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GRADO EN INGENIERÍA ELECTROMECÁNICA

TRABAJO FIN DE GRADO

UNINTERRUPTIBLE POWER SYSTEM
(WANDA, THE WAKE-UP WINDOW)

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Madrid
Mayo de 2019

UNIVERSIDAD PONTIFICIA DE COMILLAS
ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

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Acknowledgement

First of all, I would like to thank my teammates, Rebecca Lentz and Nayantara Chaisson, our advisor Jonathan Wierer and ECE lab manager Theodore Bowen, for giving me the opportunity to develop such interesting project during my stay in Lehigh University, trusting without knowing me personally that I would work and achieve all of the objectives we wanted to accomplish.

Moreover, I would like to express my most sincere gratitude to my parents and my brother, and everyone else in my close family, who always were there cheering for me and believing in me even when I could not trust myself or my own performance.

A special thanks to all my friends and colleagues from Pontificia Comillas ICAI University and Lehigh University, who showed me how with hard work and dedication (and a bit of luck) you are capable of doing extraordinary things, and who were always there for me. Thank you to my best friends from high school, who always supported me during these years and believed in me to become the Engineer and professional woman I am growing into.

UNINTERRUPTIBLE POWER SUPPLY (WANDA, THE WAKE UP WINDOW)

Autor: Fernández Oceja, Paula.

Director: Wierer, Jonathan.

Entidad colaboradora: Lehigh University.

RESUMEN DEL PROYECTO:

1. INTRODUCCIÓN:

Actualmente, el uso del conocido vidrio inteligente (*Smart Glass*) está en continuo crecimiento: aparte de ser utilizado en salas de reuniones en grandes oficinas, para así conseguir el deseado efecto de privacidad, se ha implementado en otras disposiciones, como puede ser en aviones, o en hoteles, ayudando a crear un ambiente lujoso y más cómodo. Debido a que su uso es cada vez más común, consiguiendo que su precio disminuya, se ha querido buscar la manera de incluir esta tecnología en el hogar, buscando desarrollar un producto innovador que procure una mayor comodidad en el día a día.

El principal objetivo de este proyecto para un futuro es diseñar una ventana inteligente que, combinada con un control vía App, sea capaz de conectarse a la alarma de cualquier individuo, regulando la luz entrante un tiempo específico antes de que suene, simulando así un amanecer, y ayudando a levantarse de manera natural, lo que se ha estudiado que conlleva a un mayor descanso a lo largo de la jornada y, por tanto, a un mayor grado de comodidad y felicidad (***https://www.mindbodygreen.com/0-28702/if-you-want-to-wake-up-happy-try-this-alarm-clock-t rick.html)***.

El estado natural de determinado vidrio es mantenerse completamente opaco si no existe una tensión que lo alimente. En casos de emergencia que conlleve a una situación de perdida de la tensión de alimentación, o en un simple apagón, se crearía una atmosfera oscura que resulta incómoda para cualquier individuo, y que debe evitarse. Esto, unido a que el cristal se alimente con corriente alterna y cuya carga sea ínfima, lleva a pensar un diseño no convencional respecto a los sistemas de alimentación ininterrumpidos que existen en la actualidad, ya que estos mismos están diseñados para alimentar varias cargas externas alimentadas por corriente continua (normalmente 5V CC), como pueden ser ordenadores, televisiones, o electrodomésticos comunes a todo tipo de hogares.

El diseño pensado se compone de dos bloques generales, uno que funcione en caso general, y otro que actúe en caso de emergencia, los cuales serán controlados por un relé que cambie la fuente que alimente al circuito que regula el voltaje de alimentación del vidrio. Este voltaje de entrada será monitorizado desde un microcontrolador Arduino, conectado a la App mediante tecnología Wifi.

Por otro lado, en caso de pérdida de tensión en el alojamiento, el circuito se alimentaría con un sistema externo, compuesto por una batería y un módulo de carga para la misma cuyo circuito interno se cierra en cuanto la batería está completamente cargada, evitando que se sobrealimente y dañe la vida de esta.

El circuito tiene que ser capaz de funcionar en cualquiera de las situaciones proyectadas, y poder la opacidad ser regulada de manera manual por la aplicación para ser considerado completamente satisfactorio. En un primer momento, no se tuvo mucho en cuenta la eficiencia (aunque se calculará e incluirá en el documento), si no conseguir resultados visuales como prototipo previo para un futuro producto final.

2. METODOLOGÍA:

La figura 1 muestra el diagrama de bloques global del circuito que ha sido desarrollado, y que ha sido soldado en una placa de pruebas en su totalidad, circuito que podemos observar en la figura 2, a excepción del microcontrolador Arduino, para verificar su correcto funcionamiento:

