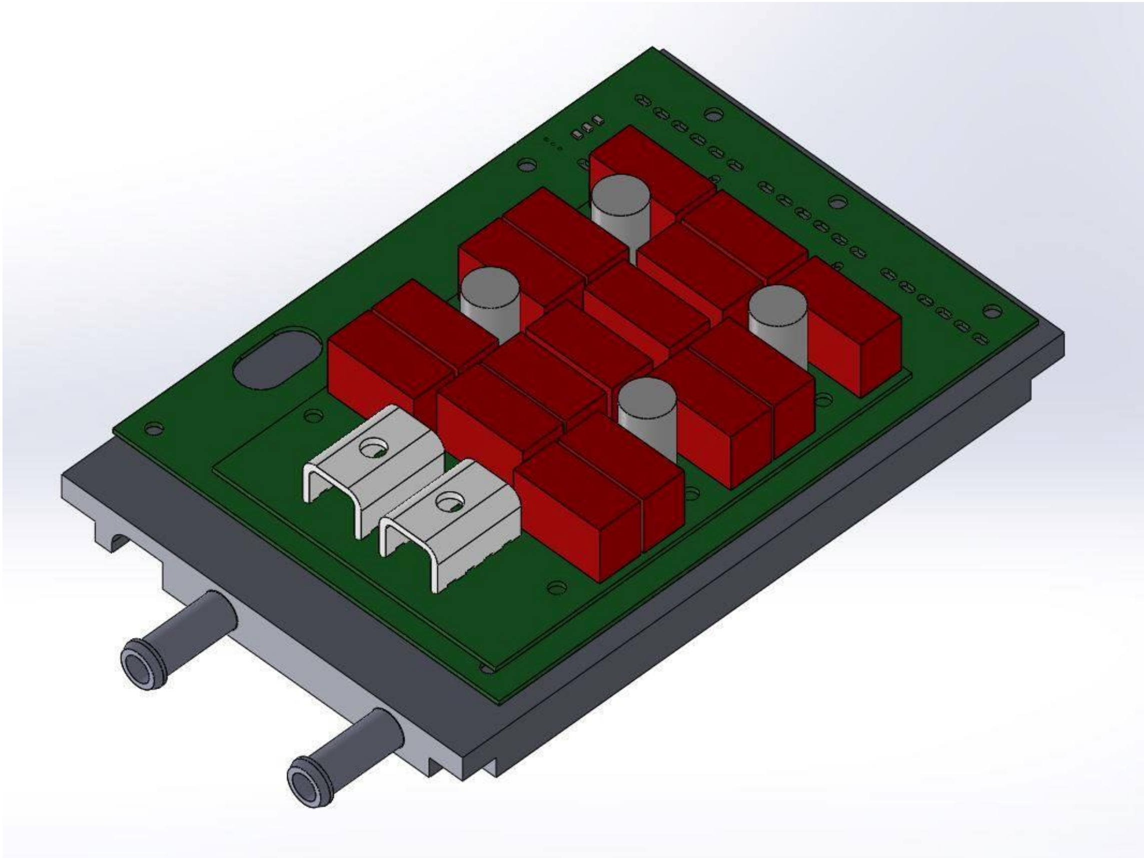

Formula SAE Motor Inverter

FINAL REPORT

Anthony Kellam | BEB802 | November 4, 2016
Supervisor: Associate Professor Geoff Walker

Executive Summary

In 2016, Queensland University of Technology is competing in Formula SAE with an ambitious electric vehicle. This project features four-wheel drive with independent in-hub motors, utilising a 15kW brushless DC motor in each wheel. With the unique packaging and communications requirements of the project, along with its extreme weight sensitivity, a new type of motor inverter was required to achieve the project's goals.

The initial design challenges commenced with producing an extremely compact, water-cooled enclosure. With a low DC bus voltage of 90V resulting in peak currents of more than 150A, bespoke high-current PCB interconnects needed to be developed, along with a stacking multi-PCB layout to keep the inverter below the 1500 cm^3. In conjunction with the mechanical design work, software was developed allowing the controller to run in constant speed or constant torque modes, whilst utilising the ultra-low latency CANbus based control protocol.

The project delivered an inverter design which allowed the vehicle to meet all its initial design goals. Further design work will be needed to improve the efficiency of the inverter thus allowing the performance of the vehicle to reach its ultimate limit.

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1.0 Introduction

QUT Motorsport is a student engineering and business team, which sets about competing in the formula SAE event held in Melbourne each year. This competition centres around the concept, design, manufacture, assembly and testing of a vehicle conforming to the FSAE rules [1]. Ultimately, the team together with their vehicle will compete against teams from other Universities both from Australia and abroad.

The current vehicle in development is electric and features an all-wheel-drive system with one motor per wheel. Since each motor requires its own inverter, it follows that the project also requires four inverters. For several reasons including packaging constraints as well as EMI mitigation the decision was made to locate each inverter as close as practicable to its respective motor. It became apparent that it would be difficult to find a pre-existing solution on the market which would satisfy and so the team set about designing a unit to meet the specific requirements of the EV project.

The motors being used on the vehicle are a brushless DC unit, rated at 15kW with a maximum speed of 6000 rpm and peak torque of 30Nm [2]. The vehicle has a bus voltage of 90V nominal. Therefore, the current research topic is to design, prototype, build and verify a controller capable of meeting these specifications as well as the physical attributes which the vehicle's overall design requires. These extra requirements include a target mass of below 3kg, water cooling and an enclosure envelope of approximately 200mm x 120mm x 60mm; below 1.5 litres' volume.

This report represents the final submission on the project, detailing the current state of the design, along with an analysis of its current performance level as well as recommendations for future work which will further advance the design. Delays and other challenges are also discussed. Finally, the conclusion will cover what this project represents by way of knowledge contribution.

