Technical White Paper

Electrical Vehicle Improvements With a Highly Efficient Traction Inverter Design

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ABSTRACT

The traction inverter is one of the crucial parts of every electrical vehicle. The trend to go to 800V battery system and SiC devices with high switching frequency helped significantly in increasing inverter efficiency. To have a highly efficient system, both hardware and software need to have high performance, from the advanced technology ICs, layout, and precise sensors for the feedback signals, to the control algorithms and fast control loops that control the switches. Increased inverter efficiency means lower losses, but one of the main questions is what effect increased efficiency has on the electrical vehicle. In this paper, we show the systems requirements followed by high-power test results of 300kW, 800V traction inverter (TIDM-02014) and four key factors that are influenced by the inverter efficiency.

Table of Contents

1 Introduction

The TIDM-02014 is a 300kW, 800V Traction inverter reference design developed by Texas Instruments in a collaboration with Wolfspeed. Gate driver, control board and control cards developed by Texas Instruments are combined with Wolfspeed's XM3 power modules to have a high-performance traction inverter system. This inverter can be controlled with two different MCUs, the AM263P and the TMS320F280039C. Design files, technical documentations and the software packages are available at TI.com. The TIDM-02014 reference design is shown in Figure 1-1.

Figure 1-1. TIDM-02014

2 Traction Inverter System Requirements

Power levels in the traction inverters today go above 200kW. Requirements for the increase in the power density brings together the requirements for the increase in the motor speed. The speeds of a motor go up to 20000rpm. Since the efficiency has a direct effect on the driving range, automotive companies are doing the evaluation running some of the driving cycles (CLTC, WLTP). This document presents the efficiency during the CLTC together with the key parts which help in achieving the efficiency target.

2.1 Gate drivers

Earlier generations of the gate drivers used in HEV/EV were much simpler. Systems safety requirements have become more complex and additional features have been implemented to achieve higher efficiency. Although these features can be implemented discretely, having them inside the package saves a lot of the space on the board and reduces the system cost. Active short circuit (ASC), DESAT, soft turn-off, Miller clamp and on-fly programmable drive strengths are just some of the features that are implemented in the UCC5880-Q1 isolated gate driver.

Adjustable drive strength has a significant effect on the efficiency improvement. Having the possibility to drive a power switch with higher current minimizes the turn-on and turn-off time and therefore the switching losses. Although this strong drive increases the inverter efficiency, this must not be used all the time. Fast switching brings the benefits at the light load conditions and when battery voltage is lower, while the slow switching is mainly used for heavy loads. Each power module is rated for the specific maximum voltage (for example EAB450M12XM3 is rated for 1200V). Due to the stray inductance, stronger switching leads to the higher voltage overshoot and therefore close to the voltage limit of the module. If gate driver continues switching this way, it brings the stress on the power module and therefore decreasing the lifetime. Another benefit of having the adjustable gate drive strengths is the EMI improvement. Changing the dv/dt improves the EMI after the 2nd corner frequency. Figure 2-1 and Figure 2-2 show the high-power test results taken at 800V DC-Link voltage, 7000rpm and 150Nm, for the weak and strong drive respectively. These waveforms are showing the difference in the Vgs falling and rising edges as well as the Vds overshoot when driving with two different gate strengths. Channels descriptions are as following:

- M2 (Phase U(A)): Phase current, 200A/div
- Ch2 (Vgs): Gate-source voltage, 10V/div
- Ch4 (Vds): Drain-source voltage, 400V/div

