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A review on role of power electronics in electric vehicles: state-of-the-art and future trends

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In the current world scenario of increasing environmental issues and oil prices, development of Electric Vehicles (EV) have gained considerable importance and attention. Electrifying the conventional transportation system can reduce the use of depleting fossil fuels and can lead to better performance and reduced pollution. Power electronics will play a key role in making highly efficient electric vehicles which are low in emissions and having better fuel economy. This paper presents a review of the state-of-the-art power electronics technology in electric vehicles in detail focusing both semi-conductor devices as well as material technology. Also it discusses about the various power electronics systems placed in an electric vehicle. The paper concludes with a discussion of expected future trends in power electronics technology that will improve the markets for electric vehicles in coming years.

Keywords: *Power electronics, electric vehicles, semi conductor materials, wide band gap semiconductors*

1.0 INTRODUCTION

During the starting few decades of the 19^{th} century, electric vehicles were equally dominant as the conventional Internal Combustion Engine (ICE) vehicles. As years passed the popularity of electric vehicles (EVs) have reduced drastically due to various reasons which includes better research and development in the field of ICE vehicles, identification and exploration of new oil mines which reduced oil prices, better performance of ICE vehicles, premature technologies in EVs etc. By the 1970's the EVs again gained interest due to numerous reasons including the environmental damage created by ICE engines, a gradual decrease of fossil fuels which thereby led to hike in oil prices, an increased number of vehicles on road which led to massive pollution of air, water, etc. Also stringent rules implemented by various countries on pollution mandated the use of EVs. Studies on the environmental effects of Conventional Vehicles (CVs) called for an alternative technology which boosted the research in much cleaner vehicle technology, i.e., EVs. The need of electric vehicles has been explicitly discussed in literature [1]–[3] along with its developmental evolution over the years [4].

The role of power electronics in future energy engineering is highly influential [5][6]. Electronics were always a part of automotive system over years in areas like entertainment, safety, sensors for smooth operation, battery charging etc. However, the use of electronics in power trains for better engine propulsion and their control has gained sufficient attention recently. It was seen that replacing the conventional mechanical and hydraulic systems with electric systems in an EV has highly improved efficiency. This has invited considerable exploration about the role of power

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electronics in electric vehicles. A brief look on the areas where power electronics semiconductor devices have been extensively used in an EV are discussed below.

Electric propulsion: The Electric supply from the source (Batteries, Ultra capacitors, Fuel Cells etc.) is transferred to the wheel through various stages of power conversions and vice versa. Power electronics components play an important role in this part which is often considered as the heart of EVs. Electric propulsion can be further break down into the following parts:

- Electric Source (Batteries, Ultra capacitors, Fuel Cells etc.)
- Power Converter (DC-DC converters, Inverters etc.)
- Motor and Transmission (DC motor, Induction Motor etc.)

Energy Management: Effective energy utilization is as important as energy generation in electric vehicle perspective. An efficient and adequate energy management technique has to be incorporated in an EV to enhance its performance. Apparently numerous power conversions happen internally in an EV architecture which calls for sophisticated control that yields in a better performance and efficiency of an EV. An excellent advantage of EVs are regenerative braking where the kinetic energy while braking is not wasted in the form of heat, as in case of conventional vehicles and in fact it is effectively used to charge the battery bank in EV. Also control of energy usage by various vehicle subsystems according to different drive cycles and the proper selection of battery charging technique will greatly contribute towards energy saving. This will lead to improved performance along with cost competency.

It is absolutely clear that an EV without a power electronics` component in it is unimaginable presently. This paper is intended to discuss about the role of power electronics in various parts of EVs like electric propulsion and its energy management system. A brief discussion about various power electronic converters, topologies and their controls in an EV is carried out in future sections. The power electronic switching devices employed in an electric vehicle along with the available semiconductor materials for their fabrication are briefly discussed. The paper concludes with the recent technological advancements and the future trends in EVs.

2.0 POWER ELECTRONICS IN EV'S

The role of power electronics in EVs basically depends on the type of EV. An electric vehicle can be broadly classified into four types as shown in Figure 1 and are discussed exclusively in literature [7]–[11].

