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Electric and Hybrid Vehicle Power Electronics Efficiency, Testing and Reliability

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Abstract

System efficiency together with the reliability are the most critical factors in the design, characterization and operation of Electric and Hybrid Vehicles. This paper summarizes those aspects from the system level down to the component details and shows practical methods for evaluation and improvement. This paper concentrates on a small to medium size personal vehicles in electric vehicle (EV) and parallel hybrid (HEV) configuration.

Even though the main focus of the paper is the traction inverter, other critical high power EV and HEV building blocks such as a DC/DC and AC/DC on board charger are also characterized and discussed to certain depth.

Some test methods for evaluation of the individual units and their components including extreme conditions such as heavy overload, short circuit and overvoltage are explored along with examples of experimental results on the prototype units.

Keywords: list: Efficiency, Reliability, traction inverter, EV power electronics, Vehicle power electronics

1 Introduction

The inevitable global shift towards the EV & HEV development brought number of challenges that were not applicable to a standard vehicle powered only by an internal combustion engine (ICE). Even in the HEV, where the ICE is still present, the entire system and its operation went through a dramatic change. Smooth torque transition among the ICE, E-motor/generator and the not-electrical part of the breaking system is essential. New failure modes, some of them potentially disastrous, have been introduced. Consequently a number of precautionary systems and strategies became inevitable.

The proper operation of the legacy low voltage vehicle electrical system required introduction of DC/DC converter. This unit accepts a portion of the energy stored in the high voltage traction

battery and converts it into low voltage required by the vehicle (typically 12V). A low voltage battery for this system remains a necessity, though its capacity may be reduced.

In most instances at least a small AC/DC converter /On-board charger is also required as a functional block of the EV or HEV.

The environmental challenges typically dictate liquid cooling of the power electronics, E-motor(s) and if present also the ICE. In the case of HEV, sharing of the cooling system between the ICE and EV components of the vehicle is desirable and beneficial but challenging for the EV design.

Heating and cooling environmental equipment has been replaced by more efficient and smaller heat pump.

2 EV and HEV Power Train

EV power train consists of energy storage, inverter(s), E-motor(s) and a mechanical distribution. HEV contains in addition the ICE with appropriate mechanical system coupling.

2.1 Configuration

There are several possible configurations for power train of the EV and HEV. Fig. 1 depicts the options for the EV.

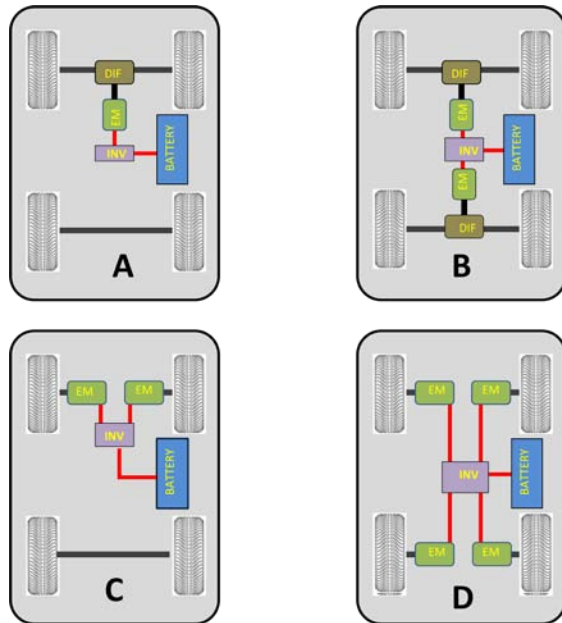


Fig. 1: EV Configurations

The left part of the picture depicts two-wheel drive, the right one deals with the four-wheel drive. The difference between the upper and lower part of the figure is in the way how the function of the differential is implemented. A & B uses a mechanical differential and C & D electronic one. The efficiency of the mechanical differential is ~94%. Consequently its use impacts the driving distance per charge. It also adds some weight to the vehicle. Using two motors is more economical; two E-motors are less expensive, weight less and performs better than the mechanical differential and a single E-motor. There are many possibilities how and where to place the E-motors; details in the motor section.

HEV configuration options are shown in Fig. 2. Case “A” powers only one axle. A satellite transmission combines the torque from the ICE and the E-motor. “B” also combines the torque from both sources however the coupling is done through the tires and the road.

Case “C” is an enhancement of “B”. The mechanical differential and an E-motor in the front axis are replaced by two motors of smaller size.

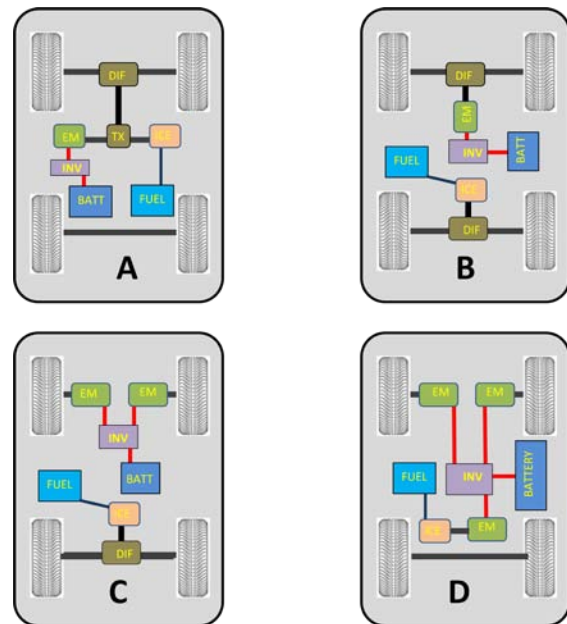


Fig. 2: HEV Configurations

Last segment “D” represents the series hybrid; the ICE is running at its optimum regime most of the time, charging the battery and supporting the traction E-motor. The E-motor(s) produce(s) the torque to move the vehicle. Such technique is practical for use in larger vehicles and buses.

