

A New Fully Integrated Power Module for Three Phase Servo Motor Driver applications

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Abstract

Today's solution for Motor Control Applications require more flexibility and a higher level of integration that could be achieved only through specialized products. In this paper a new family of Intelligent Power Modules developed for Servo Motor Drive Application is presented.

The module's architecture includes several key design features needed in these applications, such as motor phase current sensing, DC bus voltage control and short circuit protections while the embedded DSP allows easy realization of the current loop and even speed loop at the module level without any external components.

INTRODUCTION

Today's Servo Motor Driver application require an increasing level of performances in a usually limited space, integrated motor-control systems (so called IMD i.e. Integrated Motor Drivers) are becoming the real challenge for the future; the benefit of this new approach has to be seen in a lower system cost, by eliminating separated packaging and long cables, as well as in a cost effective performances improvement thanks to the easier matching of the motor – driver system and EMI reduction due to the elimination of long and noisy connections between the two parts.

Power products today available on the market give motor driver manufacturer the opportunity to design their own driver, though still leave the designer all control electronics to be defined and designed, so called IPMs (i.e. Intelligent Power Modules) often integrate IGBTs, Diode and Gate Drivers while only few of them also provide Current Sensing and fault/protection feedback.

The PI-IPMTM here presented is a new generation Intelligent Power Module designed specifically to implement itself a complete motor driver system, the device contains all peripherals needed to control a six IGBTs inverter, including voltage, temperature and current output sensing, completely interfaced with a 40Mips DSP, the TMS320LF2406A from Texas Instruments. All communications between the DSP and the local host, including DSP software installing and debugging, is realized through an asynchronous isolated serial port, either a CAN bus or an isolated port for incremental encoder inputs is also provided making this module a complete user programmable solution connected to the system only through a serial link cable.

In the following we will describe the first devices realized and tested in our laboratories, Table 1 lists all features and Power rating of these first samples.

SYSTEM DESCRIPTION

The PI-IPMTM is realized in two distinct parts: the Power Module "EMPTM," ("EcoManyPackTM," to recall the idea of different configurations availability) and the Embedded Driving Board "EDB," these two elements assembled together

Table 1: PI-IPM Features and Power Ratings

IGBTs Collector-Emitter voltage	1200	V
IGBTs continuous collector current @ T _C = 85 C	50	A
Diodes Reverse Breakdown voltage	1200	V
Diodes Continuous Fwd Current @ T _C = 85 C	50	A
Sensing Resistors	2	m?
Embedded DSP	TMS320LF2406A	
Interfaces	SCI	
	Incremental Encoder	

constitute the complete device with all performances described in the following.

Before analyzing those two sections we glance at the total block schematic showing all function implemented in the product, as represented in fig. 1. The new module concept includes everything depicted within the dashed line, the power module only includes IGBTs, Diodes and Sensing Resistors while all remaining electronics is assembled on the EDB that is fitted on the top of it as its cover with also a mechanical protection function.

Connections between the two parts are realized through a standard connector from AMP, this particular solution has been chosen not only to speed up and ease the final product assembly in the manufacturing line but also to maintain a certain flexibility, always considered a big plus in the motor driver market. In fact the EDB only, without disassembling the power module from the system mechanic, could be easily substituted “on site” for an upgrade, a system configuration change (different control architecture) or a board replacement. Also software upgrades are possible but this does not even require any hardware changes thanks to the DSP programmability through the serial or JTAG port.

THE “EMP™” POWER MODULE

This module contains six IGBTs + HexFreds Diodes in a standard inverter configuration. IGBTs used are the new NPT 1200V-50A (current rating measured @ 100C), irgc50b120kb generation V from International Rectifier; the HexFred diodes have been designed specifically as pair element for these power transistors and the coupled part is the hf50d120ace. Thanks to the new design and technologic realization, this gen V devices do not need any negative gate voltage for their complete turn off and the tail effect is also substantially reduced compared to competitive devices of the same family. This feature simplifies the gate driving stage as will then be described in a dedicated chapter. Another not standard feature in this type of power modules is the presence of sensing resistors in the three output phases, for precise motor current sensing and short circuit protections, as well as another resistor of the same value on the DC bus minus line, needed only for device protections purposes.