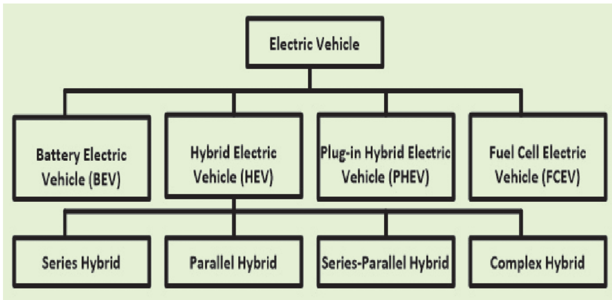

FIG. 1 BROAD CLASSIFICATION OF ELECTRIC VEHICLE

A hybrid electric vehicle may incorporate more complex control than a battery EV. Again a multi-input (Like Battery-Ultra capacitor hybrid source) electric vehicle will increase the complexity of control and the number of components used in it. But the core power electronic components used in any type of electric vehicle are more or less the same which comprises of a bidirectional/ unidirectional (or both) DC-DC converter and a DC-AC converter (Inverter) which only differs in their ratings, but strictly adheres to their functions. A standard classification of power electronics systems in an EV is shown in Figure 2 [11].

The applications of power electronic and drive systems for vehicles, both current and future are discussed by Rahman *et al.* [12]. Particular attention is given to propulsion and power supply requirements. A brief description of the various power electronic devices and their uses in EVs along with simulation studies are carried out by Kumari *et al.* [13] and by Chan *et al.* [14]. The role of power electronics components in individual parts of an EV is discussed in detail below.

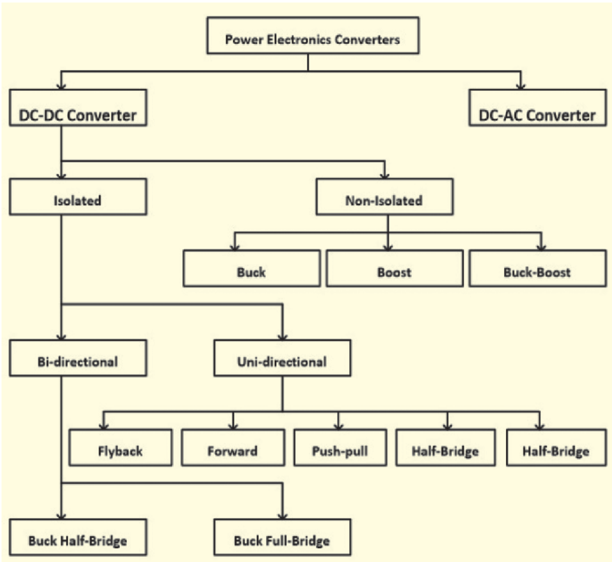

FIG. 2 STANDARD POWER ELECTRONICS CONVERTERS FOR ELECTRIC VEHICLES

2.1 Source (Batteries, Ultracapacitors, Fuel Cells etc.)

For a BEV, the source is a battery which provides the entire power to run the vehicle. A study on various types of batteries suitable for EV application is available in literature [1][4][7][15]–[18]. The source is not made of power electronic components and it generates electric power solely based on the electro-chemical (for batteries and fuel cells) and/or electrostatic (for ultra-capacitors) properties to propel the vehicle. Large amounts of energy can be stored in a battery, but is not suitable for supplying a large amount of power in a very short time. This is due to a low power output density. An ultra-capacitor has low storage capacity, but can supply a large burst of power [19].

The study on fuel cells and ultra-capacitors has identified that none of the sources (including battery) for a pure electric vehicle can stand alone and give the required performance according to various drive cycles [20]. This has led to the hybridization of sources with which an optimum performance can be obtained by having the best traits of all sources placed in the EV [21]–[24]. For eg., an UC and a battery when combined together can meet storage and peak current characteristics. This is achieved by connecting the two energy sources in a parallel arrangement [25][26].

2.1.1 Hybrid Energy Storage Systems in EV's

The challenge what most manufacturers face while deciding the source for EV are the unavailability of a high specific-energy and a high specific-power device which can meet all the performance requirements. Developing a Hybrid Energy Storage System (HESS) by combining two or more storage units and modules to realize the required energy and power characteristics would be the preferred choice for most of the EVs [24][27]. One of the main challenges in a HESS configuration is how to interface battery and ultra-capacitor units to the DC bus. Different converters such as Buck-Boost, Cuk, SEPIC, Half-Bridge, and Full-Bridge may be utilized as the interface in HESS for vehicular applications which are discussed in literature [28]–[31]. Various HESS topologies are also discussed [32] and found out that a partially-decoupled configuration with the ultra-capacitor unit directly connected to the DC bus and battery unit connected via a bidirectional DC-DC converter is one of the most promising interfacing topology in EV/HEV applications. A novel control strategy for Battery-Ultracapacitor Hybrid Energy Storage System were discussed by Garcia *et al* [33].

