High-Functionality Compact Intelligent Power Unit (IPU) for EV/HEV Applications

G. Majumdar(1), K.H. Hussein(2), K. Takanashi(1), M. Fukada(1), J. Yamashita(3)
H. Maekawa(4), M. Fuku(4), T. Yamane(4), and T. Kikunaga(5)

(1)Mitsubishi Electric Power Device Division, (2)Fukuryo Semicon Engineering Corporation (Japan)
(3)Mitsubishi Electric ULSI Development Center, (4)Mitsubishi Elec. Automotive Electronics Development Center (Japan)
(5)Mitsubishi Electric Advanced Technology R&D Center (Japan)
Tel: +81 (0) 92 805 3303, Fax: +81 (0) 92 805 3745, e-mail: khalid@mail.oka.melco.co.jp

Abstract

A new high-functionality compact integrated Intelligent Power drive Unit (IPU) for electric and hybrid-electric vehicles (EV/HEV) is introduced in this paper for the first time. The IPU utilizes low-loss, rugged 5th Generation Sub-μ planar IGBT and ultra soft-recovery FWDi chips, and, in addition to various control functions, the IPU integrates a specially designed solid DC-Link capacitor. Through parts counts reduction and high functional integration, the newly developed IPU achieves an overall inverter system size and weight reduction of about 40~60% when compared with conventional systems. The IPU thus provides EV/HEV applications with high-efficiency, high-functionality, and high-reliability compact inverter systems.

Introduction

During the last two decades of the 20th Century, as it is well known, global concerns to reduce the automotive harmful exhaust gasses (e.g. NOx, CO, and CO_2) and to improve the fuel efficiency have been steadily increasing. Although the concept of electrically propelled vehicles, or EVs, dates back as early as the 19th Century, their production in mass-quantities comparable to internal-combustion vehicles (ICVs) is yet to be realized. Recently, the commercial production of vehicles using electric motors (EV) and hybrid-vehicles using a combination of electric motors and internal-combustion engines (HEV) for power-train became feasible (1, 2). This progress was achieved with the help of recent advances in power electronics and battery technologies (3). Among the various requirements of EV/HEV applications, the inverter system size, weight, efficiency, and reliability have a vital importance. Therefore, existing EV/HEV inverter systems generally use intelligent power modules (IPM) in an attempt to achieve compact and efficient designs. However, other external electric components in the inverter system, particularly DC-Link capacitor bank, drive control power supplies, and pre driver unit (PDU) tend to be large in size and heavy in weight. Also, external connectors and wire-harness used to interconnect these components with the IPM require extra space and affects the over-all system noise performance and reliability. With these drawbacks in mind, the main concepts behind the new IPU design were based on achieving a very compact overall inverter structure while addressing the EV/HEV system functional needs and vital performance and reliability requirements.

IPU Concept

As can be seen from Fig. 1, the IPU integrates, in a novel multi-assembly package, the power chips necessary for efficient 3 ϕ inverter operations (300A / 600V IGBT and FWDi) in addition to a specially developed, compact DC-Link capacitor eliminating the need for external, bulky electrolytic DC-Link capacitors. Further, the IPU integrates dedicated VLSI-ASIC chips performing a full range of IGBT drive, protection, and status monitoring functions in addition to a built-in central processing unit (CPU), DC/DC converter with a low-profile sheet-transformer, and isolation ICs.
The IPU thus eliminates the need for the Pre-Driver Unit (PDU) usually found in conventional EV/HEV systems. A more advanced IPU concept (future version) integrates the Motor Control Unit (MCU) and motor current sensors resulting in even higher-functionality and further size and weight reductions.

