# **VTS for On-board charger** Hexagon case study



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### **Case Study**

Hexagon Applied Solutions On-Board-Charger (OBC)



Parameter	Value/description
Power	11 kW
Voltage AC side	230 Vac (ph – N)
Voltage DC side	400 / 800 Vdc
Number of phases	1ph / 3ph
Power flow	Bi-directional power flow
Cooling	Water cooling
Power devices technology	Discrete SiC MOSFETs

\*For the first prototype, 3 separate PCBs were designed and manufactured for the 3 OBC stages.

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## **Case Study**

Hexagon Applied Solutions On-Board-Charger (OBC)

#### AC line filter



- LCL filter
- Common mode choke
- Pre-charge circuit
- Protection fuses

## AC/DC stage



- 3ph full bridge with neutral
- SiC MOSFET technology

#### DC/DC stage



- Full bridge CLLLC topology
- Bi-directional power flow
- Reconfigurable transformer for 400 and 800V batteries

### **Case Study**

Hexagon Applied Solutions On-Board-Charger (OBC)

Control board and software development

- Based on Texas Instrument C2000 DSP.
- Fully flexible design (8x ADC inputs, 4x Sigma delta ADC digital inputs, 8x PWM outputs).
- 14-pins automotive connector (with additional analog&digital inputs and outputs), CAN bus connectivity, interlock circuit.
- In-house software development including base software layer and application layer.



CCS - OBC\_V ------SOBC V

OBC VS

OBC_VS/ACDC_CONTROL C - Code Composer Stud	lo			×
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6 Binaries	573 ·····			
🕫 includes	374 //GALCULATE TRIDS			
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CPU1_RAM	278 //DERECT PARK			
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IOW_LEVEL				
e targetConfigs	ADD CONTROL VARS. PT_PLL.F + ACDC_CONTROL_VARS.V.Q			
M ACDC_CONTROLC	<pre>SM p1(AACDC_CONTROL_VARS.P1_PLL);</pre>			
LE CONTROL_BOARD.c	D26 //ieturation			
CONTROL BOARD	187 1F (ACDC CONTROL_WARS, PT, PTL, s14PLL, PAK, PRQ), ACDC CONTROL_WARS, PT, PTL, s14PLL, PAK, PRQ), else #FACOC CONTROL_WARS, PT, PTL, s14PLL, PAK, PRQ), ACDC CONTROL_WARS, PT, PTL, s14PLL, PAK, PRQ), ICAN, PTL, PTL, PTL, PTL, PTL, PTL, PTL, PTL			
R CONVERTERA	100 Auto design and design and design and the local			
2 DCDC CONTROL C	11 If (ACC_CONTROL, VARS.thetm >+ 2.91) ACC_CONTROL VARS.thetm -+ 2.92 J			
a main CPUIte	WI wise if (ACDC_CONTROL_VARS.theta < 0) ACDC_CONTROL_VARS.theta ++ _2_PI_3			
E promote				
@ threephase.c	915 //VCC CONTROL ACDC CONTROL WARS, PT VDC. # = ACDC CONTROL WARS, VBC REF = ACDC CONTROL WARS, VBC1			
& threephase.h	<pre>337 pi(AACDC_CONTHOL_VARS.PT_VDC))</pre>			
2837xD RASH Ink coulternd	759 //Seturate 16 ref. Is ref			
di chanoelog.txt	end ACD_CONTROL_VARS_PF_UDC_satter			
Jinker.cmd	402 ACD_CONTROL_WAS_Id_RF + I_SAT;			
	AG3 ACOC_CONTROL_VARS.PI_VOC.ust=1;			
	<pre>if(ACDC_CONTROL_WARS.10_REP &lt; -1_SAT_)(</pre>			
	400 ACC CONTROL VARS. (1, 400 - 1, 3AT) 400 CONTROL VARS. (1, 400 - 1, 3AT)			
	an 1			
	FLOAT 16 REF 2 + ACDC CONTROL WARS.16 REF*ACDC CONTROL WARS.16 REF;			
	(1) (() TH BR TALTY ()WIDD VIAS TO BREATLY (DUTING VIAS TO BREAT T))			
	113 41(ACC CONTRO_VARS.10, 827-0)			
	<pre>416 ACDC_CONTROL_WARS.IU_REF+sq*t[I_SAT_2.1d_REF_3]; 415 else</pre>			
	<pre>418 ACDC_CONTROL_WARS.T0_REF=&gt;00*([_547_2-14_REF_2))</pre>			
	(1) //DQ CARKINI CONTROL AND OWNERS WAS BEED as AND CONTROL WAS TA BEE - AND CONTROL WAS TAC.			
	421 ACDC CONTROL, WAS-FT, G. # - ACDC CONTROL, WAS-12, RFF - ACDC CONTROL WAS-1.14			
	423 425 ACDC_CONTROL_VARS.PI_D.set = modulator_set;			
	<pre>c)i ACDC_COWTROL_WARS.PI_0.sst = modulator_sst;</pre>			
	<pre>bl(&amp;ACDC_CONTROL_VARS.PI_D);</pre>			
	427 D1(AxCbc_CORTNOL_VARS.F1_0)) (23			
	429 IF(ACDC_CONTROL_WARS.WASC))			
	of else			
	412 _3_M0C_41			
	454 If(ACDC_EMADLE && (ACDC_STATE 1- ACDC_FAULT))[			1
	429 ar(ACK_TEST_COMPER_INMALE); 436 if (test_comper_ACK_TEST_COMPTER_REG);			1
	407 C00FF_51091 to 307 T0 811			
	479 }			
	640 641 (forestational)			
	et3 prescaler=01			
	443 test_counter+*;			
	445 7/test_counter++;			
	447 F			
	and subth(ADE_MOR))[			
	ACCC (MODE CONFIDENT CONTROLS)			
	411 ACC CONTROL (WAS. 14 AFF = 480, 20 AFF 14-3; 400 ACC CONTROL (WAS. 14 AFF = 480, 20 AFF 14-3;			
A state	455 ACDC_CONTROL_WARS.vmod.d = ( * (ACDC_CONTROL_WARS.FI_D.y * ACDC_CONTROL_WARS.1.q * wL)) * _1_VDC_;			
Contraction of the second s	454 ACDC_CONTROL_WARS.WHEA.g = ( = {ACDC_CONTROL_WARS.FI_Q.y + ACDC_CONTROL_WARS.I.d * WL}) * _1_VOC_1 https://			
	c56 cese(ACOC_VOLTAGE_CONTROL)1			
1	417 ACDC_PODE=ACDC_PODEADC_COM/RDC1 418 ACDC_COM/RDC_VARAAS_VCC_REF_2			
	ACC CONTROL WARS 10 8FF - ACCC CONTROL WARS F1 VOC.y1			
	40 ACC CONTROL VARS. 10, 827 - 800 10, 827-10-3;			
1.0 m (2)	4CD CONTROL VARS. Med. # = ( - (ACDC CONTROL VARS. HT D. Y - ACDC CONTROL VARS. I. 4 * 4()) * 1 VAC. 1 ACDC CONTROL VARS. Med. # = ( - (ACDC CONTROL VARS. HT D. Y - ACDC CONTROL VARS. I * 4 * 1) * 1 VAC.			
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Alexand S .	ACX CONTROL VIAS Wood 8 + 855 WOOD 8 * 14-31			
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0	castriACC TEST DEVICES):			
S. Brandon S.				
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## **Case Study**

