ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

DEGREE IN ELECTROMECHANICAL ENGINEERING

POWER GENERATION FROM DYNAMIC HUMAN MOTION: PROTOTYPE DESIGN

SPECIALTY ELECTRIC

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Madrid

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POWER GENERATION FROM DYNAMIC HUMAN MOTION: PROTOTYPE DESIGN

AUTOR: Fuente Pascual, Ignacio.

DIRECTOR: Carney, Paul Scott.

ENTIDAD COLABORADORA: University of Illinois at Urbana-Champaign.

SUMMARY OF THE PROJECT

Introduction

The world is developing faster than ever with new advances in technologies. The downsides of such fast development should not be ignored. The energy consumption needed to power our lives contribute to rampant pollution. Under these circumstances, studies on green energy have been rising and new systems have come into the spotlight. Solar plants are producing power from predicting the Sun's path so that they can maximize the exposure and wind turbines are equipped with system that chases the wind direction. This project aims similar target and tries to apply principles of kinetic power harvesting while introducing the use of digital systems to make a basis for small energy harvesting that is not possible in autonomous systems.

The idea is to implement a device that will convert the kinetic energy to a stable DC voltage. The device is to be portable and eco-friendly so that it will contribute to reduce the pollution and improve scarcity of resource from smaller scales.

Objectives

The primary goal is for the project is to create a design that justifies the expenditure of energy that is used on the system.

The functions include collecting energy using oscillating core inside and inductor and take voltage meter readings and use them to control a synchronous rectifier.

The main benefit is a more efficient energy extraction through a full range of motion. It features a very rough prototype for extracting kinetic energy that can hopefully lead to more similar designs in the future.

The design will gather the kinetic energy generated by the ankle's swinging and jumping that naturally happen during jogging movement and store the voltage into a lithium battery. Alongside this, the project will attempt to capture smaller voltage impulses from walking, be as conspicuous as possible, and justify any power expended during its use by delivering a net power that is more than what a simpler design would have.

Design

Over the project's course different alternatives that could be used to the design have been considered, but they were not finally implemented. The first suggestion was to use a center tapped transformer in order to rectify the circuit with ground referenced to the center tapped. This would allow for a boosted voltage output, which would cause less loss over resistance, but in turn would increase the bulk of the system.

Another future design implementation would be the inclusion of a tunable capacitor inside of the resonance circuit. While this would mean more complexity and another feedback circuit, controlling the capacitance would allow a tool for fine tuning the resonance frequency. While it is extremely difficult to capture the random pattern from a random outside source in a resonant circuit, a tuning mechanism might expand the range of usable signal frequencies for this circuit.

Other method that was taken into account was to include piezo-electric materials such as PZT and PVDF or electro-active polymers. The advantage of using piezo-electric materials is the portability and un-obtrusive installation but they have the disadvantage of getting very low power extracted in comparison with the high voltage produced.

The design finally used is meant to be a possible method of extracting useful electrical power from the mechanical motion of walking. As such, other way of extracting power which works with considerable lower voltage levels was used. Instead of working with PZT, we decided to build a magnetic generator that would produce an AC signal. This design produces electrical power by using the change in magnetic flux linkage caused by a magnet in a solenoid coil. The device built can be easily carried and uses the energy involved in everyday walking to generate an AC signal that will be later modified in order to be able to charge Lithium metal hydride rechargeable battery.

The block diagram of the design used can be found in Figure 1.

Each block was designed and tested separately. Eagle software was used for the circuit design although the final construction was built in both a regular board and a vector board.

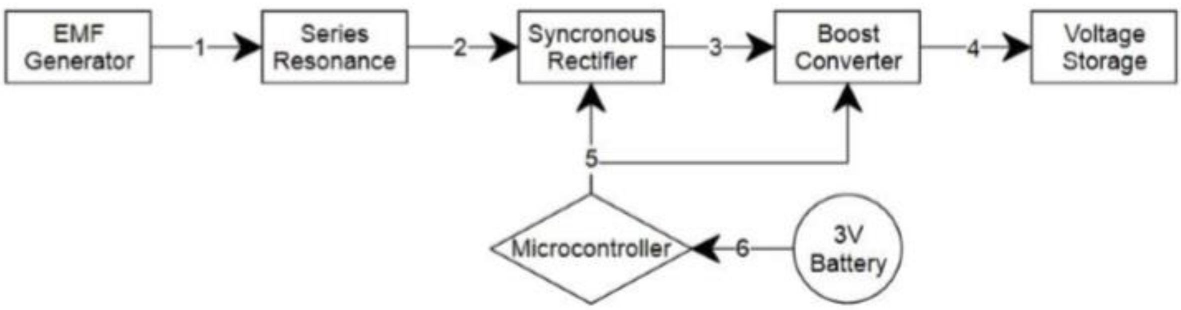

Figure 1 Top Level Block Diagram

Figure1:

1. AC impulse signals
2. Amplified AC signals
3. A stable DC signal
4. Stepped-up DC voltage
5. Pulse Width Modulation signal
6. 3V battery to feed the microcontroller

Conclusions

After the demonstration of the project at University of Illinois at Urbana-Champaign, all the different elements had been tested and tried separately.

While the entire project did not work collectively, the design was able to convert mechanical energy into a small voltage, and it also was able to rectify and amplify voltage below the .7 threshold voltage set by full bridge rectifiers in previous projects.

When the MOSFET full bridge rectifier attempted to capture both the positive and negative half of the AC input, there was a severe drop in voltage as compared to simply capturing one side of the AC input, which output an expected half signal. This can possibly be due to the signal delays incremented by the microcontroller allowing voltage stored to be cancelled out by adding increasingly more negative voltage.

References

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

[2] P. Sannuti ,“Series and Parallel Resonance” Rutgers University, December 2004.

[3] “http://www.electronics-tutorials.ws/accircuits/series-resonance.html”

[4] FAIRCHILD, "BAS40SL Schottky Barrier Diode Datasheet," [online]. [Accessed February 2015]

[5] “Analyzing full wave-rectifiers with capacitor filters”

http://powerelectronics.com/power-management/analyzing-full-wave- rectifiers- capacitor-filters

RESUMEN DEL PROYECTO

Introducción

El mundo se está desarrollando más rápido que nunca con los nuevos avances en tecnologías. Las desventajas de este rápido desarrollo no deben ser ignoradas ya que el consumo de energía necesaria en nuestra vida contribuye de forma significativa a aumentar los niveles de contaminación. Bajo estas circunstancias, los estudios sobre la energía verde han aumentado y nuevos sistemas alternativos de producir energía se sitúan en el centro de atención. Por ejemplo, las plantas solares producen potencia a partir de la predicción de la trayectoria del sol de tal modo que puedan maximizar su exposición al mismo. Por otro lado, los aerogeneradores están equipados con un sistema que en todo momento sigue a la dirección del viento. Este proyecto está orientado en esta misma dirección, ya que tiene como objetivo aprovechar la energía empleada en nuestro día a día de tal modo que pueda ser reutilizada con otros fines.

La idea es implementar un dispositivo que convierta la energía utilizada al caminar en una tensión de CC estable. El dispositivo debe ser diseñado para ser portátil y ecológico. De este modo contribuirá a reducir la contaminación y mejorar la escasez de recursos a pequeña escala.

Objetivos

El objetivo principal de este proyecto es crear un diseño capaz de conseguir una tensión de continua lo suficientemente alta como para cargar una batería y que a su vez justifique el gasto de energía que se utiliza en el sistema.

Las funciones incluyen la recolección de energía mecánica con un generador magnético y tomar lecturas del voltímetro para controlar el rectificador síncrono.

El principal beneficio es una extracción de energía de manera eficiente a través de una amplia gama de movimiento. El prototipo diseñado para extraer la energía cinética es muy rudimentario, con el propósito de que en el futuro, este diseño pueda ser implementado y mejorado.

El diseño transforma la energía cinética generada por movimientos de balanceo y saltos que ocurren de forma natural mientras andamos en energía eléctrica, y almacena tensión en una batería de litio. Junto a esto, el proyecto tratará de captar incluso los impulsos de tensión más pequeños producidos al caminar, ser tan concupiscible como sea posible, y justificar cualquier potencia gastada durante su uso mediante la entrega de una potencia neta mayor.

Diseño

Durante el diseño del proyecto, diferentes alternativas que habrían sido válidas fueron consideradas, pero no fueron finalmente implementadas. Por ejemplo, la primera sugerencia a tener en cuenta fue la de usar un transformador a la salida del generador magnético para amplificar el voltaje AC. El inconveniente que suponía era un considerable aumento del peso y del tamaño del prototipo final.

Otro posible diseño válido incluye el uso de un condensador ajustable en el "Series resonance circuit". Aunque esto incrementaría la dificultad del proyecto, controlando la capacidad se puede ajustar de forma adecuada la frecuencia de resonancia. Este condensador básicamente se encargaría de expandir el abanico de frecuencias posibles para el circuito, ya que con un condensador fijo como el que se utilizó, es muy difícil de captar la frecuencia deseada.

Otra posibilidad de diseño es la de incluir materiales piezoeléctricos como PZT y PVDF o polímeros electroactivos. La ventaja de usar materiales piezoeléctricos es la portabilidad y facilidad que tienen para ser instalados, pero tienen la desventaja de producir muy poca potencia en comparación con el alto voltaje que se emite.

El diseño finalmente usado tiene como finalidad extraer potencia eléctrica a partir de la energía mecánica empleada al caminar. De este modo, otra manera de extraer potencia que trabaja con voltajes pequeños fue empleada. En lugar de trabajar con PZT, se construyó un generador magnético. El diseño produce potencia eléctrica gracias al cambio en el flujo magnético que se produce al mover un imán en el interior de un solenoide. El dispositivo finalmente implementado puede ser fácilmente transportado y usa la energía empleada en el caminar para producir una señal AC que será posteriormente modificada para ser capaz de cargar una batería recargable de litio.

El diagrama de bloques del diseño se muestra en la Figura 1.

Cada bloque fue diseñado y probado por separado. Eagle software fue usado para el diseño del circuito aunque finalmente el montaje se produjo en una placa normal y en un vector board.

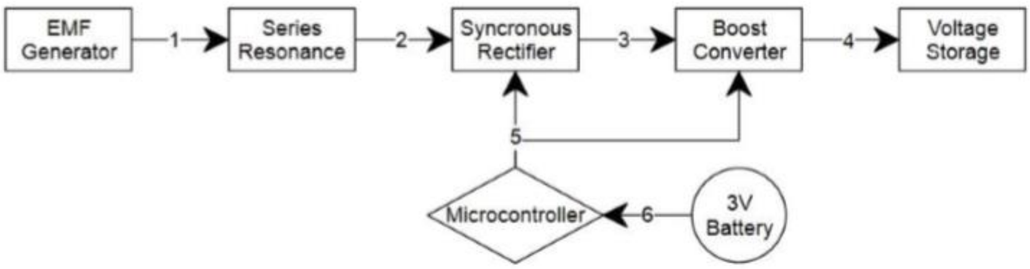

Figure 1 Top Level Block Diagram

Figure1:

1. Señal impulso AC
2. Señal AC amplificada
3. DC señal estable
4. DC señal amplificada
5. Señal de Pulse Width Modulation
6. Batería de 3V para alimentar el microcontrolador

Conclusiones

Después de la demostración del proyecto en la University of Illinois at Urbana-Champaign, todos las diferentes partes habían sido probadas y diseñadas por separado.

Aunque el proyecto no funcionó de forma completa, el diseño fue capaz de convertir energía mecánica en una pequeña señal de voltaje. Además, también fue capaz de rectificar y amplificar el voltaje al nivel deseado con una caída de tensión menor a los 0.7V establecidos por el "full bridge rectifier" que se había conseguido en proyectos pasados.

Cuando el "full bridge rectifier" con MOSFET en lugar de diodos intentó capturar tanto la parte positiva como la negativa de la entrada de AC , hubo una severa caída en la tensión en comparación con simplemente la captura de un lado de la entrada AC. Esto posiblemente puede ser debido a los retrasos de señal implementados por el microcontrolador, que permitieron al voltaje almacenado ser cancelado mediante la adición de tensión cada vez más negativa.

Referencias

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

[2] P. Sannuti ,"Series and Parallel Resonance" Rutgers University, December 2004.

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ABSTRACT

This project aims to implement a device that generates electromagnetic field then converts it to a stable DC voltage to be able to charge a Li-ion battery. The electromagnetic field generator will contain a strong magnet inside coiled tube so that when it moves, electromagnetic field is induced. Then this unstable impulse-like signal is put into AC/DC converter to be able to fed into the following boost converter. For AC/DC converter, synchronous rectifier is tried using MOSFETs instead of diodes to minimize voltage drop across, with alternative choice of simple full-bridge diode rectifier. The boost converter uses inductor, capacitor and switching transistor to step up the smaller DC input to higher DC output to charge a battery.

Having each component of the circuit working, future work is still needed to gather all the parts connected so that straight from the electromagnetic field generator, the battery can be charged as desired.

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Part I REPORT

1. Introduction

Nowadays, with the rise of green energy, there have been great strides in harnessing human power intelligently. With fossil fuel prices on the rise, the search for sources of alternative energy sources becomes increasingly more important. Commonly used sources include solar and wind power. With solar power, plants use calculations of the sun's predicted path to best aim their panels and maximize exposure. With wind turbines, using a motor system is necessary to rotate the wind base for matching wind direction. Technology has shown that with time comes a natural development to going about the same process. This project design, aims to go in a similar direction and try to apply these same principles to kinetic power harvesting. By revolving the project around a trite idea, a fresh perspective around how to approach power harvesting on smaller scales is hoped to be brought.

One new area of alternative energy is the energy collected from the everyday motions of the people. Every single day, people from all over the world expend many joules of energy walking, jogging and running. These are situations in which power supplies are not possible to be used. This projects seeks to find a way to harness all of that energy in order to convert it into electrical energy that can be used for multiple purposes, like charging a battery.

The idea of designing this project comes from the department of Power and Energy from the University of Illinois at Urbana-Champaign. They offered this project because despite the fact that many attempts had been tried in the past, none of them proved to be highly effective until date.

1.1 Statement of Purpose

The primary goal is for the project is to create a design that justifies the expenditure of energy that is used on the system. The functions include collecting energy using oscillating core inside an inductor. The main benefit is a more efficient energy extraction through a full range of motion. It features a very rough prototype for extracting kinetic energy that can hopefully lead to more similar designs in the future.

The design will gather the kinetic energy generated by the ankle's swinging and jumping that naturally happen during jogging movement, and store the voltage into a storage device. Alongside this, the project will attempt to capture smaller voltage impulses from walking, be as conspicuous as possible, and justify any power expended during its use by delivering a net power that is more than what a simpler design would have. The circuit will use MOSFETs in order to regulate the switches of the converters used.

The design needs to be safe for the user and that is why possible hazards and dangerous situations will be considered prior the design. Once the project is finished, it will be an object to be used in multiple and different times.

1.2 Motivations

In my senior year of college, I had the opportunity of study abroad in Illinois. There, I took courses like ECE 464: Power Electronics and ABE 425: Engineering Measurement Systems. I realized how important is to know about electronics for an electrical engineering. That is why I decided to do my senior project design about this idea.

Another motivation that made me choose the project is that the topic seemed very interesting for me since the very first beginning. There are countless situations in which we get frustrated because we run out of battery in our phone in a moment that we would like to use it. With this project, I would be able to use a portable device that uses the energy we waste walking to charge a storage device.

2. Objectives

Specifications

As the Project was suggested by the department of Power and Energy at the University of Illinois at Urbana-Champaign, some of the characteristics that the design needed to have were defined by them.

Below are shown the specific requirements that will be tried to be achieved with the final design:

- The EMF induced from the generator will be very small thus capturing the maximum from the generator is required.
- When converting from the AC signal to the DC signal there should be some ripple which needs to be minimized to be fed into the boost converter for voltage step-up.
- Boost converter should step-up the DC voltage to be able to charge the battery.
- Minimize the voltage drop across the circuit to maximize the efficiency is a priority.

Features

- Non-obstructing and portable design. This feature is the most important for the whole project. The design must be as light as possible.
- Adaptable system. The generator has to be able to capture voltage for a wide range of movements.
- Many uses for charging capacity. The output must be a constant DC voltage signal than can be used to charge a lithium battery but also other storage devices like a supercapacitor.

- The magnetic generator must include another feature in order to make it safer. Since it includes a very strong magnet, an isolating plastic tube must be added to this part of the project.

Benefits

The main benefit of this project is the fact that the device built is meant to generate the electricity from normal human walking motion. Thus, no extra effort is needed.

It also includes a low cost system thanks to which the whole design can be afforded by the majority of the people. For example, instead of buying a boost converter chip, the boost converter of the design is built part by part. This increases the complexity of the project and at the same time minimizes its cost. Alongside this, the whole project seeks to have low maintenance cost.

Finally, being eco-friendly is another benefit of the final design. It does not either pollute or produce toxic waste.

3. Design

Over the project's course different alternatives that could be used to the design have been considered, but they were not finally implemented. The first suggestion was to use a center tapped transformer. This would allow for a boosted voltage output, which would cause less loss over resistance, but in turn would increase the bulk of the system.

Another future design implementation would be the inclusion of a tunable capacitor inside of the resonance circuit. While this would mean more complexity and another feedback circuit, controlling the capacitance would allow a tool for fine tuning the resonance frequency. While it is extremely difficult to capture the random pattern from a random outside source in a resonant circuit, a tuning mechanism might expand the range of usable signal frequencies for this circuit.

Other method that was taken into account was to include piezo-electric materials such as PZT and PVDF or electro-active polymers. The advantage of using piezo-electric materials is the portability and un-obtrusive installation but they have the disadvantage of getting very low power extracted in comparison with the high voltage produced.

The design finally used is meant to be a possible method of extracting useful electrical power from the mechanical motion of walking. As such, other way of extracting power which works with considerable lower voltage levels was used. Instead of working with PZT, it was decided to build a magnetic generator that would produce an AC signal. This design produces electrical power by using the change in magnetic flux linkage caused by a magnet in a solenoid coil. The device built can be easily carried and uses the energy involved in everyday walking to generate an AC signal that will be later modified in order to be able to charge Lithium metal hydride rechargeable battery.

3.1 Block Diagram

The block diagram of the design used can be found in Figure 1.

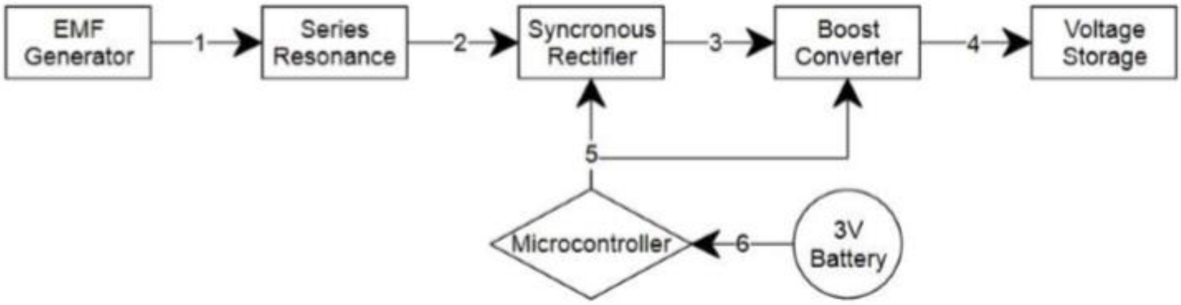


Figure 1: Top level block diagram

Figure1:

1. AC impulse signals
2. Amplified AC signals
3. A stable DC signal
4. Stepped-up DC voltage
5. Pulse Width Modulation signal
6. 3V battery to feed the microcontroller

3.2 Block Description

Emf Generator

It is basically a magnetic generator (a solenoid inductor) with a spring mass system that moves back and forth inside a wire to produce an induced voltage. The design needs to make sure that it reach a reasonable voltage winding in order to be connected to the rectifier. The magnet chosen has to be available in the market and it has to provide as much as magnetic strength as possible to optimize the voltage reached. We have settle down the magnet to be neodymium because of its extremely dense magnetic field. The design must also seek to be light-weight so that the user does not have problems to carry it while jogging.

