Making the Case for Electrified Transportation

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***Abstract*—In order to achieve lower fuel consumption and less greenhouse gas (GHG) emissions, we need higher efficiency vehicles with improved performance. Electrification is the most promising solution to enable a more sustainable and environmentally friendly transportation system. Electrified transportation vision includes utilizing more electrical energy to power traction and nontraction loads in the vehicle. In electrified powertrain applications, the efficiency of the electrical path, and the power and energy density of the components play important roles to improve the electric range of the vehicle to run the engine close to its peak efficiency point and to maintain lower energy consumption with less emissions. In general, the electrified powertrain architecture, design and control of the powertrain components, and software development are coupled to facilitate an efficient, high-performance, and reliable powertrain. In this paper, enabling technologies and solutions for the electrified transportation are discussed in terms of power electronics, electric machines, electrified powertrain architectures, energy storage systems (ESSs), and controls and software.**

***Index Terms*—Electric machines, electric vehicles (EVs), electrified powertrains, energy storage, energy storage systems (ESSs), hybrid EVs (HEVs), plug-in HEVs (PHEVs), power electronics, transportation electrification, vehicle control software.**

I. INTRODUCTION

TODAY, mobility is one of the most important parameters to achieve economic growth and high standards of living. To enhance mobility, we need a reliable, inexpensive, clean, and, most importantly, sustainable transportation system. However, due to high dependence on fossil fuels as the main source of energy, our transportation system is not sustainable. Contributing to nearly one-third of the total greenhouse gas (GHG) emissions, our transportation system is not environmentally friendly either.

There are more than 900 million vehicles in use around the world today. More than 250 million of these vehicles are located in the U.S. There is already 80 million vehicles manufactured every year worldwide and these numbers are expected to keep rising in next few decades, especially in Asia. The vast majority of these vehicles is powered solely by internal combustion engines (ICEs) and requires fossil fuels as the energy source. The carbon dioxide (CO_2) generated by burning fossil fuels is a major contributor to the GHG emissions [1]. In addition, even though there is a decreasing trend in the last few years, a significant portion of the oil used in the U.S. transportation system is still imported [2].

In order to create a sustainable and cleaner transportation system, we need higher efficiency vehicles with significantly lower fuel consumption. In 2012, the U.S. government announced new fuel economy standards. They mandate that the average fuel economy of passenger cars and light-duty trucks in the U.S. has to rise to 54.5 mi/gal (4.3 L/100 km) by 2025 [3]. These aggressive targets cannot be achieved solely by improving the ICE technology. The average efficiency of an ICE is less than 30% and most cars today can achieve only 10%–20% overall efficiency.

Alternatively, electric energy storage systems (ESSs), electric machines, and power electronic converters can provide much higher efficiencies; therefore, electrification is the most promising solution to achieve the targets. Electrified transportation is a paradigm shift from conventional ICE-based vehicles to more efficient and cleaner electrified vehicles. The architecture of the powertrain, the design of the powertrain components, and the controls and software development are coupled with each other to maintain high-performance, high-efficiency, reliable, and affordable vehicles.

In this paper, the critical components of electrified powertrains, including power electronics, electric machines, electrified powertrain architectures, ESSs, and controls and software, are discussed to achieve the transportation electrification vision. The available technologies, applications, solutions, and future trends are investigated.

II. TRANSPORTATION ELECTRIFICATION

Transportation electrification vision includes using more electrical energy to power propulsion and nonpropulsion loads in vehicles. Conventionally, ICEs are not highly efficient and they can achieve an average efficiency of less than 30%. Electrical systems can, however, provide much higher efficiencies. Electric motors can be designed to operate with efficiency levels above 90% [4]. Furthermore, electrical systems are faster and can be controlled easily as compared to mechanical systems. In addition, electrical energy can be generated from many

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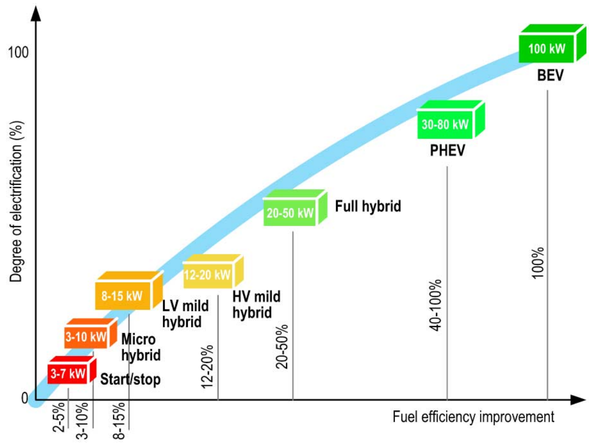


Fig. 1. Degree of electrification: typical fuel efficiency improvement and electric traction motor power [7].

resources, such as wind, solar, and hydro, which are renewable and carbon free. Transportation electrification is an evolving paradigm shift from nonsustainable transportation 1.0 of conventional vehicles to more sustainable transportation 2.0 of electrified vehicles [5].

A. *Degree of Electrification*

Electrification in automobiles can occur both in propulsion and nonpropulsion loads. The electrification level for the given vehicles defines the ratio of electrical power available to the total power. Fig. 1 shows the fuel-efficiency improvement on the same vehicle platform for different electrification levels. Today, most of the vehicles being manufactured have 10%–20% of electrification. These more-electric vehicles (MEVs) employ electrified nonpropulsion loads, such as electrically assisted power steering, electrically driven air conditioning, pumps, fans, and so on. Mild hybrids have a higher degree of electrification and they provide auto start/stop function, regenerative braking capability, and some use of electric power for propulsion. Depending on the system requirements, integration complexity, and cost, mild hybrids can be designed as low- or high-voltage systems. This typically provides between 8% and 15% improvements in fuel efficiency. By 2017, 70% of the new vehicles are expected to have start/stop function in Europe [6].

Full hybrid EVs (HEVs) have a higher degree of electrification. Depending on the design of the powertrain, full hybrids can achieve 20%–50% and more reduction in fuel consumption [7]. In power-split hybrids, two electric motors are coupled with an engine to create an electrically variable transmission. The design of the powertrain defines the fuel-efficiency improvement in city and highway driving conditions.

By 2013, 3 million hybrids were sold in the U.S. Around 1.4 million of these vehicles were Toyota Prius, which is a power-split hybrid and it provides a balanced city and highway fuel efficiency. Ford fusion hybrid is also a power-split hybrid and it constitutes around 8% of the hybrid sales in the U.S. Hyundai Sonata hybrid has a simpler design and it employs one main traction motor and one integrated starter-generator. It provides high fuel economy in the highway driving conditions, because the engine operates with a higher efficiency and electric motor provides torque assist when higher power is required. Hyundai Sonata hybrid had around 4.5% of the total hybrid sales in the U.S. in 2013 [8].

