Building a Basic Inverter

AMF-AUT-T0144

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Applications Engineer
Introduction Topics

- EV/HEV History at Motorola / Freescale
- Automotive High Power IGBT Product Overview
- Introduction to Induction Motors
- Description of Freescale’s Automotive EV/HEV Inverter
- Inverter Testing using Basic V/F Motor Control
- V/F Freq. & Voltage Waveform Generation
- Dead Time Generation Discussion
- Gate Drive Board and Schematic Overview
- IGBT Switching Characteristics and Challenges
- Advanced Gate Drive IC Concepts
Many Years of EV Experience Since Early 1990’s

- Dodge Dakota
- GVW 6020 lbs
- 324V Battery Pack
- 24 -12V Gel-Cells
- 1 -12V Aux Battery
- 50HP Continuous
- 140HP Peak
- 24 -12V Gel-Cell
- 1750 lb Battery Pack
- Motorola Designed 300A 400V Inverter
- On-board Opportunity Charger
1994 Ford Custom 400A 600V IPM Half Bridge

Déjà Vu

Anand, we would like to use a connector like the one shown below for the control leads.

It would be part of the cap and would protect the control leads much more. Add short Mitsubishi currently does. Please give me inputs on dimensions x, y, z, etc. as shown.

Thickn ess will be about .060 in.

Upon receipt of your feedback, I will design this connector into the cap.

Best Regards,

Alex Peto

Question:

- How can we make a custom connector for these leads? (Vec & Gears) 2 pins or 1?
- Key mechanism to avoid putting it in wrong?
- Snap fit mechanism?

Fact:

* Argo Molexian Connector is used now.

Add ADAS
Freescale Uniquely Positioned To Address HEV/EV

Start Stop
- Drivers
- Re-Gen Braking
- Power Devices

LV Battery Monitoring
- MCU
- Voltage Monitoring
- Packaging

Inverter
- Control & Safing MCU
- Isolation
- Drivers
- Power Devices
- FOC Software
- Modeling and Simulation Tools

HV Battery Management
- MCU
- Charge Monitoring
- Charge Balancing
- Communications
- Isolation

Charge Point
- MCU
- Communications
High Voltage Motor Dynamometer LAB in Phoenix

EV team in Phoenix with the necessary skills to do:

- Competitive analysis / existing product evaluation
- Validating new ideas / inventions IP & patents
- Define new potential products. Provide requirements / prototypes
- Help with evaluation of potential partners / acquisitions
- Integrate products / leverage ideas from across the Corporation
- Provide an environment for rapid prototyping
- Testing / making business case on new concepts
Continuing To Build On Our Real World Experience

Freescale Designed

- Controller Board
- Gate Driver Board
- Common Mode Filter Board
- Motor Control Software
- Enclosure

65kW Prototype Inverter Developed for an Auto OEM
What We Were Seeking:

- Access to auto qualified IGBT, Diode components, modules
- Influence over IGBT, module roadmap
- Ability to get to market quickly
- Profitable cooperation model
- Security of supply

Potential Partners

- **Semikron**
  - Packaging Modules

- **Danfoss**
  - Packaging Modules
  - Cooling

- **MaxQ**
  - Cold plates

- **Fuji Automotive IGBTs**
  - 650V / 400A Half H Bridge
  - High speed switching
  - Low inductance module structure
Freescale Semiconductor and Fuji Electric partner to increase efficiency of hybrid electric vehicle

Freescale enhances its powertrain portfolio with Fuji Electric IGBT technology to help improve automotive industry’s ‘miles per watt’

AUSTIN, Texas – April 11, 2011 – Freescale Semiconductor has entered into a strategic alliance with Fuji Electric Co., Ltd. to collaborate on insulated-gate bipolar transistor (IGBT) technology and products for hybrid electric and electric vehicles (HEV and EV). Working with Fuji Electric, Freescale will add high-power IGBT products to its existing portfolio of solutions for electronic powertrain applications, market those products to its automotive customers and define and produce new products based on customer input.

IGBTs are currently the largest segment of the market for EV power systems. With the addition of IGBTs to its portfolio, Freescale will offer all of the major electronic components of EV systems, including microcontrollers, analog gate drivers, battery monitoring ICs, power IGBTs and modeling / simulation tools, and software components / tools for motor control development.