2.2 Power Converter (DC-DC converters, Inverters etc.)

Automotive electrical systems are complex in nature which includes different types of energy conversion. Requirement of power electronics are both On-Board (mounted in vehicle) and Off-Board (mounted outside vehicle, mostly in charging stations and power distribution networks) for an EV. Converters are also important in driving and controlling the electric motor which in turn drives the wheel. Basically an EV needs a DC-DC converter, DC-AC inverter, and AC-DC rectifier. The particular uses of power electronic converters in EVs are shown in Figure 3 and discussed below.

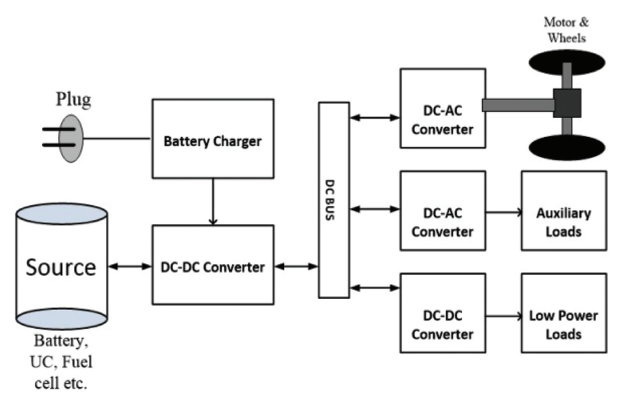

FIG. 3 ROLE OF POWER ELECTRONICS CONVERTERS IN EV APPLICATIONS

2.2.1 Bidirectional AC-DC converters

Power electronics converters certainly adds to the weight and volume of EV. So the selection of any converter and its topology should be done to minimize these traits without compromising in the performance of the vehicle. A bidirectional AC-DC converter is mainly used for charging purposes of Plug-in Hybrid Electric Vehicles (PHEVs) [4]. One method to reduce the number of switches and passive components is by integrating the on-board charger with the bidirectional DC-DC converter [34]–[36]. Dusmez *et al.* proposed a new interface for integration of On-board charger and DC-DC converter with reduced switches which offers better performance with comparison to existing charger topologies [37]. Different converter topologies for EV charger which covers types of bi-directional AC-DC and bidirectional DC-DC converters are available in literature [4][38] and shows that the combination of a front-end AC-DC converter and a back-end DC-DC converter is the most common charger configuration. The front-end AC-DC converter is normally an active rectifier.

2.2.2 Bidirectional DC-DC converters

A bi-directional DC-DC converter couples the AC-DC converter (from the On-board charger) to the energy storage unit (as a back-end DC-DC converter mentioned earlier) [4]. It converts the DC output voltage of the AC-DC converter into a suitable voltage to charge the batteries and to convert the battery power for transmission according to the system needs. Numerous topologies used for DC-DC converters are available in literature [39]–[43]. Full-bridge converters with high efficiency and wide output voltage range are a common choice for DC-DC converters [44]–[46]. Also, the presence of transformer gives isolation between input and output which is an added advantage. Another conventionally used converter topology is the Half-bridge type [47][48] which has a reduced switching losses. The Cuk converter and SEPIC converters are also in use recently.

Three different topologies of bidirectional DC-DC converters are discussed by Dylan *et al.* [38] namely the dual active bridge, the two quadrant (buck-boost), and a variation on the buck-boost converter. Karshenas *et al.* has carried out a detailed study on various non-isolated and isolated bidirectional DC-DC converters and their configurations for energy storage systems [49]. A comparative study of DC-DC converters in hybrid electric vehicles are carried out by Schupbach *et al.* and their design is also discussed [50]. A hybrid energy storage system based electric vehicle will further incorporate additional DC-DC converter and/or a complex control technique [42][51].