2.0 Project Objective

The final objective for the FSAE motor inverter project was finally defined as the design, construction and characterisation of a brushless DC motor inverter which would meet the following specifications:

- 10kW continuous, 20kW peak
- 70-120V
- 3kg maximum
- 200mm x 120mm x 60mm
- Sub 1.5 litre volume

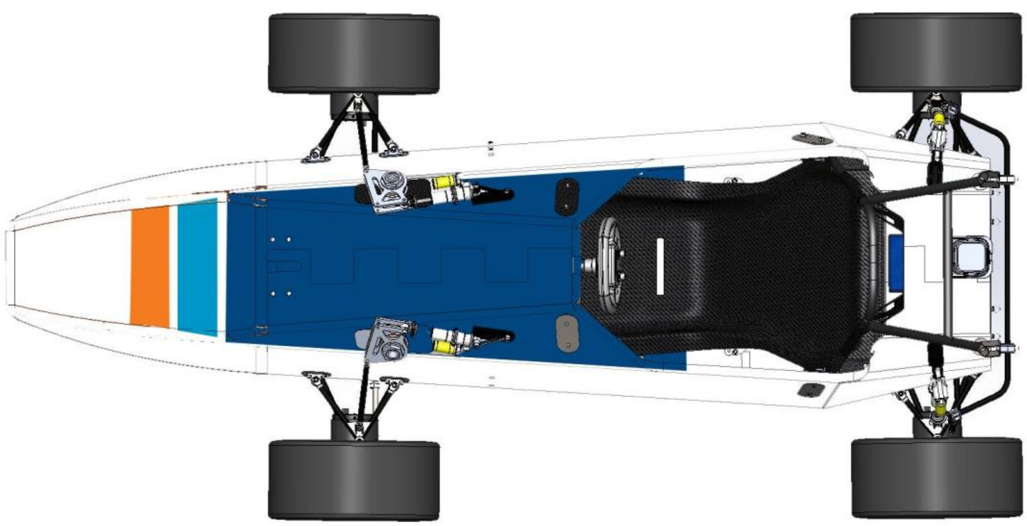


Figure 1 - QUT EV1 with motors visible in each upright

3.0 Project Approach

3.1 DESIGN

The approach used with the project was to iterate from an initial concept through successively higher power levels until a resulting version was realised which met the design specifications and goals. In the initial schematic design, several key devices and solutions were selected which achieved certain key aspects of rules compliances from the event organisers.

With the creation of a circuit design which met the project specifications a proof of concept version of the PCB was laid out in Altium Designer. The goals of this iteration were to provide a platform which would confirm certain design aspects as well allow the initial development of the control software eventually leading to a turning (unloaded) motor. This version of the design was to be rated at ~0.5kW with a target bus voltage of 30V.

Once the proof of concept version was constructed and development was ongoing, parallel work would be done on the mechanical design of a full power version of the inverter using essentially the same schematic design. Thermal design of the water cooling pate would be undertaken in conjunction with mechanical engineering students within the team.

Once a prototype full power inverter was constructed and operational, thorough testing of its performance could commence with a planned iteration to follow pending the outcome of this testing. As this stage was nearing completion, the design was to be documented with known operating areas, performance specifications, repair procedures and a complete description of the control messaging protocol and fault detection protocol.

With a full power design version then proven, manufacturing of the four to five units ultimately required for the vehicle project would be undertaken for final assembly, testing and installation into the vehicle.

3.2 TESTING

The testing plan would consist of validating the isolation and gate drive approach using the 0,5kW proof of concept version. This would require a library of helper functions set up to utilise the microcontroller's capabilities. At this stage, the CAN protocol could be built up as required with each stage being tested thoroughly.

4.0 Design Detail

4.1 DESIGN FOUNDATION

It stands to reason that the design at its most basic level would be a triple half bridge converter controlled by an appropriate microcontroller. Due to the power levels of the vehicle's motors, namely the relatively low voltage combined with moderate to high current, mosfet switches were selected as the most appropriate switching element type. These will be discussed below, along with the design choices in relation to microcontroller design, isolation strategies, current sensing as well as mechanical and software topics.

4.2 SWITCHING STAGE

As mentioned previously, mosfets were selected as the best fit for the operating conditions expected in the inverter design. A wide variety of devices from many vendors were collated and investigated. Ultimately mosfets from IXYS were selected, with part number IXFX170N20T.

4.3 MICROCONTROLLER SELECTION

The main aim with microcontroller selection was to keep the design compact, affordable and easy to develop. With these goals in mind the ATmega64M1 microcontroller from Atmel was selected. These MCUs feature an AVR core and feature some extra peripherals which are relatively uncommon in the 8-bit market segment. These features are what cemented the choice of MCU. The ATmega64M1 includes a 3phase motor control peripheral which feature triple half bridge control with complementary outputs, automatic dead time insertion and safety shutdown features. The other important peripheral included in this MCU is a comprehensive CAN controller which meant that all the microcontroller's cores responsibilities could be undertaken with very few external components required.

4.4 GALVANIC ISOLATION

The FSAE rules mandate the complete galvanic isolation between the vehicles grounded low voltage (GLV) power system and the HV/tractive power system. This means that at some stage within the inverters themselves, an isolation boundary must be implemented. There are two typical locations for this boundary – either at the initial communications level meaning all the inverters' logic and control would be on the HV side or between the logic elements and the gate drive. For this design the second option was selected for two reasons; powering the logic would allow certain measurements and status checks to be performed on the inverters with the vehicle not in a ready-to-drive (armed) state. This could potentially help with temperature and cooldown profiling. The second reason is one of power management. Due to aspects of the rules in regards to accumulator capacity, the project was limited to 24MJ of battery storage for the tractive system. By moving the logic power requirements to the GLV system this took further stress from the HV batteries which would result in a greater vehicle operating range.

With this design choice made, the actual hardware which would produce the isolation was investigated. Ultimately RF type digital isolators were chosen from Silicon Labs – the Si8660 and Si8663. These devices were chosen due to their predictability of operation with one or the other separation side de-powered. They are also extremely fast guaranteeing accurate gate drive timing. Lastly, their wide operating voltage with asymmetry meant that should logic changes be required into the future possibly requiring 3V3 rails, major design changes would not be needed.

4.5 GATE DRIVERS

From the multitude of gate drivers available on the market the most suitable was soon found to be the FAN73933 from Fairchild semiconductor. These integrated half-bridge drivers include a bootstrap system for the high side switches, programmable dead time to give some redundancy from the MCU and a very healthy gate drive capability which would be essential with the chosen IXYS mosfets.

