Topology, design, analysis and thermal management of power electronics for hybrid electric vehicle applications

Chris Mi*

Department of Electrical and Computer Engineering,
University Michigan, Dearborn, MI, 48128, USA
E-mail: mi@ieee.org
*Corresponding author

Fang Z. Peng

Department of Electrical and Computer Engineering,
Michigan State University, East Lansing, MI 48824, USA
E-mail: fzpeng@egr.msu.edu

Kenneth J. Kelly, Michael O'Keefe and Vahab Hassani

National Renewable Energy Laboratory, Golden, CO 80401, USA
E-mail: Kenneth_kelly@nrel.gov
E-mail: Michael_OKeefe@nrel.gov

Abstract: Power electronics circuits play an important role in the success of electric, hybrid and fuel cell vehicles. Typical power electronics circuits in hybrid vehicles include electric motor drive circuits and DC/DC converter circuits. Conventional circuit topologies, such as buck converters, voltage source inverters and bidirectional boost converters are challenged by system cost, efficiency, controllability, thermal management, voltage and current capability, and packaging issues. Novel topologies, such as isolated bidirectional DC/DC converters, multilevel converters, and Z-source inverters, offer potential improvement to hybrid vehicle system performance, extended controllability and power capabilities. This paper gives an overview of the topologies, design, and thermal management, and control of power electronics circuits in hybrid vehicle applications.

Keywords: DC/DC converter; electric drives; electric vehicles; fuel cell; hybrid electric vehicles; power electronics, motor control.

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Biographical notes: Chris Mi is Associate Professor of Electrical and Computer Engineering at the University of Michigan, Dearborn. He received his BSEE and MSEE degrees from Northwestern Polytechnical

University, China, and a PhD from the University of Toronto, Canada. His research interests are in power electronics, hybrid electric vehicles, electric machines and renewable energy systems. He is the recipient of numerous awards, including the Distinguished Teaching Award from the University of Michigan, the National Innovation Award and the Government Special Allowance Award from China, and many IEEE and SAE Awards.

Fang Z. Peng is a professor of the Department of Electrical and Computer Engineering at Michigan State University and a fellow of the Institute of Electrical and Electronic Engineers. He obtained his BS from Wuhan University, China and MSc and PhD from Nagaoka University of Technology, Japan. His current research interests include power electronics for renewable energy sources, hybrid electric vehicles, and motor drives.

Kenneth J. Kelly has worked at the National Renewable Energy Laboratory, Golden, CO, since 1991. He is currently the task leader for research and development of advanced thermal control technologies for power electronics in the Advanced Vehicles Group. Previously, he led efforts in robust design for fuel cells and advanced heavy-duty hybrid electric vehicles. He also has experience with alternative fuel vehicle emissions testing and fleet evaluations. He worked in industry as a manufacturing engineer with the Swagelok Company. He holds MS and BS degrees in mechanical engineering from Ohio University.

Michael O'Keefe received his BS in mechanical engineering from Northern Arizona University in 1996 and MS in Mechanical Engineering and MS in Technical Japanese from the University of Washington in Seattle in 2000. He joined the National Renewable Energy Laboratory in 2000 in the area of vehicle systems analysis and helped to develop the ADVISOR vehicle simulation code. He currently works on DOE's Advanced Power Electronics and Electric Machines Program, in the area of thermal management and power electronics reliability.

Vahab Hassani worked at NREL from 1990 to 2007, when he died from ALS. Over his life he contributed to energy efficiency technology in buildings, thermal systems, automotive power electronics and fuel cells. He held a PhD and MS in mechanical engineering from the University of Waterloo, Ontario and a BS in mechanical engineering from Shiraz University, Shiraz, Iran. He also served as an adjunct professor of mechanical engineering at the Colorado School of Mines, University of Colorado, and Colorado State University. He holds six patents and has received numerous awards for outstanding research. His contributions will continue to be recognised by the scientific community for years to come.

1 Introduction

A critical factor propelling the shift from conventional gasoline/diesel engine vehicles to electric, hybrid, and fuel cell vehicles is the revolutionary improvement in performance, size, and cost of power electronics circuits over the past decade, with parallel improvements in sensors and microprocessors.

Typical power electronic circuits used in hybrid electric vehicles (HEV) include rectifiers, inverters and DC/DC converters. In this paper, we first provide an overview of the topological evolution of power electronics circuits, including buck converters, bidirectional boost converters, rectifiers and full bridge inverters. Novel topologies, such as multilevel converters, Z-source inverters and bidirectional isolated converters, are discussed. Modelling and simulation of power electronics circuits are investigated, including system level modelling, physics based device modelling, feedback control and stability analysis. Practical circuitry design and electromagnetic compatibility (EMC) are also briefly discussed.

The issues to be addressed in the design of HEV power electronics circuits include[1] (Amrhein and Krein, 2005; Bose, 2000; Chan et al., 1996; Di Napoli et al., 2002; Ehsani et al., 1997, 2001; Emadi et al., 1999, 2006; Hamilton, 1996; Hayes and Egan, 1999; Jahns and Blasko, 2001; Katsis and Lee, 1996; Krein et al., 1994; Marei et al., 2005; Miller, 2003; Namuduri and Murty, 1998; Rahman, 2004; Rajashekara, 2003; Solero et al., 2005; Tolbert et al., 1998; Vezzini and Reichert, 1996; Xingyi, 1999):

- *Electrical design*: including main switching circuit design; controller circuitry design; switching frequency optimisation; and loss calculations.
- *Control algorithm design*: including developing the control algorithm to achieve the desired voltage, current and frequency at the output, and to realise bidirectional power flow as needed.
- *Magnetic design*: including the design of inductors, transformers, and other components, such as capacitors, needed for filtering, switching, and gate driver units.
- *Mechanical and thermal design*: including modelling of the loss of power devices and magnetic components; cooling system, heat sink, and enclosure design; and integration of the power electronics unit.

