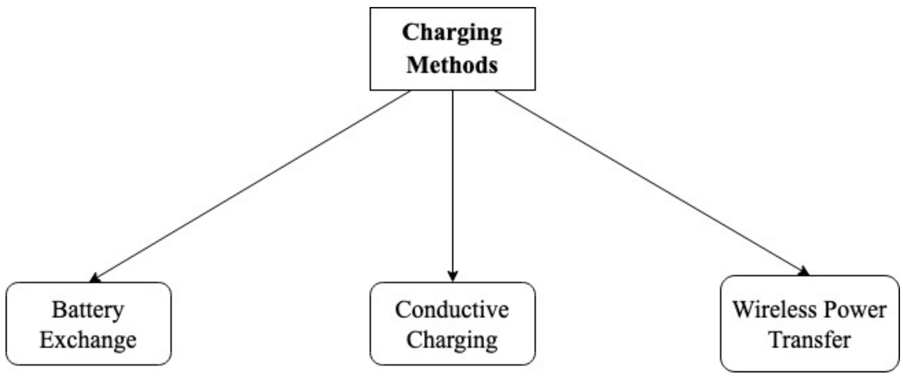


Figure 12. The three charging methods currently available for electric vehicles.

Regarding the utilization of the hybrid energy storage system, battery swapping is feasible as the system is compact and installed as a single module [99]. No additional space is required, so swapping can take place in the same way as a typical battery array, although the disadvantages cannot be overcome at present. Conductive charging meets the same requirements for the hybrid system with respect to capacity and voltage regulation of the units. The ultracapacitors can be charged at maximum capacity to power the vehicle during acceleration after stopping. The WPT is the ideal choice for the layout as it is easy, and both energy sources (battery and ultracapacitors) are protected via the DC link from overcharging [100]. Therefore, maximum efficiency can be achieved as the ultracapacitor array is constantly charged even if the low power output of this charging method is considered, seemingly supporting the battery pack on the propulsion of the vehicle.

Discrete energy management strategies can be applied to monitor and control the hybrid energy storage system in order to ensure the protection and maximum performance [96]. Obviously, from the literature, it is evident that the fuzzy logic controller, rule-based approach and dynamic programming are the most preferable strategies based on real-time optimization. By implementing a sophisticated energy management system that monitors, calculates and configures the power split ratio of the hybrid energy system through machine learning, maximum efficiency and range are validated, although the trade-off for complexity has been thoroughly investigated [101]. A highly adaptive and fast approach would be costly, complex and hardware-intensive, while a simple energy strategy may lack the ability to control and protect the two individual energy sources.

Therefore, it is crucial to inspect the ideal motor technology, which when coupled with the hybrid system, will provide the best efficiency and driving comfort. Brushed DC is not applied at any newer EV, so it will not be incorporated in this comparison. Flux reversal is also still a new technology, not implemented at EVs, so at present, it is skipped.

The chosen criteria were designated from the literature [98,102–109]. They have considered the top features an EV motor must inherent. The hybrid system is compatible with about the same motor characteristics as a battery EV. Specifically, the list includes the following:

1. Torque ripple;
2. Noise level;
3. Efficiency;
4. Cost;
5. Size;
6. Reliability;
7. Fault tolerance;
8. Overload capacity;
9. Power density;
10. Wide speed range;
11. Control simplicity.

The score is scaled between 1 and 5 from worst to best for easier validation and understanding of each parameter. The scale of this approach is solely driven by the literature studies, with only a small correspondence from qualitative to quantitative parameters at certain values, such as torque ripple, so the outcome is unified and presentable. Specifically, the scaling includes the following:

1. Very low grading corresponds to score equal to 1;
2. Low grading equals to score 2;
3. Moderate scoring accounts to score 3;
4. High classification matches to score 4 and finally;
5. Very high or ultimate evaluation to score 5.