The IGBT is a high-voltage, high-current switch connected directly to the traction motor in a hybrid electric or electric vehicle. It takes direct current energy from the car’s battery and, through the inverter, converts the alternating current control signals into the high-current, high-voltage energy needed to commutate or turn the motor. The IGBT is an ideal motor inverter switch for 35 KW to 85 KW EV motors due to its high efficiency and fast switching. The more efficient the IGBT, the less power is lost to wasted heat, resulting in better mileage or “miles per watt” (MPW) of energy.

"Freescale chose Fuji Electric’s IGBT technology based on its high-performance characteristics and capability,” said Tom Deitrich, senior vice president and general manager of Freescale’s RF, Analog and Sensor Group. “Coupled with Freescale’s automotive portfolio and pedigree, this alliance accelerates our ability to provide automotive customers with higher-efficiency inverter solutions.”

“We are pleased to work with Freescale on IGBT technology and draw on their automotive capability. This alliance will enable our IGBT technology to contribute to the increased efficiency of electric vehicles,” said Kuniaki Yanagisawa, executive officer and general manager of Fuji Electric’s Electronic Devices Business Headquarters.

Freescale is a leader in the automotive semiconductor industry with a successful legacy in powertrain electronics. With its microcontrollers designed into many EV systems today, Freescale is well-positioned to supply customers with IGBTs and other devices that will be critical to the advancement of the electric vehicle.

About Fuji Electric
Fuji Electric is a leading company providing solutions for Energy and the Environment with its wide variety of products. Power semiconductors, one of its competitive product categories, are essential in the reduction of energy consumption in electric vehicles, industrial machines and home electronic appliances. Further information is available at Fuji Electric Group web site: http://www.fujielectric.com

About Freescale Semiconductor
Freescale Semiconductor is a global leader in the design and manufacture of embedded semiconductors for the automotive, consumer, industrial and networking markets. The privately held company is based in Austin, Texas, and has design, research and development, manufacturing and sales operations around the world. www.freescale.com.
Hybrid Vehicles installed Fuji’s IGBT products
Our IGBTs are adopted for many type of vehicles

• Fuji IGBTs are used in half of the Japanese EV/HEV market except Prius, and a quarter of whole Japanese EV/HEV market including Prius

1995

Lexus
GS450h
Hino
Dutro

Nissan
Altima

Today

Lexus
LS600h
(2007)

Toyota
Crown

Toyota
Camry

Toyota
Estima

Lexus
RX450
(2009)

Lexus
HS250h,
SAI

Toyota
Crown

Lexus
HS250h,
SAI

Toyota
Estima

Nissan
Altima

Toyota
Camry

Toyota
Estima
**Standard Product Roadmap**

**Samples Now**
- **Voltage:** 650V
  - **Current:** 400A

**Samples Now**
- **Voltage:** 650V
  - **Current:** 600A

**April – Under Study**
- **Voltage:** 650V
  - **Current:** 900A

**Production: 500K / Yr @ 0.0 PPM**
- **Voltage:** 1200V
  - **Current:** 600A
Fuji IGBTs Auto Applications

Boost Converter IPM (DC-DC Converter)

1200V/600A 2in1
Since 2005

Integrated IGBT Module

Traction Motor

Motor Generator

1200V/400A 1in1
Since 2007

PCU

Power chip by Fuji

Module

Volume 500K / Yr @ 0.0 PPM
This experiment proved Ford’s 15-20% Hybrid Sales Estimate if they eliminate the Electrification Penalty.
Ford Hybrid Electric Powertrain

The Inverter will mount on the transmission
Induction Machines
Invented over a century ago independently by Nikola Tesla & Galileo Ferraris

- Stator same as BLDC
- Difference in rotor construction
- If properly controlled provides constant torque
- Low torque ripple
- No permanent magnets
- Think of it as a rotating transformer.
- Stator is the primary
- Rotor is the secondary
- Rotor current is “induced” from stator current

Model of Tesla’s 1st Induction Motor Demonstrated 1885
AC Induction Motor Slip

• Basic Principle:
  - The **stator** is a classic three-phase stator with the winding displaced by 120°
  - The **rotor** is a squirrel cage rotor in which bars are shorted together at both ends of the rotor by cast aluminum end rings
  - The rotor currents are **induced** by stator magnetic field.