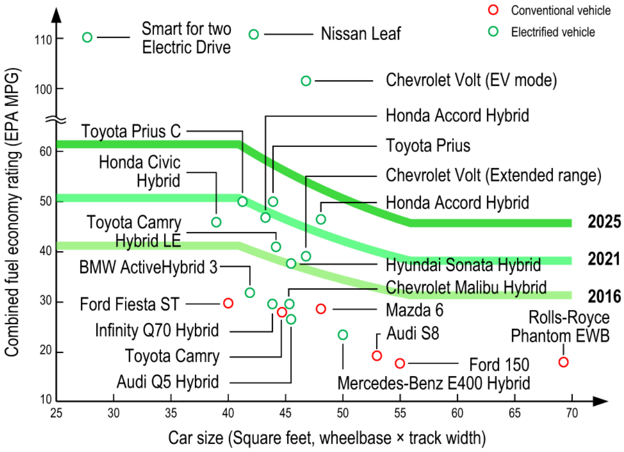


Fig. 2. Fuel economy targets and current status of vehicles.

By increasing the degree of electrification, higher fuel efficiency can be gained. Plug-in HEVs (PHEVs) and extended-range EVs (EREVs) have larger battery packs; therefore, they can provide a longer all-electric drive with plug-in charging. In the U.S., about 85% of the vehicles are driven less than 100 km a day. Therefore, PHEVs are very attractive. In an EREV, the powertrain topology looks more like a series hybrid and the engine runs the generator to supply electric power to the traction motor. GM's Chevy Volt is an example; however, the engine can still propel the wheels through a coupling mechanism. Between December 2010 and March 2014, Chevy Volt sold around 60 K units in the U.S. [9].

In all-EVs, the traction power is supplied solely from an electric motor and an electric ESS. One of the main concerns in EVs is the limited driving range, which is dependent on the energy density of the battery cells and also the temperature [10]. Today, there are many EVs available on the market, such as Nissan Leaf, Fiat 500e, and Ford Focus Electric. Between December 2010 and March 2014, Nissan Leaf sold around 47 K units in the U.S. and it has a 24-$\mathrm{kW \cdot h}$ battery pack. Tesla Model S is a higher performance EV and sold around 25 K units in the U.S. since March 2014. It offers options of either a 60- or 85-$\mathrm{kW \cdot h}$ battery pack, which provide a much longer driving range.

In the next decade and beyond, the electrification level in all new vehicles will need to increase to meet the fuel economy requirements, which, e.g., mandate a fuel economy equivalent to 54.5 mpg by 2025 in the U.S. for light duty vehicles. Fig. 2 shows the fuel economy status of some of the current electrified vehicles and conventional vehicles with respect to the fuel-efficiency standards. With the new regulations, 12 billion barrels of reduction in oil consumption, $1.7 trillion cost saving and 6 billion metric tons of GHG emission reduction are estimated [11]. This will create a more sustainable and environmentally friendly transportation system that produces lower emissions.

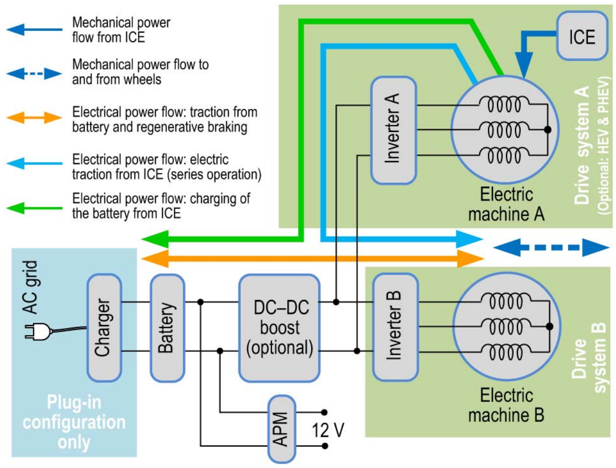


Fig. 3. Typical electrified propulsion system architecture.

TABLE I
POWER ELECTRONIC CONFIGURATIONS IN DIFFERENT VEHICLES

Module	Battery	DC–DC boost	Drive system B	Drive system A	Charger
Toyota SDS II Ford Fusion Hybrid	✓	✓	✓	✓	
Hyundai Sonata Hybrid	✓	✓	✓	✓	
Chevrolet Volt	✓	✓	✓	✓	✓
Nissan Leaf Ford Focus Electric	✓		✓		✓

III. POWER ELECTRONICS

In electrified vehicles such as HEVs, PHEVs, and EVs, power electronic circuits act as the connection between the energy sources, e.g., battery pack, and the power actuators, i.e., traction motors. They convert, transform, and transfer electrical power through the powertrain. One of the main advantages of the power electronic systems is that they can be bidirectional and provide high efficiency ($> 90\%$). However, they require complex design and manufacturing process due to their multidisciplinary nature including electrical, thermal, mechanical, control, software, and magnetic aspects.

Converters used in electrified propulsion systems are different depending on the powertrain. Fig. 3 shows a typical architecture for electrified propulsion system architecture and Table I summarizes the configurations used in different vehicles on the market. In some configurations, a dc–dc boost converter is used between the battery pack and the drive system to step-up the voltage. This offers more flexibility for selecting the voltage rating of the battery pack and the motor, as well as for controlling the system [12]. However, this requires development and implementation of an additional converter and brings additional cost.

As depicted in Fig. 4, a power converter is a system made by several components. Power switches, cooling system, capacitor, coils, sensors, control board, and housing are the major ones. All of these components interact together to achieve electrical power conversion in an effective, efficient, and reliable way. Functionality, volume, and cost of these components affect the characteristics and performance of the converter.

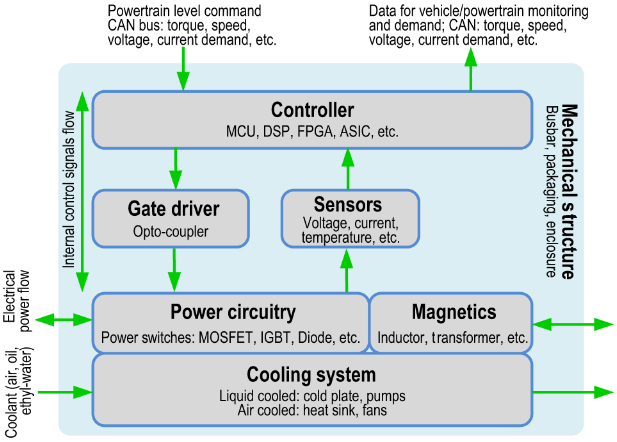


Fig. 4. Power converter structure.

A. Power Switches

For automotive applications, two types of switches are mainly used: 1) insulated gate bipolar transistor (IGBT) for systems rated between 200 and 1200 V and 2) MOSFET for converters rated at a lower voltage, such as in 12 or 48 V systems. Semiconductors are available in standardized packages containing 1 (discrete), 2 (dual), 4 (fourpack), or 6 (sixpack) switches. Moreover, for large-scale applications, custom configurations can be developed to achieve specific functionality and higher power density. This is what has been developed by Toyota in the synergy drive system II (SDS II) where 14 IGBTs and diodes have been placed in the same module to achieve functionalities of the two inverters and the dc–dc boost converter [13].