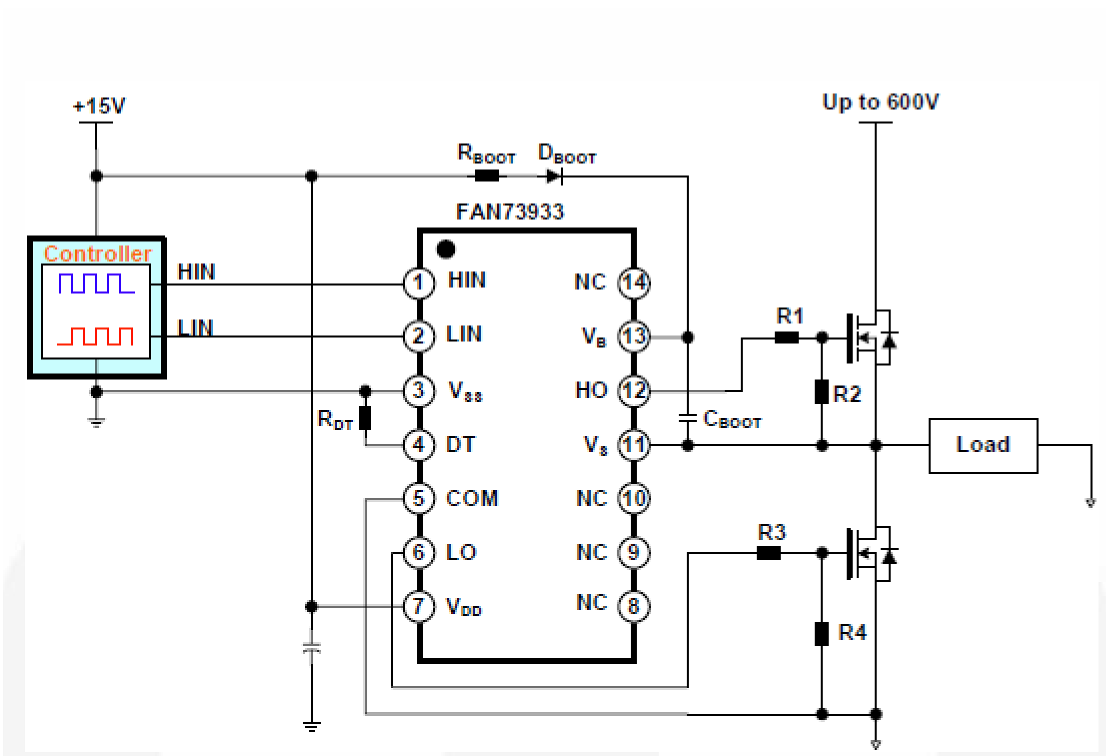


Figure 2 - FAN73933 typical application

4.6 WATER COOLING

A mechanical design concept was built up in conjunction with mechanical engineers from within the team. This was based on a 20mm 6061 Aluminium plate with machined water galleries and a sealing plate. The mosfet stage is bolted to the top of this plate with end plates and a main cover added thereafter.

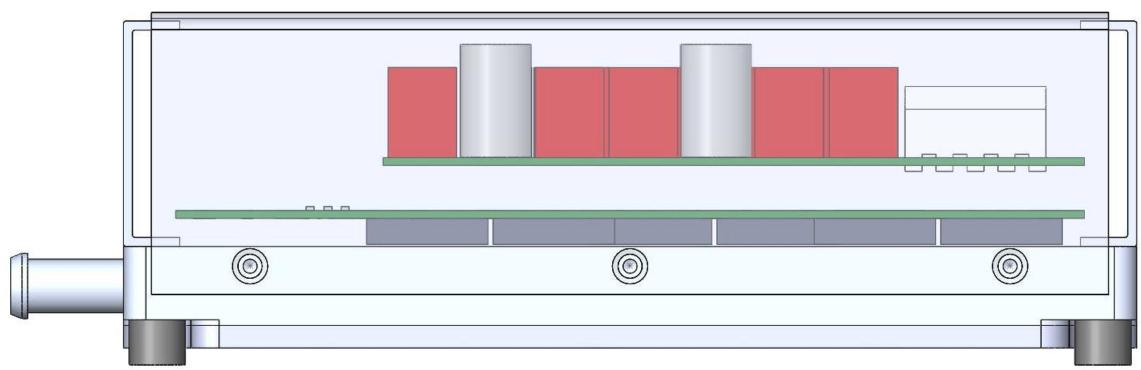


Figure 3 - Inverter thermal design detail

4.7 SOFTWARE

Two control methods are being implemented in the inverter – a speed command method and a torque command method. The speed mode utilises a control loop to maintain an RPM setpoint as commanded by the chassis controller or similar. This mode is mainly for testing and alternative applications. Achieving this mode required the addition of some background code using timers and hall state interrupts to constantly update an RPM measurement for the system's use. This RPM can then also be reported back to the chassis controller to form part for the control strategy for its vehicle dynamics and safety systems.

The second control method, commanded torque, requires the integration of more of the sensors which have been included in the inverter's design. Specifically, the current sensors available on two of the three phases need to be brought online for this mode to work successfully. Adding these sensors also allows for a critical fault mode to be detected being overcurrent or current faults.

CAN bus communications are at the centre of the projects system level integration. The tractive system has its own dedicated bus to allow for control with the lowest possible latency. Torque commands for each of the 4 motors are packaged in a single CAN packet which allows for even lower response delays. Whilst the fact that the inverters and the remaining control systems are being produced within the team means these protocols can be highly optimised, it also means there is a lot more software to develop. A lot of effort has been put into the tractive CAN protocol and this has been developed on the prototype inverter.

The last area where software work has been carried out in in the start-up code. This is the system which initially achieve motor rotation before any significant movement has occurred.

4.8 CONTROL AND COMMUNICATIONS

CANbus is used extensively in the vehicle and it is the main communications layer for the control of the inverters. A protocol was developed where the inverters could be addressed within a common CAN packet using flags to mark the intended recipient(s). The CAN protocol then allows enough data to embed four differing command values with a single packet giving an extremely high bandwidth real time torque request to all four inverters simultaneously. This system has been fully developed and tested on four nodes in the same configurations as the vehicles. It performs well and easily achieves a bandwidth in excess of 1kHz which far exceeds the requirements of any future torque vectoring scheme which may be utilised in the vehicle.

5.0 Analysis

Initially, the 0.5kW version was analysed for its software responsiveness and performance as well as the starting sequence for initial motor rotation. Following this a full power version was assembled with a temporary logic board repurposed from a concept version inverter.