In addition to hybrid vehicles, in order to meet the increased electric demand in conventional vehicles, there will be a major change in the electrical architecture by moving the system from the current 14 V to 42 V. The proposed 42 V system will help lower the current draw from the battery and reduce electrical system losses. Power electronics is also an enabling technology for the implementation of control-by-the-wire systems in future vehicles, intended to increase the safety and comfort features.

Figure 1 shows the configuration of a parallel HEV powertrain used for the Toyota Highlander Hybrid Sport Utility Vehicle (SUV).[1] In this configuration, the front wheel is driven by a hybrid powertrain, while the rear wheel is driven by a separate electric motor (MG3) to achieve all-wheel driving capability without the need for a conventional differential. The front hybrid powertrain contains a planetary gear set, an internal combustion engine (ICE), and two electric machines MG1 and MG2. MG1 serves primarily as a generator to split the engine power, whereas MG2 serves primarily as a motor to drive the vehicle and recover the regenerating braking energy.

2 Circuit topologies

Figure 2 shows the integrated power electronics unit used to control the hybrid vehicle shown in Figure 1. The power electronics unit consists of a bidirectional DC/DC converter that links the lower voltage hybrid battery and the higher voltage DC bus, and three motor drive circuits that control the front and rear motor/generators.

Figure 1 The powertrain layout of a hybrid vehicle with a front hybrid powertrain and a separate rear motor

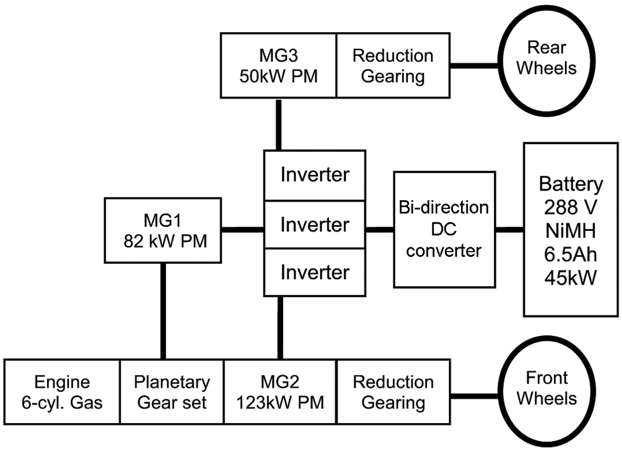
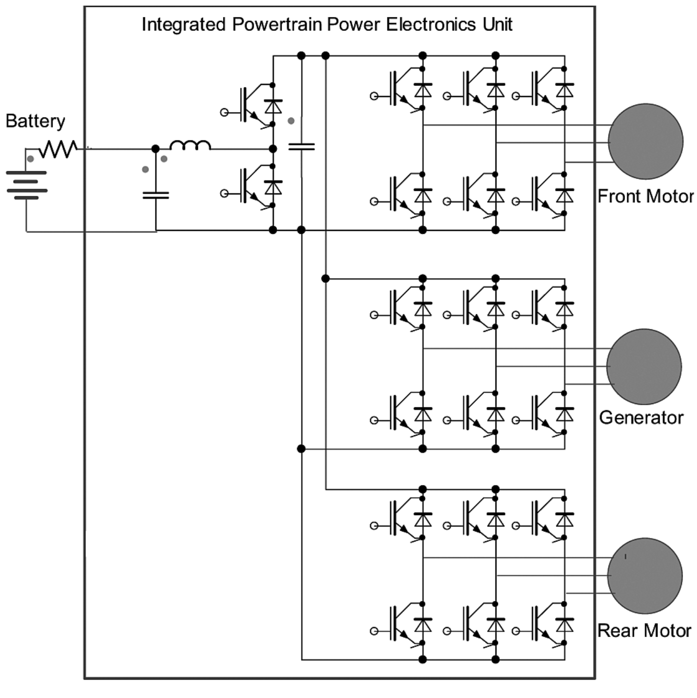


Figure 2 The integrated powertrain power electronics unit used to control the hybrid vehicle shown in Figure 1



