Double-sided Cooling Integrated Power Module and Power Control Unit

Dynex Semiconductor

AESIN Conference - October 20th 2016
PART 1: COMPANY PROFILE

PART 2: HEV/EV Application

PART 3: Capabilities

PART 4: Performance
1. COMPANY PROFILE

Dynex

Dynex has more than 50 years experience in the design and production of high power semiconductors...

One constant throughout all this change is that our manufacturing and R&D has been based in Lincoln UK since 1956

This has maintained continuity of personnel which is important for:

- R&D
- Manufacturing expertise
- Our customers

A significant change to Dynex...

With major implications to our future development and the products and services we provide to our customers around the world

75% owned by CSR Times Electric
1. COMPANY PROFILE

Overview

Railway Developed Technologies Applied to EV

The company has developed a series of products including Electric drive systems, hybrid power system assemblies and complete electric vehicles, etc., incorporating proprietary technologies, through nearly 10 years of research and application by extending core technologies that CRRC accumulated in the field of rail transit over the past 50 years to the field of electric vehicles. These technologies include electric motors and control systems, converter systems and network control.
1. COMPANY PROFILE

Structure Overview

- CRRC ZHUZHOU INSTITUTE CO., LTD
  - CRRC QINGDAO SIFANG CO., LTD
  - CRRC ZHUZHOU ELECTRIC LOCOMOTIVE CO., LTD
  - CRRC ZHUZHOU ELECTRIC MOTOR CO., LTD
  - CRRC QISHUYAN INSTITUTE CO., LTD
  - CRRC YANGTZE CO., LTD
  - .......

- ZHUZHOU CRRC TIMES ELECTRIC CO., LTD
  - ZHUZHOU TIMES NEW MATERIAL TECH. CO., LTD
  - ZHUZHOU CRRC TIMES ELECTRIC VEHICLE CO., LTD
  - XIANGYANG CRRC ELECTRIC MACHINERY CO., LTD
  - .......

- DYNEX SEMICONDUCTOR LTD

Global centre for R&D of high reliability IGBT chips, Modules and SiC

CSR ZHUZHOU INSTITUTE CO., LTD:

- 10 subsidiaries, 20k employees, US$ 4.7 billion in 2015
- Rail transportation (traction drive system, the control network system, on-board information system and auxiliary power supply system), electric vehicles, wind/photovoltaic power generation, marine propulsion, Engineering machinery, Mining/Special vehicles
- Member of SoE Electric Vehicle Industry Alliance, Drive system and its generic technology
PART 1: COMPANY PROFILE

PART 2: HEV/EV Application

PART 3: Capabilities

PART 4: Performance
## Package Requirements of Vehicle Power Electronics

### Challenges of Vehicle Electronics Package

<table>
<thead>
<tr>
<th>Type</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical</td>
<td>High power density, high switching frequency, low loss, low parasitics, and high SOA</td>
</tr>
<tr>
<td>Thermal</td>
<td>High operation temperature, low thermal resistance, matched CTE</td>
</tr>
<tr>
<td>Mechanical</td>
<td>Anti mechanical vibration and shock capabilities, small volume, light weight</td>
</tr>
<tr>
<td>Reliability</td>
<td>Thermal cycling and power cycling capabilities, high mechanical reliability</td>
</tr>
</tbody>
</table>

### Development Target of Vehicle Electronics Devices

<table>
<thead>
<tr>
<th>Year</th>
<th>Cost($/kW)</th>
<th>Power Ratio (kW/kg)</th>
<th>Power Density (kW/l)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>5</td>
<td>12</td>
<td>12</td>
<td>93%</td>
</tr>
<tr>
<td>2020</td>
<td>3.3</td>
<td>14.1</td>
<td>13.4</td>
<td>94%</td>
</tr>
</tbody>
</table>
Integrated Power Module

