HIGH-QUALITY LOW-LOSS LOW-COST DC MOTOR CONTROLLER

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Degree in Electromechanical Engineering

Specialty: Electrical

Escuela Técnica Superior de Ingeniería (ICAI)

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Fdo.: José P. Fecha: 07/05/2015

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HIGH-QUALITY LOW-LOSS LOW-COST DC MOTOR CONTROLLER

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SUMMARY OF THE PROJECT

Introduction

There are multiple products in the market that allow the user to control electric motors, but there is a problem when you try to find the adequate for everyday person appliances like shopping carts, golf carts or small electric vehicles, the controllers you can find in the market can be more expensive than what you need, they can be cheap, but with very poor efficiency and it can be very difficult to find one with good reliability and performance for a good price. Taking this into account the aim of the project was to design a very efficient dc motor controller, with the lowest cost possible.

The idea of the controller was to keep it as simple as possible, therefore with the lowest losses as it could be, cheap but with high quality components and reliable while functioning.

Objectives

The main objective of the project is to keep the controller working very efficiently, at least 90% in continuous use.
This is not the only objective in mind for the project, the controller wants to be kept reliable and comfortable for the user, very intuitive and secure.

The user wants to feel safe and comfortable while using the device, so that is why the controller includes some safety features to make it reliable and comfortable, the user wants to feel in control of the system all the time and that is why the controller will have a microcontroller implemented in the system, to have a real-time control of it.

Since the controller is to be used with electric motors for appliances that require some power the current that it is going to have to manage is important. To put some numbers to this, the continuous power consumption of these appliances is estimated not to be bigger than 120W, with a 12V battery delivering the power to the system, the current through the controller is to be 10A at the most for a continuous use.

The controller has to be able to handle this current rating with at least a 90% efficiency, this efficiency is achieved by keeping things simple and choosing well the components.

To sum everything up, the system has to be able to:

- 90% efficiency at 10A.
- Real-time control of the device.
- Reliable and safe for the user.

<u>Design</u>

Since the controller wants to be kept simple, for the interest of efficiency, the type of dc-dc converter that is chosen for the design is a simple buck converter, this converter is going to be supplied power with a 12V battery pack and the only other components that it needs are an inductor, a capacitor, a mosfet and a diode. The components are chosen carefully because they have to be able to handle 10A continuously with low voltage drops so that the power loss is as small as possible.

The 10A rating is not the only current rating that the components have to handle, this 10A are for continuous use, but what if the motor needed a sudden and fast acceleration in a determined moment of time? In that case the controller would need to deliver more current to the motor and therefore the current could raise to more than 10A.
This is why the controllers´ components are bought to handle up to 20A for 1 minute and 30A for 5 seconds. If the current goes above those values for more than those times, the

controller will shut down and it will stop delivering power. This time limits will be set by an Arduino microcontroller that will receive the current data of the buck converter in real-time to decide whether to stop or not from delivering energy.

The Arduino will receive data from a current sensing resistor that will be included in the buck converter, making the final schematic design for the converter the one in the figure below:

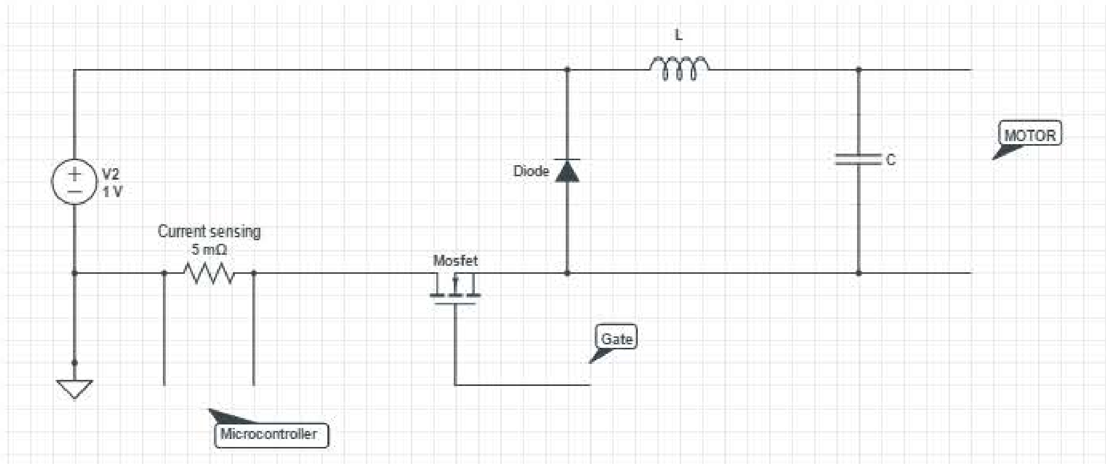

Figure 1

The circuit shown in figure 1 is the final design chosen for our converter, as it can be seen it keeps things simple and therefore it has low power losses.

The whole system that is going to be designed is graphically explained in figure 2, which distinguishes between power lines and signal connections:

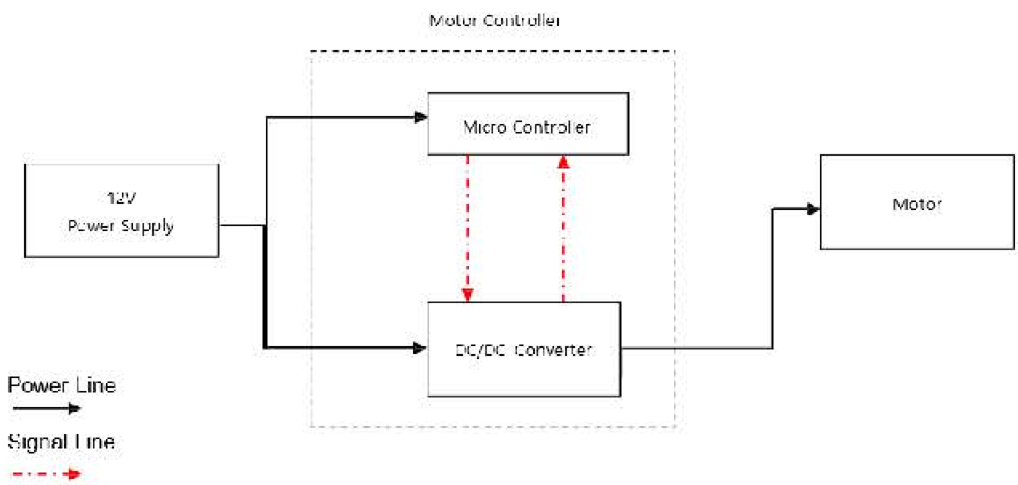

Figure 2

The power line is where the power is going to flow through and the signal line is the receiving and sending of the current information and the time limits from the microcontroller to the converter.

Now that all the system has been explained lets see the ratings for the components of the converter:

- Diode: 12V voltage blocking, 10A forward current.
- Mosfet: 12V voltage blocking, 10A forward current.
- Inductor: 10A current rating.
- Capacitor: At least 12V rating.
- Current sensing resistor: 0.005 Ω.

Conclusions

The prototyping of the design worked satisfactory so the design can be considered a success, but despite the prototype worked correctly, there are some things that can be widely improved and that have to be considered for future work. Something to improve is the Arduino code which has to be made smoother and more accurate when reading the current values and sending the information to the mosfet gate.

And the most important thing to consider for future work is to create a small package to make the controller mobile and safe, so the user has no problem when recharging it or changing it from place to place.

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[1] *Battery Application and Specification*, YUASA, Laureldale, PA, 2014
[2] *IPB05N03LB Data Sheet,* Infineon, München, Germany, 2006
[3] *DSS 40-0008D Data Sheet*, IXYS, Milpits, CA, 2004
[4] *Arduino source code for smoothing*, [Online], Available:
http://arduino.cc/en/Tutorial/Smoothing?action=sourceblock&num=1
[5] *Arduino source code for temperature limit*, [Onine], Available:
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[6] *ACS710 Family Datasheet*, Allegro MicroSystems LLC, Worcester, MA, 2013
[7] Philip T.Krein, "*Elements of Power Electronics*" ECE 464 Power Electronics, Fall 2014.

HIGH-QUALITY LOW-LOSS LOW-COST DC MOTOR CONTROLLER

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RESUMEN DEL PROYECTO

Introducción

Hay múltiples productos en el mercado que te permiten manejar un motor eléctrico sean cuales sean sus dimensiones o potencia, pero suele haber problemas al intentar encontrar el adecuado para el uso que uno le quiere dar al motor o la potencia que éste tendrá, algunos usos para el día a día pueden ser carritos de la compra, pequeños vehículos eléctricos para niños o incluso un carrito de golf. Los controladores que uno encuentra en el mercado pueden ser demasiado caros para lo que uno los necesita, o demasiado poco precisos y fiables, es aquí donde se encuentra el desarrollo del proyecto, en crear un controlador barato, fiable y de gran eficiencia con el menor coste posible y asumible para todos.

La forma de conseguir la mayor eficiencia posible con el menor coste es haciendo las cosas lo más simple que se pueda, sin dejar de lado la calidad y la fiabilidad.

Objetivos

El principal objetivo del proyecto es el de conseguir que el controlador alcance un 90% de eficiencia por lo menos durante el uso continuado.

Pero el controlador también se quiere mantener seguro y cómodo de usar para el usuario ya que si no se encuentra cómodo con el controlador el resto es de poca importancia, por

ello se hará intuitivo y de manejo fácil.
Para que el usuario se sienta con el control total del dispositivo, dentro del controlador se implementaran algunas medidas de seguridad que harán que el usuario se sienta seguro, éstas medidas de seguridad se impondrán a través del microcontrolador que el dispositivo llevara implementado y que facilitaran el control a tiempo real.

Para los usos que se han descrito anteriormente, no se requiere una gran potencia y por ello el controlador se diseñara para manejar hasta 120W de potencia de forma continuada, se utiliza una batería de 12V que de energía al sistema, lo que significa que el controlador debería ser capaz de manejar hasta 10A de corriente sin ningún tipo de problema y durante todo el tiempo de utilización del sistema de control.

El controlador tiene que ser capaz de manejar estos 10A sin caer por debajo del 90% de eficiencia, ya que este se considera el principal objetivo del proyecto, lo cual se conseguirá manteniendo las cosas sencillas y eligiendo bien todo lo que se hace y los componentes.

Para resumir, el sistema tiene que:

- Manejar 10A con un 90% de eficiencia.
- Control en tiempo real del motor.
- Uso cómodo, fiable y seguro para el usuario.

<u>Diseño</u>

Ya que el controlador se quiere mantener lo más eficiente posible, un mínimo del 90%, el tipo de convertidor que se utilizará para controlar el motor será uno tipo buck, que es sencillo y es ampliamente utilizado para usos de gran eficiencia. Éste convertidor estará alimentado por una batería de 12V y los únicos componentes que necesita son un diodo, un mosfet, una capacidad y una inductancia, estos componentes tiene que ser capaces de manejar 10A de corriente sin ningún tipo de contratiempo y además tiene que tener las caídas de tensión lo más pequeñas posibles para minimizar la perdida de potencia.

Hay un hecho que se tiene en cuenta durante el diseño del controlador, ¿y si el motor necesita una rápida y breve inyección de potencia extra para subir una cuesta por ejemplo?

En tal caso el controlador debería ser capaz de entregar al motor más de 10A de corriente durante un tiempo delimitado para permitir al motor superar ese obstáculo sin problemas, de este modo el controlador y sus componentes se eligen de tal forma que puedan soportar hasta 20 A durante 1 minuto y hasta 30A en un máximo de 5 segundos. Este límite de tiempo será impuesto por el microcontrolador, en este caso un Arduino, que recibirá la señal de cuánta corriente hay en el circuito y enviara ondas pwm dependiendo de si el controlador debe seguir funcionando o debe pararse.

El Arduino recibirá la lectura de corriente desde una resistencia de precisión, haciendo que el esquema final del diseño sea el que se muestra en la figura 1:

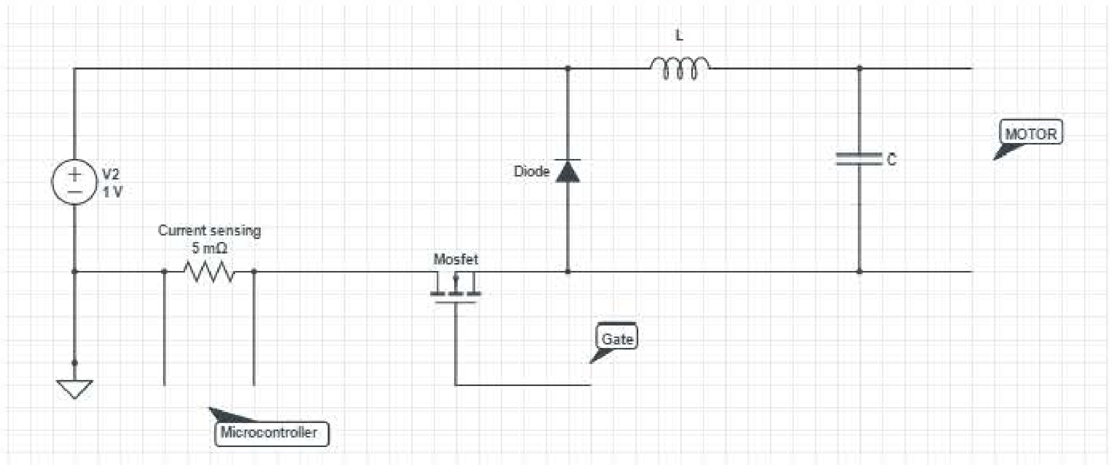

Figura 1

Como se puede ver el diseño es sencillo y tiene pocos componentes que atenúen la potencia y provoquen excesivas pérdidas.