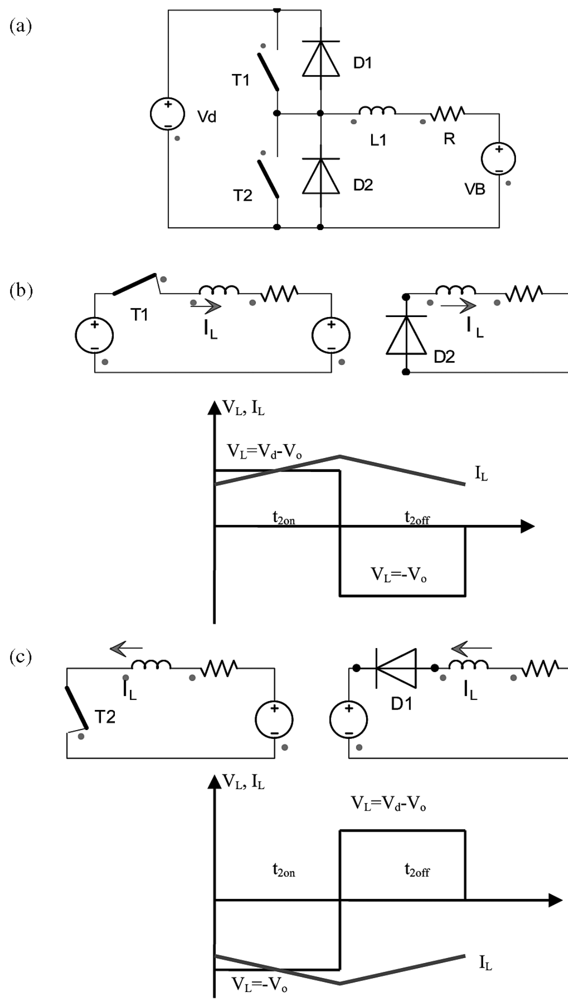
In conventional vehicles, the air-conditioning (A/C) compressor is belt-driven by the engine. In more advanced hybrid vehicle designs, the engine is turned off very often during stop-and-go driving patterns. In order to have A/C while the engine is off, the A/C compressor needs to be driven by an electric motor that runs off the hybrid battery. In addition, it is necessary to have a bidirectional DC/DC converter to link the 14 V auxiliary battery with the hybrid battery. Both the A/C motor controller and the low power bidirectional DC/DC converter can be integrated with the main power electronics unit.

2.1 Bidirectional boost converter

There are typically two bidirectional DC/DC converters in hybrid vehicle applications. One of them is a high-power converter that links the hybrid powertrain battery at a lower voltage with the high voltage DC bus. A second low-power DC/DC converter links the hybrid battery with the low voltage auxiliary battery.

The DC/DC converter provides bidirectional power transfer. The operating principle is shown in Figure 3.

Figure 3 Operation of the bidirectional boost converter: (a) circuit topology; (b) inductor voltage and current waveform during buck operation; (c) inductor voltage and current waveform during boost operation



2.1.1 Buck operation

In buck operation, as shown in Figure 3(b), the power is transferred from V_d to V_B. When T_1 is closed and T_2 is open, since $V_d > V_B$, $V_L = V_d - V_B$ and the inductor current I_L builds up. When T_1 is open, the inductor current I_L continues to flow through D_2. $V_L = -V_B$.

Assume ideal components and a constant V_o, the inductor current over one cycle in steady state operation will remain the same, e.g.

$$\int_0^{t_{1on}} (V_d - V_o)dt = \int_{t_{1on}}^{t_{1on}+t_{1off}} (-V_o)dt \tag{1}$$

$$V_o = \frac{t_{1on}}{T} V_d = D_1 V_d \tag{2}$$

where D_1 is the duty ratio defined as the percentage of on-time of switch T_1.

$$D_1 = \frac{t_{1on}}{T}. \tag{3}$$

2.1.2 Boost operation

In boost operation, the power is transferred from V_B to V_d. When T_2 is closed and T_1 is open, V_B and inductor form a short circuit through switch T_2 as shown in Figure 3(c), therefore $V_L = -V_B$ and the inductor current I_L builds up. When T_1 is open, the inductor current continues to flow through D_1 to V_d, therefore $V_L = V_d - V_B$.

$$\int_0^{t_{2on}} V_o dt = \int_{t_{2on}}^{t_{2on}+t_{2off}} (V_d - V_o)dt \tag{4}$$

$$V_d = \frac{1}{1 - D_2} V_o \tag{5}$$

where D_2 is the duty ratio defined as the percentage of on-time of switch T_2.

$$D_2 = \frac{t_{2on}}{T} \tag{6}$$

In the bidirectional boost converter control, since T_1 and T_2 cannot be switched on simultaneously, a practical control strategy is to turn T_2 off while T_1 is on and vice versa. In this case,