The full power inverter was connected to a 47uH 100A air cored inductor which was created to closely match the inductance of a target motor winding. Some waveforms from the inverter follow:

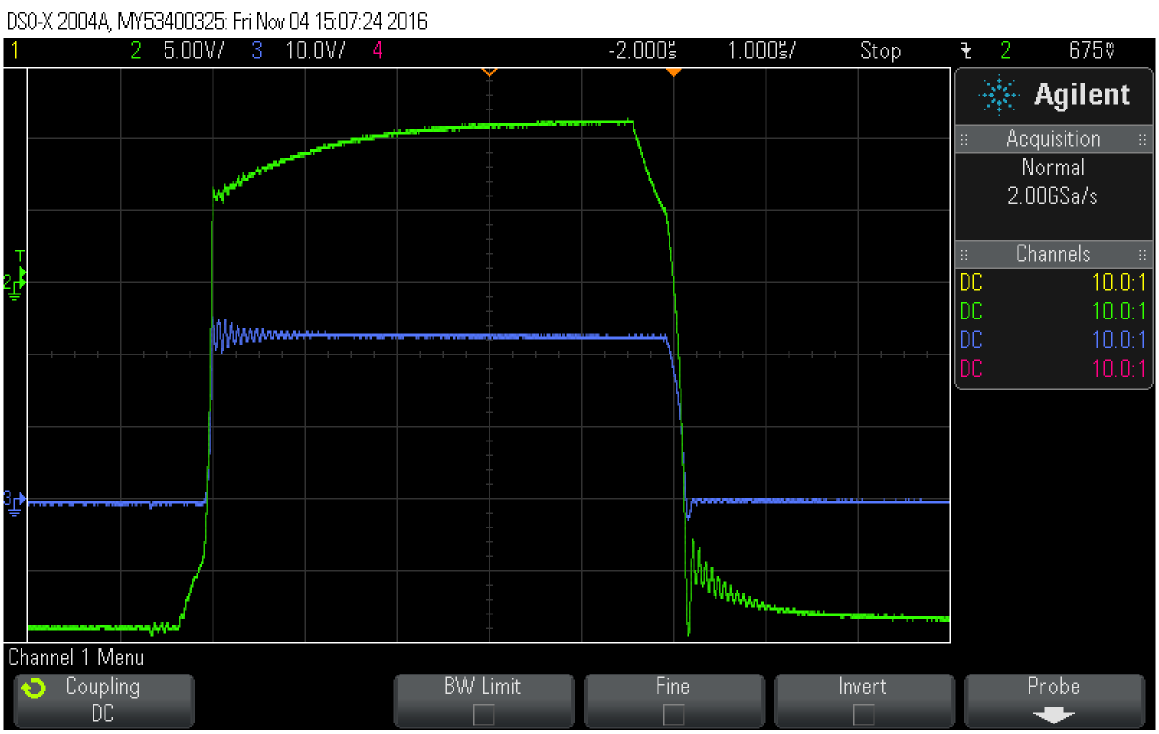


Figure 4 - Gate Drive (green) vs Output Voltage (Blue) 120W resistive load

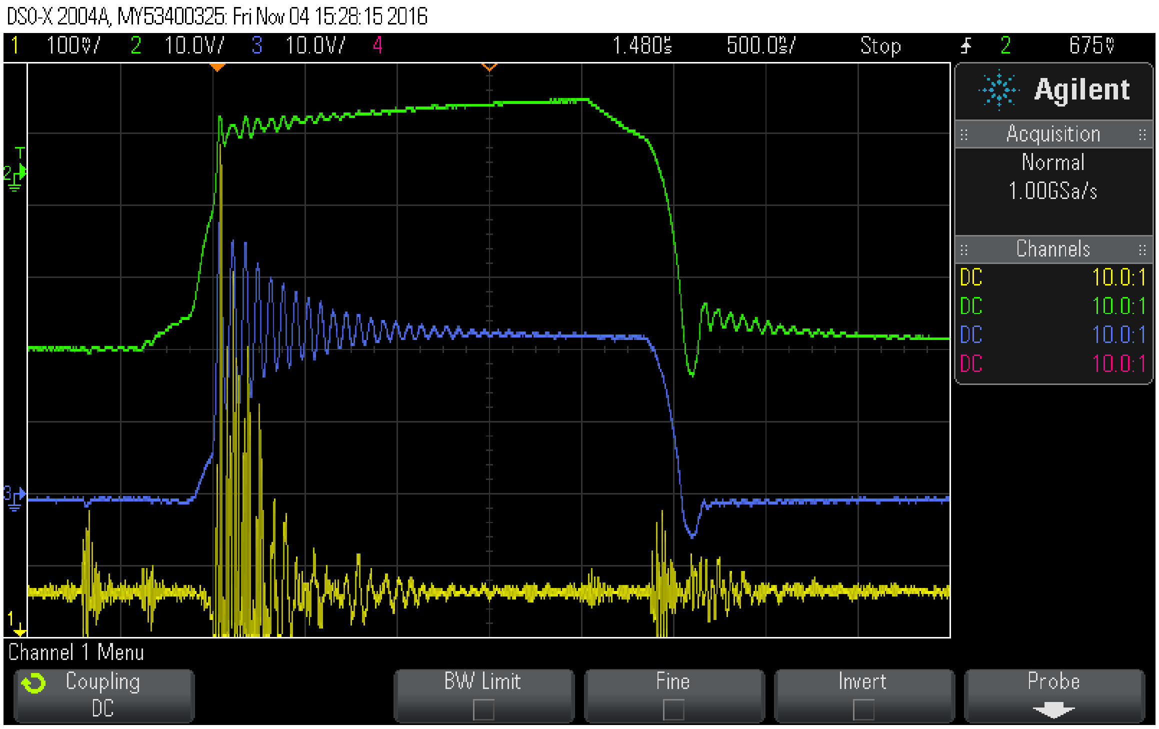


Figure 5 - Output (Blue), High Side Gate (Green) and current (Yellow) for inductive load - 4% D.C.

