A Review on Electric Vehicle Powertrain System Components and the Challenges Involved in their Large-Scale Introduction

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Abstract: The human race has reached pinnacle of technological achievements, advanced transportation technology being one of its major accomplishments, but in the process, has somewhat ignored its repercussions on the environment. This has led to the problem of Global Warming, which is affecting the world as a whole. Moreover, the diminishing fossil fuel reserves are pushing the world towards an energy crisis. Therefore, there is a growing interest in developing enhanced propulsion systems for electric and hybrid electric vehicles as transportation sector not only plays a major role in global warming due to emission of Greenhouse Gases (GHG) from the vehicles, but also has large dependency on petroleum products. Hence, this sector is expected to be affected the most if alternative power sources are not found. But, the path towards greener and more efficient transportation systems of the future is not straightforward and has lot of challenges to be faced. This paper will discuss briefly about the basic components of any Electric Vehicle (EV) Powertrain System and the research done on them. It will also point out fields where research is required to be done to fulfil the consumer's requirements, such that EVs of the future can successfully replace their IC Engine counterparts and become more consumer friendly.

Keywords: Electric Vehicles, Traction Motors, Power Electronics, Batteries.

Introduction:

Global Warming has become a major concern for the whole world today as level of pollution is increasing day by day. It is evident from Fig1 that the level of Carbon-dioxide has kept on increasing incessantly since the industrial age due to the consumption of various fossil fuels in several sectors. However, it is observed that, in recent times, ICE vehicles are the main contributor of urban pollution. "According to figures released by the U.S. Environmental Protection Agency (EPA), conventional ICE vehicles currently contribute 40%–50% of ozone, 80%–90% of carbon monoxide, and 50%–60% of air toxins found in urban areas" [1], and not just urban but even if we consider the overall GHG emissions, its contribution is of about 23% of the total. [2]

This has resulted the world to look for alternative means to power the present transportation sector which not only reduces the environmental degradation caused by it, but also reduces its dependency on oil reserves which are estimated to be extinct in about 48 years at current rate of consumption [3].

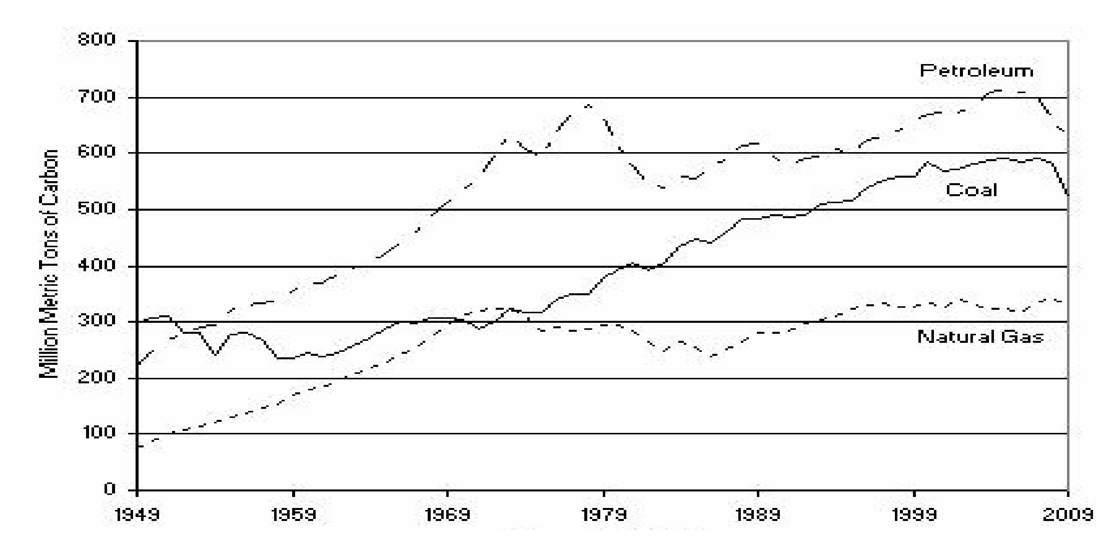

Fig1: Carbon-dioxide emission [29]

Electric vehicles are being seen as a hope and a viable solution in this direction as they have zero tail pipe emissions, which has resulted in extensive research in this field.

This paper has been divided into two sections, in the first section basic information about the main EV powertrain system components has been discussed and in the second section, research work and observations done on these components as well as the problems faced by the industry in meeting customer demands, have been reviewed.

