New Technologies to Improve the Performance of your Servo Drive

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Agenda

- Overview of three phase inverter power stage for motor drives
- Technology trends: GaN & isolated delta sigma

Part 1 – High Frequency GaN Inverter
- Advantages of TI’s GaN power modules for 3-phase motor drives
- Example system for 2 KW high frequency GaN Inverter for 230 Vac servo drives (TIDA-00915)

Part 2 – High Performance Reinforced Isolated In-Phase Current Sensing
- Advantages of delta sigma modulators for in-phase current sensing in motor drives
- Example system for reinforced isolated in-phase current sense using delta sigma modulators (TIDA-00914)
Generic Servo Drive Hardware Block

**Analog Processor**

**Isolation**
Architecture specific

**Safety Options**
- Analog Processor

**Communication**
- Industrial Ethernet, Fieldbus, I/O, ...
- Service Interface
  - ESD
  - Ethernet PHY
  - RS-485 PHY
  - CAN PHY
  - PMIC/DCDC
  - SVS
  - Comms MPU
  - I/O

**Power Supply**
- Protection
- OR
- Wide Vin DC/DC
- High Vin DC/DC

**Control**
- Control Loop Processor
- DC/DC Converters
- LDOs
- Watchdog
- SVS
- FAN Drive
- Temp Sense
- ISO
- VREF
- CLK

**Position Feedback Sensor Interface**
- Processor
- DC/DC
- OVP/OCP
- RS-485
- ESD
- ADC
- AMP

**Power Stage**
- 24V Isolated DC/DC
- Isolated Gate Drivers

**Braking/Regeneration**
- Analog Processor

**Position Feedback Sensor**
- Contactless
- Current Shunt
- Voltage

**I-V Feedback Sensing**

DC bus, typ. 300...1000V and more

TIDA-00915

TIDA-00914

Analog and/or digital interface + power

Texas Instruments
Servo Drive Cascaded Control Loops

- Voltage control
- Torque/current control
- Speed control
- Position control

**Motion Profile [Trajectory Generation]**
- Position Control
- Speed Control
- Torque Control

**Current Control [Field-Oriented Control]**
- Voltage control
- Torque/current control
- Speed control
- Position control

- Current Reference $I_{Q-REF}$
- Current Feedback $I_A, I_B, I_C$
- Angle Reference $\theta_{REF}$
- Angle Feedback $\theta_f$

- Motor
- Angle Sensor

**PWM Unit**
- $V_{DC} = 300-1200V$
- $3x$

**ADC**
- Current Feedback $x3$

**Trajectory Generation**
- Position Control
- Speed Control
- Torque Control

**Field-Oriented Control**
- Current Control
- Voltage Control

**Angle Sensor I/F**
- Angle Feedback

**PWM**
- Control
- Current Feedback $x3$
Technology Trends: GaN and Isolated Delta Sigma Modulators

Motor drive power stages are becoming smaller, more efficient while providing precise torque and position control for applications such as CNC machines, robotics etc.

Gallium Nitride (GaN) Power FET’s Enable:
• High PWM frequency -> Increased system bandwidth & reduced harmonics
• Efficiency -> Lower power losses
• Form factor reduction
• Motor Integrated Drives

Isolated Delta Sigma Modulators Enable:
• Accurate high resolution position control -> Better manufacturing quality and precision
• Reduced torque ripple -> Quieter motors and lesser vibrations
High Frequency GaN Inverter
Advantages of GaN Inverters in Electrical Drives

CNC, Robotics, Servo Drives

✓ GaN allows increase PWM frequency to 100kHz and more
  • Drive very low inductance PM synchronous motors or BLDC motors
  • Precise positioning in servo drives/steppers through minimum torque ripple

✓ GaN reduces/eliminates heatsink through inverters with highest power efficiency
  • Minimize space and weight

✓ GaN reduce/eliminate switch node oscillations
  • Lower radiated EMI, no additional snubber network (space, losses) required