El Sistema completo se detalla en un diagrama de bloques en la figura 2, que se puede encontrar justo a continuación de estas líneas:

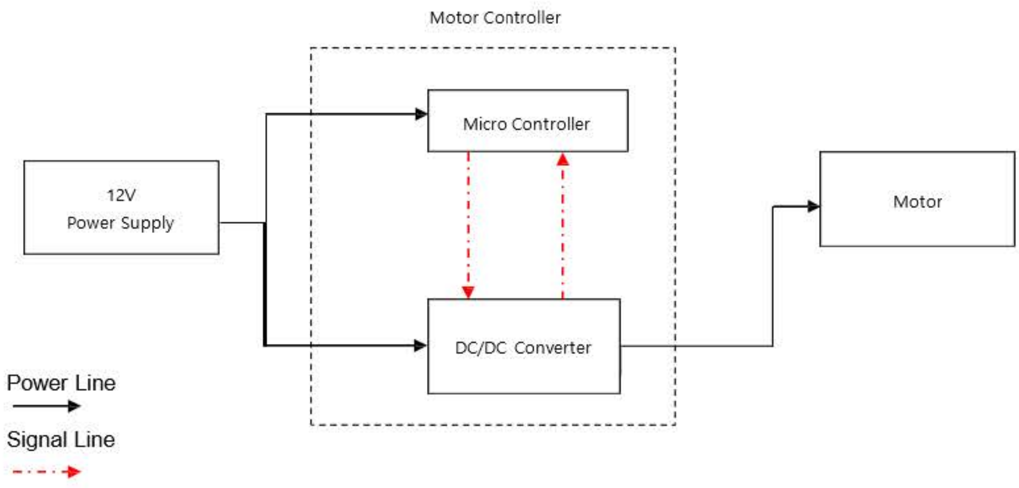

Figura 2

La linea de potencia (la negra) es por la que circulara la corriente y la linea de señal (roja discontinua) es la que representa la comunicación entre el convertidor y el microcontrolador.

Para terminar de describir el diseño los alcances de los componentes del convertidor serán:

- Diodo: 12V voltaje de bloqueo, 10A corriente a conducir.
- Mosfet: 12V voltaje de bloqueo, 10A corriente a conducir.
- Inductancia: 10A de corriente.
- Capacidad: Al menos 12V.
- Resistencia de precision: 0.005 Ω.

Conclusiones

La fase de prototipo fue un éxito ya que se consiguió la eficiencia deseada y los componentes aguantaron las pruebas sin mayores complicaciones, pero aun así se pueden mejorar muchas cosas, todas ellas relacionadas con la experiencia del consumidor. El código de Arduino debe mejorarse para que sea más preciso e instantáneo durante la lectura de los valores de corriente desde la resistencia de precisión.

Y lo más importante que quedaría por mejorar de cara al consumidor y usuario sería la de crear un envoltorio para todo el sistema que permitiese que fuese fácilmente desplazable y recargable.

Referencias

[1] *Battery Application and Specification*, YUASA, Laureldale, PA, 2014

[2] *IPB05N03LB Data Sheet*, Infineon, München, Germany, 2006

[3] *DSS 40-0008D Data Sheet*, IXYS, Milpits, CA, 2004

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[7] Philip T.Krein, "*Elements of Power Electronics*" ECE 464 Power Electronics, Fall 2014.

High-quality low-loss low cost dc motor controller

Author: José Pedro Garcerán Sánchez

Director: Paul Scott Carney

Final design report

Abstract

There are multiple products in the market that allow the user to control electric motors, but there is a problem when you try to find the adequate for everyday person appliances like shopping carts, golf carts or small electric vehicles, the controllers you can find in the market can be more expensive than what you need, they can be cheap, but with very poor efficiency and it can be very difficult to find one with good reliability and performance for a good price. Taking this into account the aim of the project was to design a very efficient dc motor controller, with the lowest cost possible.

The idea of the controller was to keep it as simple as possible, therefore with the lowest losses as it could be, cheap but with high quality components and reliable while functioning.

Contenido

1. Introduction

1.1 Purpose

The main purpose of this project is to design and prototype a high efficiency control system for dc motors with a low cost. This motor control system can be applied to various items, such as to shopping carts, to golf carts, or to small electric vehicles. In order to apply this controller to end-user item, the safety is also a key factor for this project. This project shows a motor controller with some safety features in order to help the user feel comfortable and safe.

1.2 Objectives

The main objective of the project is to keep the controller working very efficiently, at least 90% in continuous use.

This is not the only objective in mind for the project, the controller wants to be kept reliable and comfortable for the user, very intuitive and secure.

The user wants to feel safe and comfortable while using the device, so that is why the controller includes some safety features to make it reliable and comfortable, the user wants to feel in control of the system all the time and that is why the controller will have a microcontroller implemented in the system, to have a real-time control of it.

Since the controller is to be used with electric motors for appliances that require some power the current that it is going to have to manage is important. To put some numbers to this, the continuous power consumption of these appliances is estimated not to be bigger than 120W, with a 12V battery delivering the power to the system, the current through the controller is to be 10A at the most for a continuous use.

The controller has to be able to handle this current rating with at least a 90% efficiency, this efficiency is achieved by keeping things simple and choosing well the components.

To sum everything up, the system has to be able to:

- 90% efficiency at 10A.
- Real-time control of the device.

- Reliable and safe for the user.

1.3 Block level change

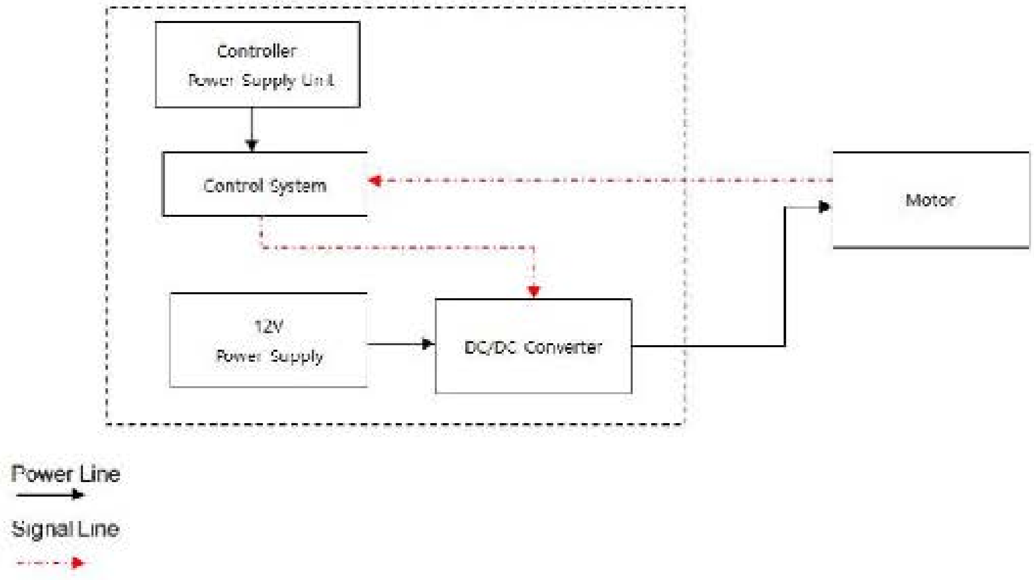


Figure 1

In the initial design, there was Controller Power Supply unit. However, we remove the block, and replace it as voltage regulator and merge the voltage regulator into the Control System block. Additionally, the block name for "control system" is changed into "micro-controller". The final system block diagram is shown in figure 2.

1.4 Block diagram

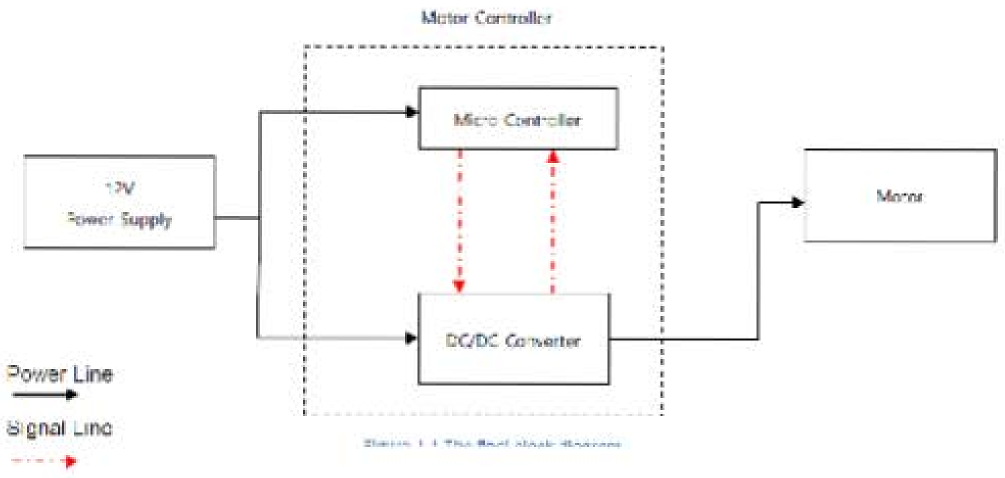


Figure 2: Final block diagram

1.5 Brief block description

Power supply

The initial intention was to use a 12V battery to deliver the power to the whole system, but for the sake of prototyping faster and safer the power supply that was finally used is the SORENSEN 2050, located in the senior design laboratory.

DC/DC converter

This unit takes the 12V delivered from the power supply and according to the load that is present in the motor and the duty cycle that the user sets through the control system (microcontroller) delivers a certain voltage and current. The type of converter used is a simple buck converter, keeps things simple since as it has little components and therefore has the lowest losses possible.

For better functioning and safety the controller should not exceed 11V in the output, which is limited by the microcontroller.

This converter has to be able to support 10A continuously, 20A for 60 seconds and 30A for 5 seconds at the most.

Micro-controller

The control system is responsible for basically controls the current. The controller we choose is the Arduino Uno. It has 16-MHz processor and can hold up to 6 different input signals and 6 output signals.

The advantage of choosing the Arduino Uno as a control system is that it is programmable with user-friendly language such as C++ interface. It takes 5V voltage input from 12V power with the voltage regulator. This unit has 2 logical inputs: one from the current input and the other one from the current sensor. The output signal of this component goes to the DC/DC converter.

The voltage source for this unit is separated 5V battery. In addition, one of main job for the controller is to allow the motor accelerates smoothly by implementing function. Consequently, the controller is the main unit for the safety feature and limitation for acceleration.

Motor

Should be able to support the same current ratings as the converter. 10A continuously, 20A for 60 seconds and 30A for no more than 5 seconds.

1.6 Possible applications

- Shopping carts.
- Golf carts.
- Small electric vehicles.

2 Design

2.1 Design procedure

12V power supply

The 12V power supply distribute the voltage into two units: one to the DC/DC converter, the other one to the control system through the voltage regulator. We firstly thought the battery is required part in this project, we can use the power supply in the ECE lab as an alternative.

We prefer to use a battery for the final product, since the application for this motor controller is for the mobile, such as an electric wheelchair and an electric shopping cart. The basic power flow from this unit is shown in figure 3.

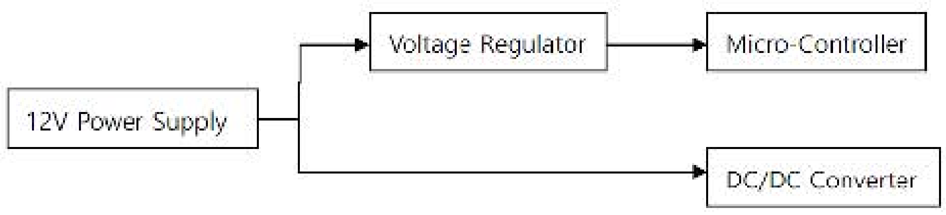


Figure 3: Basic power flow.

DC/DC converter

The DC/DC converter unit has buck converter and current sensor. The sensor reads the current from the buck converter, and sends the value to the control unit in order to make appropriate decision depends on the situation.

For example, if the current goes over 30A, the control unit stops whole unit operation, or if the value of the current goes over 10A for more than 60 seconds, the control sends the signal to the converter to stop. As it is mentioned in the objectives, one of these is to achieve a 90% efficiency for a 10A current, this means that if settled a theoretical output of 10V, the real value we should have read must have not been less than 9 V.

In order to keep this losses as small as possible and to adjust the cost, the type of converter chose is the buck converter which will be explained in more detail further in the report.

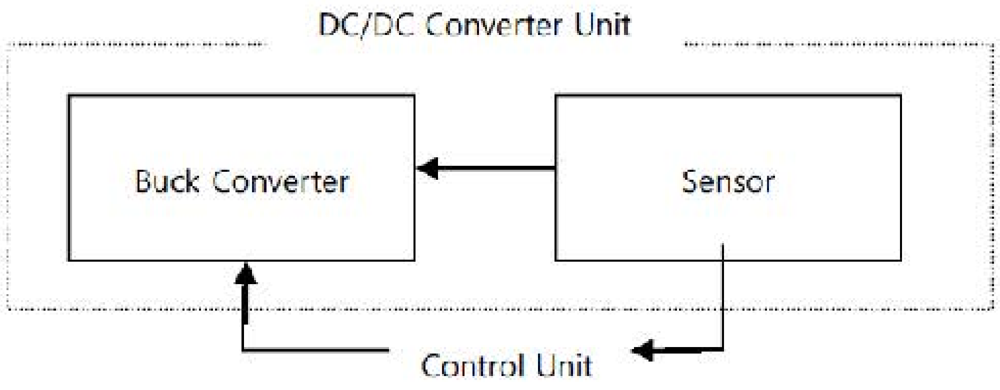


Figure 4: Interaction between converter and micro.

Micro-controller

Basically, as it is shown in the figure 4, the micro controller takes input from current sensor and transmits output signal to the gate in DC/DC converter. The Arduino Uno R3 is used for this unit. There are many alternatives for the micro controller, but the Arduino is the most user friendly and easier to program and easier to conduct the experiment compare to other programmable micro-controllers.

2.2 Design details

Power supply

At first, the idea was to put a battery that could be able to deliver 12V ±1V and up to 2 hours of power when continuous usage (10A), this means:

$$12V * 10A * 2\ hours = 240Wh$$

This calculation should be considered for future applications, instead of prototyping, this means, when the product is finally prepared to get to the market, since prototyping with a battery can be less safe.

DC/DC converter

As it has been explained in some other points before on this report, the converter type used is a simple buck converter (figure 5), which has very few components and because of the little components that it needs, it helped us achieve the efficiency we desired.

As it can be seen in the figure, the components are: MOSFET, diode, inductor, capacitor and a current sensing resistor.