INPUT	Mechanical motion (10cm, 2Hz)
OUTPUT	Decomposing Sinusoid T=(0.5s), Amp = (0.2V)

Table 1: Input and output of the Generator

Series Resonance Circuit

The point of the resonance circuit is to amplify incoming voltages from the emf generator by setting the resonant frequency to that of the spring mass system. This will cause constructive interference that we calculated for a runner with a step rate of 2 Hz.

INPUT	Decomposing Sinusoid T=(0.5s), Amp = (0.2V)
OUTPUT	AC with RMS of 2V

Table 2: Input and output of the Resonance circuit

Synchronous Rectifier

The synchronous rectifier takes input voltage from the resonant circuit and converts it into a DC signal. In order to do this, the circuit has two mosfet transistors that allow current to pass through them. We will synchronize the transistor with the input signal by using the microcontroller's AC input to measure the input voltage signal's rate of change. And in order to convert the output into DC, we will use a high capacity capacitor to smoothen the output signal.

INPUT	AC with RMS of 2V
OUTPUT	DC voltage from Rectifier (1.3V)

Table 3: Input and output of the Rectifier

Boost Converter

The DC voltage from the Rectifier will need to be stepped-up by the boost converter so that it will have enough voltage to charge the battery. This is done by choosing the value of capacitor and inductor to get the desired voltage output from small input. The converter contains two parts: inductor part and the output part. When the switch #1 which is a MOSFET is on, the inductor will charge up until the voltage across gets same as the input voltage. Then we open the switch#1 and the current will go through the diode which is the second switch. Then the capacitor will charge up, then the output voltage will be the input voltage + the capacitor voltage which will be higher than the input voltage.

INPUT	DC voltage from Rectifier (1.3V)
OUTPUT	Stepped-up DC voltage (2.5V)

Table 4: Input and output of the Boost Converter

Microcontroller

The microcontroller is responsible for controlling the switching time of the MOSFETS. Both the Boost Converter and the Synchronous rectifier include in the design transistors, thus, microcontroller will be used for these parts of the circuit.

1. Rectifier

The microcontroller functions by measuring voltage output of the resonance circuit. By measuring the rate of change of voltages, we are able to define when the voltage amplitude will be at its peaks and allowing the main positive changes in voltage to pass while blocking negative changes in voltage or voltages that are too low.

2. Boost Converter

The microcontroller will send signal to the boost converter to send a voltage signal that will short and open the inductor circuit in order to create compressed boosts in current that will be big enough to store on the lithium battery.

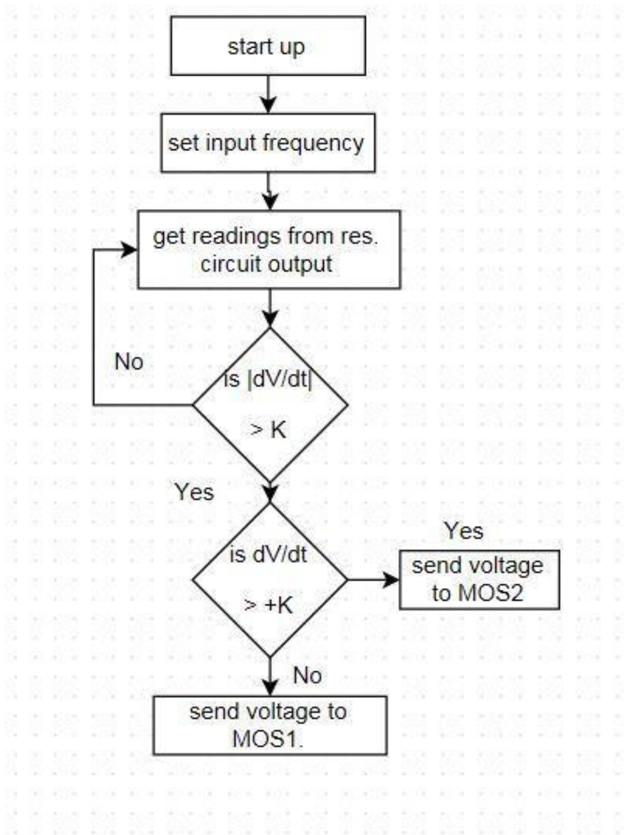


Figure 2: Flow chart of the microcontroller

3.3 Schematics

Below are represented the schematics for the different parts of the project:

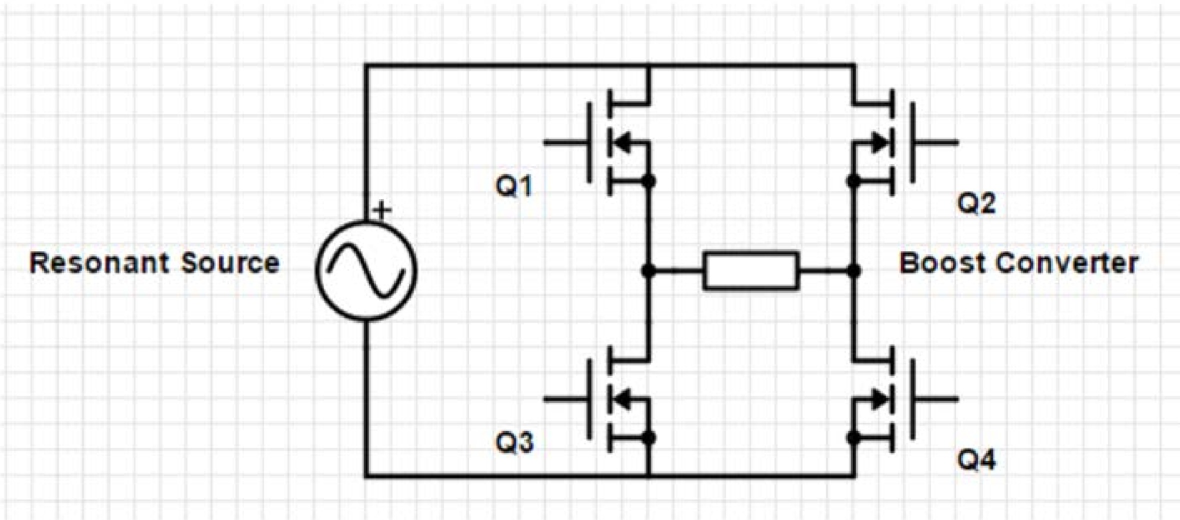


Figure 3: Synchronous Rectifier with MOSFETs

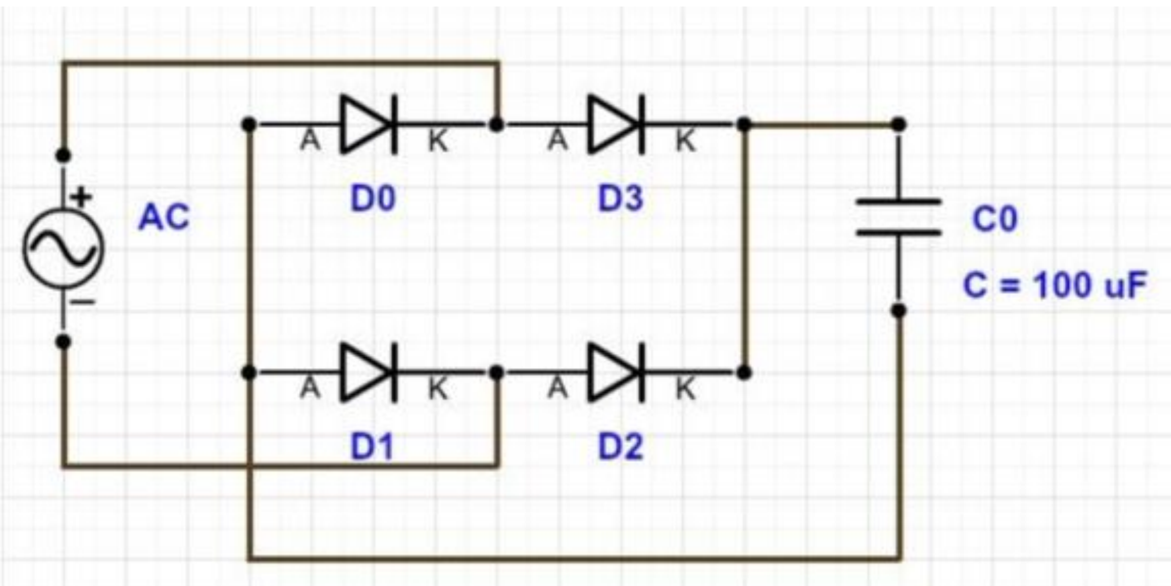


Figure 4: Schematic of Full-Bridge Diode Rectifier

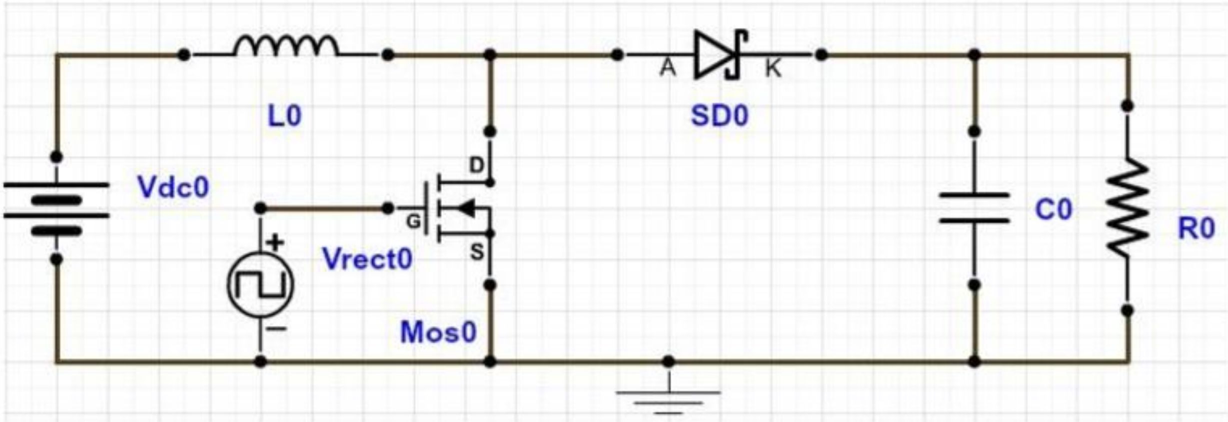


Figure 5: Schematic of Boost Converter

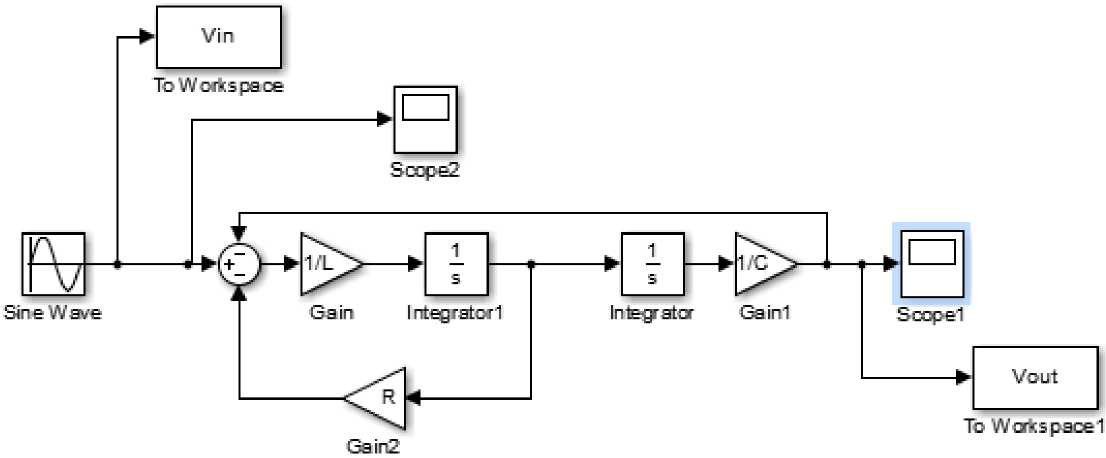


Figure 6: Block diagram for the Series Resonance Circuit

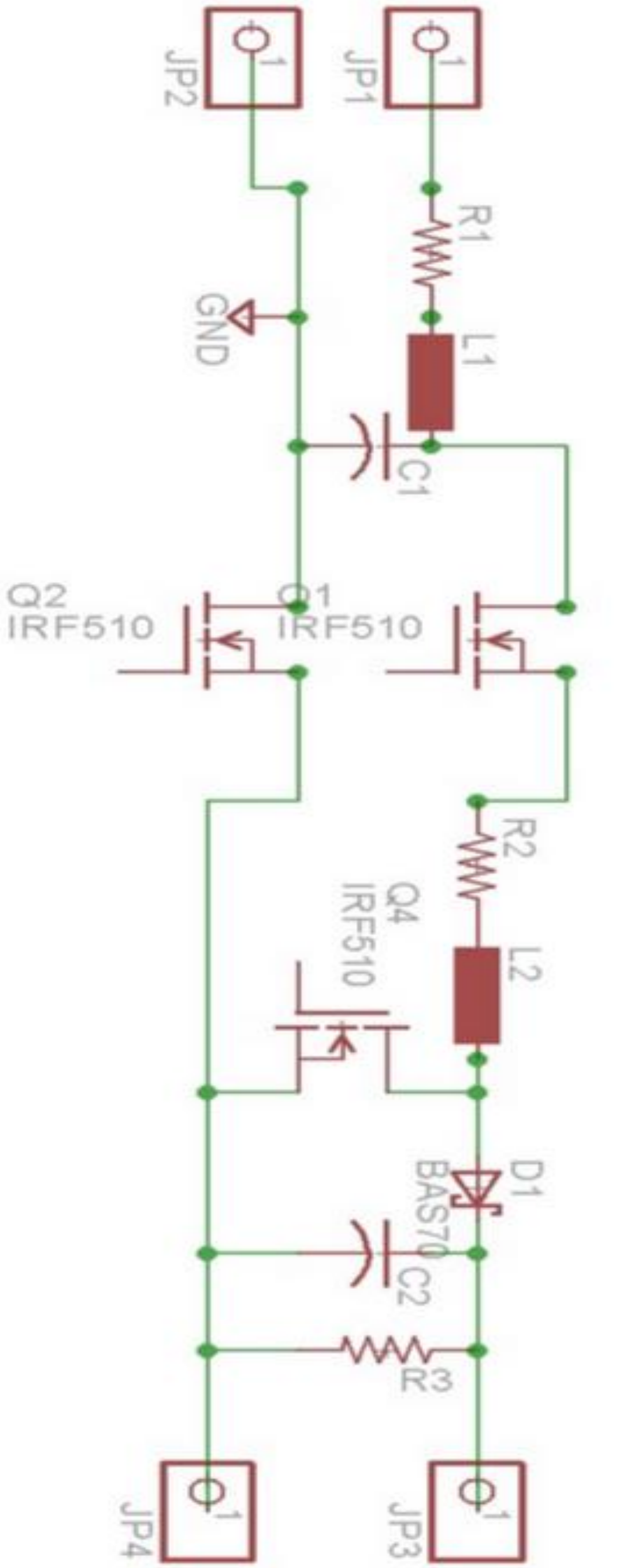


Figure 7: Eagle schematic of the whole circuit

4. Calculations

4.1 Magnetic Generator

The idea here is to use a spring-mass system that moves back and forth to produce an induced voltage in a solenoid inductor.

First of all it was necessary to do research on what kind of magnet was needed for the design. Neodymium magnets are the strongest magnets available on the market, so quite a few of them were bought to test the voltage with different magnetic fields. In the beginning, we ordered spherical magnets. However, in the machine shop of the Electrical Engineering building of the University of Illinois at Urbana-Champaign they could not hook up the spherical magnet with the spring so it was used for the design a disc magnet instead.

Once the magnet was chosen, it was possible to calculate the voltage induced. According to Faraday's law of Electromagnetic Induction, we can calculate the voltage and current in the coil thanks to a changing in the magnetic flux. For a magnetic dipole, the magnetic field at any point from the source is given by the following expression:

$$B(r) = \frac{\mu_0 MVol}{2\pi r^3} \qquad \text{(eq.1)}$$

Where

M: Magnetic field strength in the surface.

Vol: Volume of Magnet.

r: Distance from the magnetic source.

$\mu o = 4\pi 10 \wedge -7$ (Magnetic permeability in the free space)

Alongside this, Faraday's law of Electromagnetic Induction, that allows us to calculate the induced voltage in a coil, has the following expression:

$$\varepsilon = -N\frac{d\phi}{dt} \qquad \phi = BA \quad => \quad \varepsilon = -N\frac{\Delta B \times A}{\Delta t} \qquad \text{(eq.2)}$$

Where

ε: Electromagnetic force induced in the coil [V]

ϕ :Magnetic flux [Wb]

t: Time[s]

N: Number of turns [-]

A: Area of the surface where the magnetic field passes through [m2]

B: Intensity of the magnetic field [T]

Since the objective is to capture the highest voltage possible, there are two parameters from eq.2 that can be modified: the number of turns around the coil and the magnetic field strength, which depends on the type of magnet used. Next step for the design of this part of the project is to do some research on magnets, copper wire and springs.

Magnet

As mentioned before, Neodymium magnets are the strongest magnets available. They can be used for multiple purposes because of their great strength and small size. For this project it is necessary a magnet that was simultaneously very strong and easy to carry. Finally, it was used a D88-N52 disc magnet. Magnetic field visualization for D88-N52 magnet can be found in appendix 3.

The characteristics that matter for the design are:

Dimensions: ½" dia. x ½" thick

Surface field: 6619 gauss (=0.6619 T)

Therefore, the volume of the magnet is 1.669e-6 m3

Since the design had to be light and easy to carry, the casing was kept as small as possible. Once it was built, the distance that the magnet travels when the generator is shaked from its steady state can be measured, and we got that r=8cm.

With this value, and knowing that M=0.6619T, we can calculate the magnetic field in the top and bottom part of the magnetic generator (according to eq.1), that it turns to be B(r=8cm)=4.315e-10T.

Once that we know the magnet in the top point, it is easy to calculate the difference of magnetic field that will go to eq.2 (B=M-B(r=0.08)).

Wire

When choosing the type of wire that was going to be used for the design, it was necessary to do some research on magnet wires, finding out that the midrange of wires available go from 15AWG to 30AWG. The wire required had to be easy to manually wind the coil so the design was built with with 28AWG magnet wire.

Appendix 6 includes a tableau with the different properties of each type of wire.

With the wire we can calculate the number of turns N that we put around the coil dividing the length of the tube (12cm) by the diameter of the wire (0.321mm). The result is that 374 turns were put, much more than the 100 turns that were assumed for initial calculations.