✓ GaN reduces dead-time distortions of phase voltage thanks to negligible dead-time
  • Better drive performance at light load

Drones ESC & Turbo Compressor

✓ Increase PWM to 60kHz … 100kHz to achieve sinusoidal voltages above 1-2kHz
  • Very high-speed motors

✓ Increase PWM beyond 60kHz to avoid interaction w/ ultrasonic sensors (20kHz-50kHz)
  • High out-of-band PWM.
Switching at higher frequency for low inductance motor results in reducing ripple in motor line current.
GaN FET Advantages
GaN HEMT: Gallium Nitride High Electron Mobility Transistor (GaN FET)

- **C<sub>G</sub>, Q<sub>G</sub>** Low gate capacitance/charge:
  - Faster turn-on and turn-off, higher switching speed
  - Reduces gate drive losses

- **C<sub>OSS</sub>, Q<sub>OSS</sub>** Lower output capacitance/charge:
  - Faster switching, high PWM switching frequencies
  - Reduced switching losses

- **Zero Q<sub>RR</sub>** No ‘body diode’, zero reverse recovery:
  - Almost eliminate over-/under-shoot and ringing on switch node and hence reduce EMI
  - Allows operating GaN FETs at higher DC-Link voltage compared to Si-FET with same maximum voltage rating.
GaN “Body Diode”: 3rd Quadrant Operation

- GaN does not have an intrinsic junction body diode, but can conduct in third-quadrant mode!

LMG3410 600-V GaN Power Module Datasheet
## Cascode D-Mode vs TI Smart Direct Drive

<table>
<thead>
<tr>
<th>Mode</th>
<th>Cascode D-Mode</th>
<th>TI Direct Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Circuit</strong></td>
<td><img src="image" alt="Circuit Diagram" /></td>
<td><img src="image" alt="TI Direct Drive Diagram" /></td>
</tr>
</tbody>
</table>
| **Advantage** | ✓ Depletion-mode GaN: Low cost and better performance (compared to E-Mode GaN)  
✓ Low forward voltage drop in diode mode | ✓ Zero reverse recovery  
✓ Low gate charge  
✓ No LV MOSFET switching loss  
✓ Integrated gate driver with programmable dv/dt  
✓ MOSFET used for cycle-by-cycle OCP, OTP |
| **Disadvantage** | o High $C_{oss}$  
o Same reverse recovery of the cascode MOSFET body diode, >50nC  
o Potential for MOSFET avalanche at high $V_{DS}/dt$ | o Requires special gate drive circuit |
Discrete GaN Driver Limits System Performance

When switching at high slew rates, parasitic inductances (1-6) can cause switching loss, ringing and reliability issues. \( L_S \) is always in the loop!

Why pay for GaN if you cannot get best system performance?
Integrating the driver eliminates common-source inductance and significantly reduces the inductance between the driver output and GaN gate, as well as reduce inductance in driver grounding.

$L_S$ is not in the loop to drive the GaN FET!
**TI-GaN: Making System Design Easier and Smarter**

### High-Performance GaN FET
- TI developed HV GaN process and manufacturing
- Industry benchmark for reliability

### Smart Direct-Drive Technology
- >100V/ns slew rate capable
- Temperature, over-current, and UVLO protection

### Low-Inductance Packaging
- Zero common-source inductance
- Bottom and top-side cooled packaging

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LMG3410 600-V 12-A Single Channel GaN Power Stage

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Texas Instruments
LMG3410 Key Differentiators for 3-Phase Inverters

400V\textsubscript{DC}/7A\textsubscript{RMS}

- Optimized integrated driver with zero common-source inductance enables high-speed low loss switching
- Slew rate by resistor setting to control EMI
- Regulated gate drive bias provides reliable GaN switching
- Integrated UVLO, over current and temperature protection with fault feedback to controller
- LDO to Power Digital Isolator
- Zero reverse-recovery current reduces voltage ringing across switch
- Enable Si-FET ensure no accidental reverse conduction inverter is off
Three Phase GaN Inverter System Block Diagram