2.2 The Power Electronics System

The power electronics system is depicted in Fig. 3. The sizes in kilowatts and voltages are examples that fits small to medium personal EV or HEV. The 400V battery is the energy storage of the entire system; it may be charged by the on board charger (AC/DC) using a regular outlet or larger fast charger, external to the vehicle. Battery disconnect is a safety device collocated with the battery. It connects or disconnects both, the positive as well as the negative pole of the battery from the rest of the system. Most vehicles uses normally ON device that is activated only during emergencies to prevent fire or explosion. Exceptionally this device is normally OFF and is controlled by the vehicle driver; more in the inverter section. The HV DC bus distributes the power to the inverter, DC/DC converter and accepts the power from the AC/DC during the charging period. The low voltage battery and the entire 12V legacy system are supplied by the DC/DC converter. This system low voltage system also provides power to all the other components of the EV/HEV control system. The main controller along with HMI provides high level control and

supervision to all components of the system. Each individual Blok has its own controller that performs the local control and reports to the main controller.

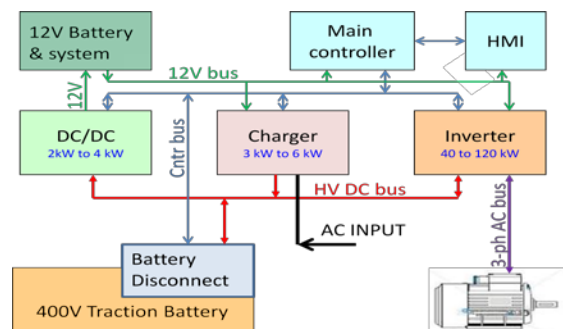


Fig. 3 Power Electronics System

The HV DC bus uses HV conductor, shielded to contain the radiated EMI. This bus is floating with respect to the chassis. Safety device similar to ground fault interrupt (GFI) is used to detect possible leakage current. If the fault detected, the battery disconnect separates the battery from the rest of the electrical system.

2.3 Inverter

The inverter is a bi-directional converter, Fig. 4 that accepts the high voltage from the traction battery and converts it typically in the three phase AC voltage suitable for the traction

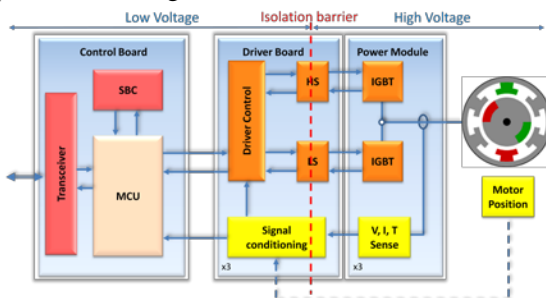


Fig. 4 Inverter Block Diagram

E-motor. During the deceleration (regenerative braking period) the motor absorbs the torque and provide the AC voltage to the inverter. The inverter controls the amount of the energy generated by the motor and consequently the intensity of the braking. The harvested energy is applied back to the HV battery as a charge. The regenerative braking improves significantly the vehicle efficiency and in turn the distance the vehicle can travel on a given battery charge [7]. A large capacitor in the size of 0.5 to several mF (milifarad) is an essential part of the inverter. Its role is to decouple the bus voltage, limit the switching ripple and most importantly limit the voltage overshoot on the IGBT during its turn OFF. There are specific requirement on the

capacitor; it must have low equivalent series inductance (ESL) and resistance (ESR), operate at high temperature and have a long lifespan. In most instances multilayer film capacitors are used. It is also important to minimize the interconnect impedance between the capacitor and the switching devices.

2.3.1 Topology

The most common topology of the EV & HEV inverter is the three-phase bridge [8], Fig 5. It uses IGBTs with anti-parallel diodes as a switch. There

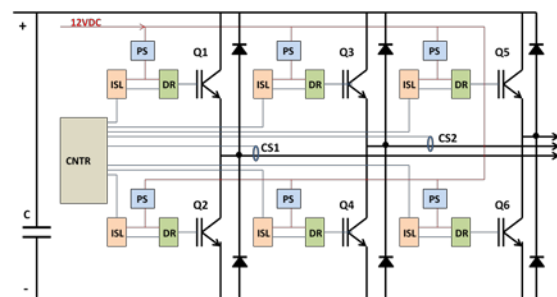


Fig. 5 Standard 3-ph Inverter Topology

are many variations of this topology as well as in the power semiconductor devices used.

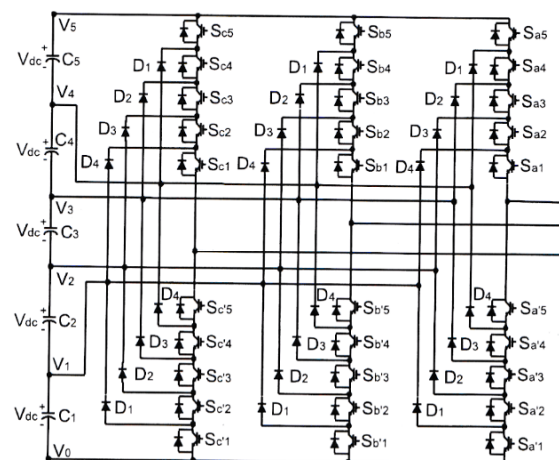


Fig. 6 Example of a Multi-Level Inverter

There are topologies specific to improve quality of waveform (THD), efficiency and reliability of the traction system. Those include multi-phase (more than 3-phase), multi-level (more than two voltage levels) or resonant (using resonance to limit switching losses). Those enhanced topologies are more complex and require many more components [10]. It is a cost adder, hard to justify in the extremely cost-sensitive automotive arena. Nevertheless it may be an excellent option for racing or military vehicle. An example of an 11-step cascade inverter is in Fig. 6.

