The latest in electric vehicle power management

Steve Taranovich - October 17, 2016

Save our planet from pollution! That is the cry from scientists and concerned people in general around the world to lower greenhouse gas emissions. Motor vehicles worldwide propelled via fossil fuel combustion engines are a huge culprit. Although several alternatives can propel a motor vehicle, only one is readily available today: electricity.

Enter electric propulsion technology, where a totally new architectural drivetrain is integrated into the vehicle. This new addition requires multi-disciplinary research into appropriate system components. The electric vehicle system is composed of an electric motor, power electronics converters, and energy storage devices like Lithium-ion batteries. The new architectural system must be optimized to maximize system efficiency in order to get maximum drive distance on a single charge. All this electronics technology comes with the caveat of having a major thrust to reduce transportation emissions.

Electric vehicles (EVs) and hybrid electric vehicles (HEVs)

Electric vehicles (EVs) run on batteries as do hybrid electric vehicles (HEVs) which also have a fossil fuel-fired combustion engine assist. Energy efficiency is paramount for the success and future of such technologies powering these vehicles, so clever power management schemes are needed to maximize the efficiency in conversion of battery energy into the mechanical drive to the wheels for increasing mileage capability on a single charge, without increasing carbon emissions and ideally significantly lowering them.

Silicon carbide (SiC) power in EVs

The weight, size and cost of an EV, as well as drivable distance on a single charge, is directly related to the efficiency of its electronic power conversion system. SiC power elements are capable of operating very well in the high temperature environment experienced in automobiles. Let’s take a close look at silicon carbide power elements in the improvement of efficiency of these systems.
Lower weight means extended mileage capability. One typical way to lower weight, cost and size of a power conversion system is to raise the switching frequency in switching regulators. At higher frequencies we know that active elements like inductors, capacitors and transformers will shrink down in size and weight. Enter SiC solutions.

Although silicon (Si) power devices can also operate at high frequencies, SiC holds an advantage of being able to handle much higher voltages than Si. SiC is a wide bandgap semiconductor device and a wider bandgap translates to a higher critical field (critical field is the blocking voltage in the off-state). The high voltage capability of wide bandgap (WBG) SiC devices allow them to achieve lower on-state resistances leading to faster switching speeds and unipolar operation in part because its carriers need to be accelerated to a much higher speed (higher kinetic energy) to overcome that wider gap. Although gallium arsenide (GaAs) and gallium nitride (GaN) also have high critical fields and are also improvements for high power solutions, SiC has some other advantages such as a higher maximum operating temperature, a high *Debye temperature*, high thermal conductivity (in polycrystalline SiC), high saturation velocity of carriers giving fast switching and low resistivity in an electric field, the easy formation of silicon dioxide (SiO$_2$) leading to lower production costs, and high threshold energy leading to more robust radiation hardening.

SiC devices have many key applications in the EV. Existing electric traction drives presently are able to convert 85% of their power to mechanical energy to the wheels which is pretty efficient, but SiC can help improve efficiency here too. It is the electronic power converter that can benefit by improvements in efficiency since it can be used in bringing battery power to the engine, as well as being used in the battery charger circuitry and any auxiliary power supply needs (*Figure 1*).

*Figure 1* SiC power devices have many uses in the electric vehicle (Image courtesy of Reference 1).

Some good examples of how SiC power devices have increased efficiencies in EVs is in a SiC-based power supply converting 750V to 27V for the low voltage EV bus. This architecture has increased efficiency from 88% to a whopping 96%, reduced the size and weight by 25% and eliminated the
need for fans to cool the excess heat in comparison to a Si solution. Table 1 shows some more important applications of SiC power devices in EVs. References mentioned in the table can be found by accessing Reference 1 at the end of this article.

Table 1 Some SiC applications in an EV electronics architecture (Image courtesy of Reference 1)

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(PCU is the Power Control Unit; APS is the Auxiliary Power Supply)

Table 1 Some SiC applications in an EV electronics architecture (Image courtesy of Reference 1)

GaN power in EVs

GaN power in EVs\(^2\)

GaN is no slouch either when it comes to power improvements in an EV. The wide usage of IGBTs in motor drive and DC/DC control has been Silicon-based until recently. These designs exhibited switching times in the order of 10 to 100 kHz whereas a GaN device is able to attain nanosecond switching times with the bonus of being able to easily operate in 200ºC automotive environments.

GaN, just as SiC, devices will also shrink down the size of inductors, capacitors and transformers in the power supply architecture with their higher switching speed capabilities. They also reduce the volume and weight with the reduction in sizes of those passive devices.

We will look at power efficiency here in light of the battery chemistries in EVs like Lithium-based
chemistries and NiMH with their high energy density capabilities. As mentioned in the previous SiC device section, efficiency needs to be improved in power conversion architectures in order to drive a greater distance on a single charge.