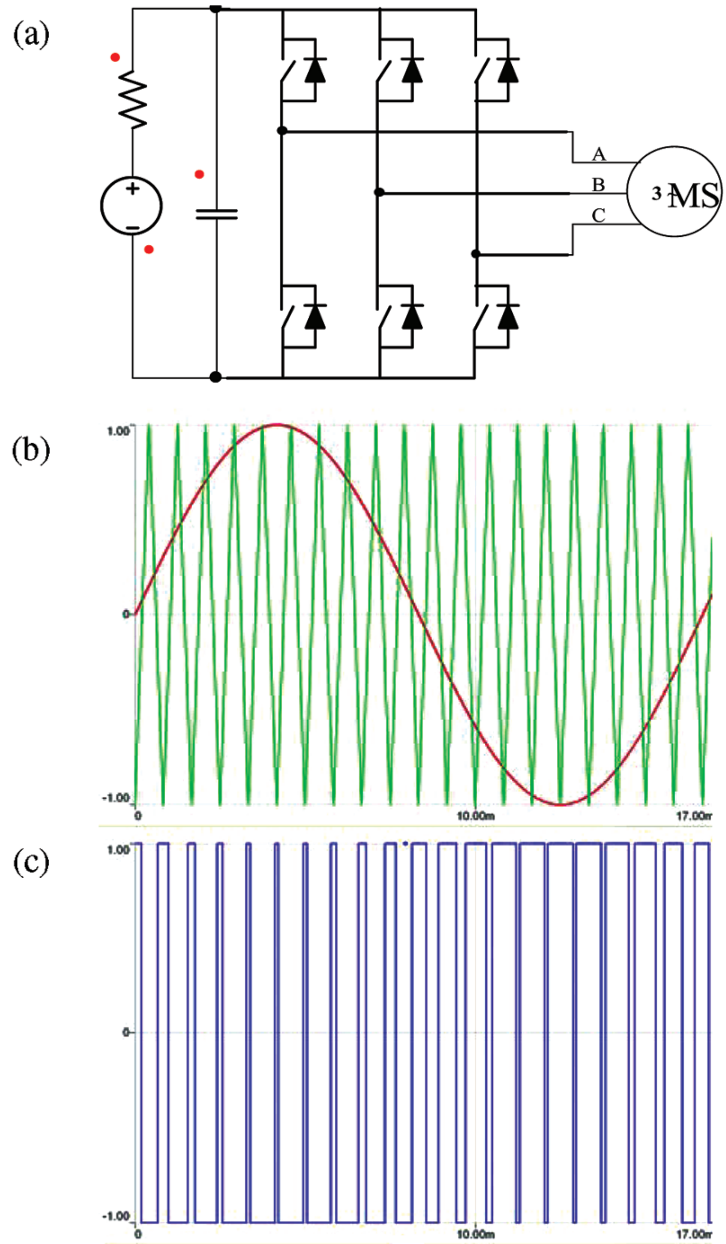
$$D_2 = 1 - D_1. \tag{7}$$

2.2 Voltage source inverter

Voltage source inverters (VSI) are used in hybrid vehicles to control the electric motors and generators. Figure 4 shows the power electronic circuits arrangement of a VSI to control induction motors, permanent magnet synchronous motors, and permanent magnet brushless motors. The switches are usually IGBTs for high- voltage high power hybrid configurations, or MOSFETs for low-voltage designs.

The output of the VSI is controlled by means of a pulse-width-modulated (PWM) signal to produce sinusoidal waveforms. Certain harmonics exist in such a switching scheme. High switching frequency is used to move the harmonics away from the fundamental frequency.

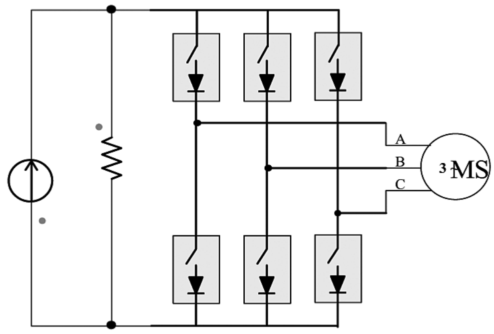
Figure 4 Voltage source inverter: (a) circuit diagram; (b) control of the switches; (c) gate control signal via PWM waveform (see online version for colours)



2.3 Current source inverter

Figure 5 shows the circuit topology of a current source inverter (CSI). The CSI operates using the same principle that operates a VSI, with the input as a current source. Three small commutating/filtering capacitors may be needed on the ac side.

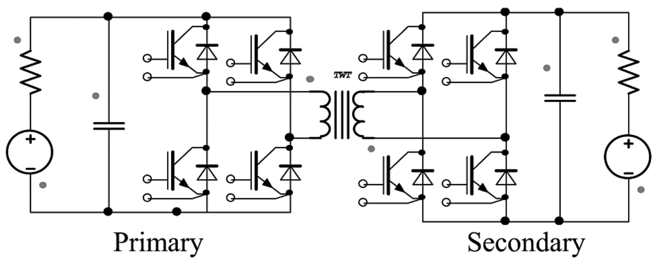
Figure 5 Current source inverter



2.4 Isolated bidirectional DC/DC converter

In some applications, galvanic isolation between the battery and the load units is necessary and desirable. Figure 6 shows a full bridge isolated bidirectional DC/DC converter (Gargies et al., 2006).

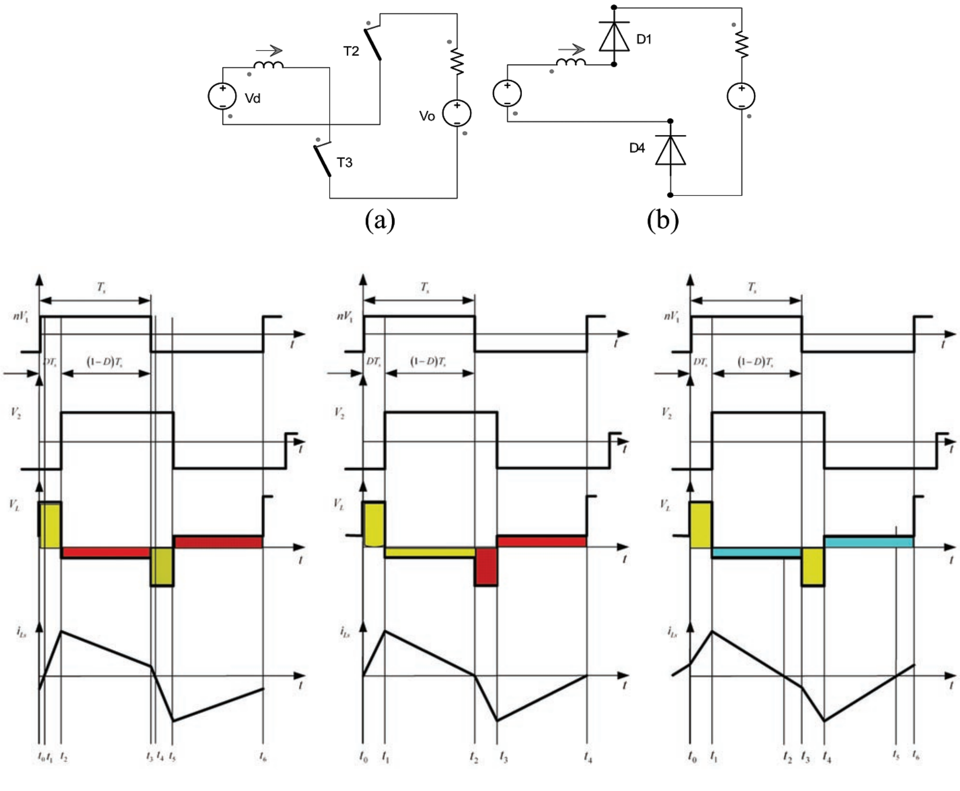
Figure 6 Isolated bidirectional DC/DC converter