Quantitative values offer an easier and more precise representation of the capabilities of each motor under normal or dynamic conditions (peak load, acceleration, regenerative braking), taking into consideration a graphical description. Moreover, the research preceded has evaluated the various and discrete states that a drive system must cover based on the demanded load and power from the battery pack. Since the characteristics and technology of the motor are standardized while being irrelevant to the power source, the HESS will supply the required energy that matches the needs of the drive system, and therefore this concept is only the subject of this study. Finally, the motor with the highest score, in the end, will be declared most suitable for EVs powered by HESS.

Torque ripple, or fluctuation as the motor spins, is a very important aspect. Consistency is needed at the entire speed range and especially at high loads, so the torque output of the motor has to be consistent. Noise level is also important, as well as efficiency, although ultracapacitors have a positive impact on total power output. Figure 13 declares the permanent magnet motor as the winner for these three parameters as it is quiet, with low torque ripple and high efficiency.

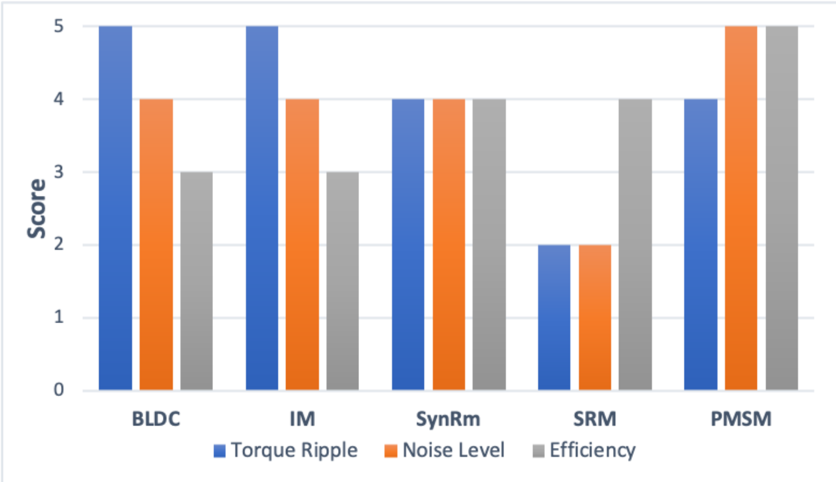


Figure 13. Comparison of efficiency, noise and torque ripple factors for the 5 researched motors score.

Cost and size are important for the violability of the project, as the end price and robust construction have significant value. Motors must be compact for easy installation at any electric vehicle, with reduced cost, to limit the average price of the car. Powertrains with high value, in comparison to the average price, achieve the lowest score in the scaling pattern price. Accordingly, heavy motors score poorly, while lightweight units reach maximum points for the size factor. Switched Reluctance Motor, for example, has a medium performance on both criteria. Results for both parameters are presented in Figure 14.

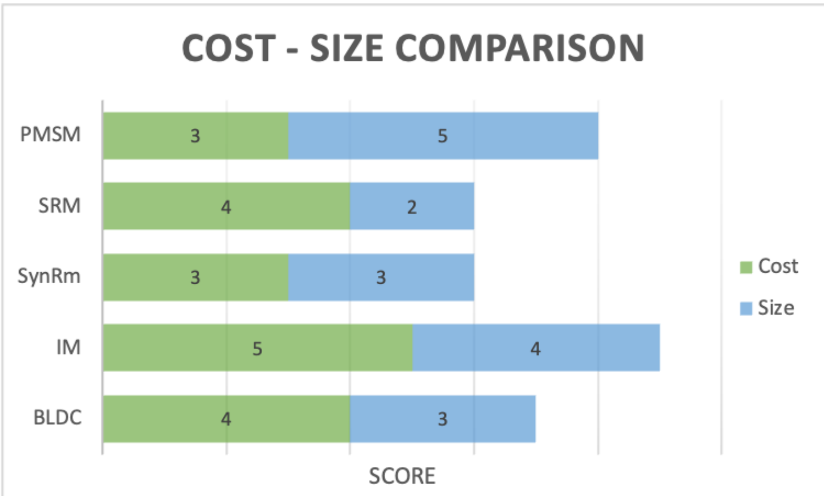


Figure 14. Direct comparison regarding cost and size parameters scoring of different motors.