Hexagon Applied Solutions On-Board-Charger (OBC)

Preliminary design and controller tuning

- Topology selection.
- Script-based optimization of the AC/DC and DC/DC passives with PLECS.
- Control design and behavioral model using PLECS.
- Validation of DSP control code via c-script block.



## Thermal analysis

PCB Thermal analysis

### Preliminary design and controller tuning

- The PCB routing was imported as gerber files which were generated from the Altium project.
- The PCB has 6 layers, so a total of 6 gerber files were imported.
- The current analysis was executed within scStream in order to calculate the Joule losses to be used in the thermal analysis.





#### Gerber file import in scStream





#### Current density and Joule losses calculated by scStream

## Thermal analysis

PCB Thermal analysis

#### Initial design with 6 layers, all with the same thickness (35um)



High delta temperature (around 20degC)

#### Option 1: keep the same PCB routing and increase the thickness to 70um



Less copper = cost saving

Option 2: keep the same PCB thickness (35um) and optimize the routing to remove current choke points





## Thermal analysis

Thermal analysis on the full converter

- The AC/DC stage of the OBC was imported as an IDF file which was generated from the Altium design project .
- The internal parts of the MOSFETs are modelled within scStream.
- The MOSFET components are: the mold, the plate, the leads, the chip (where the losses are applied) and the bonding between chip and the plate
- A 0.5mm layer of TIM was placed between each MOSFET and the cold plate.







#### MOSFET (TO-247-4) model



## Thermal analysis

Thermal analysis on the full converter

- A water-cooled cold plate with 4 passes was built in scStream.
- The water flowrate and inlet temperatures are:
- Flowrate = 5 lpm
- Inlet temperature = 60degC
- The MOSFETs were mounted on top of the coldplate.



## Thermal analysis

Thermal analysis on the full converter

#### Temperature on the case of the MOSFETs



#### Temperature on the chip area of the MOSFETs



#### Temperature of the cooling water



## Thermal analysis

Thermal analysis on the full converter



Pressure distribution in the cooling pipe



#### Velocity field in the cooling pipe

## Experimental tests

## The prototype was tested within the University of Sheffield laboratories





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## Experimental tests

## Results of the thermal tests

- To thermally characterize the OBC, 16 thermocouples were installed. 10 of these were installed on the device case.
- Tests were performed changing the OBC operating conditions as well as the cooling performance (both water inlet temperature and flowrate were varied).
- The test results were then used by Newtwen to calibrate the Virtual Thermal Sensors in order to achieve an unprecedented accuracy in the real time temperature monitoring.









