Building a Basic Inverter

AMF-AUT-T0144

Neil Krohn
Applications Engineer

September 2013

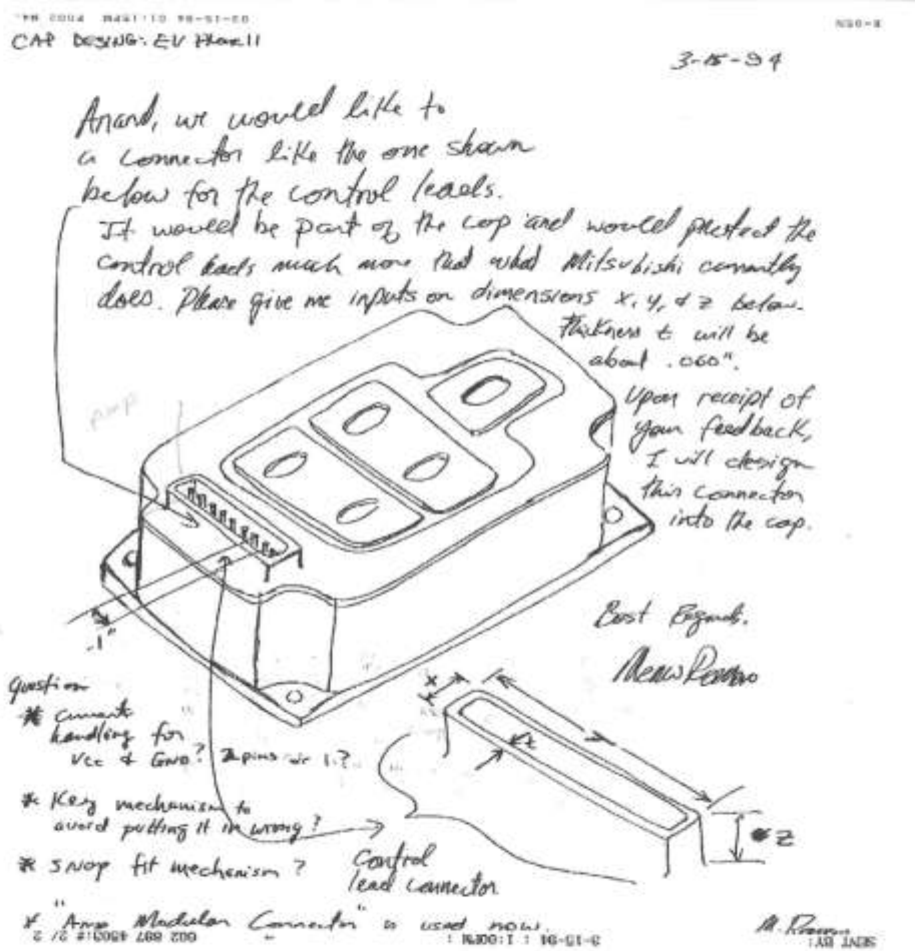
Introduction Topics

- 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



CAP DESIGN: EV Phase II

3-15-94

Anand, we would like to 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 than what Mitsubishi currently does. Please give me inputs on dimensions x, y, & z below.
Thickness t will be about .060".

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

.1"

Best Regards.

Mario Romero

Question
* Current handling for Vcc & GND? 2 pins or 1?
* Key mechanism to avoid putting it in wrong?
* Snap fit mechanism ?

Control lead connector

x

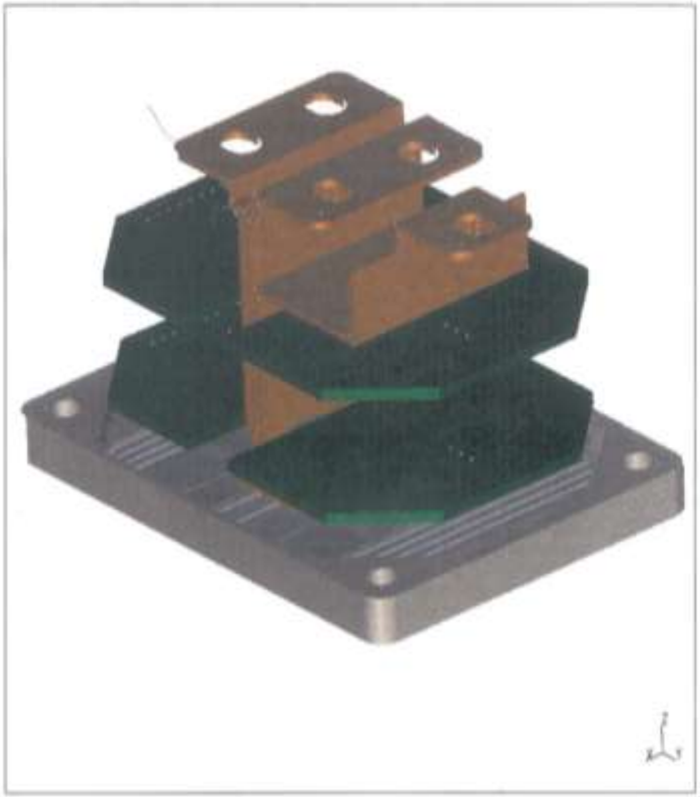
t

z

* "Amp Modular Connector" is used now.

M. Romero

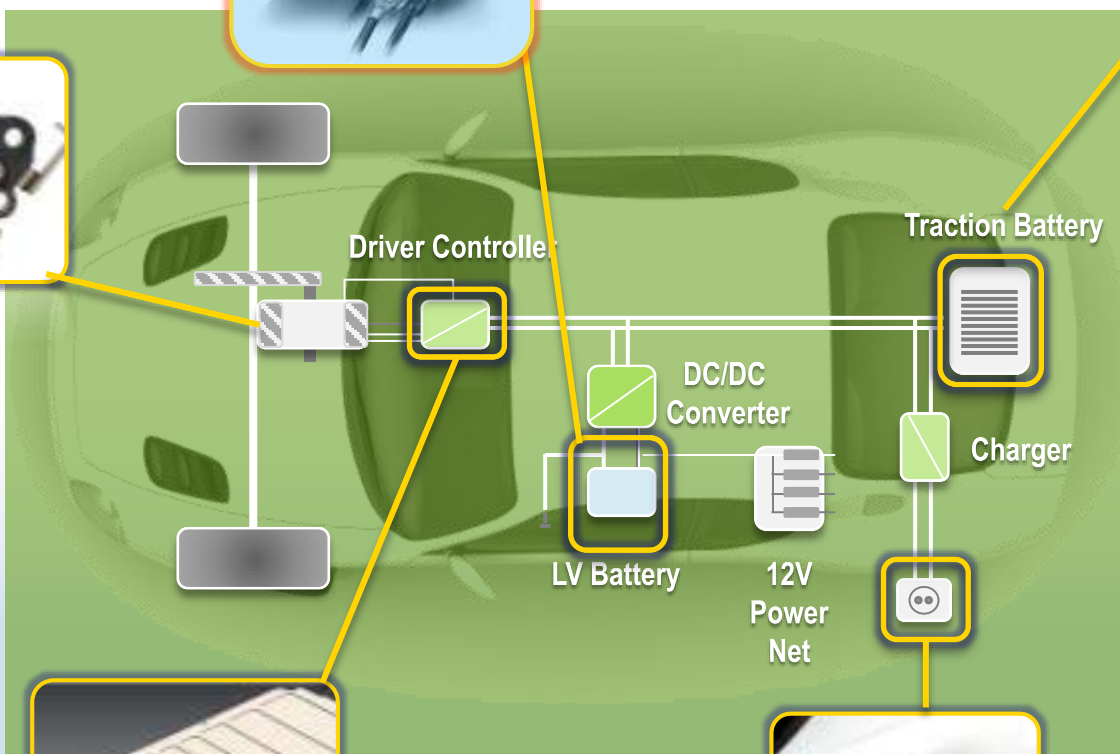
Déjà Vu



Freescale Uniquely Positioned To Address HEV/EV

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

LV Battery Monitoring
- MCU
- Voltage Monitoring
- Packaging



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

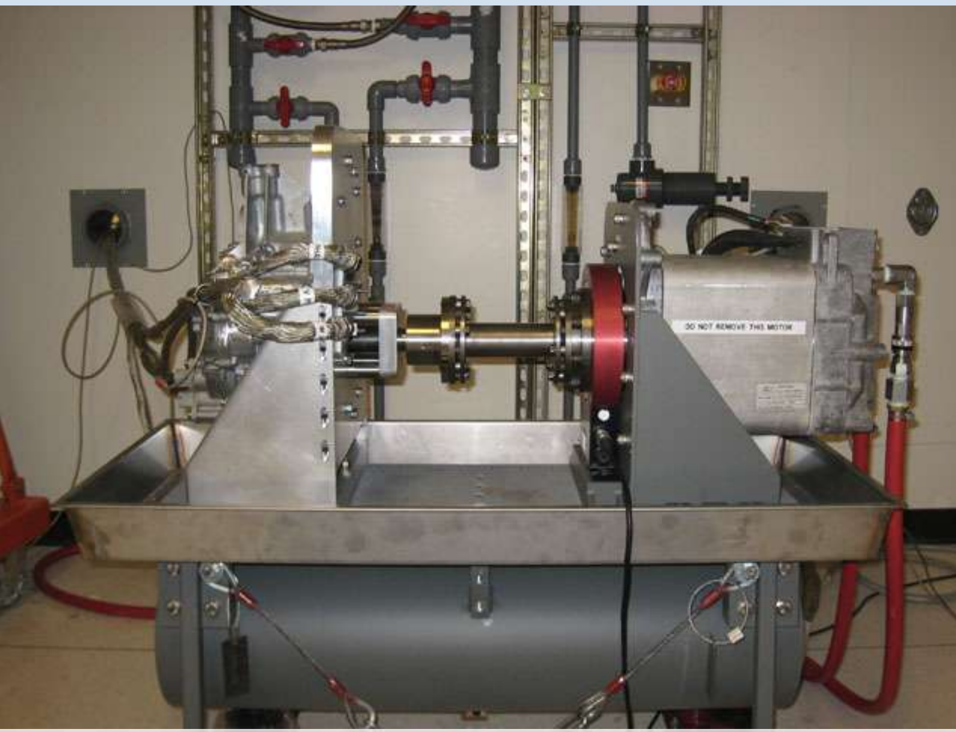
Inverter
- Control & Safing MCU
- Isolation
- Drivers
- Power Devices
- FOC Software
- Modeling and Simulation Tools

Charge Point
- MCU
- Communications

…gh 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

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Partnering Provides FSL Quick Market Access

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

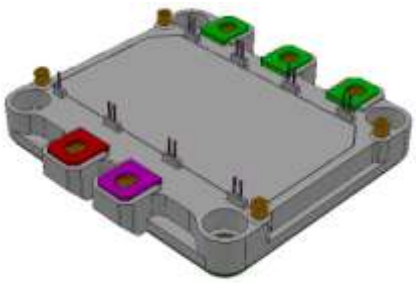
Potential Partners

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 → **Today**

Lexus
GS450h

Lexus
LS600h
(2007)

Lexus
RX450
(2009)

Hino
Dutro

Toyota
Crown

Lexus
HS250h,
SAI

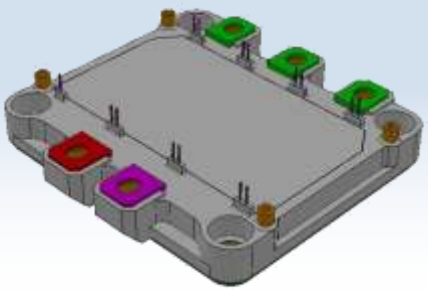
Nissan
Altima

Toyota
Camry

Toyota
Estima

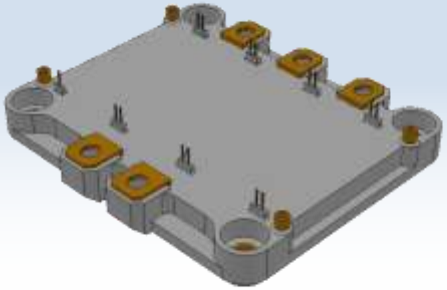
Standard Product Roadmap

Samples Now



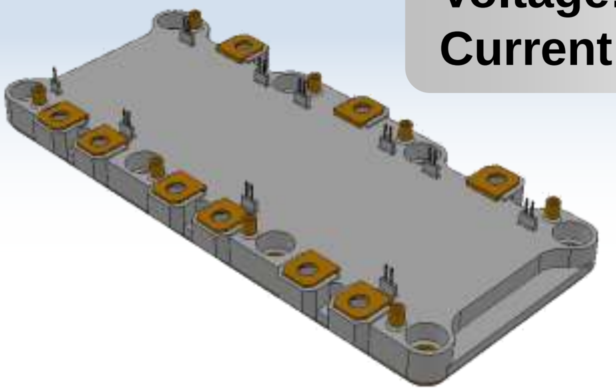
Voltage: 650V
Current: 400A

Samples Now



Voltage: 650V
Current: 600A

April – Under Study



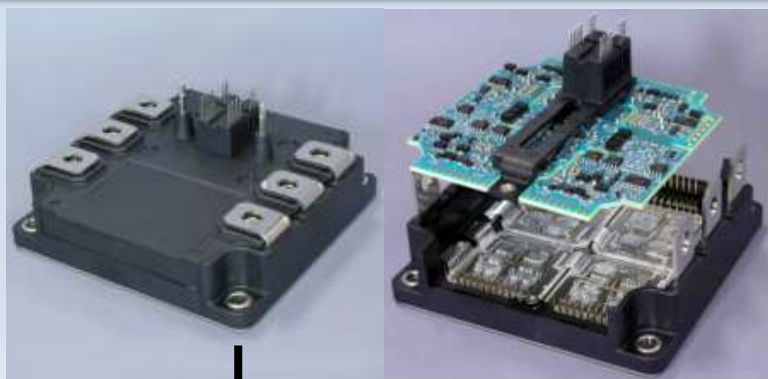
Voltage: 650V
Current: 900A

Production: 500K / Yr @ 0.0 PPM

Voltage: 1200V
Current: 600A

Fuji IGBTs Auto Applications

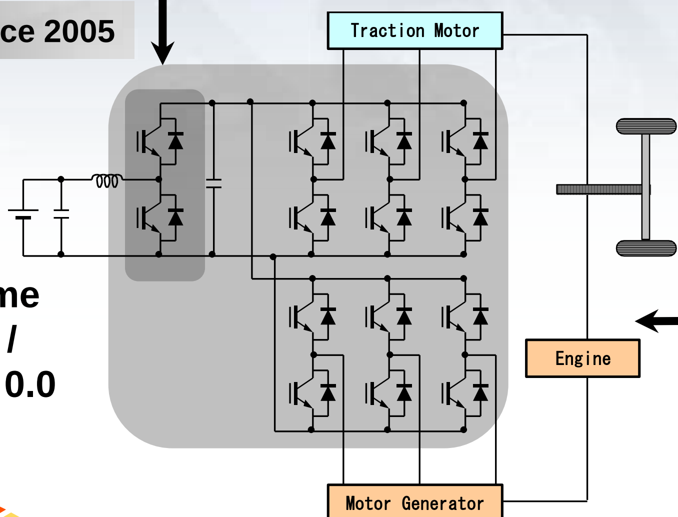
Boost Converter IPM
(DC-DC Converter)



1200V/ 600A 2in1

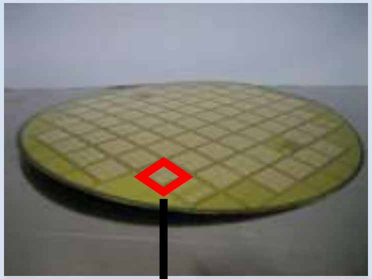
Since 2005

Integrated IGBT Module

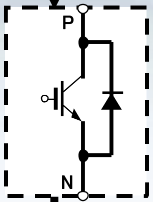


Volume 500K / Yr @ 0.0 PPM

IGBT Wafer



Power chip by Fuji



Module

1200V/ 400A 1in1

Since 2007

PCU

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Lincoln WEB site shows same base price for Gas and Hybrid

This experiment proved Ford's 15-20% Hybrid Sales Estimate if they eliminate the Electrification Penalty

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More Shopping Tools

Summary | Detailed Comparison | Side by Side Photo Gallery | Lincoln Advantages | Comparably Equipped

LINCOLN

Where you see a Lincoln logo in the chart below, you have a Lincoln advantage. Click on a logo to get an explanation.