Control board with C2000 controlCARD

- +5Vdc
- Adapter Board
- PWM(U)
- PWM_L(U)
- DM
- Delfino control card

Low side of digital isolator powered from 5V_LDO output from LMG3410

High side of driver powered through bootstrap

Heat sink on bottom

Interface SIGNAL CONNECTOR

All components rated for 125°C

- PWM(X6)
- FAULT
- +5V
- GND
- Vdc bus sense
- Current sense signals

TIDA-00915 Power Board

+ 12Vdc (Gate Drive Supply)

Integrated driver + 600-V / 12-A GaN

Digital Isolator ISO7831

GaN Power Stage LMG3410

GaN Power Stage LMG3410

Digital Isolator ISO7831

X3

Three Phase GaN Inverter System

Low Inductance Servo Motor

PWM(X6)

FAULT

+5V

GND

Vdc bus sense

Current sense signals

Amc1306

Amc1306

Iu

IW

Iu

IW

Integrated driver + 600-V / 12-A GaN

Heat sink on bottom
Inverter Output Rising $dV/dt$ Switching at 300V\(_{\text{DC}}\)

- \(F_{\text{PWM}} = 100\text{kHz}\)
- \(V_{\text{DC Link}} = 300\text{V}\)

Fastest transient is during hard switching

- No over-shoot, no ringing!
- Can operate much closer to maximum voltage than Si-FET

TIDA-00915 Test Results
TIDA-00915 Test Results
Inverter Output Rising dV/dt Switching at 300VDC → Zoom

Result of fastest transient
dV/dt = 20kV/μS

✓ LMG3410 configurable slew rate allows custom optimizations
TIDA-00915 Test Results
Inverter Output Falling dV/dt Switching at 300VDC

F_{PWM} = 100kHz
V_{DC Link} = 300V
Fastest transient is during hard switching

No under-shoot, no ringing!
TIDA-00915 Test Results
Inverter Output Falling dV/dt Switching at 300VDC → Zoom

Result of fastest transient
dV/dt = 21.875kV/µS
TIDA-00915 Test Results
Efficiency and Thermal Test Setup

TIDA-00915 PCB Top Side with LMG3410

PMSM Servo Motor

Cabling to Power Analyzer

TIDA-00915 PCB bottom Side w/ Heatsink

C2000 Control Board
TIDA-00915 Test Results

Power Loss and Efficiency Results

Output power up to 2kW, output phase current up to 4.5A_{RMS}

Power Losses vs. Phase Current

Efficiency vs. Phase Current / Output Power

\[ P_{\text{out}} = \sqrt{3} \times \frac{300}{\sqrt{2}} \times 1.15 \times I \]

V_{\text{DC Link}} = 300V

Fastest Transient is During Hard Switching

Dead band = 50nS
TIDA-00915 Test Results
Thermal Analysis at 23°C Ambient

100kHz PWM, 4.5A_{RMS} output current

PCB Top Side LMG3410

PCB Bottom Side: Heat Sink
High Performance Reinforced Isolated In-Phase Current Sensing
Motor Current Sensing

Why motor current feedback is needed:

- Torque control (e.g. FOC algorithm)
- Motor short circuit protection
- Motor power monitoring – Derating current output based on module temperature
- Motor health diagnostics – Key motor parameters which are used to diagnose motor health are calculated from motor current

Induction motor torque, $T \propto \Phi I_2 \cos \Phi_2$

PMSM motor torque, $T \propto \Phi I$

Inverter output power, $P = \sqrt{3}VI \cos \Phi$

Short in load – Miss wiring or load short circuit

Ground fault – Miss wiring or dielectric breakdown
Where to Sense Motor Current

**Location of Current Sensing:**

1) **Low-Side Current Sensing**
   - Most common due to cost and common GND
   - Multiple configurations based on accuracy desired – Single shunt, two shunt or three shunt resistors
   - Discontinuous current, exact timing is critical