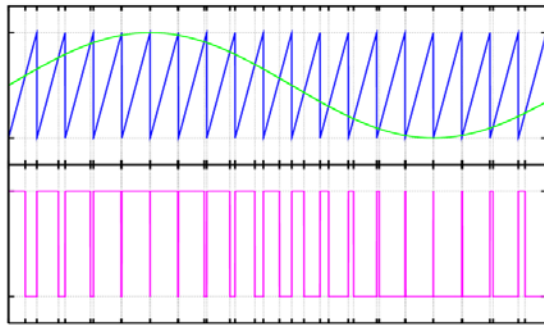


Fig. 7 Generation of Two-Level PWM

The semiconductor switch is typically implemented by silicon based IGBT and diode. When the new materials such as SiC or GaN become more rugged and affordable the silicon will be undoubtedly replaced. Focus of this paper remains with the standard 6-switch topology depicted in Fig. 5 with two-level modulation. Principal of operation of this most commonly used inverter in Fig. 4 is simple. The semiconductor switches are turned on and off using pulse-width modulation (PWM) to approximate a sine wave of desired frequency. Principal of generating sine-wave in two level environment and analog domain is in Fig. 7. The saw-tooth wave form is compared with a reference sine-wave, resulting in the PWM that is applied to the drivers and the IGBTs. In order to generate sine wave with acceptable distortion, the switching frequency of the individual switches must be substantially higher than the desired output frequency [9]; typical multiplier is 4 xs to 12 xs. Today more sophisticated digital principals are used to generate the PWM signal. Often is beneficial to vary the switching frequency with load to optimize the switching loss.

Since the IGBT is a unidirectional device; an anti-parallel diode is used to enable current conduction in the opposite direction. State of

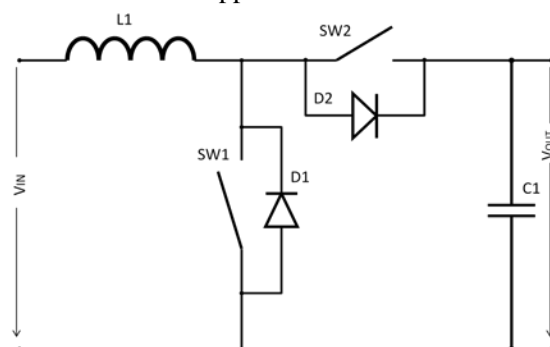


Fig 8 Optional Boost Converter

each IGBT is controlled by an IGBT driver. There is a benefit to accompany the standard inverter with a DC/DC converter, typically in

boost topology. The converter conditions the voltage from energy source(s) before it is applied to the inverter. The advantages include [3]: enablement of high resolution PWM, reduction of the torque ripple, elimination of acoustic noise, better utilisation of the inverter semiconductors and finally higher energy density and added safety (should the voltage at the inverter DC terminals be higher than the DC bus voltage, the DC/DC converter prevents the current flow). Such DC/DC (boost converter) is a trivial device shown in Fig. 8 above.

2.3.2 IGBT and Anti-Parallel Diode

Besides the obvious parameters of the semiconductor switch such as current handling capability, saturation voltage and break down

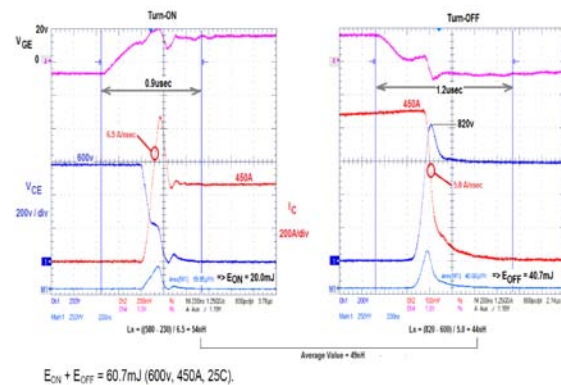


Fig. 9 IGBT Switching Waveform

voltage, there are dynamic properties that govern the switching performance of the device. Fig. 9 shows a typical turn ON and OFF waveform of a 600V, 450A IGBT with a matching anti-parallel diode. The dV/dt and the di/dt determine the switching loss of the device as apparent from the switching energy (the lowest trace in Fig. 9). It appears that the steeper the slope (di/dt & dV/dt), the less energy is wasted during the transition. This may lead to a conclusion that the IGBT should be switched as fast as possible. It is true up to some extent, but there are several limiting factors:

- the IGBT driver has limited sourcing and sinking capability. It must fight not only the G-E capacitance but also the larger, dynamically changing C-G (Miller) capacitance with its charge
- fast switching generates EMI
- high di/dt on turn OFF produces large voltage overshoot, in our case (Fig. 9) 220V over the bus of 400V (or 55%)

The voltage overshoot in our example required the use of 1200 V semiconductor. Higher breakdown

voltage comes with increased V_{SAT} and in the consequential increase of the conduction loss. There are however different possibilities how to reduce switching time without such impact. Details are in the driver section.