View all Lincoln advantages

	 2012 LINCOLN MKZ FWD	 2012 LINCOLN MKZ Hybrid	 2012 LEXUS ES 350	 2012 CADILLAC CTS SPORT SEDAN 3.6L Performance
	Choose Different Lincoln	Choose different vehicle or another Lincoln	Choose different vehicle or another Lincoln	Choose different vehicle or another Lincoln
Price	FWD	Hybrid	350	3.6L Performance
Base Price	$34,755	$34,755	$36,725	$42,290
Destination & Delivery	$875	$875	$875	$895
Comparably Equipped	$35,630	$35,630	$38,740	$46,400

Internet

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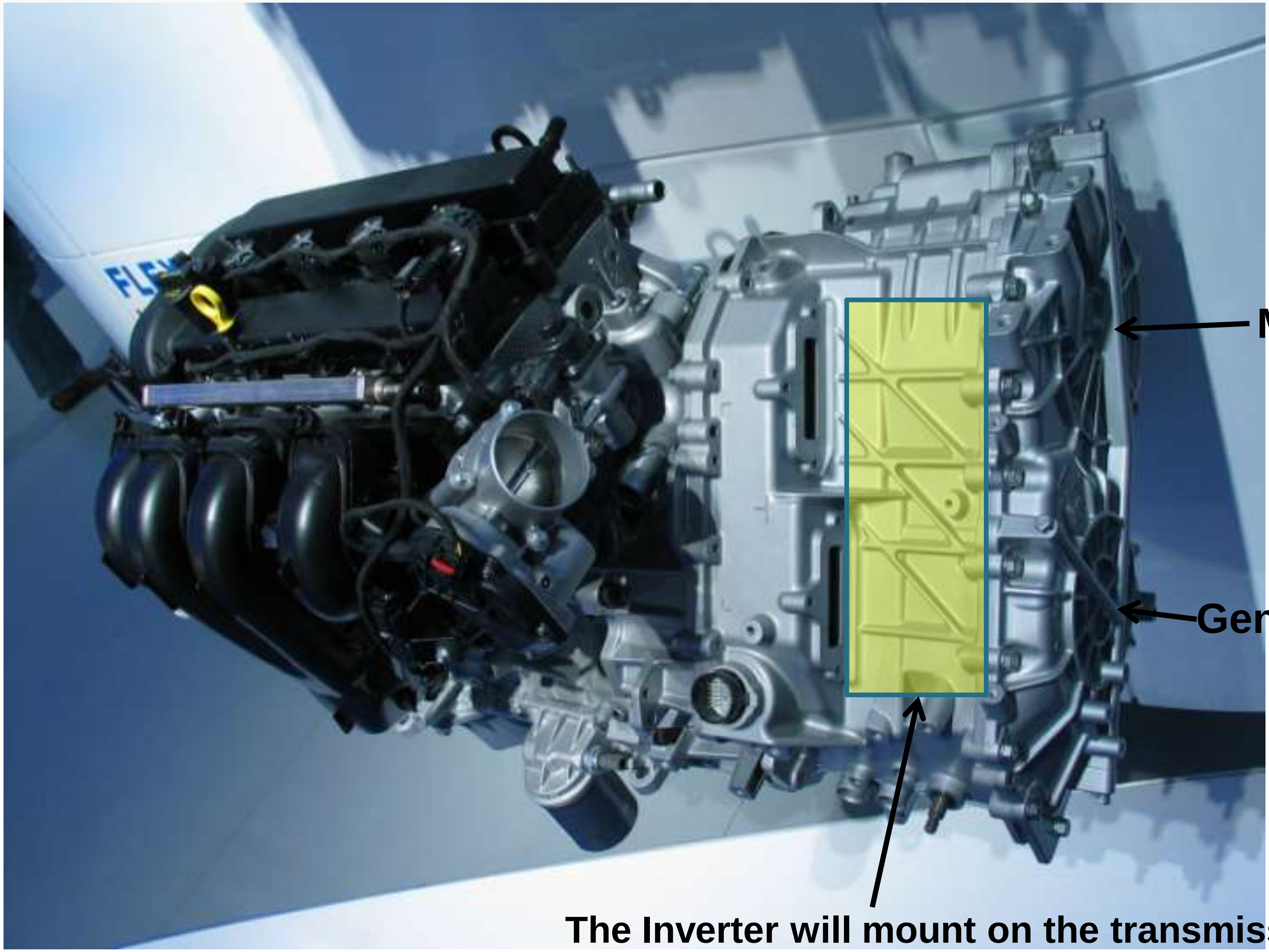
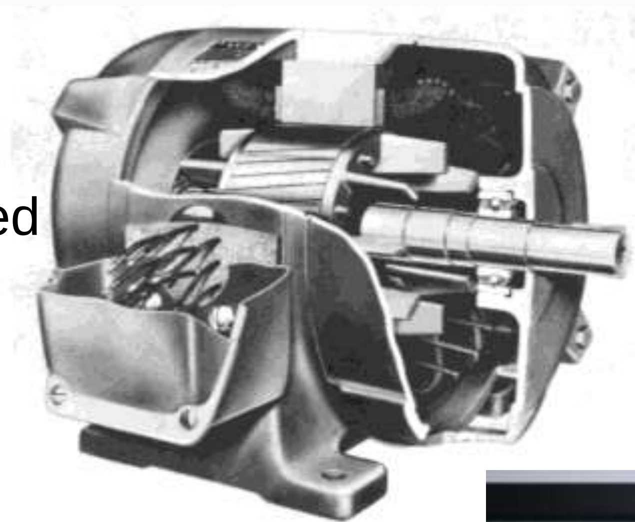
Ford Hybrid Electric Powertrain

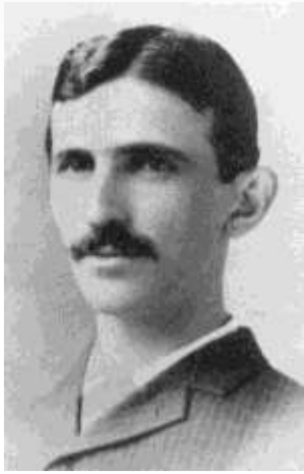


Induction Machines

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

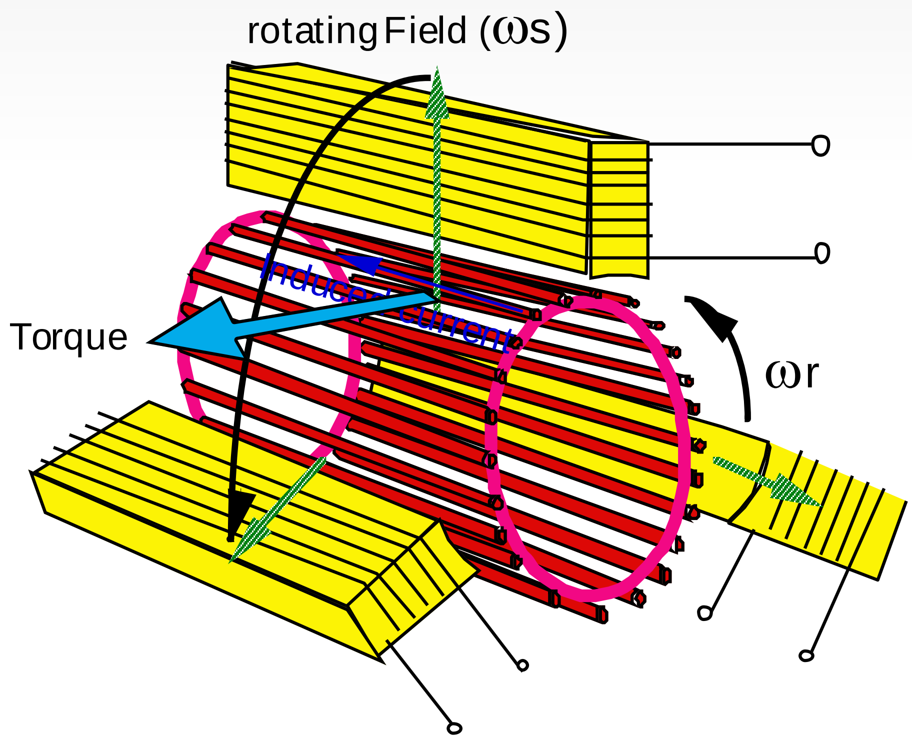




Model of Tesla’s 1st Induction Motor Demonstrated 1885

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.

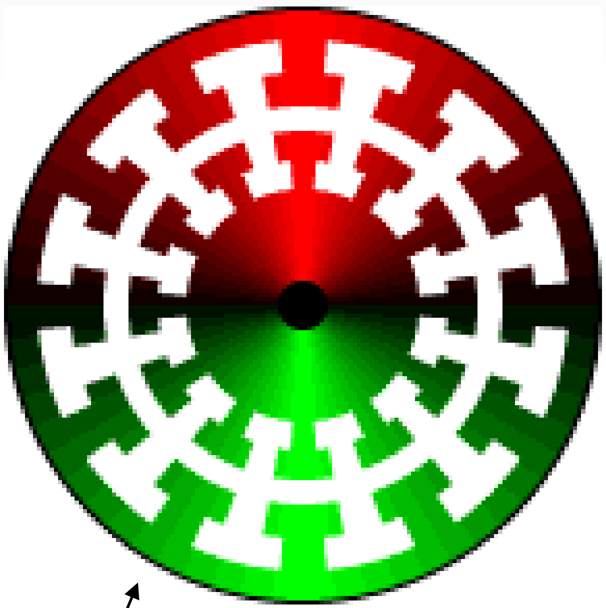


- The motor torque is generated by an interaction between the stator magnetic field and induced rotor magnetic field

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.

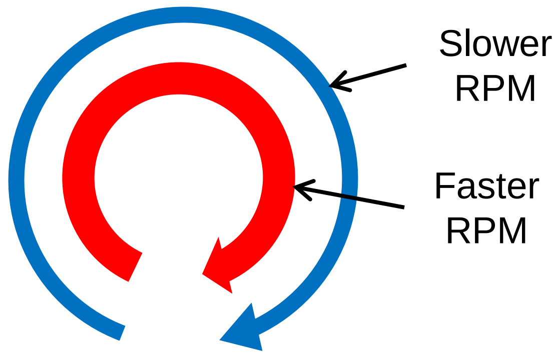
4 Quadrant Operation

Stator

Rotor

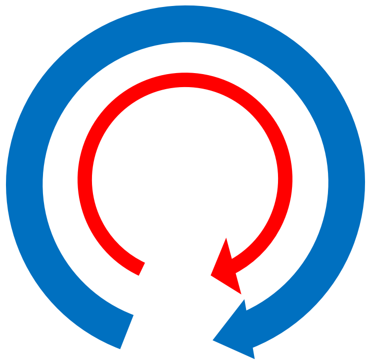
Generating / Braking

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

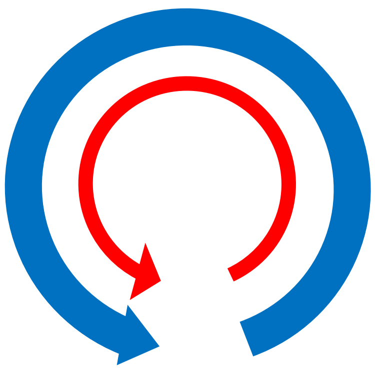


Driving

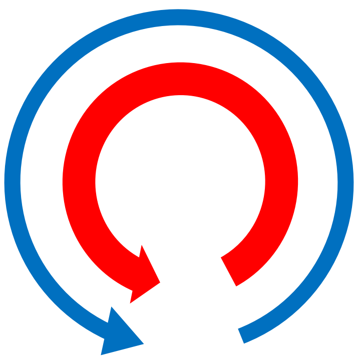
If the rotating magnetic field is faster than the armature speed & in the same direction, your driving



Driving



Generating / Braking



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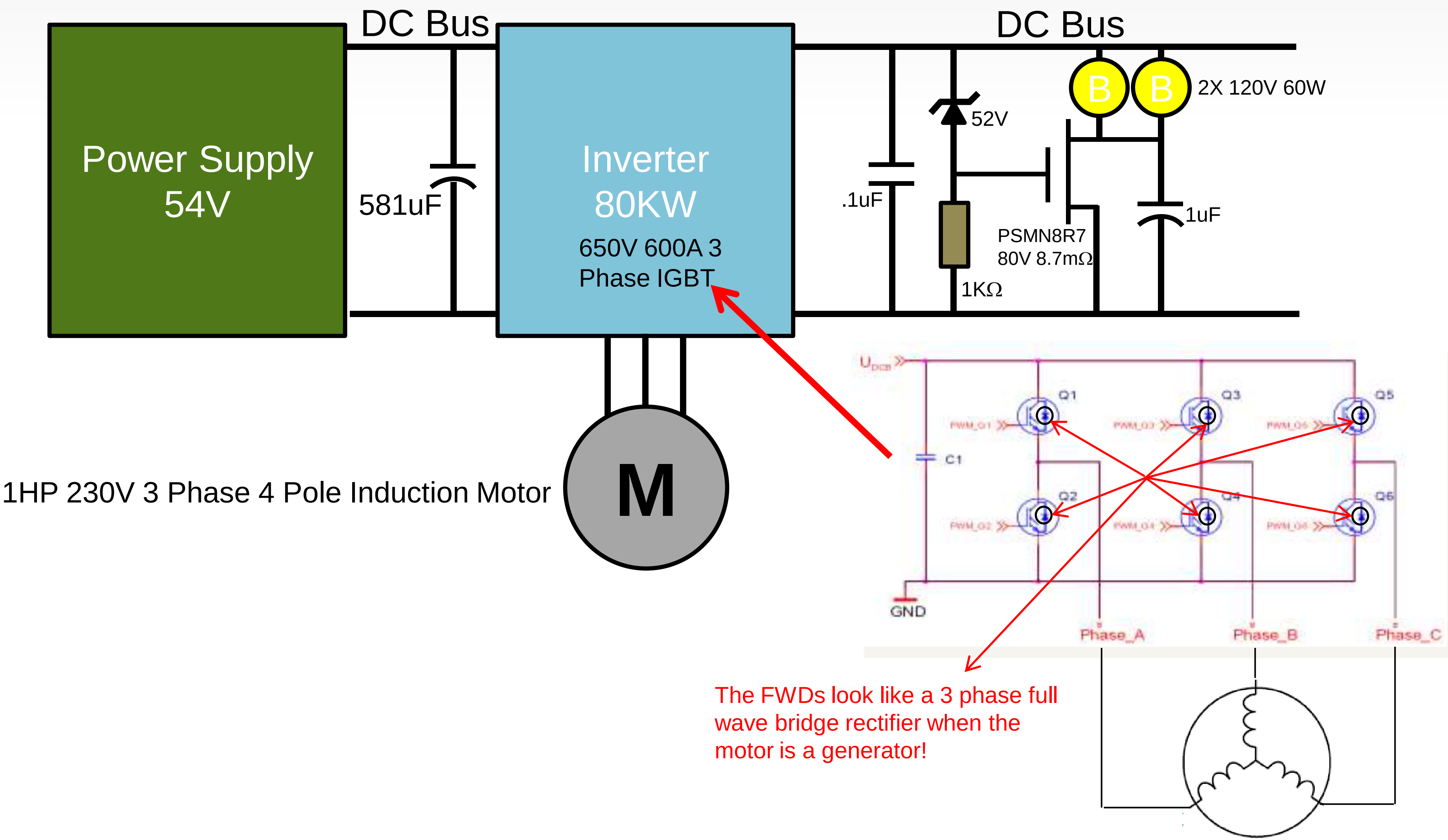
Regeneration and Braking on the Test Inverter



RPM and Slip Equations

$$n_s = \frac{120 \times f}{p}$$

ns = synchronous RPM
f = freq in Hz
p = number of motor polls
c =120 = 2*60 -> 2 converts pole pairs to poles & 60 converts Hz to RPM

Ex. 1hp 3 phase 4 poll motor running at 60Hz 120 * 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
ns = stator speed
nr = 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% or 1800-1725 = 75 RPM.