The aim is to enable researchers understand the current trends and help them select the domain for their research.

SECTION – 1 : BASIC POWERTRAIN SYSTEM COMPONENTS

TRACTION MOTORS

Selecting an appropriate traction motor plays a critical role in designing the various systems of an Electric Vehicle (EV) or Hybrid Electric Vehicle (HEV). There are total four types of motors that are used in electric vehicles, namely:

1. DC Motors
2. Three Phase AC Induction Motors
3. Permanent Magnet Synchronous Motor (PMSM)
4. Switched Reluctance Motors (SRM)

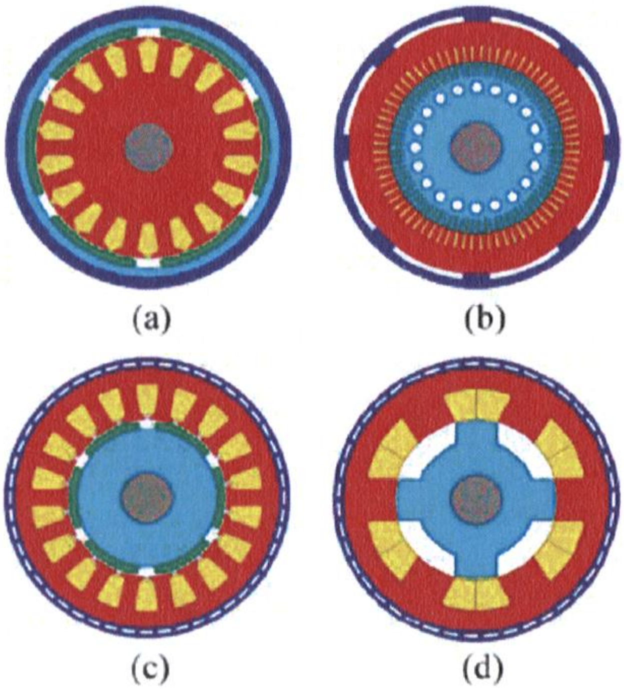

Fig 2: Different electric motors for use in traction motors: (a)- DC Motor, (b)- Induction Motor, (c)- Permanent Magnet Brushless Motor and (d)Switched Reluctance Motor. [20]

- ***DC Motors:***

DC motors were the most widely used traction motors in the 1900s. It has various advantages such as High Starting Torque capability. Speed control can also be done quite easily and also is capable to withstand a sudden increase in load. All these benefits make it a suitable choice as a traction motor.

However, this motor has high maintenance cost due to the brushes and commutators which also make it heavy and less reliable for high speed modern EVs. Hence, they are only used in low-speed vehicles such as carts for logistic movement in factories, etc. [4]

- ***Induction Motors:***

Squirrel cage Induction motors are one of the most widely used traction motors in EVs. The characteristics that make it so desirable are as follows:

- Simple yet robust structure
- Affordable price
- Less noisy
- Less requirement of maintenance

They can be made to run over 15000 rpm with a wide constant power range. The main characteristics of induction motor are shown in fig 3.

However, one of its major drawbacks is the requirement of a complex control circuit and its low efficiency compared to PMSMs (Permanent Magnet Synchronous Motors) due to the presence of rotor windings.