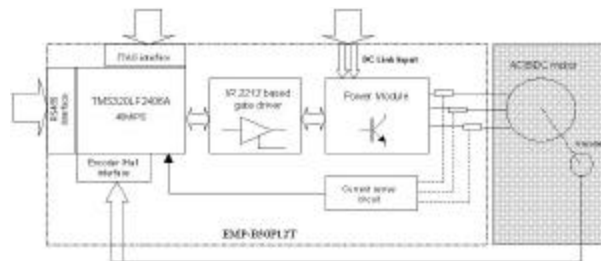


Fig. 1: PI-IPM™ block diagram

Complete schematic of the EMP™ module is shown in fig. 2 where sensing resistor have been clearly evidenced, a thermal sensor is also embedded and directly coupled with the DSP inputs.

The package chosen is mechanically compatible with the well known EconoPack outline, also the height of the plastic cylindrical nuts for the external PCB positioned on its top is the same, so that, with the only re-layout of the main motherboard, this module could be swapped into the same mechanical fixing of the standard Econo II package thus speeding up the device evaluation in an already existing driver.

An important feature of this new device is the presence of Kelvin points for all feedback and command signals between the board and the module, because of this the standard EconoPack pin out couldn't be used and a total redesign of the package has been done. The cost of a non-common configuration is however balanced by the advantage of having all emitter and resistor sensing points independent from the power path giving the tremendous result of having all low power signal from/to the controlling board unaffected by parasitic inductances or resistances inevitably present in the module power layout.

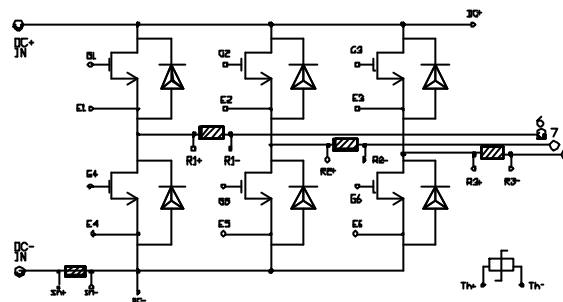


Fig. 2: EMP™ Power Module Schematic

Without this effort the realization of the system would have been seriously compromised because of false voltages spikes and voltages levels seen at the DSP input pins though filtered by conditioning circuitry.

The new package outline is depicted on fig. 3, where the signal and power pins are clearly shown and recognizable.

Fig. 4 shows the module layout, clearly evident are the sensing resistors on the three output phases and the DC bus minus, note that, because of high current spikes on those inputs, the DC bus power pins are doubled in size comparing to the other power pins. Module technology uses the standard and well know DBC: over a thick Copper base an alumina (Al_2O_3) substrate with a 300 μ m copper foil on both side is placed and IGBTs and Diodes dies are directly soldered, through screen printing process. These dies are then bonded with a 15 mils aluminum wire for power connections and 6 mils wire for signal connections. All components are then completely covered by a silicone gel with mechanical protection and electrical isolation purposes.

THE “EDB” EMBEDDED DRIVING BOARD

This is the core of the device intelligence, as previously described all control and driving functions are implemented at this level, the board

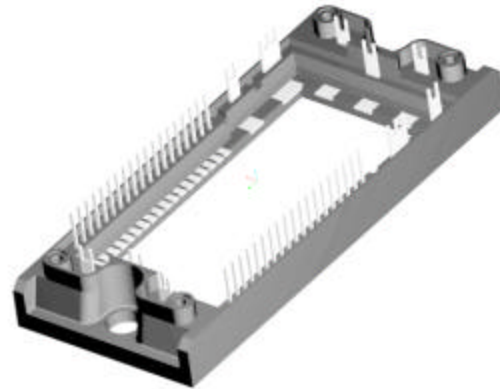


Fig. 3: the EMP™ package

finds its natural placement as a cover of the module itself and has a double function of mechanical enclosure and intelligent interface. DSP and all other electronics are here assembled, on fig. 5 the board schematic is presented and all connection pins clearly shown.

Looking at the schematic, all diamond shaped pins are signal connections, some belonging to the RS485 port interface and some to the IEEE 1149.1 (JTAG) connector. All other pins are used for communication between the board and the module, they are positioned laterally in the board so that the module doesn't have any pins in the middle of