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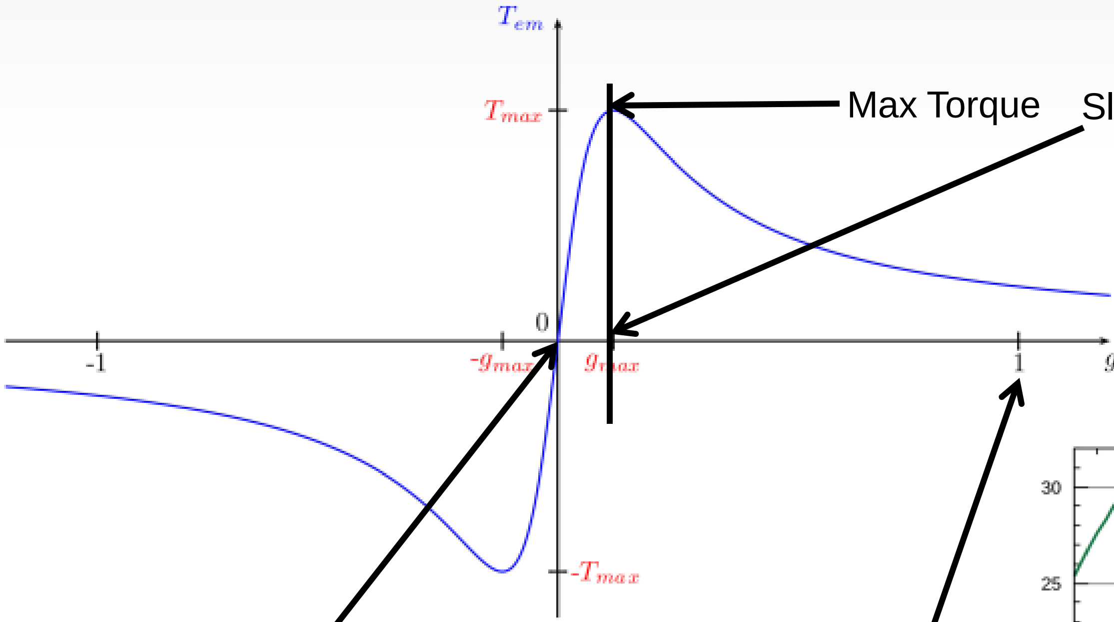
Induction Motor Torque vs. Slip Relationship

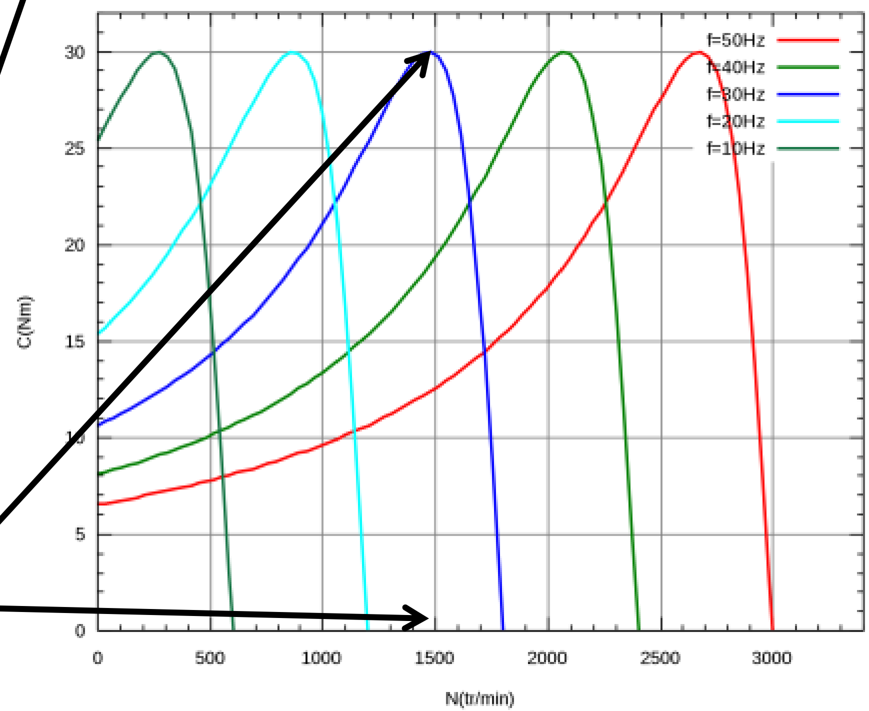


Max Torque

Slip approximately 5%

Synchronous speed. Torque= 0 Slip = 0%

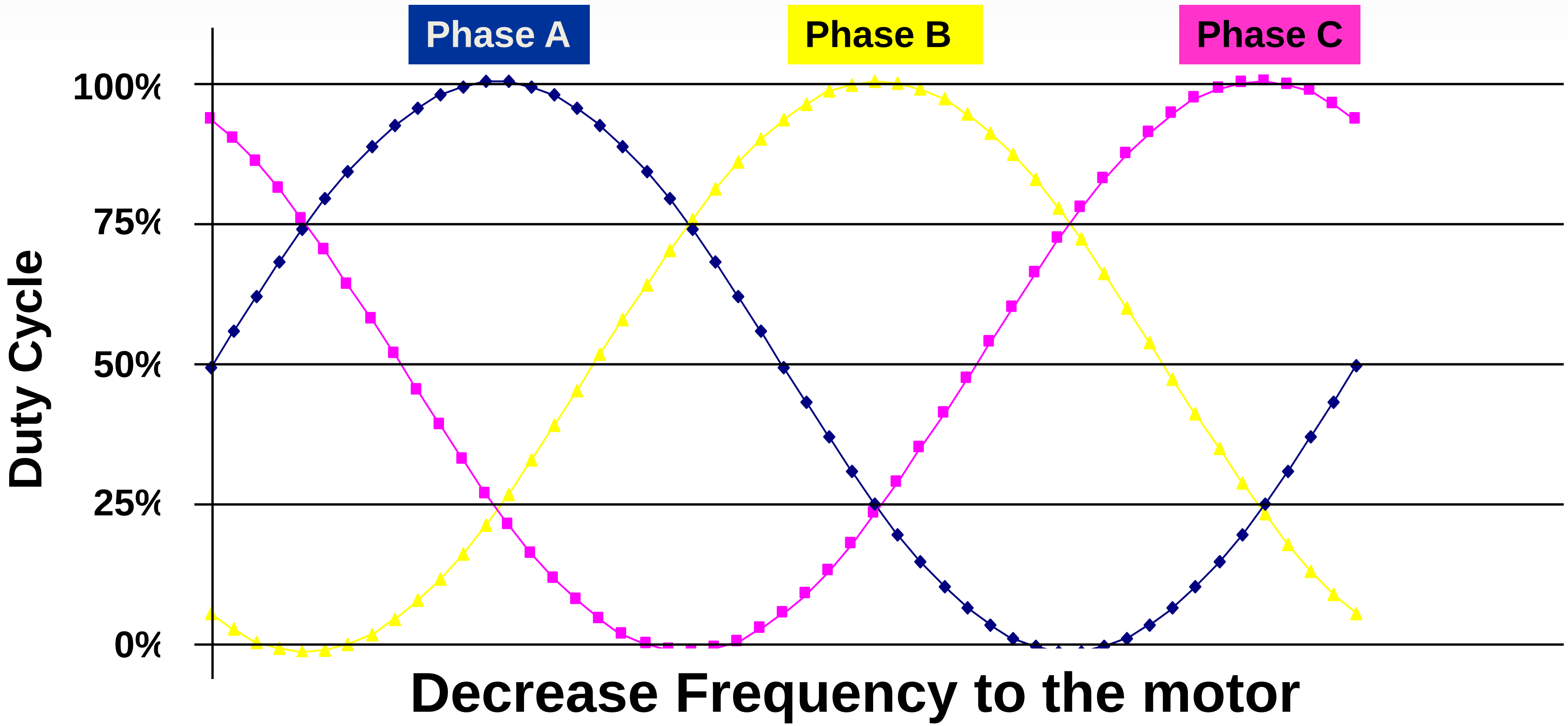
Armature is at 0 RPM slip = 100%



Slip can be stated as a % or RPM

By changing Freq. & Voltage we can generate rated torque at any RPM

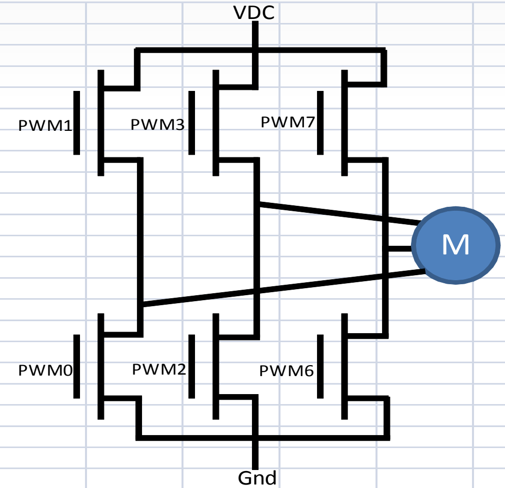
Sinusoidal PWM Generation – ACIM / PMSM



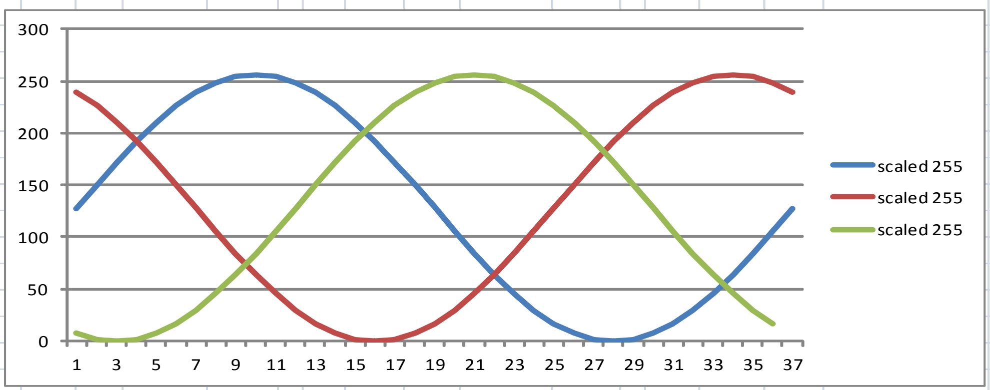
Phase Sine Wave Generation

deg	rad	sin	scaled 255	hex	deg	rad	sin	scaled 255	hex	deg	rad	sin	scaled 255	hex
360	6.282	0.00	128	7F	120	2.094	0.87	239	EE	240	4.188	-0.87	17	11
10	0.175	0.17	150	96	130	2.269	0.77	226	E2	250	4.363	-0.94	8	7
20	0.349	0.34	172	AB	140	2.443	0.64	210	D2	260	4.537	-0.98	2	1
30	0.524	0.50	192	BF	150	2.618	0.50	192	C0	270	4.712	-1.00	0	0
40	0.698	0.64	210	D2	160	2.792	0.34	172	AB	280	4.886	-0.98	2	1
50	0.873	0.77	226	E2	170	2.967	0.17	150	96	290	5.061	-0.94	8	7
60	1.047	0.87	239	EE	180	3.141	0.00	128	80	300	5.235	-0.87	17	11
70	1.222	0.94	248	F8	190	3.316	-0.17	106	69	310	5.410	-0.77	30	1D
80	1.396	0.98	254	FE	200	3.490	-0.34	84	54	320	5.584	-0.64	46	2D
90	1.571	1.00	256	FF	210	3.665	-0.50	64	40	330	5.759	-0.50	64	3F
100	1.745	0.98	254	FE	220	3.839	-0.64	46	2D	340	5.933	-0.34	84	54
110	1.920	0.94	248	F8	230	4.014	-0.77	30	1E	350	6.108	-0.17	106	69
120	2.094	0.87	239	EE	240	4.188	-0.87	17	11	360	6.282	0.00	128	7F
130	2.269	0.77	226	E2	250	4.363	-0.94	8	7	10	0.175	0.17	150	96
140	2.443	0.64	210	D2	260	4.537	-0.98	2	1	20	0.349	0.34	172	AB
150	2.618	0.50	192	C0	270	4.712	-1.00	0	0	30	0.524	0.50	192	BF
160	2.792	0.34	172	AB	280	4.886	-0.98	2	1	40	0.698	0.64	210	D2
170	2.967	0.17	150	96	290	5.061	-0.94	8	7	50	0.873	0.77	226	E2
180	3.141	0.00	128	80	300	5.235	-0.87	17	11	60	1.047	0.87	239	EE
190	3.316	-0.17	106	69	310	5.410	-0.77	30	1D	70	1.222	0.94	248	F8
200	3.490	-0.34	84	54	320	5.584	-0.64	46	2D	80	1.396	0.98	254	FE
210	3.665	-0.50	64	40	330	5.759	-0.50	64	3F	90	1.571	1.00	256	FF
220	3.839	-0.64	46	2D	340	5.933	-0.34	84	54	100	1.745	0.98	254	FE
230	4.014	-0.77	30	1E	350	6.108	-0.17	106	69	110	1.920	0.94	248	F8
240	4.188	-0.87	17	11	360	6.282	0.00	128	7F	120	2.094	0.87	239	EE
250	4.363	-0.94	8	7	10	0.175	0.17	150	96	130	2.269	0.77	226	E2
260	4.537	-0.98	2	1	20	0.349	0.34	172	AB	140	2.443	0.64	210	D2
270	4.712	-1.00	0	0	30	0.524	0.50	192	BF	150	2.618	0.50	192	C0
280	4.886	-0.98	2	1	40	0.698	0.64	210	D2	160	2.792	0.34	172	AB
290	5.061	-0.94	8	7	50	0.873	0.77	226	E2	170	2.967	0.17	150	96
300	5.235	-0.87	17	11	60	1.047	0.87	239	EE	180	3.141	0.00	128	80
310	5.410	-0.77	30	1D	70	1.222	0.94	248	F8	190	3.316	-0.17	106	69
320	5.584	-0.64	46	2D	80	1.396	0.98	254	FE	200	3.490	-0.34	84	54
330	5.759	-0.50	64	3F	90	1.571	1.00	256	FF	210	3.665	-0.50	64	40
340	5.933	-0.34	84	54	100	1.745	0.98	254	FE	220	3.839	-0.64	46	2D
350	6.108	-0.17	106	69	110	1.920	0.94	248	F8	230	4.014	-0.77	30	1E
360	6.282	0.00	128	7F	120	2.094	0.87	239	EE	240	4.188	-0.87	17	11