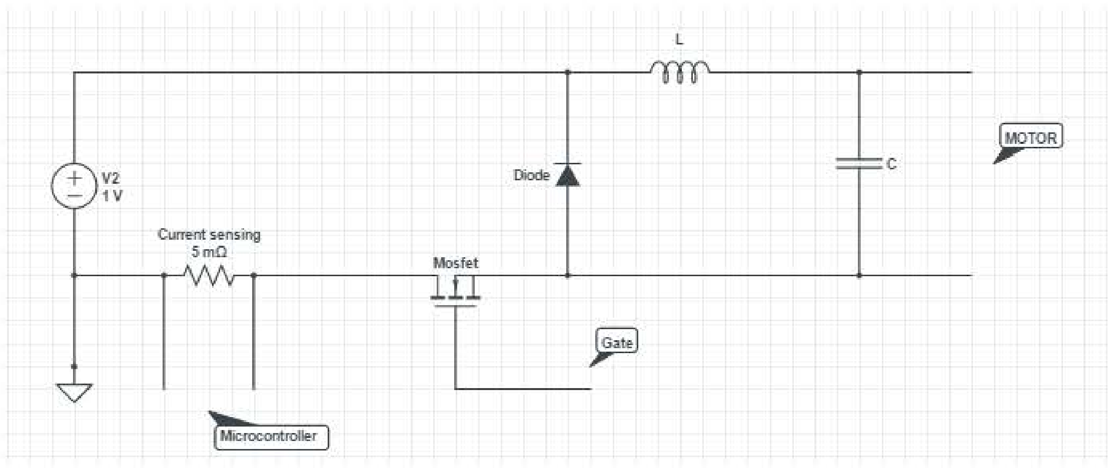


Figure 5: Final schematic of buck converter

Mosfet

The mosfet is the component in charge of controlling the output of the converter. This is possible because the mosfet gate is going to be a PWM, and the duty cycle of this wave is going to be controlled by the user.

When the duty cycle is 50% the output of the converter should be 6V, without considering losses, and 5.4V, considering the maximum losses acceptable for the efficiency we reach.

We know this relationship because of the equation that characterizes buck converters and that we took from the book "Elements of power electronics, second edition, Philip T. Krein"=>

$$V_{out} = D_{transistor} * V_{in} \ (eq1)$$

When designing buck converters you need to have an acceptable ripple you want to see in the output, the normal ripple in this type of applications is around a 5% of the output voltage.

We can calculate the inductor we will need to reach at least this ripple from the equation taken out of “Elements of power electronics, second edition, Philip T. krein” that says=>

$$V_{inductor} = L * \frac{\Delta I_{inductor}}{\Delta t_{transistor}} \ (eq2)$$

Example of inductance for a 10v output of the converter with an acceptable current ripple of 5%.

Analyzing when D1 is on and for a f_{switch}= 20 kHz.

$$V_{\mathrm{L}} = L * \frac{dI_L}{dt} => Linearising => V_{in} - V_{out} = L * \frac{\Delta I_L}{\Delta t} \ (eq3)$$

$$for\ V_{in} = 12V, V_{out} = 10V, \Delta I_L = 0.75A, \Delta t = D_1 * T_{switch}$$

$$Being\ D_1 = 0.833 = \frac{V_{out}}{V_{in}} and\ T_{switch} = \frac{1}{f_{switch}} = \frac{1}{20 * 10^3}$$

$$L = 0.111\ mH$$

Initially our design instead of including both the capacitor and the inductor it just included the inductor, this means that all the ripple filtering was made with the inductor, which in order to reach a 5% ripple had to be of 0.110 mH (calculation shown on eq3 and below it) but the inductor we ordered initially for some reason didn’t work well, this may seem strange but it was maybe because of it’s strange way of assembling with two wires for the same core, not being a coupled inductor, what could have made this inductor behave strangely. This made us seek for another inductor in the shortest time possible, so we had decided to make it smaller. This can be achieved in buck converters by just adding a capacitor in parallel to the output.

Since we had to change the design in so little time, we didn’t have time to adjust and chose whatever values we wanted, so we managed to get a 100mF capacitor and a 8.2uH inductor. This makes our 5% ripple impossible to achieve since the capacitor is not big enough to smooth the ripple to 5%, this can be seen in the scope pictures that you will find below this lines.

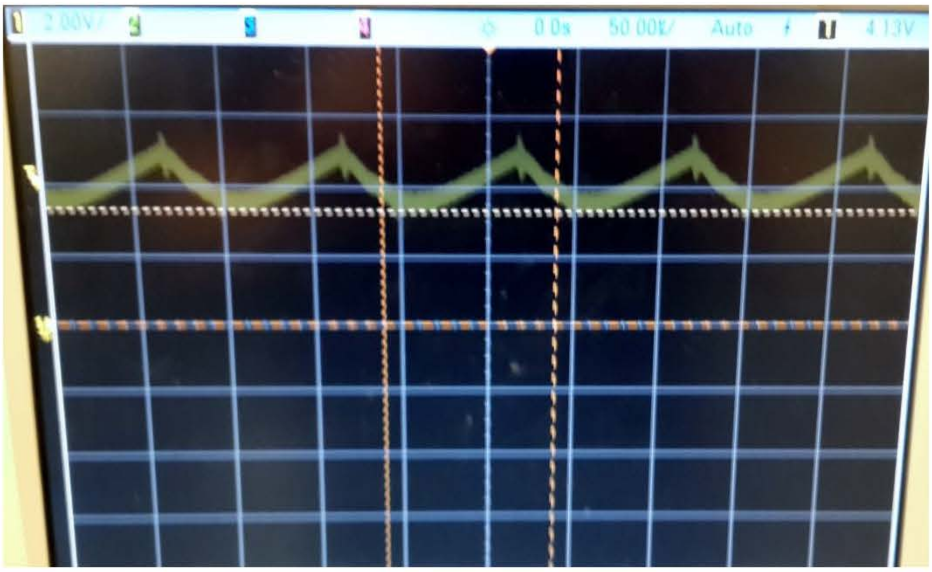


Figure 6

Scope capture for 70% duty cycle and 6 V input.

As we can see the relationship from equation 1 is maintained in the converter=>

$$V_{out} = D_{transistor} * V_{in}\ (eq1) => 6.1V * 0.7 = 4.27V$$

$$Ripple\ in\ the\ output\ voltage\ is\ more\ or\ less\ 2V\ which\ is\ much\ higher\ than\ the\ 5\%\ that\ we\ wanted.$$

$$Eff = 1 - \frac{ideal\ value - real\ value}{ideal\ value} = 1 - \frac{4.27 - 4.13}{4.27} = 96.6\%$$

$$\frac{2V}{4.27V} * 100 = 46.8\%$$

10 times bigger than what we wanted, for future work, the calculation is simple, if you maintain the capacitor value, you will only need to buy an inductor 10 times bigger, since the relationship between ripple and inductance is linear as we can observe in equation 1.

The efficiency objective is achieved even though the test in the picture was done with 6V, the percentage values change of course when changing the input from 6V to 12V, but the quantity of the losses are maintained pretty much constant, so the percentage does not have big variations.

Micro-controller

The micro controller, Arduino, gets signals from the sensor in the DC/DC converter, then it process the dedicated function, such as acceleration, sensing the overload, and stop. The processed signal goes directly into the gate pin, which is indicated as "Gate of the MOSFET" in the figure 7. It stimulates the gate according to the result of process. The micro controller takes input from the potentiometer, then transmit the reading value from the potentiometer to the gate.

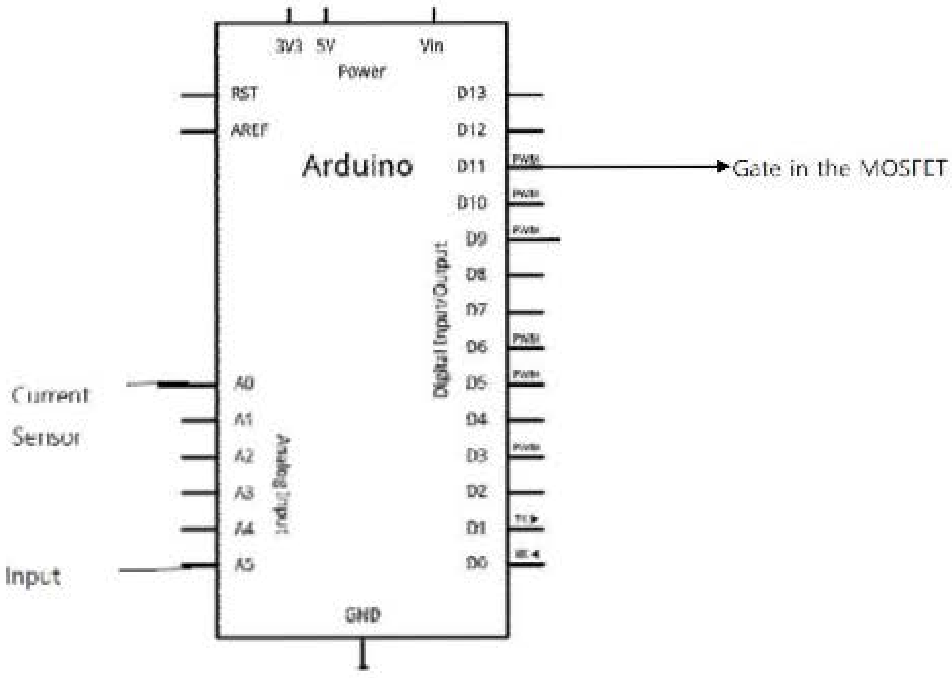


Figure 7: Arduino diagram.

The micro controller initializes upon the power-on status, at first, then it allows the current to increase or decrease as the input from the variable resistor. If the variable resistor increases the current allowed too fast, the micro controller reduces the increased amount of current that goes to the converter. Furthermore, the controller will shut down the converter when the current goes over 30 A. Additionally, if the current goes through the converter is at 30 A, it starts to count for 50 seconds. The program flow chart is shown in figure 8. The basic principle for using micro controller is that it can control the output to the motor by modifying the duty cycle.

The duty cycle generated by the microcontroller is transferred to the gate of a MOSFET in DC/DC converter. Since the minimum operational gate voltage for MOSFET is more or less 3V and the PWM output voltage in the micro controller is 5V, there is no need to implant devices that amplifies the voltage from the PWM controller to the gate. Therefore, the output connection from the Arduino will be directly connected to the gate.

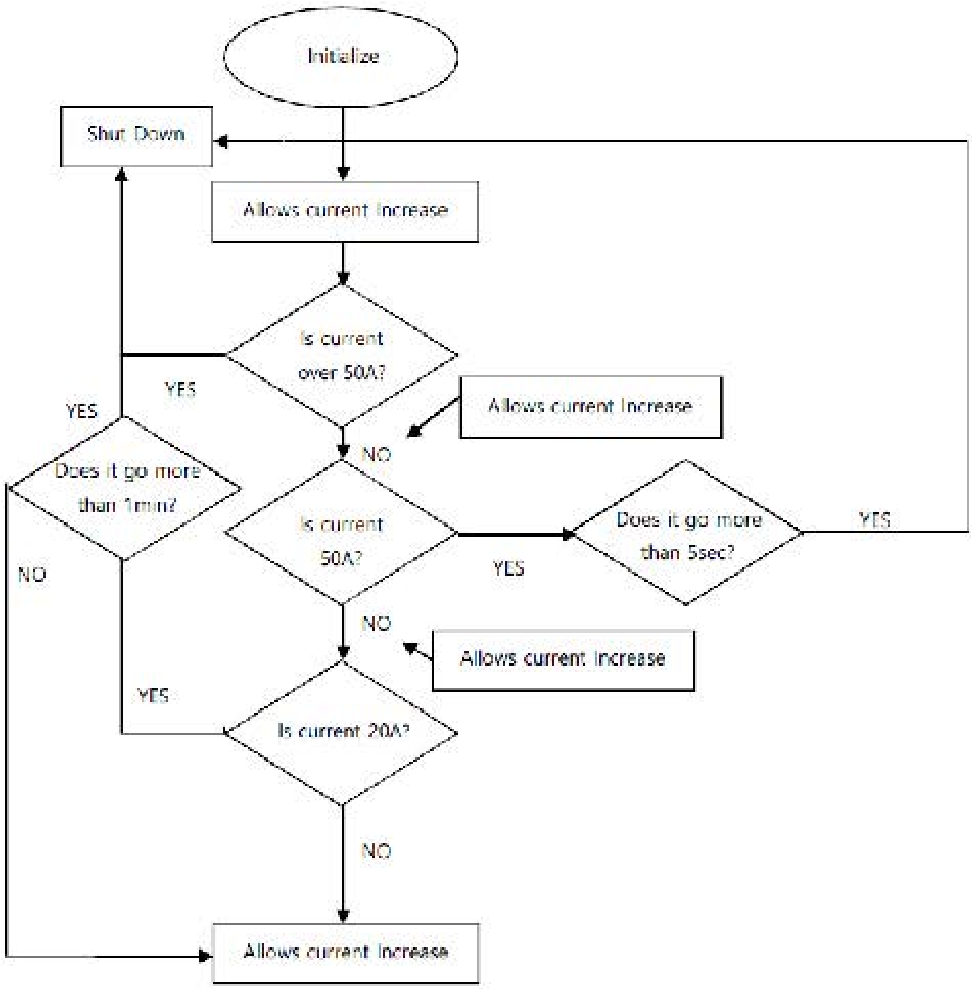


Figure 8

To setup the flowchart, the strictest condition should be placed first, then the strictness of condition should be gradually lower than the previous one in order to flow well in the program code. The flowchart in the figure 8 describes the basic condition for 30A and

20A. The condition for shutdown-after-time between 30A and 20A is gradually decreases as the current value is increasing.

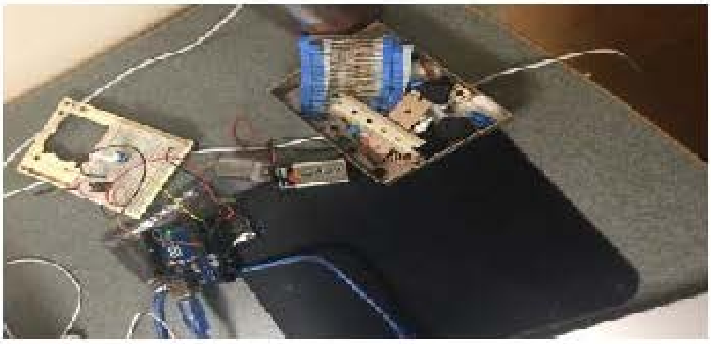


Figure 9: Smaller versión of design.