With silicon devices having reached their maximum limit in switching speed and lowest on-state resistance, GaN is looking like a solution of choice to move beyond these limits. Experiments have shown that if the switching frequency can be increased fivefold, an inductor’s and capacitor’s volume could be reduced as much as fivefold. Very high speeds are possible in today’s GaN technology.

GaN power devices excel in four key areas as a power element: high temperature operation, higher breakdown voltage, low $R_{\text{ON}}$, and nanosecond switching ranges for higher frequency operation advantages mentioned above. So GaN looks similar to SiC in these advantages, but two other points that set it apart are that LEDs and RF transistors have been already produced with GaN and many Si fabrication processes are compatible with the GaN process which lowers the cost of wafers and process-related costs as compared with a SiC higher substrate cost.

Today’s technology has shown the first GaN high electron mobility transistor (HEMT) devices in production, since conquering their reliability issues early on in 2003. These are normally-on devices, so a gate voltage of 0V leads to a conductive state and any voltage less than 0 will turn the device off. In the early days a SiC substrate was used, but once a Si substrate was perfected for use with GaN, the production costs came down significantly. In 2014 a new cascade architecture was realized that changed the normally-on device to a normally-off one.

Driver technology has significantly improved since the early days and higher levels of integration are seen as possible. Significant advances have been made in power inverters as well. GaN devices excel in the battery charger end of the EV made up of a AC/DC converter stage followed by a DC/DC converter. This combination is a power factor controller (PFC) (Figure 2).

![Figure 2](image.png) A typical EV power architecture (Image courtesy of Reference 2)

Again here with GaN, smaller passive components are realized with the higher switching speed
capabilities of GaN HEMTs. The increased frequency leads power architectures to a lower ripple current via the smaller inductor. An improved power factor is achieved because of this and in turn gives us a smaller and lower cost capacitor. The lower ripple current also provides less stress on the capacitor which improves its reliability and lifetime.

**GaN reliability** has been raised to a very high standard in the last few years which is a key to its use in automobiles.

**Lowering GHG emissions with HEV powertrain efficiency**

**Lowering global greenhouse gas (GHG) emissions with HEV powertrain efficiency**

Today, road vehicles produce about 72% of transportation emissions. Improving the design of the HEV powertrain to increase efficiency may be a big part of lowering these emissions. One suggested method to achieve this is to enhance the efficiency of the DC-link voltage control architecture. This means that the efficiency of power converters in a series HEV powertrain needs to be improved as a first big step.

The DC-link typically connects the three powertrain branches related to series HEVs: The primary source composed of a three-phase rectifier; the secondary source made up of a dual active bridge (DAB) DC/DC converter; and the propulsion load composed of a three-phase inverter (**Figure 3**).

**Figure 3** A HEV powertrain block diagram (Image courtesy of Reference 3)

In a design topology in which the DC-link and the battery voltages are not equal, a DC/DC converter intermediate solution is necessary. The paper "Voltage Control for Enhanced Power Electronic Efficiency in Series Hybrid Electric Vehicles" (**Reference 3**), outlines many approaches in research regarding different architectures for these cases as well as ideas for variable DC-link voltage and DC/DC converter control.

In this section we will address a proportional control law, which will control the dynamic DC-link voltage for the phase shift between the gate switching waveforms of the bridges of a DAB DC/DC converter which is between the DC-link and the battery of a series HEV powertrain as shown in **Figure 4**. In this scenario the controller is able to achieve lower power electronic losses of the DC/DC converter as well as in the total powertrain.
The HEV powertrain interconnections are shown in the control schematic. The internal combustion engine (ICE), continuously variable transmission (CVT), permanent magnet synchronous generator (PMSG) or the primary power source in the HEV, permanent magnet synchronous motor (PMSM) or the propulsion load in the HEV, are key parts of the system shown. (Image courtesy of Reference 3)

In this model, the diesel engine is the primary source of power to the HEV and the DC battery is the secondary source. The supervisory control system (SCS) controls the relative portion of power supplied by each of these two sources based upon the battery state-of-charge (SOC) and the motor load.

In essence the DC-link voltage, in this series HEV, puts a restraining condition on the desired operating region of the PMSM and the PMSG which corresponds to the unity modulation index; that keeps the system from an over-modulation condition which would distort the system signal and thus hinder system efficiency goals. The overall efficiency can be improved in the power electronics system of the powertrain by keeping the modulation indices close to unity, which maximizes the inverter and rectifier efficiencies, whose dominant source of efficiency loss is the switching process. Thus dropping the switching voltage will increase the efficiency.