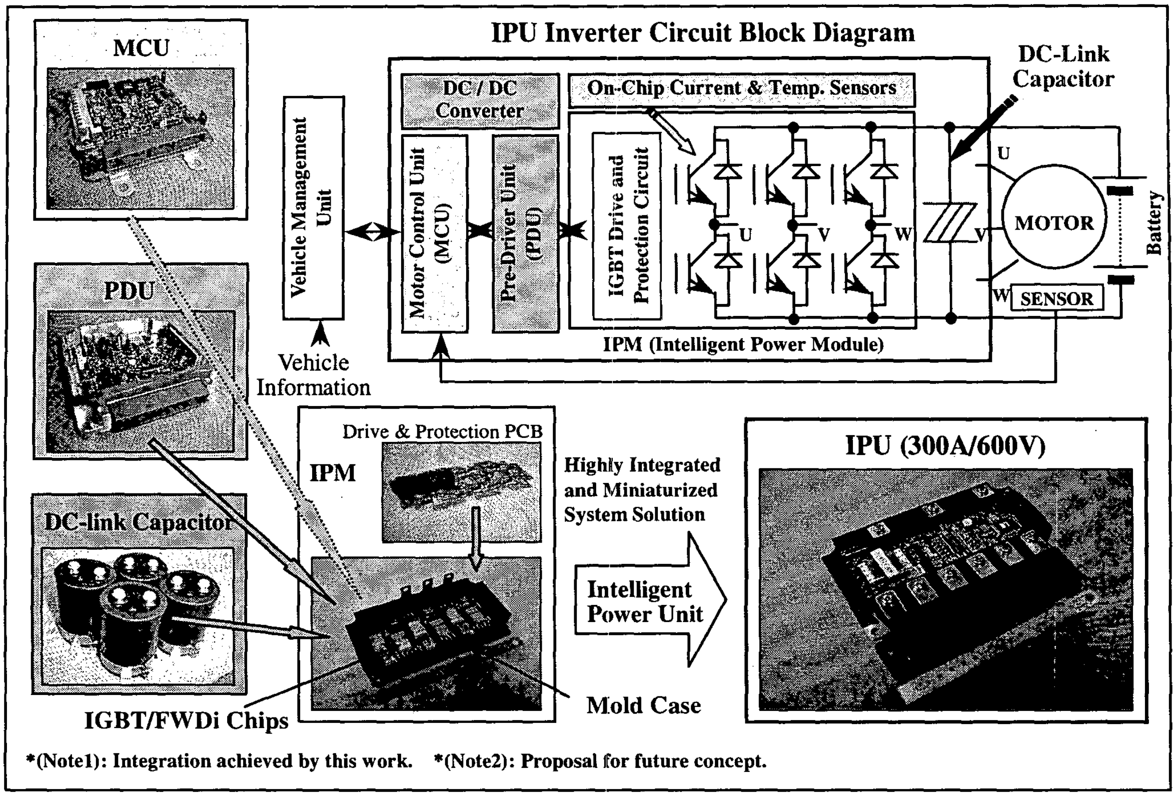

Fig. 1 General Block Diagram Illustrating the IPU Concept

IPU Package

Details of the IPU package internal construction can be explained with the help of Fig. 2 in the following. The IPU contains both the power and control devices and components mounted on a 2 level optimized package structure. The power devices (IGBT & FWDi) are mounted on copper base, direct bond copper (DBC) plate providing both sufficient electrical isolation and efficient thermal characteristics. Good thermal characteristics help minimizing thermal cycling the thing that reflects favorably on the IPU long operational life and, hence, addressing the crucial overall EV/HEV system reliability. The IPU various drive, protection, and control parts are assembled on a high-density multi layer printed circuit board (PCB). The PCB pattern and components layout was optimized to achieve both high-functionality and satisfy the severe noise-immunity levels required by EV/HEV systems. As an extra measure to reduce noise interference from the nearby power chips (i.e. EMI considerations) a shield plate is placed between the PCB and the power chips.

In addition to a full-range of IPM drive and protection functions provided by special VLSI-ASIC chips mounted on the PCB (e.g. drive voltage abnormality, short circuit, over current, over temperature, gate-control, HV isolation, ... etc.), the IPU is equipped with a built-in CPU and an isolated DC/DC converter. The CPU facilitates communication between the IPU and the EV/HEV main controller (e.g. control commands input and status monitoring feedback) and enables flexible on-board parameters adjustment by software, i.e. digital trimming. Thus, the built-in CPU plays an important role in improving the accuracy of the IPU internal functions without the need for costly and time consuming trimming process during the production phase.

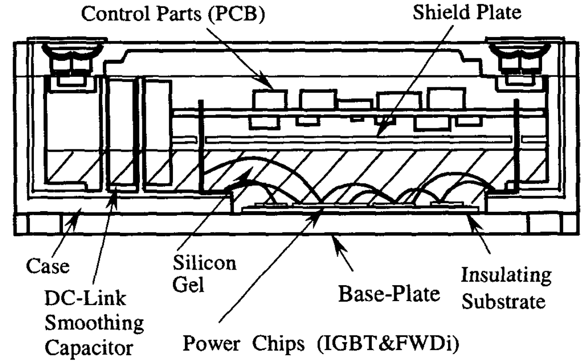

Fig. 2 IPU Package Internal Structure

The IPU drive and control power supplies are provided by the built-in isolated DC/DC converter which is basically a switching power supply with a newly developed low-profile sheet-transformer.