This table generates 3-120 degree out of phase sinwave 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



PWMs from University Board

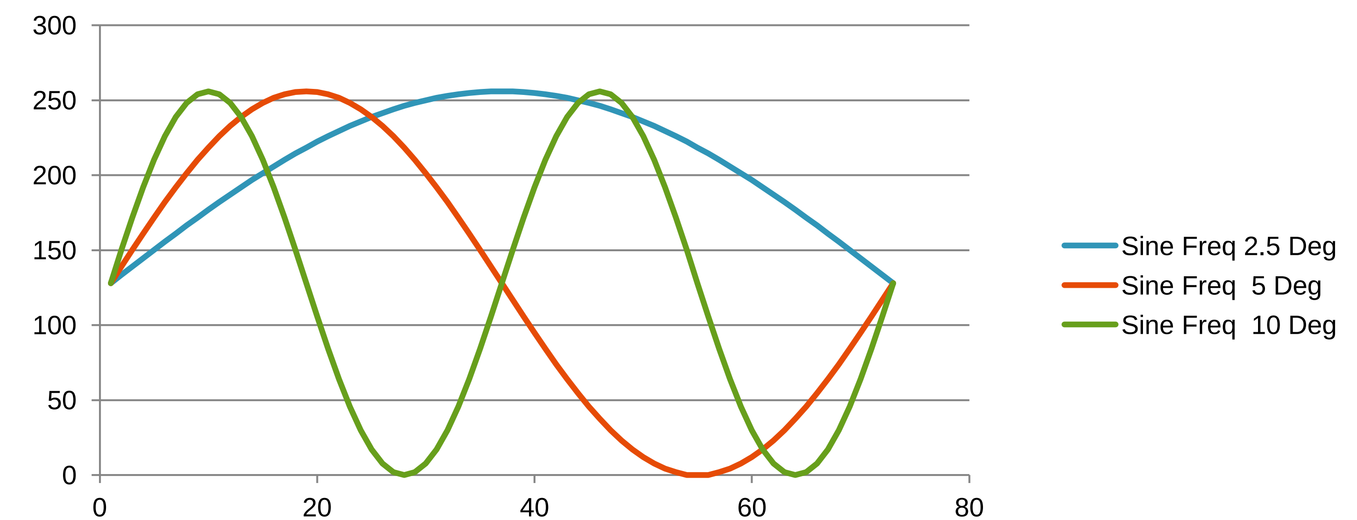


Phase Voltage and Current

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

Freq Modulation

deg	rad	sin	Sine Freq 2.5 Deg		deg	rad	sin	Sine Freq 5 Deg		deg	rad	sin	Sine Freq 10 Deg
0	0	0	128		0	0	0	128		0	0	0	128
2.5	0.043633	0.043619	134		5	0.08727	0.08715	139		10	0.17453	0.173645	150
5	0.087265	0.087154	139		10	0.17453	0.17365	150		20	0.34906	0.342015	172
7.5	0.130898	0.130524	145		15	0.2618	0.25881	161		30	0.52359	0.499992	192
10	0.17453	0.173645	150		20	0.34906	0.34201	172		40	0.69812	0.642779	210
12.5	0.218163	0.216436	156		25	0.43633	0.42261	182		50	0.87265	0.766035	226
15	0.261795	0.258815	161		30	0.52359	0.49999	192		60	1.04718	0.866017	239
17.5	0.305428	0.300701	166		35	0.61086	0.57357	201		70	1.22171	0.939686	248
20	0.34906	0.342015	172		40	0.69812	0.64278	210		80	1.39624	0.984804	254
22.5	0.392693	0.382677	177		45	0.78539	0.7071	219		90	1.57077	1	256
25	0.436325	0.422612	182		50	0.87265	0.76604	226		100	1.7453	0.984813	254
27.5	0.479958	0.461741	187		55	0.95992	0.81914	233		110	1.91983	0.939704	248
30	0.52359	0.499992	192		60	1.04718	0.86602	239		120	2.09436	0.866043	239
32.5	0.567223	0.537292	197		65	1.13445	0.9063	244		130	2.26889	0.766069	226
35	0.610855	0.573568	201		70	1.22171	0.93969	248		140	2.44342	0.642819	210
37.5	0.654488	0.608753	206		75	1.30898	0.96592	252		150	2.61795	0.500038	192
40	0.69812	0.642779	210		80	1.39624	0.9848	254		160	2.79248	0.342064	172
42.5	0.741753	0.675581	214		85	1.48351	0.99619	256		170	2.96701	0.173697	150
45	0.785385	0.707097	219		90	1.57077	1	256		180	3.14154	5.27E-05	128



Voltage Modulation

deg	rad	sin	100% Voltage	hex	C array		75% Voltage		50% Voltage		25% Voltage	hex	C array
0	0	0	128	80	0x8080,		128		128		128	80	0x8080,
5	0.087265	0.087154	139	8B	0x8B8B,		136		134		131	82	0x8282,
10	0.17453	0.173645	150	96	0x9696,		145		139		134	85	0x8585,
15	0.261795	0.258815	161	A1	0xA1A1,		153		145		136	88	0x8888,
20	0.34906	0.342015	172	AB	0xABAB,		161		150		139	8A	0x8A8A,
25	0.436325	0.422612	182	B6	0xB6B6,		169		155		142	8D	0x8D8D,
30	0.52359	0.499992	192	BF	0xBFBF,		176		160		144	8F	0x8F8F,
35	0.610855	0.573568	201	C9	0xC9C9,		183		165		146	92	0x9292,
40	0.69812	0.642779	210	D2	0xD2D2,		190		169		149	94	0x9494,
45	0.785385	0.707097	219	DA	0xDADA,		196		173		151	96	0x9696,
50	0.87265	0.766035	226	E2	0xE2E2,		202		177		153	98	0x9898,
55	0.959915	0.819143	233	E8	0xE8E8,		207		180		154	9A	0x9A9A,
60	1.04718	0.866017	239	EE	0xEEEE,		211		183		156	9B	0x9B9B,
65	1.134445	0.9063	244	F4	0xF4F4,		215		186		157	9D	0x9D9D,
70	1.22171	0.939686	248	F8	0xF8F8,		218		188		158	9E	0x9E9E,
75	1.308975	0.96592	252	FB	0xFBFB,		221		190		159	9E	0x9E9E,
80	1.39624	0.984804	254	FE	0xFEFE,		223		191		160	9F	0x9F9F,
85	1.483505	0.996193	256	FF	0xFFFF,		224		192		160	9F	0x9F9F,
90	1.57077	1	256	FF	0xFFFF,		224		192		160	9F	0x9F9F,

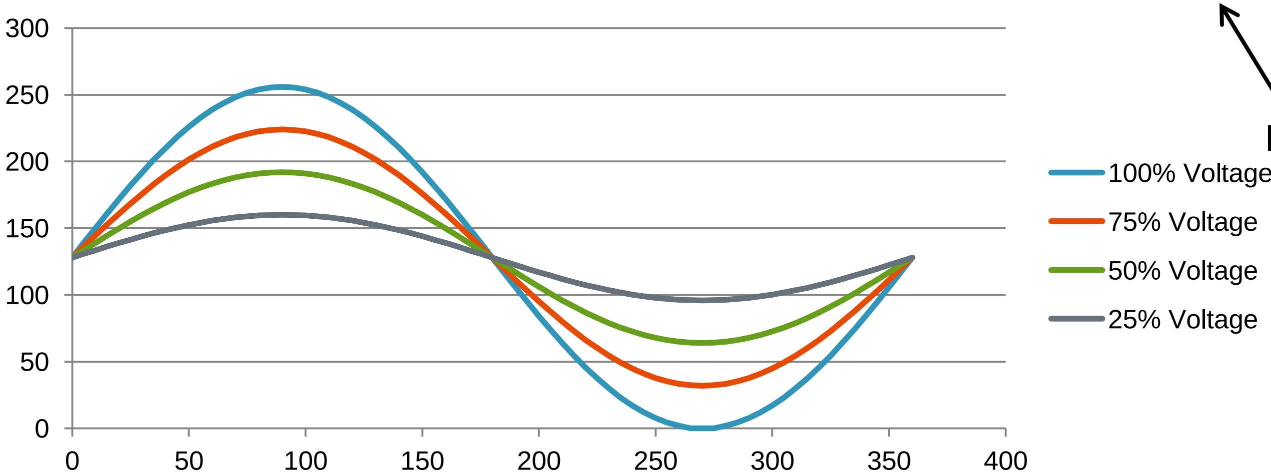
="0x"&M2&M2&","

Very useful for generating C tables

=BIN2HEX(DEC2BIN(L2))

PWM = sin* (0-1)*50%+50% General Form

=((C2*0.75)*128)+128 Excel



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.

Volts	HZ	Period ms
230	60.00	16.67
220	57.39	17.42
210	54.78	18.25
200	52.17	19.17
190	49.57	20.18
180	46.96	21.30
170	44.35	22.55
160	41.74	23.96
150	39.13	25.56
140	36.52	27.38
130	33.91	29.49
120	31.58	31.67
110	28.95	34.55
100	26.32	38.00
90	23.68	42.22
80	21.05	47.50
70	18.42	54.29
60	15.79	63.33
50	13.16	76.00
40	10.53	95.00
30	7.89	126.67
20	5.26	190.00

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};
```

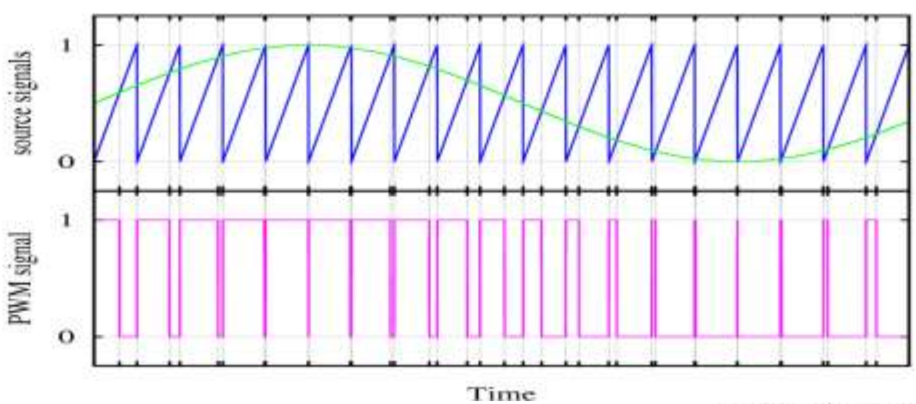
LSPWM HSPWM

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 */
    }
```



deg	rad	sin	A scaled 255	hex
10	0.175	0.17	150	96
20	0.349	0.34	172	AB
30	0.524	0.50	192	BF
40	0.698	0.64	210	D2
50	0.873	0.77	226	E2
60	1.047	0.87	239	EE
70	1.222	0.94	248	F8
80	1.396	0.98	254	FE
90	1.571	1.00	256	FF
100	1.745	0.98	254	FE
110	1.920	0.94	248	F8
120	2.094	0.87	239	EE
130	2.269	0.77	226	E2
140	2.443	0.64	210	D2
150	2.618	0.50	192	C0
160	2.792	0.34	172	AB
170	2.967	0.17	150	96
180	3.141	0.00	128	80
190	3.316	-0.17	106	69
200	3.490	-0.34	84	54
210	3.665	-0.50	64	40
220	3.839	-0.64	46	2D
230	4.014	-0.77	30	1E
240	4.188	-0.87	17	11
250	4.363	-0.94	8	7
260	4.537	-0.98	2	1
270	4.712	-1.00	0	0
280	4.886	-0.98	2	1
290	5.061	-0.94	8	7
300	5.235	-0.87	17	11
310	5.410	-0.77	30	1D
320	5.584	-0.64	46	2D
330	5.759	-0.50	64	3F
340	5.933	-0.34	84	54
350	6.108	-0.17	106	69
360	6.282	0.00	128	7F