Spring

The third thing we needed in order to complete the design of the generator was a spring that allowed the movement of the magnet inside the plastic tube. In the beginning, some springs were bought online, but after trying them, they did not act as expected, because there are many mechanical variables like the air friction that were not considered for simulations. For this reason, the alternative was to go to the machine shop of the ECE building at University of Illinois, and there try with different springs they had in stock until it was found one that matched the preferences. The one that we finally used has:

OD (outer diameter): 0.3”
Wire diameter: 0.012”

Once that the different parts were decided and bought, the emf expected from (eq.2) can be calculated. Setting the frequency of jogging to 10Hz, we have that the emf expected is 0.702V peak to peak.

Figure 8: Magnetic Generator Design

The isolating plastic tube that can be appreciated in the picture was built by the people who work in the machine shop of the ECE building. They had many things in stock that can be used by 445 students.

With the voltage calculated, we can estimate the instantaneous power extracted. The solenoid wire resistance for our 28AWG wire is:

R= 212.9Ω/Km * 0.022324 Km = 4.75Ω

Induced = 0.702V/4.75Ω = 0.1478A

Pout = = 0.702V*0.1478A = 0.1W

From these calculations, we expect to get 0.1W of power at a maximum voltage of 0.702V and a current of 0.1478A.

4.2 Series Resonance Circuit

Now that we have calculated the voltage that the magnet is going to generate, we need to boost it in order to go into the rectifier. There are basically three different ways to increase the value of this voltage. One of them was to put a transformer, another one was to increase the number of turns in the material (N) and the last one was to include a series resonance circuit.

The idea of the transformer was rejected because of loses in the windings, that would affect to the current and to the efficiency, and idea of increasing N was not considered because we are already putting quite a lot of turns and if we tried to put more, the generator would be bigger and, therefore, more inconvenient to be carried. That is why it was decided to create a series resonance circuit, being the input the emf and the output connected to the rectifier.

The purpose of the series resonance circuit (RLC circuit) is to boost the AC voltage that the got from the magnetic generator in order to make it able to go through the rectifier, that requires around 2V to operate.

The alternative to this method, as it has been already mentioned, is to use a transformer, that once the project was finished, we can realize that it would have been a pretty much easier option. The explanation of this is that in the lab, it is very difficult to reach the frequency of resonance that the RLC circuit requires to boost the voltage to the level desired.
When designing the RLC circuit, the following equation was employed:

$$f = \frac{1}{\sqrt{4\pi^2 LC}} \quad \text{(eq.3)}$$

At the frequency of resonance, the impedance of the capacitor equals the impedance of the inductor. Thus, the total impedance of the circuit is minimum.

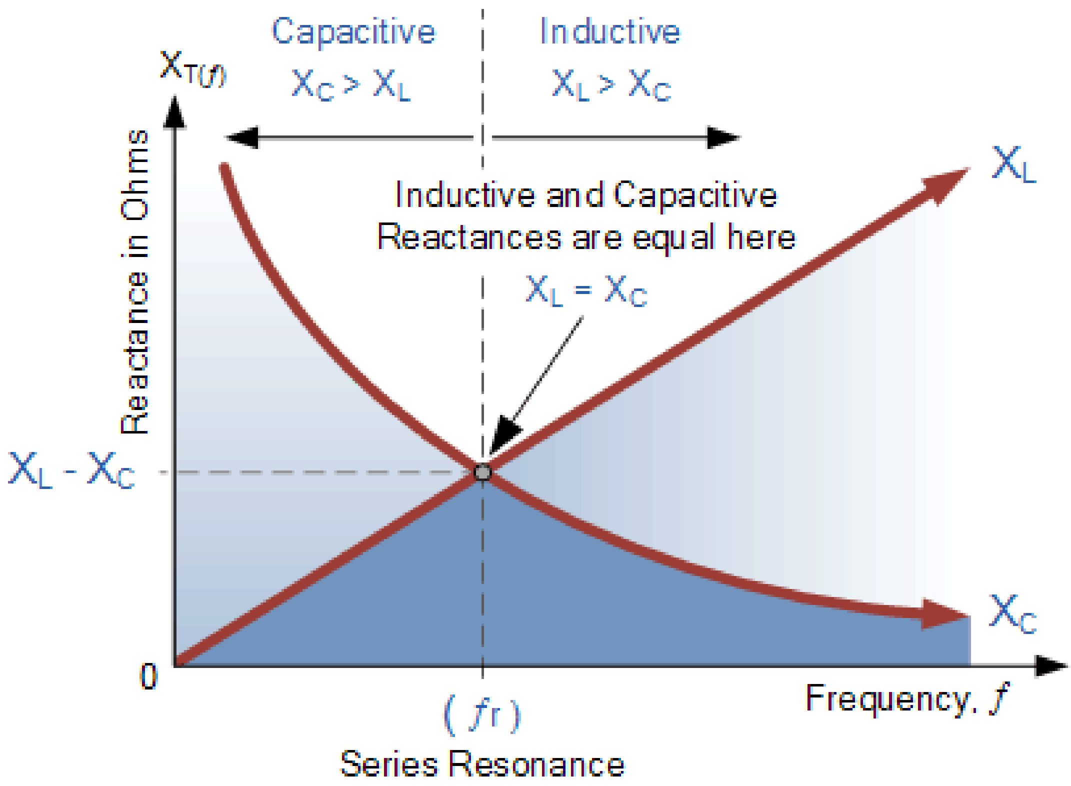


Figure 9: RLC analysis

From Figure 6, we can calculate the transfer function and thus, the bode diagram of the RLC circuit with MATLAB. The purpose of this is to find out the frequency of resonance of the circuit for a fixed value of inductor. We are assuming that the output of the magnetic generator is a pulse signal and the values of L and C are known.

The reason to do this is that it is very unlikely to get the exact frequency of the moment of the pulse from the image of the scope.

With this taken in count, we have:

L=0.01H
C=100µF
R=1Ω

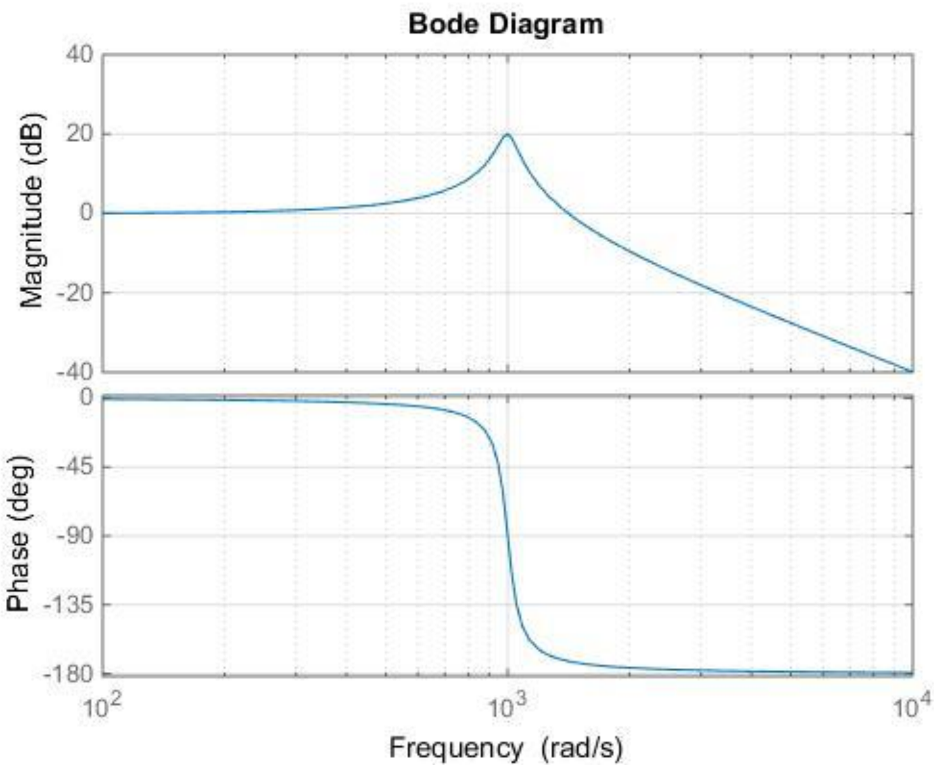


Figure 10: Bode diagram of the Series Resonance Circuit

The value of the resistor can be modified. Higher resistors mean lower currents, as we can see in the following picture.

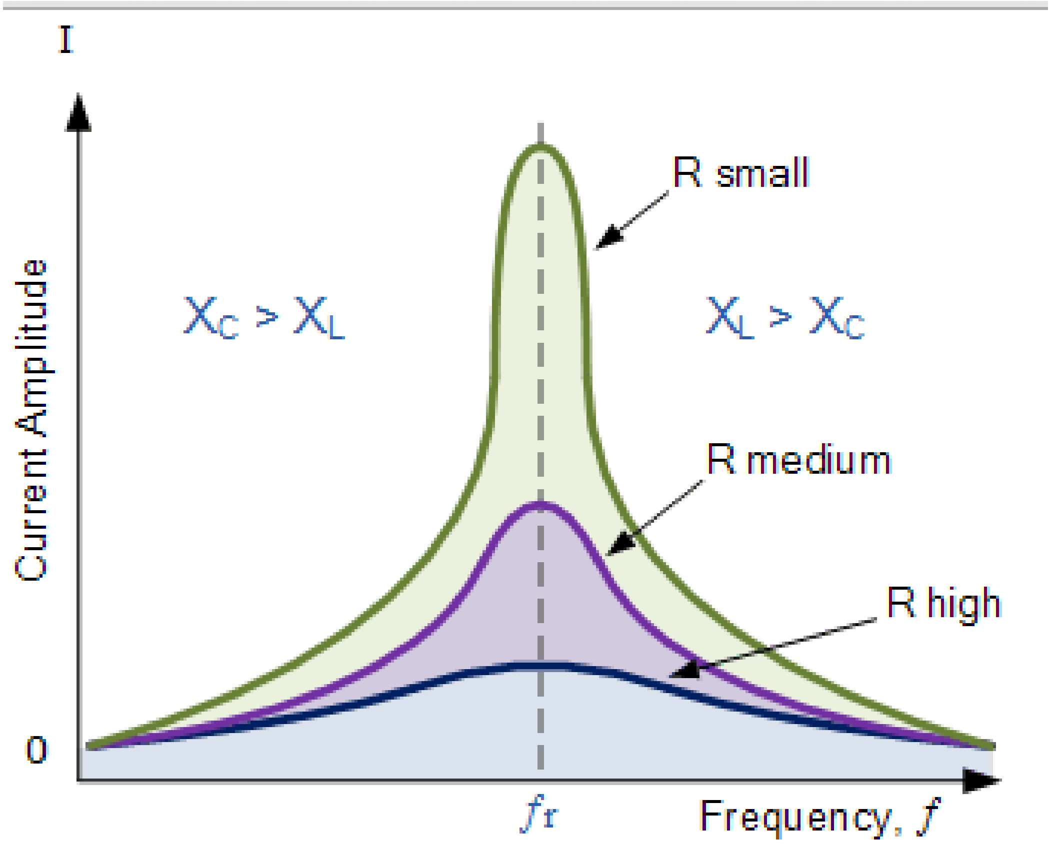


Figure 11: Current for different frequencies in a RLC circuit

4.3 Microcontroller

The microcontroller we used was the MSP430G2553, part of Texas Instrument's MSP430 low power line and is a line of standalone microcontrollers that can be integrated into a circuit without the use of a Launchpad or arduino.

The goal of our design was to utilize the microcontroller to accurately measure the voltage across the resonant circuit and to open MOSFET gates to allow the appropriately oriented current to pass through, rectifying the input voltage into a DC signal that can be stored onto a rechargeable battery. That said, when searching through microcontrollers the key deciding factors when searching through microcontrollers were the inclusion of an ADC converter, adequate sampling rate, and low power consumption.

One issue with the MSP430 that affected performance was the inability for the ADC's inability to digitalize negative voltages with reference to the chip's ground voltage, making it difficult to measure possibly resonant signals. As a solution, it was created a high resistance voltage divider that would offset the input signal by half of the microcontroller's reference voltage of 3.5 Volts. While this worked adequately to offset the AC signal, it was a large source of power loss in the control system.

According to the verification page created at the beginning of the design, the limitations for signal sampling and gate control could be a maximum delay of 3 milliseconds. as seen in figure 12, it was able to capture and open gates on average within 2.2 milliseconds.

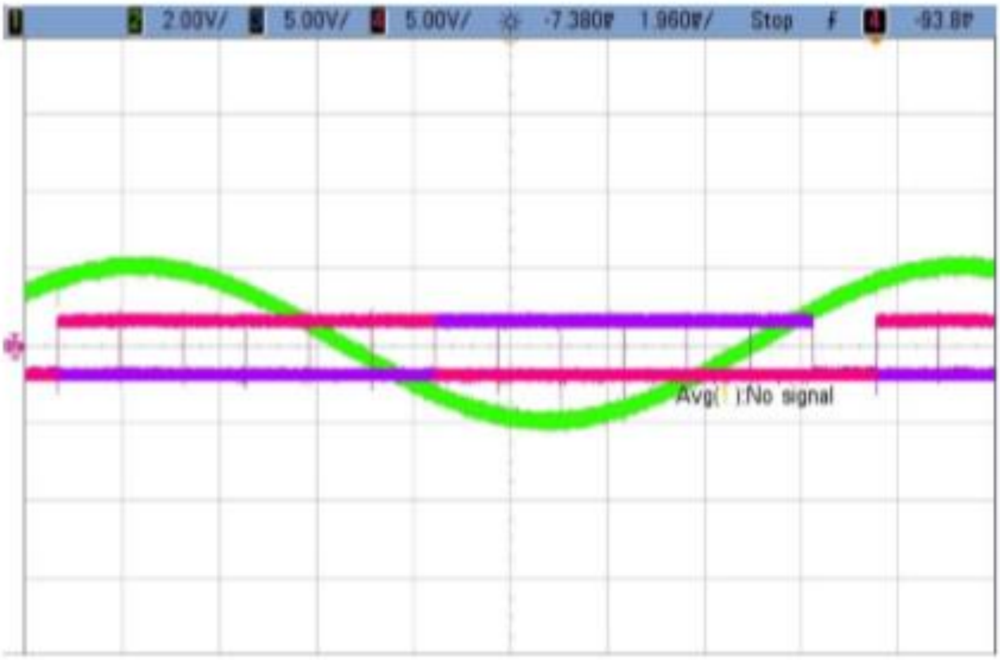


Figure 12: Output signal of microcontroller for MOSFET gate controls

The benefit of using MOSFETs for this system instead of diodes is that there is no minimum voltage that cannot get across the rectifier as long as the difference between gate voltage and source voltage is above voltage threshold. And because the MOSFET gate acts as an open circuit, there is no power loss accumulated from driving the gate voltage other than processing power.

$$I_{DS} = \mu_n C_{ox} \frac{W}{L} [(V_{GS} - V_T)V_{DS} - \frac{V_{DS}^2}{2}](1 + \gamma V_{DS}) \quad \text{(eq.4)}$$

4.4 AC/DC Rectifier

Following the series resonance circuit, amplified AC signal is to be converted into stable DC output so that it will be fed into the boost converter. Two kinds of rectifiers are implemented: full-bridge diode rectifier and synchronous rectifier with MOSFETs. A full-bridge diode rectifier is very easy to build and thus functionality is ensured, yet it requires about 1.4V of voltage drop across which is significant since the circuit deals with very small voltage. On the other hand, synchronous rectifier is more complex but has voltage drop of 0.2V which is comparatively lower than that of diodes'.

Full-Bridge Rectifier

The rectifier converts the AC signal into DC by diodes blocking the negative cycle of the signal and only allowing the positive cycle to the output. For the positive cycle, the signal will be sent to D3 from figure 3, passing the output capacitor C0 and coming back through D1. The negative cycle goes from D2 to the output and coming back through D0. The output capacitor is used to smoothen the output ripple. The signal goes through two diodes to complete a cycle resulting maximum of 2V of voltage drop [1].

Synchronous Rectifier

In order to try and capture both halves of an AC input, it was used a MOSFET adaptation of a full bridge rectifier. The schematic, as it has been already explained, it is the same but using MOSFETS instead of diodes.

4.5 Boost Converter

DC output from the rectifier goes into the boost converter to step up the voltage to be able to charge the battery. The boost converter has two phase depending on the state of the switch (a MOSFET transistor in the middle) that is driven by the microcontroller. When Pulse Width Modulation from the microcontroller is allowing the MOSFET to have the current going through it, the inductor on the left loop from the figure 3 will hold the energy from the DC input voltage, depending on its inductance. During this cycle, the diode (SD0 from figure 3) prevents current going reverse direction from the output capacitor. After capturing the energy for right amount of time, which is determined by the duty ratio, the microcontroller opens up the MOSFET and a larger loop (from figure 3, Vdc0, L0, SD0 to output). The output is larger than the input since it will contain both the original input voltage and the energy that has been held by the inductor. Output capacitor is also applied to control the output ripple.

Duty Ratio

The duty ratio determines how long the MOSFET is open for so that the current goes through. Its it critical since this will have to be the right amount of time to capture and hold the maximum energy in the inductor so that the circuit will always work in continuous mode. If the duty ratio is too short, the inductor will hold small amount of voltage which will eventually make the output voltage small as well. While the duty ratio is too large, the circuit will go into discontinuous mode in which the current across the inductor constantly hits zero after hitting the maximum point, thus wasting energy while the current is zero. When specific amount of output voltage is desired:

$$D_1 = 1 - \frac{V_{in}}{V_{out}} \qquad \text{(eq.5)}$$

Inductance

Along with the duty ratio, input inductance will also determine whether the circuit will go into discontinuous mode or not. An inductor that is too small will result in discontinuous mode since it will require smaller duty ratio because it can hold smaller energy. The inductance also controls current ripple across the inductor since the inductance is:

$$V_L = L * \frac{di}{dt} \quad \text{(eq.6)}$$

Larger inductance will reduce the rate of current change in time thus smaller current ripple. The critical inductance that will keep the circuit in the continuous mode and achieve the desired current ripple is:

$$L \geq \frac{V_{in} * \Delta t}{\Delta i} \quad \text{(eq.7)}$$

Where $\Delta t = D1*T$

Capacitance

Output capacitor is to achieve desired output voltage. Critical capacitance is:

$$C \geq \frac{i_{out} * D_1 * T}{\Delta V} \quad \text{(eq.8)}$$

Where iout is the approximated output current that can be calculated from power conservation from input side and output side.

Actual Values and Calculated Values

Parameters to calculate each component are:

Parameter	Values
Vin	1.3V
Vout	2.5V
T	1/(60KHz)
Δi	0.002A
ΔV	0.0025V

Table 5: Parameters to calculate boost converter components

When implementing real circuit, value of each component changed. Duty ratio was larger than calculated since efficiency of the circuit was to take into account. Since there was voltage drop across the circuit, to achieve desired output, MOSFET had to be open for longer period of time than calculated. Following longer duty ratio, a little larger inductance was used. Varying output capacitor, 100μF was the most suitable choice among available ones: 10μF, 100μF and 15000μF.