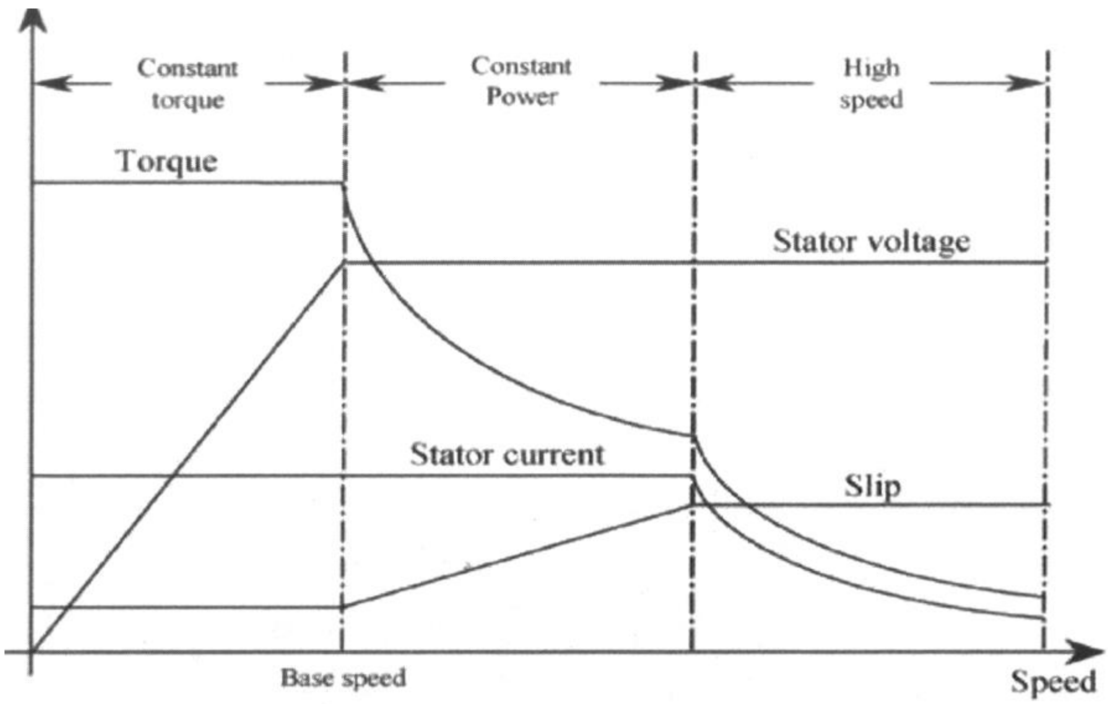

Fig 3: Different characteristics of induction motors [20]

- ***Permanent Magnet Synchronous Motor (PMSM):***

PMSMs provide a tough competition to Induction Motors. Its stator unit is similar to that of IMs with three phase windings, but the excitation windings are replaced by Permanent Magnets (PMs). They are divided into two types according to the placement of PMs, namely, Surface Mounted PMMS (SPM) and Interior Embedded type (IPM). Some of its major features include:

- High Reluctance Torque
- High Efficiency
- High Power Factor
- Simple Assembly
- Compact Size
- Lower Heating
- Low Winding Losses and Noise

However, one of its major short coming is that it can be demagnetized due to heating or armature reaction. They also have a low constant power region as shown in the Fig 4.

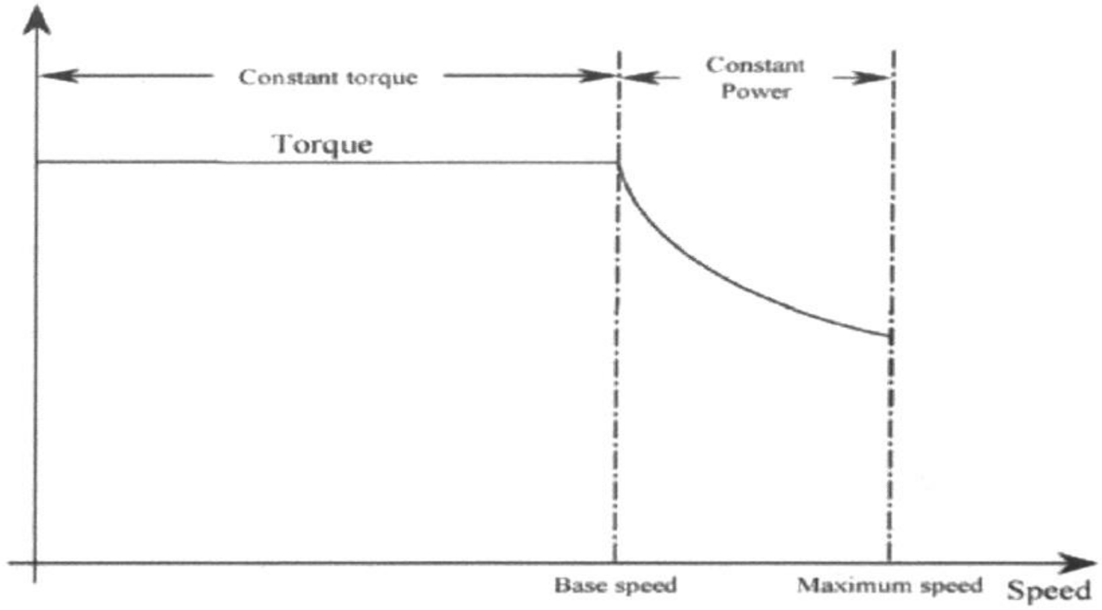

Fig 3: Torque-Speed Characteristic of PMSM [20]