Four Main Features of IGBT Power Module
The broken aluminum wire bond, high parasitic inductance and unevenly distributed temperature of dies lead to issues of product performance and reliability.
State of the Art and Development of Vehicle Power Electronics

Package Technology of Power Module

- Gen_I
  - Wire Bond
  - Single Side Interfacial Cooling
- Gen_II
  - Planar Bond
  - Integrated Cooling
  - Reliability Enhancement
- Gen_III
  - Dual Planar Bond
  - Double Sided Cooling
  - Integrated Double Sided Cooling

Nissan LEAF

Infineon HybridPack

Toyota Prius '10

Infineon HybridPack

Toyota LS600

Mitsubishi TPM

Semikron SKiN

Infineon XT

Hitachi DCPM
State of the Art and Development of Vehicle Power Electronics

Package Technology of Power Module

- Planar bonding – Enhance the reliability and performance

- Failure of Eliminating Aluminum wire bond, parasitic reduces by 80%

- Special metalisation of the front side is required
State of the Art and Development of Vehicle Power Electronics

Package Technology of Power Module

- Changes of the 3rd generation of electric vehicle IGBT package – Double-sided planar bonding, double-sided cooling, double-sided integrated heatsinks.
Integrated Power Module and Integrated Power Unit Systems

Double-sided Cooled IGBT Module

Integrated Power Module (IPM)

Integrated Power Unit (IPU)
## Integrated Power Unit

The Integrated Power Unit (IPU) is specially designed for electric vehicle applications, which is integrated with the bespoke IGBT module package and double sided cooling structure in order to achieve a high power density, high reliability and low cost design.

### IPU Technical Specifications

<table>
<thead>
<tr>
<th>Model</th>
<th>IPU60-120</th>
<th>IPU85-125</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC input voltage</td>
<td>DC100V-DC430V</td>
<td></td>
</tr>
<tr>
<td>Rated Power</td>
<td>60kW</td>
<td>85kW</td>
</tr>
<tr>
<td>Rated output current</td>
<td>200Arms</td>
<td>288Arms</td>
</tr>
<tr>
<td>Peak Power</td>
<td>120kW</td>
<td>125kW</td>
</tr>
<tr>
<td>Peak output current</td>
<td>400A@30s</td>
<td>425A@30s</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>5kHz-10kHz</td>
<td></td>
</tr>
<tr>
<td>Cooling fluid</td>
<td>50% water/50% ethylene glycol, 8L/min, up to 75°C</td>
<td></td>
</tr>
<tr>
<td>Operating ambient temperature</td>
<td>-40°C-105°C</td>
<td></td>
</tr>
<tr>
<td>Design life</td>
<td>12 years</td>
<td></td>
</tr>
<tr>
<td>Dimension, volume, mass</td>
<td>274x191x95, 5L</td>
<td>266x160x130, 5.5L</td>
</tr>
<tr>
<td>Power density</td>
<td>20kW/L</td>
<td>22.7kW/L</td>
</tr>
</tbody>
</table>
**Integrated Power Unit**

Custom developed Integrated Power Unit (IPU)

**IPU Main Features**

- Bespoke power module package for HEV/EV reduces volume and mass
- Double-sided cooling with baseplate-less structure increases thermal performance and power density
- Optimised component selection and/or design make it possible to achieve higher reliability
- Based on ISO26262 certified MCU
- Customised solutions for specific applications

IPU85-125
Integrated Power Module (IPM) used in IPUs integrates three phase IGBT modules with double side cooling plates resulting in compact size and high performance for applications.