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 */
}
```

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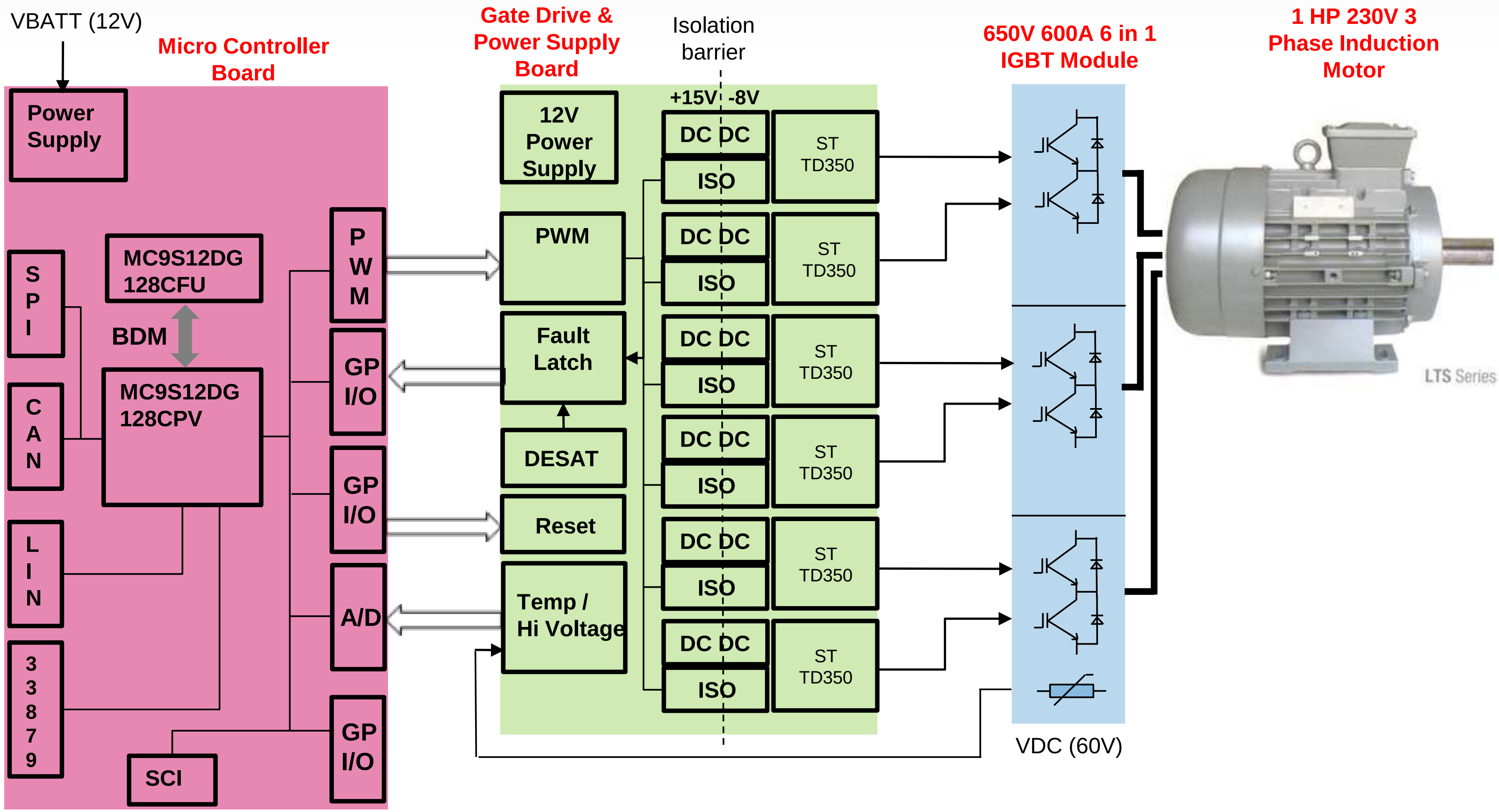
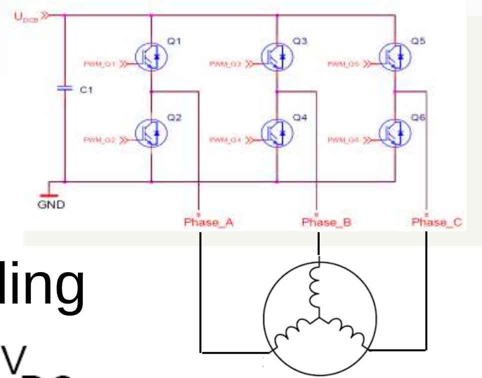
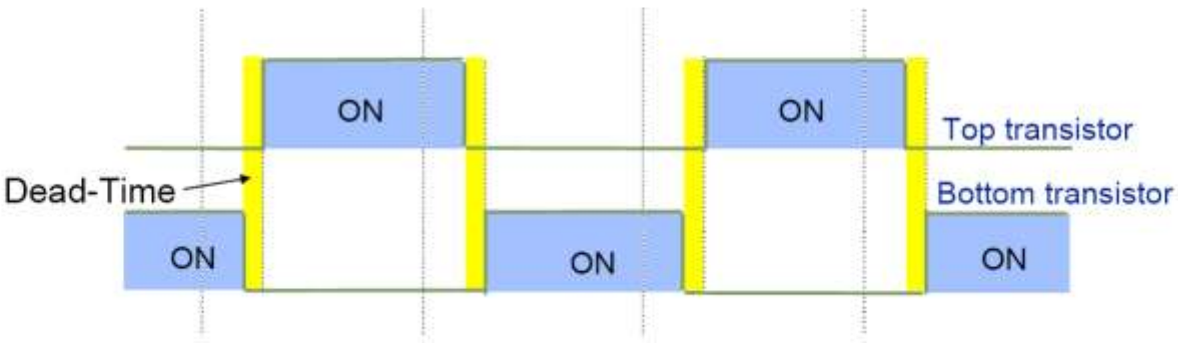
GDB Test Inverter

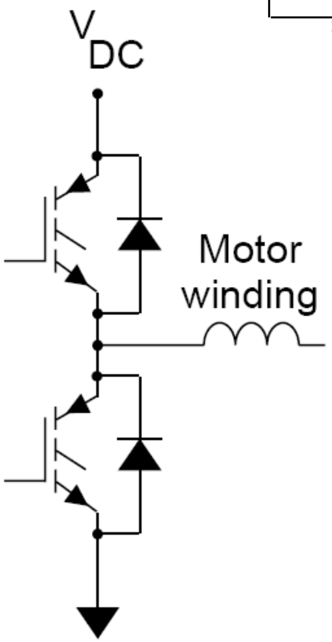


3ph AC voltage generation on a per phase basis

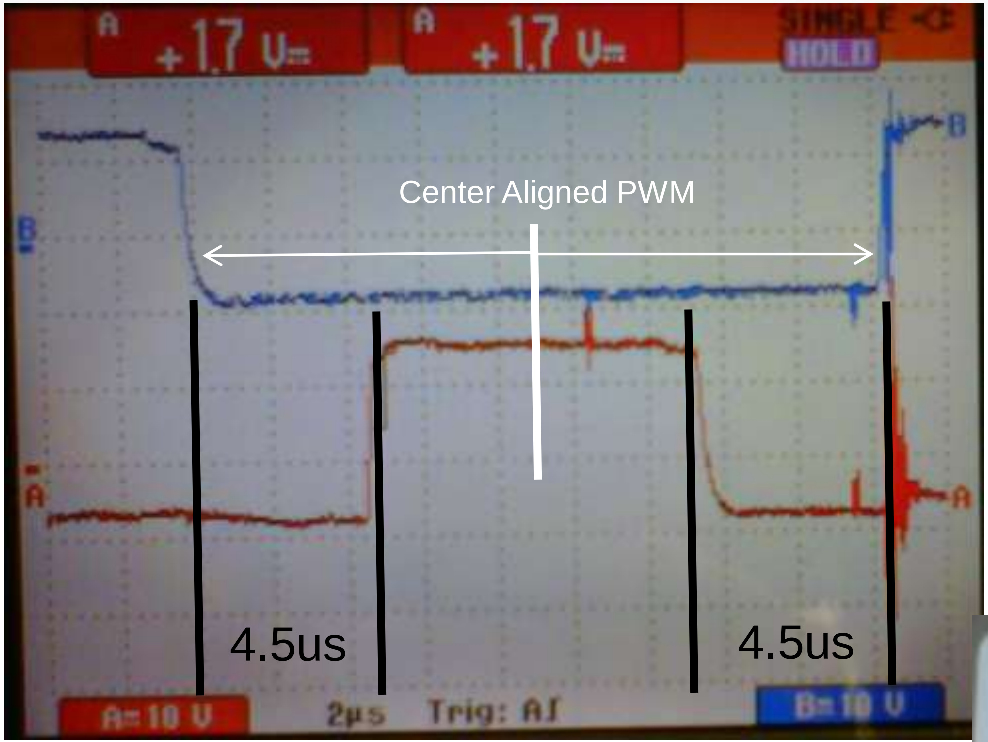
- Each phase is considered a “Half H-Bridge”
- Complementary PWMs are used
- Deadtime is needed to prevent shoot through.
- 50% duty cycle → Zero voltage on phase winding



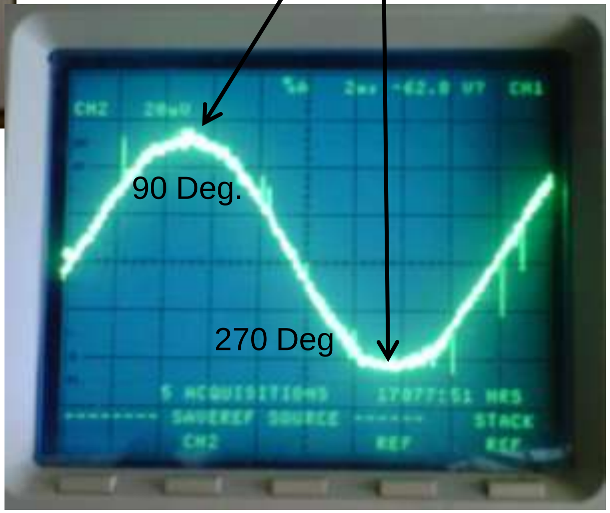




Dead Time – A Necessary Evil But….



- 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!

Deg.	C array
70	0xF8F8,
75	0xFBFB,
80	0xFEFE,
85	0xFFFF,
90	0xFFFF,
95	0xFFFF,
100	0xFEFE,
105	0xFBFB,
110	0xF8F8,

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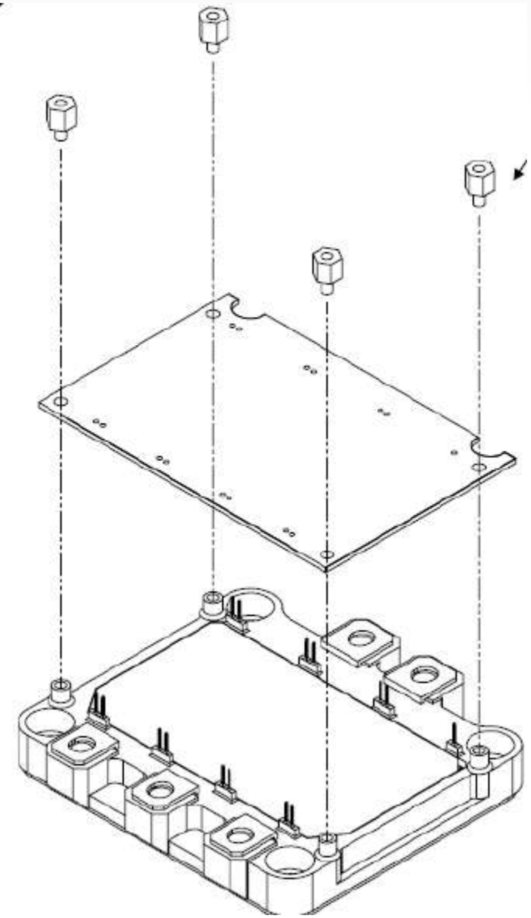
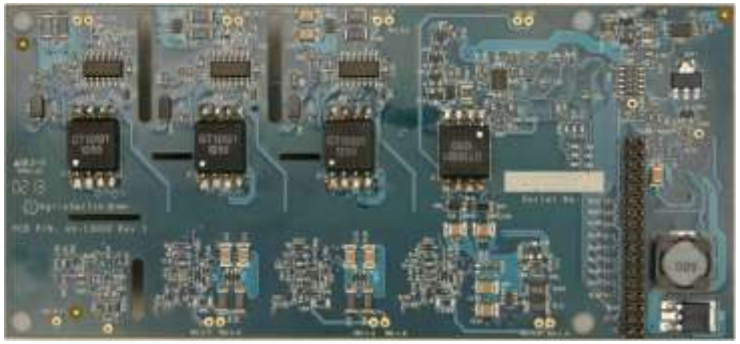
Concept Gate Drive Board Design AgileSwitch



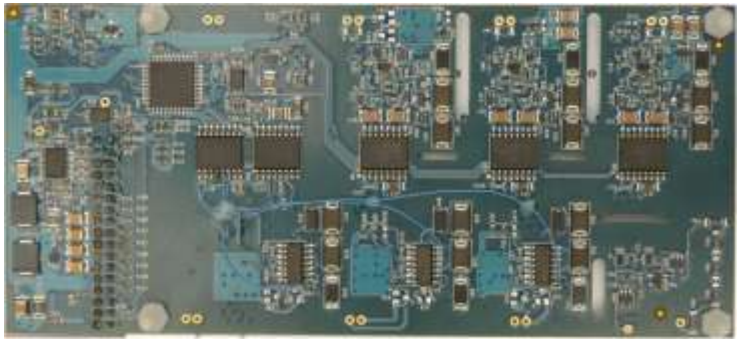
Gate Drive Board

650V 600A 6in1 Automotive IGBT Module

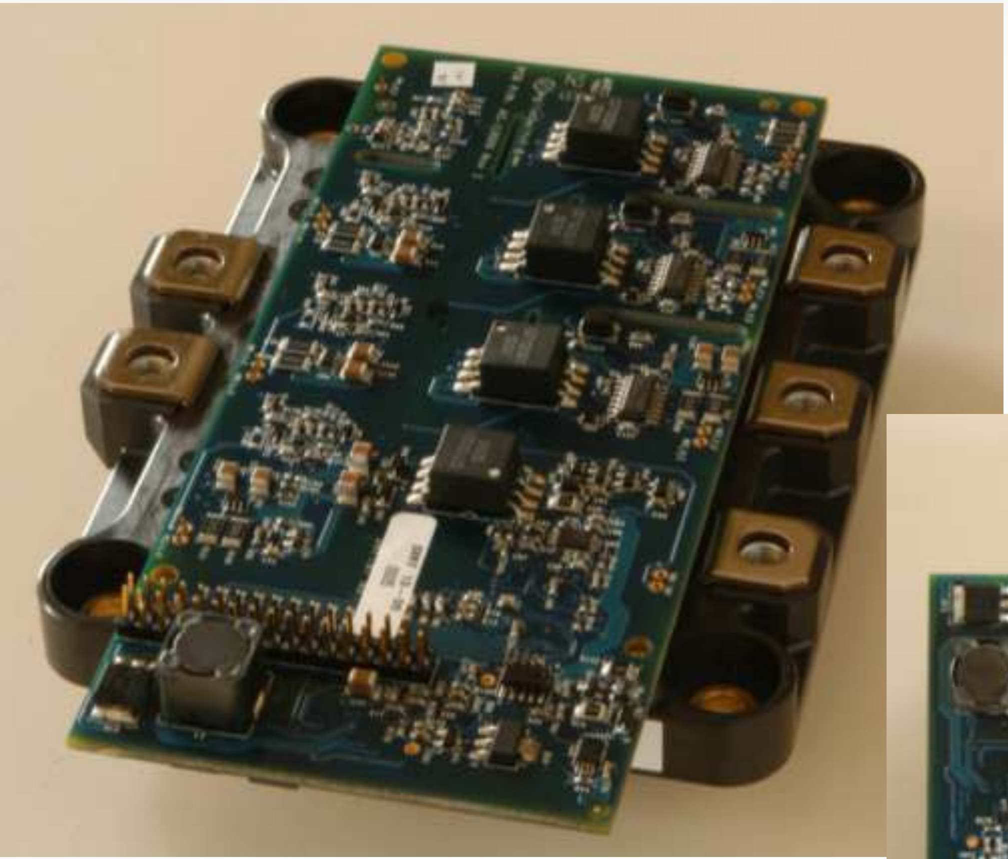
Top

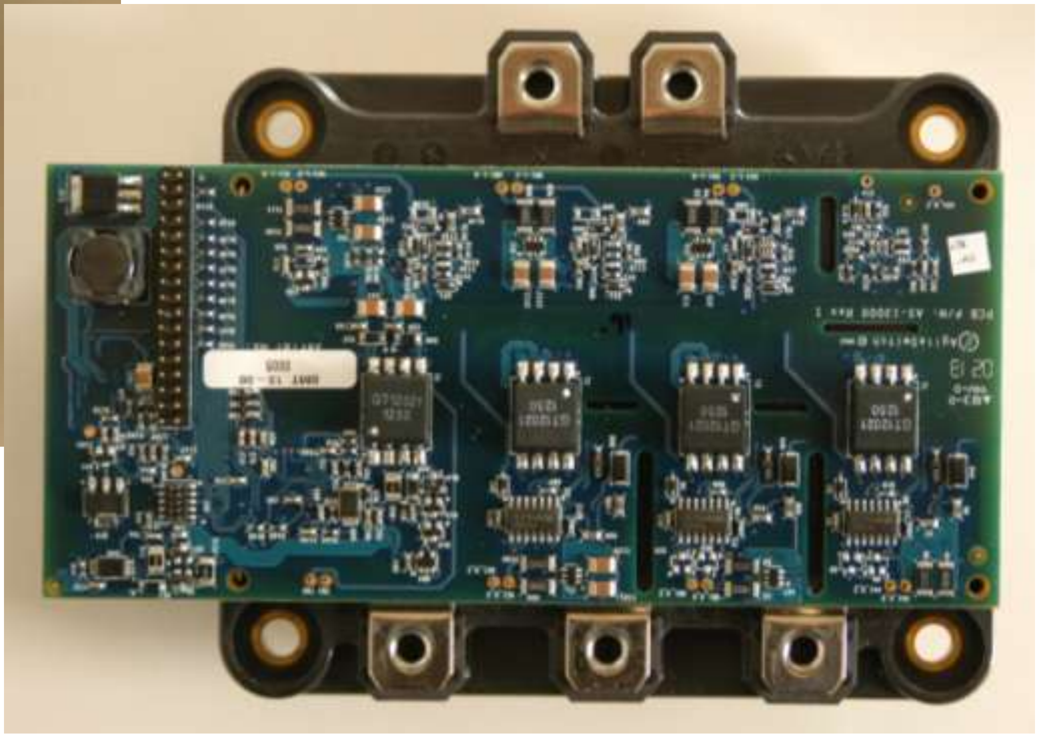


Bottom

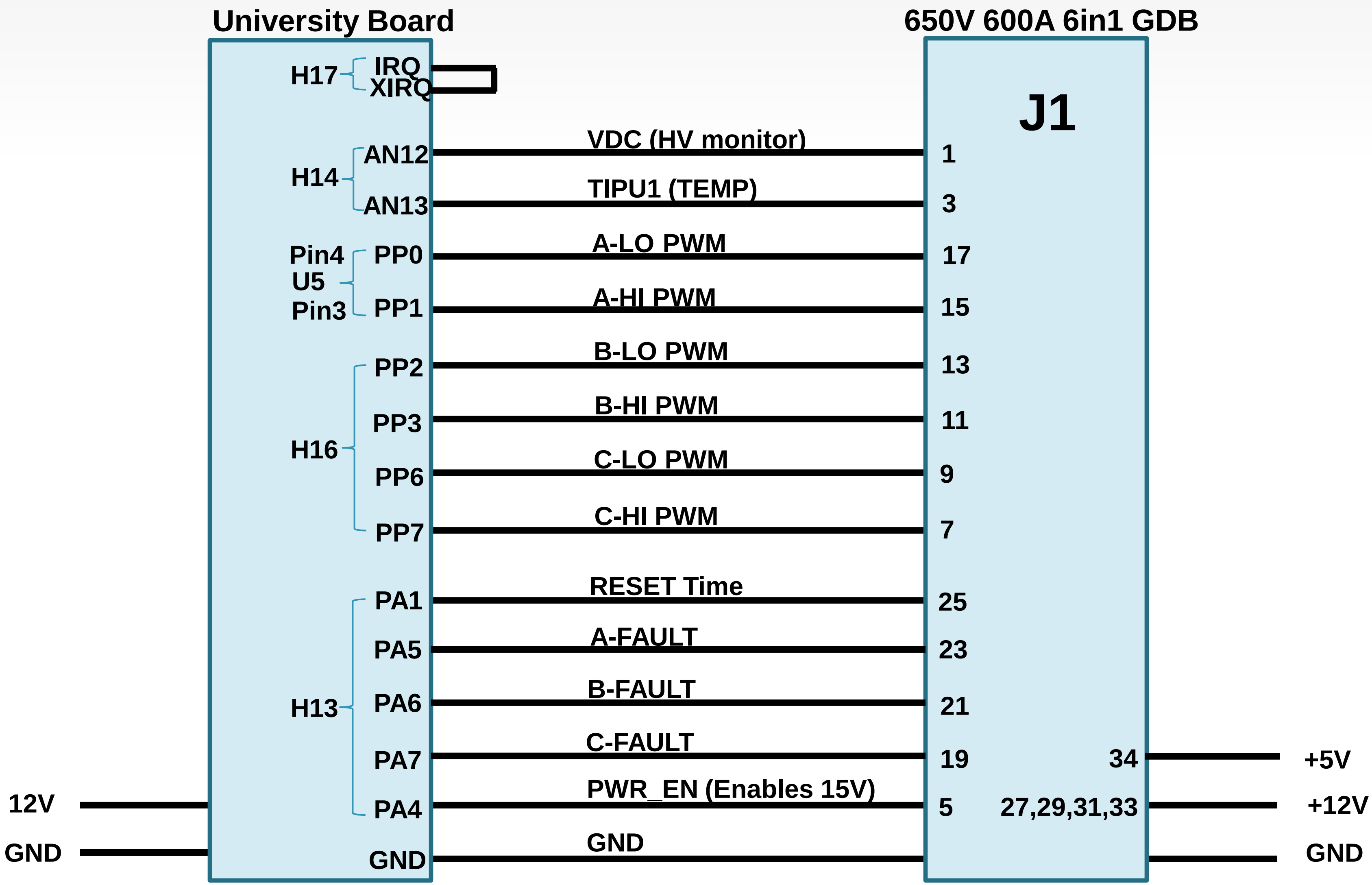


650V 600A IGBT and GDB





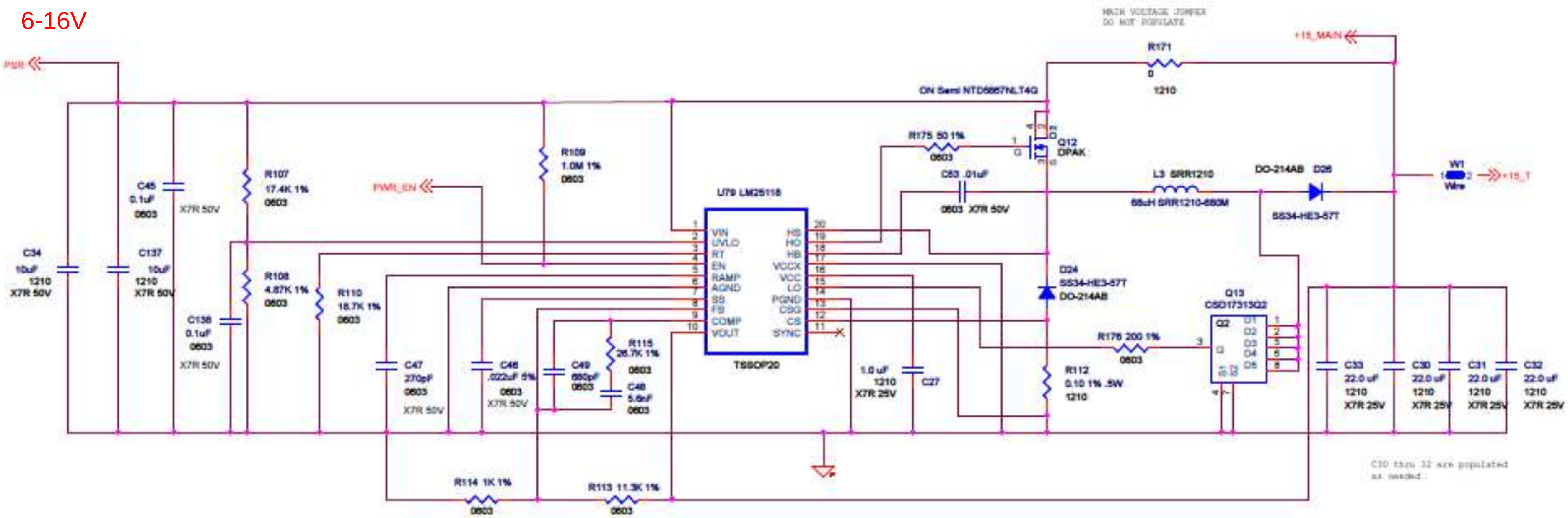
Digital Interface To 6MBI600VW-065V GDB



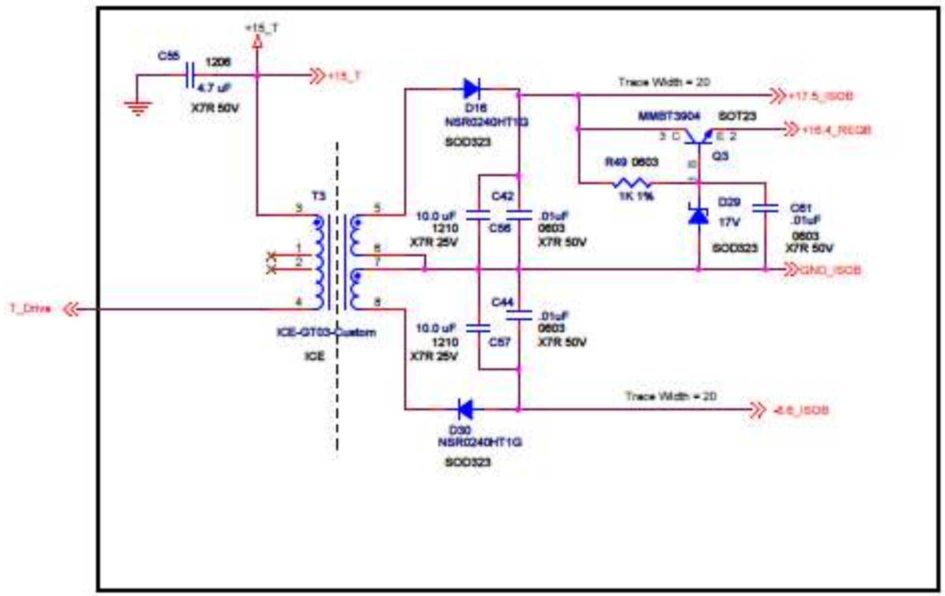
Must use isolated supply for the IGBT
Must use an isolated scope to view the gates (G to E)
Must have isolated scope channels to view HS & LS gates at the same time

All Even # Pins are Gnd
Except 34 which is
5V Logic output

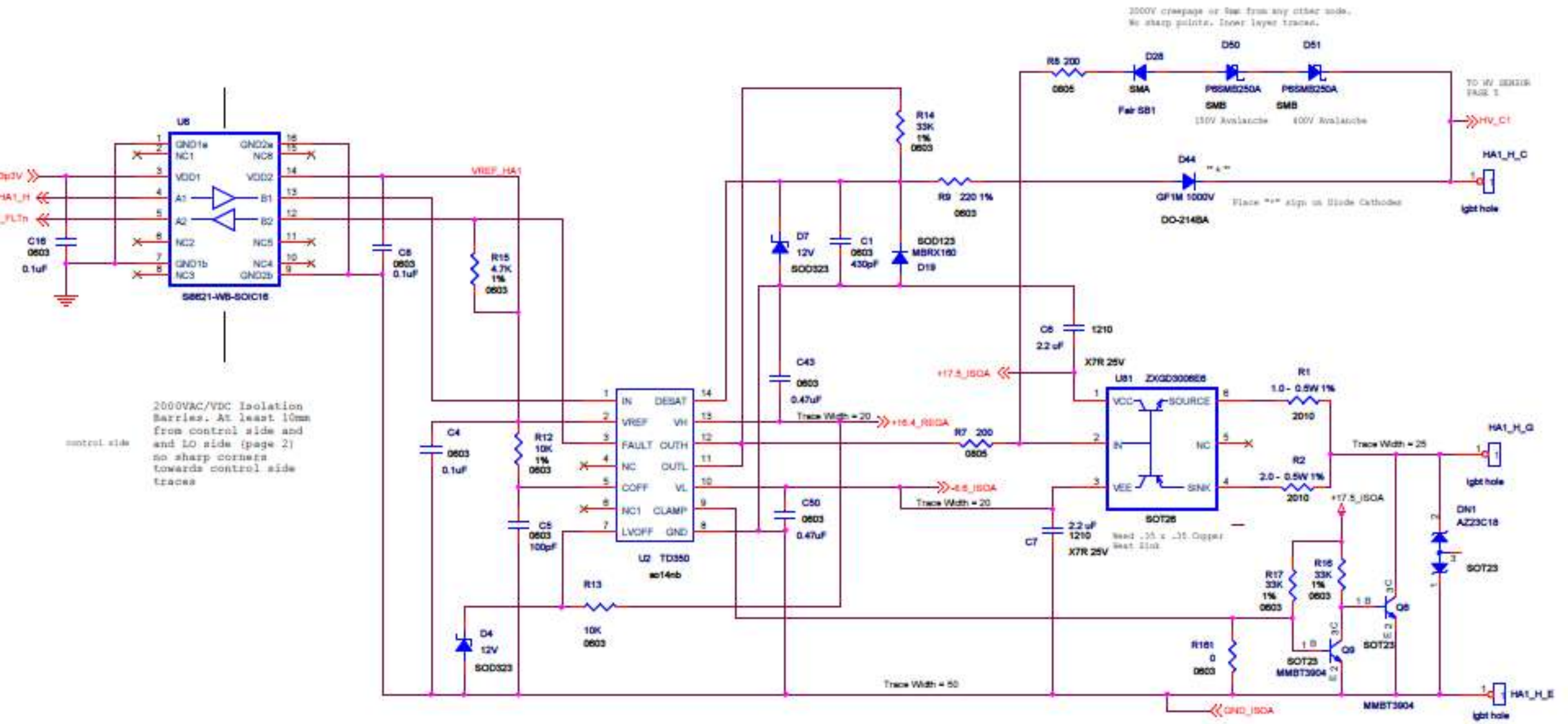