Three double input DC-DC converters has been proposed by Yalamanchili *et al.* which can be useful in full utilization of battery-ultracapacitor hybrid source for EVs [52][53]. Various types of DC-DC converters are discussed with the objective to determine their suitability for use in electric and hybrid vehicles by Iftikhar *et al.* [54] and identified that conventional and soft-switched PWM DC-DC converters look promising for electric and hybrid vehicle application. A review of high power isolated bidirectional DC-DC Converters for PHEV/EV DC Charging Infrastructure is carried out by Du *et al.* 2011 [43]. A review of non-isolated bidirectional DC-DC converters for Plug-in Hybrid Electric Vehicle is carried out by Du *et al.* 2010 [55] where several non-isolated bidirectional DC-DC Converters were discussed thoroughly and found out that Half-bridge converter is better than SEPIC/Luo converter for municipal packing deck charge station application.

2.2.3 DC-AC converters

A DC-AC converter, or generally known as an inverter is used in vehicles where the motors used for propulsion is fed with AC power. Inverters are used to convert the constant DC battery voltage to variable voltage variable frequency AC voltage which is used to run the electric traction motor. Also, it is used to supply other utility loads like vehicle lighting, air conditioning etc. Often a separate inverter set is used to serve this purpose. The AC drives are fed with inverters working in pulse width modulation (PWM) generally [7]. The most common automotive drives include Voltage Source Inverter (VSI). Typically, a three-phase VSI consists of six bidirectional switches, each with an IGBT or MOSFET switch (depending on the system rating) and an anti-parallel diode. By controlling these switches, and also employing proper filters, the DC voltage at the input of the inverter is shaped into a balanced three-phase AC output voltage of desired magnitude and frequency.

Gallagher *et al.* [56] has carried out an exclusive study on the design considerations of inverters in EVs which covered switch selection, circuit design and loss calculation. In addition to the conventional PWM inverters, resonant DC link inverters, with a series or parallel resonant circuits, are being used for battery-fed applications in EVs. A classical review on the evolution of various inverter topologies was carried out by Stemmler *et al.* [57]. Hoek *et al.* [58] discusses two topologies for traction inverter, namely the B6C and H-bridge topology. Jahns *et al.* has carried out a detailed study on the rail and road electric vehicles [59]. A new inverter technology for electric vehicles was proposed by Nakatsu *et al.* [60] which improved its reliability.

2.3 Motor and Transmission (DC motor, Induction Motor etc)

Traditional DC motors have been prominent in EV propulsion due to its simplicity in control principle. Speed and torque control was possible individually in separately excited DC motors due to the inherent decoupling of armature and field fluxes. However, recent technological developments have pushed AC motors to a new era, leading to definite advantages over DC motors like higher efficiency, higher power density, lower cost, more reliable, and almost maintenance free. Various types of EV motors and their evaluation are available in literature [16][17][61] and found out that induction motor is the best choice for EV propulsion. Types of standard electric motors are shown in Figure 4.

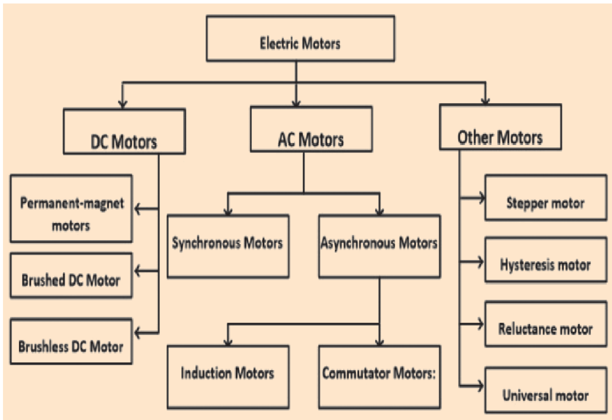

FIG. 4 TYPES OF ELECTRIC MOTORS IN EV APPLICATIONS

Technologies like vector control has made possible to control AC motor like a DC motor which was not possible before due to the inherent coupling of armature and field fluxes [61]. Also the problems faced by commutator machines were totally vanished in ac machines. As high reliability and maintenance-free operation are prime considerations in EV propulsion, ac induction motors are becoming attractive. Permanent Magnet (PM) motors and Switched Reluctance Motors (SRM) are also gaining attention in recent years in terms of its use in EVs [61]–[63]. The role of power electronics in motor construction is indirect as physically it is hard to see any power electronics components associated with electric motors. However, motor control without power electronics is highly unimaginable in the present scenario. A state of the art GTO converter fed induction motor drive is proposed by Stemmler *et al.* [57]. A Comparison of powertrain concepts for electric vehicles was carried out by Schael *et al.* [64] using distributed induction motors and found out that power train concept with two doubly-fed induction motors owns a better performance.