2) **In-Line Phase Current Sensing**
   - Most accurate
   - High common mode, often Isolation required
   - Continuous current measurement

3) **High-Side Current Sensing**
   - Isolation required especially for higher voltage
   - Generally used to detect shoot through and GND fault currents
   - Typically not used w/ 3-phase AC drives
Phase Current and Voltage During PWM

DC+ 320V\textsubscript{DC} ... >1000V\textsubscript{DC}

Key Design Challenges
- Accurate, high-resolution, low-latency phase current sensing
- Lowest latency over-current, short-circuit detection
- Isolation and EMC immunity (electrical fast transients, CMTI, surge)

![Diagram of PWM and phase current and voltage](image)

- Isolated Gate Driver
- High dV/dt ~1..10 kV/us (typ. IGBT)
- PWM, e.g. 16kHz
- V\textsubscript{L1(Phase to DC-)}
- L\textsubscript{1(Phase)}
- I\textsubscript{LowSide}
- V\textsubscript{LowSide}
- PWM

Texas Instruments
Traditional Analog Current Measurement Techniques

Example: Hall or Fluxgate based Current Transducer with Galvanic Isolation

Phase current ‘hot side’

Phase current equivalent voltage ‘cold side’

Galvanic isolated closed-loop current transducer

Typical latency <2us

Phase current (digital)

Typical 12-bit, SPI or parallel interface

Additional latency through digital interface (e.g. SPI)

Current thresholds (+/-)

typically set by DAC (programmable)

OC PWM trip

- Each stage adds error
- Typically <10 bit accuracy on system level
Limitation of Analog Isolation and SAR ADC

- **Sensor**: Linearity, drift and bandwidth of magnetic based current transducers (galvanic isolation) typically lower performance than shunt based current sensor
- **Analog isolation**: (analog signal on secondary side) more susceptible to noise than a digital signal
- **Analog IC**: For higher than 12-bit resolution cost for analog signal chain increases over-proportionally
- **Analog IC/system**: Typical single sampling at PWM period
  - Therefore typically requires higher order analog low-pass filter (amplifier) to meet Nyquist theorem
  - Hence more sensitive to noise at sample time
- **Analog system**: Additional latency due to multiple conversion stages
Isolated Delta Sigma Modulator

- Capacitive Isolation barrier
  - 100 kV/μs CMTI
  - 5000 Vrms Isolation for 1 min per UL1577

- ±250 mV and ±50 mV analog input voltage range options

- Input 0 V – Bit stream 1 and 0 high for 50% of time
- Input +FS – Bit stream 1 and 0 high for 89.06% of time
- Input –FS – Bit stream 1 and 0 high for 10.94% of time

- Clock frequency up to 21 MHz

- On-off keying

- Input to isolation channel
- Carrier signal across isolation barrier
- Output of isolation channel
Isolated Delta Sigma Modulator Signal Chain

- Single external digital signal path for both current sensing and short circuit detection
- Single conversion stage!
- All processing in digital domain!
- >14 bit accuracy on system level!

- Shunt resistor more linear, higher bandwidth and lower drift over temperature

- CMOS output or Manchester coded CMOS output

- Digital signal less immune to noise

- Digital signal less immune to noise
SINC Filtering

SINC1 filter is a moving average filter. SINC2 and SINC3 are higher order filters using cascaded SINC1 filters

\[ H(Z) = \left( \frac{1 - Z^{-OSR}}{1 - Z^{-1}} \right)^M \]

OSR: Oversampling ratio
M: SINC filter order
\( f_S \): Modulator clock frequency
\( f_{DATA} = f_S / OSR \) Decimated data rate
SINC Filter Window Placement

SINC 1/2/3 Weighing Factors vs OSR

Delta Sigma Modulator Samples

SINC filter weighing factors

SINC filter window placement
Reinforced isolated in-phase current sensing design with delta sigma modulators – TIDA-00914

- High accuracy and low drift: Calibrated full scale accuracy of <0.5% across temperature range of 0°C to 55°C
- High CMTI of modulator improves noise immunity to switching transients