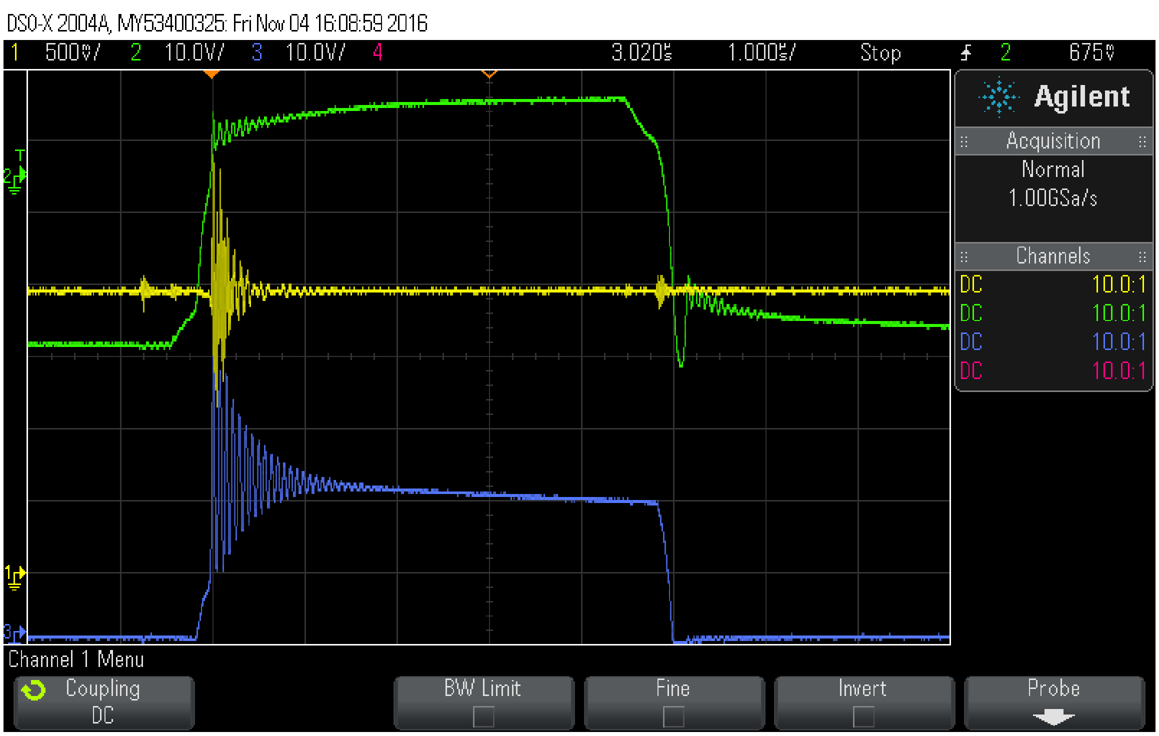


Figure 6 - - Output (Blue), High Side Gate (Green) and current (Yellow) for inductive load - 8% D.C.

6.0 Results and Findings

The analysis has uncovered some gate drive issues which could potentially cause issues with high power operation into the inductive load. These are most probably caused by a sub-optimal gate drive layout due to the utilisation of the temporary logic board.

7.0 Conclusion

In conclusion, the formula SAE motor inverter project has reached a point where the design is suitable for manufacturing and installation in the vehicle.

7.1 MEETING THE SPECIFICATION

During high current testing the temperature levels have remained close to ambient. For this reason, it is apparent that the basic design specifications of the inverter have been met. The software system which has been implemented meets all of the requirements to allow the inverters to be controlled in the vehicle to meet the initial project goals.

7.2 KNOWLEDGE CONTRIBUTION

This design has produced a motor inverter specifically suited to performance vehicular applications where mass and volume/packaging are of extreme importance. The design gives the University's FSAE team a great starting point for future motor control work inevitable leading into synchronous AC motors and more elaborate modulation techniques.

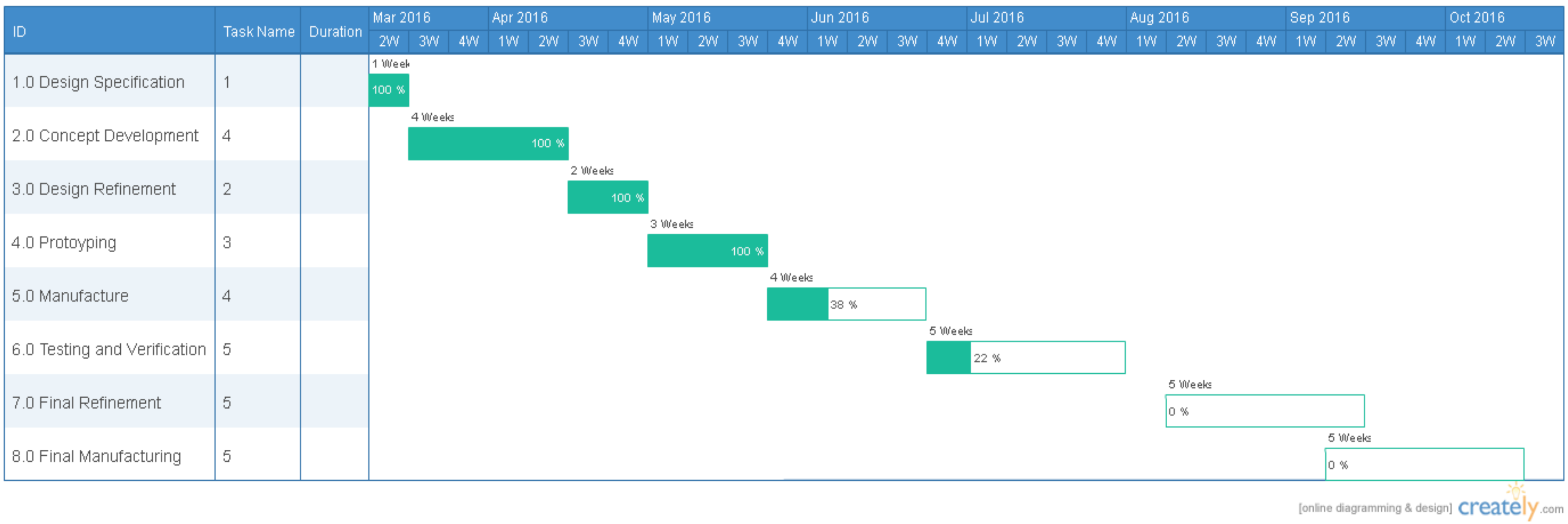
7.3 FUTURE WORK

Further testing would be of great benefit in further characterising the inverters' performance. This would best be accomplished with "back to back" testing which would involve two of the motors being coupled together and driven into each other from a common power source.