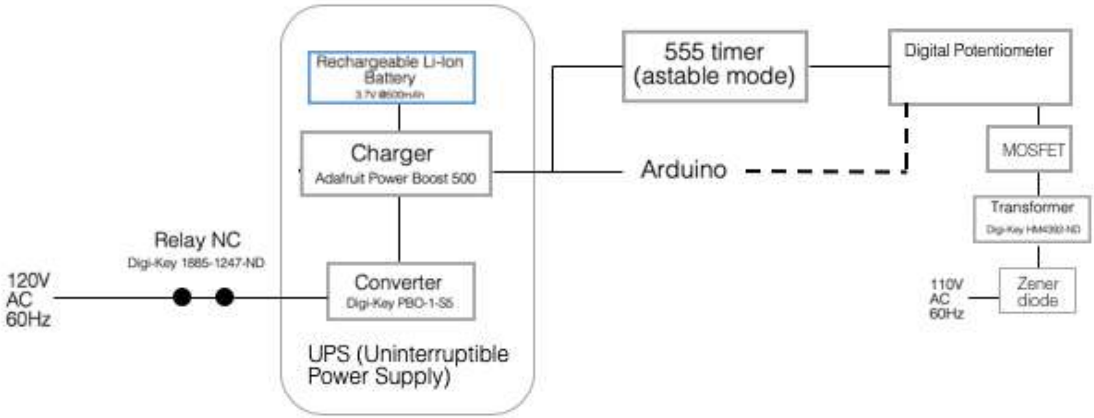


Fig.1. Diagrama de bloques

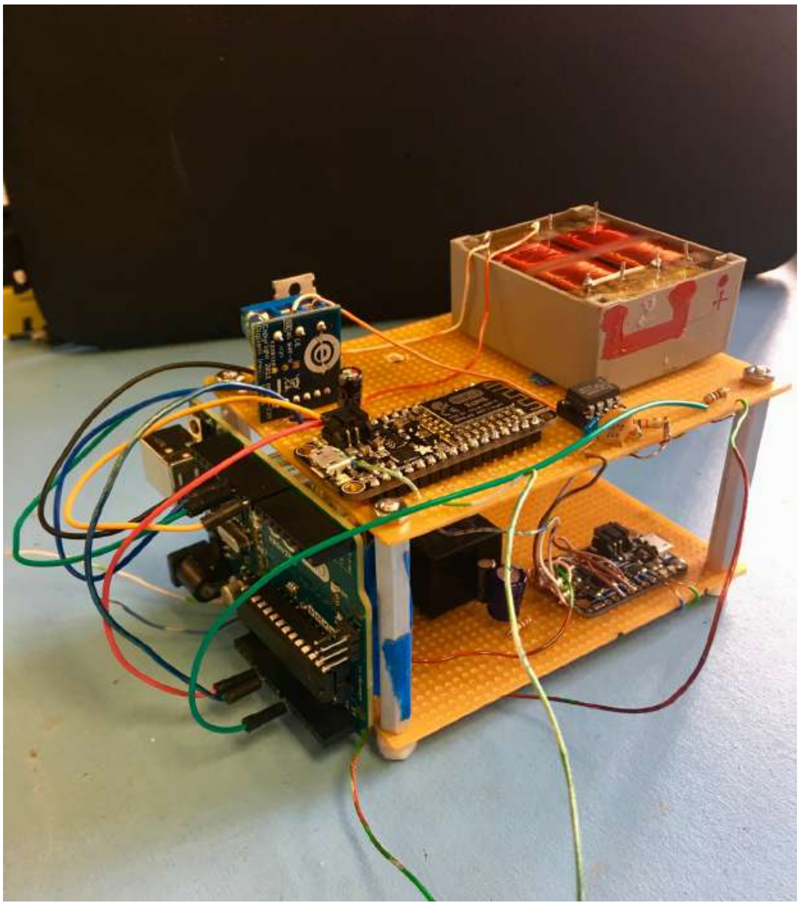


Fig.2. (a) Circuito final soldado en las placas de pruebas

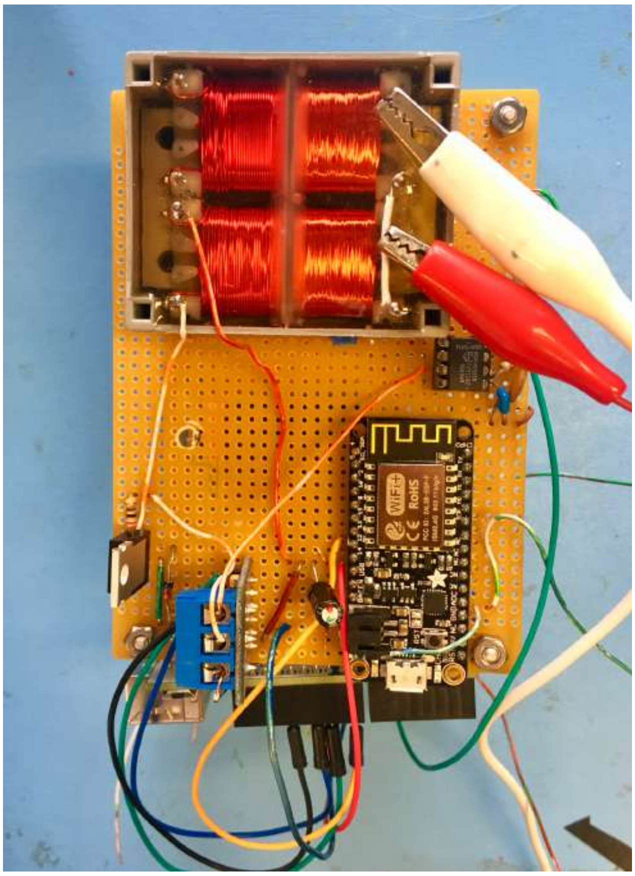


Fig.2. (b) Circuito final soldado en las placas de pruebas (Vista superior)

2.1.Sistema de alimentación ininterrumpida:

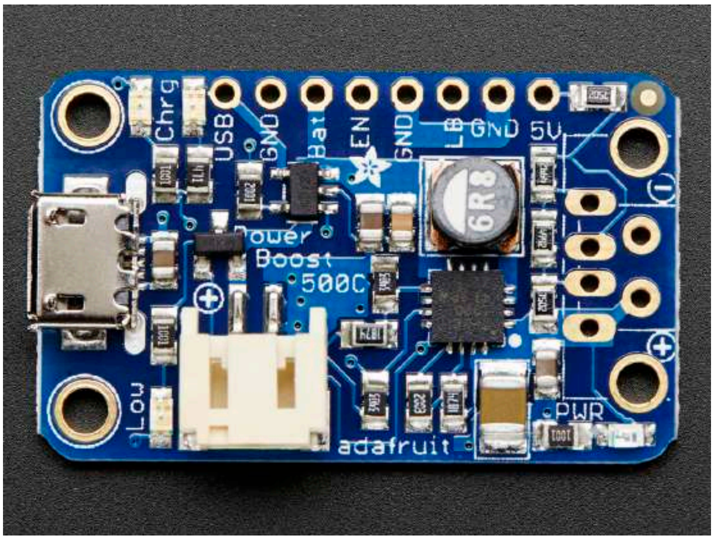
2.1.1. Batería recargable de iones de Litio:

La batería elegida de iones de litio, siendo estas las más utilizadas en proyectos para cargas pequeñas (debido a su alto nivel energético, gran eficiencia y larga vida útil). Se recargará con un módulo de carga externo adquirido, del cual se hablará en el siguiente punto.

Fig.3. Batería recargable Li-ion 500 mAh

2.1.2. Módulo de carga de la batería:

Acorde con la batería externa elegida, este módulo regula la tensión proveniente de la misma mediante un circuito boost, aumentándola de 3.7 a 5.2V, y manteniéndola constante, para así poder proveer el rango de tensión necesario para que las conexiones del circuito actúen de manera satisfactoria. En una situación normal, este módulo recargará la batería hasta el punto de máxima carga. Esta salida se cerrará automáticamente en el momento en que la carga de esta sea completa, gracias a la función de conversión síncrona incluida en su circuito interno.



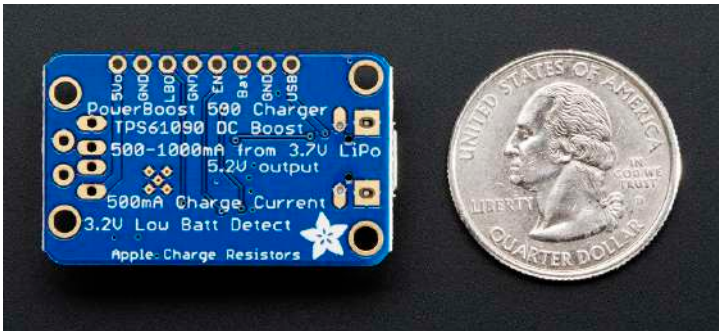


Fig.4. Adafruit Power Boost 500 Charger

2.1.3. Convertidor CA-CC:

Tal y como se puede ver en el diagrama de bloques de la figura 1, es necesario convertir la tensión de alimentación de 120V CA (proveniente de un enchufe tradicional) a corriente continua para poder conseguir los 5V necesarios para que el microcontrolador sea alimentado adecuadamente. Para ello, se utilizó el siguiente módulo convertidor 120V CA – 5V CC.

Fig.5. Convertidor CA-CC

2.2. Módulo regulador de tensión:

2.2.1. Circuito integrado 555:

Diseñando un modo de operación multivibrador astable con este circuito integrado, se es capaz de generar una tensión de salida de onda cuadrara con una frecuencia especifica que es necesaria para la entrada del transformador que irá conectado directamente al vidrio inteligente. Es una manera no muy eficiente, pero barata y eficaz de conseguir una salida "alterna" en un tamaño mínimo.

2.2.2. Potenciómetro digital y microprocesador Arduino Uno R3:

El potenciómetro digital es alimentado por la señal cuadrada de 5V con frecuencia 60Hz conseguida por el circuito integrado 555, y su salida es controlada digitalmente por el microcontrolador Arduino Uno, regulando su valor de resistencia interna con los porcentajes de opacidad deseados, consiguiendo así que sea el individuo el que ajuste a su favor la opacidad del cristal inteligente.