The next three criteria are substantial to the implementation and compliance of the two distinct systems. Ultracapacitors have a great power density and complete deployment of regenerative power, so the powertrain should be able to handle that power without overloading or the possibility of breakdown. Moreover, it is imminent that any fault occurred to the storage system or the electronics will not damage the motor as well, causing an overall failure. All the following three values are equivalently scaled: Motors with high overload capacity, fault tolerance and reliability score the maximum points. For example, the Induction motor is very reliable and can handle very high currents from the ultracapacitors, but it may fail at common faults, as depicted in Figure 15.

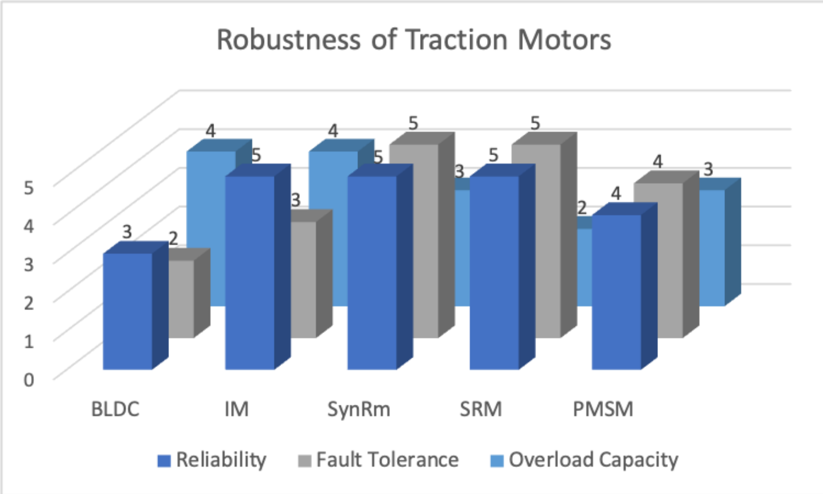


Figure 15. Reliability, stress tolerance and overload capacity scoring for the five selected powertrains.

Accordingly, motors must have a wide speed range and extensive power density to fully harness the available power of the ultracapacitors while promptly charging them via coasting for future use. Lastly, power electronics technology has evolved, managing perfect control over the operation of traction, but the exceedance of specific boundaries will disoblige the merge with the hybridized storage. It is evident from Figure 16 that the brushless motor is very easy to control; thus, it scores five on control simplicity, but it lacks high power density and speed range.

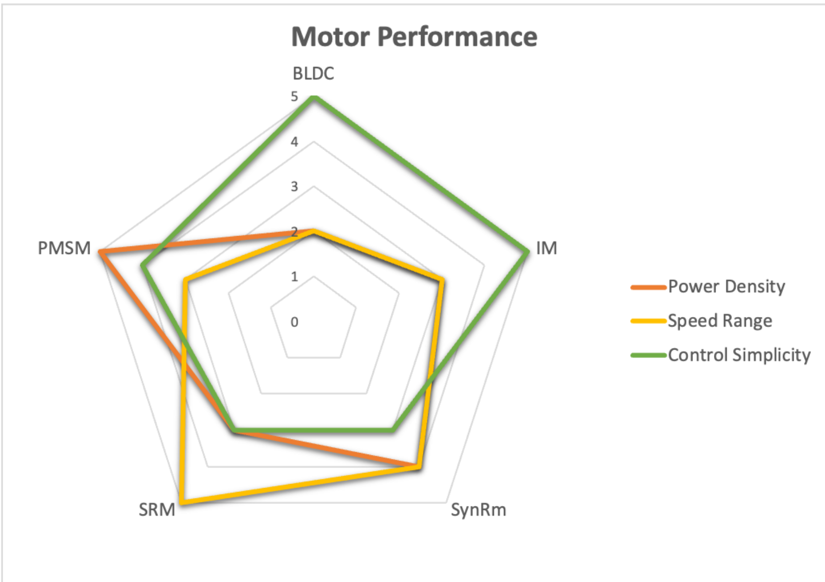


Figure 16. Performance analysis of studied motors based on speed, power and control.