In Figure 6, the primary bridge inverter switches at 20 to 50 kHz, with a 50% duty ratio. The output of the primary is a square wave voltage which is applied to the primary winding of the isolation transformer. The secondary winding of the transformer will therefore have a square wave voltage. Without any control at the gating of the secondary bridge converter, the voltage of the secondary of the transformer is rectified through the four free-wheeling diodes. The output voltage will fluctuate with load conditions and change of the primary voltage.

In order to maintain a constant output at the secondary, a phase shift control is necessary at the secondary bridge. By controlling the secondary bridge with a phase shift from the primary bridge, the amount of power flow and power direction can be controlled and regulated to maintain a constant output voltage. Figure 7 shows the phase shift operation of the converter. When the output of the transformer is positive, switches T_2 and T_3 are turned on for the duration of ΔT_S. Therefore the transformer voltage (positive), T_3, V_o, and T_3 forms a short circuit and the current in the transformer leakage inductance increases. After this duration, switch T_2 and T_3 are turned off, then the inductor current will flow through D_1 and D_4 to transfer power from V_d to V_o.

Figure 7 Operation of the phase shift control of the isolated bidirectional DC/DC converter: (a) when T_2 and T_3 are turned on; (b) when T_2 and T_3 are turned off; (c) voltage and current waveform of the leakage inductance of the transformer (see online version for colours)



In steady state operation, the output current of the converter is:

$$I_o = \frac{nV_1}{2f_s a\,L_s} D(1 - D) \tag{8}$$

For resistive load R_L, the output voltage is

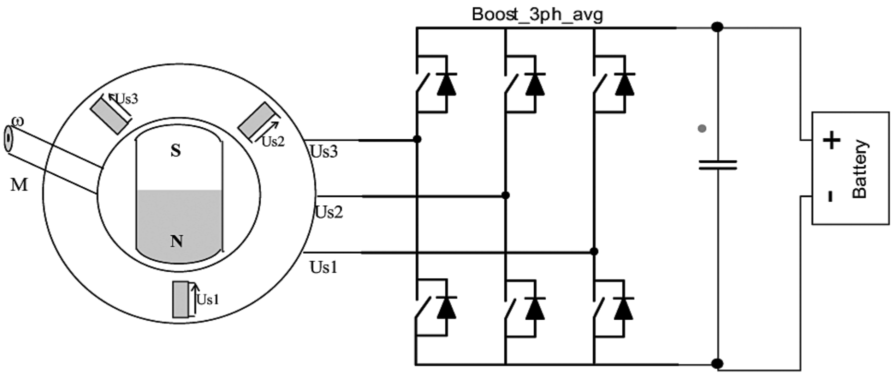
$$V_2 = \frac{nV_1}{2f_s\,L_s} R_L D(1 - D) \tag{9}$$

where D is the preset phase shift value as a percentage of the switching period, T_s is the switching period, nV_1 is the voltage at the secondary of the transformer, V_o is the DC voltage at the out put of the secondary inverter, and R_L is the load resistance is the leakage inductance of the secondary winding of the isolation transformer.

2.5 PWM rectifier

In braking mode, the motor is controlled to achieve regenerative braking. The VSI is operated as a PWM rectifier, as shown in Figure 8. The operation principle of the PWM rectifier, when the motor (operated as a generator) speed is below the base speed of the constant power region, is essentially the same as the boost operation of the isolated DC/DC converter described in the previous section.

Figure 8 PWM rectifier

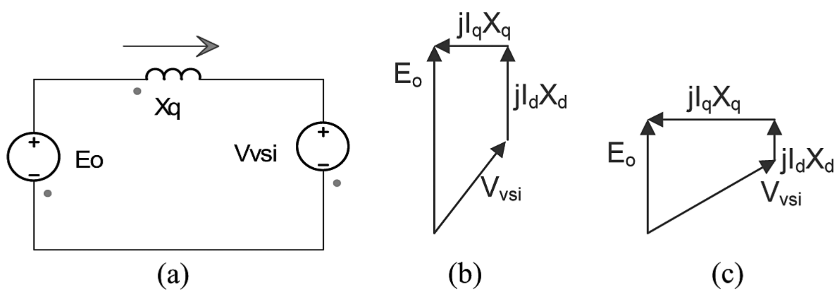


When the motor speed is above the base speed of the constant power region, the generator develops a back emf much higher than the DC link voltage, especially when a large constant power speed range is designed. In this case, the motor needs to be controlled in its field weakening region to reduce its winding terminal voltage. Neglecting the stator resistance and salience, the equivalent of the control is illustrated in Figure 9, where E_o is the induced back emf of the PM motor, L_q is the synchronous inductance, and V_{vsi} is the equivalent sine wave output of the VSI.

$$V_{vsi} = E_o - j\,I_q\,X_q - j\,I_d\,X_d \tag{10}$$

The purpose of the field weakening control is to achieve a constant V_{vsi} for higher E_o, by applying a current opposite to the d-axis direction.