Switched Reluctance Motor (SRM):

SRMs are gaining a lot attention nowadays for EV applications. A few advantages of the motor are:

- Simple yet robust structure
- Fault tolerance
- Wide constant power region (Fig 4)

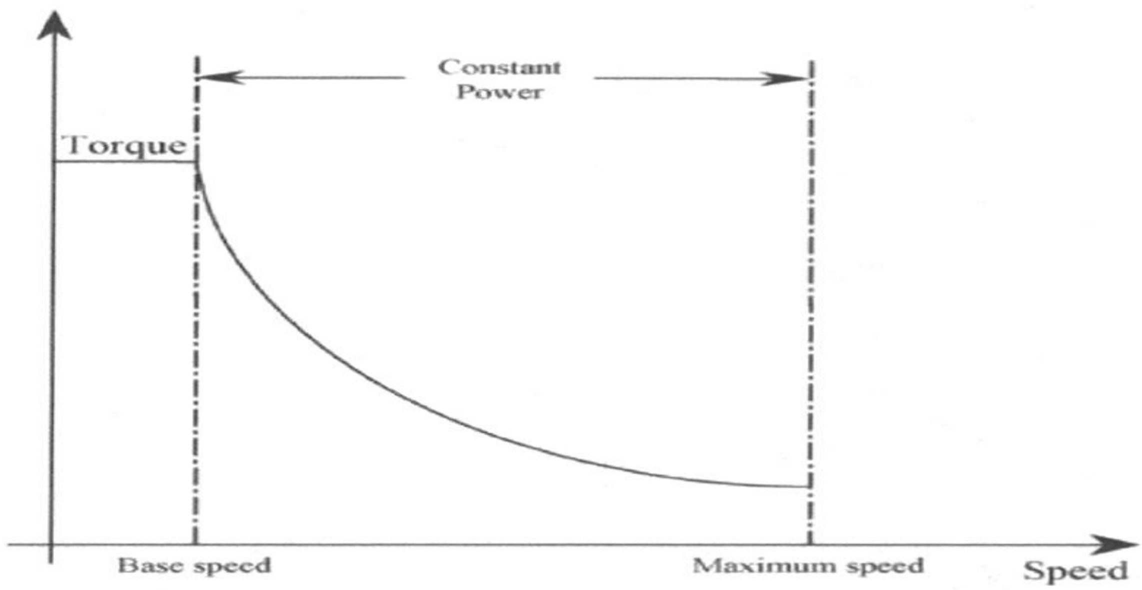

Fig 4: Torque-Speed characteristics of SRMs [20]

Several disadvantages of this motor include:

- High noise
- High torque ripple
- High vibration

ENERGY STORAGE DEVICES

Batteries are the common energy storage devices used in EVs. They are a collection of electrochemical cells with external connections [5] which are used to store electrical energy in the chemical form and release it back when demanded. When a battery is discharged, high-energy reactants are converted to low energy products as a result of a redox reaction, and the free energy difference is delivered as electrical energy to the external circuit. [6]

They can be broadly classified in two categories, namely:

1. "**Primary batteries** are the those which can be used only once and then have to be discarded. There chemical reactions are not reversible, making them non-rechargeable. When the supply of reactants is exhausted, the battery stops producing current and becomes useless." [7]

2. "**Secondary Batteries** have the potential to be recharged, that is, they can have their chemical reactions reversed by applying electric current to the cell. This regenerates the original chemical reaction making it capable to be reused multiple times." [8]

Common types of energy storage systems used in EVs: (from [9])

Following are the types of systems used in Hybrid Electric Vehicles (HEVs), Parallel Hybrid Electric Vehicle (PHEVs), and Electric Vehicles (EVs) to store energy.