Because conducting experiment with 30 A current has more danger to damage the micro controller, the behaviour experiment of micro-controller is conducted with smaller version of converter than actual. The testing environment is shown in figure 9. With the smaller scale version, it is easier to detect possible backflow of current without damaging the micro-controller. After testing the smaller scale experiment, the actual experiment is conducted. Since the resistor we are using in this project has 0.005 Ω, with 10A of current the reading from the microcontroller 0.05V. The Arduino has the voltage resolution of 5mV, so it is enough to indicate and detect current of 10A or more. In addition, there is no need for taking any action based on current reading below 10A.

Since, the temperature of component, especially for the MOSFET, can increase dramatically, but temperature drop occurs very slowly. The case when 30A of current flows for 4 second and drop to 10A for 1 second then reaches 30A repeatedly, there is tremendous amount of stress on the component in terms of temperature. In such case, the micro-controller has to prevent components from being burdened too much stress. However, the Arduino programming environment does not support the real-time timer acting as a stopwatch, we need to modify how the program works. We used loop counter instead of using real-time counter. The program sequence is operated at 2.80 milliseconds, when the controller detects the overloading condition, every 2.80 millisecond, the program increases the loop counter by 1. If the current reading is not high enough for the overloading condition, in every 2.8 millisecond, the program subtracts the loop counter by 1 until the loop counter reaches to 0. Therefore, the microcontroller can react with overloading condition more actively.

Finally, at the shut-down status, the user must reset the microcontroller manually by push reset button, or wait for 50minutes. In addition, the indication LED is lighten up when it enters to the shut-down status.

The smooth acceleration is also applied in the program. The reference code for the smooth acceleration is in the appendix A, and the reference code has been modified for this project.

The smooth acceleration takes 20 input values as samples to make average, and process the sample 30milliseconds later when the smoothed output is reaches the 30% of maximum.

The graph in the figure 10 shows that the relationship between input and output.

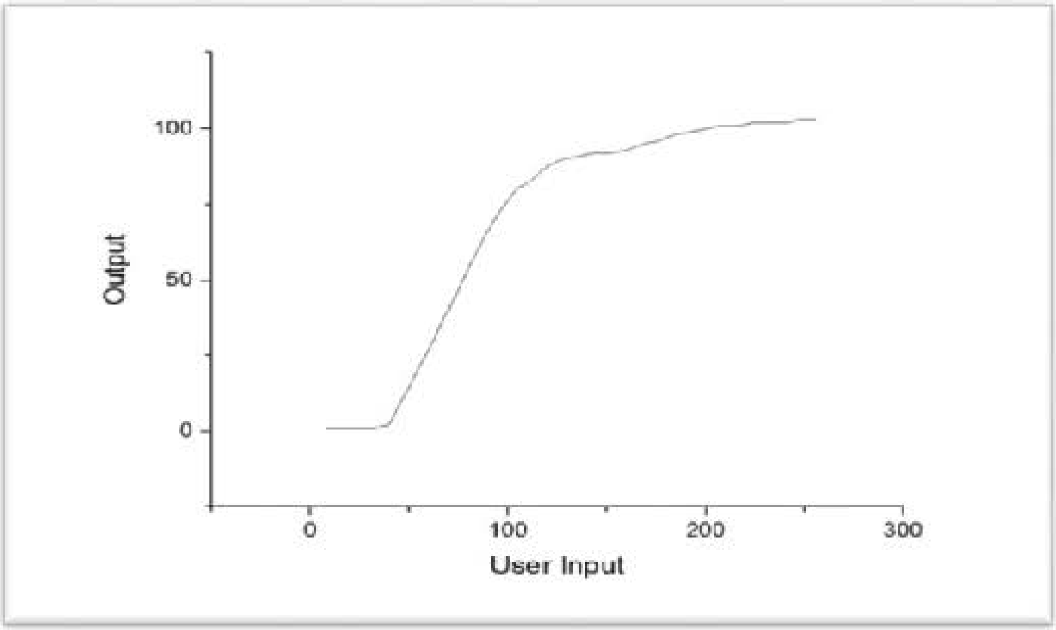


Figure 10

The graph is indicating that user input increases by 1 in every one program sequence, 2.8 milliseconds. The smooth acceleration only affects the acceleration not the deceleration. The deceleration occurs immediately as user turn the potentiometer down. Note that the maximum value for both input and output is the 255 in the Figure 10.

3 Requirements and verification

Requirements	Verification	Verified
DC/DC converter	DC/DC converter	
1. The converter has efficiency of 90% with 150W power	1. Set 10A for the power supply. Then connect with the converter and connect a resistor instead of a motor for the output. Measure both voltage and current. Check product of voltage and current is more than 135W(90% of 150W)	Checked
2. Can handle 250W power for 60 seconds without any damage in components	2. Set 20A for the power supply. Then, connect converter with resistor (same as above setting). Should work only for 60 seconds.	Checked
3. Can handle 30A for 5seconds without any component damage	3. Set power supply with 12V and 30A. Connect with this unit and replace a motor with a resistor. Should work only for 5 seconds.	Checked
Control System	Control System	
1. Shut down when the converter is overloaded	1. Run with the voltage of 0.3V(equivalent to 30Amps of current) for 5seconds And 0.2V (equivalent to 21A) for 60 seconds as an input for current sensing, and check the output for microcontroller(output to the gate of DC/DC converter) becomes 0 with the oscilloscope.	Checked
2. The current signal from control implement smooth acceleration	2. Rotate potentiometer quickly to increase the duty cycle, and check the oscilloscope that actual duty cycle changes slower than the potentiometer gives.	Checked
3. The controller gives immediate deceleration(not like acceleration)	3. Rotate the potentiometer to decrease duty cycle, , check if the output for arduino becomes 0 with the oscilloscope. It does not give the	Checked

4 Cost

4.1 Labor

Name	Hourly Rate	Total Hours Worked	Total = Hourly rate x Total Hours Worked
Jose Pedro Garceran Sanchez	$30.00	150	$4,500
Total			$4,500

4.2 Parts

Part	Part Number	Unit Cost	Quantity	Total
Power				
12V Battery	YTX30L-BS	$85.00	1	$85.00
DC/DC converter				
Transistor	IPB05N03LB	$1.00	1	$2.00
Diode	DSS40-0008D	$3.84	1	$3.84
Inductor	SRP1250-1R0MCT	$1.54	1	$1.54
PCB	########	$30.00	1	$30.00
Logic board	########	$10.00	1	$10.00
Motor				
Motor	80ZYT02A	$30.00	1	$30.00
Controller				
Alduino Microcontroller	Alduino Uno R3	$22.50	1	$22.50
Sensor				
Current Sensor	ACS758LC	$7.68	1	$7.68
	0.005 Ω resistor	$1.00	1	$1.00
Other part				
Variable resistor		$1.00	1	$1.00
Total	$194.02			

4.3 Grand total

Labor	$4,500
Parts	$194.02
Grand Total	$4,694.02

5 Conclusions

5.1 Accomplishments

The motor converter prototype works as designed and has no efficiency problems since it chives at least a 90% of efficiency.
The micro controller part can do the three major functions: smooth acceleration, time measurement and shutdown. The microcontroller is able to enter in shut-down status when current reaches over 30A and when the current reaches 20A for one minute. The converter part can deliver more than 90% efficiency at the normal load, 10A of current.

5.2 Uncertainties

Although we had a lot of problems when implementing practically the circuit, we managed to make the converter work although it did not accomplish some of its initial requirements such as the 5% ripple, which has already been explained, and the 50A current because of part limitations, the resistor to measure the current was only able to hold up to 31A of current.

Four of the MOSFETs did not work in initial condition, and we started being suspicious to our knowledge. This project gave us to think about the yield of components in certain package can be very low.

5.3 Ethical considerations

This project does not conflict with the IEEE Code of Ethics. However, the experiment for this project can harm people involved in the experiment, because it uses high current, 30A, and takes the motor into overloaded condition. Thus, the thorough theoretical calculations and analysis should be performed before the actual testing.

5.4 Future work

As it is mentioned earlier, this project can be applied for small power electric motors like golf carts or shopping carts.

More safety feature should be needed to such applications of this project; for example, mechanical brakes for the motor can be applied, stronger insulation of enclosure is needed, and the real-time RPM and temperature indicator can be applied too.

6 Citation

[1] *Battery Application and Specification*, YUASA, Laureldale, PA, 2014

[2] *IPB05N03LB Data Sheet*, Infineon, München, Germany, 2006

[3] *DSS 40-0008D Data Sheet*, IXYS, Milpits, CA, 2004

[4] *Arduino source code for smoothing*, [Online], Available:

http://arduino.cc/en/Tutorial/Smoothing?action=sourceblock&num=1

[5] *Arduino source code for temperature limit*, [Onine], Available:

http://playground.arduino.cc/ComponentLib/Thermistor2?action=sourceblock&num=1

[6] *ACS710 Family Datasheet*, Allegro MicroSystems LLC, Worcester, MA, 2013

[7] Philip T.Krein, “*Elements of Power Electronics*” ECE 464 Power Electronics, Fall 2014.

Appendix 1- Smooth acceleration code

This given code will be modified to implement smooth acceleration.[4]

```
const int numReadings = 10;
int readings[numReadings]; // the readings from the analog input
int index = 0; // the index of the current reading
int total = 0; // the running total
int average = 0; // the average
int inputPin = A0;
void setup()
{
// initialize serial communication with computer:
Serial.begin(9600);
// initialize all the readings to 0:
for (int thisReading = 0; thisReading < numReadings; thisReading++)
readings[thisReading] = 0;
}
void loop() {
// subtract the last reading:
total= total - readings[index];
// read from the sensor:
readings[index] = analogRead(inputPin);
// add the reading to the total:
total= total + readings[index];
// advance to the next position in the array:
index = index + 1;
// if we're at the end of the array...
if (index >= numReadings)
// ...wrap around to the beginning:
index = 0;
// calculate the average:
average = total / numReadings;
// send it to the computer as ASCII digits
Serial.println(average);
delay(1); // delay in between readings for stability
}
```

HIGH-QUALITY LOW-LOSS LOW-COST DC MOTOR TORQUE CONTROLLER

Individual progress report

José Pedro Garcerán Sánchez

March 2015

Contents

Introduction

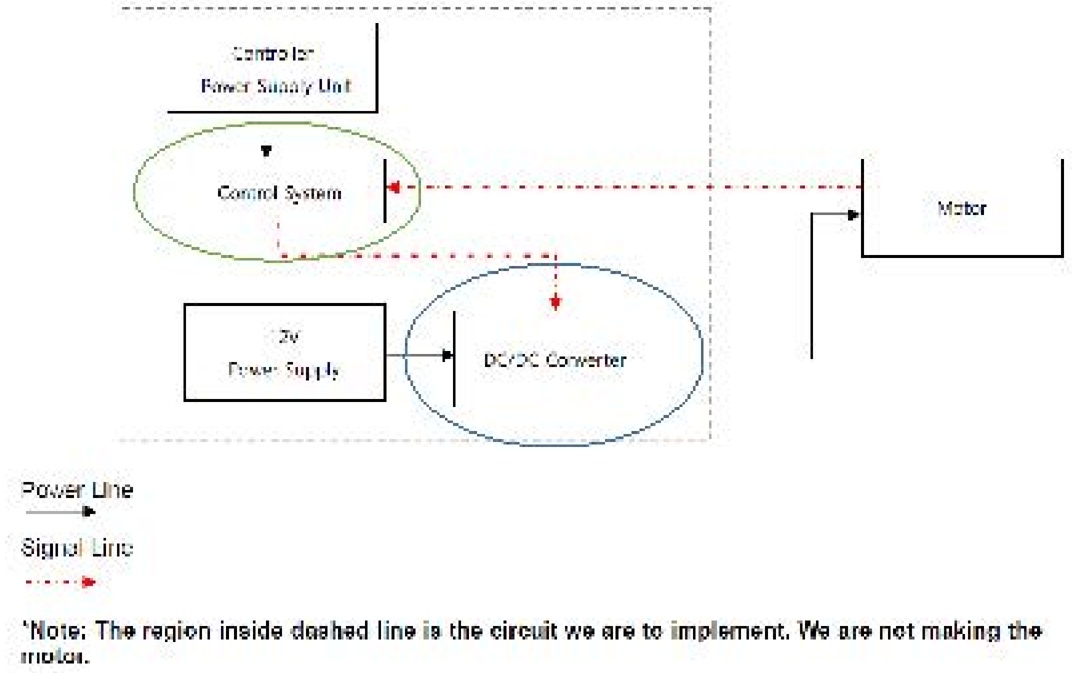
The objective of this project is to design a high-quality low-loss low-cost dc motor torque controller. It is very similar to controlling the movement of a car, when you press the pedal you impose a torque for the motor to deliver, the same for us but applied to a dc motor.

We want to deliver up to 150W continuously to the motor we are going to control, with at least a 90% efficiency, up to 25A for less than a minute and up to 50A for 5 seconds.

Within the controller there are going to be some safety features implemented o that the user feels comfortable and safe when using it.

- No sudden and fast acceleration.
- When the motor reaches a dangerous temperature or the current limit shut down.
- Immediate stop when desired by the user.
- Speed limit.
- Smooth control of acceleration and deceleration of the motor.

Block diagram



Block Diagram of the Project.

The block diagram we are going to use to explain the controller is the one above.