In the last decade, wide-band gap devices based on silicon carbide (SiC) or gallium nitrate (GaN) have been developed to improve the performance of power converters. As compared to silicon-based switches, SiC devices offer improved switching characteristics, better thermal properties, and higher voltage operation. Lower switching losses and high thermal conductivity reduce the cooling requirements and increase the efficiency [14], [15]. Wide-band gap technologies can yield significant reduction in the size of the capacitors and inductors due to their capability of switching at higher frequency. This increases the power density of the converter.

Toyota and Denso have developed a SiC-based drive unit. They increased the switching frequency ten times and managed to reduce the overall volume of the drive unit by 80% as compared to their existing converter [16]. From a vehicle point of view, Toyota observed an increase in fuel economy of more than 5% under the JC08 test cycle [17]. In addition, a study published in 2011 with the Oak Ridge National Laboratory estimated an increase of 14.7% of the fuel economy of a Toyota Prius 2004 for the UDDS drive cycle with the use of SiC components [18]. Although these numbers are very promising, by the time of the writing, there was no commercially available vehicle using this technology. This was mainly due to the relatively high cost associated with the wide-band gap devices. However, with the increase in the number of suppliers, off-the-shelf availability, rising production, and reducing prices, the market share for wide-band gap devices is expected to grow [19].

B. Passive Components

Capacitors and magnetic components are the major passive components in a power converter. Capacitors have an important role as they contribute to the power quality of the converter by filtering input and output currents. In particular, they prevent current ripple from reaching the battery. In lower voltage applications such as auxiliary power unit (APU) with 12 V output and also in 48 V mild hybrids, electrolytic capacitors are widely used. Film capacitors are usually the preferred option for the high voltage dc-link in HEVs, PHEVs, and EVs. Film capacitors are utilized in 2012 Nissan Leaf, 2012 Hyundai Sonata Hybrid, and Toyota SDS II [20].

Power inductors (e.g., in boost converters and battery chargers), high-frequency transformers (e.g., in auxiliary power converters), and chokes (e.g., EMI filters) are among the major magnetic passive components. The design of the magnetic component and the core material has significant importance in the size and efficiency. For transformers operating at high frequency (hundreds of kHz), ferrite is often preferred due to its low-cost and low-core losses. However, the low-saturation flux density of ferrite leads to a bulky design in high-power applications. For power inductors, materials with higher saturation flux density, such as iron powder or silicon steel, are preferred.

C. Cooling System

Cooling system is one of the most important components for reliability and power density of power converters. It prevents components operating at a harmful temperature. For power switches and passive components, the heat generated by the losses has to be evacuated from the module or the component first and then from the converter. For low-power applications, forced air cooling can be used. In high-power applications, such as traction inverters, liquid cooling is preferred due to its better heat dissipation capability. This enables higher power density.

To improve the cooling performance of switches, more and more features are integrated in the power modules [21], [22]. Pin-fin technology is an example, which is utilized by Infineon. It offers a direct contact between the coolant and the baseplate of the module, which yields up to 50% reduction in thermal resistance between the chip and the coolant [23].

D. Challenges for Traction Power Electronics

The U.S. Department of Energy has defined 2020 targets for power density (13.4 kW/L) and cost (3.3 $/kW) for traction power converters. The current power density values of some traction inverters are given in Fig. 5. It can be observed that prototype SiC inverters can exceed 2020 targets in terms of power density. However, these prototypes still do not meet the cost targets. Other converters using Si technology also offer high power density, but they cannot sustain a coolant temperature of 105 °C defined by the targets. This shows that cooling system and thermal limitation of switches are key challenges for power electronics.

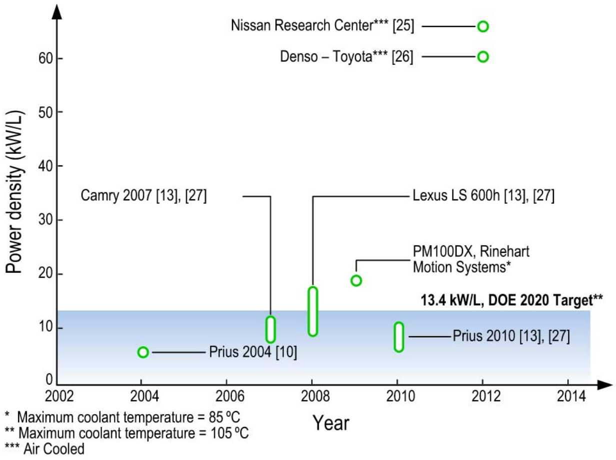


Fig. 5. Power densities of existing traction inverter products/prototypes.

One of the biggest challenges for the next generation of automotive power electronic system will be reducing the cost to provide more affordable solutions. Among possible methods to reach this goal are improvements in the manufacturing process, design scalability, and development of more integrated components and systems, such as the smart power module concept [24].

Power converters are made up of many different components with different sizes and mechanical properties. They vary from small and fragile electronic chips to bulky magnetic components and cold plates. Interactions between components and their operating conditions are so tight that an improvement at any level (e.g., switching frequency, cooling, current density, and magnetic flux density) can yield an overall enhancement of the entire design. This can be observed in SiC-based technologies which enable higher switching frequency and reduced cooling requirements.

IV. ELECTRIC MACHINES

In electrified powertrains, the efficiency and performance of the electric machines have a significant impact on the fuel consumption, acceleration, high-speed performance, and driving comfort. More efficient and higher performance electric traction motors improve the use of electrical mode and, hence, in hybrids, this helps to run the engine closer to its peak efficiency areas leading to lower fuel consumption and, in EVs, this facilitates higher all-electric range.

Electric traction motors have stringent operational requirements. Fig. 6 shows the typical torque-speed characteristics and most frequent operating points of an electric traction motor. The electric motor is required to deliver high torque at lower speeds for quick acceleration, hill climbing, engine auto-start, and reversing at high road gradient. It is also required to operate at medium speed range for city driving and, at high-speed range,

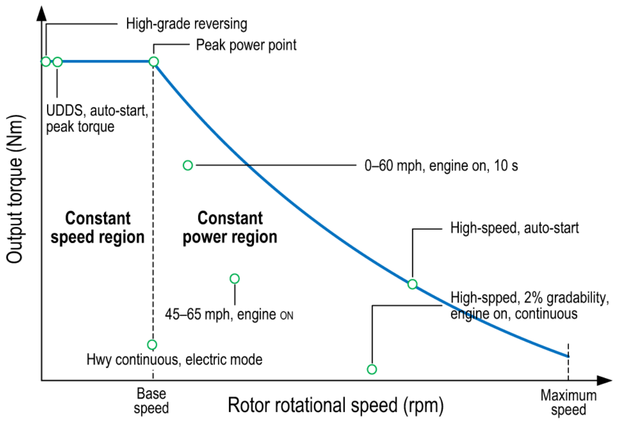


Fig. 6. Typical torque-speed characteristics and most frequent operating points of an electric traction motor in a hybrid electric powertrain.