## Interface with Twin Fabrica by Newtwen

## Hexagon input data:

- CAD Geometry
- Mesh
- Material properties and boundary conditions
- Loss model for the power devices
- CFD solution
- Test data



## Virtual Thermal Sensors by Newtwen

Newtwen

# Building OBC VTS

## What is a virtual thermal sensor?

A software solution with no sensing placement limitations, capable of accurately estimating temperature dynamics and predicting future outcomes, across the **entire spectrum of operating conditions**.

VTS are as accurate as physical sensors and can either complement or replace them entirely.





## Twin Fabrica™

The best tool to build and deploy VTS at scale.

The VTS methodology is very effective, but also resource consuming. Different data and skills need to be well integrated to succeed. With Twin fabrica you can manage the whole workflow in a very cost effective way.



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## Thermal Management & Control

- The fast time, compact size of components and user safety requirements during battery charging for electric vehicles require proper thermal management of the power electronics system.
- The hotspot temperature of the system cannot be directly measured without high manufacturing costs.
- As a result, large safety margins are applied significantly reducing the on-board charger performance.



**On-board Charger geometry** 

How the Temperature is distributed

## Twin Fabrica<sup>™</sup>: Pipeline

#### Input

CAD, material properties, and power loss characterization







Input



#### **Finite element models**

 $\sim$  0.4 milion of degrees of freedom (DOF)

### Model order reduction

From 0.4 milion DOF to just 30 DOF reduced order model (ROM)

Physics AI virtual sensors Calibration with real sensor measurements Hexagon

### Measurement from testbench

#### Output

Final software architecture to be embedded into third party platforms

## **KPIs & Activities**

KPIs defined by Hexagon:

- VTS Position: 10 thermal sensor in the MOSFETs (8 for DC/DC and 2 for AC/DC).
- Accuracy: real sensors estimation versus virtual sensor difference of maximum ±5 °C both in steady-state and transient
- Model size: < 40 kB as target for memory footprint
- Runtime: < 200 us of execution time for the virtual sensors, suitable for the 10 ms task implementation in the TI C2000.

## Twin Fabrica<sup>™</sup>: Geometry and CFD integration

In Twin Fabrica it is possible to load 3D CAD geometry and mesh, as well as CFD results of velocity field from other software, e.g. Cradle CDF.



#### Twin Fabrica<sup>™</sup>: Homepage



#### **3D CAD geometry**



Fluid velocity field

## Twin Fabrica<sup>™</sup>: Advective heat transfer

• The advective heat transfer  $\rho c \vec{v} \nabla T$  can be directly considered in the partial differential heat equation with inflow boundary condition.





### Thermal Temperature adopting lower fluid flowrate

### Thermal Temperature adopting higher fluid flowrate

## Twin Fabrica<sup>™</sup>: ROM



- Advection is considered in the model order reduction
- Decreasing from 416118 DOF of the FOM to 30 of the ROM without loosing of accuracy and resolution
- FOM Vs ROM Error analysis toolbox
- Real time feasibility

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## **ROM Simulation**

## Twin Fabrica<sup>™</sup>: FOM vs ROM

• FOM vs ROM Temperature comparison in a steady-state simulation considering a random set of parameter material properties, boundary conditions, and heat sources. As can be seen, ROM preserve high temperature distribution accuracy:



FOM Model Temperature plot



### **ROM Model Temperature plot**

## Test Bench: Sensor placement

#### Sensor probes

2x AC/DC Mosfet junction
8x DC/DC Mosfet junction



Virtual Sensor location

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### **Real Sensor location**

## Test bench: Measures

## Data pool overview

- **4** different test conditions
- **3+** hours of recording on testbench
- 10+ different load conditions
- 4 different fluid flowrates
- 10 sensors available

### GOAL

A **unique** model capable of predicting with high accuracy in real-time the dynamic temperature behavior of the modelled virtual thermal sensors

## **Example: Test bench measurements**

### Data Input



#### Data Output



Time(s)

## **Testbench Calibration Results**

- Test: calibration
- Error: 5 °C maximum along all the operating range
- Model: Physics-based ROM



#### CALIBRATION

## **Testbench Validation Results**

- Test: validation
- Error: 7 °C maximum along all the operating range (above the KPI requirements)
- Model: Physics-based ROM



#### VALIDATION

## Discrepancy model: to improve accuracy

Discrepancy model:



- Al Neural network is used to compensate discrepancy between physics-based ROM and real measures acquired from the real device under test
- It needs calibration and validation processes provided automatically inside Twin Fabrica



## Discrepancy model: validation

- Test: validation
- Error: <5 °C maximum along all the operating range (satisfying the KPI requirements)
- Model: Physics-based ROM + AI Discrepancy Model



## Real-time implementation

Digital Twin based virtual thermal sensing implementation on TI C2000:

- RAM: approx. ~1kB
- Flash: approx. ~ 20kB
- Execution time: approx. ~ 170us
- Accurate control of system hot spot temperatures enhanced by VTS



# **VTS for On-board charger** Hexagon case study