1. **Lithium-Ion Batteries (Li-ion)**

These batteries are widely used in consumer electronics such as mobile phones, laptops, etc., due to their high energy to unit mass ratio compared to other types. Other advantages include:

- High power-to-weight ratio
- High energy efficiency
- Better high temperature performance
- Low self-discharge

However, a lot of R&D is going on to make them more cost effective, extend their useful life and increasing safety in regard to overheating

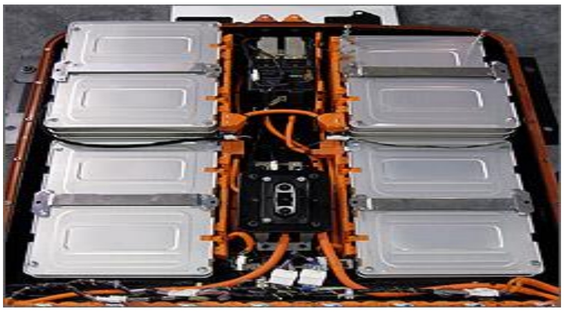

Fig 5: A typical example of LI-ion batteries used in EVs

2. Nickel-Metal Hydride (Ni-MH)

These batteries are extensively used in HEVs as they have much longer life cycle compared to lead acid batteries and are also lighter and safe and abuse tolerant.

However, characteristics which inhibit its applications in EVs are:

- High cost
- High self-discharge
- Heat generation
- Control of hydrogen loss

3. Lead-Acid Batteries

These batteries have the potential to be designed for high power application and also are inexpensive, safe, and reliable.

However, but a few points that impede its use are:

- Low specific energy
- Poor cold-temperature performance
- Short calendar and cycle life

4. Ultracapacitors

"An ultracapacitors, also called supercapacitors are high-capacity capacitors, which can store 10 to 100 times more energy per unit volume or mass than electrolytic capacitors and can accepts and deliver charge faster than batteries. They can also endure more charge / discharge cycles compared to rechargeable batteries." [10]

They store energy in a polarized liquid between an electrode and an electrolyte. Energy storage capacity increases with increase in liquids surface area.

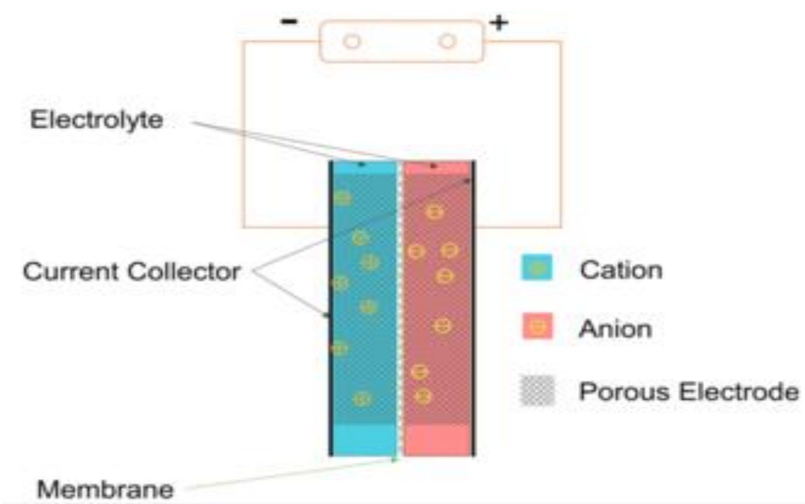

Fig 5: Schematic diagram of an ultracapacitor [30]

Technology	Cell Voltage Volts	Operating Temp. °C	Specific Energy Wh/kg (3Hr rating)	Energy Density Wh/l	Specific Power W/kg	Power Density W/l	Life Cycle [Years]	Cost $/kWh
NEAR TERM BATTERY								
Lead Acid	2.1	-35 to 70	35	80-90	125-230	230-600	500[3]-600[4]	70-130
Nickel Cadmium	1.25	-30 to 50	55	120	190	330	2000 [10]	400-500
MID TERM BATTERY								
USABC goals		*-30 to 65*	*80-100*	*135*	*150-200*	*250*	*600 [5]*	*< 150*
Nickel Metal Hydride	1.4	-20 to 60	65	175	150	400	600 [2]	
Sodium Sulfur	2.08	300 to 400	85	115	120	180	350 [2]	110
Sodium Nickel Chloride	2.59	250 to 350	130	170	168	225	1000 [5]	
LONG TERM BATTERY								
USABC goals		*-40 to 85*	*200*	*300*	*400*	*600*	*1000 [10]*	*<100*
Zinc Air	1.62	25 to 65	130	120	50	65	70	110
Lithium Iron Disulfide (Bipolar)	1.66	400-450	165	240	375	550	500 [2]	110
Lithium Polymer	2.8-4.5	0-100	160	260	200	210	300 [1]	110
Ultra capacitors			2-5		>200			
Fly Wheel			240*					