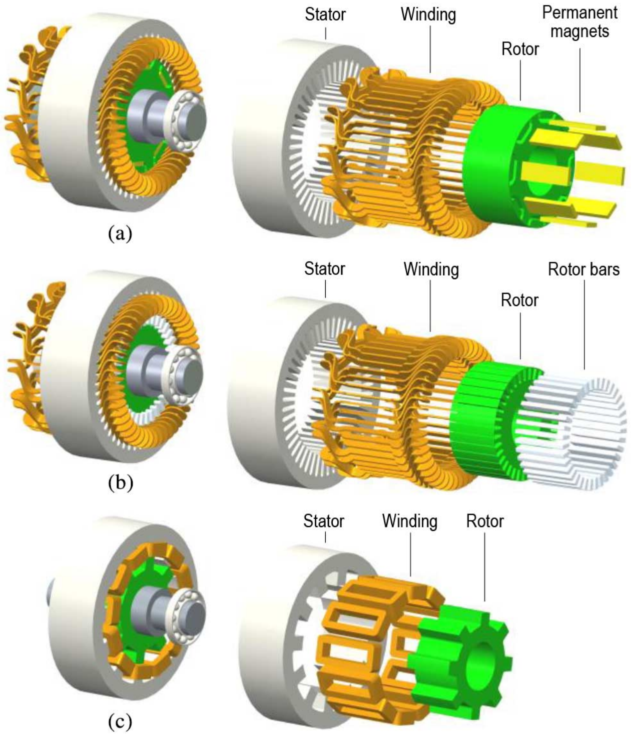
for highway driving conditions. A traction motor needs to provide high efficiency at its most frequent operating points to improve the powertrain efficiency and reduce fuel consumption.

In addition to the vehicle platform, engine size, drive cycles, volume, weight, and lifetime and cost constraints, various other parameters including the torque-speed characteristics, peak-power requirements, and thermal, structural, and noise-vibration-harshness (NVH) conditions define the selection of the right electric machine for the application. For example, in mild hybrids or belt-driven starter-generators (BSG), the maximum torque envelope of the electric motor should cover the cranking speed of the engine multiplied by the pulley ratio. In addition, since the motor is located under the hood, a BSG motor should be designed to operate at high temperatures (105–115 °C) and in high-vibration (20 G or more) environment [7]. This affects the machine design process from the selection of the core and insulation material, use of permanent magnets (PMs) and PM type, manufacturing process, to defining the number of poles, winding configuration, and so on.

A. *Interior PM Synchronous Machine (IPMSM)*

Interior PM Synchronous Machine (IPMSM) is used in most of the hybrid and EVs currently available on the market. As shown in Fig. 7(a), IPMSM has PMs embedded inside the rotor, which provides an independent excitation source. For this reason, IPMSM can provide high torque density and better efficiency especially at low and medium speed ranges.

The selection and configuration of the PMs have significant effect on the output torque of the machine. Toyota Prius is a power-split hybrid and its traction motor is connected to the final drive over the ring gear. The motor is designed to deliver a peak power of 60 kW with a maximum torque of 207 $\mathrm{N \cdot m}$ and a maximum speed of 13 500 rpm, which corresponds to 110-mph vehicle speed. The V-shape configuration of the magnets provides saliency and, hence, additional reluctance torque component, which facilitates field weakening and helps with extending the speed range [13]. In IPMSM, the configuration of the PMs is highly dependent on the torque-speed requirements. For example, 2011 version of Nissan Leaf traction motor was designed for a peak power of 80 kW with a maximum torque of 280 $\mathrm{N \cdot m}$ and a maximum speed of 10 390 rpm. This motor has a delta-shaped magnet [28]. Chevrolet Spark traction motor has 105-kW peak power with a maximum torque of 540 $\mathrm{N \cdot m}$ and a maximum speed of 4500 rpm. This motor has double-barrier rotor geometry with bar-wound windings to enable higher torque at low speeds [29].



(a)

(b)

(c)

Fig. 7. Typical electric machine types for traction applications. (a) IPMSM. (b) IM. (c) SRM.

In PM traction motors, high-energy rare-earth PMs are used to provide higher torque density. The main disadvantages of PM machines are the sensitivity of rare-earth magnets to temperature and their high cost. For example, when the temperature of the magnet increases to 160 °C, the output torque of the motor can drop by up to 46% [30]. When designing an IPMSM, maximum temperature and demagnetization should be taken into account to define the size and volume of the magnet to optimize the cost and performance.

B. *Induction Machine (IM)*

In an IM, the magnetic field generated by the stator currents induces voltage on the rotor conductors and the rotor currents create torque. As shown in Fig. 7(b), rotor is made of conducting bars which are die-casted in the slots. As compared to IPMSM, IM operates at a lower power factor with lower efficiency at low speeds due to the lack of independent rotor excitation. One of the main disadvantages of IM is the inherent rotor copper losses. Especially during high-torque operation, heat generated by the rotor copper losses can be difficult to extract. This puts a limit in the torque-density of IM [31].

Tesla EV has a 310-kW four-pole IM, which provides 600 $\mathrm{N \cdot m}$ of peak torque and a maximum speed of 14 000 rpm. The high-torque and high-speed operation with IM is achieved by using copper rotor bars and by the improvements in the mechanical design (e.g., high-strength alloy steels and ceramic bearings). Copper has 60% higher conductivity than aluminum. Therefore, copper rotor bars have lower resistance and, hence, generate less heat at high currents. However, copper has higher density than aluminum. Therefore, die-casting of copper requires higher temperature and high tonnage presses. This results in significant stress on the rotor laminations and makes the manufacturing process more challenging. Furthermore, the cost of copper die-casted rotor is significantly higher than aluminum die-casted one [31].

C. Switched Reluctance Machine (SRM)

As compared to IPMSM and IM, SRM has the simplest, most robust, and the lowest cost structure. As shown in Fig. 7(c), SRM rotor has a salient pole structure made of laminated silicon steel. It does not have conductors or PMs. The stator of SRM also has a salient pole structure and concentrated coils are wound around the poles. Therefore, SRM is very suitable to operate at high speeds and high temperature conditions.

In SRM, torque production is based on the change of magnetic reluctance. Since the relative position of the salient poles defines the length of the airgap, torque is dependent on the rotor position. The main disadvantage of conventional SRM is significant torque ripples. In addition, strong radial forces can excite the stator and this causes vibration and acoustic noise. These factors can be a limitation in the power density of conventional SRM. However, the rugged, simple, and low-cost construction of SRM makes it a significant candidate for electrified transportation in the long run. Using advanced design and control techniques, torque ripples, noise, and vibration in SRM can be reduced [32]–[34].