	Calculated Values	Actual Values
Duty Ratio	0.48	0.7
Inductance	5.2mH	100mH
Capacitance	2.5	100

Table 6: Values for boost converter components

5. Tests and Verifications

Magnetic Generator

Once that the solenoid was built, the output of the generator was connected to the oscilloscope to plot the voltage waveforms obtained. The movement of walking was simulated by manually shaking the generator

The results got are shown in the following picture:

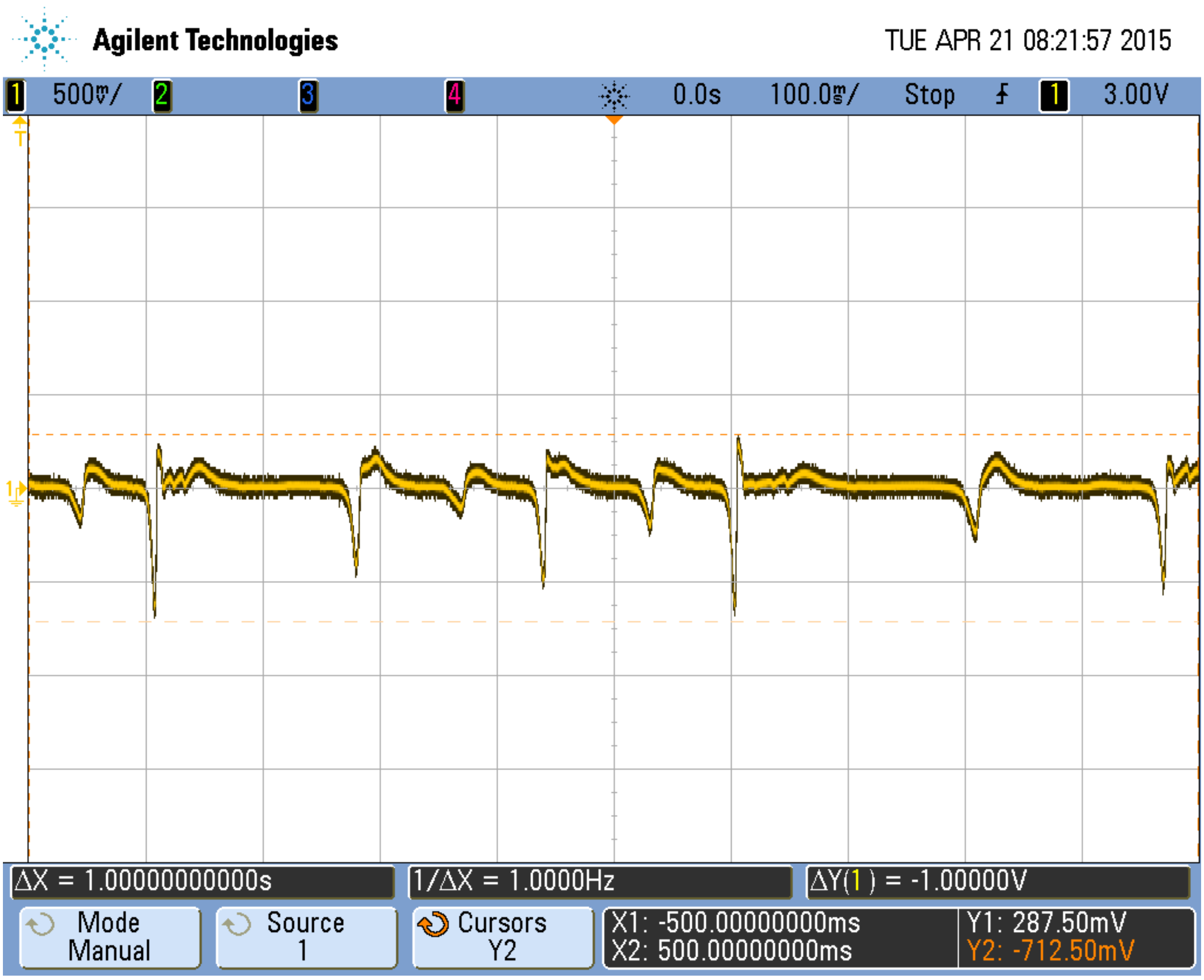


Figure 13: Magnetic generator simulation

We can appreciate that the voltage peak to peak is 1V, a little bit higher than calculated. The explanation of this is that it is very difficult to estimate how fast we have to shake the generator to have a frequency of 10Hz. Since the frequency might have changed, the voltage might vary as well. Our purpose was not to achieve the exact voltage calculated theoretically, but to prove that the generator works and it is able to plot a decent output waveform, so we consider this experiment a success.

Series Resonance Circuit

The series resonance circuit test is to verify that it actually works as a voltage amplifier. Since it was known that it was going to be highly unlikely to achieve the frequency of resonance shaking the generator, a pulse waveform was set the function generator instead and with the oscilloscope, it was possible to plot the voltage across the inductor.

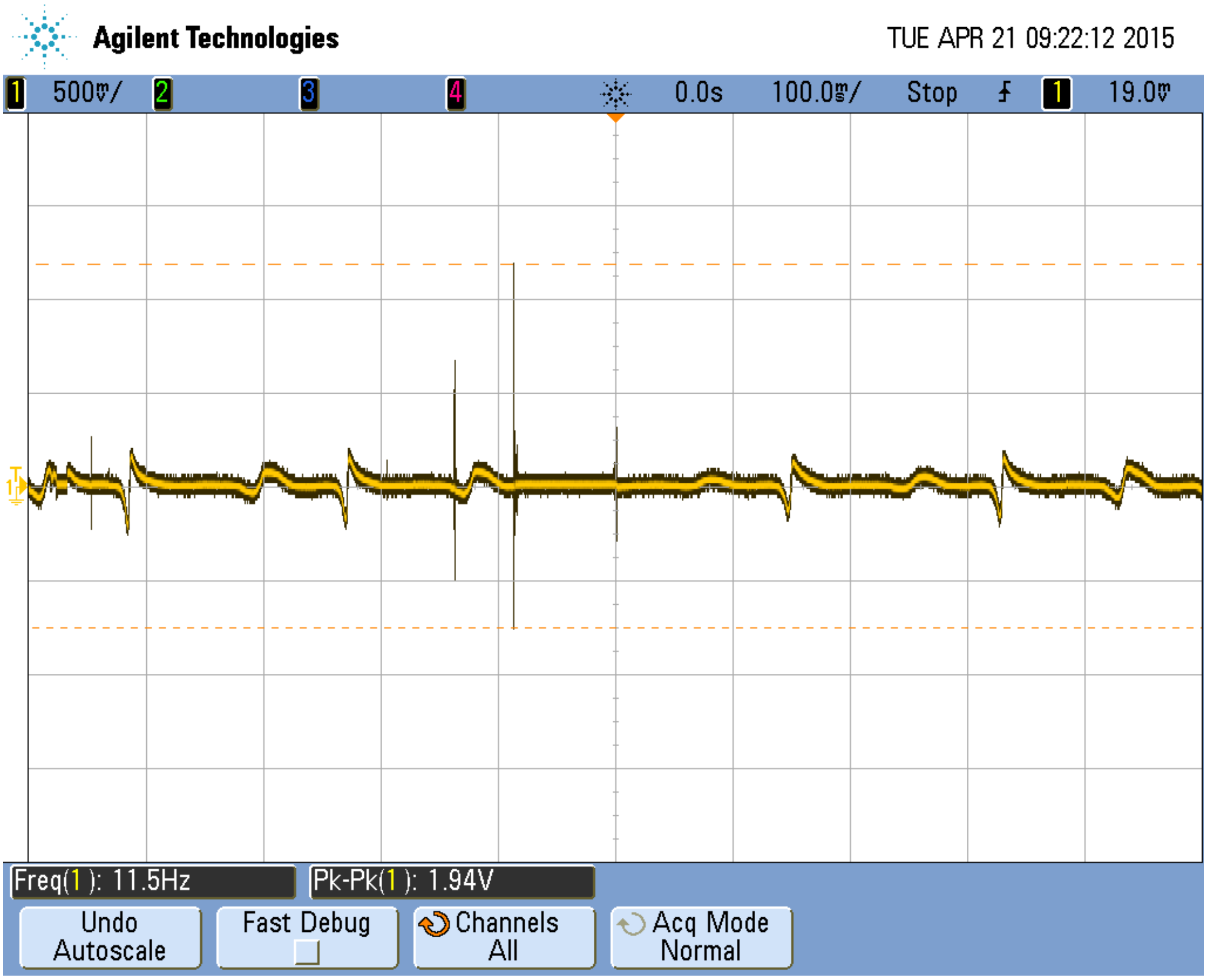


Figure 14: Series Resonance Circuit results

The peak to peak output voltage at a frequency of 11.5Hz turns to be 1.94V. This seems to be enough voltage to be rectified into a DC signal, but there are a lot of issues with this plot. For example, it was made the assumption that it was possible to capture only the pulse from the output of the magnetic generator and get rid of the rest of the waveform. Not only this, but also we can appreciate from the picture above that we only get one pulse of 1.94V. The rest of the voltage is not high enough to work for a rectifier.

As a consequence, it is strongly recommend for future designs to implement this part with a transformer instead of using a RLC circuit. Transformers are definitely bigger and heavier, but they do not have frequency issues. RLC works great theoretically and with computer simulations, but the problem appears when going to the lab because achieving the frequency of resonance is a task quite difficult.

Full-Bride Diode Rectifier

Trying to implement the synchronous rectifier with MOSFET rather than the diode rectifier, the main focus was to check the functionality of it, thus the voltage value was not one of the concerns.

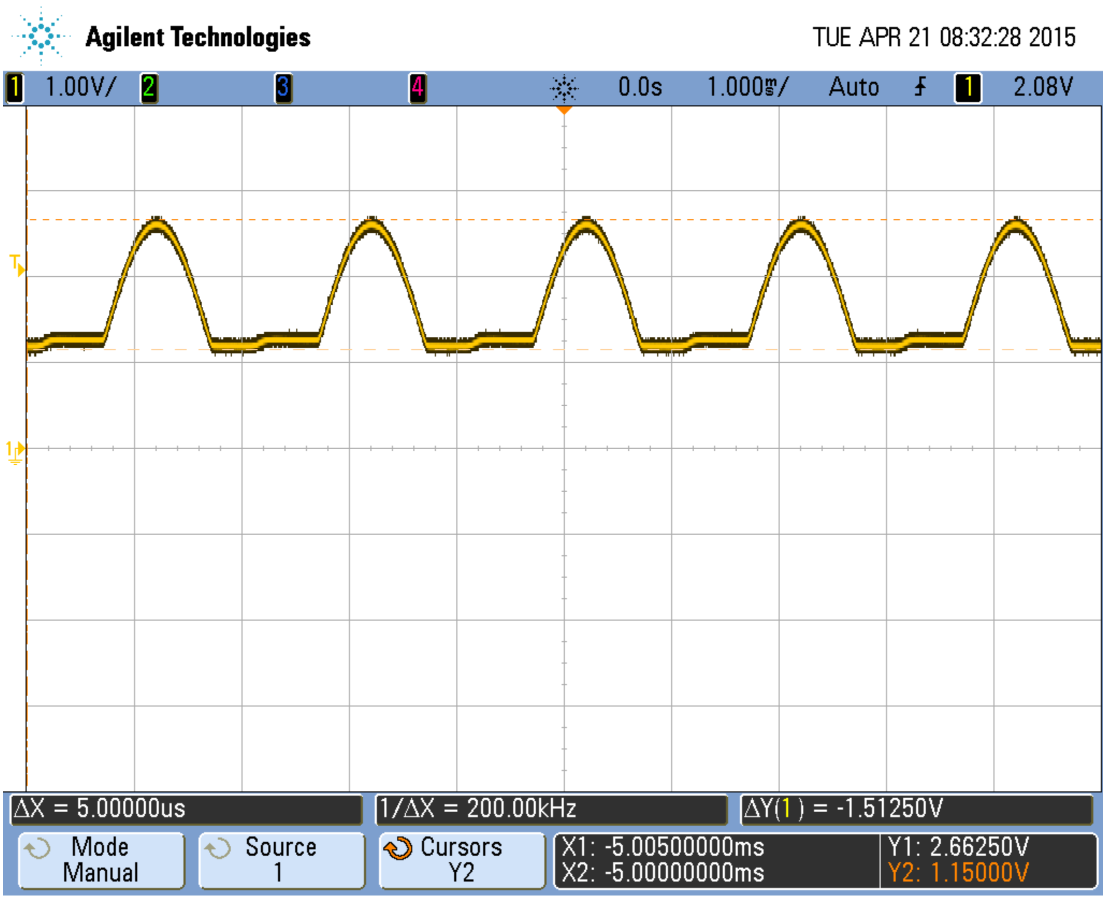


Figure 15: Output of the full-bridge rectifier

Figure 16 shows the output from the diode rectifier without the smoothing capacitor at the end. The rectifier correctly cuts out the negative phase of the sine wave input.

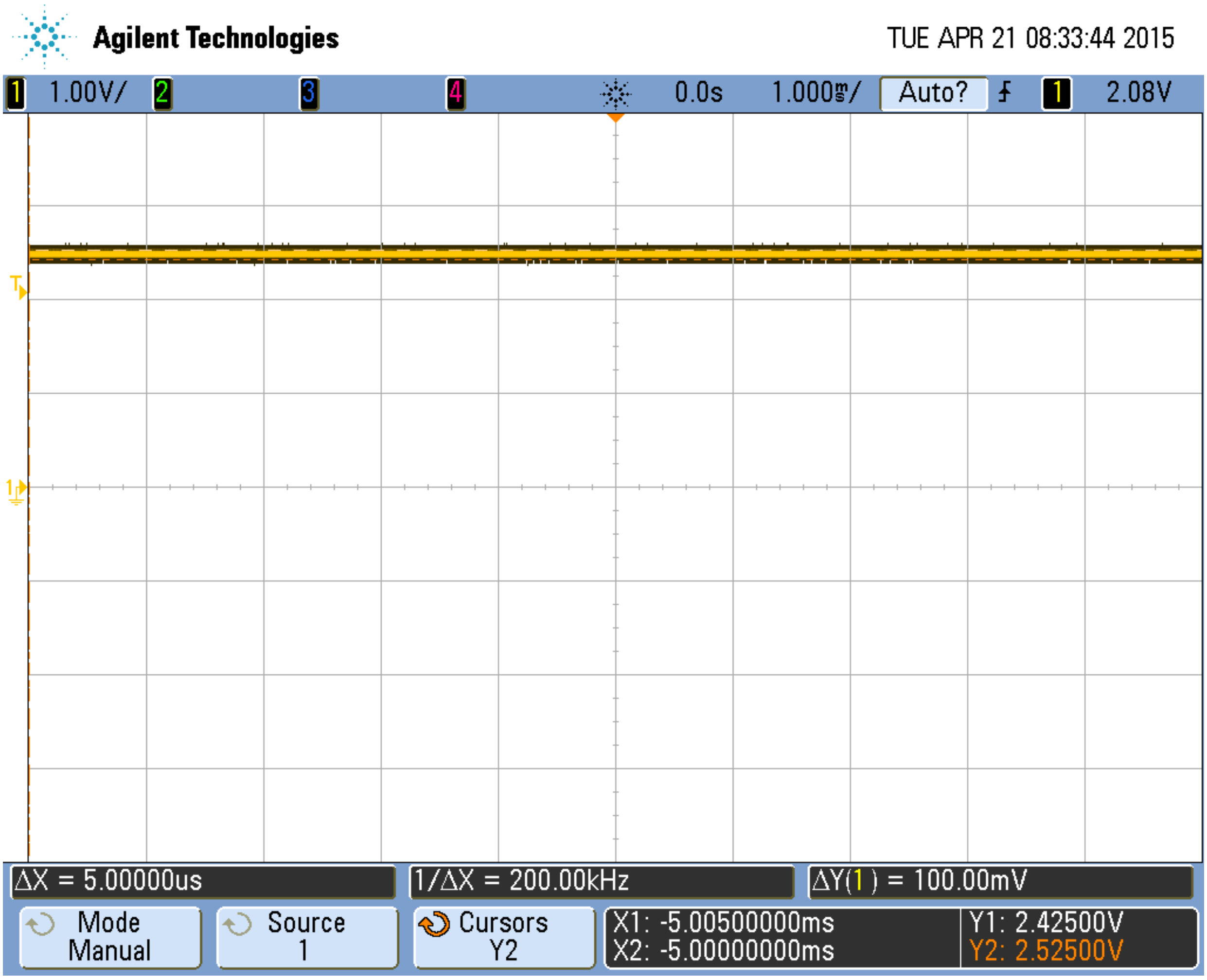


Figure 16: Output of the full-bridge rectifier with a smoothing capacitor

By having output 100 µF capacitor, output is more stable with less ripple.

Microcontroller

The output of the microcontroller was a bit unstable at moments as visible by the inconsistent sampling of the input signal. Even when under a stable AC input, there was a noticeable delay for the output signals. While it was acceptable by the design's verification, it might have caused problems when integrating with the boost converter system.

This is most likely a failure of the design of the coding and oversight on the natural delay of wires carrying the signals. In this particular case, it was acceptable because of the low frequency of the rectified signal, but would be worthless in higher frequency inputs.

Synchronous Rectifier

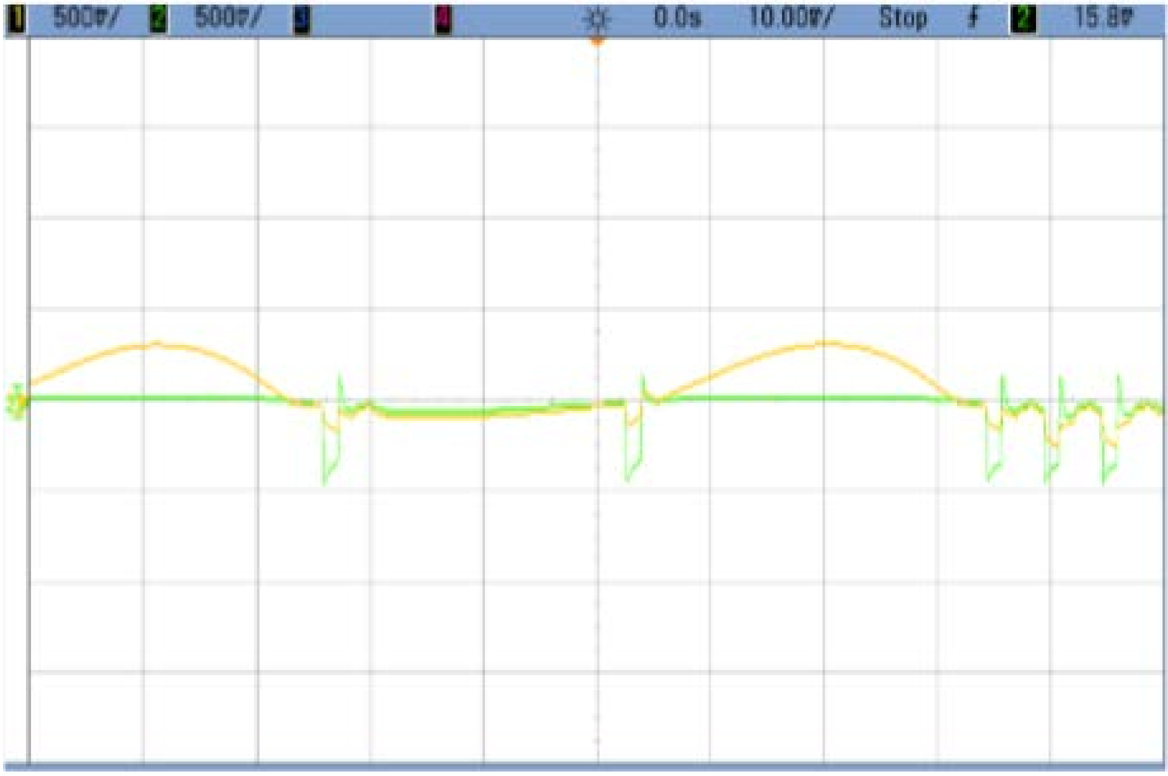


Figure 17: Signal across voltage source (yellow) 17 Hz, 600mVPP vs Voltage output of rectifier (green) .25mV D

Unfortunately, this consolidation of full bridge rectification and a digital system had its issues. While it did rectify the signal, when the rectifier attempted to capture both the positive and negative half of the AC input, there was a severe drop in voltage as compared to simply capturing one side of the AC input. This can possibly be due to the signal delays incremented by the microcontroller.