• The **motor torque** is generated by an interaction between the stator magnetic field and induced rotor magnetic field

**NO BRUSHES, NO PERMANENT MAGNETS**
AC Induction Motor

- The **STATOR** windings are distributed around the stator to produce a roughly **sinusoidal distribution**.

- When three phase ac voltages are applied to the stator windings, a rotating magnetic field is produced.

- The **ROTOR** also consists of windings or, more often, a **copper squirrel cage**.

- An electric current is **induced** in the rotor bars which also produce a magnetic field.

Notice the rotor slip!

The Rotor does not quite keep up with the Rotating Magnetic Field of the stator.
4 Quadrant Operation

Generating / Braking
If the rotating magnetic field is slower than the rotor speed & in the same direction, your generating & braking

Driving
If the rotating magnetic field is faster than the armature speed & in the same direction, your driving
Regeneration and Braking on the Test Inverter

Power Supply 54V

Inverter 80KW
650V 600A 3 Phase IGBT

DC Bus

1uF

52V

PSMN8R7 80V 8.7mΩ

1KΩ

2X 120V 60W

1uF

.1uF

DC Bus

1HP 230V 3 Phase 4 Pole Induction Motor

The FWDS look like a 3 phase full wave bridge rectifier when the motor is a generator!
RPM and Slip Equations

\[ n_s = \frac{120 \times f}{p} \]

- \( n_s \) = synchronous RPM
- \( f \) = freq in Hz
- \( p \) = number of motor poles
- \( c = 120 = 2 \times 60 \rightarrow 2 \) converts pole pairs to poles & 60 converts Hz to RPM

Ex. 1hp 3 phase 4 poll motor running at 60Hz \( 120 \times 60 / 4 = 1800 \) RPM

- Slip is defined as the difference between the synchronous or stator (magnetic field) and the armature speed.
- Slip can be expressed as a percentage or RPM

\[ s = \frac{n_s - n_r}{n_s} \]

- \( s \) = slip
- \( n_s \) = stator speed
- \( n_r \) = rotor speed

Ex. @ 1725 RPM the above motor puts out full rated torque. That motor runs at 1800 RPM synchronously. \( 1800-1725/1800 = s = 4.1\% \text{ or } 1800-1725 = 75 \text{ RPM.} \)
Induction Motor Torque vs. Slip Relationship

Synchronous speed. Torque= 0  Slip = 0%
Armature is at 0 RPM slip = 100%

Slip can be stated as a % or RPM

By changing Freq. & Voltage we can generate rated torque at any RPM
Sinusoidal PWM Generation – ACIM / PMSM

- **Phase A**: Decrease Voltage to the motor
- **Phase B**: Increase Voltage to the motor
- **Phase C**: Increase Frequency to the motor, Decrease Frequency to the motor
### Phase Sine Wave Generation

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This table generates 3-120 degree out of phase sinewave PWMs. Produces 3 inverter sine waves on the 3 phase bridge. The lower PWMs are inverted from the Upper PWM signal on the same 1/2 H.

#### Phase Voltage and Current

![Phase Voltage and Current Diagram](image)

- **Phase Voltage**
- **Phase Current**
- **Zero Crossing**

**PWMs from University Board**

- **PWM0**
- **PWM1**
- **PWM2**
- **PWM3**
- **PWM4**
- **PWM5**
- **PWM6**
- **PWM7**

**VDC**

- **M**
- **Gnd**
- **VDC**
- **PWM3**
- **PWM2**
- **PWM7**
- **PWM6**
- **PWMs from University Board**
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<table>
<thead>
<tr>
<th>Excel</th>
<th>General Form</th>
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<tr>
<td>=&quot;0x&quot;&amp;M2&amp;M2&amp;&quot;,&quot;</td>
<td>PWM = sin* (0-1)*50%+50%</td>
</tr>
<tr>
<td>Very useful for generating C tables</td>
<td>=B12</td>
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</table>

General Form

100% Voltage

75% Voltage

50% Voltage

25% Voltage

---

**freescale™**
Voltage to Frequency Table for a 230V 60Hz Induction Motor

- The V/F ratio must be maintained fairly closely
- A 230V 60Hz motor has a ratio of 3.83.