*Oak Ridge National Laboratory: *Technology Brief*

Fig 6: Present Energy Storage Technologies with their properties [25]

"Some of the emerging battery types that are being heavily researched are:

- Aluminium-air
- Lithium-air
- Sodium-air
- Zinc-air
- Liquid Metal
- Tin Nanocrystal Lithium-Ion" [11]

Recently, the Government of India has invested to develop an Israeli Aluminium-air Battery Technology as it is potentially cheaper, gives better range and are safer. This will also reduce India's dependency on Lithium which is scarcely available and exploit the large Bauxite reserves found in India, which make it the second-biggest smelter of Aluminium.

One of its major problems is that it cannot be recharged. But a solution to it could be to replace it with a new battery pack with a new one on recharging stations and send the old one for recycling. This swapping of batteries will take around 3 minutes, which is less than the time taken for refuelling at gas stations as said by S.S.V Ramakumar, Director of R&D at Indian Oil Corporation, which has collaborated with a start-up named Phinergy Ltd to develop this technology. [12]

POWER ELECTRONICS

The main function of power electronics in an electric vehicle is to process and control electrical energy from the energy storage device (batteries) by supplying voltage and current in a form that is required by the traction motor depending on the load on the vehicle.

Today's power electronic systems make use of silicon-based semiconductor. But, wide band gap (WBG) semiconductors prove to be more efficient and have better high temperature tolerance. Due to this the overall cost of the system decreases as it eliminated the need of complex thermal management systems. [13]

"Both the elements are digital in nature, except that one manipulates power in gigawatts and other only in milliwatts. Appropriate use this technology offers reduced size, cost advantages and high-level performance." [14]

The Power Electronic Components used in Electric Vehicles are: (from [13] and [15])

1. **Inverters:**
   An inverter is used to convert from DC current from the Energy Storage Devices to AC current to drive the traction motor. The inverter controls the speed of the motor by varying the frequency od AC current and the torque produced by controlling the amplitude of the current.

2. **DC/DC Converters:**
   They are used to change the voltage of Dc supply as per the need of the vehicle, if the traction motor like an IPM is used which requires higher voltage then, it will require a boost DC/DC converter. If the vehicle systems like infotainment, lights, etc., require low voltage then a buck DC/DC converter is used to convert the voltage od DC current to 12 V level.

3. **Controller:**
   It is like the brain of the electric vehicle. It controls the rate of charge entering and leaving the battery according to information received from it. It also senses the pressure on the accelerator pedal and adjust the speed of the motor with the help of the inverter. It is basically a inverter-converter combination, which also plays a crucial role in regenerative braking function in EVs which charges the battery during braking by converting the kinetic energy.

4. **On-board chargers:**
   These convert the AC power to DC in order charge the battery of the EV. They are based on high-frequency circuits fitted in the vehicle of in the fast charger provided with the vehicle. However, research is being done to develop a technology which will merge the entire charging unit with the power electronics of the vehicle and use inductance of the motor for charging. This will reduce the number of parts and also reduce the overall cost. It also consists of an Mattery management System (BMS) which controls the charge provided to the battery to overheating of cells.

LITERATURE REVIEW

A. **"A Survey on Electric Vehicle Powertrain Systems by Mustafa Karamuk"** [16] studies multiple features of Electric Vehicle Powertrain Systems. The conventional and electrical powertrain systems are compared to demonstrate the performance benefits of automotive application of electrical machines. Induction machine and interior permanent magnet synchronous machine being the most common electrical machine types, are compared. The electric version of FIAT New Doblo has been presented as a case study including the test results of on acceleration performance. Analytical and experimental analysis of Impact of vehicle weight on traction power demand has also been performed and presented. This work highlights the research and development fields for motor drives in electric vehicles while keeping cost reduction, efficiency and reliability issues in consideration.