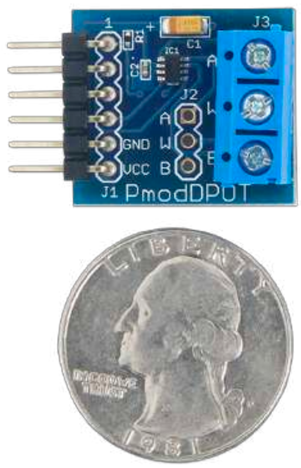


Fig.6. Potenciómetro digital

2.2.3. MOSFET + diodo Zener:

Debido a que la señal de salida del circuito integrado 555 y el potenciómetro digital comunicaba una corriente muy pequeña, y producía unos picos de voltaje no deseables, detalles por los cuales el transformador no conseguía realizar una clara conversión, se incluyó en el diseño original un pequeño circuito para amplificar la corriente en cuestión, con ayuda de un pequeño transistor MOSFET y una resistencia de valor medio, y un diodo Zener encargado de reducir esos picos.

2.2.4. Transformador:

Capaz de convertir la tensión de salida del potenciómetro digital de corriente continua a corriente alterna para que el vidrio inteligente actúe y regule su opacidad dependiendo de la amplitud de la tensión generada por los pulsos del microprocesador.

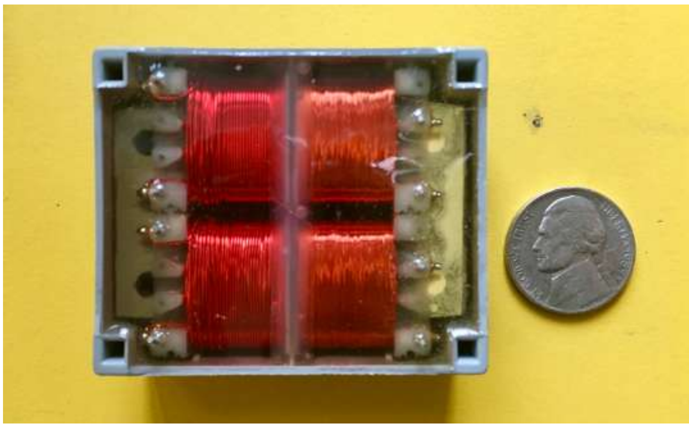


Fig.7. Transformador 115-5V CA

3. RESULTADOS:

Todos los requisitos de este proyecto han sido satisfechos, al haber sido capaces de conseguir alimentar en ambas situaciones (normal y en modo emergencia) al vidrio inteligente con la tensión suficiente de manera que se mantuviera la situación deseada en la estancia en la que se encontrara el mismo. Se ha desarrollado una aplicación donde el usuario es capaz de regular el porcentaje de opacidad del cristal, y en caso de pérdida de tensión en la residencia, la situación se mantiene constante.

4. CONCLUSIONES:

El mayor problema que hemos encontrado al realizar este proyecto ha sido el conseguir desarrollar un control rápido y flexible con el nivel de opacidad del cristal (la ciencia de partículas tras él funciona con un rango de cambio menor del que esperábamos). Creemos que una vez se vaya utilizando esta tecnología en diversas situaciones, y alimentando varias cargas en vez de un solo prototipo, se podrá reducir tanto el precio como la complejidad de este diseño, incluso llegando a conseguir que todo pueda ser implantado en un circuito PCB.

UNINTERRUPTIBLE POWER SUPPLY

ABSTRACT:

1. INTRODUCTION:

Currently, the use of the technology known as Smart Glass is becoming a trendy new addition to buildings across the globe: besides having been installed in business headquarters, so as to achieve the desired privacy effect it was meant for, it has been implemented in other locations, such as airplanes, or hotels, in order to create a more luxurious and comfortable environment. On account of its use becoming more and more frequent, a new way to incorporate it in every home has been explored, towards the development of an innovative product which will procure comfort in every household.

The main objective of this project for a close future is to design a smart window (Wanda) that, combined with an App-control, will be able to connect itself to the alarm of any customer, constantly customizing the light entering a room so that the user can wake-up to natural light just as they might have back in the day, which has been studied that increases wakefulness throughout the rest of the day and overall happiness levels (*https://www.mindbodygreen.com/0-28702/if-you-want-to-wake-up-happy-try-this-alarm-clock-t rick.html)*.

The glass natural state is to stay frosted when no voltage is applied to it. Specifically, the product that was purchased, with no voltage on has a light transmittance of 7%, which creates an uncomfortable dark atmosphere when there is a grid failure or a power outage in our home that needs to be avoided. Additionally, an AC supply was necessary for this low-load glass to run, so in order to surpass this inconvenience, it was decided to design a circuit that will enable the glass to be powered up in case of emergency, which leaded to arrange an unconventional design compared to the actual uninterruptible power systems used nowadays, as these are modeled to supply power to several DC loads (usually 5V DC), like PC computers, televisions, or any other electrical appliances found in any household.

The final design is formed by two major general blocks: the first one will work on an average situation, and a second one that will supply the necessary power in case of emergency. Both these blocks will be controlled by a relay that will connect and disconnect the existing sources that provide power to the circuit that regulates the voltage that goes into the smart glass. This input voltage will be monitored from an Arduino One Microcontroller, connected to the App through a Wi-fi module.

On the other side, in case of power outage or any other local loss of power, the circuit would get its power from an external system, formed by a Li-Ion battery and a charger module which its internal circuit closes when the battery is fully charged, preventing it to be overcharged and damaging its life or cycles.

The circuits need to be able to perform in any of the situations projected, and any individual has to be able to regulate manually through the App the opacity of the glass to be considered satisfactory. On a first approach, efficiency was not really kept in mind (although it will be figured and included in this document), but to achieve a visual result for this previous prototype for the future product.

2. METHOLODOGY:

Figure 1 shows the global block diagram of the circuit that has been design and soldered on a breadboard in its totality, circuit that we can observe on Figure 2, except for the Arduino microcontroller, to verify its correct performance:

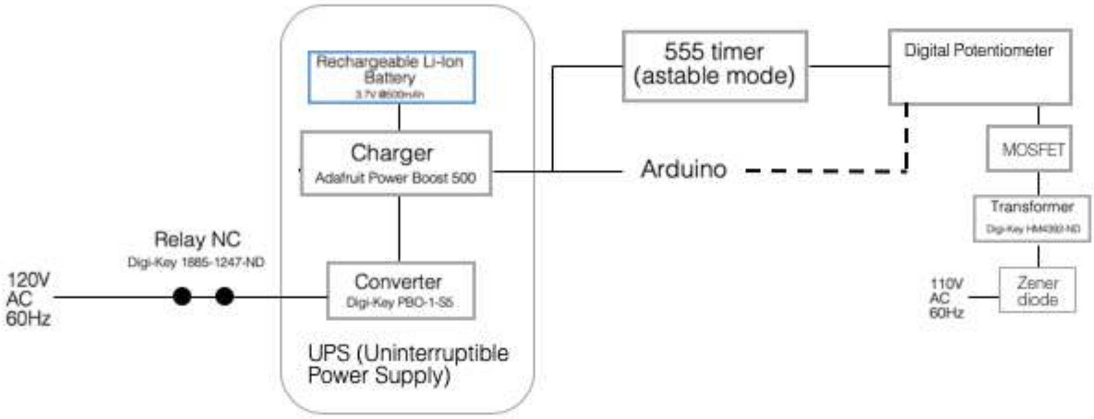


Fig.1. Block Diagram

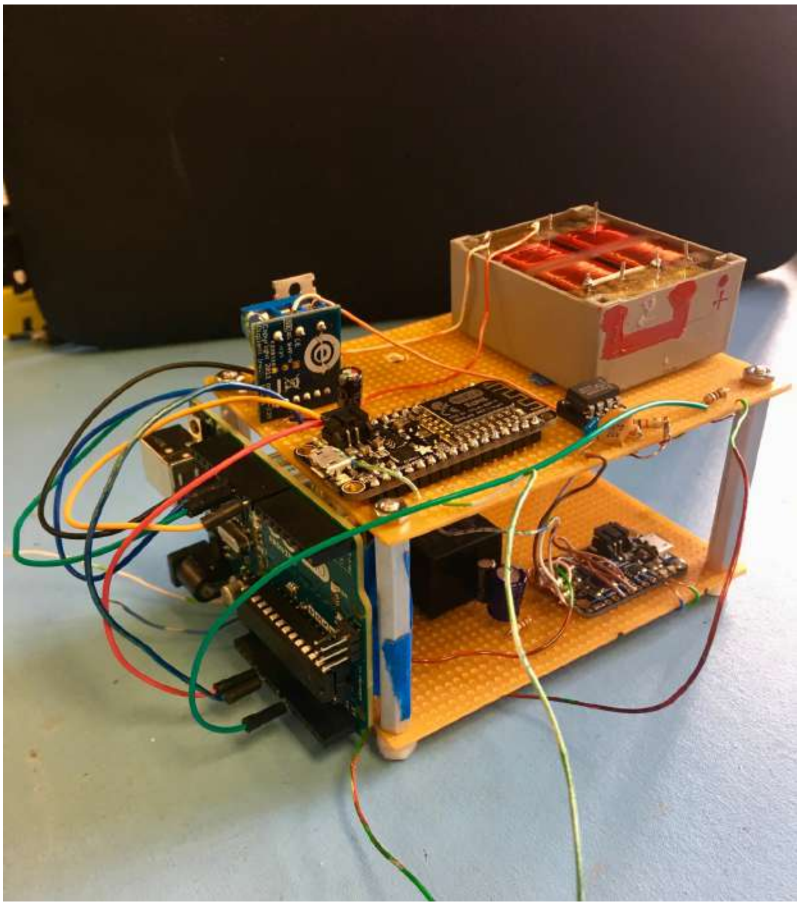


Fig.2. (a) Final circuit welded on breadboards

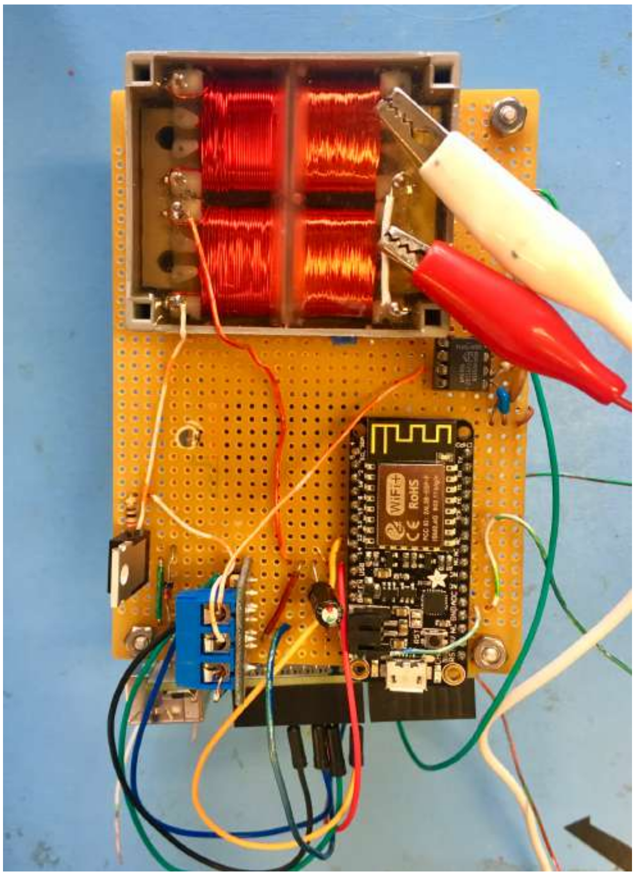


Fig.2. (b) Final circuit welded on breadboards (Top View)

2.1. Uninterrupted Power Supply:

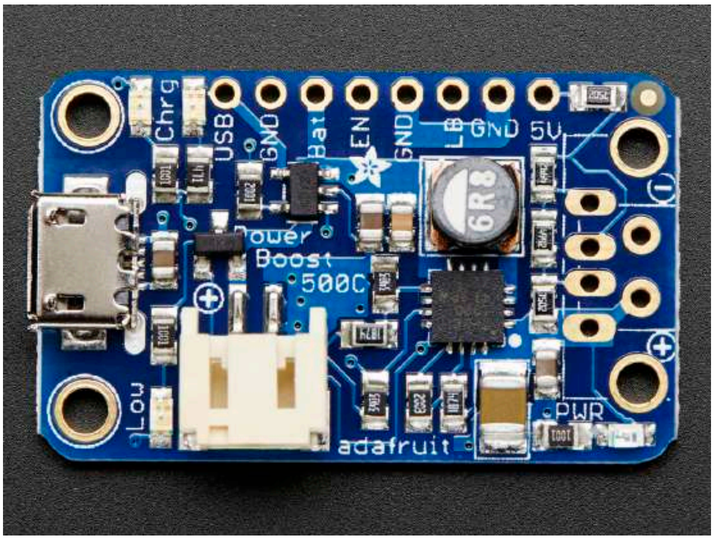
2.1.1. Li-ion battery:

The chosen battery is Li-ion, being this technology the most used for low-load projects, due to its large energetic supply, great efficiency and long battery life). It will be charged through an external charge module, which will be discussed in the next point.

Fig.3. Li-ion 500 mAh rechargeable battery

2.1.2. Charge module:

According to the chosen external battery, this module regulates the voltage provided by it through a boost circuit, increasing it from 3.7V to 5.2V, and keeping it constant so as to keep the voltage range necessary for the connections of the circuit to perfectly work. On an average situation, this module will fully charge the battery. This output will close itself automatically when the charge is completed, thanks to the synchronous function included in the internal circuit of this element.



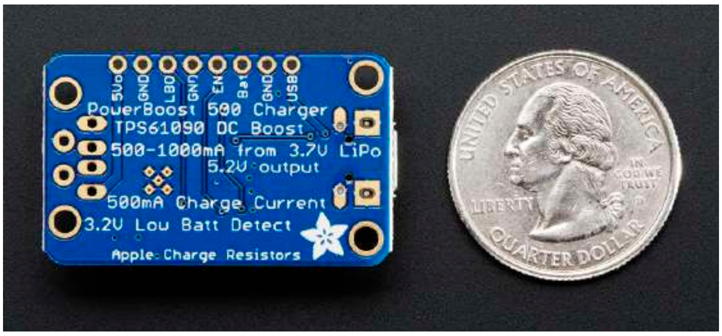


Fig.4. Adafruit Power Boost 500 Charger

2.1.3. AC – DC Converter:

As we can observe on the block diagram on Figure 1, it is necessary to convert the supply voltage of 120V AC (coming from any household outlet) to DC so as to get 5V to supply power to the microcontroller. For this purpose, the following 120 VAC – 5V DC converter module was used:

Fig.5. AC-DC Converter Module

2.2. Voltage regulation circuit:

2.2.1. 555 Timer:

Designing an astable mode with this integrated circuit, we are capable to generate a specific frequency square wave output necessary for the input of the power transformer (as it works with AC) which will be connected to the smart glass. It is a way not really efficient, but cheap and effective to get an “alternating” output on a minimum space.