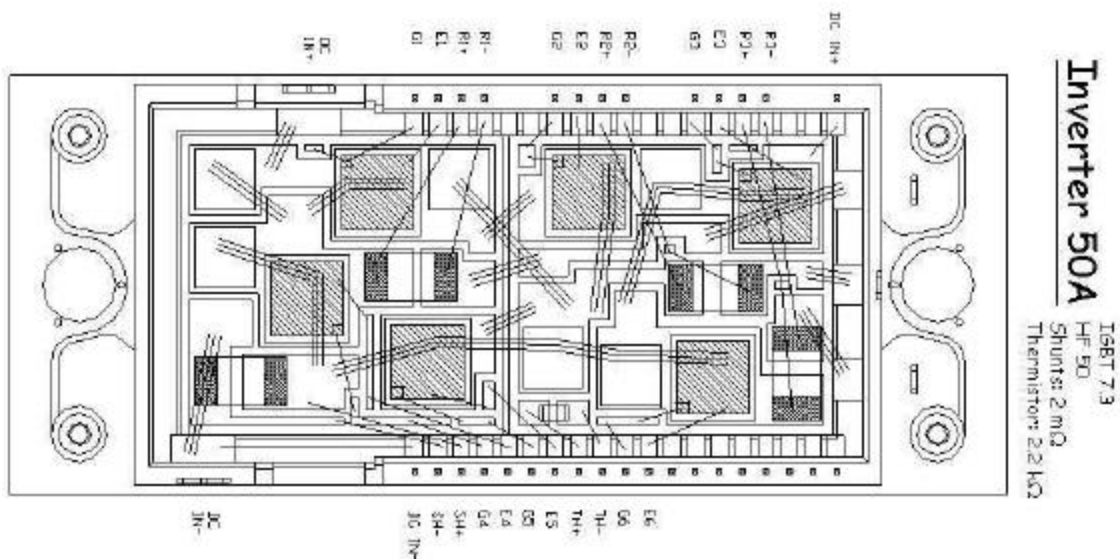


Fig. 4: the inverter configuration layout

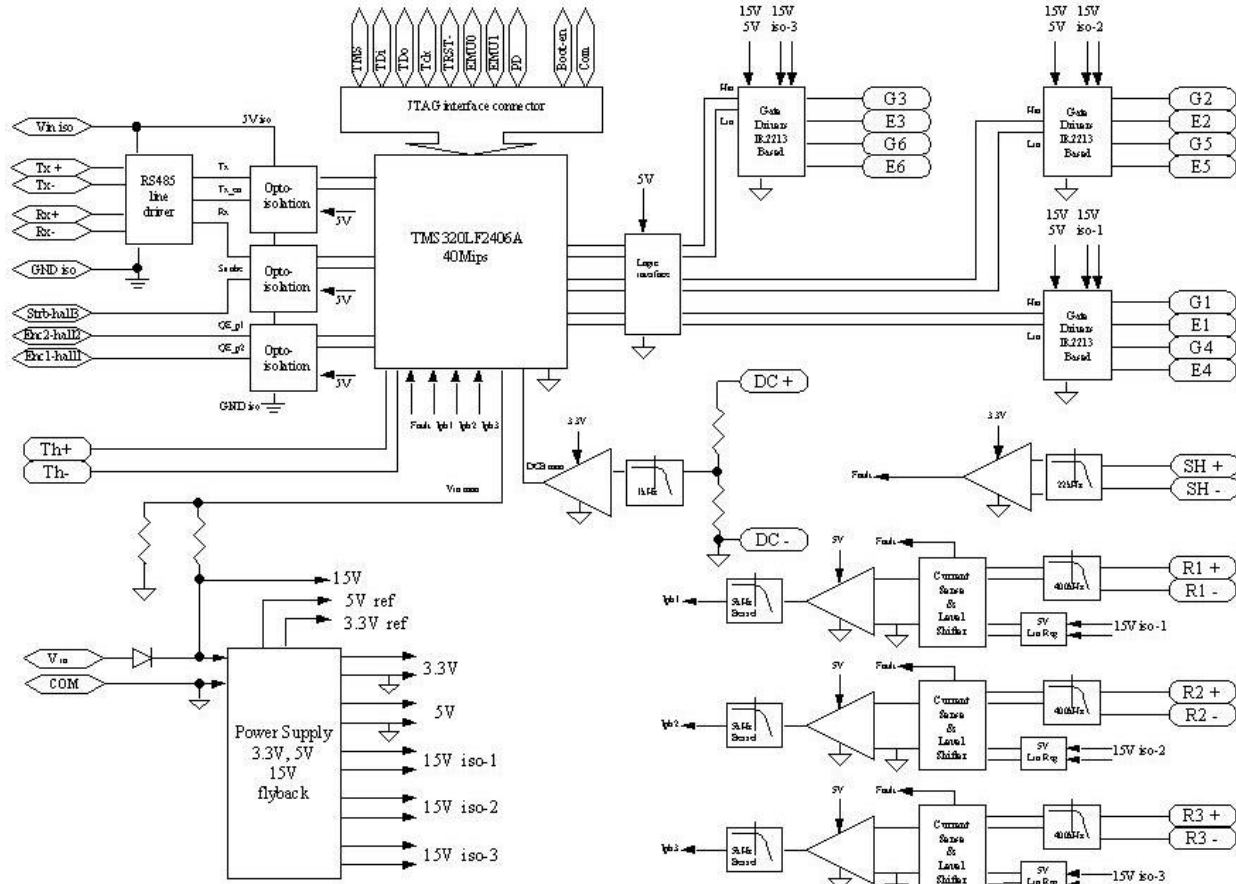


Fig. 5: Embedded Driving Board Block Schematic

its body, in this way all PCB internal area is available for components mounting and copper