**Main Feature**

The IPM is characterised by a **double-sided cooling structure** with thin and lightweight cold plates, which increase power density by more than 30% compared with a conventional single-sided cooled module approach.
# Integrated Power Module

**IPM Technical Specification**

<table>
<thead>
<tr>
<th>Type</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6 in 1 IGBT module with thermal monitoring</td>
</tr>
<tr>
<td>Configuration</td>
<td></td>
</tr>
<tr>
<td>Rated voltage and current</td>
<td>650V/600A</td>
</tr>
<tr>
<td>Maximum temperature under switching conditions</td>
<td>150°C</td>
</tr>
<tr>
<td>Cooling method</td>
<td>Double-sided liquid cooling</td>
</tr>
<tr>
<td>Per IGBT thermal resistance, junction to coolant*</td>
<td>0.094K/W</td>
</tr>
<tr>
<td>Per Diode thermal resistance, junction to coolant*</td>
<td>0.134K/W</td>
</tr>
</tbody>
</table>

* 50% water/50% ethylene glycol, 8L/min

**IPM Circuit Structure**

* Ex’ is specially designed for gate drive di/dt control.
CONTENT

PART 1 COMPANY PROFILE

PART 2 HEV/EV Application

PART 3 Capabilities

PART 4 Performance
CAPABILITIES

Overall capabilities

Converter manufacturing capabilities

- 13 professional and flexible converter product lines
- Annual output of 10 GW converters = 100k motor controllers of 100kW
- Another 50,000 Units/Y EV inverter dedicated fab line is under construction
CAPABILITIES

Motor Manufacturing Capacity

**Electrical Machine Pilot Test Base**
As an electrical machine incubation base, it focuses on motor research, development and experimental test. It has capacity to manufacture 5000 special motor prototypes which are below 500kW annually.

**Xiangyang Industrial Park**
As a volume production base, it has capacity to manufacture 10000 EV&HEV motors, 4560 industrial motors, marine motors and 2080 special motors annually. The factories also reserve production capacity for 50000 passenger car motors annually.
CAPABILITIES

Total Silicon Capabilities

4-inch line
- Building area: 1.9 hectares
- Clean room area: 2000 m²
- Clean level: class 1000 in chip area
- Capacity: 300k ppy
  (ppy=pieces per year)

Lincoln Headquarters
- Building area: 1.4 hectares
- Clean room area: 3200 m²
- Capacity (6-inch): 150k ppy

6-inch line
- Building area: 2.2 hectares
- Clean room area: 5000 m²
  - Clean level: class 100
  - Capacity: 100k ppy

8-inch IGBT line
- Building area: 5.2 hectares
- Clean room area: 10000 m²
  - Clean level: class 10
  - Capacity: 120k ppy
2. CAPABILITIES

Trench Gate Field Stop IGBT Chip

Chip design and process capability, excellent overall characteristics

- **Advantages**
  - Lower on-state voltage drop
  - Better trade-off between on-state and switching loss
  - Wider SCSOA
  - Solderable top metal process in development

- **Design Features**
  - 650 to 1700V process (6500V in other IGBT technologies)
  - Tailored emitter contact
  - Low gate capacitance for shorter switching delay
  - Corner gate pad design
  - Excellent design of emitter & buffer
  - Hexagonal, stripe and circular cell structure for various applications
2. CAPABILITIES

State of the art packaging processes

- **Ultrasonic welding**
  - Low impedance
  - High current capacity
  - High intensity and reliability
  - Anti-shock and vibration performance

- TLP(Transient Liquid Phase) Bonding and low temp. Silver sintering
- Copper/copper-clad Al wire bonding
- Planar bonding&Double-side cooling

![Graph showing Tensile Strength (N) for Ultrasonic welding and soldering over different temperatures and cycles.](image)
CAPABILITIES

State of the art packaging processes

- Ultrasonic welding
- TLP (Transient Liquid Phase) Bonding and low temp. Silver sintering
  - Low electrical resistivity
  - High thermal conductivity
  - High thermal stability
  - High power cycling capability

- Copper/copper-clad Al wire bonding
- Planar bonding & Double-side cooling
CAPABILITIES

State of the art packaging processes – Sintering Equipment

Boschman sinter Star F-XL

- Pressure unit on top of each die. Excellent pressure uniformity on dies.
- Fixed sinter tool for each product.
- N2 options for Cu surface sintering.
CAPABILITIES