The reason why the original design was not used for a synchronous rectifier is that the coding design for both the synchronous rectifier and boost converter had autonomous functionality.

Meaning, in order to prove each part worked separately, the coding allowed both interrupts to occur within separate independent time cycles with no logic connecting either of their functionality.

With the synchronous rectifier and boost converter acting independently and with no type of storage unit in between the two, the system to capture and boost rectified voltage would have not worked as originally intended.

Boost Converter

Since the circuit was not able to work as a whole, boost converter was tested individually with a DC supply with 2V which is the approximated voltage level from the rectifier.

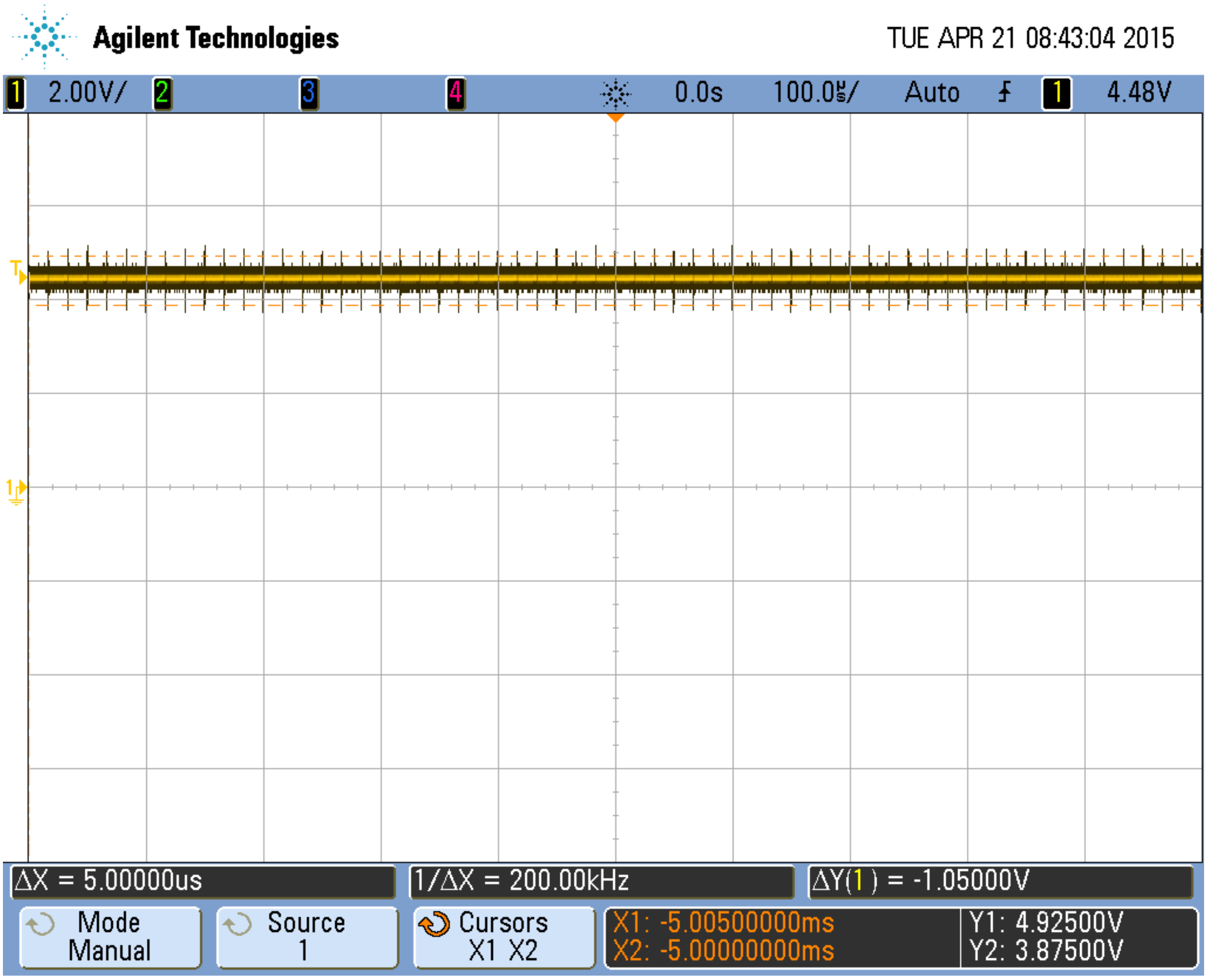


Figure 18: Output from the boost converter

Due to noise, ripple shown in the figure 12 is about 1V. The boost converter was able to produce desired voltage to charge a battery which has minimum voltage of 2.5V to charge.

6. Ethics and Safety

6.1 Ethics involved

The whole project has to comply with the IEEE Code of Ethics.

The ethical considerations for this machine are as follows:

- By stating it as a mechanical energy capturing source, we do not want to falsely assure that all mechanical energy is being converted, but that a narrow amount of mechanical movement at a specified frequency can currently be captured.
- By designing the product to be carry-able, we avoided false claims or threat of physical harm by limiting the designs weight and bulk.
- By labeling our product as eco-friendly, we will not claim that it is a completely self-reliant energy source, but one that tries to capitalize on digital systems to better capture mechanical energy.

By 2014, the IEEE had ten different codes listed. The ones that had to be taken into account when designing the product were:

1. To accept responsibility in making decisions consistent with the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment.

We must make sure that the design has no risk of shocking its users. We must uphold the design's intent to be environmentally friendly.

3. To be honest and realistic in stating claims or estimates based on available data.

We will be honest about the power consumption and power generation based on trials and test data.

7. To seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors, and to credit properly the contributions of others.

8. To treat fairly all persons and to not engage in acts of discrimination based on race, religion, gender, disability, age, national origin, sexual orientation, gender identity, or gender expression.

10. To assist colleagues and co-workers in their professional development and to support them in following this code of ethics.

6.2 Safety

The general lab safety manual must be follow when implementing the design.

In addition to that, when measuring the voltage from the induced EMF of the inductor, it is necessary to make sure that the testing procedure must not harm the tester. When dealing with the power circuit, it is also necessary to make sure to turn off the power source before handling anything in the circuit and to allow some amount of time for the capacitors to discharge.

7. Conclusion

7.1 Accomplishments

Although the entire project did not work collectively, the design was able to convert mechanical energy into a small voltage, and it was also able to rectify and amplify voltage below the .7 threshold voltage set by full bridge rectifiers in previous projects.

7.2 Uncertainties

When the MOSFET full bridge rectifier attempted to capture both the positive and negative half of the AC input, there was a severe drop in voltage as compared to simply capturing one side of the AC input, which output an expected half signal. This can possibly be due to the signal delays incremented by the microcontroller allowing voltage stored to be cancelled out by adding increasingly more negative voltage.

7.3 Future work

Over the project's course alternatives that could be used as alternates to our design have been considered, but that were not finally implement. The first suggestion to use a center tapped transformer in order to rectify the circuit with ground referenced to the center tapped. This would allow for a boosted voltage output, which in turn would cause less loss over resistance, but in turn would increase the bulk of the system.

Another future design implementation would be the inclusion of a tunable capacitor inside of the resonance circuit. While this would mean more complexity and another feedback circuit, controlling the capacitance would allow a tool for fine tuning the resonance frequency. While it is extremely difficult to capture the random pattern from a random outside source in a resonant circuit, a tuning mechanism might expand the range of usable signal frequencies for this circuit.

Part II PARTS & COMPONENTS

1. List of Parts

The parts have been either taken from the ECE building or have been bought online. For the parts used from the ECEB and for the magnetic generator tube, the price is an estimation based on similarities with other products that can be found on the market.

Part	**Manufacturer**	**Quantity**	**Cost Per Unit ($)**	**Total Cost ($)**
D88-N52 Magnet	K&J magnetics	1	3.98	3.98
28AWG Copper Wire	ECE Store	1	16.04	16.04
1 Ohm Resistor	ECE Store	5	1.07	5.35
0.01H Fixed Inductor	ECE Store	2	1.27	2.54
100 µF Capacitor	ECE Store	3	0.3	0.9
Magnetic Generator Tube	ECE Machine Shop	1	10	10
N-MOSFET	International Rectifier	5	1.13	5.65
1K Ohm Registor	ECE Store	3	1.07	3.21
15000µF	ECE Store	1	1.3	1.3
Microcontroller	Texas Instruments	1	2.8	2.8
Total				51.77

Table 7: List of Parts

2. Datasheets

The only datasheet included in any appendix is the N-MOSFET. Here is detailed part of the description for each of the parts bought to an online provider. For the microcontroller, a link with the 76 pages data sheet is included in the references.

D88-N52 Magnet

- Dimensions: 1/2" dia. x 1/2" thick
- Tolerances: ±0.004" x ±0.004"
- Material: NdFeB, Grade N52
- Plating/Coating: Ni-Cu-Ni (Nickel)
- Magnetization Direction: Axial (Poles on Flat Ends)
- Weight: 0.426 oz. (12.1 g)
- Pull Force, Case 1: 18.08 lbs
- Pull Force, Case 2: 20.38 lbs
- Surface Field: 6619 Gauss
- Max Operating Temp: 176ºF (80ºC)
- Brmax: 14,800 Gauss
- BHmax: 52 MGOe

28 AWG Copper Wire

- Diameter: 0.0126in
- Turns of wire: 79.1 per in
- Area: 0.081mm2
- Copper resistance: 212.9 Ω/km

N-MOSFET

- Drain-to-Source Breakdown Voltage: 40V
- Static Drain-to-Source On-Resistance typical: 1mΩ
- Continuous Drain Current at 25ºC: 414A

MICROCONTROLLER

- Low Supply-Voltage Range: 1.8 V to 3.6 V
- Ultra-Low Power Consumption
- Ultra-Fast Wake-Up From Standby Mode in C™ Less Than 1 μs

References

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

[2] P. Sannuti ,“Series and Parallel Resonance” Rutgers University, December 2004.

[3] “http://www.electronics-tutorials.ws/accircuits/series-resonance.html”

[4] FAIRCHILD, "BAS40SL Schottky Barrier Diode Datasheet," [online]. [Accessed February 2015]

[5] “Analyzing full wave-rectifiers with capacitor filters”

http://powerelectronics.com/power-management/analyzing-full-wave- rectifiers-capacitor-filters

[6] IEEE. (2014, February). 7.8 IEEE Code of Ethics. Retrieved from http://www.ieee.org/about/corporate/governance/p7-8.html

[7] Texas Instrument, Microcontroller MSP430G2553
“http://www.ti.com/product/MSP430G2553/technicaldocuments”

Credits

- Mr. Dennis Yuan (ECE 445 TA and grad student at University of Illinois at Urbana-Champaign)

- Professor P.Scott Carney (Professor in the Department of Electrical and Computer Engineering at the University of Illinois)

- Professor Philip T. Krein (Professor in the Department of Electrical and Computer Engineering at the University of Illinois)

- Mr. Brady Salz (ECE 445 TA and grad student at University of Illinois at Urbana-Champaign)

- Mr. Skee G. Aldrich (Laboratory Mechanic at the Machine Shop of the University of Illinois)

Appendix

1. Source Code

```
#include <msp430.h>

#define L_THRESHOLD = 520
#define H_THRESHOLD = 500
#define MAX_RISE = 4
#define MAX_FALL = -4
#define rate = 0

volatile unsigned short int adcVal;

int Control = 0;
int main(void) {

        volatile unsigned int i,count;
        volatile signed int scrub, ans;
                scrub = 0;
                count = 0;

                i = 0;

            WDTCTL = WDTPW + WDTHOLD;              // Stop WDT
            ADC10CTL0 = ADC10SHT_2 + ADC10ON + ADC10IE; // ADC10ON,
interrupt enabled
            ADC10CTL1 = INCH_3;                  // input A1
            ADC10AE0 |= 0x08;                   // PA.3 ADC option select pin 3
            P1DIR |= 0x41;                      // Set P1.0 to output direction
            P1OUT &=
~0x41;                                                //default off


        DCOCTL = 0;                          // Select lowest DCOx and MODx
        BCSCTL1 = CALBC1_8MHZ;                       // Set range
        DCOCTL = CALDCO_8MHZ;                        // Set DCO step + modulation

        P1DIR |= BIT2;                                    // P1.2 set as output
        P1SEL |= BIT2;                                    // P1.2 selected Timer0_A
Out1

        TA0CCR0 |= 130; //+ BIT6 + BIT7;                          // PWM Period
        TA0CCTL1 |= OUTMOD_7;                             // TA0CCR1 output mode
= reset/set
```

```
        TA0CCR1 |= 104;                                  // TA0CCR1 PWM duty
cycle
        TA0CTL |= TASSEL_2 + MC_1;                // SMCLK, Up Mode (Counts to
TA0CCR0)

        P2DIR |= BIT0+BIT2;                              //enable output PWM ports

        for (;;)
    {
     ADC10CTL0 |= ENC + ADC10SC;            // Sampling and conversion start
    // __bis_SR_register(CPUOFF + GIE);       // Low power mode 0, ADC10_ISR will
force exit
     i = 1000;
     while (i>0)
     {i--;}
     count = count + 1;
        if (ADC10MEM> 570){
                        P1OUT &= ~0x41;
                        P1OUT |= 0x01;
                        P2OUT &= ~0x05;
                        P2OUT |= 0x01;
                        scrub = ADC10MEM;
        }
                else if (ADC10MEM< 569){
                        P1OUT &= ~0x41;
                        P1OUT |= 0x40;
                        P2OUT &= ~0x05;
                        P2OUT |= 0x04;
                        scrub = ADC10MEM;
                }
                else {
                        P1OUT &= 0x00;
                        P2OUT &= 0x00;
                        scrub = ADC10MEM;}
    }
   }




#pragma vector=ADC10_VECTOR
__interrupt void ADC10_ISR(void)
{

//          __bic_SR_register_on_exit(CPUOFF);       // Clear CPUOFF bit from 0(SR)
optional
```

```
}
#pragma vector=TIMER0_A0_VECTOR     // Timer0 A0 interrupt service routine
__interrupt void Timer0_A0 (void) {
P1OUT ^= BIT2;                                         //boost rectifier
signal flip PWM

}
```

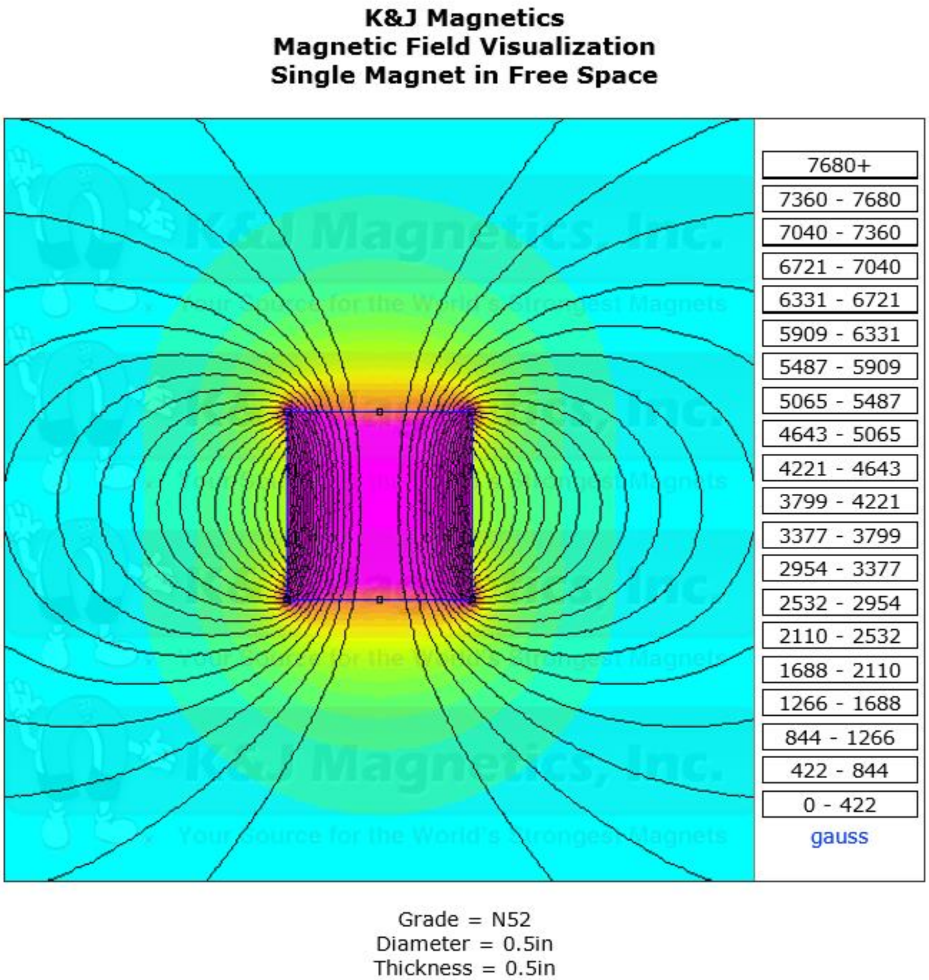
2. Requirements and Verifications Table

Requirement	Verification	Verification status (Y or N)
Magnetic Generator Having strong enough magnet and wire around the tube so that the generator will produce an EMF	Magnetic Generator Having two wires coming out from at each end of the generator, probing oscilloscope will verify that there is an induced EMF	Y
Series Resonance Circuit Correct values for resistor, inductor and capacitor to get desired amplification of the AC signal from the generator	Series Resonance Circuit Measuring input of the circuit with oscilloscope and compare it to the output. Output signal should have larger amplitude	Y
Synchronous Rectifier Correct switching of transistors so that it captures the positive cycle of the AC signal and convert the negative cycle into positive signals as well	Synchronous Rectifier Input a sine wave from the function generator and feed the signal into the rectifier. DC voltage meter to check the output. Also probing oscilloscope to see the shape of the output signal	N
Microcontroller Correctly producing Pulse Width Modulation signal to control MOSFETs	Microcontroller Probing oscilloscope to the output of the microcontroller to see the shape of the PWM generated	Y
Full-Bridge Diode Rectifier Correctly converts the AC signal input to DC output, minimize the voltage ripple with output capacitor	Full-Bridge Diode Rectifier Feeding the rectifier with function generator with sine wave then probe output with oscilloscope to see the DC output. Take the difference between minimum voltage and the maximum voltage of the output to check the ripple	Y