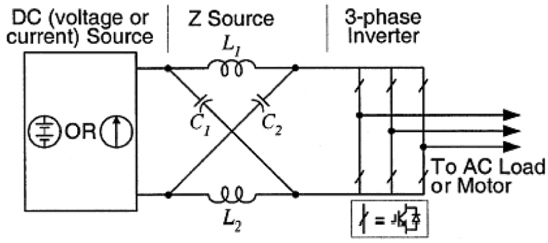
Figure 9 Regenerative braking in the constant power region: (a) equivalent circuit; (b) phasor diagram at high speed in the constant region; (c) phasor diagram at lower speed in the constant power region



2.6 Z-source inverters

In hybrid vehicles, the inverter and the motor are usually oversized to meet the wide speed range for constant power operation. A Z-source inverter, as shown in Figure 10, can potentially provide cost effective and reliable solutions (Fang et al., 2004; Huang et al., 2005; Peng, 2003, 2004; Peng et al., 2003, 2004, 2005; Shen et al., 2004a,b).

Figure 10 Z-source inverter used in the powertrain motor control

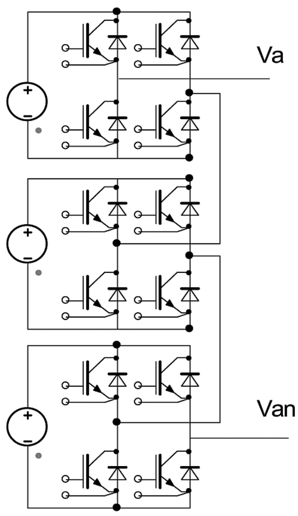


2.7 Multilevel converters

In high power and high voltage applications, traditional two-level VSI or CSI have limitations in operating at high frequency, because of switching losses and the constraints of device ratings. Multilevel converters have been used in electric power systems and large motor drives. Multilevel converters can reduce device stress, achieve high voltages with low harmonics, and produce minimum electromagnetic interference or common-mode voltage.

Different methods can be used to construct multilevel converters. One example is to use a cascaded connection, as shown in Figure 11. The advantage of such a configuration is the ability to use multiple DC inputs at each level. This is particularly true when multiple onboard energy storage devices or energy sources are available. The disadvantages of multilevel converters are the increased number of devices with the increase in the number of levels.

Figure 11 Cascaded multilevel single phase converters



3 Modelling and simulation of power electronics circuits

Modelling and simulation plays an important role in the design and development of power electronics circuits. The simulation of power electronics circuits in hybrid vehicle applications can be divided into two categories: device level simulations and system level simulations (Amrhein and Krein, 2005; Filippa et al., 2005; Hak-Geun et al., 2000; Mi et al., 2005; Onoda and Emadi, 2004; Williamson et al., 2006).

3.1 Device level simulation

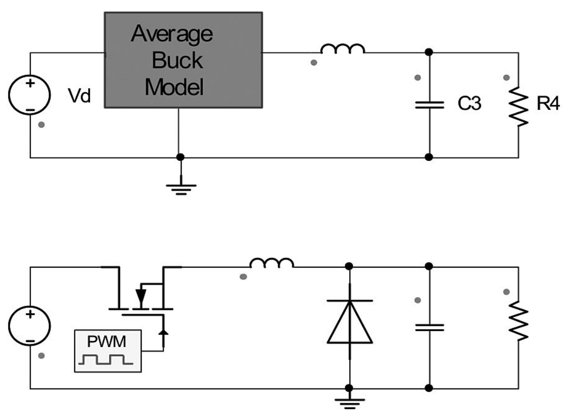
Device level simulation can reveal the details of the device behaviour. To obtain detailed loss data, over-voltages, and other component stresses, due to the non-ideal nature of the power electronics devices and the stray inductance and capacitance of the circuitry, it is necessary to simulate a number of cycles of detailed switching pertaining to the worst case scenario.

3.2 System level model

Detailed device level simulation can take a significant amount of time, because of the high switching frequency used in the power electronics circuits, whereas the mechanical constants of the vehicle system could be a few seconds or more. Therefore, the device level simulation, although can simulate the dynamic performance of the circuit, is not suitable to simulate the vehicle performance, such as gradeability, acceleration and fuel economy. On the other hand, the electronics circuits have very fast transients, when compared with vehicle dynamics.

In system level simulations, the average model is generally used. For example, a buck converter can be represented in the simulation by an average model, as shown in Figure 12(a). A simulation of the system performance of one second only takes two seconds of simulation time. Whereas Figure 12(b), which use detailed device level models, takes about 20 minutes to obtain the system performance of one second.