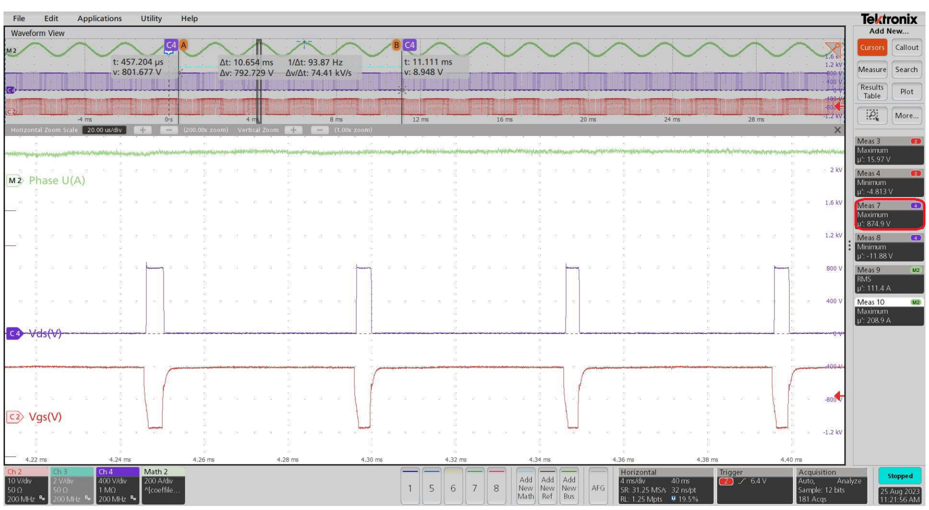

Figure 2-1. Switching Waveforms at 800V, 7000rpm, 150Nm and Weak Drive

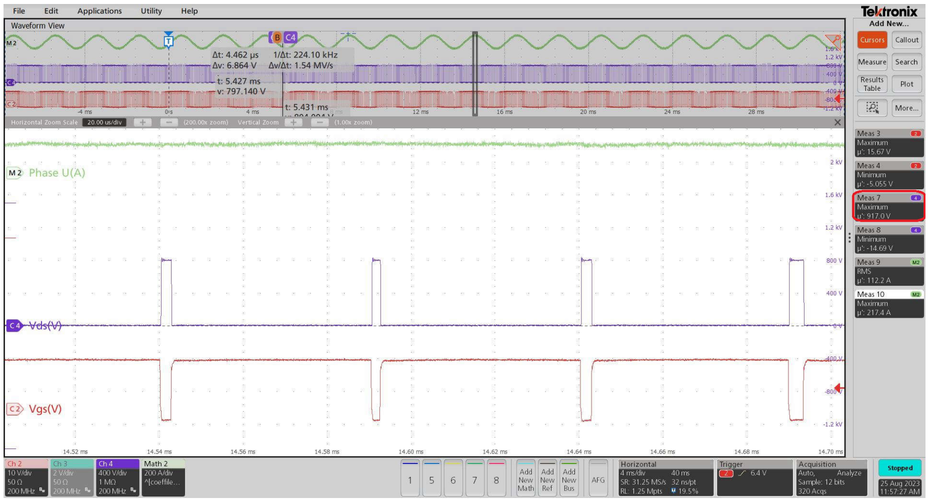

Figure 2-2. Switching Waveforms at 800V, 7000rpm, 150Nm and Strong Drive

From the oscilloscope is visible that the maximum voltage overshoot for the weak drive and this specific operation point was 75V, while the strong drive was 117V.

2.2 Microcontroller

To have a highly efficient traction invertor system, both hardware and software have to be optimized. Besides gate drivers, one of the key component is the MCU. In addition to having the accurate position, current and voltage sensing, a fast control loop has a big influence on the torque signal. Torque ripple can lead to the speed oscillations, noises and vibrations.

In this reference design, a 20kHz PWM switching frequency is used to control the XM3 SiC power modules. To achieve a higher control performance, FOC and SVPWM algorithm are called every 25us, which means that the PWM duty is updated at 40kHz. As the TI MCU (for example F280039C and AM263P) has a trigonometric math unit (TMU) to accelerate the trigonometric function calculation, the central processing unit (CPU) load can be kept at a lower percentage.

TI MCU supports software resolver-to-digital conversion (RDC). To improve the CPU load performance, F280039C can use Control Law Accelerator (CLA) to execute the RDC algorithm. CLA is an independent, fully-programmable, 32-bit floating-point math processor that brings concurrent control-loop execution to the C28x family.

In the motor control software, to control the motor at highest efficiency point, MTPA (Maximum Torque Per Ampere) and MTPV (Maximum Torque Per Voltage) are implemented using a lookup table. The most efficient work points are stored in the constant data. The software gets the appropriate direct (d) and quadrature (q) stator current commands according to torque, electrical speed and DC bus voltage. MTPA and MTPV are shown in Figure 2-3.

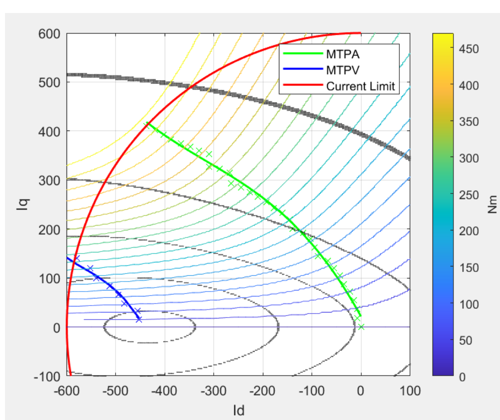

Figure 2-3. MTPA and MTPV Curves

3 High-Power Test

A high power test was performed at a Wolfspeed lab using the E-motor emulator (E-ME) from AVL. E-motor emulator gives an option to choose between different motor types with the mathematical model specified from the user's side. The mathematical model can be linear or non-linear. Since E-ME emulates the behavior of the real motor, E-ME also contains the emulators which emulate the position feedback. In this high power test, a non-linear PMSM motor parameters and resolver emulator were used. TI developed the closed-loop motor control algorithm to work in torque mode. The torque command was sent from the PC, while the speed command was provided from the TCP Client (AVL GUI) directly to the E-ME. This control system is shown visually in Figure 3-1.