GDB Main Supply



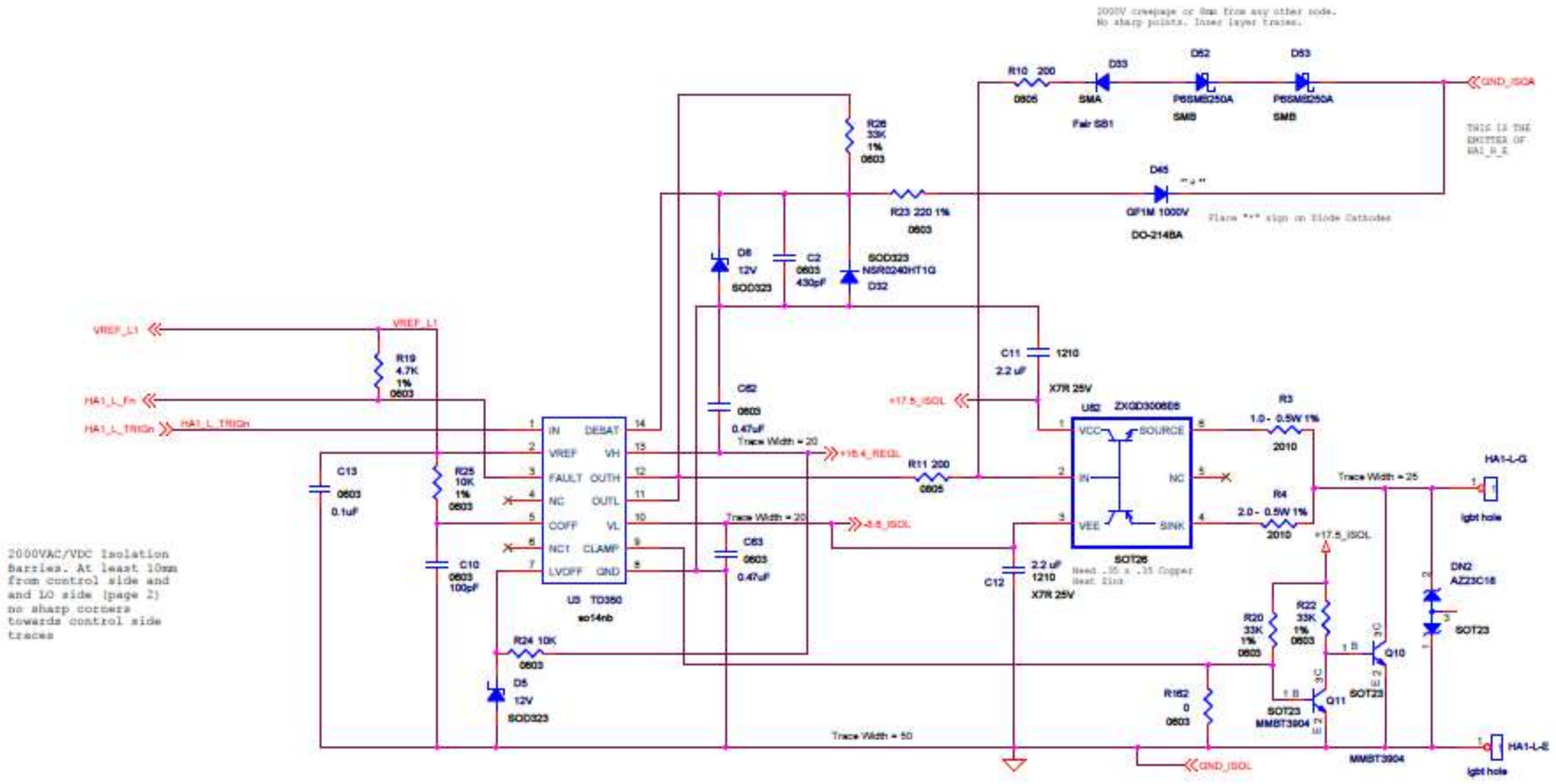
GDB Typical HS & LS Power Supply



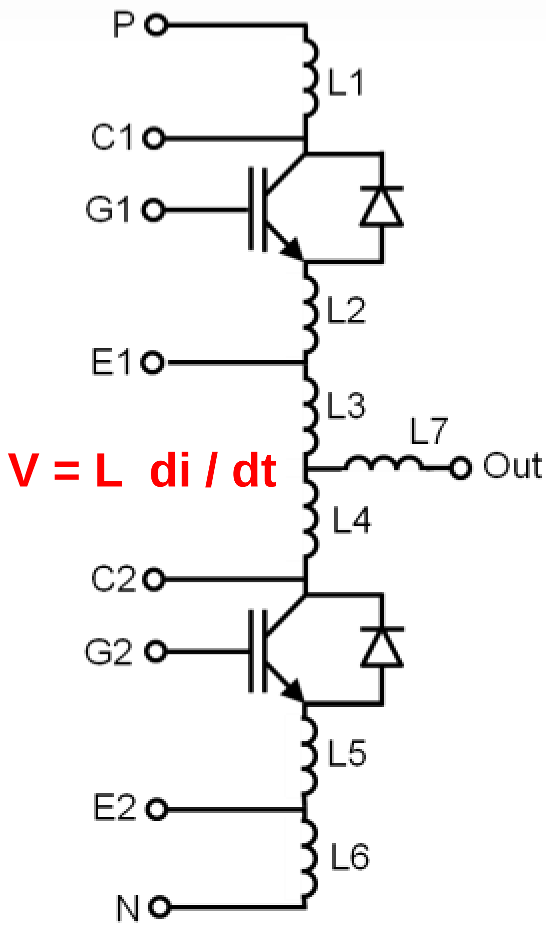
GDB High Side Drive



GDB Low Side Drive



Challenges of Inverter Design

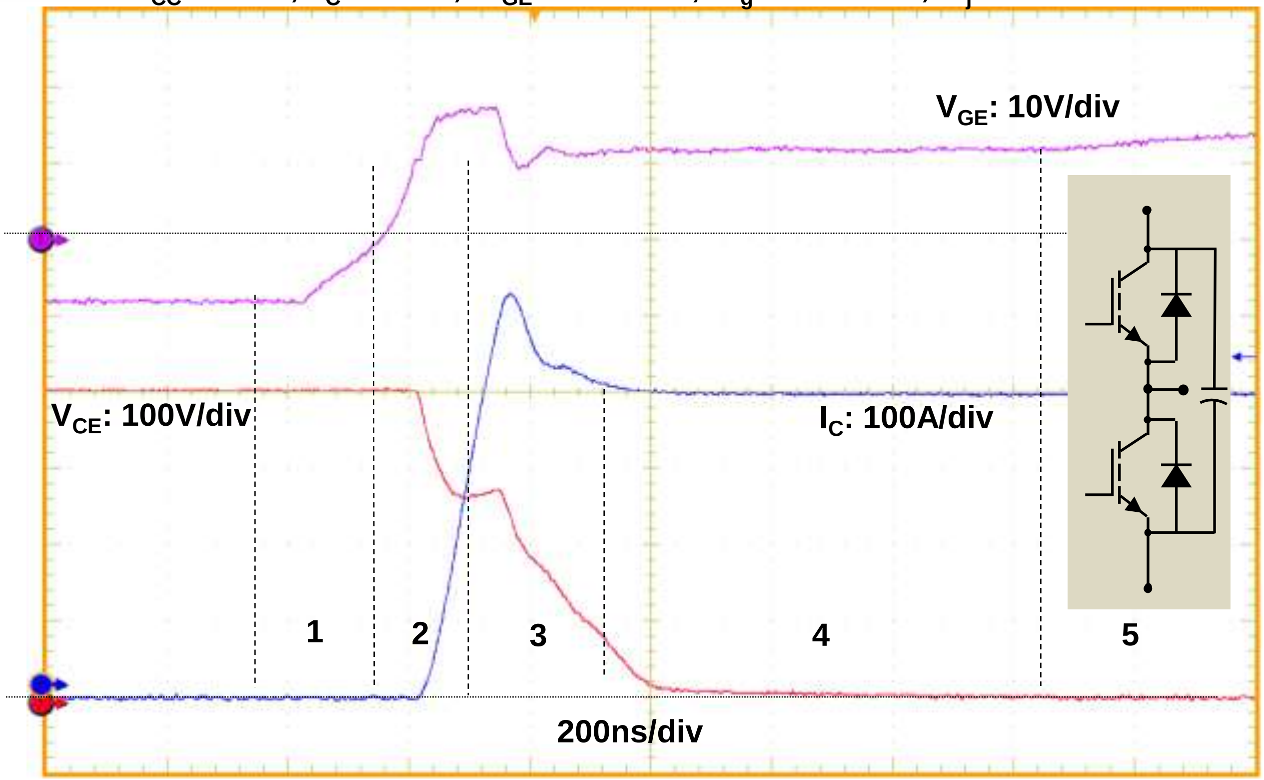


- L2 and L5 are small inductances (~1nH, typical) that are common to the gate drive as well as the emitter. These inductances slow turn on and turn off because their induced voltages negatively affect the desired voltage appearing at the gate-emitter terminals of the die.
- The 6MBI400VN-065V has a total 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 over shoot. With a 400V battery bus you would need a 750V device, and it gets worse at cold!**

6MBI400VN-065V Turn-on Characteristics

(while clearing a reverse recovering rectifier)

V_{CC} = 400V, I_C = 400A, V_{GE} = $^{+}$15V/$^{-}$8V, R_g = $^{+}$3.9/$^{-}$12Ω, T_j = 25°C



From: Fuji's "*Device features of the 6MBI400VN-065V_03-June-2011.pdf*"

1 – V_{GE} begins to charge. Input capacitance increases as V_{GE} crosses 0V. IGBT has no collector current yet.

2 – V_{GE} crosses its threshold voltage. Rapid di/dt disallows accurate monitoring of V_{GE} and V_{CE} at the die. V_{CE} at the die remains at V_{CC}. Opposing diode is not yet forward biased.
Load current commutates to the IGBT and IGBT begins clearing the diode's Q_{rr}, its reverse recovery charge.

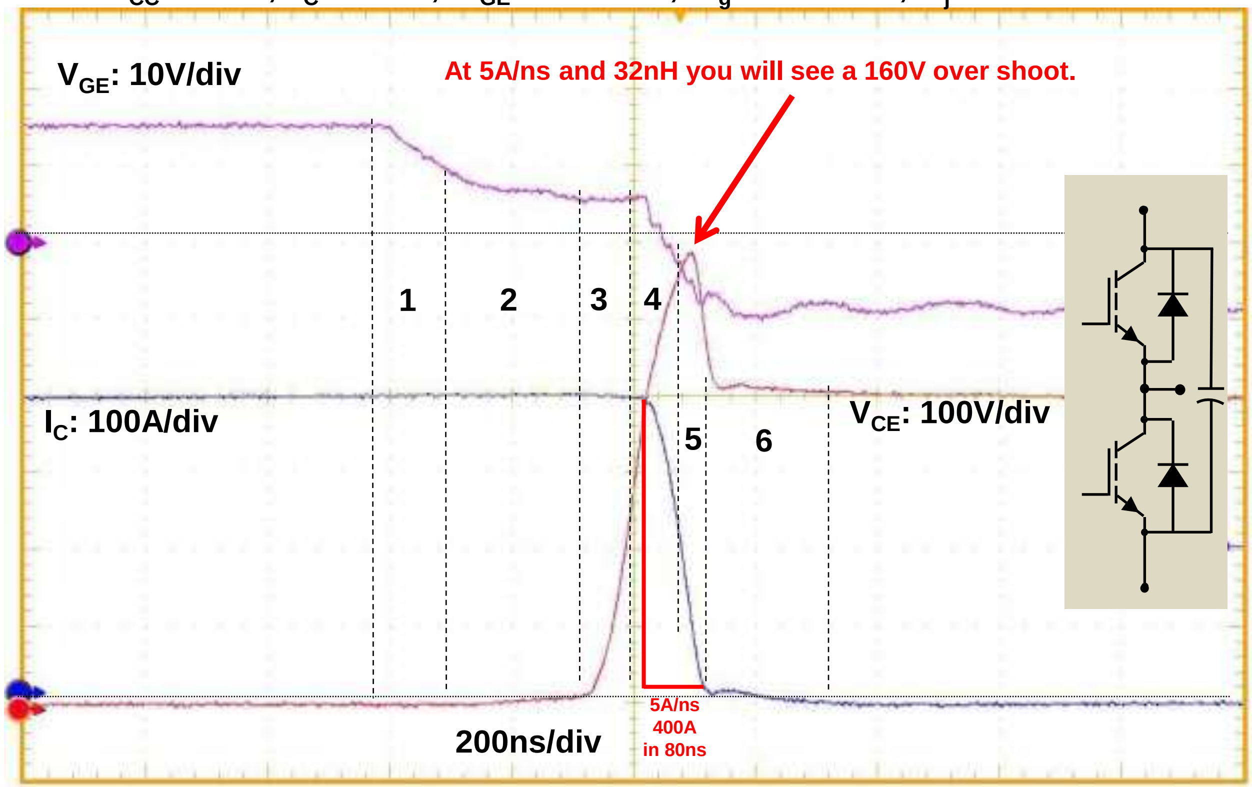
3 – Diode characteristics control reverse recovery. Polarity of di/dt changes and again affects observed V_{GE} and V_{CE}.

4 – Gate drive very slowly charges C_{GC}, which is now very large. Slope is very shallow.