Table 2: TMS320LF2406A vs TMS320F240

	'F2406	'F240
MIPS	40	20
RAM	2.5Kw	544w
Flash	32Kw	16Kw
ROM	—	—
Boot ROM	256w	—
Ext. Memory I/F	—	Yes
Event manager	Yes	Yes
• GP timers	4	3
• CMP/PWM	10/16	9/12
• CAP/QEP	6/4	4/2
Watchdog timer	Yes	Yes
10-bit ADC	Yes	Yes
• Channels	16	16
• Conv. time (min)	500ns	6.6?s
SPI	Yes	Yes
SCI	Yes	Yes
CAN	Yes	—
Digital I/O pins	37	28
Voltage range	3.3V	5 V

lines layouting, to ease the board realization.

From the top left, in anti-clockwise direction we identify the following blocks that will be then described in details:

1. DSP and opto isolated serial and JTAG ports
2. Flyback Power Supply
3. Current Sensing interfaces, over-current protections and signal conditioning
4. Gate drivers
5. DC bus and Input voltage feedback

1. DSP and opto isolated serial and JTAG ports.

This block is shown in fig. 6. The DSP used in this application is the new TMS320LF2406A from TI, it is a improvement of the well known in the motor driver market "F240" used in many motor driver applications. If we compare this new device with the predecessor, the new DSP has some

2. Flyback Power Supply

Though the board space is pretty limited (only 80mm X 44mm ca.) we found enough space to accommodate a power supply for the floating stages. The real limit however was the footprint dimension, we couldn't allocate more than a 10 pins (2 row of 5) transformer thus limiting the maximum number of outputs to four. As the block schematic in fig. 7 shows, we have three 15V outputs for the floating stages, isolated from each other at 1.5kV minimum, and a single 5V and 3.3V output.

The 5V supplies all low voltage electronics and a 3.3V linear regulator is used to feed the DSP and some analog and logic interfaces to it. This 5V and 3.3V are directly referred to the DC bus minus, so that all control circuitry is alternately at one of the input lines potential, isolation (as previously stated) is provided at the DSP serial link level, then avoiding all delays due to opto couplers insertion between DSP and control logic. Note that also the required 15V input voltage is referred to the same DC bus minus and directly supplies the low side gate drivers stages, this is necessary because of the already mentioned limited space on the transformer footprint, then the user should pay some attention on how this supply line is realized in his application. Just for completeness, fig. 8 gives a possible solution to that that doesn't impact heavily on the user application: normally a 5V power supply is already present, for displays, electronics and micro processor, the same 5V could be used for the 5V iso supply of opto-couplers and line driver, the

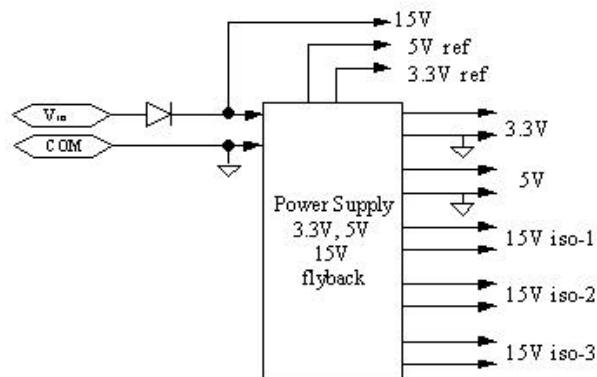


Fig. 7: PI-IPMTM embedded flyback power supply

15V could be realized as an added winding in the secondary side of the flyback transformer, the only care that should be taken is in keeping its isolation from the above mentioned 5V at the required level (at least 1.5kV).

To avoid noise problems in the measuring lines due to the commutating electronics during normal functioning of the system, references are kept separated. A 5V linear regulator, directly supplied from the 15V input, is used to provide the reference voltage to the current sensing amplifying and conditioning components while a precise op-amp, configured as a voltage follower, acts as a buffer of the partition at 3.20V created down the 5V reference. This 3.20V is used as a reference for the DSP A/D converter. It is to be noted that in the schematic we are using the same linear regulator as a starting point for all reference voltages. In fact if the 5V linear regulator derives in temperature or time, then all references (even the 3.20V being this a simple partitioning) follow in track and still keep the overall chain precision. The trimming is then done only once, in a single point of the measuring chain, that is the conditioning op-amp collecting the current sensing ICs signal as will be described in the following chapter.