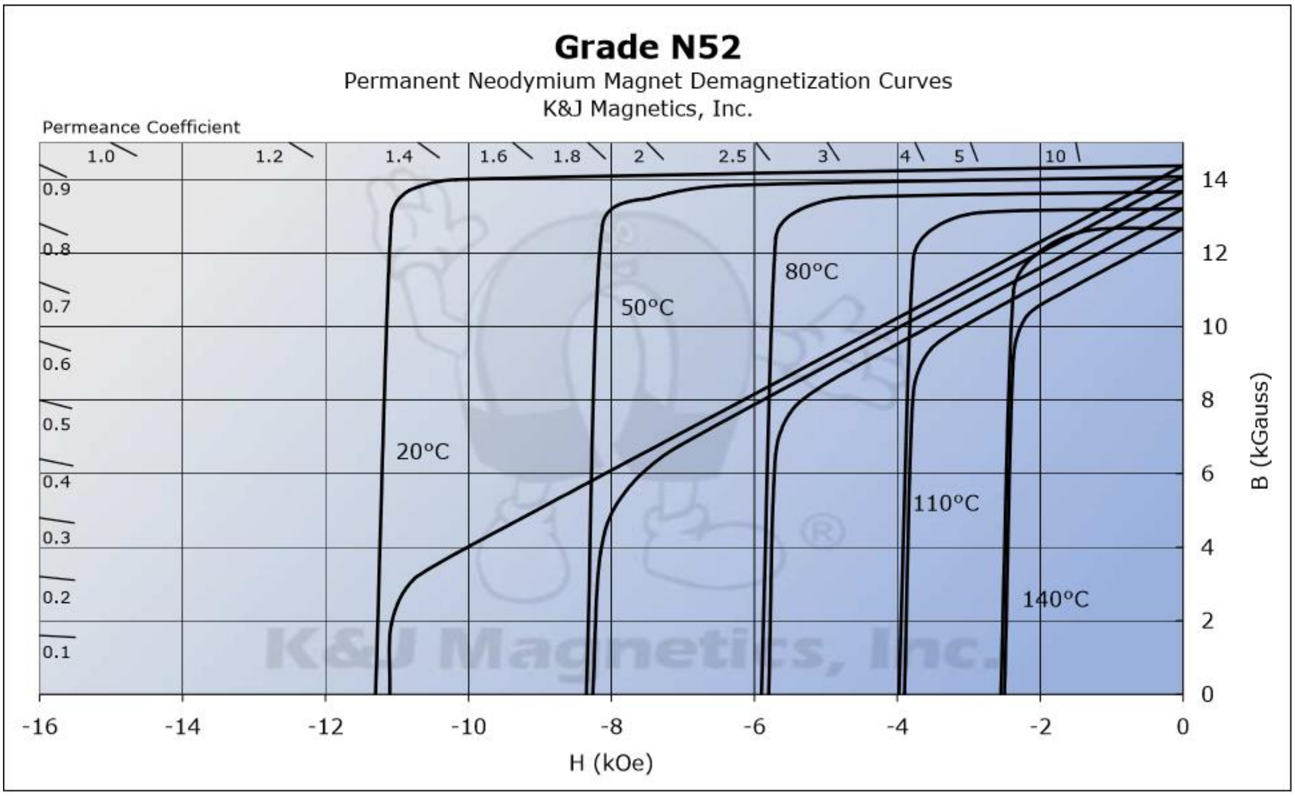
Boost Converter Step up the DC input to the desired output voltage level (over 2.5V) with required values of inductor and capacitor	Boost Converter Feed DC input to the boost converter, control the MOSFET with microcontroller with calculated duty ratio. Measure the output DC voltage	Y
Working as a whole Integration of the whole circuit from magnetic generator to the voltage storage(battery) at the end	Working as a whole Connect each component of the circuit. Generate the AC signal from the magnet and probe the output of the boost converter to see if it's producing desired voltage to charge up the battery	N

Table 8: Requirements and Verifications

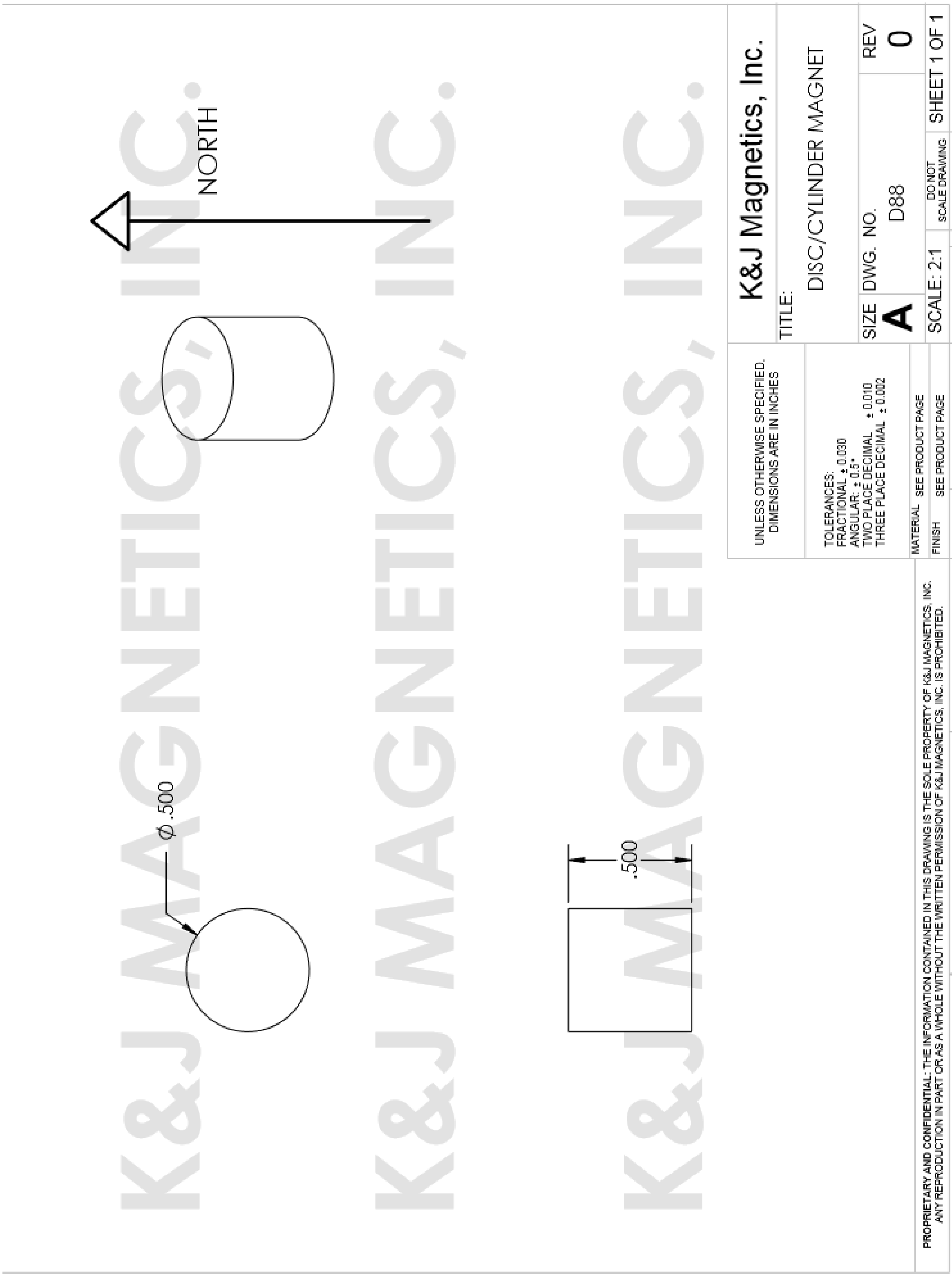
3. Magnetic Field Visualization



4. Demagnetization Curves



5. Magnet



NORTH
Ø .500
.500
K&J MAGNETICS, INC.
K&J Magnetics, Inc.
TITLE:
DISC/CYLINDER MAGNET
SIZE
A
DWG. NO.
D88
REV
0
SCALE: 2:1
DO NOT SCALE DRAWING
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ± 0.030
ANGULAR: ± 0.5°
TWO PLACE DECIMAL ± 0.010
THREE PLACE DECIMAL ± 0.002
MATERIAL SEE PRODUCT PAGE
FINISH SEE PRODUCT PAGE
PROPRIETARY AND CONFIDENTIAL: THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF K&J MAGNETICS, INC. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF K&J MAGNETICS, INC. IS PROHIBITED.
1
2
3
4
5

6. American Wire Gauge (AWG) Sizes and Properties Chart / Table

AWG	Diameter [inches]	Diameter [mm]	Area [mm^2]	Resistance [Ohms / 1000 ft]	Resistance [Ohms / km]	Max Current [Amperes]	Max Frequency for 100% skin depth
0000 (4/0)	0.46	11.684	107	0.049	0.16072	302	125 Hz
000 (3/0)	0.4096	10.40384	85	0.0618	0.202704	239	160 Hz
00 (2/0)	0.3648	9.26592	67.4	0.0779	0.255512	190	200 Hz
0 (1/0)	0.3249	8.25246	53.5	0.0983	0.322424	150	250 Hz
1	0.2893	7.34822	42.4	0.1239	0.406392	119	325 Hz
2	0.2576	6.54304	33.6	0.1563	0.512664	94	410 Hz
3	0.2294	5.82676	26.7	0.197	0.64616	75	500 Hz
4	0.2043	5.18922	21.2	0.2485	0.81508	60	650 Hz
5	0.1819	4.62026	16.8	0.3133	1.027624	47	810 Hz
6	0.162	4.1148	13.3	0.3951	1.295928	37	1100 Hz
7	0.1443	3.66522	10.5	0.4982	1.634096	30	1300 Hz
8	0.1285	3.2639	8.37	0.6282	2.060496	24	1650 Hz
9	0.1144	2.90576	6.63	0.7921	2.598088	19	2050 Hz
10	0.1019	2.58826	5.26	0.9989	3.276392	15	2600 Hz
11	0.0907	2.30378	4.17	1.26	4.1328	12	3200 Hz
12	0.0808	2.05232	3.31	1.588	5.20864	9.3	4150 Hz
13	0.072	1.8288	2.62	2.003	6.56984	7.4	5300 Hz
14	0.0641	1.62814	2.08	2.525	8.282	5.9	6700 Hz
15	0.0571	1.45034	1.65	3.184	10.44352	4.7	8250 Hz
16	0.0508	1.29032	1.31	4.016	13.17248	3.7	11 k Hz
17	0.0453	1.15062	1.04	5.064	16.60992	2.9	13 k Hz
18	0.0403	1.02362	0.823	6.385	20.9428	2.3	17 kHz
19	0.0359	0.91186	0.653	8.051	26.40728	1.8	21 kHz
20	0.032	0.8128	0.518	10.15	33.292	1.5	27 kHz
21	0.0285	0.7239	0.41	12.8	41.984	1.2	33 kHz
22	0.0254	0.64516	0.326	16.14	52.9392	0.92	42 kHz
23	0.0226	0.57404	0.258	20.36	66.7808	0.729	53 kHz
24	0.0201	0.51054	0.205	25.67	84.1976	0.577	68 kHz
25	0.0179	0.45466	0.162	32.37	106.1736	0.457	85 kHz
26	0.0159	0.40386	0.129	40.81	133.8568	0.361	107 kHz
27	0.0142	0.36068	0.102	51.47	168.8216	0.288	130 kHz

AWG	Diameter [inches]	Diameter [mm]	Area [mm^2]	Resistance [Ohms / 1000 ft]	Resistance [Ohms / km]	Max Current [Amperes]	Max Frequency for 100% skin depth
28	0.0126	0.32004	0.081	64.9	212.872	0.226	170 kHz
29	0.0113	0.28702	0.0642	81.83	268.4024	0.182	210 kHz
30	0.01	0.254	0.0509	103.2	338.496	0.142	270 kHz
31	0.0089	0.22606	0.0404	130.1	426.728	0.113	340 kHz
32	0.008	0.2032	0.032	164.1	538.248	0.091	430 kHz
33	0.0071	0.18034	0.0254	206.9	678.632	0.072	540 kHz
34	0.0063	0.16002	0.0201	260.9	855.752	0.056	690 kHz
35	0.0056	0.14224	0.016	329	1079.12	0.044	870 kHz
36	0.005	0.127	0.0127	414.8	1360	0.035	1100 kHz
37	0.0045	0.1143	0.01	523.1	1715	0.0289	1350 kHz
38	0.004	0.1016	0.00797	659.6	2163	0.0228	1750 kHz
39	0.0035	0.0889	0.00632	831.8	2728	0.0175	2250 kHz
40	0.0031	0.07874	0.00501	1049	3440	0.0137	2900 kHz

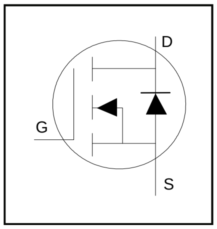
7. MOSFET Datasheet

StrongIRFET™
IRL40B209

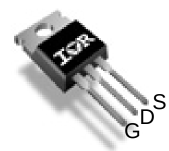
HEXFET® Power MOSFET

Application

- Brushed Motor drive applications
- BLDC Motor drive applications
- Battery powered circuits
- Half-bridge and full-bridge topologies
- Synchronous rectifier applications
- Resonant mode power supplies
- OR-ing and redundant power switches
- DC/DC and AC/DC converters
- DC/AC Inverters



V_{DSS}		40V
$R_{DS(on)}$ typ.		1.0mΩ
	max	1.25mΩ
I_D (Silicon Limited)		414A①
I_D (Package Limited)		195A



TO-220AB
IRL40B209

Benefits

- Optimized for Logic Level Drive
- Improved Gate, Avalanche and Dynamic dV/dt Ruggedness
- Fully Characterized Capacitance and Avalanche SOA
- Enhanced body diode dV/dt and dI/dt Capability
- Lead-Free
- RoHS Compliant, Halogen-Free

G	D	S
Gate	Drain	Source

Base part number	Package Type	Standard Pack		Orderable Part Number
		Form	Quantity	
IRL40B209	TO-220	Tube	50	IRL40B209

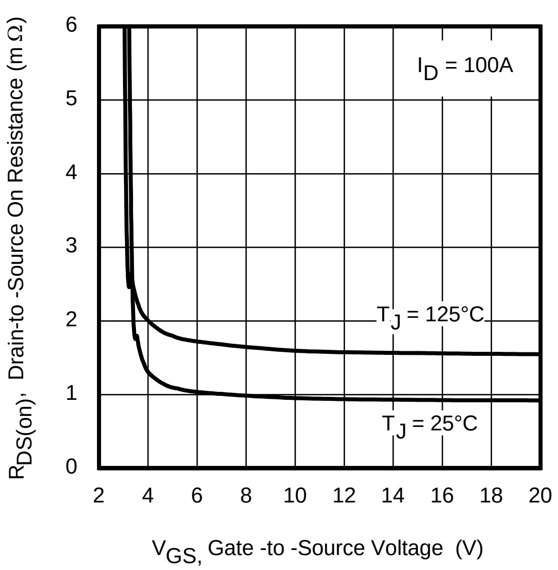


Fig 1. Typical On-Resistance vs. Gate Voltage

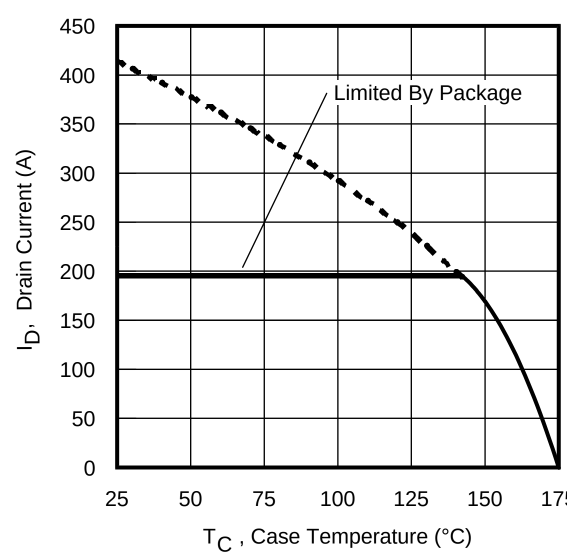


Fig 2. Maximum Drain Current vs. Case Temperature

Absolute Maximum Rating

Symbol	Parameter	Max.	Units
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 10V (Silicon Limited)	414①	A
I_D @ T_C = 100°C	Continuous Drain Current, V_{GS} @ 10V (Silicon Limited)	293①	
I_D @ T_C = 25°C	Continuous Drain Current, V_{GS} @ 10V (Wire Bond Limited)	195	
I_{DM}	Pulsed Drain Current ②	1707 ⑩	
P_D @T_C = 25°C	Maximum Power Dissipation	375	W
	Linear Derating Factor	2.5	W/°C
V_{GS}	Gate-to-Source Voltage	± 20	V
T_J T_{STG}	Operating Junction and Storage Temperature Range	-55 to + 175	°C
	Soldering Temperature, for 10 seconds (1.6mm from case)	300	
	Mounting Torque, 6-32 or M3 Screw	10 lbf·in (1.1 N·m)	

Avalanche Characteristics

$E_{AS\ (Thermally\ limited)}$	Single Pulse Avalanche Energy ③	730	mJ
$E_{AS\ (Thermally\ limited)}$	Single Pulse Avalanche Energy ⑨	1420	
I_{AR}	Avalanche Current ②	See Fig 15, 16, 23a, 23b	A
E_{AR}	Repetitive Avalanche Energy ②		mJ

Thermal Resistance

Symbol	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case ⑧	——	0.4	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat Greased Surface	0.50	——	
$R_{\theta JA}$	Junction-to-Ambient	——	62	

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

Symbol	Parameter	Min.	Typ.	Max.	Units	Conditions
$V_{(BR)DSS}$	Drain-to-Source Breakdown Voltage	40	——	——	V	V_{GS} = 0V, I_D = 250µA
$\Delta V_{(BR)DSS}/\Delta T_J$	Breakdown Voltage Temp. Coefficient	——	0.031	——	V/°C	Reference to 25°C, I_D = 5mA ②
$R_{DS(on)}$	Static Drain-to-Source On-Resistance	——	1.0	1.25	mΩ	V_{GS} = 10V, I_D = 100A⑤
		——	1.2	1.6		V_{GS} = 4.5V, I_D = 50A ⑤
$V_{GS(th)}$	Gate Threshold Voltage	1.0	——	2.4	V	V_{DS} = V_{GS}, I_D = 250µA
I_{DSS}	Drain-to-Source Leakage Current	——	——	1.0	µA	V_{DS} =40 V, V_{GS} = 0V
		——	——	150		V_{DS} =40V,V_{GS} = 0V,T_J =125°C
I_{GSS}	Gate-to-Source Forward Leakage	——	——	100	nA	V_{GS} = 20V
	Gate-to-Source Reverse Leakage	——	——	-100		V_{GS} = -20V
R_G	Gate Resistance	——	2.1	——	Ω	

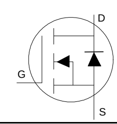
Notes:

① Calculated continuous current based on maximum allowable junction temperature. Bond wire current limit is 195A. Note that current limitations arising from heating of the device leads may occur with some lead mounting arrangements. (Refer to AN-1140)
② Repetitive rating; pulse width limited by max. junction temperature.
③ Limited by T_{Jmax}, starting T_J = 25°C, L = 0.15mH,R_G = 50Ω, I_{AS} = 100A, V_{GS} =10V.
④ $I_{SD} \leq$ 100A, di/dt $\leq$ 930A/µs, $V_{DD} \leq V_{(BR)DSS}$, $T_J \leq$ 175°C.
⑤ Pulse width $\leq$ 400µs; duty cycle $\leq$ 2%.
⑥ C_{oss} eff. (TR) is a fixed capacitance that gives the same charging time as C_{oss} while V_{DS} is rising from 0 to 80% V_{DSS}.
⑦ C_{oss} eff. (ER) is a fixed capacitance that gives the same energy as C_{oss} while V_{DS} is rising from 0 to 80% V_{DSS}
⑧ R_θ is measured at T_J approximately 90°C.
⑨ Limited by T_{Jmax}, starting T_J = 25°C, L = 1mH, R_G = 50Ω, I_{AS} = 53A, V_{GS} =10V.
⑩ Pulse drain current is limited at 780A by source bonding technology.