Currently, SRM is not used in any of the major hybrid or electric on-road passenger cars on the market as the traction motor. However, John Deere has utilized SRM in their hybrid loaders as in-wheel traction motors. Four wheel-hub SRM traction motors are used in the 944 Hybrid Loader architecture. They are powered by two interior PM generators that are driven by a 600 HP, 13.5 L Deere diesel engine [35].

V. ELECTRIFIED POWERTRAINS

Electrified powertrains differ from conventional powertrains in terms of on-board vehicle power paths and transmission configurations, which integrate electric power systems including power electronics, electric machines, battery pack, and control units into vehicle platforms. Compared to the conventional powertrains where engine is the only power source, electrified powertrains add an electric power path to assist or replace the conventional mechanical power path. In hybrid and plug-in hybrid vehicles, the electric power path intermingles with mechanical power path through transmission integration, whereas in EVs, the electric power path works exclusively to provide all the power for traction and auxiliary loads. Typically, higher degrees of electrification represent larger electrical power path ratio and, thus, lead to lower fuel consumptions and less tailpipe emissions.

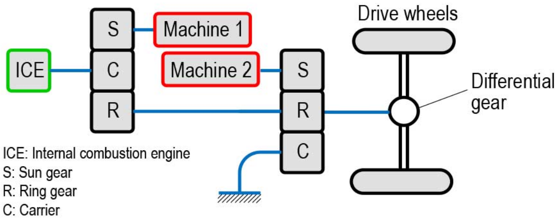


Fig. 8. Toyota Prius hybrid synergy drive system.

A. Parallel Hybrids

One of the most widely used hybrid architecture is the parallel hybrid configuration. It has been the powertrain of choice for many auto manufacturers as one of their first steps into the vehicle electrification due to its simple but effective fuel-saving powertrain design. Up to date, a dozen of major auto brands including Acura, Audi, BMW, Buick, Chevrolet, Honda, Infinity, Mercedes, Nissan, Porsche, and Volkswagen have released hybrid models in North America for a wide range of vehicle classes based on parallel hybrid configuration [36]. The parallel architecture consists of an electric machine placed alongside with the ICE. Depending on the location of the electric machine, either an integrated motor assist (IMA) configuration such as in Honda Civic Hybrid, a BSG configuration such as Chevrolet Malibu Hybrid, or a parallel-through-the-road configuration can be formed. The electric machine provides assistance to the engine for greater acceleration and performance, or provides regenerative braking during vehicle deceleration. For the IMA and BSG configurations (mild hybrids), it provides auto-start function to crank the engine and generate power for the vehicle auxiliary loads replacing the original alternator.

B. Full Hybrids

Full hybrid powertrains with higher degrees of electrification have been developed and many architecture varieties have been evolved with great commercial success. The power-split system is an input-split hybrid transmission, which utilizes power-split devices, i.e., planetary gear sets, at the input side of the transmission that connects the engine and electric machines. The planetary gear set splits the engine power into different mechanical and electric power ratio and achieves variable transmission output speed and torque. One example of the power-split system is shown in Fig. 8, which illustrates the 2010 Toyota Prius Hybrid SDS [13]. Variations in the power-split transmissions have been applied to other models and brands such as Ford C-Max Hybrid, Lincoln MKZ Hybrid, Lexus RX450h, Lexus LS600h, Toyota Camry Hybrid, and Toyota Highlander.

Two-mode hybrid is another electrified powertrain that incorporates the engine, electric machines, and mechanical gear sets in a compound two-mode hybrid system. Similar to the power-split system, the two-mode hybrid transmission takes advantage of the planetary gear sets to integrate the mechanical power path with the electric power path. However, two-mode hybrid provides more operating modes when compared to the Toyota power-split system by coordinating the electric machines,

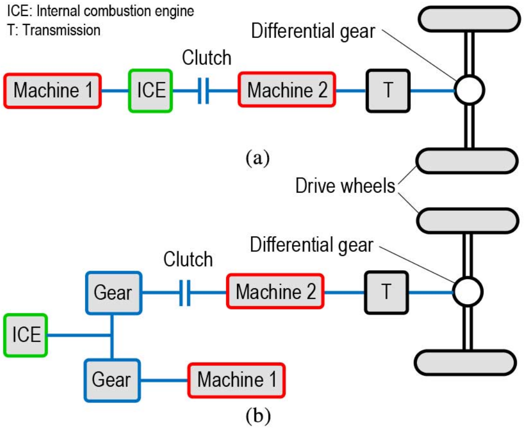


Fig. 9. Series–parallel hybrid powertrain configurations. (a) Hyundai Sonata Hybrid/Kia Optima Hybrid series–parallel configuration. (b) Honda Accord Hybrid series–parallel configuration.

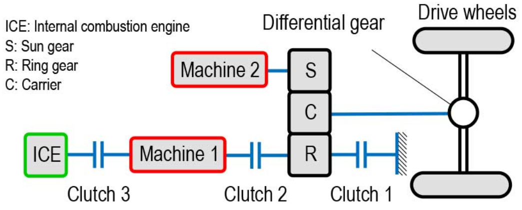


Fig. 10. Chevrolet Volt powertrain configuration.

clutches, and brakes while utilizing multiple planetary gear sets [37].

In addition, the series–parallel hybrid is an alternative architecture that uses direct mechanical connection to split the transmission power flow instead of using planetary gear sets. In this architecture, one of the machines is always connected to the engine to function as both a starter motor and a generator. A second machine acts as the main traction motor and is separated from the engine and generator by a clutch, which enables multiple modes such as electric-only operation, series operation, and series–parallel operation. Fig. 9(a) and (b) illustrates two configurations of the series–parallel hybrid used by Hyundai Sonata Hybrid and Kia Optima Hybrid and Honda Accord Hybrid.

C. Plug-In Hybrids and EVs

PHEVs and EREVs contain even higher degrees of electrification levels. They are equipped with larger battery capacities that are capable of operating on battery power alone for a considerable range and they can be charged directly from the grid. Conventional engines are still employed to provide power assist or used as the secondary power source. Charge depleting, charge sustaining, and all-electric driving modes are available depending on the state-of-charge (SOC) of the ESS and the control strategy. One example of an EREV powertrain is the Chevrolet Volt as illustrated in Fig. 10. Two electric drive modes and two range extended modes are available by engaging different combinations of the clutches suited for various torque and speed requirements from the road.

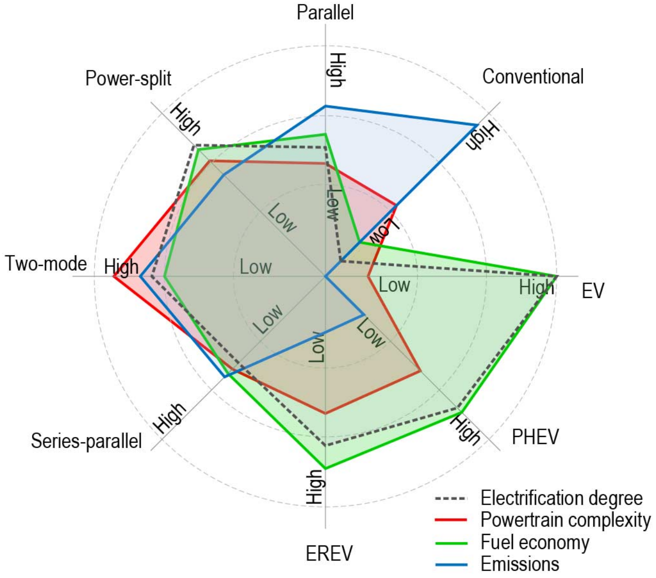


Fig. 11. Electrified powertrain architecture comparisons.