The chief problem of the silicon based anti-parallel diode is its reverse recovery charge and its “snappy” behaviour especially at low temperatures [1]. The reverse recovery is a

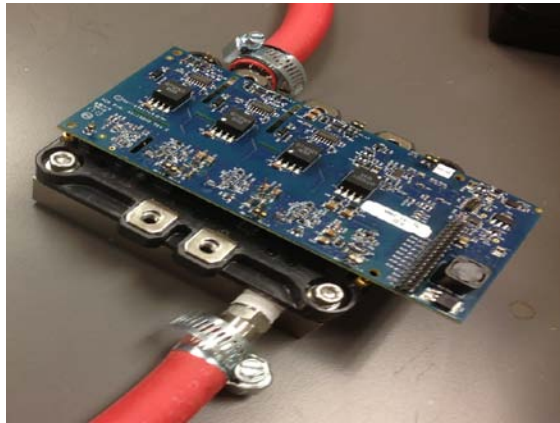


Fig. 10 Automotive 3-Phase PM

charge (caused by minority carriers) that needs to be removed from the diode in order to restore its blocking properties. In silicone diodes it can be somewhat reduced and the diode could be made softer by the design but such improvement is not significant. A technologically better solution is the use of SiC diodes. They literally don't display the reverse recovery phenomena. A comparative experiment was conducted where the Si diodes were replaced by the SiC equivalent. The measured improvement (on 60 kW drive) in efficiency was 2%. Unfortunately for a cost-sensitive automotive application those diodes are prohibitively expensive. For automotive as well as industrial applications the IGBT and the diode dies are packaged into power modules (PM). Example of an automotive PM is in Fig. 10. The picture shows 3-phase, 650V, 450A PM with the integrated liquid cooling and a gate driver PCB on the top. Typical PM contains several IGBT and diodes placed on a substrate that is attached to the cold plate. The configuration of the internal dies depends of the application [2]. For the traction applications a six-switch bridge with antiparallel diodes is the most common configuration; sometimes the fourth phase is added to perform the boost function as described in the inverter section. Often two or more dies are connected in parallel to increase the current handling capability and reduce the V_{CE} ; a single temperature sensor

(thermistor) is also a standard part of the assembly for monitor the PM temperature.

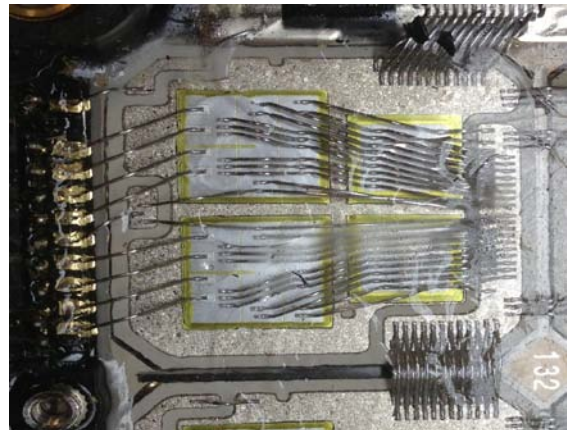


Fig. 11 Experimental Module with Die Sensors

Advanced PMs may contain additional elements, such as current and temperature sensors and even a driver. Having a temperature and current sense per each individual die enables detailed monitoring that may reveal wear out conditions of the semiconductors. Experimental module in Fig. 11 displays detail of a PM's substrate with current mirror and temperature sensor on each die. Combined with historical data and proper algorithm a prediction of failure may be derived. The self-check determines that the system is OK before a trip is made nevertheless it is much more valuable to know that the system still will be OK for next, for example 300 miles. Integrated cooling is another distinct advantage of this PM (Fig. 10). Such integration eliminates several thermal resistances between the die and the coolant. That significantly improves cooling performance, and the die temperature variation, resulting in better reliability [2]. The form factor of the entire assembly is also improved [3].

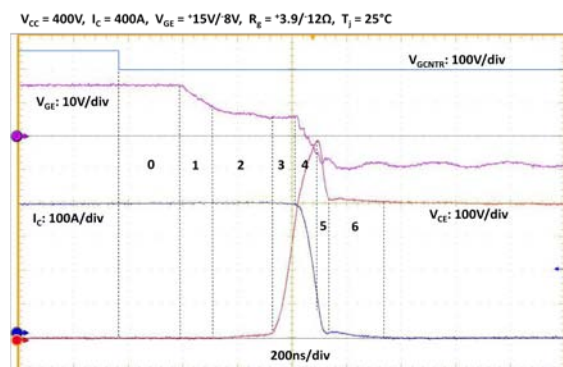


Fig. 12 Detail of IGBT Turn OFF

2.3.3 IGBT Driver

The historical purpose of the driver is to modify sufficiently the incoming PWM signal and apply it to the IGBT gate. Since the emitter of the high side (HS) IGBTs are referenced to each phase which is constantly moving between the negative and the positive rail, the HS drivers must have not only functional but also safety isolation. The same is true about the power supply supplying the housekeeping power to the secondary side of those drivers. Even if not functionally necessary often also the lower side (LS) switches are isolated. Isolation of the LS devices improves the signal integrity, safety and electromagnetic emission (EMI).

The PWM signal generated by the controller is brought to the primary side of the isolator. The secondary side is referenced to the emitter of each IGBT and connected to the gate. Most of the drivers on the market today enable bipolar supply. Typically a 15V is used to turn the IGBT ON and -8V to turn the IGBT OFF. Some manufacturers reduced the negative voltage to -5V. This change is based on experimental results. While optimizing the negative voltage for various IGBTs it was discovered that inverter efficiency improvement is noticeable by increasing the turn OFF voltage from 0 to -3V. After -3V there is no improvement. 5V has been chosen to provide sufficient margin. This is a positive change since the voltage swing is reduced with all its benefits. Besides the ON/OFF control of the IGBT the driver may accommodate additional protection, safety and reporting functions. Recently more sophisticated drivers entered the market. Intelligent modification of the dV/dt and di/dt at the correct time of the transition brings the benefits without the constraints. Fig. 12 depicts details of the IGBT turn OFF. The time interval "0" represents a delay caused by the PWM signal isolation and internal driver circuitry. Interval "1" shows the initial gate voltage drop without any influence on the power circuit. Period "2" is beginning of the Miller effect and the V_{CE} starts to increase slightly, no change in current is noticeable yet. Within area "3" there is a rapid increase of the V_{CE} and the current starts to drop down; the Miller effect ends. The time period "5" is characterised by rapid current decrease and the consequent voltage overshoot that is proportional to the di/dt along with the stray inductance in the circuit. Area "6" shows the recombination of the minority carriers within the diode and restoration of the blocking capabilities of the switch. It is clear that the switching time can be manipulated by controlling the gate voltage and current [1]. Experiments have been conducted with multiple

drivers that are turned ON and OFF in sequences. This way the optimal switching performance may be obtained. The critical part of such approach is the definition and process execution of the proper timing of each sequence.