B. **"Development of electric vehicle powertrain system: Experimental implementation and performance assessment by Young-IL Lee et al"** [17]
   presents an experimental evaluation of a complete EV system and then performance of each plant is verified and evaluated. The experimental drivetrain includes two permanent magnet synchronous motors (PMSMs), two converters with their gate drivers, the control board of TMS320F28335 DSP and an Energy Storage System (ESS) which includes battery cells, Battery Management System (BMS) and Ultracapacitor unit. A commercial dynamometer was used to demonstrate and evaluate the dynamic performance of the vehicle at both out-vehicle and in-vehicle operation. The appropriateness of EV in different road conditions were verified through this experimental test. It has

been found that the energy required by the EV has been successfully delivered by the used Battery Pack (BP). In this paper, an Ultracapacitor (UC) has been effectively unified to the BP in lab with preliminary results. Future work of this paper will be dedicated to enhance the efficiency of the hybrid UC/BP ESS.

C. **"Propulsion System Design of Electric and Hybrid Vehicles by Ehsani et al"** [18] focuses on developing system design philosophies of propulsion systems used in electric and hybrid electric vehicles. It studies the vehicles' dynamics to obtain an ideal torque-speed profile for electric propulsion system. It is revealed that if the powertrain is made to function in the constant power region for most of the time, then, the vehicles basic working requirements such as initial acceleration and grade can be fulfilled with minimum power rating. This importance of constant power region has been bolstered with the help of various examples. Various motors are also studied I the paper with a conclusion that induction motor is the most suitable for present EVs and HEVs. The methodology used in this paper can be used as a basis of the detailed design.

D. **"Overview of Permanent Magnet (PM) Brushless (BL) Drives for Electric and Hybrid Electric Vehicles by Chau et al"** [19]**,** focuses on machine topologies like Rotor-PM, Stator-PM, Hybrid-PM, Memory-PM, drive operations like BLAC and BLDC Operations and Constant-Power Operations, and control strategies such as Efficiency Optimising Control (EOC), Direct Torque Control (DTC), Artificial Intelligent Control (AIC), Position-Sensor less Control (PSC) to give a summary of PM BL drives for EVs and HEVs. Also, the PM BL drive systems such as the magnetic-geared outer-rotor system, integrated starter-generator system, and the electric variable-transmission (PM BL EVT) system have been discussed in detail by also providing their comparison. Finally, it is anticipated that PM BL EVT will be a major research topic in the field of HEVs.

E. **"Comparative Study of Using Different Electric Motors in the Electric Vehicles by Nasser et al"** [20] have compared different electric motors to observe the advantages and point out the best of all for EV application. Five major types of motor have been analysed, which are, DC, Induction, SRM, PMSM and BLDC. In this study it has been found that though induction motors are technologically more developed, BLDC and PMSM are more effective and better for EV application as they have high power to volume ratio and also reduce the pollution.

F. **"Comparative Study of Different Battery Types for Electric Vehicles by C. Iclodean et al"** [21] presents in this paper a study which compares the characteristics of different batteries with same energy storage efficiency by using it in an electric vehicle and running them on a driving cycle, in real time, digitized by computer simulation. The battery types analysed are Lithium Ion (Li-Ion), Molten Salt ($Na\text{-}NiCl_2$), Nickel Metal Hydride (Ni-MH) and Lithium Sulphur (Li-S). It has been proved that Li-S batteries can be the most optimum solution for systems requiring high energy storage capacity as they have highest energy consumption of about 17.2 kWh/100km along with low weight and price compared to other battery technologies. This paper also points out that Li-ion batteries do have a large demand in EV market due to their moderate energy consumption (14.7kWh/100km), decreasing cost, advanced manufacturing technology, increased life cycle, low weight and high energy storage consumption. However, high temperature functioning of these batteries is a major drawback which reduce its performance and lifespan posing threat to safe operation of the vehicle.

G. **"A New Battery / Ultracapacitor Hybrid Energy Storage System (HESS) for Electric, Hybrid, and Plug-In Hybrid Electric Vehicles by Emadi et al"** [22] uses a smaller dc/dc converter compared to the conventional HESS systems. The main purpose of it is to maintain voltage value of ultracapacitor above that of the battery for majority of city driving conditions. As soon as its value drops, the remaining power is provided by the battery, which results in in a constant load profile of the battery. Moreover, battery is not used to store energy generated through regenerative braking resulting in prevention of frequent charges thereby increasing the battery life. In future, the prime focus of this paper will be to increase the efficiency of the system in high voltage conditions and, sizing of the dc/dc converter compared to the UC will be dealt with to make the system more economical without compromising its benefits. It has been proved that the composed system is electrically feasible.