2.2.2. Digital potentiometer and Arduino One R3 microcontroller:

The digital potentiometer input is the square wave coming from the 555 timer, and its output will be digitally controlled by the Arduino One, adjusting the internal resistance value according to the opacity percentages desired, so as to implement the manual regulation for the opacity of the glass desired by the customer.

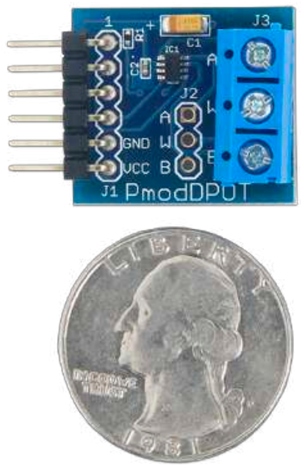


Fig.6. Digital Potentiometer Pmod DPOT

2.2.3. MOSFET + Zener Diode:

Being the output current from the combination of the 555 timer and the digital potentiometer really low for the transformer to work correctly, and creating some problematic peak voltages on the signal, a MOSFET transistor combined with a small resistor was decided to be used in the original design in order to drive that current and amplify it, including the Zener diode so as to soothe those peaks.

2.2.4. Transformer:

Capable of converting the output voltage coming from the digital potentiometer to a higher voltage AC voltage for the smart glass to work and regulate its opacity, depending on the amplitude of the pulses coming from the microcontroller that manages the resistance of the potentiometer.

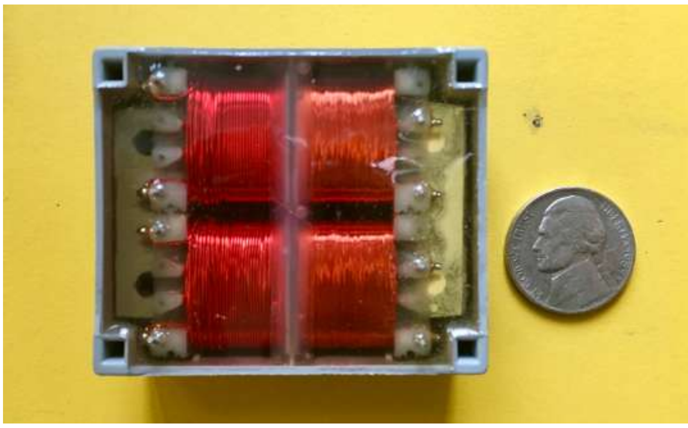


Fig.7. 115-5V AC transformer

3. RESULTS:

Every requisite of this project has been satisfied, as our team was able to supply power to the product in both situations (average and emergency mode) with the sufficient voltage so the smart glass to maintain the desired clarity in the room where placed. An App where the user is capable to regulate the percentage of opacity of the glass has been developed, and, in case of power outage, the situation is maintained.

4. CONCLUSIONS:

The biggest problem found when developing this project has been achieving the development of a fast and flexible control related to the percentage of opacity of the glass (for the particle science behind works between an opacity percentage change range smaller than we expected). We think that, once this technology has a more frequent use, the price and complexity of this design could be optimized, even achieving the circuit to be set up on a PCB.

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PART 1: REPORT

1. INTRODUCTION:

This report will be arranged into five parts, starting with the report of the work done during this past academic year, which itself will be separated into sections, beginning after this short presentation. As a first section, the rationale on why this project wanted to be developed will be introduced, as well as the objectives wanted to be achieved for the circuit and for the full model during this past time.

The second section will discuss the design of the final circuit that was assembled.

Then, for the third and fourth section, theoretical calculations needed and requirements and verifications for each individual component of the circuit will be presented.

For a fifth section, an analysis of costs for this project and future costs of mass production will be examined. Finally, for the last section, some ethical considerations that were found significant during class this past year will be shown.

As for the second segment for this report, a point of view on the future work related to this initial prototype will be presented, what the next steps to get to a completed and how a more functionable product could be developed.

The third part of this record will talk about the conclusions reached after working towards the objectives of this project.

Lastly, parts five and six are formed by the references used to finish this document and the datasheets of the purchased elements, for any necessary observation needed.

1.1. Statement of purpose:

Electronically dimming glass is becoming a trendy new addition to buildings across the globe. This recently-developed technology has been installed in business headquarters, airplanes, hotels, high-end residences, and even hospitals.

According to *BCC Research*, global revenues reached $1.6 billion in as early as 2011. As the glass becomes more common and the price lowers, the next logical step for this commodity is integration into the average home. With this integration, customers will be desiring comprehensive and simple methods for their windows to meet the needs of their daily life.

Our final product, *Wanda*, is a Smart Window that provides a simple and elegant product to fulfill these desires. *Wanda* allows the user to control the amount of light coming through their window from the outside using an app. In the modern era, humans have lost touch with their natural sleep cycles, often going to sleep long after the sun sets, and waking up far after it rises. This window is designed to customize the light entering a room so that the user can wake-up to natural light just as they might have back in the day. Studies show waking up to natural light increases wakefulness throughout the rest of the day and overall happiness levels (*https://www.mindbodygreen.com/0-28702/if-you-want-to-wake-up-happy-try-this-alarm-clock-trick.html*). Additionally, this window can frost at the press of a button, allowing users privacy without compromising their access to natural light. Initially, the window will be controllable via a mobile app, and it exists the aim to eventually make it voice-controllable.

The window will come with an external sensor to sense the amount of natural light that is incident on the window pane. This will help to keep light levels constant for the user's settings. Using the sensor, it is possible to adjust the dimness of the window to compensate for the lack of light coming through, allowing more natural light to maintain the same level of comfort.

A possible concern with this automated window is that it will need to be controlled using electricity. Since the glass' resting tendency is to be opaque, it would not be ideal in a power outage. The solution to this issue is to include an external power system for the window so as it can still work even during a power outage, allowing natural light into the house.

1.2. Objectives:

The major purposes for this circuit to be considered satisfactory are the following:

i. Power up the microcontroller and the whole circuit from any power outlet indefinitely.
ii. Power up the microcontroller and the whole circuit from the additional battery, in case of emergency for a specified time (t_{min} = 1h).
iii. Proof that the circuit would be able to power several loads, if necessary.
iv. Dimensionally small, acceptable to hide and move around.

As for the whole product, the main objectives for the prototype to be completed are listed below:

I. Control the dimming of the glass through a phone App or web platform.
II. Connect both the App and desktop setup so if you change the specs from one, the other corrects it as well.
III. Design an intuitive App background.
IV. Design an external power system to power up the load in case of emergency.
V. Adapt the signal coming from the photodiode to respond correctly on the control.

2. DESIGN:

2.1. Block diagram:

The system is divided into four central blocks, the DC signal input circuit, the UPS (Uninterruptible Power Supply) circuit, the Controller module and the AC signal output circuit.