2.3.4 Isolation

The signal isolation between the controller and the output stage of the driver is an inevitable part of the inverter design. It may be an integral part of the driver integrated circuit (IC) or separate component. Integration with the driver is beneficial but not an absolute necessity. There are several ways the isolation may be implemented:

- Optical coupling
- Inductive coupling
- Capacitive coupling

Optical coupling of the PWM signal was the traditional way. Optocoupler uses light emitted by LED that is received by a detector located next to the LED; a fiberoptic cable between the emitting LED and the detector is an option for a very high voltage applications and high safety standards. Optocoupler is an inexpensive, component that is not susceptible to electromagnetic field interference. Within the last decade "digital isolators" became a very popular way of isolating the PWM and other signals. The digital isolator offer substantial and compelling advantages over the optical isolator; including: physical size, speed, latency, reliability, power consumption and ease of use [6]. The digital isolator is implemented as an IC devices that may contain from a single up to 8 devices per package. Various combinations of the signal directions are available. The inductive isolator is shown in Fig. 13. There are two basic ways how the signal may

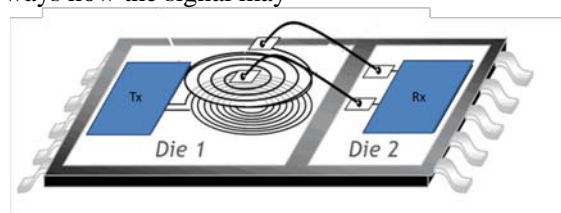


Fig. 13 Principal of Inductive Isolator

be transferred across the isolation barrier. The first option consists of a modulator (marked Tx) that generates HF carrier frequency (0.8 to 3.5 GHz). The input signal modulates the RF frequency which is then transferred through a coreless transformer to the secondary side. The demodulator (marked Rx) recovers the original signal. Other option uses a pulse generator (marked Tx), driven by the input signal. The

receiver (marked Rx) then reconstructs the original signal.

The capacitive coupling is somewhat younger than its inductive counterpart. An example of the differential capacitive isolation is shown in Fig. 14. The principal is self-explanatory from the

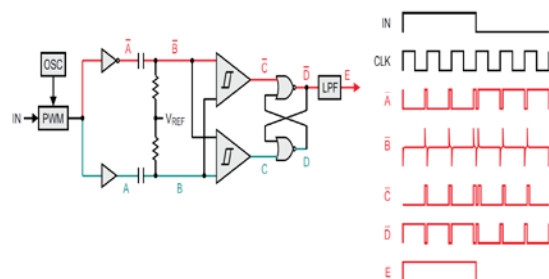


Fig. 14 Example of a Capacitive Digital Isolator

schematic and waveforms. Today both systems are widely used. The performance of both system is similar. Applications where safety is a major concern give the preference to an inductive coupling since it demonstrates better reliability; (the capacitors are using SiO as an isolator that may be damaged under extreme circumstances and break the isolation).

2.3.5 Controller

The controller is the brain of the inverter, typically implemented by a microcontroller unit (MCU). It accepts control commands from the driver in the form of throttle and breaks along with other inputs and turns them into organized, conditioned PWM signals for each IGBT driver. There are several control strategies that perform the vehicle motor control. Widely used Field Oriented Control (FOC) is presented as an

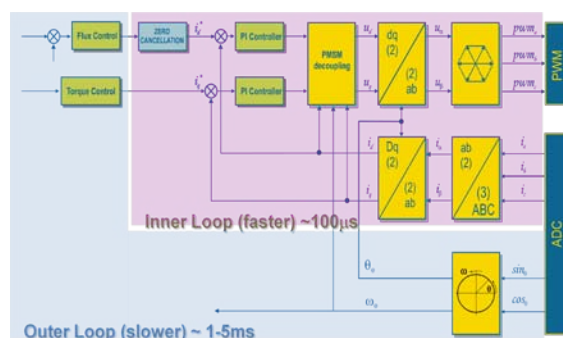


Fig. 15 Example of FOC controller

example. FOC provides independent control of the torque and magnetic flux [4]. Fig. 15 depicts its functional blocks. FOC may use sensors such as encoder or resolver to determine exact position and speed of the rotor or be sensor-less.

Functional safety is extremely important for the road vehicle and must be built into the control system architecture. An example of a “safe assure” system is shown in Fig. 16.

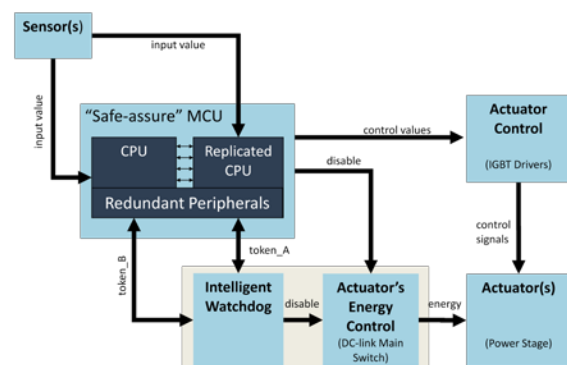


Fig. 16 Example of Fail-Safe Vehicle System

The housekeeping power supply for the controller, sensors and gate driver is typically provided by the 12V legacy vehicle system. This is one of the weak spots of the system – see the improvement suggestions.