All the selected factors studies, along with the received scoring gathered and processed by research previously mentioned are gathered in Table 8 below.

Table 8. Criteria for motor technologies compatibility with hybrid energy storage based on the literature [37,38,97–109].

Criteria	BLDC	IM	SynRm	SRM	PMSM
Torque ripple	5	5	4	2	4
Noise level	4	4	4	2	5
Efficiency	3	3	4	4	5
Cost	4	5	3	4	3
Size	3	4	3	2	5
Reliability	3	5	5	5	4
Fault tolerance	2	3	5	5	4
Overload capacity	3	4	3	2	3
Power density	2	3	4	3	5
Speed range	2	3	4	5	3
Control simplicity	5	5	3	3	4

4. Discussion

According to Table 5 in the previous chapter, structured from the literature-gathered data, some important and interesting results are visible. The brushless DC motor has low noise, cost and torque ripple while embracing a simple structure. On the other side, it suffers in the performance and reliability of chapters. The induction motor, widely applicable, achieves a great overall score, 2nd behind the Permanent Magnet motor, due to moderate sizing, efficiency at high speeds and power density [110]. The Synchronous Reluctance powertrain is 3rd on the score list as cost, sizing and control simplicity still has a major impact on its implementation, although Tesla overcame these challenges with complex and expensive power electronics.

Switched Reluctance motor is great on reliability and important aspects such as cost, efficiency and speed range but lacks in many factors such as size and noise. Lastly, the adoption of PMS traction is evident as follows: excellent efficiency, performance and size as well as power density without high complex electronics, at least like SynRm, but cost and speed range remain moderate. The final results show the typical order as an average approach, shown in Figure 17.

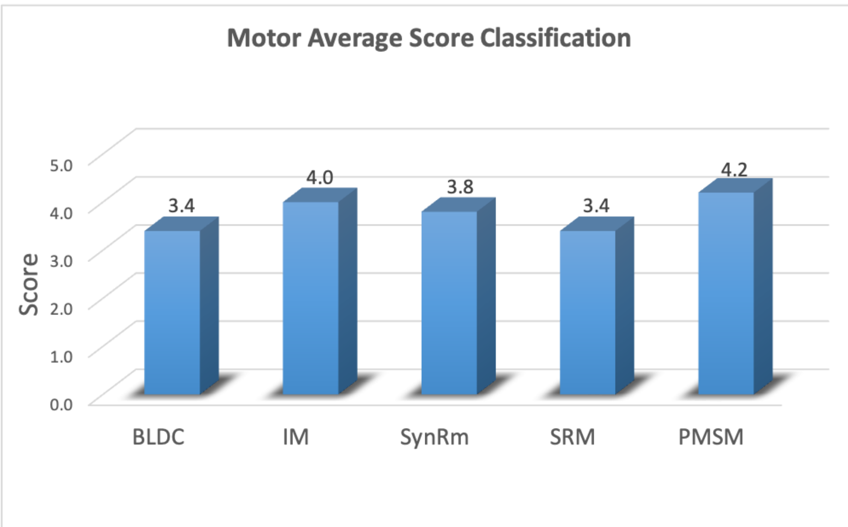


Figure 17. Classification and average score of different motors.

However, the selected criteria currently under consideration do not have the same impact on the cooperation with HESS as a power supply. Noise and other factors are valuable but do not directly affect the implementation. The five most important criteria for the performance of the selected motor, in accordance with the hybrid system, are the following: (i) torque ripple, (ii) reliability, (iii) overload capacity, (iv) power density and (v) speed range [76]. Hence the previous figure is transformed into Figure 18 below.