Design improvements could also be undertaken to increase the ease of servicing on the inverter design to make any repairs more easily accomplished.

8.0 Appendix

8.1 GANTT CHART



8.2 PLETTENBERG DATA SHEET

High End Elektromotoren

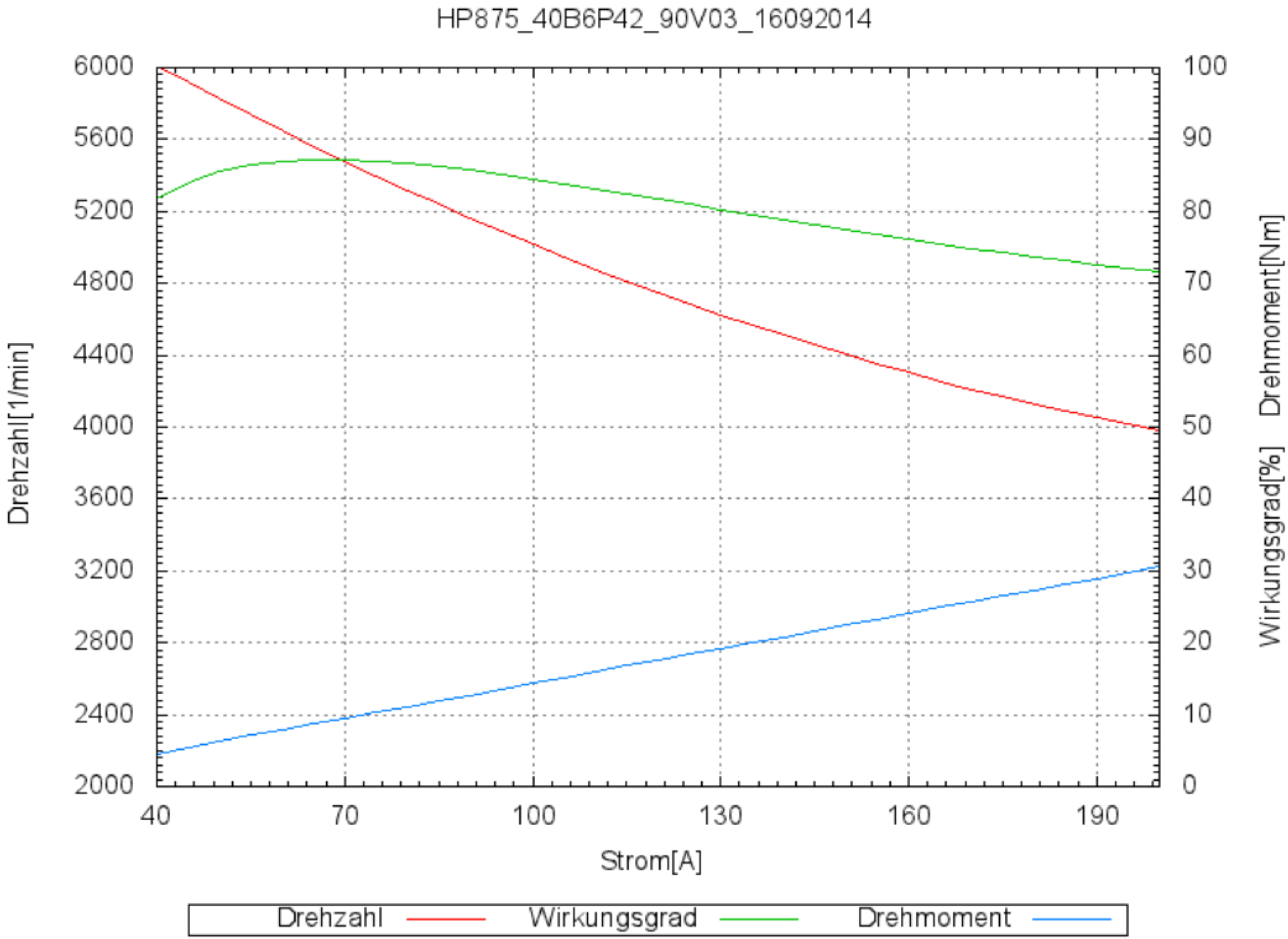
PLETTENBERG

NOVA 15/40/6 P42

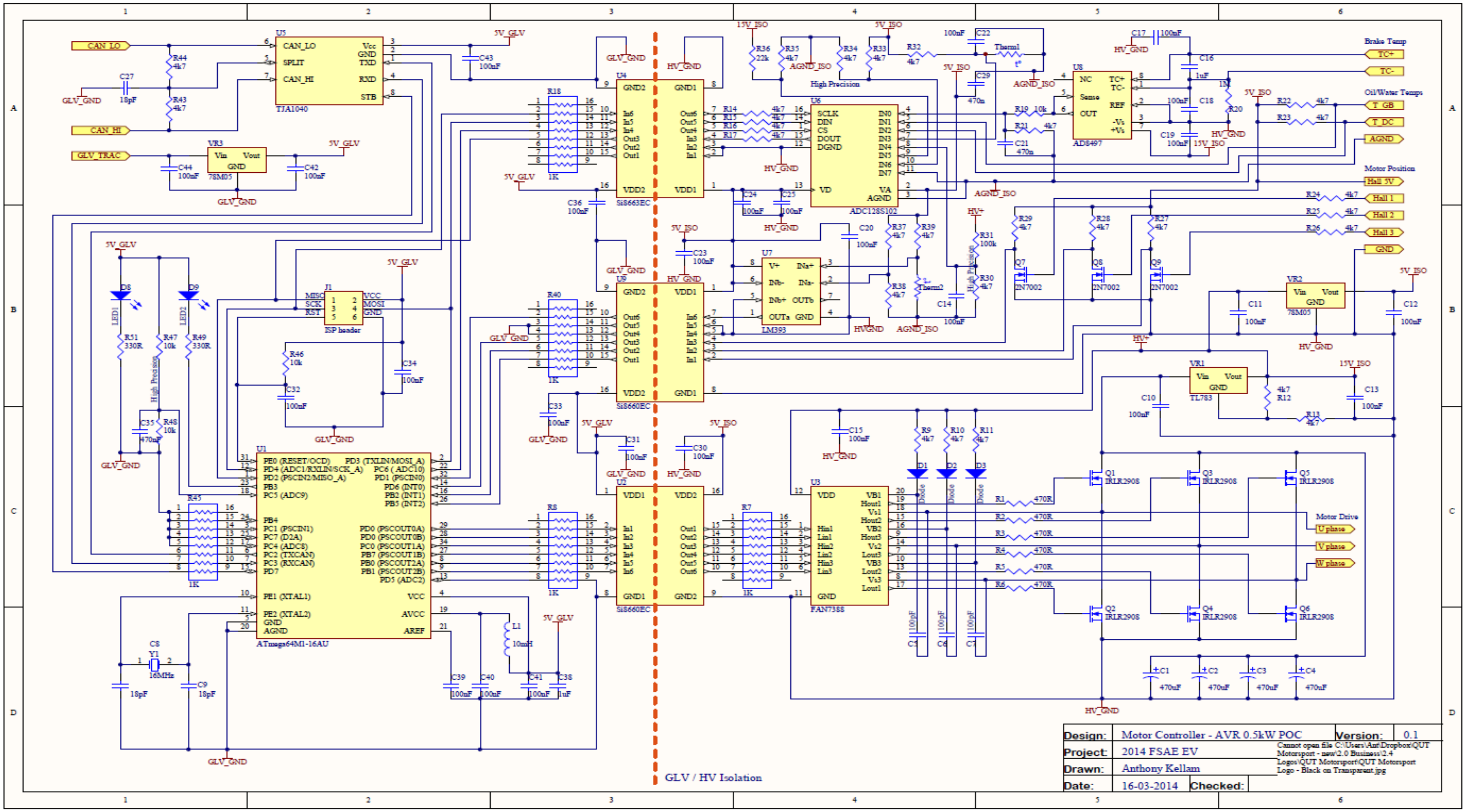
Spannung: 90 V

nl=6259.0U/min	Io=5,4A	
ns=71,6U/min/V	kn=-13,52U/min/A	kM=16.20Ncm/A

Spannung [V]	Strom [A]	Drehzahl [U/min]	Pin [W]	Pout [W]	Drehmoment [Ncm]	Wirkungsgrad [%]
89.4	40.0	6011.9	3576.7	2927.4	465.0	81.85
89.4	45.0	5918.2	4023.2	3383.6	546.0	84.10
89.4	50.0	5826.4	4469.7	3825.2	626.9	85.58
89.4	55.0	5736.7	4916.0	4252.8	707.9	86.51
89.4	60.0	5648.8	5362.2	4666.7	788.9	87.03
89.4	65.0	5563.0	5808.4	5067.5	869.9	87.24
89.3	70.0	5479.1	6254.3	5455.7	950.9	87.23
89.3	75.0	5397.1	6700.2	5831.7	1031.8	87.04
89.3	80.0	5317.1	7146.0	6196.2	1112.8	86.71
89.3	85.0	5239.1	7591.6	6549.5	1193.8	86.27
89.3	90.0	5163.0	8037.2	6892.2	1274.8	85.75
89.3	95.0	5088.8	8482.6	7224.8	1355.7	85.17
89.3	100.0	5016.7	8927.9	7547.7	1436.7	84.54
89.3	105.0	4946.5	9373.1	7861.5	1517.7	83.87
89.3	110.0	4878.2	9818.2	8166.7	1598.7	83.18
89.2	115.0	4811.9	10263.1	8463.8	1679.7	82.47
89.2	120.0	4747.6	10708.0	8753.2	1760.6	81.74
89.2	125.0	4685.2	11152.7	9035.5	1841.6	81.02