3 E-Motor

There are four types of an E-motor suitable for moving the vehicle. The oldest is a series DC motor which was used mainly for street cars and small golf cart type transportation devices. Today this motor has very limited use in automotive applications due to necessary maintenance (high current brushes and comutator). With the progress of power electronics DC brushless motors become the preferred solution to most of the traction applications. Construction-wise those are three (or more)-phase AC motors either synchronous or asynchronous (induction). Asynchronous (induction) motor has been successfully used in EVs and HEVs. Its use has some advantages as well as constrains over the synchronous motor. Tab. 2 displays the comparison between both types of E-motor.

	rotor	rotor field	speed	control	cost	self-start	maintanance	reliability
synchron	PM or wound	stationary	synch	must	higher	NO	YES	less
induction	squirrel	moving	< synch	no need	less	YES	NO	more

Tab 2 Induction Versus Synchronous Motor

In terms of efficiency, the synchronous, PM motor is slightly more efficient (elimination of rotor conduction loss) and slightly smaller (15%) but much more expensive (40%) than his asynchronous counterpart. In automotive applications there is an important safety difference; the induction machine – unless excited by the inverter – does not have the rotor magnetic field,

thus is unable to produce voltage during the rotor motion. PM machine on the other hand has its permanent magnets in the rotor; as a consequence any movement of the rotor produces voltage on the motor terminals. This is important during failures or even during the towing of the vehicle. (see the failure mode section) Construction-wise the induction motor is the simplest, least expensive and most reliable electric machine known today. There are two types of synchronous motor; one has the excitation winding on the rotor that generates the magnetic field, the second and today the most popular E-motor used in automotive traction is the permanent magnet (PM) motor. The rotor excitation winding is replaced by permanent magnets. No excitation circuitry is needed. Due to the small size of the magnets this motor has the highest power density. For a comparison, synchronous motor with the excitation winding on the rotor would be about 15% larger. Induction motor would be about 20% larger. Cost-wise, the PM motor is about 40% more



Fig. 17 Example of E-motor integration

expensive than the induction machine. E-motor can be created in many shapes, have various electro-mechanical characteristics and may be integrated together with some electrical and/or mechanical devices. From the efficiency and simplicity point of view would be ideal to use a direct drive with no step-down transmission and integrate the motor inside the wheel. An example is the “electric wheel”, Fig. 17. This is truly an innovative approach that may solve number of known issues.



Fig. 18 Example of integration Inverter with the E-motor

One remains – the large spring mass associated with the wheel. Until a truly light-weight motor becomes practical, this solution is very limited. Example of a mechanical integration is the accommodation of an E-motor, mechanical transmission and differential in one unit. A single block – not much larger than the mechanical differential - provides mechanical support, power and regenerative braking to the entire axle. Electrical integration may include the switching devices encapsulated inside the motor or even the entire inverter integrated together with the motor. An example of such integration is in Fig. 18.

To minimize the form factor, most of the EV and HEV manufacturers are using a high speed motor with a step-down transmission. This is contrary to the direct drive with low speed motor without the mechanical transmission. A slow RPM, large number of poles E-motor has larger form factor and is somewhat heavier than its high speed counterpart that include the transmission. At present the direct drive is practical heavier vehicles such as trucks and busses. The preference for personal vehicles is high speed motor with the step down

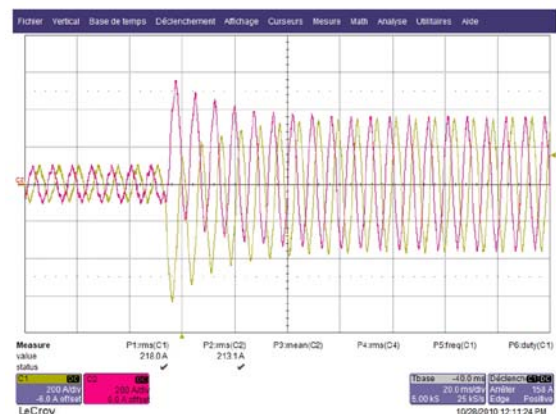


Fig. 19 Example of PM motor SC

transmission. Electro-mechanical properties of the motor govern the performance and safety of the car. For example the torque characteristic must support maximum torque at zero speed. Short circuit characteristic in generator mode is essential for the safety. Many carmakers require a special feature in the inverter supplying a PM motor. It is a current limit in the case of a three-phase short circuit at high speed. The rationale for that is an emergency, when the PWM signal to the drivers is no longer available and the vehicle is still moving. In this case all three horizontal switches (LS or HS) are turned ON at the same time. Under normal operating conditions the energy generated by the motor is proportional to the rate of electrical (regenerative) braking and is tightly regulated by the inverter. In the case of the inverter or driver

failure such regulation does not exist and the energy generated by the motor may exceed the capability of the system, causing fire or explosion. The three-phase short may prevent such events. It is however important that the motor is designed to generate manageable short circuit current. Example of an E-motor suitable for such short circuit is in Fig.19. The DUT PM motor used for this test was a 3-phase, 65kW, 6-pole PM motor with following parameters: IRMS = 365A; Ld = Lq = 260 uH; RS = 9mΩ; Fmax = 850Hz; measured ISC max = 640A for 4ms, then reduced to almost nominal current [4]. The 3-phase SC will produce certain, but not excessive breaking power. Many high performance motors (i.e. racing car) have the SC current several times higher [5]. That excludes this feature from available options and another precaution must be implemented; that may include mechanical break link or fusing.