H. **"Modelling, design and control of a light electric vehicle (LEV) with hybrid energy storage system (HESS) for Indian driving cycle by Vidya and Balaji"** [23] describes a HESS for a three wheeled LEV which consists a combination of Li-ion battery (primary energy source) and Ultracapacitors (auxiliary energy source), interfaced via a bi-directional converter. For determining the size of the HESS, power required during various operating modes such as constant speed operation, acceleration mode, road gradient and deceleration or braking mode have been considered. An improved power split strategy has been discussed for effective utilisation of HESS and compared with conventional methods. This has improved the life span of the battery by reducing the RMS (Root Mean Squared) current by efficient incorporation of the UC. The superiority of the proposed HESS compared to BESS has been tabulated with various parameters.

I. **“Energy storage system using battery and ultracapacitor on mobile charging station for electric vehicle by Tinton Dwi Atmaja and Amin”** [24]shows that Lithium-Iron phosphate (LiFePO4) is the best suited battery and electric double-layer capacitor (EDLC) is the most appropriate capacitor for MCS (Mobile Charging Station) application. The grouping of battery and ultracapacitor provide current and voltage respond which is fit for fast and ultrafast charging application. The paper additionally provides an ESS to enable installation of battery and ultracapacitor in MCS truck utilizing the rear compartment, side panels, and dash board. It is assumed that this unit can facilitate smarter transportation system that supports future electricity distribution system.

J. **“Power Electronics in Electric Vehicles: Challenges and Opportunities by Xingyi Xu et al”** [25] highlights the customers’ concerns and expectations from an EV. According to this paper, Safety, Reliability, Performance, Cost and Maintainability and Serviceability are some of the major outlooks of customers. It concludes that battery development is the most challenging task. Some challenges related to power electronics are also mentioned in the paper, Other major issue responsible for lower customer acceptance pointed out in this paper is the lack of infrastructure supporting electric vehicles.

K. **“An Overview of Electric Vehicles - Challenges and Opportunities by C. C. Chan and K.T. Chau”** [26] have discussed in this paper the challenges for EV propulsion, battery charging and power accessories from power electronics point of view. It has been explained that EVs have a multidisciplinary nature, hence the process of identifying the preferred features and packaging options for system integration should be done at system level as the interaction between these sub-systems affect the overall performance, cost and safety of the EV. Finally, it has been concluded that power electronics has a major role to play for the development of EVs and expansion of its market.

L. **“Power Electronics Intensive Solutions for Advanced Electric, Hybrid Electric, and Fuel Cell Vehicular Power Systems by Emadi et al”** [27] focuses on power electronics intensive power system architectures for various drive train topologies such as Battery EV, Series HEV, Parallel HEV, Series-Parallel HEV, and FCV. It then also discusses particular application of dc/dc and dc/ac converters in automotive power systems. It is shown in the paper that power electronics has high application potential in HEVs and FCVs. Bidirectional dc/dc converters are suggested to be employed in existing 12-V batteries in a typical HEV power system.

CONCLUSIONS

Environmental concerns and rapidly depleting oil reserves have compelled the world to look for better and cleaner means of transportation. This has led to a lot of research and development in the field of EVs as they seem to be the hope for the future of automobile sector. IC engine vehicles are considered as far superior to electric vehicle in terms of the performance they provide. However, the technological advancements in the field of EVs by various business giants like Tesla in the past decade have proved that more efficient and high performance delivering electric vehicles can be manufactured. The recent example for this is the Tesla Model S Plaid, which has become the first production car to break the 2 second barrier, that is, to achieve 0 – 60 mph in less than 2 seconds, something which none of its IC engine counterparts have ever achieved. It also has a top speed of 200 mph and a decent range of 396 miles [28]. Hence, it is very clear that performance is no longer an issue with electric cars.

The challenge now is to provide such characteristics at a cost that is affordable for the common people so that large scale introduction of the EVs can be done.

In this paper, details of the basic components used in EVs and research done on them have been discussed and reviewed.

It can be concluded that in order to make the dream of affordable EVs for all a reality, more research is required in the field of power electronics and hence is an attractive field for researchers. Also, various other ESS topologies need to be explored in such a way that we find solutions to reduce the dependence on natural materials for the batteries in the future. A HESS of battery integrated with ultracapacitors seems to be a good option as it reduces the size of the battery required and also increases its life by reducing the number of charge/discharge cycles especially during regenerative braking. However, for this an efficient power split strategy is required to be developed so that it can also be utilised in high voltage automobile application.

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