<table>
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<th>HZ</th>
<th>Period ms</th>
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<tr>
<td>20</td>
<td>5.26</td>
<td>190.00</td>
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</table>

How Many Lines of C Code will it take to commutate the Induction Motor?
Induction Motor Freq. Control

word sine[36] = {0x8080, 0x9696, 0xabab, 0xc0c0, 0xd2d2, 0xe2e2, 0xeeee, 0xf8f8, 0xf8fc, ..., 0x5454, 0x6969};

By changing the HS vs. LS table values you can generate dead time!

for(i=0; i<=35; i++) /* walk through the array and generate the sine wave*/
{
    vardly(); /* POT1 sets the fundamental frequency */
    j=(i+12)%35; /* offsets j 120 degrees from i */
    k=(i+24)%35; /* offsets k 240 degrees from i */
    PWMDTY01 = sine[i]; /* write the dutycycle register with the sinewave table data */
    PWMDTY23 = sine[j]; /* write the dutycycle register with the sinewave table data */
    PWMDTY67 = sine[k]; /* write the dutycycle register with the sinewave table data */
}
Induction Freq. & Voltage Control

word sine[72]={0x8080, 0x8B8B ,0x9696 ,0xA1A1 ,0xABAB ,0xB6B6, 0xBFBF ... ,0xEEEE ,0xF4F4 ,0xF8F8 ,0xF9F9 ,0xF9F9 ,0xFAFa ,0xFFFF
for(i=0; i<=71; i++) /* walk through the array */
{
    j=(i+24)%72; /* offsets j 120 degrees from i this is for the 5 degree table 72 elements */
    k=(i+48)%72; /* offsets k 240 degrees from i this is for the 5 degree table 72 elements */
    vardly(); /* POT1 sets the fundamental frequency */

    /****** voltage control *****/
    tempi = sine[i];
    tempj = sine[j];
    tempk = sine[k];

    if (ATD1DR1H < 0x40) voltlv = 4; else if (ATD1DR1H < 0x80 ) voltlv = 2; else voltlv = 1; /* sets the voltage at 100% or 50% */

    tempi= (((tempi&0x00ff) - 0x80)/voltlv)+0x80; /* based on voltlv = 1 or 2 scale the pwm phase i */
    tempi = tempi & 0x00ff;
    tempi = tempi + (tempi << 8);

    tempj= (((tempj&0x00ff) - 0x80)/voltlv)+0x80; /* based on voltlv = 1 or 2 scale the pwm phase j */
    tempj = tempj & 0x00ff;
    tempj = tempj + (tempj << 8);

    tempk= (((tempk&0x00ff) - 0x80)/voltlv)+0x80; /* based on voltlv = 1 or 2 scale the pwm phase k */
    tempk = tempk & 0x00ff;
    tempk = tempk + (tempk << 8);

    PWMDTY01 = tempi; /* write PWMs 0&1 */
    PWMDTY23 = tempj; /* write PWMs 2&3 */
    PWMDTY67 = tempk; /* write PWMs 3&4 */
}
GDB Test Inverter

Micro Controller Board

Power Supply

12V Power Supply

PWM

Fault Latch

DESAT

Reset

Temp / Hi Voltage

DC DC

ISO

ST TD350

ST TD350

ST TD350

ST TD350

ST TD350

ST TD350

VDC (60V)

1 HP 230V 3 Phase Induction Motor

Power Supply (12V)

VCAP

MC9S12DG 128CPV

MC9S12DG 128CFU

BDM

SPI

CAN

LIN

33879

SCI

PWM

GP I/O

GP I/O

A/D

GP I/O

Gate Drive & Power Supply Board

Isolation barrier

+15V / 8V

650V 600A 6 in 1 IGBT Module

Gate Drive & Power Supply Board
3ph AC voltage generation on a per phase basis

- Each phase is considered a “Half H-Bridge”
- Complementary PWMs are used
- Deadtime is needed to prevent shoot through.
- 50% duty cycle → Zero voltage on phase winding
Dead Time – A Necessary Evil But….