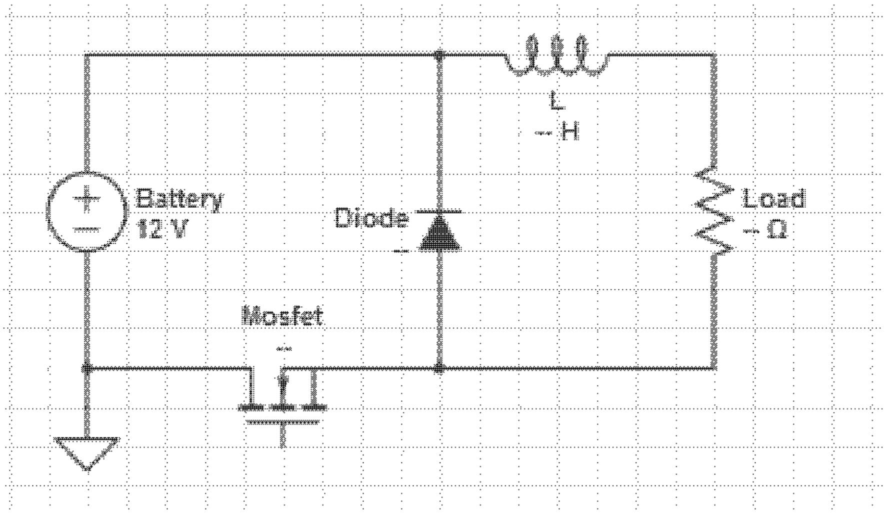
As can be seen in the diagram there are two parts circled, the control system (circled in green) and the dc/dc converter/circuit itself (in blue).

In the control system I am in charge of designing the PI to control the error between the duty ratio that we want the controller to have and the one that is going to have in each moment, my partner Byeong is going to be in charge of implementing it into the microcontroller.

In the dc-dc converter/circuit I am in charge of designing the values for the MOSFET the diode and the inductor. Also estimating the losses of this components and calculating the frequency in which the converter is going to make the MOSFET work.

The dc-dc converter is going to be a buck converter with a power supply of 12V. We have decided to make it a buck converter because we do not need high speeds, and therefore high voltages, we just want high torque and this is achieved by manipulating the current.

Circuit and component election.



Buck converter simplified circuit.

As we can see the circuit is very simple and doesn't have much components. As I mentioned before I am in charge of designing the values for the inductor, finding a suitable MOSFET and a suitable Diode.

Mosfet election.

Since our intention is to deliver 20A continuously to the motor and a peak of 50A we have to look for a Mosfet that is capable of carrying a peak of 50A .

The Mosfet also has to be able of blocking 12V when off since that is the voltage of the power supply.

Definite ratings for the Mosfet: 12V block and 50A peak of current carrying.

Diode Election.

The diode when off has to block up to 12V from the power supply and has to be able to carry the same amount of current that is going to go through the motor, this is 20A continuously and a peak of 50A.

Definite ratings: 12V block at least and 50A peak current.

Inductor election.

To set the value for the inductor we first have to set some other constants to the circuit:

- Frequency.
- Acceptable current ripple.

Equation used to calculate/estimate the minimum value of inductance needed for the frequency and ripple accepted.

$$V_{bat} - V_{load} = L * \frac{\Delta I_L}{\Delta t}$$

$$\Delta t = D_1 * T_{switch}$$

Being D_1 the duty ratio of the mosfet ON.

Since we have to decide, we finally are going to implement a 20kHz frequency to the switching of the Mosfet and the diode, and we are going to consider acceptable a peak to peak ripple lower than 5% for the current.

Using these factors and the equation above written we estimate that we are going to need at least a 111uH inductor.

Considering the highest voltage that we can deliver to the motor (not going to be 12 because of the losses), we are going to take 10V as an example

$$for\ V_{in} = 12V, V_{out} = 10V, \Delta I_L = 0.75A, \Delta t = D_1 * T_{switch}$$

$$Being\ D_1 = 0.833 = \frac{V_{out}}{V_{in}} and\ T_{switch} = \frac{1}{f_{switch}} = \frac{1}{20 * 10^3}$$

$$L = 0.111\ mH$$

Now that we have a reference for a minimum inductance that we need, we just have to choose one.

The one we chose gives a total of 0.4mH which is way bigger than the minimum one that our calculations said.

The reason of choosing such a big inductor compared to the one resulting from the calculation is because in this way we assure that the ripple that gets to the motor is small enough to not interfere with its good functioning.

The inductor that has been chosen is also cheap compared to others that have lower inductance so that is another reason.

And of course it has been chosen so that it works with a 50A peak current.

Estimating power losses in Mosfet and Diode.

The formulas that we are going to use to estimate the losses are the ones presented in the next row.

MOSFET

$$P_{loss} = \frac{D_{onm} * T_{switch} * V_{resid} * I_{on} + D_{offm} * T\_switch * V_{off} * I_{resid} + W_{switch}}{T_{switch}}$$

$$Wswitch = \frac{Voff * Ion * (t_{turn_{on}} + t_{turn_{off}})}{2}$$

DIODE

$$P_{loss} = \frac{D_{ond} * T_{switch} * V_{resid} * I_{on} + D_{offd} * T_{switch} * V_{off} * I_{resid}}{T_{switch}}$$

D_{onm}-> Duty ratio of mosfet ON.

D_{offm}-> Duty ratio of mosfet OFF.

W_{switch}-> Energy lost because of the turning on and off delays of the mosfet.

t_{turnon}-> Time the mosfet delays on turning ON.

$t_{turnoff}$-> Time the mosfet delays in turning OFF.

T_{switch}-> Period of switching frequency applied to the mosfet and diode. (1/20kHz)

V_{off}-> Voltage blocking when ON.

V_{resid}-> Residual voltage drop when ON.

I_{on}-> Current carrying when ON.

I_{resid}-> Residual current when OFF.

D_{ond}-> Duty ratio of diode ON.

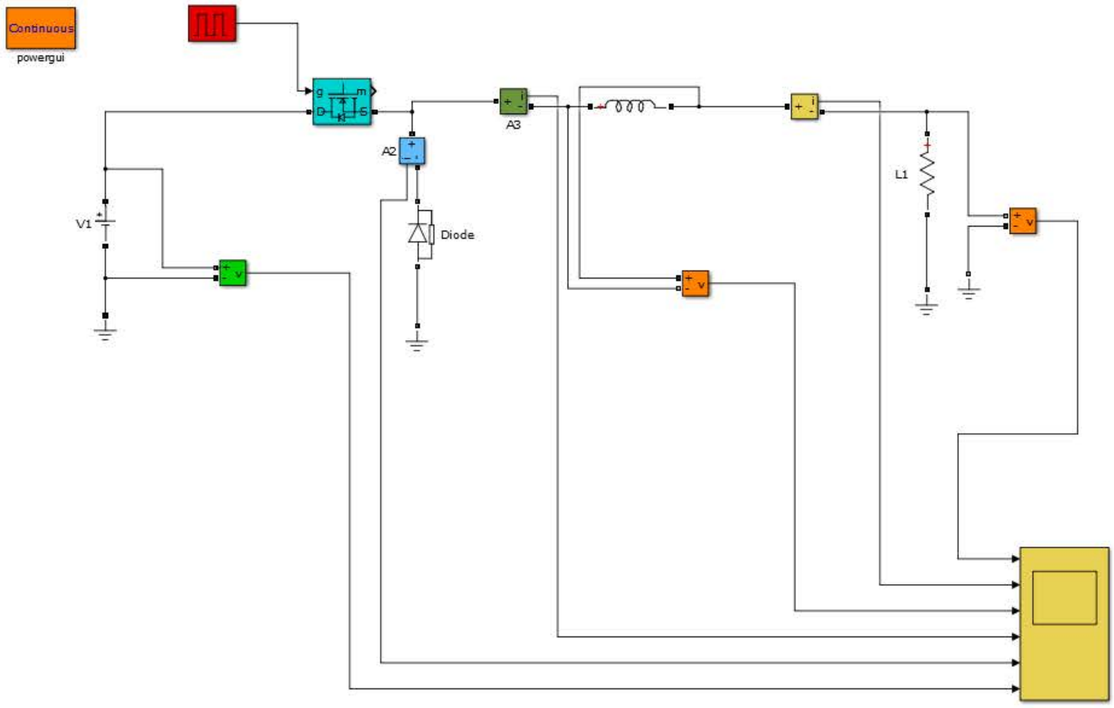
D_{offd}-> Duty ratio of diode OFF.

Using all the datasheet information from the diode and the mosfet and the formulas that appear above we get an estimate of a 5W loss.

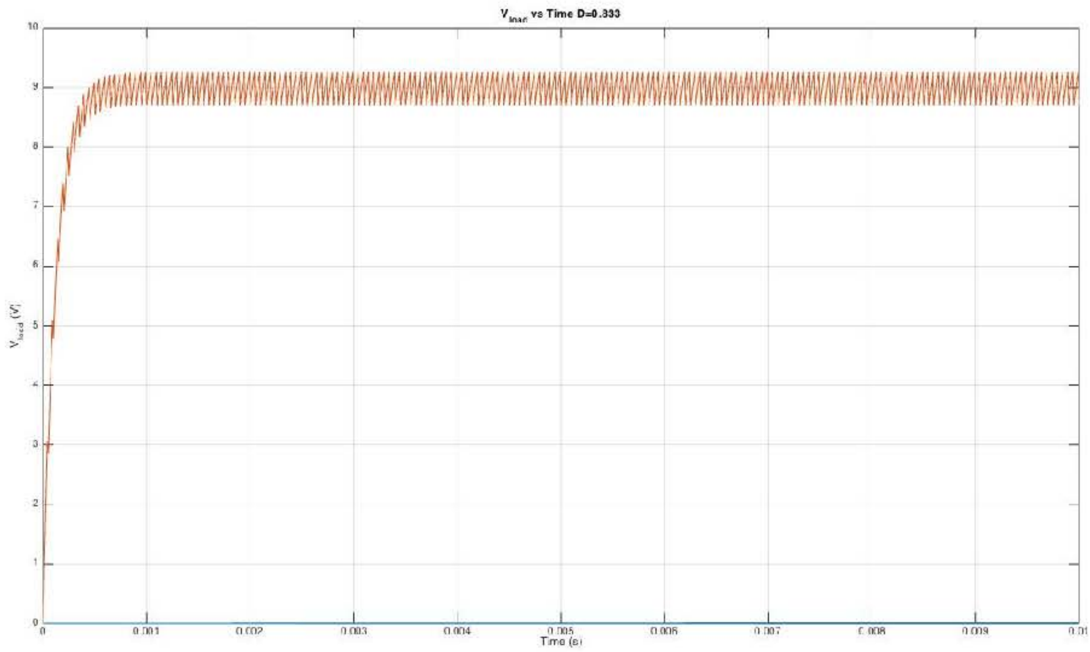
Which in total is 5/150*100= 3.33% of the total power which is very good since we want to achieve at least a 90% efficiency.

Simulation with fixed duty ratio (not including the PI).

The next model is very simple, but helps have an idea of how it is going to work and if the values are more or less correct.



With a value of the inductor of 111uH used to simulate. We have the next simulation for a D_{mosfet}=0.833 => 10V output.



As we can see, the buck gives an output of 9V instead of 10V, this is because of the losses and because the model is very simple but what we have to get out of it is that it gives us the output we want roughly. The next step is to build the circuit, check that the diode and the transistor work when they have to, this means programming a fixed duty ratio in the mosfet and check if the output is the one desired and after that, implement the PI and start checking that everything works as it has to.

This means that the power supply gives more or less 12V, that the diode is ON when the mosfet is OFF and finally implement the safety procedures in the micro.

Ethical discussion

As I mentioned in the introduction, the converter is meant to be used by someone physical to control a motor for some type of function. Because of this fact, the mayor ethical question is to make the converter safe and stable. We cannot allow this product to be of harm or injure the user, that is why there are going to be safety features included within it, to make sure that doesn't create problems during its life.

Proving that the safety functions work is going to be one of the main focuses of this project, we aren't looking for a cheap and very efficient device that can harm people and be of no potential use because of its danger.

International
IOR Rectifier

PD - 94266

SMPS MOSFET

IRLR3714
IRLU3714

HEXFET® Power MOSFET

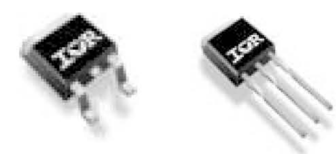
V_{DSS}	$R_{DS(on)}$ max	I_D
20V	**20mΩ**	**36A**

Applications

- High Frequency Isolated DC-DC Converters with Synchronous Rectification for Telecom and Industrial Use
- High Frequency Buck Converters for Computer Processor Power

Benefits

- Ultra-Low Gate Impedance
- Very Low $R_{DS(on)}$ at 4.5V V_{GS}
- Fully Characterized Avalanche Voltage and Current



D-Pak IRLR3714 I-Pak IRLU3714

Absolute Maximum Ratings

Symbol	Parameter	Max.	Units
V_{DS}	Drain-Source Voltage	20	V
V_{GS}	Gate-to-Source Voltage	± 20	V
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 10V	36 ⑤	A
I_D @ T_C = 70°C	Continuous Drain Current, V_{GS} @ 10V	31	
I_{DM}	Pulsed Drain Current①	140	
P_D @T_C = 25°C	Maximum Power Dissipation③	47	W
P_D @T_C = 70°C	Maximum Power Dissipation③	33	W
	Linear Derating Factor	0.31	W/°C
T_J , T_{STG}	Junction and Storage Temperature Range	-55 to + 175	°C

Thermal Resistance

	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	–––	3.2	°C/W
$R_{\theta JA}$	Junction-to-Ambient	–––	50	
$R_{\theta JA}$	Junction-to-Ambient (PCB mount)④	–––	110	

Notes ① through ⑤ are on page 10

06/15/01

Static @ T_J = 25°C (unless otherwise specified)

	Parameter	Min.	Typ.	Max.	Units	Conditions
$V_{(BR)DSS}$	Drain-to-Source Breakdown Voltage	20	—–	—–	V	V_{GS} = 0V, I_D = 250μA
$\Delta V_{(BR)DSS}/\Delta T_J$	Breakdown Voltage Temp. Coefficient	—–	0.022	—–	V/°C	Reference to 25°C, I_D = 1mA
$R_{DS(on)}$	Static Drain-to-Source On-Resistance	—–	15	20	mΩ	V_{GS} = 10V, I_D = 18A ③
		—–	21	28		V_{GS} = 4.5V, I_D = 14A ③
$V_{GS(th)}$	Gate Threshold Voltage	1.0	—–	3.0	V	V_{DS} = V_{GS}, I_D = 250μA
I_{DSS}	Drain-to-Source Leakage Current	—–	—–	20	μA	V_{DS} = 16V, V_{GS} = 0V
		—–	—–	100		V_{DS} = 16V, V_{GS} = 0V, T_J = 125°C
I_{GSS}	Gate-to-Source Forward Leakage	—–	—–	200	nA	V_{GS} = 16V
	Gate-to-Source Reverse Leakage	—–	—–	-200		V_{GS} = -16V