Figure 12 Device level and system level modelling of a buck converter: (a) system level model only taking into account the non-linear characteristics of the inductor; (b) device level model involving detailed switching of the MOSFET



4 Emerging power electronics devices

The present silicon (Si) technology is reaching the material's theoretical limits, and cannot meet all the requirements of hybrid vehicle applications in terms of compactness, lightweight, high power density, high efficiency and high reliability under harsh conditions. New semiconductor materials, such as silicon carbide (SiC) based power devices have the potential to eventually overtake Si power devices in hybrid vehicle powertrain applications (Dreike et al., 1994; Johnson et al., 2004; Kelley et al., 2006; Ohashi, 2003; Ozpineci et al., 2001, 2002, 2005; Traci et al., 1999).

The SiC power devices potentially have much smaller switching and conduction losses and can operate at a much higher temperature than comparable silicon power devices. Hence, a SiC based power converters will have much higher efficiency than that of converters based on silicon power devices, if the same switching frequency is used. Alternatively, a higher switching frequency can be used to reduce the size of the magnetic components in a SiC based power converters. In addition, because SiC power devices can be operated at much higher temperatures without much change in their electrical properties, ease of thermal management and high reliability can be achieved.

5 Circuit packaging

The electromagnetic interference (EMI) is one of the most challenging problems in power electronics circuits. The high switching frequency and high current generates electromagnetic fields that will permeate the other components in the vehicle system, creating considerable electrical noise. In order to minimise EMI, components must be carefully placed so that EMI is not contained by shielding and will have a minimal effect on the rest of the system. All paths must be kept as close as possible so that the generated fields will nullify one another. To minimise parasitics and aid in resolving EMI issues, the lengths of the wires need to be kept as short as possible.

The control circuit needs to provide protection for over current, short circuit, over voltage and under voltage. The capability to detect any fault signal and turn off the gate drive signals to the primary switches is a critical part of the power electronic circuit design. Fast fuses need to be used in the circuit for safety and to protect the converter from being damaged by any other faults.

6 Thermal management of power electronics

At power levels of 100 kW, even with efficiency of 96 to 98%, the power losses of each power electronic unit are 2 to 4 kW. With two or three powertrain motors and associated power electronics circuits, as well as a high power bidirectional DC/DC converter, the heat generated in the hybrid system could be significant.

Significant advancements in the thermal management of both the power electronics and motors for the HEV propulsion system must be achieved to meet the automotive industry's goals of reduced weight, volume and cost (Alaoui and Salameh, 2005; Tatoh et al., 2000; Traci et al., 1999; White et al., 2004). Through the optimisation of existing technologies, and the expansion of new pioneering cooling methods, higher power densities, smaller volumes and increased reliabilities can be realised in the hybrid powertrain components. Investigations and advances in thermal issues can provide a viable path to bridging gaps still plaguing the successful achievement of automotive technical targets, while simultaneously enhancing the ability to apply new technologies in automotive applications as they mature.

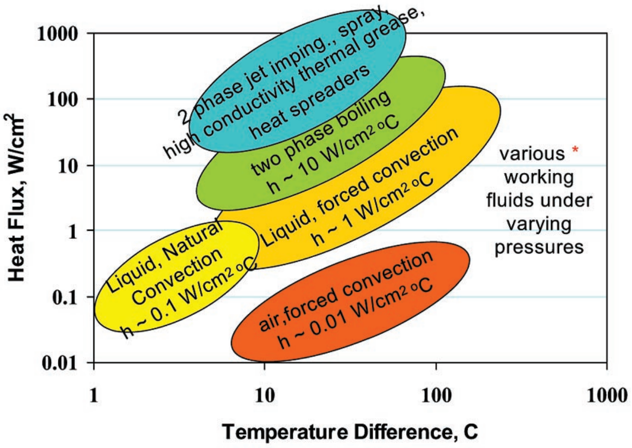
The thermal performance of a power module is measured by the maximum temperature rise in the die at a given power dissipation level, with a fixed heat sink temperature. The lower the die temperature, the better the electric performance will be. As the thermal resistance from the junction of the die to the heat sink is reduced, higher power densities can be achieved for the same temperature rise or for the same power density, and a lower junction temperature can be attained. It is important to reduce thermal cycling or maintain low ambient temperature, to improve the life length and reliability of the dice.

The main areas of concern in the thermal management of power electronics are:

- operating temperature of IGBTs (which should be less than 125°C)
- contact resistance between various layers of a power module
- low thermal conductivity thermal paste
- heat flux limitations (ideally, faster IGBTs would have to reject heat at a rate of 250 W/cm^2)
- limitations on the inlet cooling fluid temperature (it is desirable to use the engine coolant at 105°C)
- the cost of the cooling system; weight and volume.

The existing cooling technologies are depicted in Figure 13. It is shown that conventional cooling techniques, such as forced convection and simple two-phase boiling techniques, are not capable of removing high heat fluxes (in the range of 250 W/cm^2) at low temperature differences (20°C). However, this figure shows clearly that employing enabling technologies, such as spray cooling and jet impingement along with some other innovative improvements, will be able to meet the goals of the automotive industry.