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

Symbol	Parameter	Min.	Typ.	Max.	Units	Conditions
gfs	Forward Transconductance	270	——	——	S	V_{DS} = 10V, I_D =100A
Q_g	Total Gate Charge	——	180	270	nC	I_D = 100A
Q_{gs}	Gate-to-Source Charge	——	51	——		V_{DS} = 20V
Q_{gd}	Gate-to-Drain Charge	——	88	——		V_{GS} = 4.5V⑤
Q_{sync}	Total Gate Charge Sync. (Qg – Qgd)	——	92	——		
$t_{d(on)}$	Turn-On Delay Time	——	56	——	ns	V_{DD} = 20V
t_r	Rise Time	——	198	——		I_D = 30A
$t_{d(off)}$	Turn-Off Delay Time	——	188	——		R_G= 2.7Ω
t_f	Fall Time	——	150	——		V_{GS} = 4.5V⑤
C_{iss}	Input Capacitance	——	15140	——	pF	V_{GS} = 0V
C_{oss}	Output Capacitance	——	1990	——		V_{DS} = 25V
C_{rss}	Reverse Transfer Capacitance	——	1370	——		*f* = 1.0MHz, See Fig.7
$C_{oss\ eff.(ER)}$	Effective Output Capacitance	——	2340	——		V_{GS} = 0V, VDS = 0V to 32V⑦
$C_{oss\ eff.(TR)}$	Output Capacitance (Time Related)	——	2900	——		V_{GS} = 0V, VDS = 0V to 32V⑥

Diode Characteristics

Symbol	Parameter	Min.	Typ.	Max.	Units	Conditions
I_S	Continuous Source Current (Body Diode)	——	——	414①	A	MOSFET symbol showing the integral reverse p-n junction diode. 
I_{SM}	Pulsed Source Current (Body Diode) ②	——	——	1707⑩		
V_{SD}	Diode Forward Voltage	——	——	1.2	V	T_J = 25°C,I_S = 100A,V_{GS} = 0V ⑤
dv/dt	Peak Diode Recovery dv/dt④	——	2.4	——	V/ns	T_J = 175°C,I_S = 100A,V_{DS} = 40V
t_{rr}	Reverse Recovery Time	——	41	——	ns	T_J = 25°C V_{DD} = 34V
		——	42	——		T_J = 125°C I_F = 100A,
Q_{rr}	Reverse Recovery Charge	——	46	——	nC	T_J = 25°C di/dt = 100A/μs ⑤
		——	50	——		T_J = 125°C
I_{RRM}	Reverse Recovery Current	——	2.0	——	A	T_J = 25°C

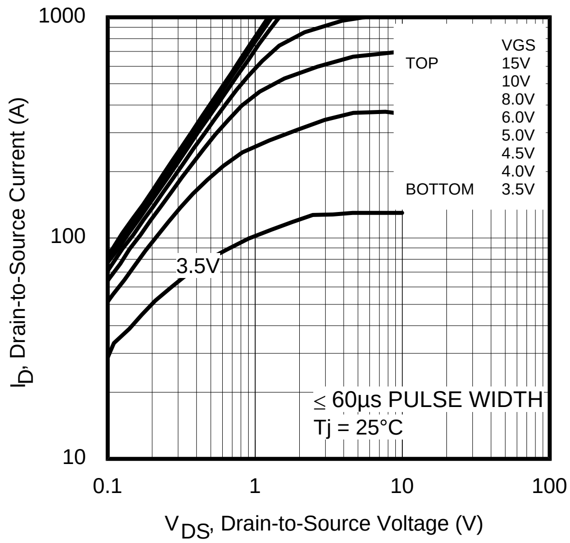


Fig 3. Typical Output Characteristics

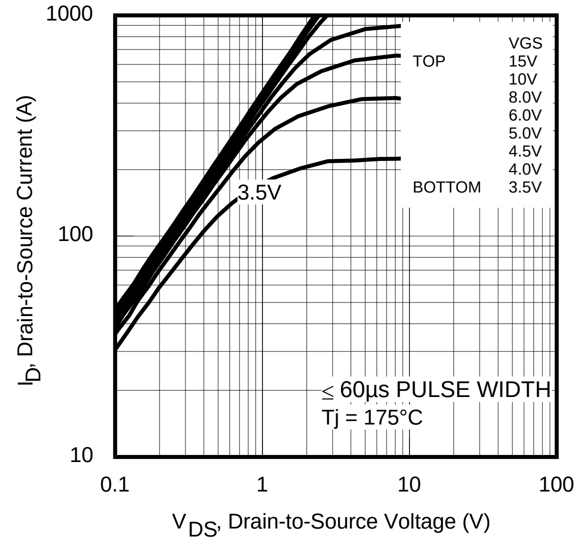


Fig 4. Typical Output Characteristics

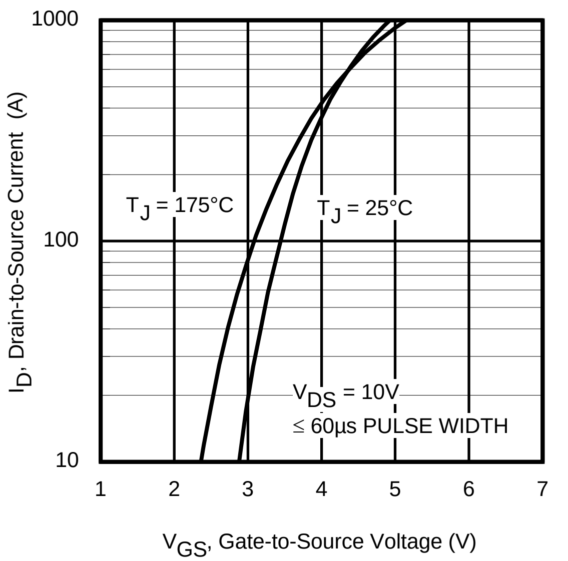


Fig 5. Typical Transfer Characteristics

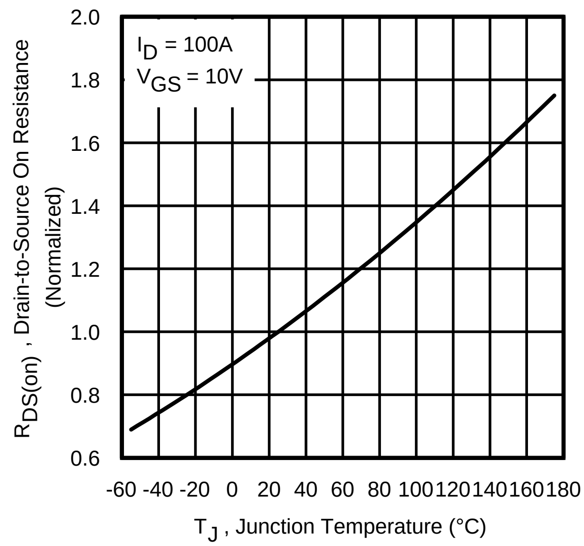


Fig 6. Normalized On-Resistance vs. Temperature

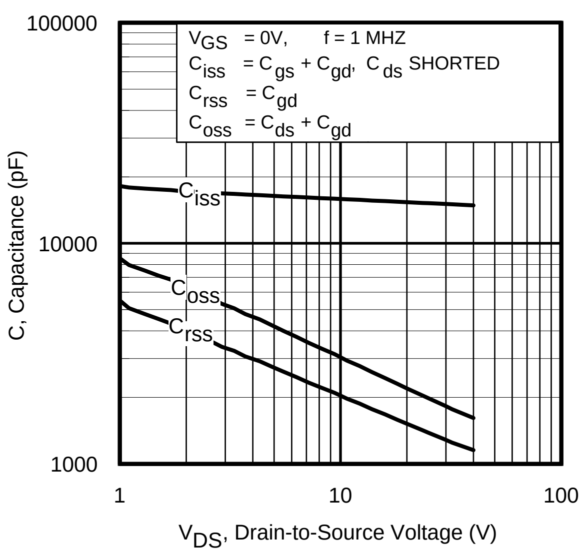


Fig 7. Typical Capacitance vs. Drain-to-Source Voltage

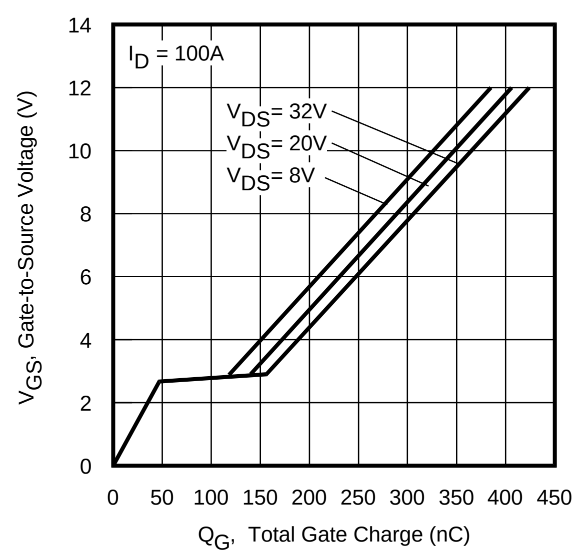


Fig 8. Typical Gate Charge vs. Gate-to-Source Voltage

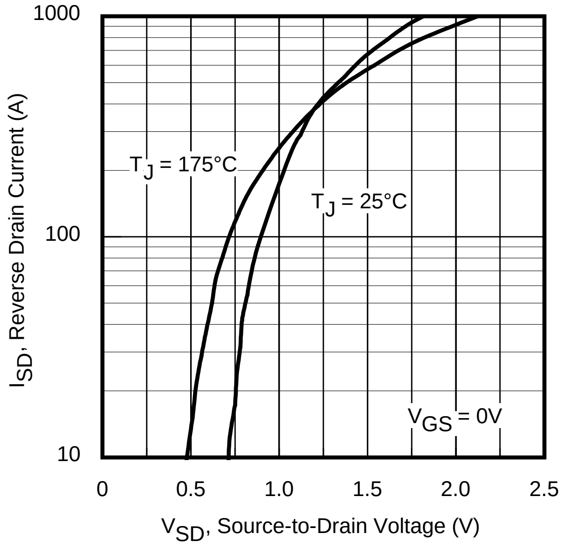


Fig 9. Typical Source-Drain Diode Forward Voltage

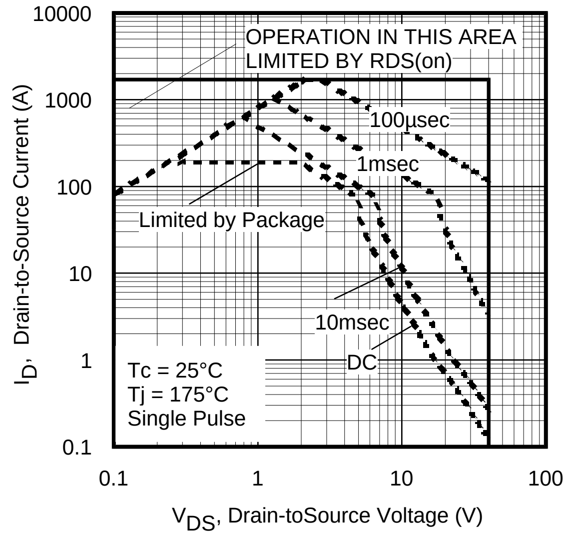


Fig 10. Maximum Safe Operating Area

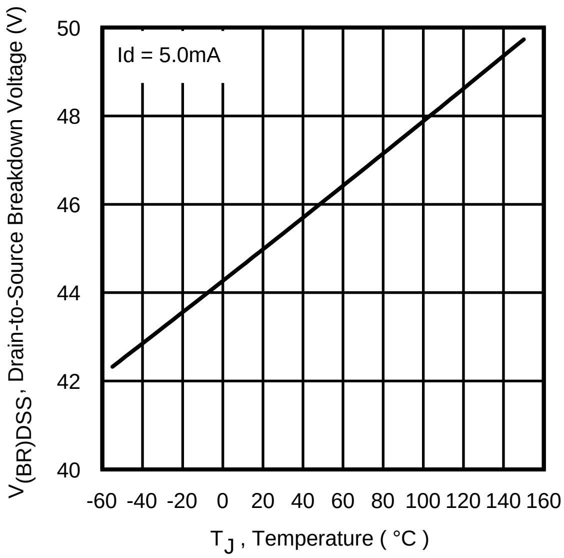


Fig 11. Drain-to-Source Breakdown Voltage

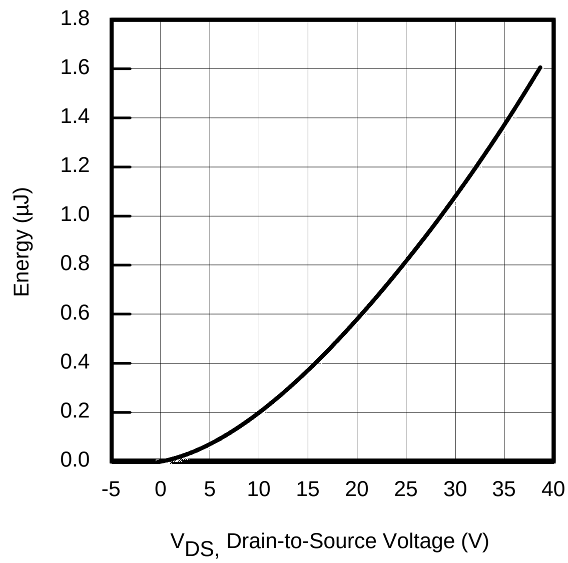


Fig 12. Typical C_{oss} Stored Energy

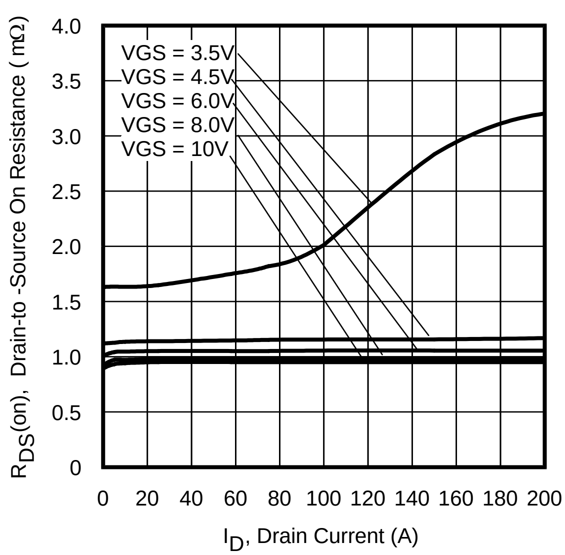


Fig 13. Typical On-Resistance vs. Drain Current

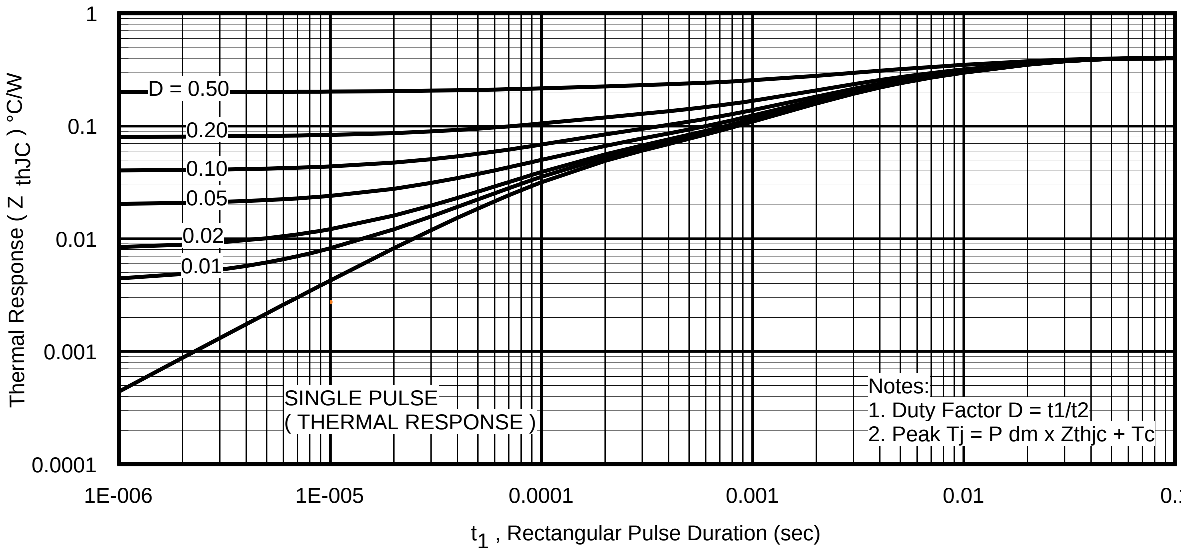


Fig 14. Maximum Effective Transient Thermal Impedance, Junction-to-Case

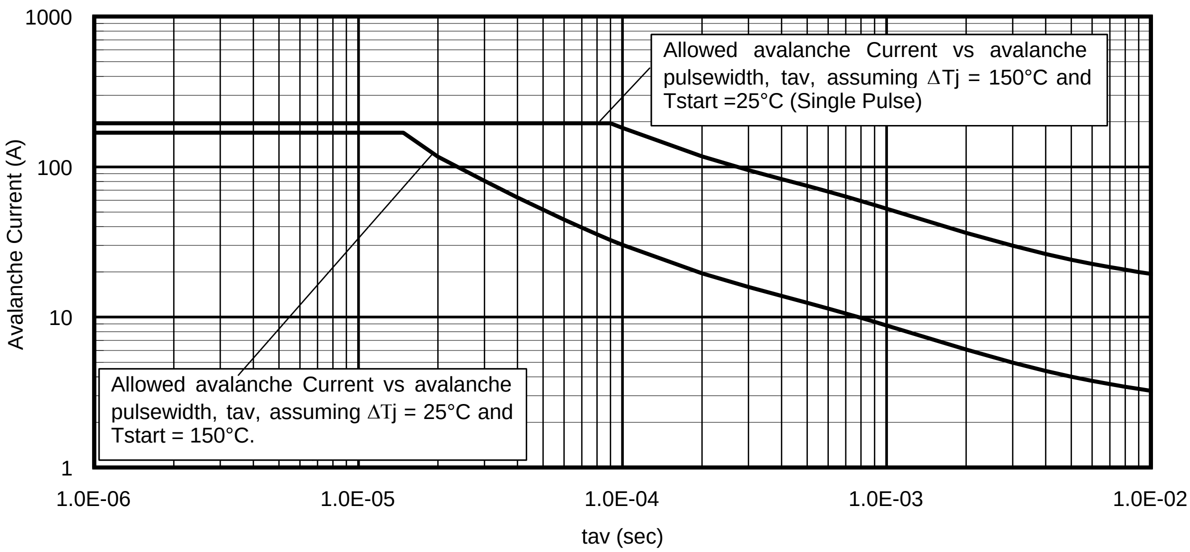


Fig 15. Avalanche Current vs. Pulse Width

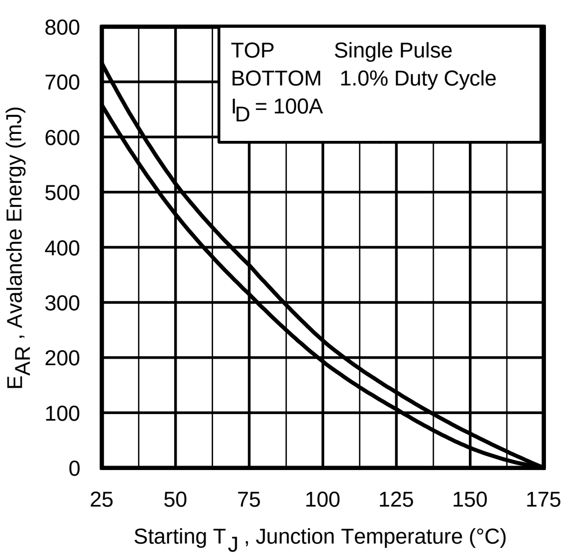


Fig 16. Maximum Avalanche Energy vs. Temperature

Notes on Repetitive Avalanche Curves , Figures 15, 16:
(For further info, see AN-1005 at www.irf.com)