Another major miniaturization factor achieved by the IPU is the integration of the DC-Link capacitor which, in conventional EV/HEV systems, is usually a bulky aluminum electrolytic capacitor bank occupying large space and adding extra weight to the system. Unlike general purpose and industrial inverters where the main power source is a rectified AC voltage containing considerable ripple that necessitates filtering and smoothing, the main power source in EV/HEV systems is originally a DC voltage (e.g. from a battery) with far less ripple contents. Therefore, capacitance of the DC-Link capacitor in EV/HEV inverter systems can be considerably reduced without affecting the inverter system performance. The main considerations followed in determining the built-in capacitance minimum value were: battery characteristics, input power line impedance, control technique, and more importantly, the maximum DC-Link voltage rise during the inverter regenerative (or brake) operation mode. In order to have the minimum possible size, the shape of the capacitor was designed to have cubic outlines instead of the usual cylindrical shape that results in unused extra space between capacitor units. Besides its compact size, the newly developed solid capacitor was designed to have very small effective series inductance and resistance (ESL and ESR, respectively) in order to provide efficient snubbing effect to the IPU during switching. Another important merit gained by integrating the DC-Link capacitor is the minimization of the wiring inductance between the power chips and the capacitor and hence effectively reducing the switching surge voltage.

With such high-level of integration within the IPU package, the IPU greatly reduces the overall EV/HEV inverter system size and weight, and improves reliability through the reduction of external parts and connectors. Using the IPU, an overall size reduction of 40~60% can be achieved over conventional systems as detailed in Fig. 3.

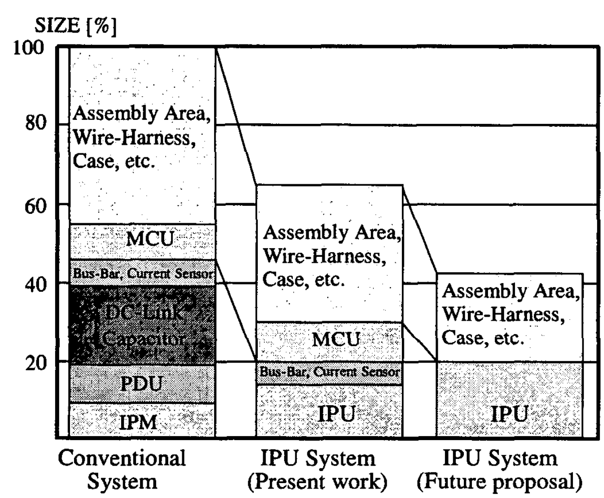

Fig. 3 Overall Size Reduction Achieved by using the IPU

IPU Power Chips

Performance of inverter systems greatly depends on the quality of its power chips. Efficiency and reliability of the IPU is realized by using new low-loss, rugged 5th Generation IGBT, and new ultra soft-recovery FWDi. The 5th Generation IGBT chip was developed using state of the art Sub-μ planar IGBT process technologies. Detailed structure and characteristics of the 5th Generation IGBT chip are listed in (4). When compared with existing 3rd Generation IGBT chips (3μ process rule), a current-density increase from 130 A/cm^2 to more than 200 A/cm^2 was achieved allowing a 30% chip size reduction. Further, saturation voltage drop (Vce(sat)) reduction of about 0.5~0.6V was also achieved over the 3rd Generation IGBT chip as can be seen in Fig. 4.

The main development targets for the IPU new FWDi chip were to achieve ultra soft recovery characteristics while at the same time reducing total power losses. FWDi soft-recovery characteristics are desired in order to reduce EMI noise occurring during fast IGBT switching instants. FWDi power loss reduction is particularly important for EV/HEV systems because of the frequent regenerative inverter operations and stall modes. Soft recovery FWDi designed by conventional carrier lifetime control tend to have higher forward-voltage drop (Vf) and hence higher conduction losses. Ultra soft-recovery characteristics of the new FWDi were achieved without sacrificing the Vf value by adopting localized carrier life time control, near the anode, using Helium irradiation as illustrated by the comparative structure diagram in Fig. 5.

IPU Experimental Performance

Experimental results confirming the successful operation of the IPU in general, and the built-in DC-Link capacitor in particular, under actual motor drive conditions are shown in Fig. 6.