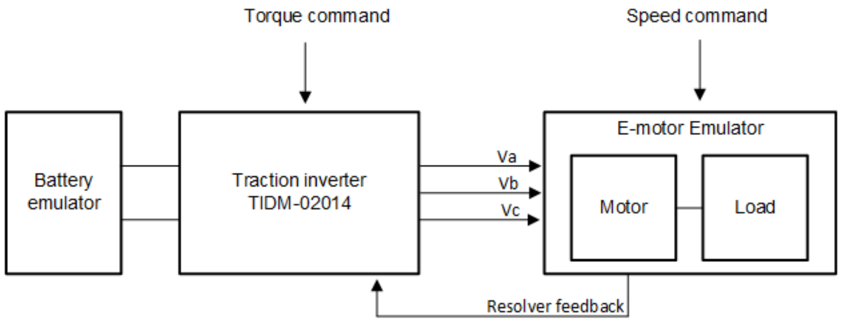

Figure 3-1. Control Commands Using E-Motor Emulator

In Figure 3-2, the E-ME cabinet is shown as a part of AVL setup where the inverter was physically placed and connected. The Yokogawa WT5000 power analyzer and Tektronix 5-Series oscilloscope were used for monitoring the signals and collecting the measurement data.

Figure 3-2. Inverter Test Setup in a Wolfspeed Lab

3.1 Test Results

The high power test was done for multiple torque and speed commands with a 800V DC-Link voltage. This data is shown in the inverter efficiency maps in Figure 3-3 and Figure 3-4. Figure 3-3 shows the efficiency for the weak gate drive strength (5A) while Figure 3-4 shows the efficiency for the strong gate drive strength (20A). The X axis shows the mechanical speed in rpm, with the range from 0 to 9000 rpm. The Y axis shows electrical torque in Nm, with the range from 0 to 150Nm. Each of the curves presents the specific efficiency. If the same point is taken, 5500rpm and 110Nm for example, the inverter efficiency for the weak drive is 98.41%, while the strong drive is 98.94%.

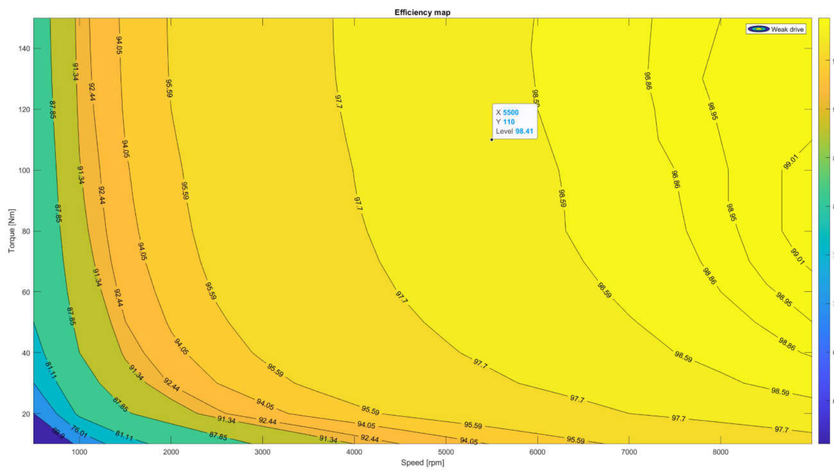

Figure 3-3. Efficiency Map for Weak Drive (5A)