State of the art packaging process

- Ultrasonic welding
- TLP (Transient Liquid Phase) Bonding and low temp. Silver sintering

- Copper/copper-clad Al wire bonding
  - Low electrical resistivity
  - High thermal conductivity
  - Low coefficient of thermal expansion
  - High power cycling capability

- Planar bonding & Double-side cooling

Publication on PCIM 2012, R. Schmidt et al.
CAPABILITIES

State of the art packaging processes

- Ultrasonic welding
- Transient Liquid Phase (TLP) Bonding and low temp. Silver sintering
- Copper or copper-clad aluminium wire bonding
- Planar bonding & Double-side cooling
  - Parasitic inductance and resistance reduced by more than 50%
  - Heat evenly
  - Developed for automotive applications
Through the full system simulation model, we can investigate electrical responses of all the components under different driving cycles including NEDC(+Highway), FTP75, US06, etc.

### Simulation work architecture

1. **Driving cycle—vehicle level**

2. **Operating condition—IPU**
   - (output current, modulation ratio, power factor)

3. **Operating condition@IGBT module level**
   - (transient loss)
   - RC network, thermal model
   - Transient junction temperature of IGBT module
   - Lifetime & reliability analysis

Electrical response of driving system under specific driving cycle
CAPABILITIES
Reliability oriented design and verification platform

Technology studies:

- Machine-electrical-thermal-magnetic effect simulation and experiment
- High power density integration technology
- Efficient heat dissipation technology
- IGBT drive and protection technology
- Reliability & lifetime design and evaluation platform
- Power HiL simulation and verification system
**CAPABILITIES**

Motor Control Software Structure

- **Functions**
  - EM 4-quadrant operation mode.
  - EM full speed range control.
  - MTPA control strategy.
  - Output torque/speed/voltage slope setting
  - Output torque/speed/voltage/power limitation
  - Adjustable torque/speed/voltage response overshoot
  - DC current estimation
  - Motor monitoring and de-rated operation
  - Torque prediction
  - Demagnetization detecting
  - Anti-Jerk control
  - Other functional safety requirements

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**Diagram:**
- **VSC**: Vehicle commande
- **Operating mode select**: Mode select
- **Speed request**: Speed request
- **Speed close loop control**: Close loop control
- **Torque request**: Torque request
- **Vehicle command**: VSC
- **Multi Channel select**: Multi channel select
- **Torque refer**: Torque refer
- **Torque close loop control**: Close loop control
- **Torque feedback**: Torque feedback
- **Speed feedback**: Speed feedback
- **Voltage feedback**: Voltage feedback
- **Feedback calculate**: Feedback calculate
- **Igbt Pulses**: Igbt Pulses
- **IPU**: Power exchange
- **E-Machine**: Motor current
  - Motor position
  - Motor speed
  - Bus dc voltage
  - Bus dc current
CAPABILITIES
High Performance PMSM Motor Control

- Stator flux trajectory tracking control algorithm
  - An optimised Direct Torque Control (DTC)
  - Excellent dynamic performance
  - Lower harmonics compared with traditional DTC control
- Nonlinear PMSM motor parameters used in the control software
CAPABILITIES

Functional Safety Design – Dual Core lock/step micro and watchdog

- Fundamental layer software design to ensure safety
  - MCU is configured in dual-core lock-step mode to prevent MCU single point failure
  - Self-diagnostics mechanisms have been integrated to prevent failure
  - The MCU internal and flash power supply voltage monitoring is combined with other methods to prevent common cause failure

- Fault collection and control unit

- Dual redundant approach to rotor position and speed detection
  - Motor resolver
  - Automatic rotor position identification

- AC current detection circuit designed with redundancy

- IGBT power stage protection strategy
State of the Art and Development of Vehicle Power Electronics