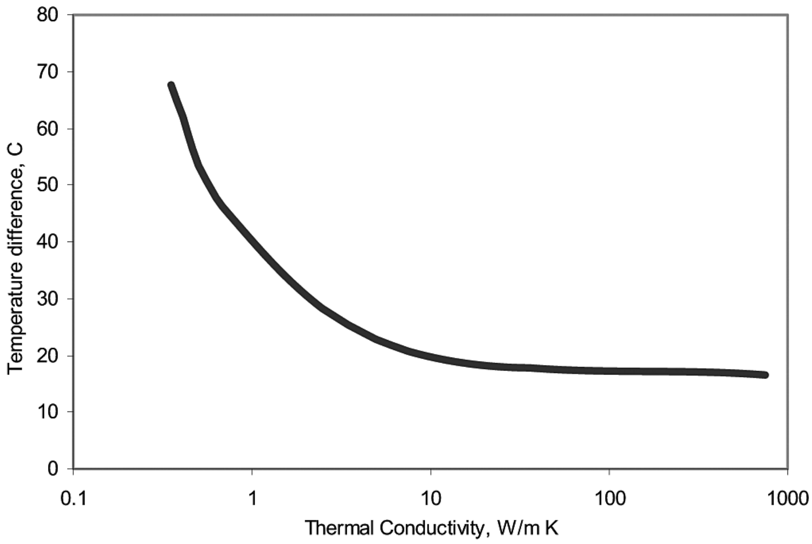
Figure 13 Existing cooling technologies (see online version for colours)



Ideally, it would be more beneficial if IGBTs could be designed to operate at higher temperatures. The industry is pursuing various long-term research projects to evaluate and achieve that objective. However, to meet the immediate need of the automotive industry, the existing IGBTs should be operated at temperatures below 125°C.

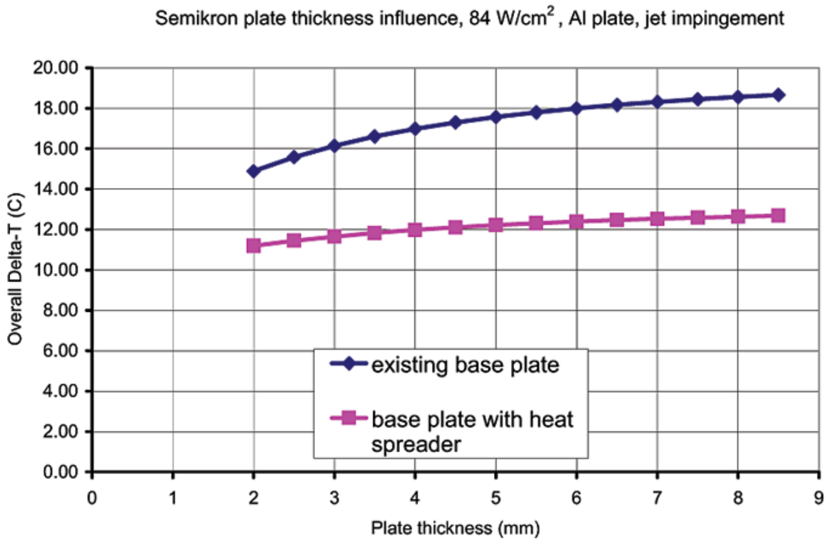
The existing power modules are constructed by bonding the die, copper layers, substrate and the base plate together. The whole module is then mounted on a heat sink using thermal grease or a thermal pad. The thermal greases used by the industry today that can stand high temperatures have very low conductivities on the order of 0.3 to 0.5 W/mK. As a result of this low thermal conductivity, the thermal grease constitutes 30 to 40% of the total thermal resistance between the junction and the heat sink. Therefore it is crucial to reduce this resistance by increasing the thermal conductivity of the thermal grease. Figure 14 shows the impact of the conductivity of the thermal grease on the overall temperature difference between the junction and the heat sink. For a thermal conductivity of 0.5 W/mK, the temperature difference is about 65°C. If the thermal conductivity of the thermal grease is doubled to 1.0 W/mK, the maximum temperature difference can be reduced to 35°C.

Figure 14 Impact of thermal interface material conductivity on temperature difference



To improve the power density of power modules, higher heat fluxes should be removed from the module because of increased switching frequencies. An important approach for removing higher heat fluxes from the IGBTs is to spread out their heat flux over a larger surface. Existing copper or aluminium base plates spread the heat 20 to 30%, reducing the maximum heat flux by a corresponding amount. The use of more effective heat spreaders, such as highly conductive metal layers, mini-heat pipes, and or phase change materials inside the cold plate, can spread out the high heat flux of the IGBTs over a larger surface area and reduce the maximum heat flux that must be removed by as much as 40%. This is a reduction of 50% in the maximum heat flux that must be removed and this requirement can easily be met by one of the enabling cooling technologies, such as jet impingement and spray cooling, currently being considered. Figure 15 shows the effect of utilising a heat spreader that results in an additional 4 to 6°C temperature reduction at the junction.

Figure 15 The impact of utilising heat spreaders on junction temperature (see online version for colours)



One approach to maintaining the power module's temperature at 125°C or below is to provide a separate cooling loop where the coolant can enter the heat sink at temperatures as low as 85°C, hence providing an adequate temperature difference to maintain IGBT's temperature at the desired value, while removing heat fluxes as high as 250 W/cm^2.

7 Conclusion

This paper presented an overview of the power electronics circuits for HEV applications focusing on circuit topologies, analysis and thermal management. Novel power switching devices and power electronics systems have the potential to improve the overall performance of hybrid vehicles. Continued effort in power electronics circuit research and development will likely to be focused on innovative circuit topologies, optimal control, novel switching devices and novel thermal management methods.

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Note

[1] http://www.toyota.com.