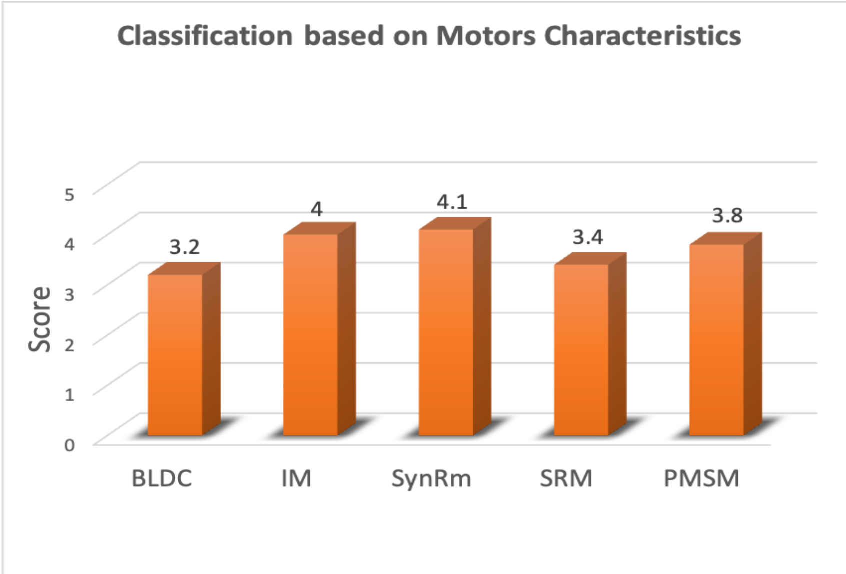


Figure 18. New classification according to the five-criteria rule for motor characteristics based on hybrid energy storage parameters.

The new five-criteria rule classification justified the transition that manufacturers such as Tesla and Toyota carried out and switched to synchronous reluctance powertrains. Regarding motor performance, plus the necessity to cover and exploit the high-power density of the ultracapacitors while protecting the battery, SynRm is the way to go. Induction motor is second on the list, but low efficiency at high speeds practically forbids possible application. PM motor comes next on the list, but the adoption of this motor technology requires precise control. Overload capacity is a must for hybrid energy EVs, as ultracapacitors deliver great power in a very short time. It is safe to say that both SynRM and PMSM are the most capable motors to handle and cooperate with HESS, but sizing has to be taken into consideration.

5. Conclusions

Motor technologies are crucial to the operation of EVs. The choice of motor technology is a significant factor in the performance, efficiency and cost of an EV. This paper presents a review of different commercially available motor technologies for EVs. Motor technologies studied include direct current, induction, synchronous reluctance, switched reluctance, permanent magnet and flux reversal motors. Various characteristics were examined in order to decide which motor is ideal for utilization with a hybrid energy storage system consisting of batteries and ultracapacitors. Eleven criteria were selected to evaluate the different aspects of the powertrains. The criteria were the torque ripple, noise level, efficiency, cost, size, reliability, fault tolerance, overload capacity, power density, wide speed range and control simplicity. The results and comparison show that PMSM and IM are the most complete choices, with all criteria being anticipated, such as sizing, cost and noise of the electric motors. Afterward, a five-criteria rule that only addresses the critical aspects involving cooperation with HESS was applied. The conclusion is that SynRM and PMSM are the perfect candidates for this merge of the hybrid energy system and an electric motor. This result reveals the current trend that major manufacturers have accepted. Each manufacturer focuses on synchronous reluctance and permanent magnet motors for battery electric as well as hybrid-powered automobiles. Future work includes motor comparison based on EV dynamic conditions through real-time testing. Finally, the examination of the effect of load and output torque variations on motor performance and efficiency is the next goal for research on the motor response at EVs.

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Abbreviations

BEV	Battery Electric Vehicles
BLDC	DC Brushless Motor
CVT	Constant Variable Transmission
EDLC	Electric Double Layer Capacitors
EVs	Electric Vehicles
EST	Energy Storage Technologies
HESS	Hybrid Energy Storage System
ICE	Internal Combustion Engines
IM	Induction Motor
PMSM	Permanent Magnet Motor
SRM	Switched Reluctance Motor
SynRM	Synchronous Reluctance Motor

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