3. Current sensing interfaces, over-current protections and signal conditioning.

This block is the real critical point of the system. Current measuring performances directly impact on motor control performances in a servo application: errors in current evaluation, delay in its measuring chain or poor overall precision of the system, such as scarce references or lower number of significant A/D bits, inevitably results in unwanted trembling and unnatural noise coming from the motor while running at lower speed or at blocked shaft conditions.

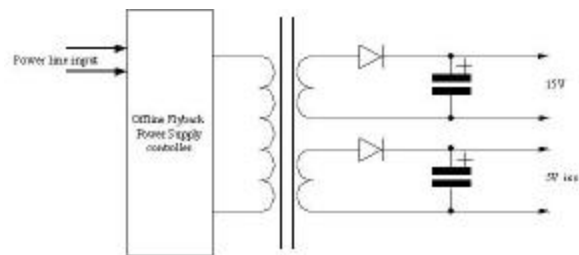


Fig. 8: examples of power supply for PI-IPMTM 15V and 5V iso inputs

To avoid all these afore mentioned problems the current sensing chain has to comply with usually good performances that could be easily listed:

bandwidth ? 5kHz

latency ? 15?s ? 20?s

A common mistake is to look only at the bandwidth without taking too much care at the delay that the information carries with it. This inevitably leads to close the current loop with lower gains than expected (to avoid instability and work with a decent phase margin) and consequent poor performances due to the limited system precision in torque control. Most used devices for current measuring are hall effect sensor, their precision and bandwidth is far enough for a servo motor driver application, closed loop ones have usually 100kHz BW measured at a phase lag of only 10deg, however their cost is pretty high and in many cases also their dimensions does not fit in the limited space available in the driver or in the motor connection box.

Because of these simple reasons another viable solution for current sensing is gaining popularity: though not used for high current level, because of power dissipation constraints, the sensing resistor dropout measurement is still adequate up to around 100A – 150A, with the benefit of a lower area and somewhat a lower cost. This is the solution chosen in the PI-IPM™ with the added value of having the shunts element embedded in the power module and all Kelvin connections available.

As the block schematic in fig. 9 shows, the voltage across each sensing resistor is applied, through an anti-aliasing 400kHz filter, at the input of a current sense IC. In this application we use the HCPL788J because of their bandwidth, datasheet shows 20kHz and we measured from these devices a latency of 10?s at a frequency of around 3kHz. As previously stated these performances are good enough for servo-amplifier applications, these integrated circuits also provide level shifting and galvanic isolation through the internal high speed opto-coupler; while the first function is essential the second one is not really needed and useless in this new type of intelligent power module where isolation lies at the serial link level.

International Rectifier also has some current sensing devices in its portfolio, however those devices (e.g. IR2271 or IR2273) have been developed for AC induction motor control and their performances are not suitable for servo motor driver application, driving a BLDC motor.

Signal outputted from the current sensing has a 0 to +5V dynamic, with a sensing resistor of 2mohms the input measured current range is +/- 100A then we have a situation as follows:

? 100A ? 0.0V

0.00A ? 2.5V

? 100A ? 5.0V

The DSP ADC inputs have an external reference of 3.20V then we must map this signal in a 0 – 3.20V frame and also filter the information to recover the average value of the current flowing to the motor phase. This is done in a single step: though the block schematic shows a op-amp plus an external passive filter this is simply realized implementing a VCVS cell (i.e. a Constant Gain or Sallen – Key cell) configured so that the offset and gain could be trimmed by three on board resistors. This is the setting point of all current measurement chain: in a single easy step we set the precision and recover the system offset through the soldering of two SMD resistors in the op-amp input lines, while the third one is used to re-center the damping factor 2???and the resonant angular frequency ? of the second order filter.