5 – With switching complete, the gate drive more easily charges the input capacitance.

6MBI400VN-065V Turn-off Characteristics

V_{CC} = 400V, I_C = 400A, V_{GE} = $^{+}$15V/$^{-}$8V, R_g = $^{+}$3.9/$^{-}$12Ω, T_j = 25°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.

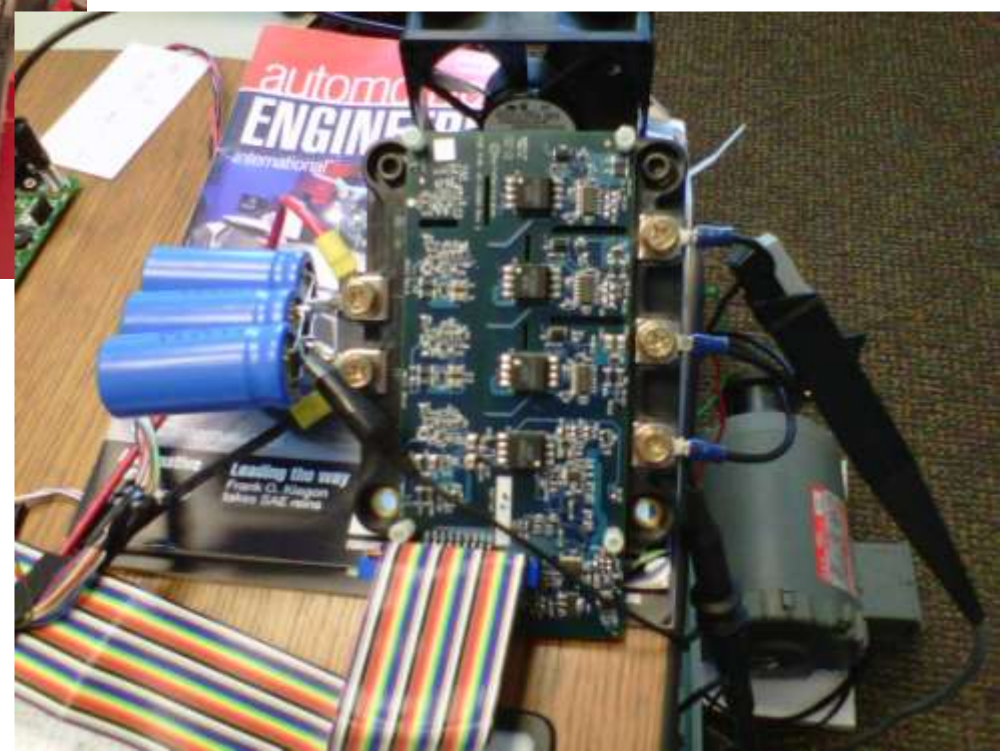
6 – IGBT current decays as carriers within the IGBT recombine.

From: Fuji's "*Device features of the 6MBI400VN-065V_03-June-2011.pdf*"

LABs

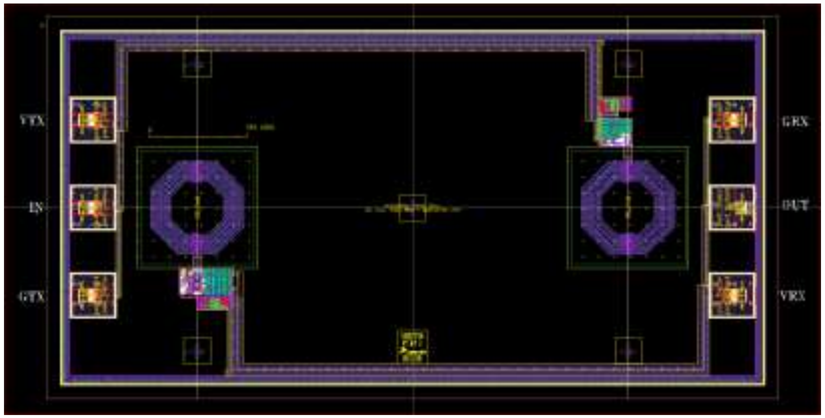
Phoenix

Detroit

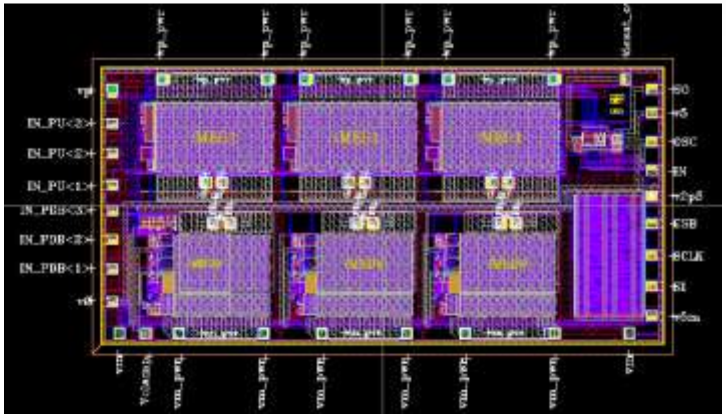


Advanced Gate Drive IC

Prototype Isolation Circuit

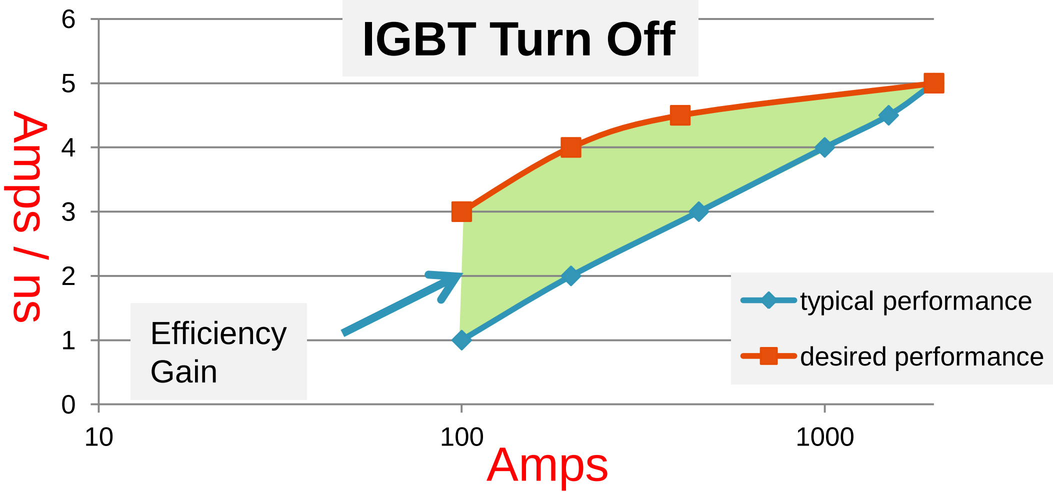


Prototype Programmable Gate Drive IC



- **Galvanic Isolation**
- **High speed communications with bidirectional option**
- **Small silicon area**

- **External control of three current drive levels for IGBT turn on & off**
- **Digital Sequencer provides 10nsec timing control**



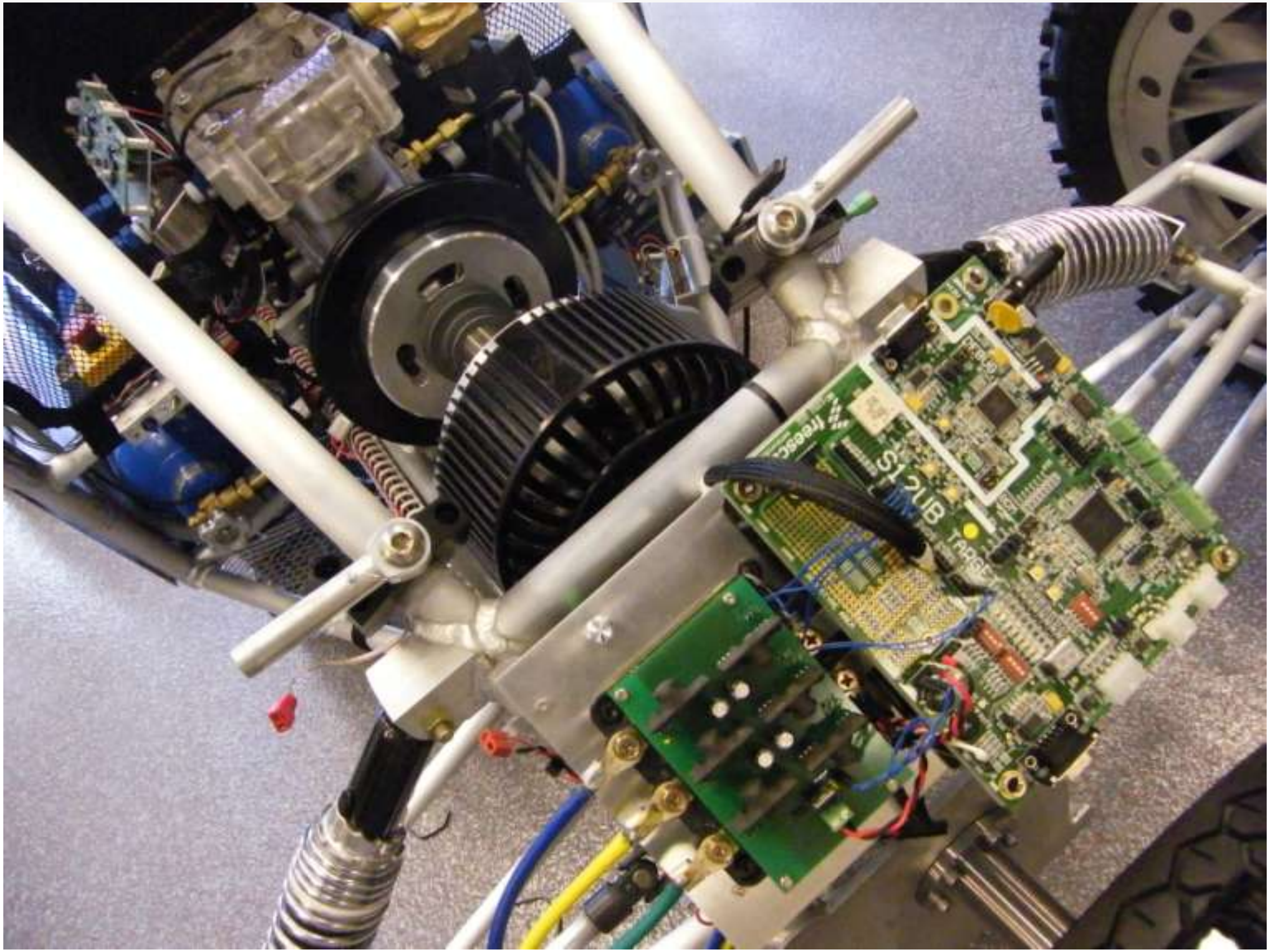
Intelligent GDIC Provides

- Tighter dynamic control
- H/S communications

Benefits

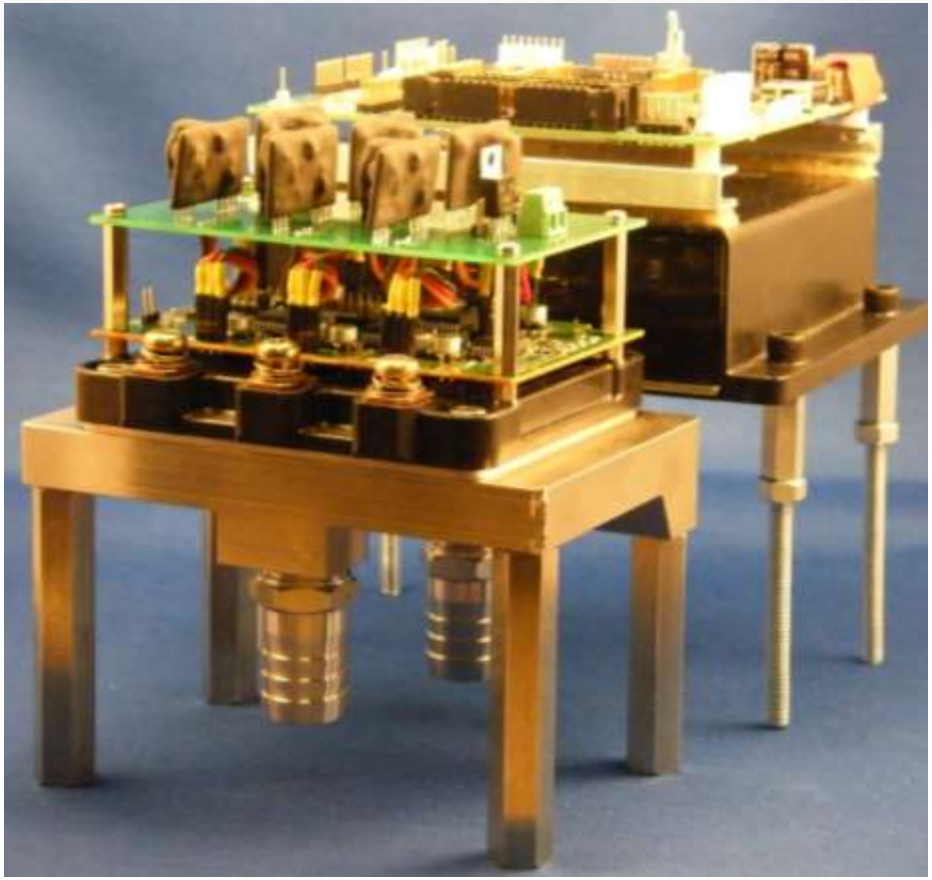
- System efficiency
- Improved diagnostics
- Systems cost savings

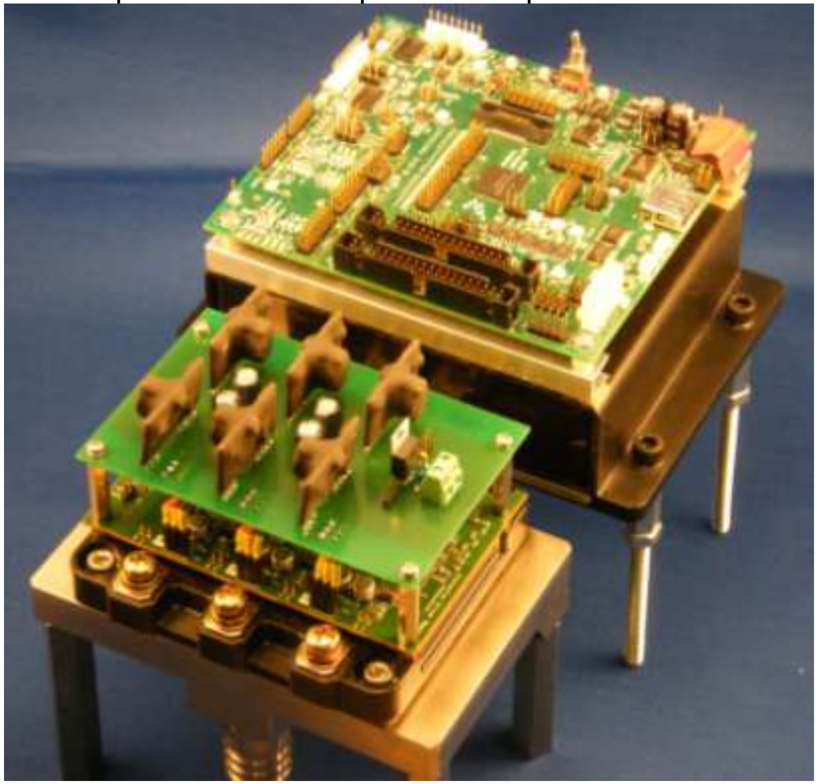
40KW Modular Inverter Reference Design



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





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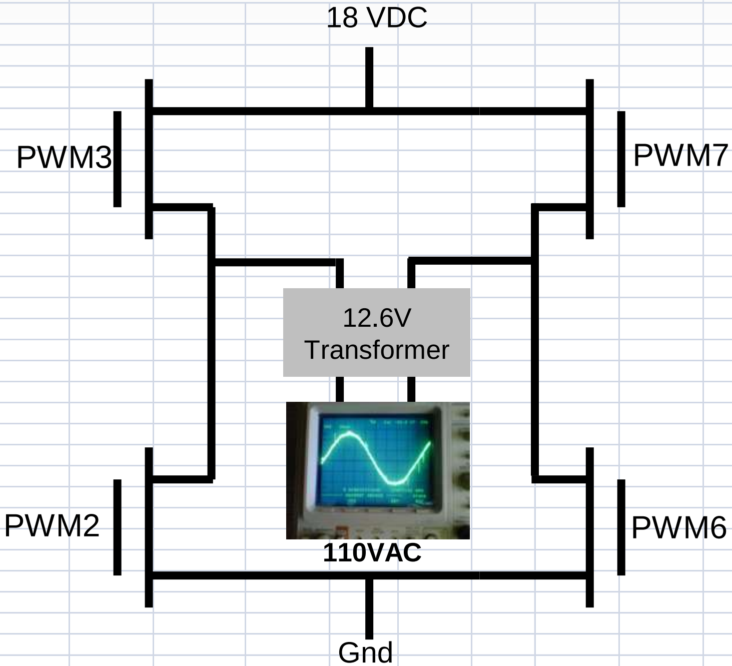
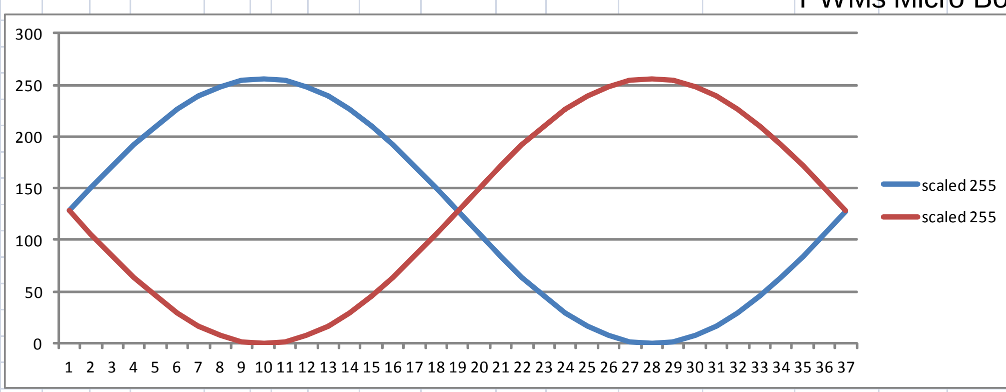
Simple Sine Wave Inverter

deg	rad	sin	scaled 255	hex		deg	rad	sin	scaled 255	hex
0	0.000	0.00	128	80		180	3.141	0.00	128	80
10	0.175	0.17	150	96		190	3.316	-0.17	106	69
20	0.349	0.34	172	AB		200	3.490	-0.34	84	54