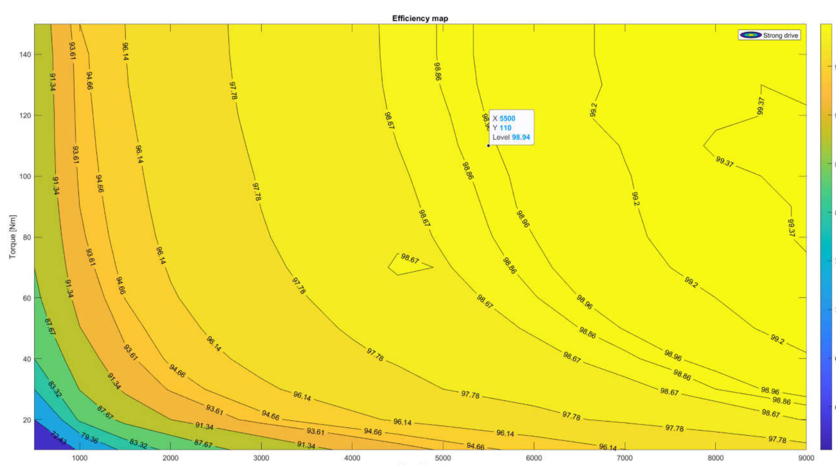

Figure 3-4. Efficiency Map for Strong Drive (20A)

The efficiency maps shown above cover the torque/speed commands required by the China light-duty test cycle – passenger cars (CLTC-P) driving cycle. Looking at the efficiency map, for the same speed and different torque commands, the higher torque inverter leads to the higher efficiency. The highest torque value required by CLTC-P for the specific vehicle vas 140Nm, which results in maximum 165Arms phase current. This driving cycle was used to show the efficiency improvement as a result of changing the gate drive strenghts on fly. Results of the adjustable gate drive strenghts during the CLTC are collected and compared with the same cycle running with only weak drive. Out of the CLTC-P speed data [km/h], required speed and torque commands are calculated for a specific vehicle type. Figure 3-5 shows the speed over the time for one CTLC driving cycle in RPM.

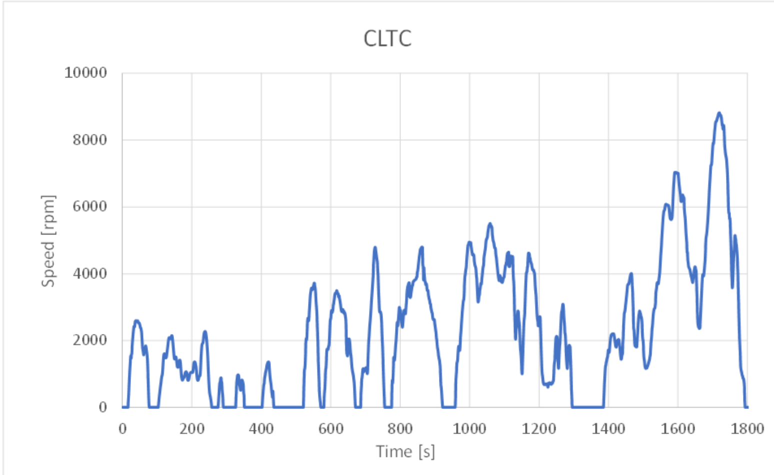

Figure 3-5. CLTC Driving Cycle

Torque and speed commands required by the driving cycle are connected to the data taken in the previous step and on that way was compared the energy consumption. In Figure 3-6 are shown the power consumption for the weak and strong gate drive during the CLTC-P driving cycle.

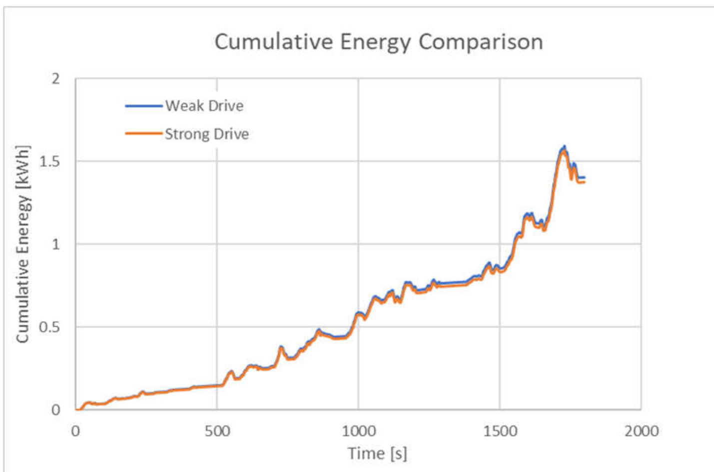

Figure 3-6. Cumulative Energy Comparison

Cumulative energy for the weak drive during the CLTC-P driving cycle is 1.407kWh, while the cumulative energy for the strong drive is 1.375kWh. The total distance of CLTC-P is 14.94km, therefore the average power consumption for the weak and strong drive are 93.9Wh/km and 92.03Wh/km, respectively.