This persistent zero voltage switching (PZVS) scheme, minimizing power losses, is best suited for vehicles with high hybridization factor, especially in an urban environment. The hybridization factor (HF) shows the ratio between the installed power from the electric source and the total installed power. This HF affects fuel consumption in an HEV.

The automotive inverter

The main power inverter controls the electric motor inside an electronic drivetrain and is an important component in the HEV/EV. The power inverter determines driving behavior just as the engine management system (EMS) does in a combustion vehicle. This inverter will operate for any
motors such as synchronous, asynchronous or brushless DC, and is controlled by an integrated electronic PC card, which auto-makers design specifically to minimize switching losses and maximize thermal efficiency. The inverter’s other function is to capture energy released through regenerative breaking and feed it back to add charge to the battery. The range of the HEV/EV is directly related to the efficiency of this main inverter (Figure 5).

![Figure 5](Image courtesy of Infineon in Reference 4)

Dual voltage battery systems

Managing the batteries of HEVs and EVs requires high-voltage technologies. Dual-voltage systems, combining 12-V and 48-V batteries, need bidirectional DC/DC conversion, illustrated in Figure 6, in order to protect the circuitry and enable architectural functionality.
Also, typically a single-phase 3.5kW or 7kW onboard charger module (OBCM) is designed into the automobile architecture to charge the EV or plug-in hybrid electric vehicle (PHEV) from the power grid. Conversely, the EV and PHEV can be used as an energy source, as well as an energy storage device in a smart grid integrated with renewable energy sources. Smart grid operation considers smart charging and discharging EVs and PHEVs, this is why the OBCM needs to be a bi-directional DC/DC charger.

Some proposals for the best architecture in this type of design have suggested a boost series resonant bidirectional topology as shown in Figure 7. This architecture is operated above the resonant frequency with zero voltage commutations and maximum power transfer at minimum switching frequency. Comparing this technology with a unidirectional power flow converter involves the replacement of diode rectifiers by MOSFET rectifiers. This solution also has high efficiency and wide battery range capability. One main deficiency in this architecture in Figure 7 is the high turn off loss of the rectifier bridge which will need to be addressed in future designs.
Delphi’s integration and cabling

Delphi has done an amazing job of integrating everything we have discussed in this article and more regarding the power electronics in the HEV (Figure 8).

Let’s not forget about the importance of proper internal connectors in an HEV/EV (Figure 9).
Figure 9 Minimizing mass is critical in an HEV/EV. Delphi has innovations in small gage cable technologies, insulation materials and lighter weight alternatives to copper such as aluminum or even using some of their special proprietary alloys (Image courtesy of Delphi Reference 7).

Electronic wheel drive system

A hub drive system for HEV and EV was proposed in "Design and Implementation of an Electric Drive System for In-Wheel Motor Electric Vehicle Applications" (Reference 8) and a Matlab SIMULINK model of a hub-driven HEV was developed with calculated performance. Two 15 kWDC brushless DC (BLDC) motors were designed and manufactured to be located inside the rim of the wheels of the HEV.

Also, two separately driven rear wheels were mounted to a Fiat Linea as well. The mechanical differential was replaced by an electronic control technique, based on the detection of the angle of the steering wheel. A CAN bus communication is designed in between the control system of the electric drive and electronic control unit (ECU) of the vehicle. A successful tandem action between electrically driven rear-wheels and ICE driven front axle was achieved.
The BLDC machine with concentrated windings was selected for the design because of its low power to weight ratio, high efficiency and ease of control.

**Figure 10** An image of the BLDC motor for one of the rear wheels (Image courtesy of Reference 8).

**Figure 11** Exploded view of the direct drive BLDC motor in the wheel rim and motor-generator setup (Image courtesy of Reference 8)

*The driver*
The BLDC motor electronic driver is composed of an integrated power module (IPM), an 8 bit microcontroller and an electronic control system. The software for the driver is developed to control the commutation of the IGBTs and pulse width modulation (PWM) voltage control of the motor. The system has opto-coupler isolation, current and temperature protection and speed, current and voltage sensors are inserted into the system as well.

So in this article we have tried to give you a look at some of the diverse latest developments in the last few years regarding EV and HEV power management. There are certainly many more developments to come which will further improve these systems and benefit our planet. Stay tuned for more detailed analyses on EDN as the technology matures even more.

Please share your ideas and experiences on this topic with our audience in order that we all may learn from each other as well in your comments below.

References

4. Infineon main HEV inverter
5. Driving the green revolution in transportation, Karl-Heinz Steinmetz, Texas Instruments
6. High Efficiency Wide Range Bidirectional DC/DC Converter for OBCM Application, Gang Liu, Dan Li, Jian Qiu Zhang, Min Li Jia, IEEE 2014

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