The Sallen - Key cell is also pretty flexible and let

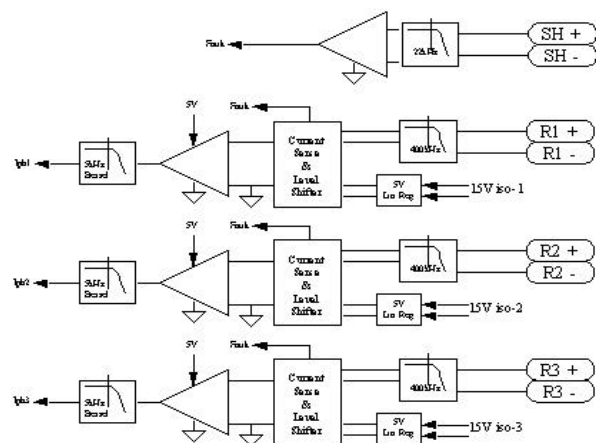


Fig. 9: Current Sensing and protections

us implement any type of second order (or even a simple single order) low pass filter. We chose for this first prototypes a second order Bessel filter with 5kHz pole frequency, the reason for this is that this type of polynomials are calculated with the aim of having a constant group delay within the pass-band frequencies, thus giving the minimum waveform distortion to the output signal up to almost twice the filter pole. In other hands we could also say that the group delay of the signal chain from the sensing resistor up to the ADC input of the DSP is constant from 0 to 5kHz.

Summing up our current measurements performances are shown in table 3.

By changing some resistors on PCB all parameters could be changed: current range, type of filter, pole frequency, leaving the flexibility of using the same circuit for module of different power levels. The “2406” DSP has a 10 bit ADC, that means that, in our prototypes, the minimum appreciable current step is approximately:

$$LSB \approx \frac{2 * 100}{2^{10}} \approx 0.1953\%$$

That is

$$1LSB \approx 195mA$$

Of course, reducing the maximum current range or simply changing the sensing resistor value (for lower power modules) this minimum current step could be sensibly reduced.

Another used feature of the HCPL788J is the over-current output signal. The related fault pin goes low when a 250mV voltage across sensing pins is detected, this means an over-current detection level of approximately 25%. Though the internal opto-coupler the delay of this line is around 3µs and fast enough to let the DSP react within the

Table 3: PI-IPM™ Current sensing chain typical performances

	value	units
current range	+/- 100	A
precision	0.3	%
bandwidth	5	kHz
latency time	10	µs

?

10µs IGBTs short circuit rating, thus providing full device protection for any phase-to-ground and phase-to-phase short circuits. The only failure not covered in this way is the cross through, where high current levels are not seen externally the module rather internally between two IGBTs of the same leg. In this case the protection is implemented by means of a fourth sensing element, with the same resistive value of the other shunts present in the power module, inserted in series to the DC bus minus. The related dropout voltage is then filtered by a 22kHz passive filter to avoid false fault detections due to unwanted induced voltage spikes and finally applied to an operational amplifier configured as a comparator.

4. Gate Drivers

This is another critical part of the system, gate drivers are responsible for correct turn on and turn off of all inverter IGBTs, avoiding cross conductions, false turn on during commutations and dangerous propagation delays between input signal and output commands. Devices used to perform this task are the well-known IR2213, capable of 2A sink and 2A source maximum gate driving current, in a SO16W package; fig. 10 shows the block schematic of the gate driving section of the module.

As previously described, the IGBTs used in the PI-IPM™ (genV NPT 1200V - 50A from IR) do not need any negative gate drive voltage for their complete turn off, this simplifies the flyback power supply design avoiding the need of center tapped transformer outputs or the use of zener diodes to create the central common reference for the gate drivers floating ground. This is a big plus

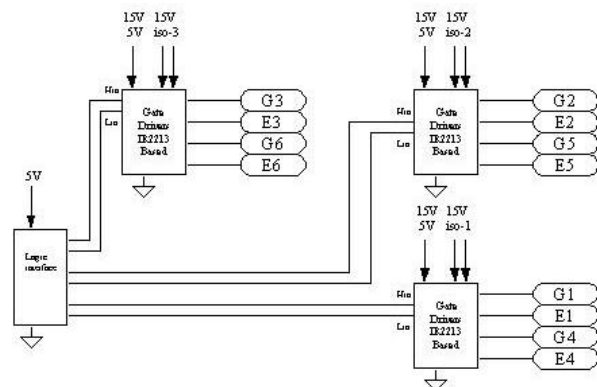


Fig. 10: Gate Drivers

remembering that the board space is very limited and that drawing three electrically floating lines instead of two (for each output phase) all across the board is a potential source of increased noise and isolation problems. Though the IR2213 do have +/- 2A of gate current capability, an easy calculation based on IGBTs gate charge, supported by instrumental observation in the laboratories, led us to use different gate resistor values for turn on and turn off as follows:

$$\text{turn ? on ? } 33\text{ohm}$$

$$\text{turn ? off ? } 7.6\text{ohm}$$

Commonly realized through a diode-resistor series in parallel with a single resistor used in turn on only. Observed rise and fall times are around 250ns – 300ns depending on the output current level and we considered this values pretty adequate for a 50A application at 16kHz symmetric PWM carrier, space vector modulation.