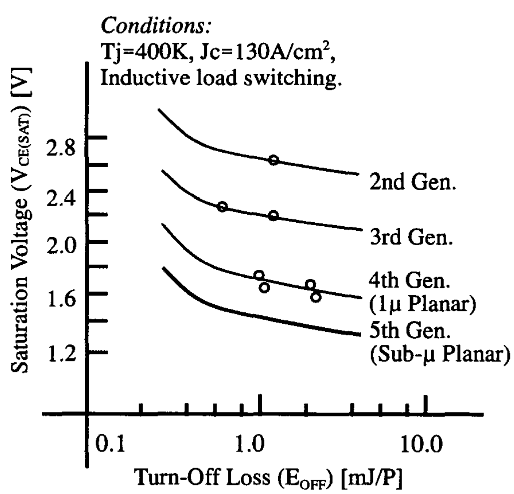

Fig. 4 IGBT Vce(sat) - Eoff Trade-Off Curves Comparison

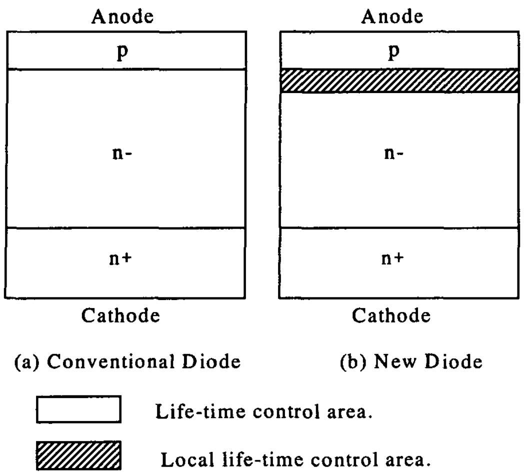

Fig. 5 Free-Wheeling-Diode (FWDi) Structure Comparison

Experimental Conditions:
Induction Motor; Phase Current: 200Arms
Power: 25kW, Battery: 288Vdc @No-Load
Ch1: Motor phase current (200A/div)
Ch2: DC current (50A/div)
Ch3: Vdc (100V/div)
Ch4: Torque reference (70Nm/div)
Time: 1.0ms / div

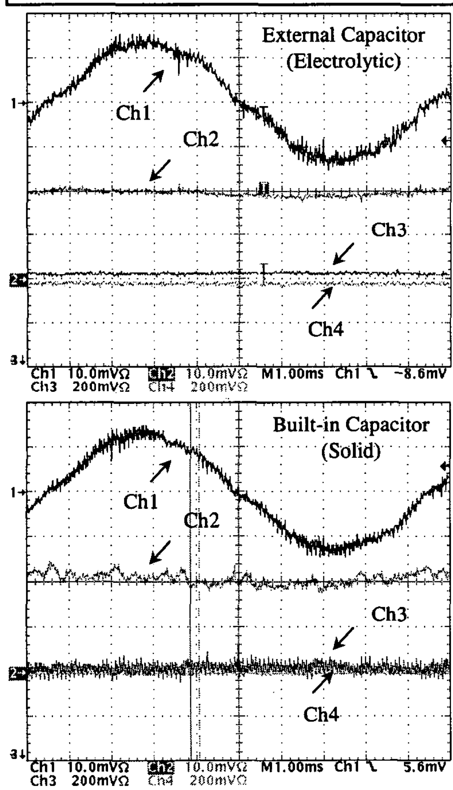

Fig. 6 Experimental Performance of the IPU Built-in DC-Link Capacitor

Conclusions

The main concept, functions, and merits of a new compact 300A/600V intelligent power unit (IPU) were presented in this paper for the first time. The new IPU is designed specifically for electric and hybrid vehicles (EV and HEV respectively) inverter systems. In addition to a 3 ϕ DC-AC inverter bridge complete with its drive circuitry and a full set of IPM protective functions, the new IPU provides extra favorable merits and functions summarized in the following points :

- Low-loss, rugged 5th Generation, Sub-μ Planar IGBTs.
- Ultra soft-recovery free-wheeling diodes (FWDi).
- Compact package with built-in DC-Link capacitor.
- VLSI-ASIC chips for efficient IGBT drive, protection and status monitoring.
- Built-in DC/DC converter with low-profile sheet-transformer for the drive and control power-supplies.
- Built-in CPU for efficient communications with the EV/HEV main control unit and for flexible on-board parameters adjustments.
- Built-in pre driver unit (PDU).

With these capabilities, the new IPU achieves the goal of inverter miniaturization while at the same time addressing the vital requirements of EV/HEV systems. The IPU high functional integration leads to higher reliability, and reduces overall system size and weight through the reduction of externally needed parts and connectors. Using the IPU concept, a 40%~60% size and weight reduction of EV/HEV inverter systems can be achieved over conventional systems. Given its encouraging performance and merits, the IPU integrated functions can be increased further to include the motor control unit (MCU) and the motor current sensors.

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