The DC signal input circuit holds the AC-DC converter that achieves a constant 5V DC when connected to 120V AC power outlet and the NC terminal of a relay that allows the power input to change to the external UPS when it senses a power outage.

The UPS is formed by three elements that provide the additional power supply to the setup in case of power outage or any other emergency situation, which are a 3.7V 500mAh Li-Ion battery, a charging module that steps up the previous voltage to 5.2V DC and internally recharges the battery when connected to any household outlet, through the converter.

On the other hand, the Controller module, which goal is to communicate and follow orders from the Arduino microcontroller and provide a frequency-based signal, is formed by the following components: a 555 timer internal circuit astable mode that is capable to create a square wave with a particular frequency, and a digital potentiometer connected to the microcontroller that regulates the amplitude of that square, which makes possible the regulation of the voltage that will provide a modulation of the dimming opacity on the window.

Lastly, the AC signal output signal will achieve to re-turn the DC signal to its initial AC state, thanks to a setup which heart is a 115V-8V AC transformer, which its input current is driven by a MOSFET transistor, and its output its corrected by a Zener diode.

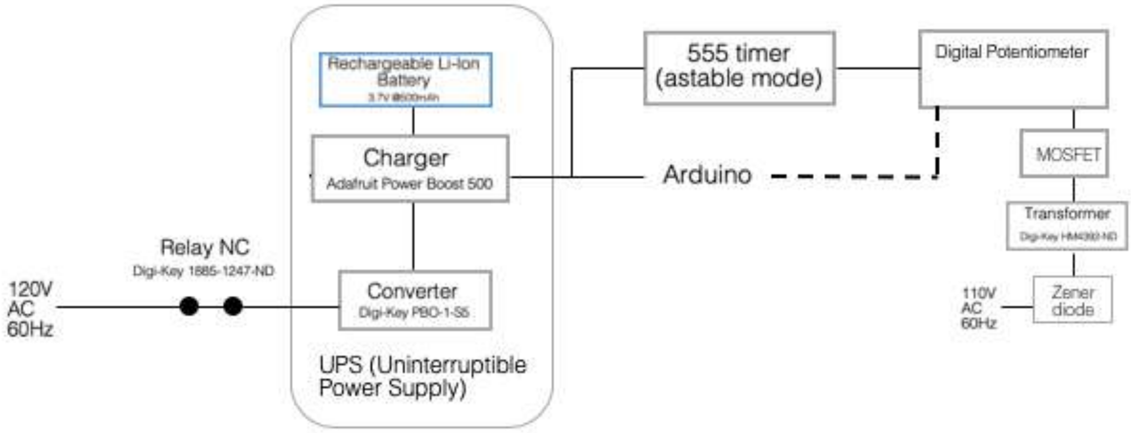


Figure 1. Block diagram

2.2. Block descriptions:

2.2.1. DC Signal input:

A single pole relay would be enough so as to open the circuit in order to protect the rest of the circuit of over currents in case of emergency, as it is the first block connected to a power outlet, even though we used a DPDT in this project due to its availability in the lab. The circuit continues with the connection of a 120V AC-5V DC converter, voltage necessary to power up the rest of elements.

2.2.1.1. Relay

Due to its availability and easy access, we decided to use a DPDT AC120V Coil Relay to connect to the power outlet. As we can see in the following schematic, when energized, paired pins 1-5 and 8-12 make contact, enabling the total 120V AC to safely supply the rest of the circuit. In case of power outage or other situation happening in the generation grid, when the coil de-energizes (goes rapidly from 120 V_{RMS} AC to 0 V), this contact opens instantly, so as to not harm the rest of the elements with immediate over-currents.

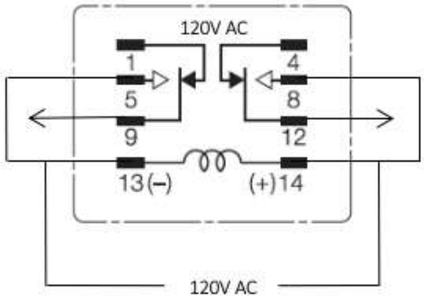


Figure 2. DPDT Relay schematic

2.2.1.2. Converter

So as to convert the input from any power outage to a DC voltage we could work with within the circuit, we decided to work with a compact converter from the series VSK-S1 from the company CUI Inc., purchased through the online platform Digi Key, as its dimensions and input-output voltage range relation (85 to 305 VAC), as well as its cost, were ideal.

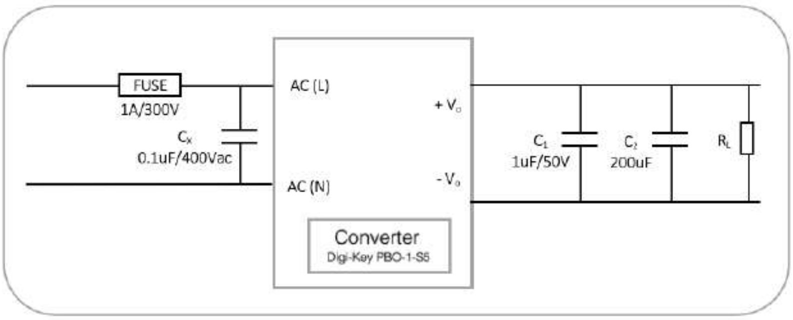


Figure 3. AC - DC Converter schematic

As for its overall efficiency, with an input through the relay of $120V_{RMS}$ AC, we get a constant voltage of around 5.07V DC, as we can see in the following figure:

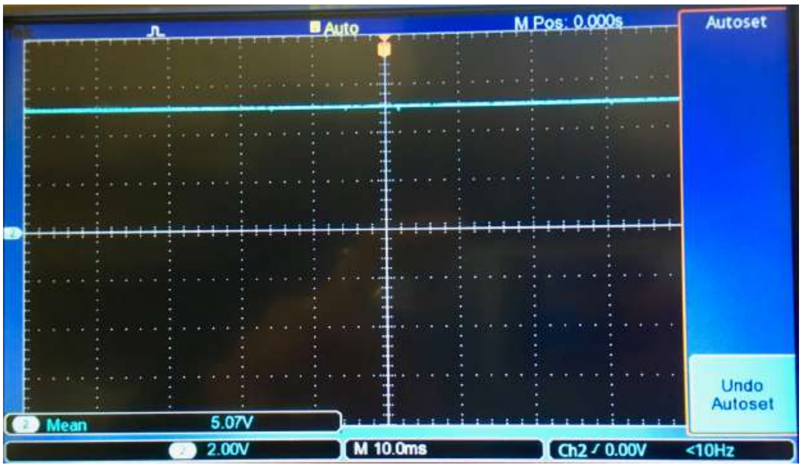


Figure 4. Converter output voltahe with 120V AC input

The output values from the converter tended to go from a 5 to 5.07 V DC range, which are logic to think because of the non-linearity of the alternating current input. The overall efficiency, looking at the datasheet, would then be:

$$\eta = \frac{V_{out}}{V_{in}} = \frac{[5 - 5.07]}{5.10} \cdot 100 = 98 - \ 99.4\%$$

2.2.2. UPS (Uninterruptible Power System):

The elements within this system are the ones that make possible the additional power up of the whole circuit in case of emergency. These kind of circuits are already been used for many services in real life, even though they tend to be big in scale, as they are used to power up several loads with several inputs, and are equipped with several internal batteries with sufficient capacity to charge any DC-powered device, like a big scale power bank.