89.2	130.0	4624.7	11597.4	9311.1	1922.6	80.29
89.2	135.0	4566.3	12041.9	9580.6	2003.6	79.56
89.2	140.0	4509.7	12486.3	9844.4	2084.5	78.84
89.2	145.0	4455.2	12930.5	10103.1	2165.5	78.13
89.2	150.0	4402.6	13374.7	10357.1	2246.5	77.44
89.2	155.0	4351.9	13818.7	10607.0	2327.5	76.76
89.1	160.0	4303.2	14262.7	10853.3	2408.5	76.10
89.1	165.0	4256.5	14706.5	11096.3	2489.4	75.45
89.1	170.0	4211.7	15150.2	11336.7	2570.4	74.83
89.1	175.0	4168.9	15593.8	11575.0	2651.4	74.23
89.1	180.0	4128.0	16037.3	11811.6	2732.4	73.65
89.1	185.0	4089.1	16480.6	12047.0	2813.3	73.10
89.1	190.0	4052.2	16923.9	12281.8	2894.3	72.57
89.1	195.0	4017.2	17367.0	12516.3	2975.3	72.07
89.1	200.0	3984.1	17810.0	12751.2	3056.3	71.60


HP875_40B6P42_90V03_16092014
6000
5600
5200
4800
4400
4000
3600
3200
2800
2400
2000
Drehzahl[1/min]
100
90
80
70
60
50
40
30
20
10
0
Drehmoment[Nm]
Wirkungsgrad[%]
40
70
100
130
160
190
Strom[A]
Drehzahl
Wirkungsgrad
Drehmoment

8.3 INVERTER SCHEMATIC



8.4 IXFX170N20T DATASHEET

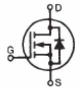
IXYS Advance Technical Information

GigaMOS™ Power MOSFET

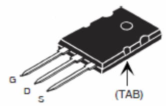
IXFK170N20T
IXFX170N20T

V_{DSS} = 200V
I_{D25} = 170A
$R_{DS(on)}$ ≤ 11mΩ
t_{rr} ≤ 200ns

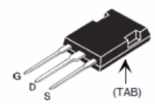
N-Channel Enhancement Mode
Avalanche Rated
Fast Intrinsic Diode



TO-264 (IXFK)



PLUS247 (IXFX)