1.Avalanche failures assumption:
Purely a thermal phenomenon and failure occurs at a temperature far in excess of T_{jmax}. This is validated for every part type.
2. Safe operation in Avalanche is allowed as long as T_{jmax} is not exceeded.
3. Equation below based on circuit and waveforms shown in Figures 23a, 23b.
4. $P_{D\ (ave)}$ = Average power dissipation per single avalanche pulse.
5. BV = Rated breakdown voltage (1.3 factor accounts for voltage increase during avalanche).
6. I_{av} = Allowable avalanche current.
7. ΔT = Allowable rise in junction temperature, not to exceed T_{jmax} (assumed as 25°C in Figures14, 15).
t_{av} = Average time in avalanche.
D = Duty cycle in avalanche = tav ·f
$Z_{thJC}(D, t_{av})$ = Transient thermal resistance, see Figure 14)

$PD\ (ave) = 1/2\ (1.3 \cdot BV \cdot I_{av}) = \Delta T / Z_{thJC}$

$I_{av} = 2\Delta T / [1.3 \cdot BV \cdot Z_{th}]$

$E_{AS\ (AR)} = P_{D\ (ave)} \cdot t_{av}$

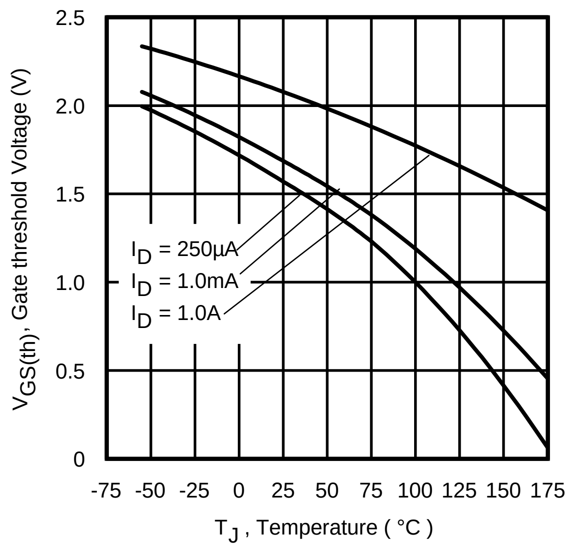


Fig 17. Threshold Voltage vs. Temperature

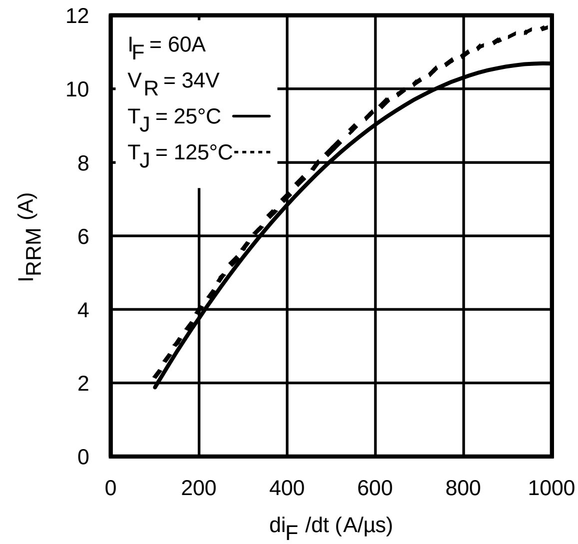


Fig 18. Typical Recovery Current vs. dif/dt

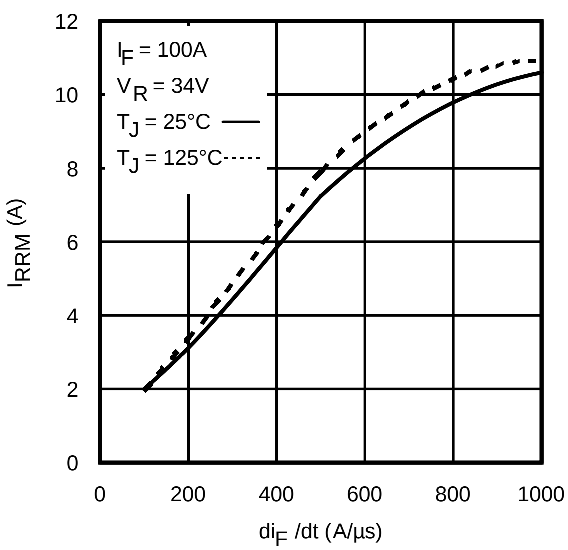


Fig 19. Typical Recovery Current vs. dif/dt

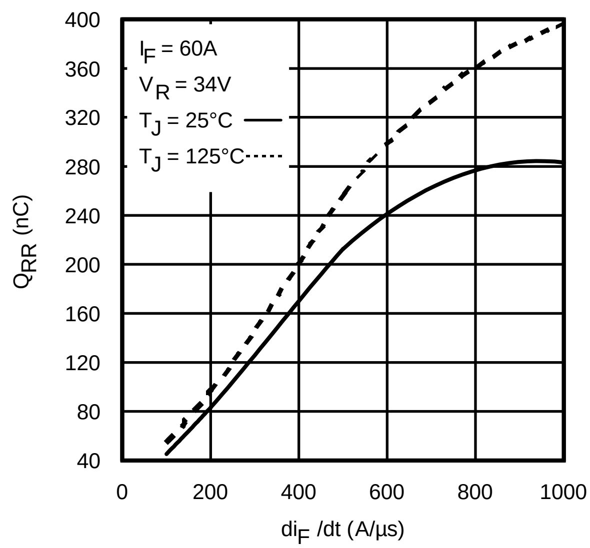


Fig 20. Typical Stored Charge vs. dif/dt

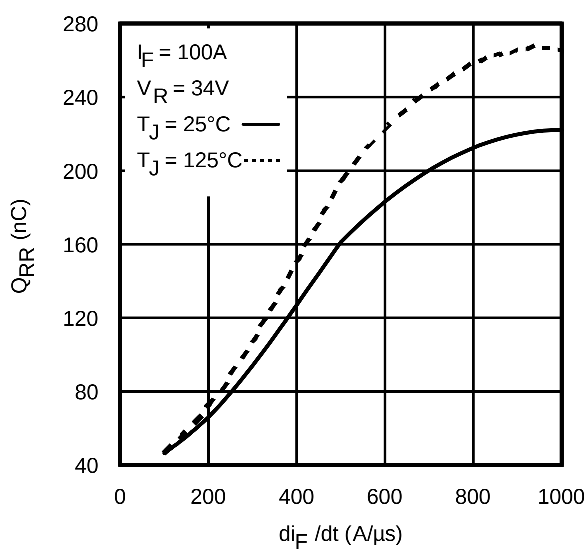


Fig 21. Typical Stored Charge vs. dif/dt

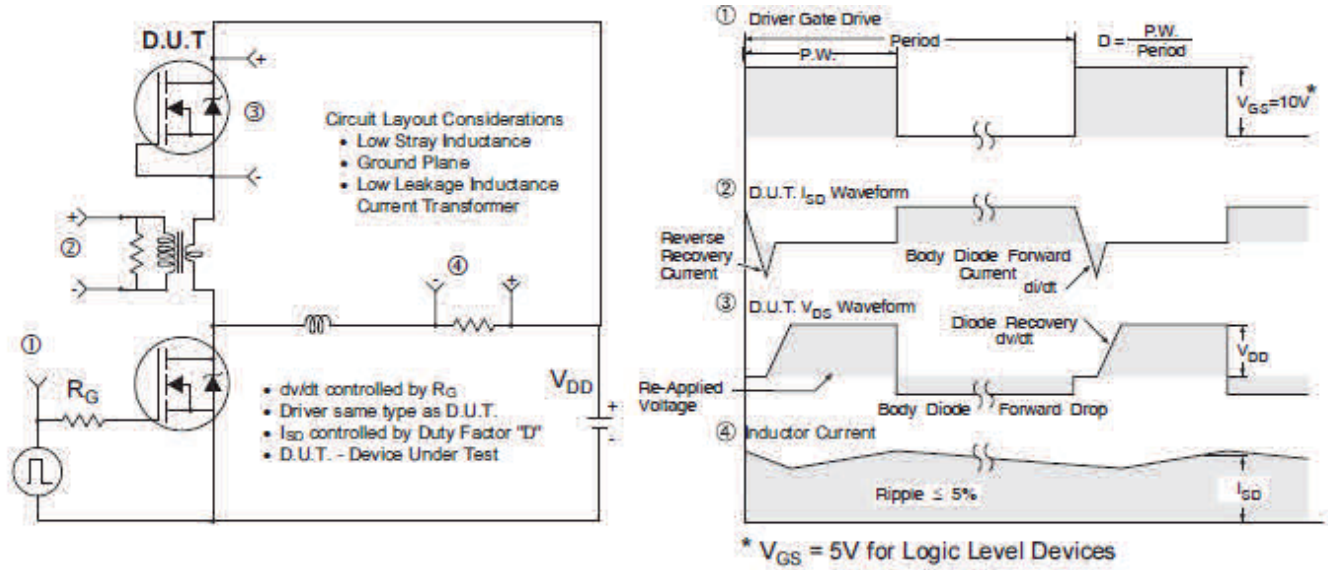


Fig 22. Peak Diode Recovery dv/dt Test Circuit for N-Channel HEXFET® Power MOSFETs

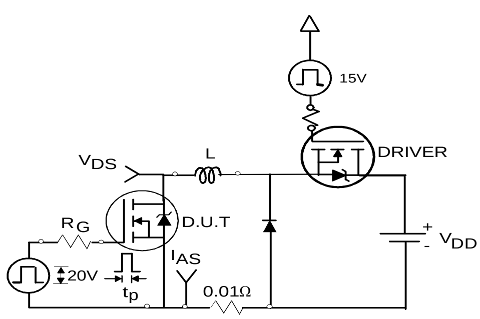


Fig 23a. Unclamped Inductive Test Circuit

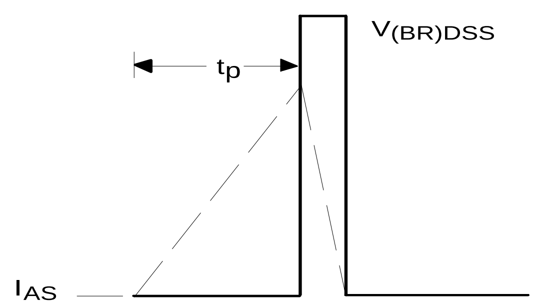


Fig 23b. Unclamped Inductive Waveforms

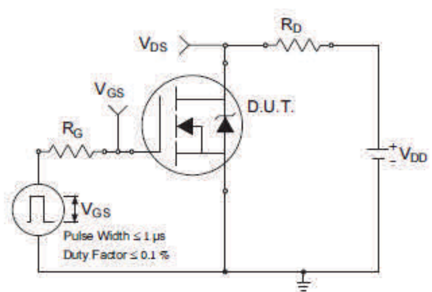


Fig 24a. Switching Time Test Circuit

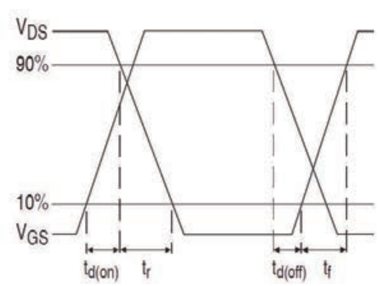


Fig 24b. Switching Time Waveforms

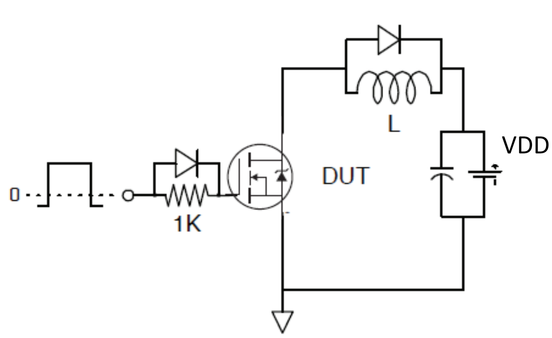


Fig 25a. Gate Charge Test Circuit

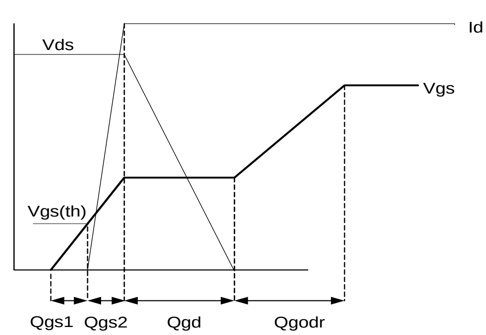
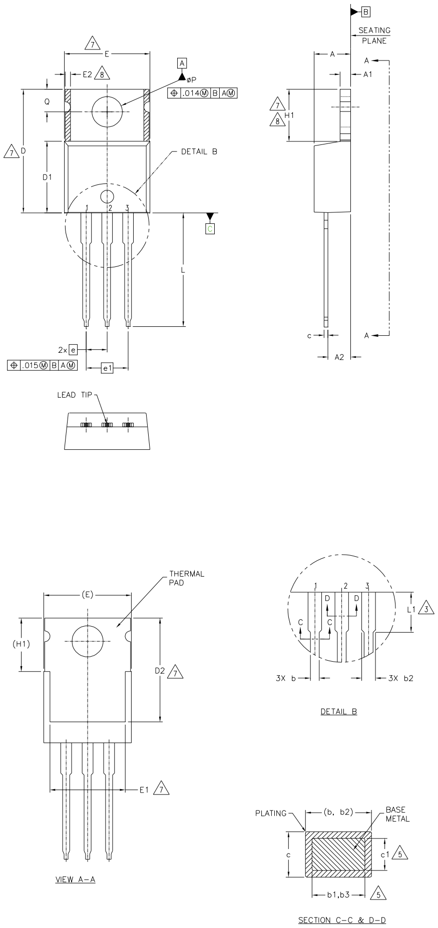


Fig 25b. Gate Charge Waveform

TO-220AB Package Outline (Dimensions are shown in millimeters (inches))



NOTES:

1.– DIMENSIONING AND TOLERANCING AS PER ASME Y14.5 M– 1994.
2.– DIMENSIONS ARE SHOWN IN INCHES [MILLIMETERS].
3.– LEAD DIMENSION AND FINISH UNCONTROLLED IN L1.
4.– DIMENSION D, D1 & E DO NOT INCLUDE MOLD FLASH. MOLD FLASH SHALL NOT EXCEED .005" (0.127) PER SIDE. THESE DIMENSIONS ARE MEASURED AT THE OUTERMOST EXTREMES OF THE PLASTIC BODY.
5.– DIMENSION b1, b3 & c1 APPLY TO BASE METAL ONLY.
6.– CONTROLLING DIMENSION : INCHES.
7.– THERMAL PAD CONTOUR OPTIONAL WITHIN DIMENSIONS E,H1,D2 & E1
8.– DIMENSION E2 X H1 DEFINE A ZONE WHERE STAMPING AND SINGULATION IRREGULARITIES ARE ALLOWED.
9.– OUTLINE CONFORMS TO JEDEC TO-220, EXCEPT A2 (max.) AND D2 (min.) WHERE DIMENSIONS ARE DERIVED FROM THE ACTUAL PACKAGE OUTLINE.

SYMBOL	DIMENSIONS				NOTES
	MILLIMETERS		INCHES		
	MIN.	MAX.	MIN.	MAX.	
A	3.56	4.83	.140	.190	
A1	1.14	1.40	.045	.055	
A2	2.03	2.92	.080	.115	
b	0.38	1.01	.015	.040	
b1	0.38	0.97	.015	.038	5
b2	1.14	1.78	.045	.070	
b3	1.14	1.73	.045	.068	5
c	0.36	0.61	.014	.024	
c1	0.36	0.56	.014	.022	5
D	14.22	16.51	.560	.650	4
D1	8.38	9.02	.330	.355	
D2	11.68	12.88	.460	.507	7
E	9.65	10.67	.380	.420	4,7
E1	6.86	8.89	.270	.350	7
E2	–	0.76	–	.030	8
e	2.54 BSC		.100 BSC		
e1	5.08 BSC		.200 BSC		
H1	5.84	6.86	.230	.270	7,8
L	12.70	14.73	.500	.580	
L1	3.56	4.06	.140	.160	3
øP	3.54	4.08	.139	.161	
Q	2.54	3.42	.100	.135	

LEAD ASSIGNMENTS

HEXFET
1.– GATE
2.– DRAIN
3.– SOURCE

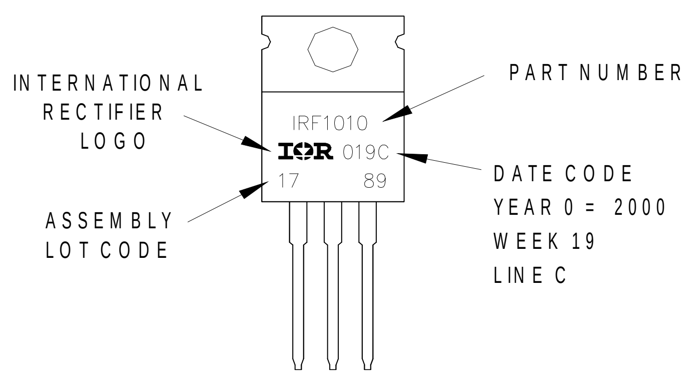
IGBTs, CoPACK
1.– GATE
2.– COLLECTOR
3.– EMITTER

DIODES
1.– ANODE
2.– CATHODE
3.– ANODE

TO-220AB Part Marking Information

EXAMPLE: THIS IS AN IRF1010
LOT CODE 1789
ASSEMBLED ON WW 19, 2000
IN THE ASSEMBLY LINE "C"

Note: "P" in assembly line position indicates "Lead - Free"



TO-220AB packages are not recommended for Surface Mount Application.

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

Qualification Information†

Qualification Level	Industrial (per JEDEC JESD47F) ††	
Moisture Sensitivity Level	TO-220	N/A
RoHS Compliant	Yes	

† Qualification standards can be found at International Rectifier's web site: http://www.irf.com/product-info/reliability/

†† Applicable version of JEDEC standard at the time of product release.

International Rectifier

IR WORLD HEADQUARTERS: 101 N. Sepulveda Blvd., El Segundo, California 90245, USA

To contact International Rectifier, please visit http://www.irf.com/whoto-call/