Contrarily to the current sensing devices, that are opto-coupled, these gate drivers do provide levels shifting without any galvanic isolation that is no opto-couplers are built inside. This turns out to be a major benefit in this stage where the usual 1µs delay of optos impacts on the system control as a systematic and fastidious delay. Only drawback of these gate drivers is the 5V logic compatible inputs that cannot be driven directly by the 3.3V logic level DSP. This forced us to insert a level shifter interface, 74HCT541 with the only purpose of logic level adaptation. New gate drivers, a substantial improvement of the IR2213, are presently in development and will soon be available to overcome this problem and also simplify other aspect of the here described schematic.

5. DC bus and Input voltage feedback

The purpose of this block is to continuously check the voltage of the two supply lines of the system: Vin and DC bus; it is shown in fig. 11. Vin is the only external power supply needed for all electronics in the EDB. The internal flyback regulator has its own under-voltage lockout to prevent all electronics from start working when an insufficient supply voltage is present; this UVLO is internally set at a typical voltage of 8.4V with an

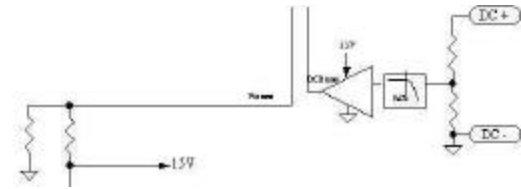


Fig. 11: DC bus and Input voltage feedback

hysteresis of approximately 0.8V, when this level is reached the internal flyback turns on and the board is alive. Remembering what described in the previous chapter dedicated to the internal flyback Power Supply, low side gate drivers are directly fed from the Vin line and there is no further control to this voltage than their own under-voltage lockout. This is typically set at 8.5V and this level could be not sufficient to properly drive the IGBT gates, then, through a standard resistor divider, we check the Vin voltage and impose that the system could start switching only when the Vin voltage is between 10V and 18V thus providing also an over-voltage control.

The DC bus voltage is also important for the system functioning and needs to be continuously kept under control, this is done through another resistor divider that unfortunately is at high voltage and had to be layouted on the EDB with a particular care, unfortunately occupying some precious space. The divider provides a partition coefficient of 3.47mV/V, having the ADC reference at 3.20V this yield a maximum mapped voltage of:

$$V_{DCbus_max} ? \frac{3.20}{3.47 * 10^{23}} ? 922V$$

As the block schematic shows, it has to be taken into account that, to avoid false detections due to voltage spikes inevitably present on the partitioned voltage, a 1kHz passive filter has been inserted between the divider and the voltage follower buffer whose output is connected to one of the ADC inputs. An easy calculation shows that the precision reached in reading the DC bus voltage is:

$$1LSB ? \frac{922}{2^{10}} ? 0.9V$$

Which is more than enough for this purpose.

PRINTED CIRCUIT BOARD REALIZATION AND COMMENTS

This so far described PI-IPM™ is a kind of PEBB (i.e. Power Electronic Building Block) for many motor driver applications and it is suitable for any type of motor: Brush-less, Induction, and Switched Reluctance. Because of the “on board” presence of a high intelligence component such as a DSP, it is also well positioned to become an interesting component in many sensor-less applications. Depending on the type of system in which it is inserted, the performances level and target cost should change to encounter the major number of possible sockets in the market.

As already stated, one of the most important features of this device is in fact flexibility, the EDB could be designed and tailored to the customer application, still leaving to the customer the benefit of developing and downloading its own proprietary software. However this is not such an easy task and many critical factors challenge the engineer in developing a good driving board for this power module.

Fig. 12 and 13 show one of the first prototypes

realized and tested in our laboratories, their performances evaluation and first experimental results will be the subject of a further paper.

During the realization we faced two major problems: isolation and noise of the environment. The first was solved only through introducing enough spacing between components and high voltage copper lines, it was also in some cases very helpful to add more layers in the PCB stratification. The EDB is in fact a six layers board: two internal layers are planes for ground and supply voltages V_{in} and V_{5-iso} ; top, bottom and a third layer are instead for low power signal interconnections; the other remaining internal layer is used for the high voltage floating lines of gate drivers and current sense devices.

Components positioning is also a major issue, some devices are noise and temperature sensitive and cannot be placed in the board bottom side while others are not so critical. Integrated circuits such as the DSP and the current sensing have been placed on top, following the above-mentioned rule, while gate drivers and the flyback controller found their socket on the bottom side.