4 DC/DC & AC/DC Converters

As shown in Fig. 4, additional power converters are an essential part of the EV and HEV electrical system. The DC/DC converter, usually sized between 1.5 kW and 3.5 kW performs the conversion from the HV energy storage to the 12V legacy vehicle system. Resonant, zero voltage switching (ZVS) converter is recommended for this application since it maintain high efficiency (typically 96 to 98%) for wide range of loading. Because the DC/DC converter seldom operates at its nominal power, its operating regime is important for the economical use of the stored energy [4]. Cycling the converter based on the condition of the 12V battery and/or cycling two or more (smaller size) converters may serve as an example.

In order to enable recharging from a regular electrical outlet, the on-board charger (AC/DC) of typical size up to 3.5 kW. Due to the regulations, it must be power factor corrected (PFC) device. Even if the efficiency of the charger is not as critical as in the case the DC/DC, the ZVS topology is recommended for saving the energy. The charger efficiency is due to the PFC slightly lower, about 94%, if resonant conversion is used. Since the vehicle liquid cooling system is during the charging process inactive, it is recommended that the charger is air-cooled. Both converters are controlled from the central processor, usually using CAN buss.

5 Failure Modes

Failure of the power electronics is closely related and directly affects the power system of the

vehicle. The high level system failures are shown in Tab.3. The table indicates possible failure and

FAILURE	CONSEQUENCE
Power train	Loss of mobility, wrong movement, wrong torque
Energy supply	Overheat, fire, explosion
Power steering	Limited, wrong or no steering function, crash
Break	Partial or full loss of breaking power, crash
Aircon	Discomfort
Lights	No lights at night / in a fog
Cooling	System overheat, power reduction, shut down, loss of mobility
ICE	partial or full loss of power, limited distance to travel
HV bus	Power loss, short circuit, fire, electric shock
LV system	Loss of control, rapid braking, possible a traffic accident

Tab. 3 High Level Failures in EV and HEV

its consequence. In order to determine reliability, the system, its building blocks and finally each critical component of those blocks needs to be taken into account [4]. The Fig. 20 is a system level example demonstrating the propagation of a failure. The first line of the table (Tab. 3) is broken

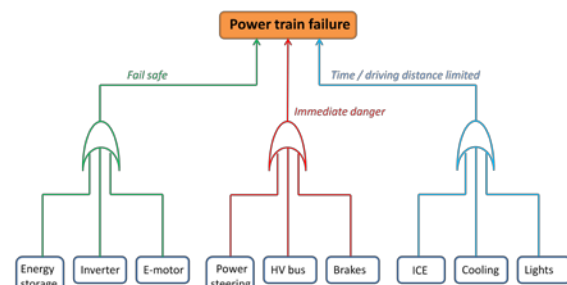


Fig. 20 Example of Failure Propagation

down to major building blocks; its criticality is colour coded. For example “the time/distance limited drive is possible” (blue) or “immediate danger” (red). Finally the component level reliability (in this example in FITs) is assigned to each component. Then the reliability tree is built up to the system level [4]. The process is depicted in Fig. 21.

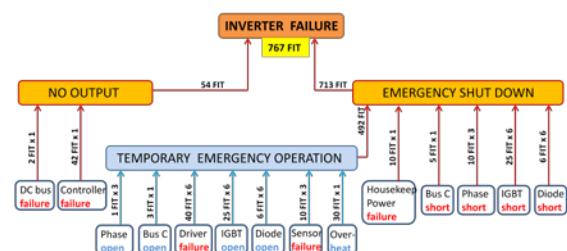


Fig. 21 Component Level and Reliability Tree

6 Cooling and efficiency

The power electronics of EVs and HEVs must be design to handle the worst condition. An example may be going up steep hill in hot day with an overloaded vehicle. As a consequence almost all EVs and HEVs are liquid cooled; it enables

absorption of the heat at the source and transfers it to a spot where it can be harmlessly released. In the case of HEV, it is a benefit if the cooling system is shared by both, the ICE and power electronics. High level integration is the key to the success [2].

Efficiency of the power electronics determines the distance which the vehicle may travel per a given charge. The overall system design is always an engineering compromise. It is always possible to increase the efficiency but it may price the vehicle out of the market. A good example would be comparison between Fig. 5 (the standard inverter topology) versus the multilevel inverter in Fig. 6. Twelve power electronics components (6 IGBTs and 6 diodes) versus 30 IGBTs and 54 diodes. The efficiency improvement is about 2 percentage points. Approximately the same improvement can be achieved by replacing the silicone diodes in the standard inverter with SiC or GaN diodes. The cost increase of the inverter in either case is about 2 xs. To determine efficiency of the vehicle, all components must be taken into account. Fig. 22 depicts comparison of the vehicle efficiency between the ICE and the EV; the HEV would fall in the space between those two. The efficiency of the ICE is extremely low, however the energy density of the fuel is multiple times higher the electrical energy storage today. This is the only reason why the ICE vehicles are still on the road.

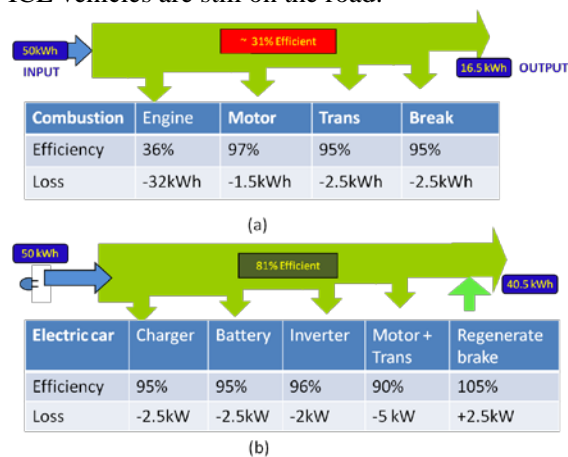


Fig. 22 Efficiency Comparison Between ICE and EV

7 Validation and Measurements

To test an inverter a dynamometer is needed. The dynamometer block diagram is depicted in Fig. 23. It may be formed by two mechanically coupled motors; one of the motors is connected to an independent inverter. The second motor is hooked up to inverter under the test (DUT). DC bus needs to be supplied to both inverters.