2.2.2.1. Li-Ion battery

For this project we decided to use a 3.7V 500 mAh Li-Ion battery chosen based on the assumptions explained next:

In any common grid emergency situation that creates a power outage in any home, the problem tends to be fixed within the maximum time of an hour, so we chose the capacitance of our battery based on that assumption. The calculations explaining how we got to our final battery purchase are discussed in section 3.

2.2.2.2. Charger module

Purchased from the same online platform as the additional battery, this charger modules serves many purposes: when receiving an input voltage of 5V coming from the converter, this module is capable of charging the battery until its full load, moment that senses it and closes the charging circuit so as to not harm the life or charge cycles of the battery; in case of emergency, it is capable of boosting the nominal voltage of the battery from 3.7V to 5.2V DC, and drive the current to the following elements of the circuit, which would be the microcontroller Arduino and the 555 timer enclosed circuit.

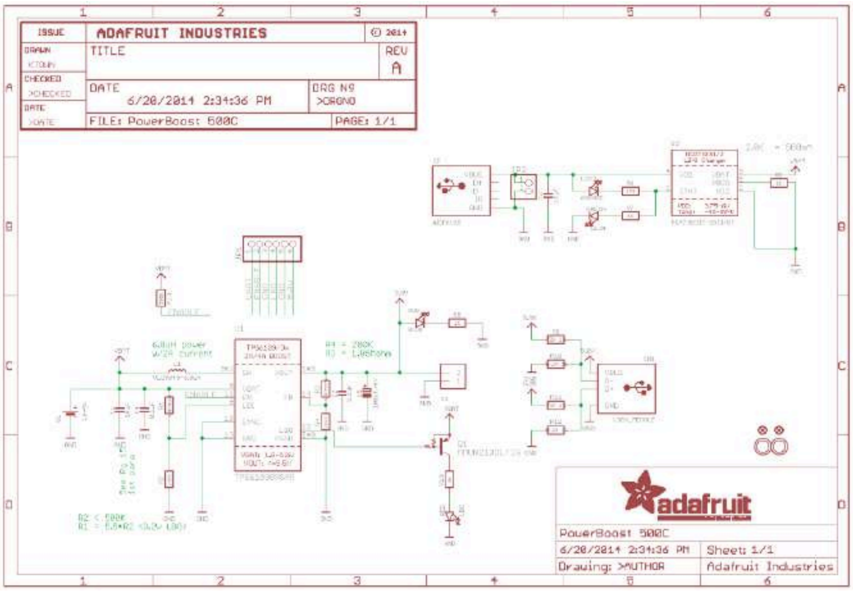


Figure 5. Schematic DC - DC boost + Charger chip of the Charger Module

2.2.3. Controller module:

This following set up is the responsible for the voltage regulation that changes the dimming percentage of the smart glass.

2.2.3.1. 555 Timer (Astable Mode)

We use this integrated circuit to create a 60 Hz square wave that we will use to simulate a sinusoidal wave that would go into the primary load of the transformer that connects to the glass. The calculations that gives us the value of the components are shown in section 3 of this report, and the schematics of the circuit down below:

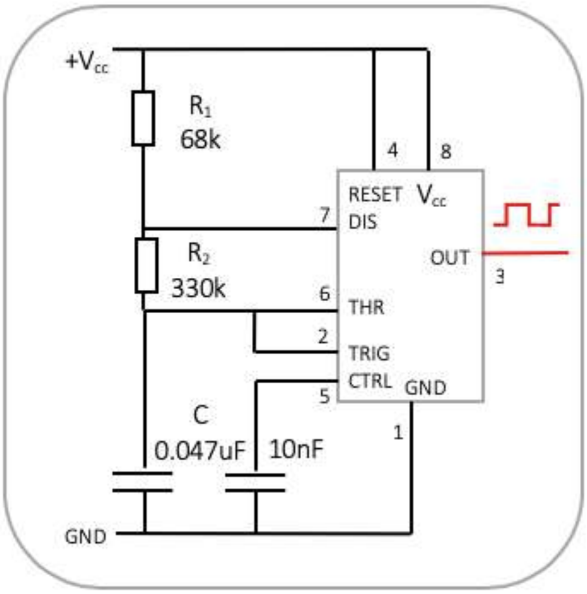


Figure 6. 555 timer astable mode schematics

The final output achieved is:

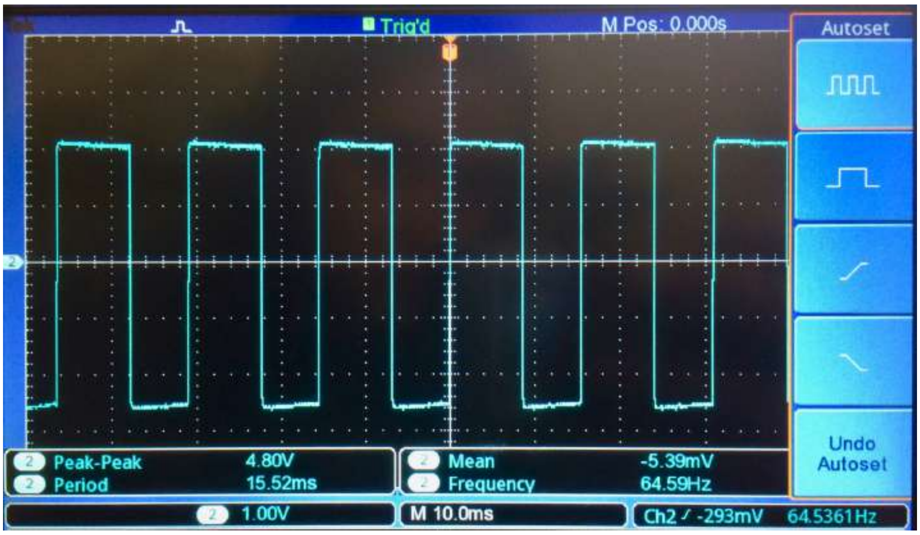


Figure 7. Square wave output with 5.10V input from the charger module

Accomplishing a final efficiency of:

$$\eta = \frac{V_{out}}{V_{in}} = \frac{4.80}{5.10} \cdot 100 = 94.12\%$$

2.2.3.2. Digital potentiometer & Microcontroller Arduino

The microcontroller Arduino R3 is powered up with the 5.10V DC we get from the charger module, and it is the one element responsible of changing the value of the internal resistance of the digital potentiometer so as to change the amplitude of the square wave generated.

The Arduino connects and integrates separate parts of our product. A schematic of the connections is shown in Figure 8. The Arduino powers the Adafruit Feather HUZZAH ESP8266 Wi-Fi Module using a 5V output that goes into the V_{usb} on the Arduino module. This Wi-Fi module obtains information from the app, and then communicates it to the Arduino Uno through pin 12 to pin 8. The Arduino Uno receives information from a photodiode (which role is explained at the end of this section) through Analog Pin 0, and then compares the information before assigning the digital potentiometer a value between 100 and 200 to modulate the voltage output. The Arduino communicates with the digital potentiometer using Serial Peripheral Interface. The potentiometer will then control the amplitude of the AC signal.