Finally, EV powertrains employ the highest electrification level and the simplest powertrain configuration in which electric machine(s) directly drive the wheels via a fixed gear reduction. Highest degrees of fuel displacement and emissions reduction can be achieved, while less mechanical maintenance is required compared to the conventional vehicle powertrains. Brand-new powertrain platforms are created such as Tesla Model S and Nissan Leaf along with powertrains evolved from existing conventional models such as Chevrolet Spark EV and Ford Focus Electric.

Fig. 11 compares different electrified powertrains along with the conventional ICE-based powertrain in terms of electrification degree, fuel economy, emissions, and powertrain complexity. It can be observed that all the electrified powertrains provide increased fuel economy and reduced emissions over the conventional one. Powertrains with higher degrees of electrification such as EREV, PHEV, and EV achieve the highest fuel economy gains, while typical mild hybrids with parallel powertrain configuration achieve a fuel-efficiency improvement without substantially changing the powertrain complexity. On the other hand, full hybrids including power-split, two-mode, and series–parallel powertrains require significant powertrain modification and system integration. Especially in the case of two-mode hybrid, the powertrain complexity is high [36]. It is apparent that EVs have the highest fuel economy and the lowest powertrain complexity. Batteries with high energy and power densities, fast recharging time, and long-lasting life cycles are desired in EVs.

VI. ENERGY STORAGE SYSTEMS

Traditionally, electrical energy storage for vehicle applications has been limited to starting/lighting/ignition (SLI) subsystems. The increase in vehicle electrification has led to an increase in the energy, power, and cycling requirements of the vehicle ESS. This has enabled not only efficient electric mobility, but also maintains faster response along with

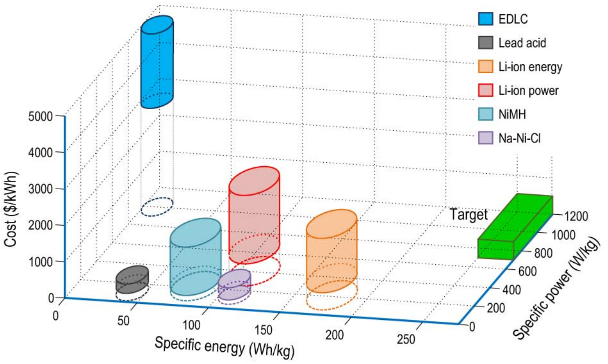


Fig. 12. Cost augmented three-dimensional (3-D) Ragone diagram.

secondary conveniences such as at-home charging, vehicle-to-home (V2H) backup power, upcoming vehicle-to-grid (V2G) infrastructure support, and the wireless charging. Fuel efficiency can generally be increased with a greater vehicle ESS by enabling greater use of more-efficient electric drive. A variety of ESS solutions are available, which are dependent on the vehicle platform and its degree of electrification. These factors have an impact on the choice of energy storage technology, its integration in the vehicle, and the design of the energy management system (EMS).

The EMS comprises the raw energy storage technology, its electronic, thermal, and control hardware and software. The EMS controls and manages the ESS to deliver the electrical power and energy requirements in a safe and efficient manner. For systems that employ batteries, the EMS is the battery management system (BMS). The EMS or BMS needs to interconnect many cells, estimate BMS/EMS states, diagnose fault conditions, report power and energy availability, and communicate with other vehicular systems such as on-board/off-board charger, infotainment, and traction control systems.

A. Battery Technologies

The different energy storage technologies are graphically compared in Fig. 12. Flooded lead-acid (FLA) cells are commonly used for SLI batteries. The cell voltage is typically 2.17–2.22 V [38]. FLA technology is very mature and highly recyclable, but has limited cycle-life and depth-of-discharge. Enhanced FLA (EFLA) batteries typically have double cycle-life to that of FLA making them suitable for the most basic start–stop hybrid platforms [39]. For increased power and cycle-life, sealed lead-acid (SLA), also called valve regulated lead-acid (VRLA), batteries are available. Compared to FLA, they have approximately 3.5 times higher cycle-life and a slightly higher cell voltage of about 2.25 V. This enables them to handle small amounts of traction and regenerative braking energy. VRLA technology is less mature and more costly as compared to EFLA.

Nickel metal hydride (NiMH) batteries have been used in HEVs for more than 15 years. The two main cell manufacturers are PEVE and Sanyo Electric (Panasonic). The technology is relatively mature and has shown longevity in vehicles such as the Toyota RAV4 EV operating after a decade and over 160 000 km [40]. The cells are manufactured in both cylindrical and prismatic hard case formats as shown in Fig. 13. The cell voltage is 1.2–1.35 V and, compared to lead-acid battery, the columbic efficiency is about 10% less. However, power/energy capabilities of NiMH cells are typically double to triple of lead-acid. A significant drawback of NiMH is the high self-discharge, which limits them to power-oriented applications such as mild and full hybrids [38].

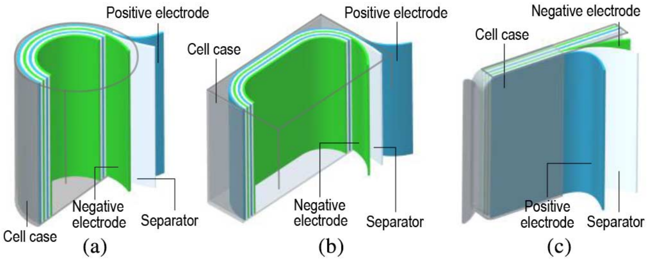


Fig. 13. NiMH/Li-ion cell formats. (a) Cylindrical. (b) Prismatic. (c) Pouch.

Commercially available ZEBRA batteries are based on sodium nickel chloride (Na-Ni-Cl) electrochemistry. The technology is mature and has been developed over the last 25 years. ZEBRA batteries are known as "hot salt" batteries since, at its operating temperature (270–350 °C), sodium is a molten liquid. They are insensitive to ambient temperature and tolerant to low resistance short-circuit faults in case of an internal cell damage. This makes them a good candidate in extreme climates. ZEBRA batteries have greater energy density, better cycle life, and lower cost as compared to NiMH. However, they have lower power density. ZEBRA batteries have been employed in some European EVs, such as Iveco Electric Daily, Think EV, and Modec EV vans.