2.4 Energy Management and their Control Strategies

Control plays a key role in a successful EV design. Various control techniques which can be utilized for EV application is available in literature [65]–[67]. A direct involvement of power electronics components in an energy management control strategy is very minute. The control strategies rather make use of low power analog or digital electronic systems to control the operation of various converters and analogous power circuits available in the system. Technological advancements in power electronics enable new applications to emerge and performance improvement in existing applications. These advancements largely rely on the control effectiveness; therefore, it is essential to apply the appropriate control scheme to the converter and to the system to obtain the desired performance.

A proper control strategy has to be done depending on various parameters like switching frequency, heating effects, power semiconductor device used, preferred topology, etc. Gate signal generation for switching ON and OFF of power semiconductor switches, detection and analysis of feedback signals, control and protection of the electrical vehicle system etc, are the primary role of control circuits. Modern microelectronic devices like micro-processors, micro-controllers, digital signal processors (DSPs), etc. are usually used in the development of control circuits. Along with hardware selection, proper selection of software techniques plays a vital role in the successful operation of EVs. A classification and review of control strategies for Plug-in Hybrid Electric Vehicles was done by Wirasingha *et al.* [68]. Different rule based control strategies were discussed for various vehicle topologies with examples. An exclusive study about different types of energy management systems for a fuel cell-battery HEV was carried out by Sulaiman et al [20] . An adaptive control strategy that will optimize itself in real time based on easily available vehicle parameters were found to be the optimum control strategy for present day applications.

3.0 POWER SEMICONDUCTOR DEVICES

A power switching device is one of the key elements to determine the performance of hybrid electric vehicles (HEVs) and pure electric vehicles (EVs). The performance offered by a power electronic switching device is broadly decided based on its switching frequency, switching losses, range of operation (in terms of both voltage and current), operating temperature, etc, and it depends on the device technology and semiconductor material used for the fabrication of it. Both these parameters are discussed briefly below.

3.1 Power Semiconductor Switches

Semiconductor switches having properties like high operating temperature, high-voltage, high-power, fast switching and very low on-resistance are of paramount importance in converters for EVs. The solid state power electronics has gained its importance with the invention of thyristor (or silicon-controlled rectifier) in the late 1950's. Gradually, other semiconductor devices such as the gate turn-off thyristor (GTO), the bipolar power transistor (BPT), TRIAC, Metal Oxide Semiconductor Field Effect Transistor (MOSFET), insulated gate bipolar transistor (IGBT), static induction transistor (SIT), static induction thyristor (SITH). MOS-controlled thyristor (MCT) and integrated gate-commutated thyristor (IGCT) were introduced. A comparison of power devices for EVs were carried out by Chan *et al.* 1996 [14]. Most of the available power semiconductor switching devices are made of silicon and its classification is shown in Figure 5 [69]–[72].

Among the available power devices, the GTO, BJT, MOSFET, IGBT and MCT are particularly suitable for EV propulsion. At present, the IGBT is most attractive because it possesses high input impedance and high speed characteristics of a MOSFET with conductivity characteristic of a BJT. In the near future, the MCT will be a good candidate for EV propulsion because it combines high switching speed, high power handling capability, and superior dynamic characteristic and high reliability.