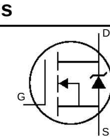
Dynamic @ T_J = 25°C (unless otherwise specified)

Symbol	Parameter	Min.	Typ.	Max.	Units	Conditions
g_{fs}	Forward Transconductance	17	—–	—–	S	V_{DS} = 10V, I_D = 14A
Q_g	Total Gate Charge	—–	6.5	9.7	nC	I_D = 14A
Q_{gs}	Gate-to-Source Charge	—–	1.8	—–		V_{DS} = 10V
Q_{gd}	Gate-to-Drain ("Miller") Charge	—–	2.9	—–		V_{GS} = 4.5V
Q_{oss}	Output Gate Charge	—–	7.1	—–		V_{GS} = 0V, V_{DS} = 10V
$t_{d(on)}$	Turn-On Delay Time	—–	8.7	—–	ns	V_{DD} = 10V
t_r	Rise Time	—–	78	—–		I_D = 14A
$t_{d(off)}$	Turn-Off Delay Time	—–	10	—–		R_G = 1.8Ω
t_f	Fall Time	—–	4.5	—–		V_{GS} = 4.5V ③
C_{iss}	Input Capacitance	—–	670	—–	pF	V_{GS} = 0V
C_{oss}	Output Capacitance	—–	470	—–		V_{DS} = 10V
C_{rss}	Reverse Transfer Capacitance	—–	68	—–		ƒ = 1.0MHz

Avalanche Characteristics

Symbol	Parameter	Typ.	Max.	Units
E_{AS}	Single Pulse Avalanche Energy②	—–	72	mJ
I_{AR}	Avalanche Current①	—–	14	A

Diode Characteristics

Symbol	Parameter	Min.	Typ.	Max.	Units	Conditions
I_S	Continuous Source Current (Body Diode)	—–	36⑤	—–	A	MOSFET symbol showing the integral reverse p-n junction diode. 
I_{SM}	Pulsed Source Current (Body Diode) ①	—–	140	—–		
V_{SD}	Diode Forward Voltage	—–	—–	1.3	V	T_J = 25°C, I_S = 18A, V_{GS} = 0V ③
		—–	0.88	—–		T_J = 125°C, I_S = 18A, V_{GS} = 0V ③
t_{rr}	Reverse Recovery Time	—–	35	53	ns	T_J = 25°C, I_F = 18A, V_R=10V
Q_{rr}	Reverse Recovery Charge	—–	34	51	nC	di/dt = 100A/μs ③
t_{rr}	Reverse Recovery Time	—–	35	53	ns	T_J = 125°C, I_F = 18A, V_R=10V
Q_{rr}	Reverse Recovery Charge	—–	35	53	nC	di/dt = 100A/μs ③