Assuming that the DUT will be tested in both, the motor and the generator mode, the DC bus must be bidirectional or a sufficient dissipative external load available. Fig. 15 is an example of a cost effective solution. The DC bus is common to both, the dynamometer inverter as well as the DUT one. It is supplied from the grid, using a 3-phase rectifier and a filter. The picture displays the case when the DUT is operating in the motor mode; the red arrows indicate the E-energy flow to the DUT inverter. The torque generated

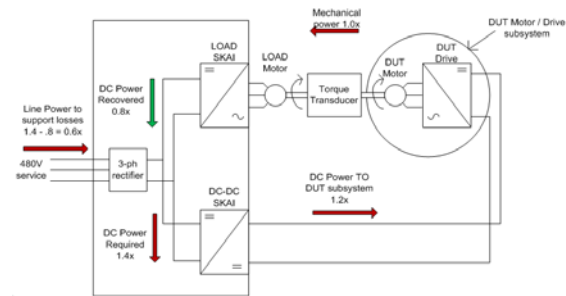


Fig. 23 Dynamometer Example

by the DUT motor is measured by an electronic torque transducer and applied to the load motor, converted to the DC by the inverter (marked “LOAD SKAI”) and applied to the shared DC bus. This way the energy generated by the load motor is not wasted but applied back to the DUT.

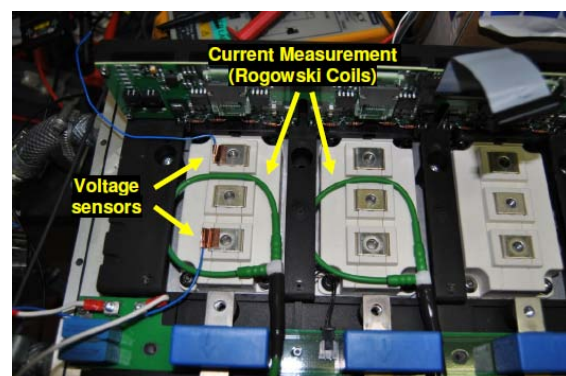


Fig. 24 PM Voltage and Current Measurement

The DC-DC converter between the common bus and the DUT provides flexibility for use of DUT inverters with different DC input voltage. Should the DUT be tested in generator mode, the energy flow reverses its direction. Pending the level of control and automation of the dynamometer, the test may be conducted under constant speed or constant torque mode in both, the generator as well as motor mode. This way a full characterisation of the DUT can be obtained, including torque/RPM characteristic and efficiency islands. Using a 3-phase power analyzer at the DUT makes the test an easy task; it enables monitoring two phases of the

inverter output along with the DC input. Getting internal waveforms i.e. IGBT switching waveforms requires additional equipment and some precautions. Measuring the collector or emitter current through the IGBT requires sensor that does not disturb the circuit. We found that Rogowski coil is the optimal device. It meets the current, resolution, bandwidth required is not invasive to the power circuit; its placement on the PM is shown in Fig. 24. Some PMs provide Kelvin connection to the die, enabling precise VCE measurement. If not available, the second best solution is shown in the same figure, Fig.24. Validation of a DC/DC requires variable DC voltage source capable of producing sufficient current and voltage defined by the converter specifications. Ideally electronic load at the output provides the emulation of the 12V system behaviour and allows the validation of the full range of the voltage and current. The AC/DC on board charger requires a variable voltage and variable frequency source and preferably electronic load or a battery emulator at the output.

8 Improvement opportunities

- a) Application of a DC/DC converter between the HV DC bus and the inverter (typically boost). It enables generation of high resolution PWM even in two level inverter, limits torque ripple and acoustic noise, improves efficiency, provides better utilisation of the bridge semiconductor switches and shrinks the form factor. It prevents reverse current flow (from motor to the battery) unless activated. It eliminates the need of 3-phase short circuit during emergencies.
- b) Use redundant housekeeping power supply. The power source is 12V vehicle system as well as the HV energy storage. In the case of 12V system failure, the operation of the power electronic system is undisturbed. Should the HV energy storage be out of limits, it allows a safe shut down of the system. Results in better availability, reliability and safety.
- c) Use motor with adequate short circuit characteristic so that (in the case of PM E-motor) the 3-phase short circuit may be safely applied in an emergency. Improves safety during emergencies.
- d) Make a provision for safe towing of the vehicle with PM E-motor; Enable inverter in safe mode of operation (limit generation of the AC voltage by the motor during emergency and towing of the vehicle. Enable cooling system

during towing of the vehicle. Use DC/DC converter between the battery and the inverter (a)

- e) Consider application of resonant and/or multi-level inverter to improve the efficiency.
- f) Use resonant topology in DC/DC and AC/DC converter to improve the efficiency. Use an intelligent algorithm to optimize efficient operation of the DC/DC
- g) Consider multitasking of the inverter as a fast grid charger. During parking of the vehicle, the inverter may serve as a high power charger to perform fast charging from the 3-phase grid.
- h) Add additional small energy storage for the gate driver to perform emergency shutdown during housekeeping power failure. During the loss of housekeeping power the shutdown of the inverter needs to be performed in a safe fashion. Small super capacitor does the job easily.

9 Conclusion

The paper presents an overview of power electronics technology and components of EV and HEV, deals with efficiency, reliability and validation (test) methods. In particular the vehicle configuration, power train and critical accessories are examined along with their efficiencies, failure modes and reliability. The known as well as potential issues are highlighted, possible solution proposed and additional improvements suggested.

Acknowledgments

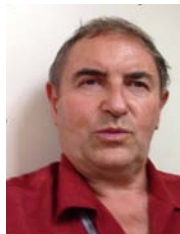
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