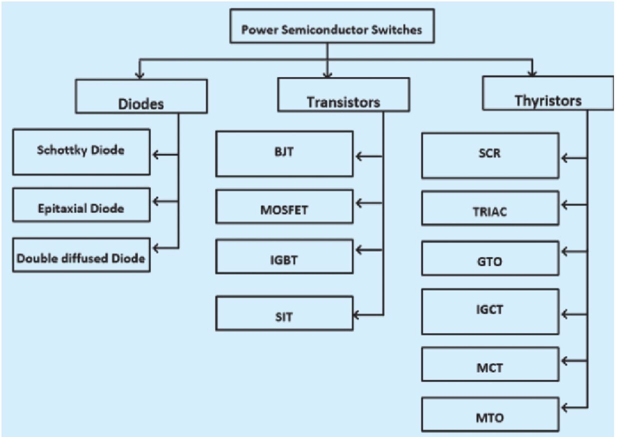

FIG. 5 CLASSIFICATION OF POWER ELECTRONICS SWITCHING DEVICES

A detailed study on active semiconductor devices was done by Iftikhar *et al.* [54] along with other converter components. Typical switch requirements for an electric vehicle propulsion inverter was explained by Gallagher *et al.* [56]. Comparisons between MOSFET and IGBT was made. Power devices for automotive electronics was discussed by Shenai *et al.* [73] along with its packaging and thermal considerations. Further low power micro electronics and discrete power device technologies where explained in brief. Thermal management issues for electronics and electrical devices in an automotive environment was also addressed by Nakayama *et al.* [74]. Power semiconductor devices for an electric vehicular system for various components was compared by Kumar *et al.* [8].

3.2 Power Semiconductor Materials

Performance of a power semiconductor device and its limitations are related to the material properties of the semi-conductor with which it is manufactured. Silicon which has been the most dominating material in the semiconductor device fabrication has reached its theoretical limits of operation like higher thermal conductivity, higher breakdown strength, higher maximum operating junction temperature, high switching frequency, etc, which has led to exploring newer wide band-gap semiconductor materials for manufacturing power electronic switching devices [39]. The effects of semiconductor material properties on the power device operation were discussed by Stefanskyi *et al.* [75] and advantages of using Silicon Carbide (SiC) as a power electronics device was studied. Of the different power semiconductor materials available SiC is found to have an upper hand in future [75]–[81].

Recent technologies and trends of power devices were studied by Majumdar *et al.* [82] in which various power module technologies were discussed and it was found out that 4H-SiC MOSFET is the optimum switching device for future applications. A bidirectional DC-DC converter for PHEVs using SiC devices has been proposed by Acharya *et al.* which offers better performance at higher operation temperature and switching frequency [83]. Automotive applications of Gallium Nitride (GaN) power devices was discussed by Kachi *et al.* [84] and found that technology still needs rapid growth but can be an alternative in the future. A traditional Si-based semiconductor switch was compared with a GaN-based switch by Letellier *et al.* [85] and found that the latter shows supreme performance. A comparison between SiC and GaN power electronics for automotive systems was done by Kanechika *et al.* [86] and found that SiC and GaN are promising materials for the future HEVs and EVs. The industrial trends and market shares of SiC and GaN devices was discussed by Gueguen and projects a promising future for these devices [87]. Cost and the quality of the wafers along with stable processing and reliability of the device performance are still an area of concern for wide band-gap power semiconductor devices.

4.0 CONCLUSIONS

An in depth study about various power electronics converters like DC-DC converters, Inverters and their topologies used in EVs are discussed in this paper. It also provides a literature review of the various converter topologies and power electronic devices. This paper has reviewed the current status of multidisciplinary technologies in EVs with emphasis on power electronics for EV propulsion, battery charging, and power accessories. It indicates that power electronics technology plays a very important role in the development of EVs. In switching devices, it is to be expected that IGBTs (Insulated Gate Bipolar Transistors)will drastically change the technique of on-board converters. Three main advantages will help the IGBTs to substitute for the GTOs and allow manufacturers to build cheaper and better inverters with reduced harmonics: high switching frequency, simple gate control and perhaps no need for snubber circuits. The use of IGBT reduces the harmonics and switching losses. Using wide band-gap semiconductor materials like SiC and GaN for semiconductor switches will reduce the loss in the power circuit of HEV and improve the overall efficiency.

Power electronics contributes significantly to the performance, efficiency, and safety of the modem automobile. The variety of electronics required for automotive applications is functionally similar to those in the ever growing consumer electronics market. Automotive electronics, therefore, stands to derive the same benefits of low power, reduced mass and volume, and higher performance achieved in consumer electronics by increasing integration. The overview of vehicle architecture and configuration shows that electrification of vehicles is a promising technology for future sustainable transportation system. At present HEVs are dominating vehicle configurations, emerging rapidly and capturing the significant market space at a very fast growth rate. The role of power electronic converters are very significant in power flow control and management, behaving as a heart of EPS in vehicle architecture. The integration and packaging of power electronic components are the challenging issues that need to be addressed properly so that weight, volume and cost can be reduced significantly.

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