Fig. 12: PI-IPM™ first prototypes

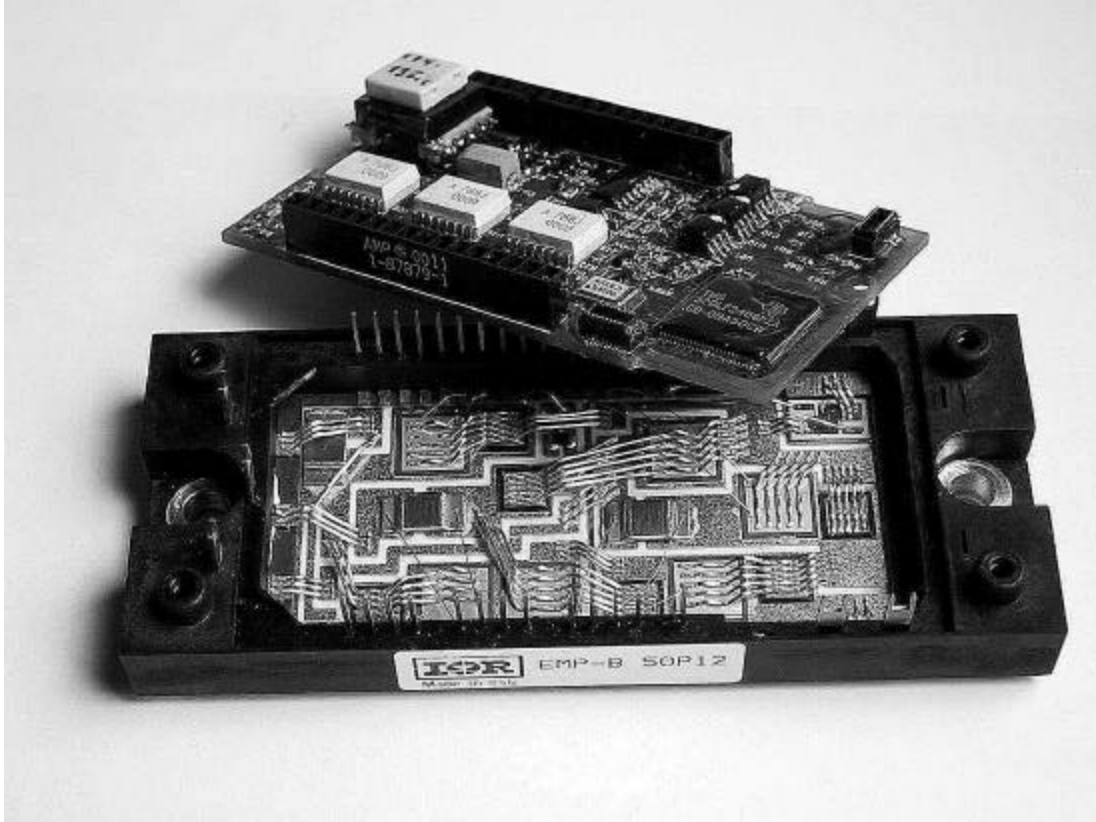


Fig. 13: PI-IPM™ module and driving board

Not only the noise of the environment (IGBTs switching in the underneath power module) is the cause of potential problems but also the printed circuit board itself. Some copper traces are a relevant source of troubles, for example the floating power supply lines of the high side gate driver stages that are, in the system normal operation, commutating between DC bus minus and DC bus plus with a voltage swing of around 500V. In this case any inductive or capacitive coupling, though very limited in absolute value, could be enough to induce a considerable noise in any analog high impedance line, thus inferring in feedback and protection signals. Those 6 lines had to be carefully drawn in the PCB layout, confined in a single internal layer, and any crossing with other lines in different layers was intentionally forced to be perpendicular to reduce likely cross-talk of any type.

Again talking about the flyback power supply, also its position in the printed circuit board is critical. The controller is switching at 200kHz and consequently is a relevant source of noise, having sensitive devices (such as the current sensing and

the DSP) in the area is not advisable, then we placed this block in one corner, at the opposite side of the DSP and as much as possible away from any other analog circuitry.

CONCLUSIONS

A new Intelligent Power Module, so called PI-IPM™, using the well-known DBC technology has been developed specifically for high performances servo motor driver application. Thanks to its considerable limited dimensions, it is particularly suited for space saving solutions where the space is a real constraint, such as Integrated Motor Drivers or Motor Drivers of the new generation.

To include all functions and reach high-level performances a new package, named EMP™, has been designed to accommodate the printed circuit board on its top, with all needed connections for a proper communication between the two parts.

With this new device a motor driver designer can easily design and debug its system with an excellent level of performances and a considerably improved time to market.