Having the possibility to use the adjustable gate drive strengths during the CLTC-P driving cycle leads to the efficiency improvement of 2%. If a 72kWh battery is used as an example, this leads to the four key improvements shown in Figure 3-7. Having a 2% increase in efficiency can lead either to saving 140$ for a battery cost with 9kg of weight and 7.5l of battery volume for the same range or can increase a driving range for 15.5km.

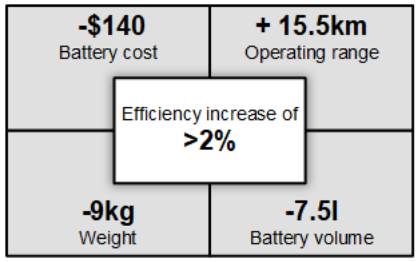

Figure 3-7. Four key factors affected by 2% efficiency improvement

The energy consumption and inverter efficiency depend on the vehicle type. Vehicle weight, maximum velocity and tire radius are just some of the factors that are important to be considered. Different vehicles also need different power to achieve the same speed within one driving cycle. If the vehicle has more weight, this requires more power and therefore the adjustable gate drive has higher influence. Another important factor that has a big impact on energy consumption is the style of driving. More frequent acceleration requires more frequent use of the adjustable gate drive strength and the efficiency improvement for that type of driving is even higher.

4 Next Generation of Microcontrollers

The rapidly evolving traction inverter requirements for MCUs in hybrid and electric vehicles (HEV/EVs) are pushing the boundaries of integration. While not yet standard, the trend of incorporating multiple functions within a single traction control MCU is increasingly popular. These functions often include vehicle control units (VCU), DC-DC converters, and, particularly in HEV designs, dual motor control. Such multifunctionality demands MCUs that provide not only high performance for swift control calculations but also large memory capacities for extensive program images and data tables. Additionally, these MCUs require advanced analog and digital peripherals, such as ADCs and PWMs, for accurate sensing and actuation.

To accommodate these varied needs and facilitate development by diverse teams within the same or different organizations, MCUs with multiple CPU cores are essential, with each core dedicated to a specific function. This approach enables modular design and enhances communication with other Electronic Control Units (ECUs), often necessitating compatibility with AUTOSAR and MCAL frameworks, particularly in the host and VCU cores.

The AM263Px MCU family adeptly addresses these complex requirements. The AM263Px MCU family combines the high performance and extensive ecosystem support of ARM CPU cores with the control peripherals from Texas Instruments' flagship real-time control MCU, C2000. This synergy results in unparalleled control performance. Furthermore, the AM263Px introduces a new hardware resolver-to-digital conversion IP, facilitating up to two resolver feedback channels complete with necessary safety checks. Meeting ASIL D safety standards and fortified with comprehensive cyber security features, the AM263Px emerges as a holistic design for the sophisticated demands of modern HEV/EV traction inverters.

5 Conclusion

There are many factors which influence traction inverter efficiency. MCU, gate drivers, sensors and control algorithms are some of them. This paper shows the influence that inverter efficiency can make on the electrical vehicle. The high-power test results of the TIDM-02014 reference design shows that, when using the adjustable gate driver strength during the CLTC-P driving cycle with specific vehicle model, traction inverter power consumption can be decreased by 2%. Having a different type of vehicle and style of driving can require more or less power and therefore have a different effect on efficiency improvement.

6 Terminology

Terminology	
ADC	Analog-To-Digital Converter
AUTOSAR	Automotive Open System Architecture
CLA	Control Law Accelerator
CLTC	China Light Vehicle Driving Cycle
CPU	Central Processing Unit
EV	Electric Vehicle
E-ME	Electric-Motor Emulator
HEV	Hybrid Electric Vehicle
IC	Integrated Circuit
MCU	Microcontroller Unit
MTPA	Maximum Torque Per Amper
MTPV	Maximum Torque Per Voltage
PMSM	Permanent Magnet Synchronous Machine
PWM	Pulse Width Modulation
RDC	Resolver-To-Digital Conversion
RPM	Revolutions Per Minute
SiC	Silicon Carbide
TMU	Trigonometric Math Unit
WLTP	Worldwide Harmonised Light Vehicle Test Procedure

7 Resources

Components

TIDM-02014

UCC5880-Q1

UCC14240-Q1

AM263P4-Q1

TMS320F280039C-Q1

AMC3330-Q1

ISO1042-Q1

TCAN1043-Q1

ALM2403-Q1

EAB450M12XM3

Equipment

E-motor Emulator from AVL

Yokogawa WT5000 power analyzer

Tektronix 5-Series oscilloscope

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