Lithium-ion-based cells have dominated the consumer portable electronics energy storage market and are currently the preferred technology for PHEVs and EVs. There are many variations in materials used for the electrodes. The positive electrode material is of lithium metal-compound oxide variety where the metal compound is either nickel (LNO), cobalt (LCO), manganese (LMO), iron-phosphate (LFP), or blended variations thereof, e.g., nickel-manganese-cobalt (NMC) and nickel-cobalt with aluminum blending (NCA). Negative electrode material is usually graphite; however, lithium titanate (LTO), hard carbon, silicon-carbon composite, and tin/cobalt alloys have also been developed. The latter three are currently used for consumer electronics [38]. The biggest concerns for this technology are safety, long-term reliability, and low-temperature performance. Thermal runaway is a critical concern that is precipitated at high cell temperatures and over-voltages; flammability of the electrolyte exacerbates this problem. As a result, significant engineering effort in cell-monitoring, voltage-control, and thermal management is necessary in vehicular applications. Lithium-ion cells are manufactured in cylindrical/prismatic hard case and soft-case pouch formats as shown in Fig. 13 in either high-energy or high-power cell designs.

B. Pack Design and Vehicle Integration

In HEVs, PHEVs, and EVs, a modular design approach is normally chosen for higher pack voltages, where multiple modules are connected in series and controlled in distributive control architecture. Most PHEVs and EVs employ liquid cooled thermal management; Nissan Leaf is a notable exception. It employs air cooling for the batteries. Improvements in physics-based modeling are helping engineers determine the best trade-off between liquid- and air-cooled systems for a given electrified architecture. A complete EV battery pack design leads to 53%–73% of the weight coming from the cells [41]. Moreover, compared to traditional ICE vehicles, the weight of a conventional EV could be 20%–37% greater [42]. This indicates that there is room for improvement through better pack design and overall vehicle platform commitment.

Hybrid ESS strategies have been heavily researched and developed into prototypes across all levels of electrification. For example, in micro-hybrids, lead-acid (EFLA or VRLA) has been combined either with NiMH, lithium-ion, or ultracapacitors [41]. Lead-acid and ZEBRA batteries have been augmented with ultracapacitors to improve the performance and battery life in EVs [43], [44]. The most common ultracapacitors for transportation applications are the electric double layer capacitor (EDLC) type. A variety of topologies and integration strategies have been researched for hybrid ESS in transportation electrification [45].

C. Future Trends and Technologies

An alternative electrochemistry seeking to replace lead-acid is nickel-zinc batteries being commercialized by PowerGenix. Advantages such as twice the service life, 65% weight reduction, and recyclability higher than NiMH and Li-ion, but comparable to lead acid, are claimed for this technology. This makes them suitable for micro/mild hybrids [46].

Advanced Li-ion chemistries are under development to increase cell voltage, and subsequently power and energy capability. Two examples are improved NMC cathode operating at 4.3 versus 4.15 V [41] and lithium vanadium phosphate (LVP) enabling cell voltages of 4.7–4.8 V. The latter has been demonstrated in a Subaru 64e prototype [47].

Hybrid capacitors have recently been commercially developed as novel cells that combine elements of electrochemical and electrostatic storage to integrate advantages from both. Two examples are UltraBattery [48] meant to replace lead-acid batteries and the lithium-ion capacitor by JSR Micro.

With the recent and forecasted developments in vehicle ESS technologies, the U.S. advanced battery consortium (USABC) has recently set more aggressive EV targets, such as system level power density of 1000 W/L and energy density of 500 Wh/L [42]. Related research has suggested that a $240+\text{km}$ range EV would be mass-marketable. Moreover, battery costs per unit mile range are forecasted to drop by 50% by 2020.

Revolutionary energy storage technologies are being researched and developed that aim to have anywhere from 2 to 15 times more energy/power capability than today's lithium-ion cells. These include lithium-sulfur batteries being developed by Oxis Energy, Zinc-air batteries pursued by ZAF energy systems, and lithium-air batteries [49]. The so-called flow batteries based on vanadium or zinc-bromine electrochemistry are also in development by American Vanadium and ZBB Energy Corp.

VII. CONTROL AND SOFTWARE

Modern vehicles contain significant amount of software; this is especially true for electrified vehicles. The size of software in some modern vehicles reaches 100 million lines of code [50] running on more than 100 electronic control units (ECUs) [51]. Embedded software has been increasingly taking over roles that traditionally belonged to mechanical, hydraulic, pneumatic, and electrical components and is being used to implement new advanced features. It is estimated that 90% of innovations in vehicle technologies are due to electronic components and software. Software increasingly performs generic vehicle functions such as arbitrating gear selection in shift-by-wire and other X-by-wire functionalities to reduce vehicle cost and weight. In addition to advanced safety features, such as antilock braking and collision avoidance, embedded software implements electrified powertrain staples, such as real-time optimal control of power flow to maximize fuel economy and drivability, motor control, optimization of battery performance and its protection, and engine start–stop.

A. System Controls in Electrified Powertrains

Electrified powertrains require multilevel control systems. A top-level powertrain control unit measures or estimates the vehicle states, e.g., applied torque on the wheels and inputs, such as throttle actuation. This controller generates commands for the lower-level subsystem control units that are the ICE, battery pack, electric drive systems, power electronics, etc. The typical goals of the powertrain control are to maximize the fuel economy, minimize the emissions, and satisfy the requested driving performance. These goals can be achieved with rule-based or optimization-based control strategies [52], [53]. Electrified powertrains can require sophisticated control systems to achieve the best performance. An example is the combined mechanical and regenerative electrical braking system that is typically implemented in electrified powertrains for safety and efficiency. Mechanical braking is used when regenerative braking is not sufficient due to the limited electric machine torque and battery current.

Electric motor drives play a key role in electrified powertrains. The main goal of a motor drive control unit is the accurate actuation of a torque with high bandwidth, e.g., using advanced control strategies [54]. Fast dynamic responses enable better performance in engine speed control, smoother engine start/stop function, and driveline damping controls. The hill-hold performance and high-speed drive quality in an HEV and EV are highly related to the torque control performance of the motor in near-zero speed and near-maximum speed, respectively [4]. The control unit is also responsible for maximizing the electric drive system efficiency by choosing the optimal operating point of the electric machine at low and high speed [55], and it can optimize the operation of the inverter [56]. Additionally, observers and estimators are increasingly used to replace sensors. In particular, "sensorless" algorithms are used to replace resolvers and encoders to increase reliability and reduce cost. Similarly, temperature estimation algorithms are available, e.g., for semiconductor junction [57] and PM on the rotor [58].