G = Gate   D = Drain
S = Source   TAB = Drain

Symbol	Test Conditions	Maximum Ratings	
V_{DSS}	T_J = 25°C to 175°C	200	V
V_{DGR}	T_J = 25°C to 175°C, R_{GS} = 1MΩ	200	V
V_{GSS}	Continuous	± 20	V
V_{GSM}	Transient	± 30	V
I_{D25}	T_C = 25°C	170	A
$I_{L(RMS)}$	External Lead Current Limit	160	A
I_{DM}	T_C = 25°C, Pulse Width Limited by T_{JM}	470	A
I_A	T_C = 25°C	40	A
E_{AS}	T_C = 25°C	3	J
P_D	T_C = 25°C	1150	W
dV/dt	$I_S \le I_{DM}$, $V_{DD} \le V_{DSS}$, $T_J \le 175°C$	20	V/ns
T_J		-55 ... +175	°C
T_{JM}		175	°C
T_{stg}		-55 ... +175	°C
T_L	1.6mm (0.062 in.) from Case for 10s	300	°C
T_{SOLD}	Plastic Body for 10s	260	°C
M_d	Mounting Torque (TO-264)	1.13/10	Nm/lb.in.
F_C	Mounting Force (PLUS247)	20..120 /4.5..27	N/lb.
Weight	TO-264	10	g
	PLUS247	6	g

Symbol	Test Conditions (T_J = 25°C Unless Otherwise Specified)	Characteristic Values Min.	Typ.	Max.	
BV_{DSS}	V_{GS} = 0V, I_D = 3mA	200			V
$V_{GS(th)}$	$V_{DS} = V_{GS}$, I_D = 4mA	2.5		5.0	V
I_{GSS}	V_{GS} = ± 20V, V_{DS} = 0V			± 200	nA
I_{DSS}	$V_{DS} = V_{DSS}$, V_{GS} = 0V			50	µA
	T_J = 150°C			3	mA
$R_{DS(on)}$	V_{GS} = 10V, I_D = 60A, Note 1			11	mΩ

Features

- International Standard Packages
- High Current Handling Capability
- Fast Intrinsic Diode
- Avalanche Rated
- Low $R_{DS(on)}$

Advantages

- Easy to Mount
- Space Savings
- High Power Density

Applications

- Synchronous Recification
- DC-DC Converters
- Battery Chargers
- Switched-Mode and Resonant-Mode Power Supplies
- DC Choppers
- AC Motor Drives
- Uninterruptible Power Supplies
- High Speed Power Switching Applications

Symbol	Test Conditions (T_J = 25°C Unless Otherwise Specified)	Characteristic Values Min.	Typ.	Max.	
g_{fs}	V_{DS} = 10V, I_D = 60A, Note 1	85	140		S
C_{iss}	V_{GS} = 0V, V_{DS} = 25V, f = 1MHz		19.6		nF
C_{oss}			1870		pF
C_{rss}			135		pF
$t_{d(on)}$	**Resistive Switching Times** V_{GS} = 10V, $V_{DS} = 0.5 \bullet V_{DSS}$, $I_D = 0.5 \bullet I_{D25}$, R_G = 1Ω (External)		33		ns
t_r			28		ns
$t_{d(off)}$			80		ns
t_f			22		ns
$Q_{g(on)}$	V_{GS} = 10V, $V_{DS} = 0.5 \bullet V_{DSS}$, $I_D = 0.5 \bullet I_{D25}$		265		nC
Q_{gs}			86		nC
Q_{gd}			67		nC
R_{thJC}				0.13	°C/W
R_{thCS}			0.15		°C/W

Source-Drain Diode

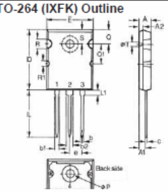
Symbol	Test Conditions (T_J = 25°C, Unless Otherwise Specified)	Characteristic Values Min.	Typ.	Max.	
I_S	V_{GS} = 0V			170	A
I_{SM}	Repetitive, Pulse Width Limited by T_{JM}			680	A
V_{SD}	I_F = 60A, V_{GS} = 0V, Note 1			1.3	V
t_{rr}	I_F = 80A, -di/dt = 100A/µs, V_R = 75V, V_{GS} = 0V			200	ns
Q_{RM}			0.59		µC
I_{RM}			9.80		A

Note 1: Pulse Test, t ≤ 300µs; Duty Cycle, d ≤ 2%.

ADVANCE TECHNICAL INFORMATION

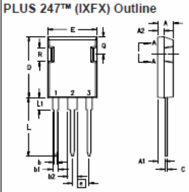
The product presented herein is under development. The Technical Specifications offered are derived from a subjective evaluation of the design, based upon prior knowledge and experience, and constitute a "considered reflection" of the anticipated result. IXYS reserves the right to change limits, test conditions, and dimensions without notice.

TO-264 (IXFK) Outline



Dim.	Millimeter Min.	Max.	Inches Min.	Max.
A	4.82	5.13	.190	.202
A1	2.54	2.89	.100	.114
A2	2.00	2.10	.079	.083
b	1.12	1.42	.044	.056
b1	2.39	2.69	.094	.106
b2	2.90	3.09	.114	.122
c	0.53	0.83	.021	.033
D	25.91	26.16	1.020	1.030
E	19.81	19.96	.780	.786
e	5.46 BSC		.215 BSC	
J	0.00	0.25	.000	.010
K	0.00	0.25	.000	.010
L	20.32	20.83	.800	.820
L1	2.29	2.59	.090	.102
P	3.17	3.66	.125	.144
Q	6.07	6.27	.239	.247
Q1	8.38	8.69	.330	.342
R	3.81	4.32	.150	.170
R1	1.78	2.29	.070	.090
S	6.04	6.30	.238	.248
T	1.57	1.83	.062	.072

PLUS 247™ (IXFX) Outline



Terminals: 1 - Gate
2 - Drain (Collector)
3 - Source (Emitter)
4 - Drain (Collector)

Dim.	Millimeter Min.	Max.	Inches Min.	Max.
A	4.83	5.21	.190	.205
A_1	2.29	2.54	.090	.100
A_2	1.91	2.16	.075	.085
b	1.14	1.40	.045	.055
b_1	1.91	2.13	.075	.084
b_2	2.92	3.12	.115	.123
C	0.61	0.80	.024	.031
D	20.80	21.34	.819	.840
E	15.75	16.13	.620	.635
e	5.45 BSC		.215 BSC	
L	19.81	20.32	.780	.800
L1	3.81	4.32	.150	.170
Q	5.59	6.20	.220	0.244
R	4.32	4.83	.170	.190