IGBT Drive Technology

Basic Function
- Isolation, drive
- Basic protection (active miller clamp, basic active clamping Vce desaturation and detecting)
- Soft shutdown/two-level shutdown happened at short circuit
  - Less flexibility, excessive margin

Enhanced Protection
- Optimised active clamp (AAC control, double clamp threshold)
- Multi threshold desaturation and monitoring could achieve more precise over current protection
- di/dt feedback helps to increase the responding speed of primary short circuit protection
  - Sacrifice the loss to a certain extent, reduce design margin and increase reliability

Intelligent Control
- Open Loop: di/dt, dv/dt trigger feedback to control loss and suppress surge
- Closed loop: di/dt, dv/dt continuous feedback to ensure measured waveform match the preset route
  - Flexible control, maximises the loss reduction, reduces margins, and increases reliability

Monitoring & Diagnosis
- Real-time online monitoring and diagnosis of key parameters, early failure detection, aging major effects
- System level diagnostics verification such as fault injection and weak to open
- Support in parameter configuration and feedback
  - Meets the functional safety requirement of ISO26262

Basic Functional Circuit

Optimised active clamp function
di/dt feedback and multi threshold desaturation and monitoring

dv/dt trigger feedback
di/dt and dv/dt continuous feedback

Real-time diagnosis and monitoring
Parameter configuration and feedback
**CAPABILITIES**

**IGBT Gate Driver**

**Active Gate Driver Technology**

- Active $dI/dt$ Control
- Active $dV/dt$ Limit
- Extensive and enhanced protection systems
- Multiple DC/DC converters for ASC strategy
- Extensive functional safety capabilities
- Full communications with control board for fault diagnosis and notifications
Active $dI/dt$ Control

- Removes requirement for active clamp but still controls turn-off overshoot
- Faster switching at lower currents enhances total switching losses
- Diode protected at turn-on
- Still resistor based but closed loop control is through active limiting function

Turn-off $dI/dt$ control
**CAPABILITIES**

**IGBT Gate Driver**

**Switching Losses Reduced**

- **Loss after switch off is 67mJ**
- **Loss after switch off is improved to 39mJ!!**
- **Active \(\frac{dl}{dt}\) control with 2\(\Omega\) resistor and overshoot limited to similar value**

- **Type I short-circuit energy is reduced by 100 and overshoot is controlled!**

**Conventional desaturation protection**

**Enhanced short circuit protection**

**Enhanced overcurrent Protection**
CONENT

PART 1
COMPANY PROFILE

PART 2
HEV/EV Application

PART 3
Capabilities

PART 4
Performance
Verified System Performance

- Thermal resistance is **reduced by 25%** compared with competitor’s module at the same voltage and current level.
- Thermal resistance is even lower than competitor’s 650V/800A module.
Verified System Performance

- **Performance Highlights:**
  - Meet the requirements of continuously operating for 30s under the battery voltage **DC450V**, output current **AC450Arms** and **10kHz** switching frequency, while with **85℃** ambient temperature.

*IPU operating with motor under the condition DC450V/AC450Arms*
Verified System Performance

- **Performance Highlights:**
  - Advanced motor control algorithm which brings **extremely fast and accurate motor torque control**. The action time of the motor torque can be around **2ms**.

Current change with 250Nm step torque of the Motor
Verified System Performance

- **Performance Highlights:**
  - Compared to competitors, the system has a larger high efficiency area, i.e. the high efficiency (>95%) area can reach up to 80%.

PCU System Efficiency Compare at Traction DC400V
(Left-based on Dynex IPM, Right-based on Competitor’s 650V/800A Module)
Conclusions

- Double-sided cooling of IGBT module is becoming the leading technology of PCU for EVs.
- CRRC-Dynex has developed the known-how and expertise in double-sided cooling IGBT and PCUs based on this technology.
- According to the benchmarking, the designed double-sided cooling IGBT and PCU have achieved the highest performance implemented in the Power Electronics area for EVs.
- The products will be released at the beginning of 2017.
Thank you for listening!