The battery pack has another critical role in electrified powertrains. In the pack, a significant amount of energy is stored that is potentially harmful if released quickly. Thus, battery packs use an EMS for protection, control, and estimation. The cells of a pack need to be protected from operation in too low and too high temperatures (fast ageing and damage), excessive current (damage), depletion (recoverable dependent on the chemistry), and overcharging (stress due to high voltage). The risk of under and overvoltage is minimized by keeping each cell SOC in balance. Balancing maximizes the effective capacity of a battery stack. It is typically achieved with dissipative hardware that transforms excess SOC into heat. Nondissipative topologies are based on dc–dc converters and they move charge from cells with high SOC to cells with low SOC. This reduces the energy losses significantly [59]. The SOC of a cell is not, in general, directly measurable, so the BMS actuates balancing currents based on an SOC estimate. One approach to obtain SOC is to estimate the so-called open-circuit voltage and then map it through a nonlinear look-up table. A monotonic nonlinear relationship has been empirically observed between the open-circuit-voltage and SOC. However, some cell chemistries, e.g., Lithium iron phosphate, have flat open-circuit voltage profiles and hence, SOC can be estimated only with large uncertainties using this technique. For these chemistries, coulomb counting is often preferred. It is a method that estimates SOC by integrating the current and dividing by the cell capacity. This method is susceptible to small measurement offsets that shift the estimate over time. More sophisticated methods overcome these shortcomings using battery modes and advanced estimation techniques, e.g., Kalman filters [60] or neural networks [61].

B. Software Requirements

Most software-related accidents occur when software still behaves as specified by its requirements; however, the requirements are flawed [62]. This occurs because of the complexity of modern systems contained mostly in interactions between different software components, hardware components, humans, and the physical environment. Almost all the software-related accidents in aerospace are due to flawed software requirements. The aerospace industry has virtually eliminated implementation errors (software not behaving according to its requirements' specification) through the use of rigorous development processes based on DO-178B and now DO-178C [63]. A key concept of software developed to comply with DO-178B/C is that, for the most critical software, 100% MC/DC (modified condition/decision coverage) testing of the code must be achieved through test cases derived from the (low-level) requirements. This obligation forces developers to create precise, unambiguous requirements' specifications and have traceability from requirements to code, which results in extensive test suites. However, this high level of rigorous quality comes at substantial cost. For the automotive industry to follow in the steps of the aerospace industry, it must find tools and techniques that reduce the current level of human effort required by the aerospace industry to achieve the same level of quality as DO-178C compliance.

C. Model-Based Development (MBD)

MBD has proved to be an effective development paradigm for automotive software. The implementation (coding) phase of software development has been streamlined by automatic code generation. Furthermore, MBD enabled moving the focus of the development from code to models, enabling early verification and validation (V&V) activities, thus significantly decreasing the development costs as errors are found early in the development process [64]. A number of methods and tools have been used in the automotive MBD process contributing to the steady decrease in the number of design and implementation errors. For example, there are tools that can automatically generate tests from models and enable verification of designs (Simulink models) against their requirements. MBD also leverages the capabilities of static analysis tools at both the model and code levels [e.g., Reactis by Reactive Systems and Simulink Design Verifier (SDV) by MathWorks at the model level and Polyspace by MathWorks at the code level]. Static analysis can discover run-time errors like division by zero, overflow, out-of-bound array index, etc.

In general, proper tool support is essential in making a software development process successful. The automotive industry has successfully embedded into its development process a set of tools highly integrated throughout the entire software life cycle: tools for requirements management, system design and models management, documentation production, configuration management, traceability across the software development lifecycle, and change management (e.g., rational suite by IBM).

Recently, system modeling tools such as MapleSim, AMESim, and Dymola have been successfully used in automotive model-based systems engineering. They provide intuitive plant modeling from engineering artifacts (e.g., from schematics of powertrain architectures or sets of differential equations). Although these tools are not geared specifically to controller design, they serve as excellent environments for real-time simulations with hardware-in-the-loop (HIL) capabilities, system analysis (parameter optimization), sensitivity analysis, etc. Ultimately, when compared to traditional plant modeling, e.g., in Simulink, these tools enable much quicker, less error-prone development [65], [66]. While these tools are yet to become a consistent part of a typical automotive MBD process, given their benefits, their use is likely to proliferate. For example, MapleSim has been used to generate relevant calibrations from physical models of different powertrains, effectively implementing variability in software due to different powertrain architectures [67].

D. Automotive Open System Architecture (AUTOSAR)

The rapid increase in the complexity of software in modern cars had prompted a need for a standardized software architecture. The AUTOSAR initiative [68] resulted in development of a standardized architecture with the main goal of reusability of software and hardware components between OEMs, suppliers, and different vehicle platforms. AUTOSAR is a layered architecture that hides the details of particular microcontroller in an ECU, and standardizes interfaces between software components. Therefore, the architecture provides a standardized platform to combine different vehicular features, providing modularity and reusability.

E. Safety

The automotive industry has always considered safety as a major engineering concern. The advent of the new international automotive standard, ISO 26262: Road Vehicles—Functional Safety [69], ratified in 2011, has recognized the need to properly address safety of electrical and/or electronic components, recognizing the rapidly increasing role of these components in performing safety critical functions in cars. ISO 26262 has become de facto standard in the automotive industry. Although the standard suffers from issues common to software engineering standards throughout different domains (e.g., ambiguity, inconsistency, and focus on process as opposed to focus on product), it represents an important step to providing proper guidelines for the development of safe vehicular software.

A key component of safety engineering is hazard analysis. Hazard analysis identifies hazards and all the scenarios that can lead to the hazards, so that they can be eliminated or mitigated against. For example, typical hazards in the automotive industry are unintended deceleration/acceleration, loss of braking, wrong direction, etc. The rapidly increasing role of software in electrified vehicles has also made some of the traditional hazard analysis techniques devised half a century ago insufficient to properly tackle all the aspects of today's large software-intensive vehicular systems rich with complex interactions with the environment and human operators. While new hybrid powertrain architectures provide unprecedented opportunities for improved energy efficiency, they also introduce multiple potential sources of hazards. The automotive industry is currently exploring new techniques that would more appropriately account for the complexity in these modern cars (e.g., systems-theoretic process analysis (STPA) [70]).

VIII. CONCLUSION

Transportation electrification is a paradigm shift from less-efficient ICE-based vehicles toward more efficient and cleaner electrified vehicles to enable a sustainable transportation system. Electrification can occur in both vehicular propulsion and nonpropulsion loads. Higher degrees of electrification represent a larger power electrical path leading to less use of fossil fuels and hence, better fuel economy and lower GHG emissions. The level of electrification starts from conventional vehicles where more nonpropulsion loads are electrified. Mild hybrids, full hybrids, plug-in hybrids, and EVs have a gradual increase in the electrification level, where the fuel consumption decreases and electric range increases.

In electrified powertrain applications, the efficiency of the electric path and the power and energy density of the components play critical roles. In addition, the selection of the powertrain architecture, design of the powertrain components, systems, controls, and software are coupled together to improve the performance and reliability of the vehicle. In this paper, the transportation electrification vision has been explained and the major components of electrified powertrains have been discussed, including power electronics, electric machines, electrified powertrains, ESSs, and controls and software. The applications, enabling technologies, solutions, and future trends are investigated.

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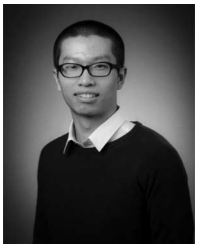

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