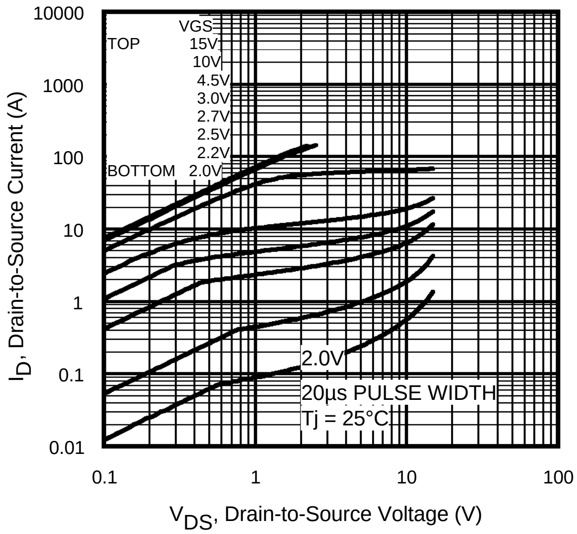


Fig 1. Typical Output Characteristics

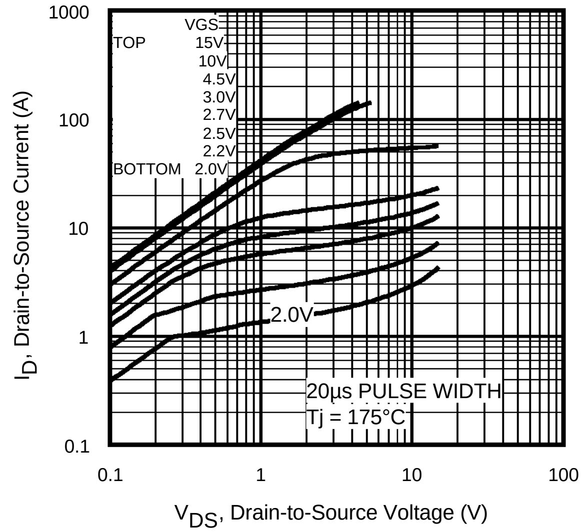


Fig 2. Typical Output Characteristics

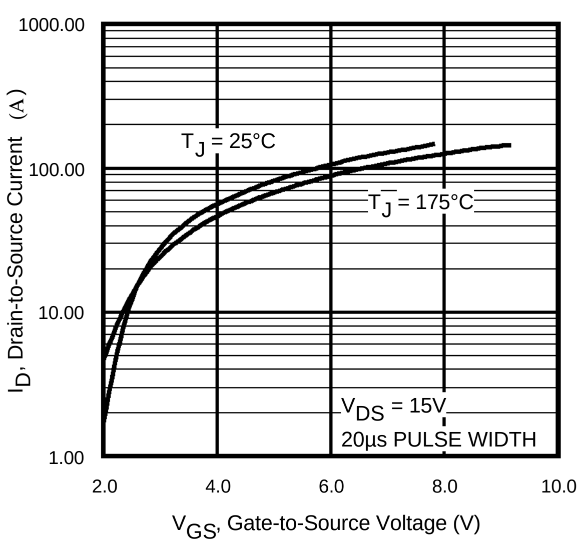


Fig 3. Typical Transfer Characteristics

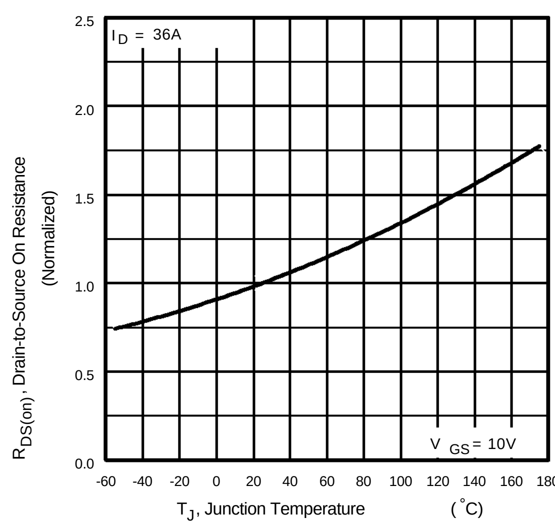


Fig 4. Normalized On-Resistance Vs. Temperature

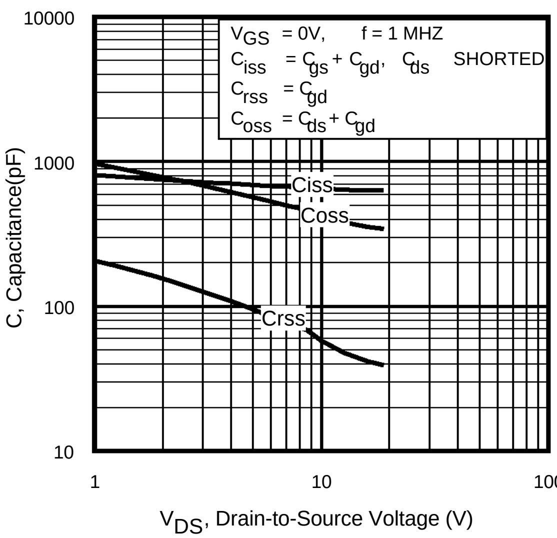


Fig 5. Typical Capacitance Vs. Drain-to-Source Voltage

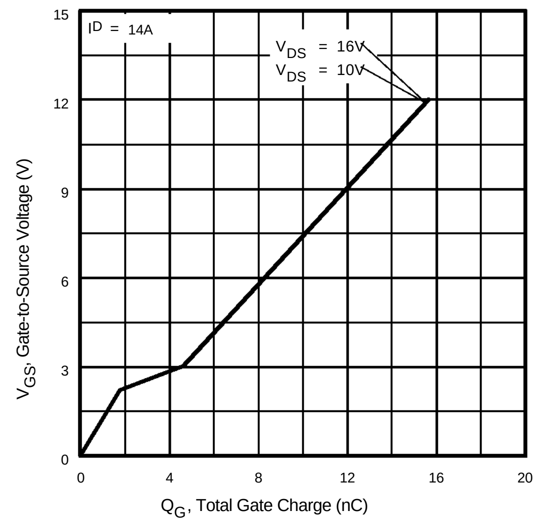


Fig 6. Typical Gate Charge Vs. Gate-to-Source Voltage

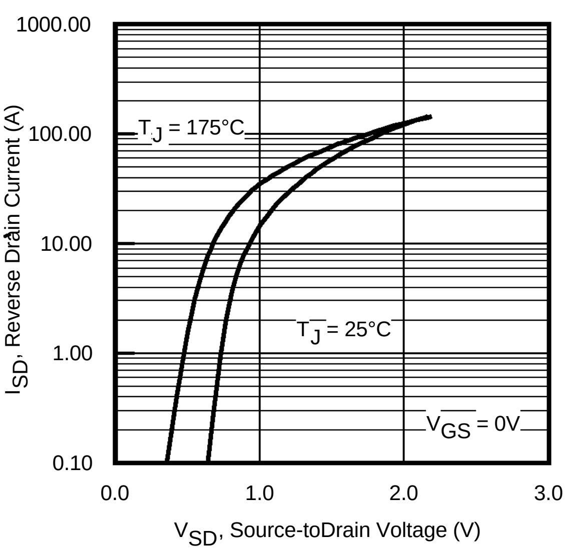


Fig 7. Typical Source-Drain Diode Forward Voltage

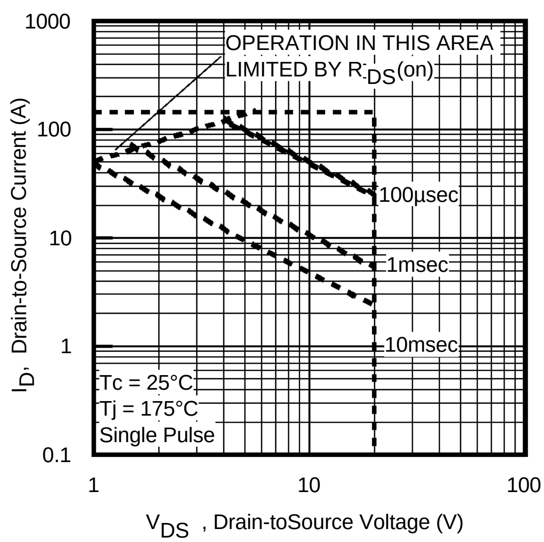


Fig 8. Maximum Safe Operating Area

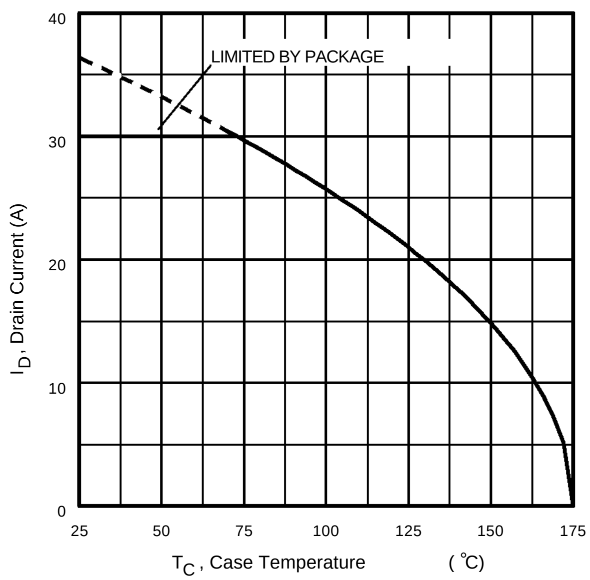


Fig 9. Maximum Drain Current Vs. Case Temperature

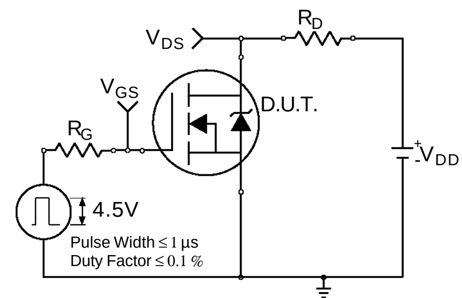


Fig 10a. Switching Time Test Circuit

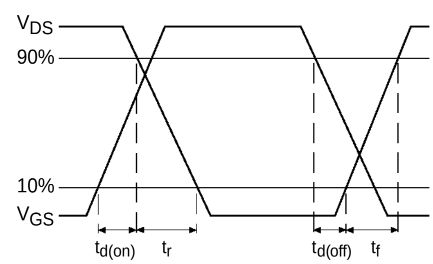


Fig 10b. Switching Time Waveforms

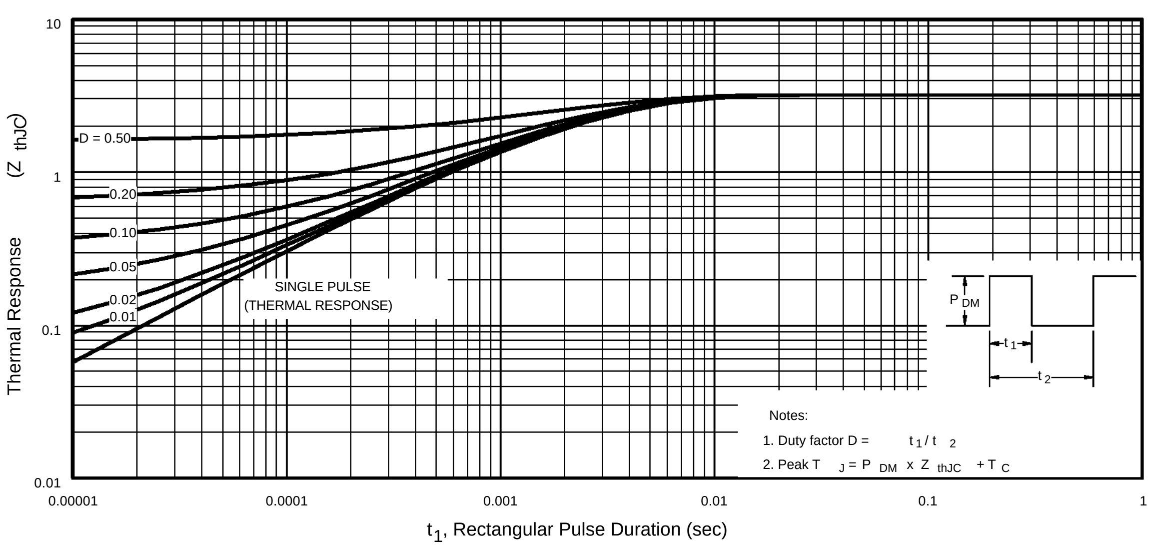


Fig 11. Maximum Effective Transient Thermal Impedance, Junction-to-Case

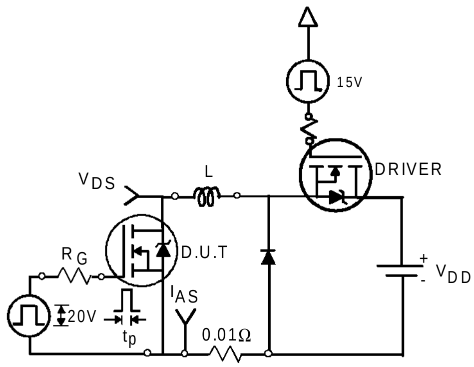


Fig 12a. Unclamped Inductive Test Circuit

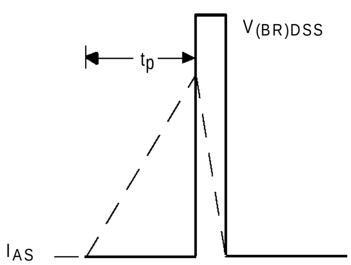


Fig 12b. Unclamped Inductive Waveforms

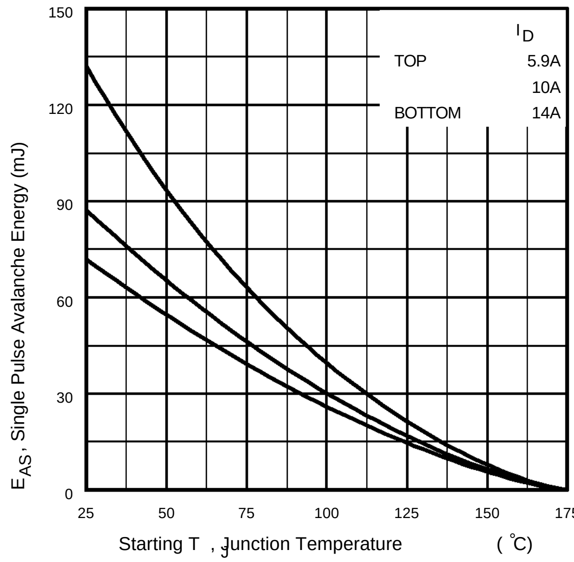


Fig 12c. Maximum Avalanche Energy Vs. Drain Current

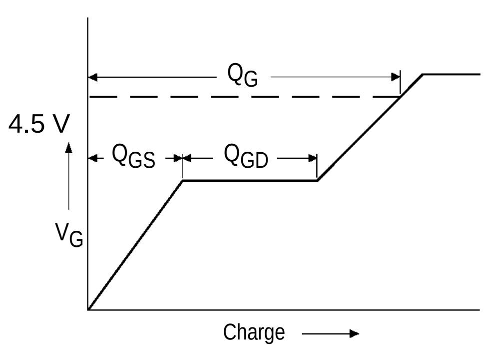


Fig 13a. Basic Gate Charge Waveform

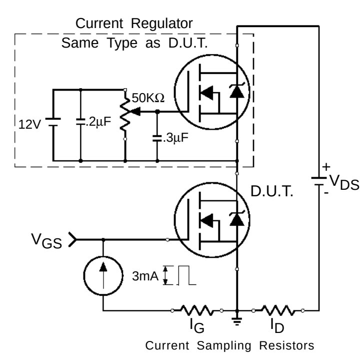
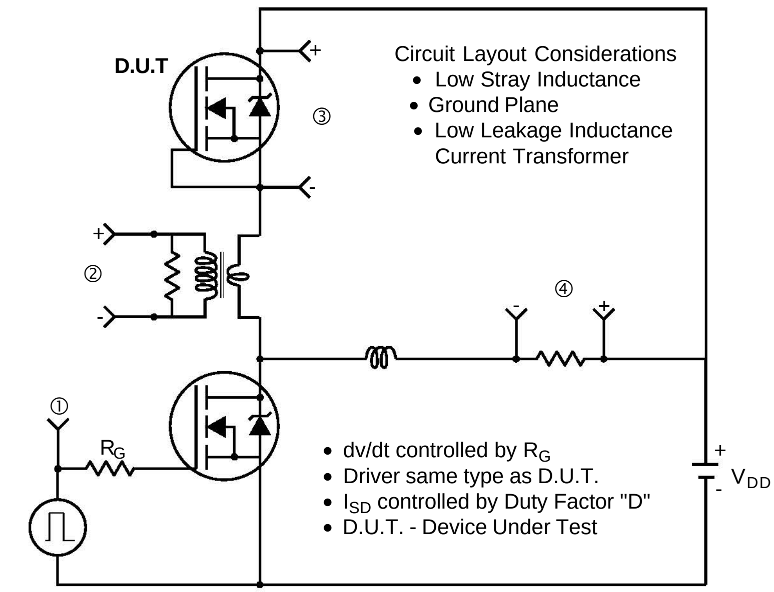
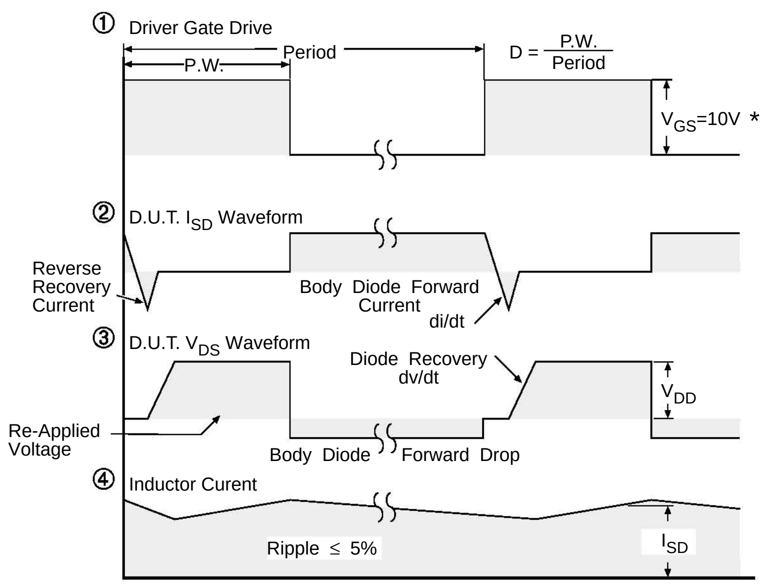


Fig 13b. Gate Charge Test Circuit

Peak Diode Recovery dv/dt Test Circuit



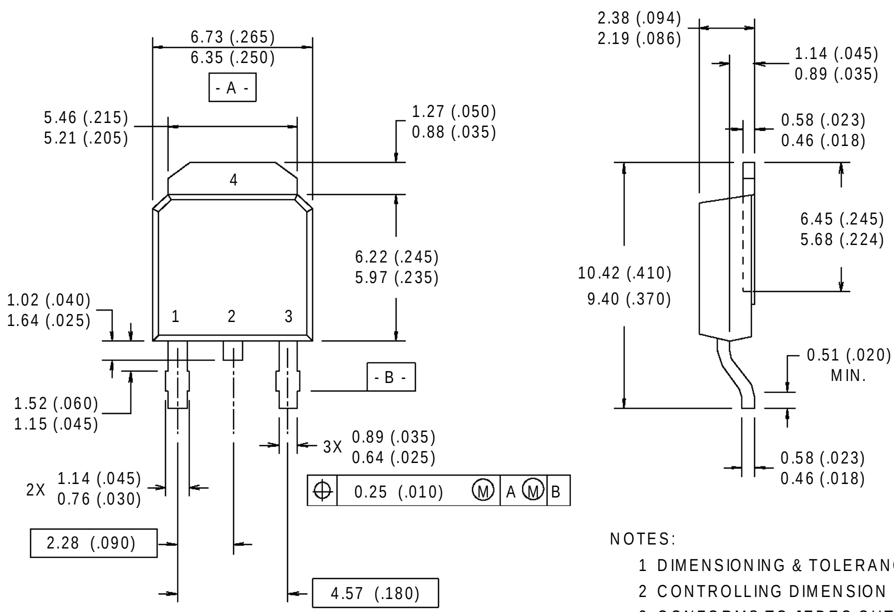


* V_{GS} = 5V for Logic Level Devices

Fig 14. For N-Channel HEXFET® Power MOSFETs

D-Pak (TO-252AA) Package Outline

Dimensions are shown in millimeters (inches)

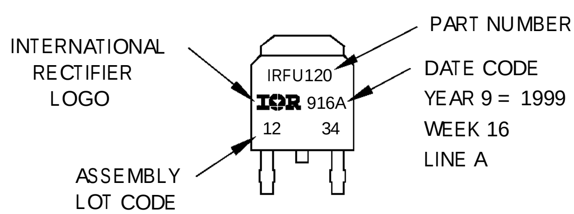


LEAD ASSIGNMENTS
1 - GATE
2 - DRAIN
3 - SOURCE
4 - DRAIN

NOTES:
1 DIMENSIONING & TOLERANCING PER ANSI Y14.5M, 1982.
2 CONTROLLING DIMENSION : INCH.
3 CONFORMS TO JEDEC OUTLINE TO-252AA.
4 DIMENSIONS SHOWN ARE BEFORE SOLDER DIP, SOLDER DIP MAX. +0.16 (.006).

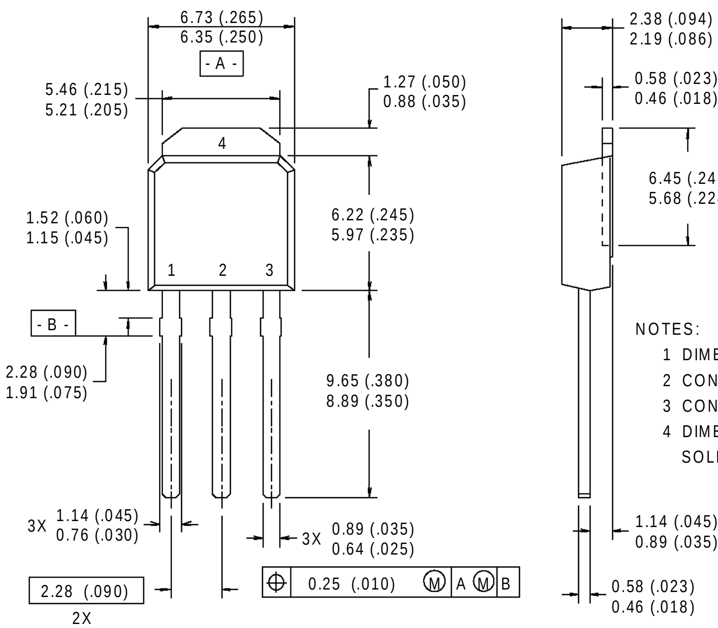
D-Pak (TO-252AA) Part Marking Information

EXAMPLE: THIS IS AN IRFR120
WITH ASSEMBLY
LOT CODE 1234
ASSEMBLED ON WW 16, 1999
IN THE ASSEMBLY LINE "A"



I-Pak (TO-251AA) Package Outline

Dimensions are shown in millimeters (inches)

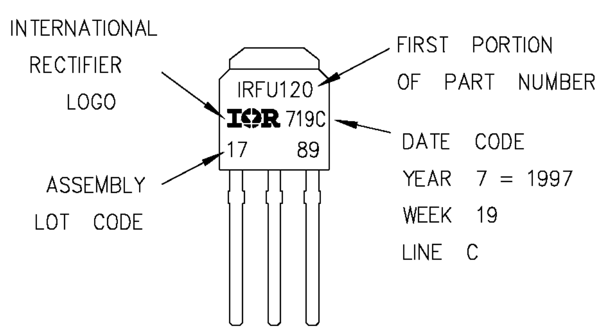


LEAD ASSIGNMENTS
1 - GATE
2 - DRAIN
3 - SOURCE
4 - DRAIN

NOTES:
1 DIMENSIONING & TOLERANCING PER ANSI Y14.5M, 1982.
2 CONTROLLING DIMENSION : INCH.
3 CONFORMS TO JEDEC OUTLINE TO-252AA.
4 DIMENSIONS SHOWN ARE BEFORE SOLDER DIP, SOLDER DIP MAX. +0.16 (.006).