- 10KHz PWM
- 100us Period
- 8-bit Duty Cycle PWM(255)
- 1-bit time = .39us
- @ 4.5us D.T. you lose 10 counts!

Dead time causes distortion in the current waveform but it can be corrected!
Concept Gate Drive Board Design AgileSwitch

650V 600A 6in1 Automotive IGBT Module

Gate Drive Board

Top

Bottom
650V 600A IGBT and GDB
Must use isolated supply for the IGBT
Must use an isolated scope to view the gates (G to E)
Must have isolated scope channels to view HS & LS gates at the same time
GDB Main Supply

6-16V
GDB Typical HS & LS Power Supply
GDB High Side Drive
GDB Low Side Drive
Challenges of Inverter Design

- L2 and L5 are small inductances (~1nH, typical) that are common to the gate drive as well as the emitter. These inductances slow turn on and turn off because their induced voltages negatively affect the desired voltage appearing at the gate-emitter terminals of the die.

- The 6MBI400VN-065V has a total phase inductance (sum of L1 through L6) of about 28nH.

- IGBTs require breakdown voltages much higher than the bus supply voltage because high di/dt during switching is creating additional voltage at the IGBT die. The higher breakdown voltage requirements are increasing die cost.

- Externally, you could see at least an additional 20nH for the bus bars and 15nH for the input capacitor.

- At 5A / ns and 63nH you could see a 315V overshoot. With a 400V battery bus you would need a 750V device, and it gets worse at cold!

\[ V = L \frac{di}{dt} \]
From: Fuji’s “Device features of the 6MBI400VN-065V_03-June-2011.pdf”
6MBI400VN-065V Turn-off Characteristics

\[ V_{CC} = 400V, \quad I_C = 400A, \quad V_{GE} = +15V/-8V, \quad R_g = +3.9/-12\Omega, \quad T_j = 25^\circ C \]

1 – \( V_{GE} \) begins to discharge
2 – \( V_{CE} \) begins to change. It rises very slowly since the gate drive is charging \( C_{CG} \), which is very large at this time.
3 – \( V_{CE} \) rises much more rapidly since \( C_{CG} \) is much smaller at this time. \( I_C \) does not yet change since the opposing diode is not forward biased.
4 – Output current is commutated to the opposing diode as the IGBT turns off.
5 – Peak \( V_{CE} \) voltage falls as \( di/dt \) decreases. Diode is now conducting all the output current.
6 – IGBT current decays as carriers within the IGBT recombine.

At 5A/ns and 32nH you will see a 160V over shoot.

From: Fuji’s “Device features of the 6MBI400VN-065V_03-June-2011.pdf”
Advanced Gate Drive IC

Prototype Isolation Circuit
• Galvanic Isolation
• High speed communications with bidirectional option
• Small silicon area

Prototype Programmable Gate Drive IC
• External control of three current drive levels for IGBT turn on & off
• Digital Sequencer provides 10nsec timing control

Intelligent GDIC Provides
• Tighter dynamic control
• H/S communications

Benefits
• System efficiency
• Improved diagnostics
• Systems cost savings

IGBT Turn Off

Amps / ns
0 1 2 3 4 5 6
Efficiency Gain
Efficiency Gain

Amps
10 100 1000

typical performance
desired performance
40KW Modular Inverter Reference Design
40KW Modular Inverter Reference Design (Late 2012)

- Fuji/Freescale IGBT 650V, 400A 3 phase module with integral pin fin cooling package
- Input Cap 581 uF custom designed to exactly bolt up to the input of the IGBT module to minimize stray inductance.
- Gate drive board mounted directly on top of the IGBT module providing drive control and fault detection.
- Isolated power supply board mounted directly on top of the gate drive board contains 6 (+15V & -8V) isolated power supplies and a +5V logic supply.
- Multiple 16 and 32 bit processor options available
This table generates sine wave PWMs used to produce an inverter sine wave on an H bridge. The lower PWM is inverted from the upper PWM signal on the same 1/2 H bridge.

This diagram illustrates an inverter sine wave on an H bridge, with PWMs and Micro Board labeled.