30	0.524	0.50	192	BF		210	3.665	-0.50	64	40
40	0.698	0.64	210	D2		220	3.839	-0.64	46	2D
50	0.873	0.77	226	E2		230	4.014	-0.77	30	1E
60	1.047	0.87	239	EE		240	4.188	-0.87	17	11
70	1.222	0.94	248	F8		250	4.363	-0.94	8	7
80	1.396	0.98	254	FE		260	4.537	-0.98	2	1
90	1.571	1.00	256	FF		270	4.712	-1.00	0	0
100	1.745	0.98	254	FE		280	4.886	-0.98	2	1
110	1.920	0.94	248	F8		290	5.061	-0.94	8	7
120	2.094	0.87	239	EE		300	5.235	-0.87	17	11
130	2.269	0.77	226	E2		310	5.410	-0.77	30	1D
140	2.443	0.64	210	D2		320	5.584	-0.64	46	2D
150	2.618	0.50	192	C0		330	5.759	-0.50	64	3F
160	2.792	0.34	172	AB		340	5.933	-0.34	84	54
170	2.967	0.17	150	96		350	6.108	-0.17	106	69
180	3.141	0.00	128	80		360	6.282	0.00	128	7F
190	3.316	-0.17	106	69		10	0.175	0.17	150	96
200	3.490	-0.34	84	54		20	0.349	0.34	172	AB
210	3.665	-0.50	64	40		30	0.524	0.50	192	BF
220	3.839	-0.64	46	2D		40	0.698	0.64	210	D2
230	4.014	-0.77	30	1E		50	0.873	0.77	226	E2
240	4.188	-0.87	17	11		60	1.047	0.87	239	EE
250	4.363	-0.94	8	7		70	1.222	0.94	248	F8
260	4.537	-0.98	2	1		80	1.396	0.98	254	FE
270	4.712	-1.00	0	0		90	1.571	1.00	256	FF
280	4.886	-0.98	2	1		100	1.745	0.98	254	FE
290	5.061	-0.94	8	7		110	1.920	0.94	248	F8
300	5.235	-0.87	17	11		120	2.094	0.87	239	EE
310	5.410	-0.77	30	1D		130	2.269	0.77	226	E2
320	5.584	-0.64	46	2D		140	2.443	0.64	210	D2
330	5.759	-0.50	64	3F		150	2.618	0.50	192	C0
340	5.933	-0.34	84	54		160	2.792	0.34	172	AB
350	6.108	-0.17	106	69		170	2.967	0.17	150	96
360	6.282	0.00	128	7F		180	3.141	0.00	128	80

This table generates sinwave 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



PWMs Micro Board



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