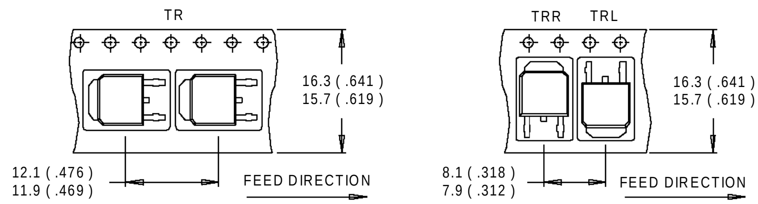
I-Pak (TO-251AA) Part Marking Information

EXAMPLE: THIS IS AN IRFU120
LOT CODE 1789
ASSEMBLED ON WW 19, 1997
IN THE ASSEMBLY LINE "C"

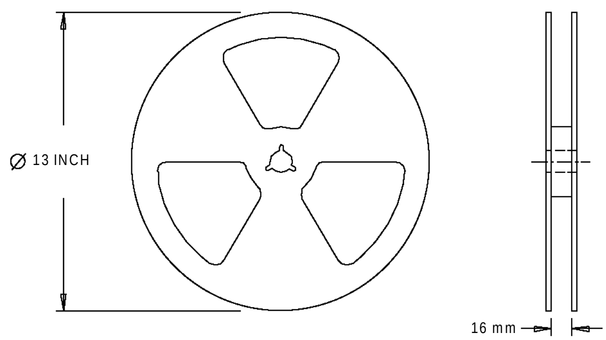


D-Pak (TO-252AA) Tape & Reel Information

Dimensions are shown in millimeters (inches)



NOTES :
1. CONTROLLING DIMENSION : MILLIMETER.
2. ALL DIMENSIONS ARE SHOWN IN MILLIMETERS (INCHES).
3. OUTLINE CONFORMS TO EIA-481 & EIA-541.



NOTES :
1. OUTLINE CONFORMS TO EIA-481.

Notes:

① Repetitive rating; pulse width limited by max. junction temperature.

② Starting T_J = 25°C, L = 0.69 mH R_G = 25Ω, I_{AS} = 14A.

③ Pulse width ≤ 400µs; duty cycle ≤ 2%.

④ When mounted on 1" square PCB (FR-4 or G-10 Material). For recommended footprint and soldering techniques refer to application note #AN-994.

⑤ Calculated continuous current based on maximum allowable junction temperature; Package limitation current is 30A

Data and specifications subject to change without notice.
These products have been designed and qualified for the Industrial market.
Qualification Standards can be found on IR's Web site.

International
IOR Rectifier

IR WORLD HEADQUARTERS: 233 Kansas St., El Segundo, California 90245, USA Tel: (310) 252-7105
TAC Fax: (310) 252-7903
Visit us at www.irf.com for sales contact information.06/01

Note: For the most current drawings please refer to the IR website at:
http://www.irf.com/package/

MBR2515L

SWITCHMODE™ Power Rectifier

Features and Benefits

- Low Forward Voltage
- Low Power Loss/High Efficiency
- High Surge Capacity
- 100°C Operating Junction Temperature
- 25 A Total
- Pb−Free Packages are Available*

Applications

- Power Supply – Output Rectification
- Power Management
- Instrumentation

Mechanical Characteristics

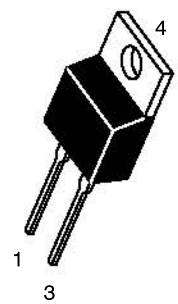
- Case: Epoxy, Molded
- Epoxy Meets UL 94, V−0 @ 0.125 in
- Weight: 1.9 Grams (Approximately)
- Finish: All External Surfaces Corrosion Resistant and Terminal Leads are Readily Solderable
- Lead Temperatures for Soldering Purposes: 260°C Max. for 10 Seconds
- ESD Rating: Human Body Model 3B
  Machine Model C

*For additional information on our Pb−Free strategy and soldering details, please download the ON Semiconductor Soldering and Mounting Techniques Reference Manual, SOLDERRM/D.

ON Semiconductor®

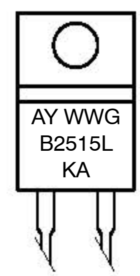
http://onsemi.com

SCHOTTKY BARRIER RECTIFIER 25 AMPERES, 15 VOLTS



TO−220AC CASE 221B STYLE 1

MARKING DIAGRAM



A	= Assembly Location
Y	= Year
WW	= Work Week
G	= Pb−Free Package
B2515L	= Device Code
KA	= Diode Polarity

ORDERING INFORMATION

Device	Package	Shipping
MBR2515L	TO−220	50 Units/Rail
MBR2515LG	TO−220 (Pb−Free)	50 Units/Rail

MAXIMUM RATINGS

Rating	Symbol	Value	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	V_{RRM} V_{RWM} V_R	15	V
Average Rectified Forward Current (T_C = 91°C per Device)	$I_{F(AV)}$	 25	A
Peak Repetitive Forward Current, per Leg (Square Wave, 20 kHz, T_C = 95°C)	I_{FRM}	25	A
Non−Repetitive Peak Surge Current (Surge Applied at Rated Load Conditions, Halfwave, Single Phase, 60 Hz)	I_{FSM}	150	A
Peak Repetitive Reverse Surge Current (2.0 µs, 1.0 kHz)	I_{RRM}	1.0	A
Storage Temperature Range	T_{stg}	−65 to +125	°C
Operating Junction Temperature	T_J	−65 to +100	°C

Stresses exceeding Maximum Ratings may damage the device. Maximum Ratings are stress ratings only. Functional operation above the Recommended Operating Conditions is not implied. Extended exposure to stresses above the Recommended Operating Conditions may affect device reliability.

THERMAL CHARACTERISTICS

Characteristic	Conditions	Symbol	Max	Unit
Maximum Thermal Resistance, Junction−to−Case	Min. Pad	$R_{\theta JC}$	1.0	°C/W
Maximum Thermal Resistance, Junction−to−Ambient	Min. Pad	$R_{\theta JA}$	70	

ELECTRICAL CHARACTERISTICS

Characteristic	Symbol	Min	Typical	Max	Unit
Instantaneous Forward Voltage (Note 1) (i_F = 25 Amps, T_j = 25°C) (i_F = 25 Amps, Tj = 70°C) (i_F = 19 Amps, Tj = 70°C)	v_F	 – – –	 0.41 0.37 0.34	 0.45 0.42 0.38	V
Instantaneous Reverse Current (Note 1) (Rated dc Voltage, Tj = 25°C) (Rated dc Voltage, Tj = 70°C)	i_R	 – –	 1.0 24	 15 200	mA

1. Pulse Test: Pulse Width = 300 µs, Duty Cycle ≤ 2.0%.

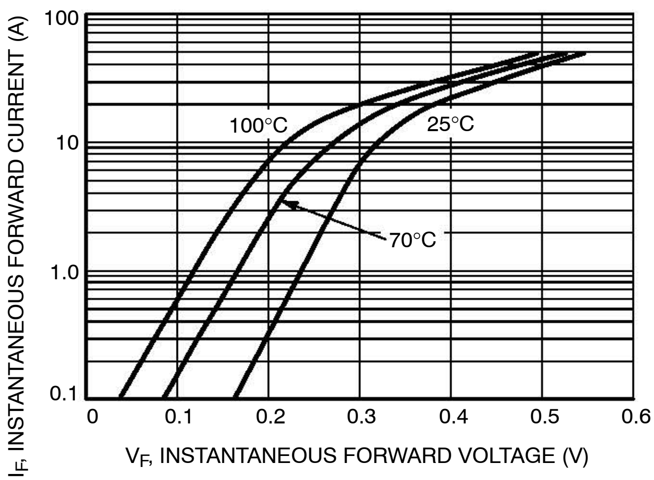


Figure 1. Typical Forward Voltage

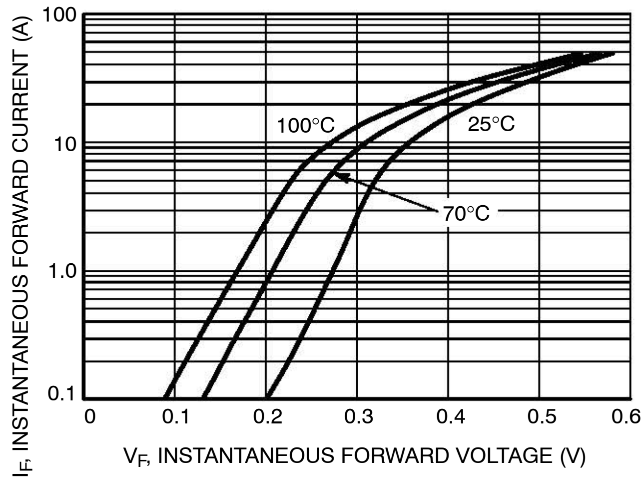


Figure 2. Maximum Forward Voltage

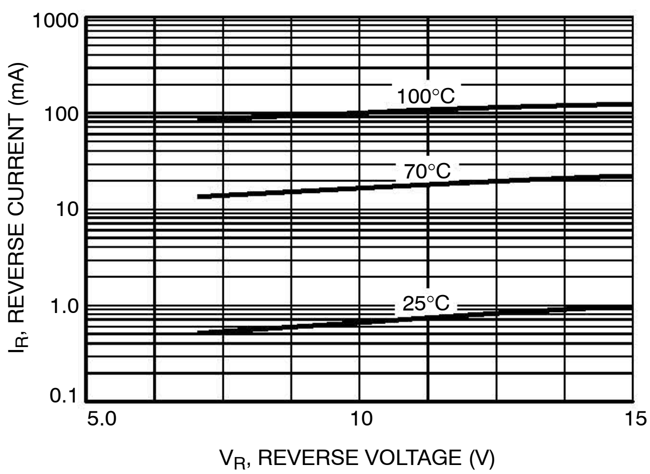


Figure 3. Typical Reverse Current

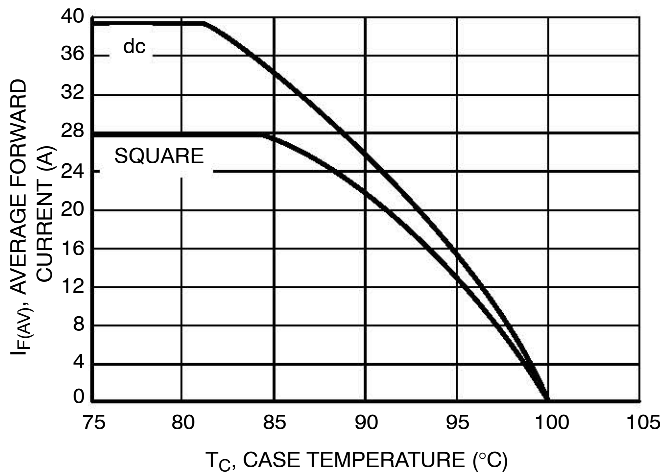


Figure 4. Current Derating, Case, Per Leg

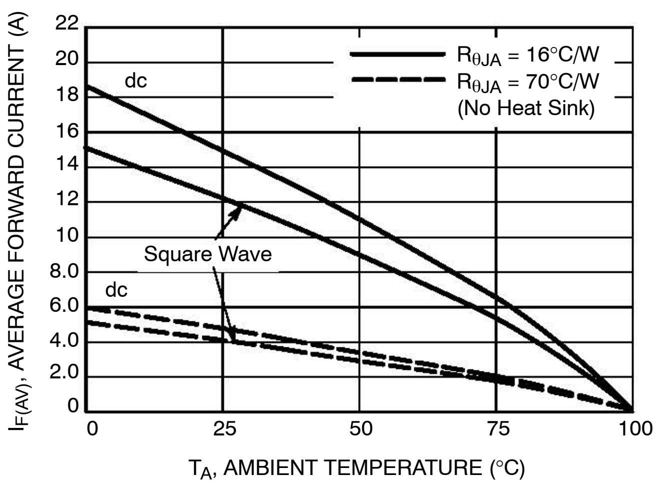


Figure 5. Current Derating, Ambient, Per Leg

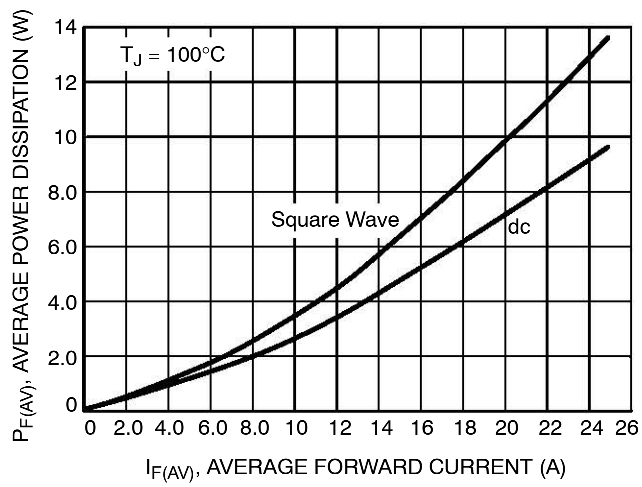
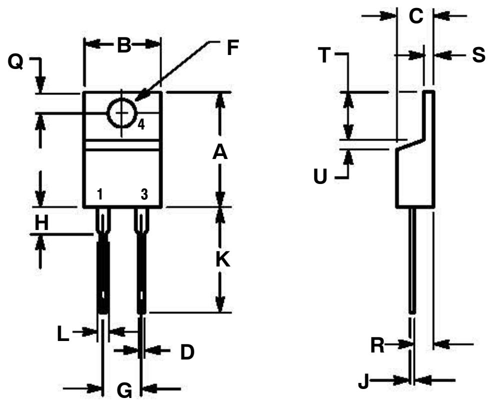


Figure 6. Forward Power Dissipation

PACKAGE DIMENSIONS

TO−220
CASE 221B−04
ISSUE E



NOTES:
1. DIMENSIONING AND TOLERANCING PER ANSI Y14.5M, 1982.
2. CONTROLLING DIMENSION: INCH.

DIM	INCHES		MILLIMETERS	
	MIN	MAX	MIN	MAX
A	0.595	0.620	15.11	15.75
B	0.380	0.405	9.65	10.29
C	0.160	0.190	4.06	4.82
D	0.025	0.035	0.64	0.89
F	0.142	0.161	3.61	4.09
G	0.190	0.210	4.83	5.33
H	0.110	0.130	2.79	3.30
J	0.014	0.025	0.36	0.64
K	0.500	0.562	12.70	14.27
L	0.045	0.060	1.14	1.52
Q	0.100	0.120	2.54	3.04
R	0.080	0.110	2.04	2.79
S	0.045	0.055	1.14	1.39
T	0.235	0.255	5.97	6.48
U	0.000	0.050	0.000	1.27

STYLE 1:
PIN 1. CATHODE
2. N/A
3. ANODE
4. CATHODE

PUBLICATION ORDERING INFORMATION

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