Loss of secondary power detect with fail safe output

Small pin count (8) enables compact solution

Simplified clock routing to delta sigma modulators due to Manchester encoded data output

Short circuit response time less than 1.5 µs
Board Picture top and bottom view
Isolation Barrier, Connection to Heat Sink
- Different clock and data line lengths (propagation delays) may cause setup and hold time issues at the MCU
- Possibility of signal integrity problems due to star routing of clock signal from control board to power board
- Makes clock termination difficult
- Need additional clock buffer IC on power board to avoid signal integrity problems
Manchester Coded CMOS Output Version

- Manchester coded data is self synchronizing
- Data can be AC coupled

Advantages of Manchester encoding:
- No setup/hold time concerns
- Easy (series) clock termination
- No clock signal required at the MCU
- Reduced and easier wiring efforts as clock signal is not required to be sent across the boards

Manchester Encoded data = CLOCK (XOR) DATA
Test setup for Current Measurement Accuracy Testing
Current Measurement Accuracy

- AMC1306 output reading in Amperes
- Motor Phase Current (A)
- High linearity
- Precise measurements
- Calibrated FSR error < 0.1 %
  @ 25 C, 4kHz PWM, SINC 3 filter, 256 OSR
- % FSR Error vs average phase current
- Absolute error vs average phase current at different temperatures
- Effect of temperature variation is very low
Response Time to Short Circuit Detection

Response time, \( t_r = n \times \frac{OSR}{f_s} \)

- \( n \) is the order of SINC filter
- \( OSR \) is the oversampling ratio of \( \Delta\Sigma \) filter module
- \( Fs \) is the modulator clock frequency (20 MHz)

<table>
<thead>
<tr>
<th>Filter order</th>
<th>OSR</th>
<th>Current measurement resolution for FSR of 80 Apk</th>
<th>Response time</th>
</tr>
</thead>
<tbody>
<tr>
<td>SINC 1</td>
<td>24</td>
<td>6.66 A</td>
<td>1.2 ( \mu )s</td>
</tr>
<tr>
<td>SINC 2</td>
<td>12</td>
<td>1.11 A</td>
<td>1.2 ( \mu )s</td>
</tr>
<tr>
<td>SINC 3</td>
<td>8</td>
<td>0.3125 A</td>
<td>1.2 ( \mu )s</td>
</tr>
</tbody>
</table>

Short current detection threshold has been set at ±40 Apk for the test result

- Fast short-circuit protection is required to protect motor and inverter power stage
- IGBT’s required to be switched off within ~4 \( \mu \)s on short detection

\( t_r = 1.32 \mu \)s
Loss of Secondary Power Detection

- If due to fault in ΔΣ modulator analog power supply (AVDD) it becomes zero. The output of the modulator is not defined and may cause system malfunctions.
- AMC1306 implements fail safe output and common mode overvoltage indication.
Input Exceeding Full Scale Range

- If input full scale voltage measurement range (± 320 mV) is exceeded AMC1306 implements a 1 or 0 every 128th bit depending on the polarity of the signal being sensed.
Thank you for your attention

References:
TI Designs showing isolated in-phase current sensing using ΔΣ modulators:
• TIDA-00914
• TIDA-00171
• TIDA-00209

More on ΔΣ modulators
• How Delta Sigma ADC's Work, Part 1
• How Delta Sigma ADC's Work, Part 2
• Digital Filter Types in Delta-Sigma ADCs
• High Precision in motor drive control enables industrial advances

TI Designs with GaN Modules:
• TIDA-00915
• TIDA-00909
• TIDA-00913

More on TI's GaN Technology
• Direct-drive configuration for GaN devices
• Optimizing GaN performance with an integrated driver
• GaN FET module performance advantage over silicon
• High Voltage Half Bridge Design Guide for LMG3410
• Smart GaN

Speed your time to market with Motor drive TI Designs
Find reference block diagrams for Motor drive Systems
Check out our Motor Drive technical documents