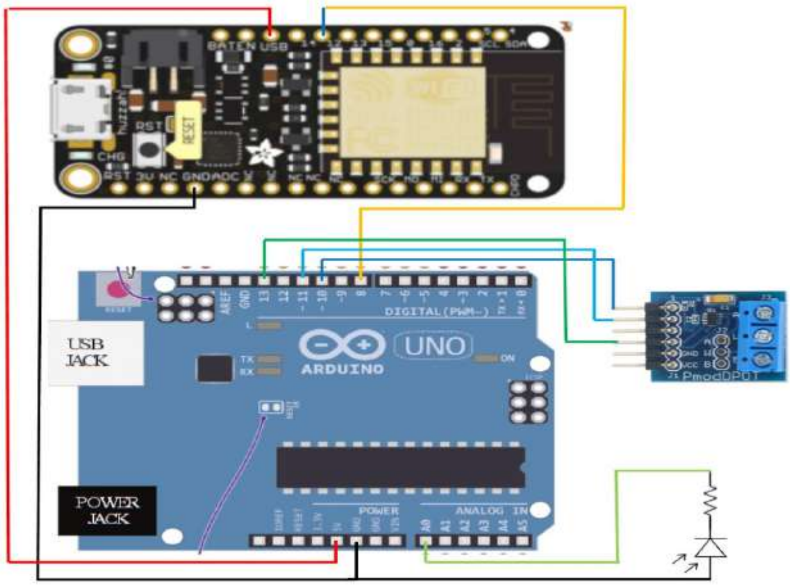


Figure 8. Arduino hardware connections

The amplitude of the square wave follows the percentage desired by the individual through the app, or the desktop platform (both connected, if one is adjusted, the other does as well) which setup is shown below: if a greater amount of light is desired to enter the room, the percentage will be high, being 100% the highest point; if a darkened or dimmed glass is desired, the percentage will be low, with a 0% meaning the glass would be completely dimmed or opaque.

Figure 9. Phone App and Desktop setup for Wanda

Through this intuitive program, we came up with the baseline design which includes an alarm to be set by the user, communication with the clock on the users phone, a switch to determine whether the alarm is one, and a slider so the user can choose what percentage of the maximum light they would like the window to transmit.

As for the purpose of the photodiode, we added it to the window as an external sensor to sense the amount of natural light that is incident on the window pane. This will help to keep light levels constant for the user's settings. For example, on a sunny day the user may want about 50% of the maximum outside light to be coming through, but when a cloud covers the house, there will be even less light coming through than they desire. Using the sensor, it is possible to adjust the dimness of the window to compensate for the lack of light coming through, allowing more natural light to maintain the same level of comfort.

2.2.4. AC Signal Output:

As we are using a 60Hz square wave as the input for our power transformer, that will be the one creating the sine wave that power up our glass, it was logic to think that some problems were going to come with it, as it is far from ideal. So, as to help amplify the signal, and then clean it, we came up with the following elements:

2.2.4.1. MOSFET + Zener diode

Using the MOSFET as a common drain/collector transistor to help drive the current into the transformer, amplifying this input signal, was the first solution we thought about when we first tried to convert the signal through the AC transformer. The Zener diode was used to get rid of an unusual large spike caused from switching the input of the transformer on and off on the voltage signal. We could easily eliminate the spike, make some of the 'heat' go away, and get rid of the malfunction of the glass, as it would start "flickering" when regulating the voltage by adding a 10V Zener diode (for a voltage reference) to the output of the MOSFET drain to ground.

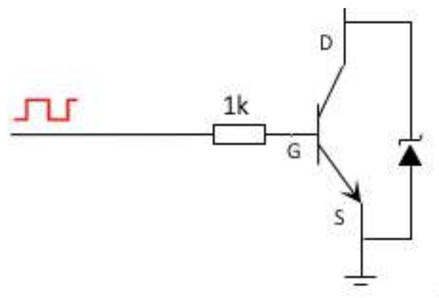


Figure 10. MOSFET + Zener diode schematic

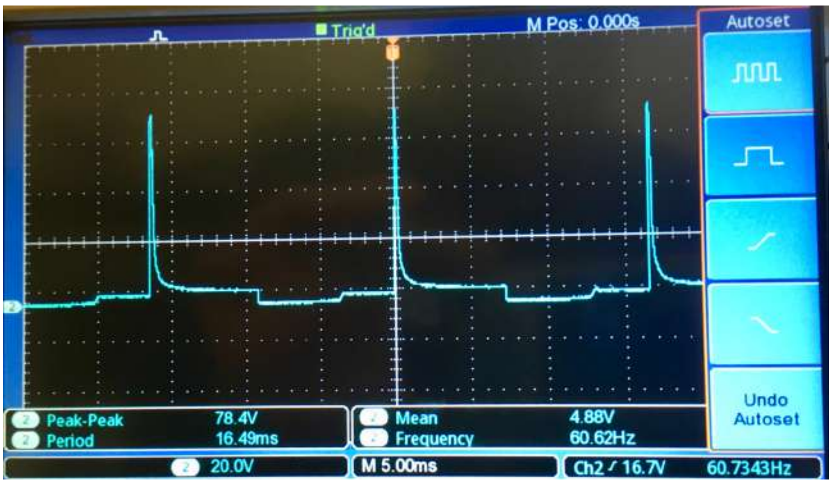


Figure 11. Voltage peaks of the signal without the Zener diode connected

Figure 12. Signal input into the transformer

2.2.4.2. Transformer

The final stage of our fully working circuit is a dual secondary 230/115 VAC transformer that enables the previous input leaving the amplifier to be converted to a 60 Hz square wave capable of powering up the smart glass.

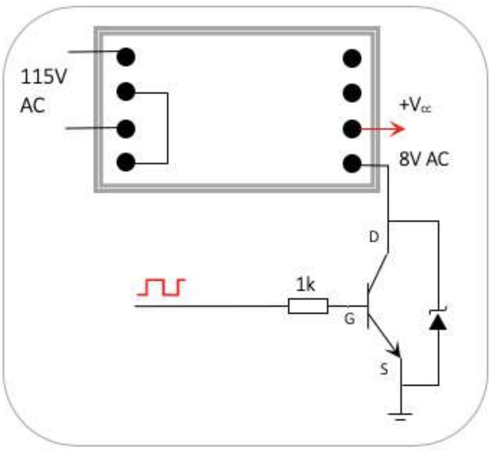


Figure 13. Transformer schematics

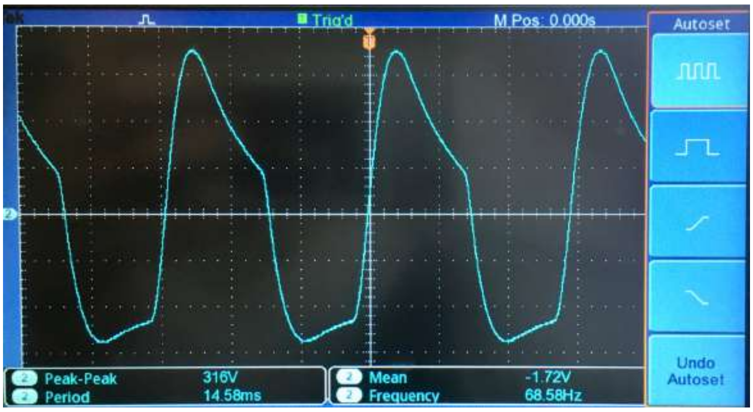


Figure 14. Output signal coming from the transformer

2.3. Software design:

2.3.1. Communication Structure:

The initial design for the communication structure, shown in Figure 15, includes an Arduino development board with a Wi-Fi Shield communicating via an IP address to a phone application or voice control device. This design required the phone application to be hosted on the smart phone using Android Studio. This is not an effective communication design due to complexity and would only be applicable to Android devices.

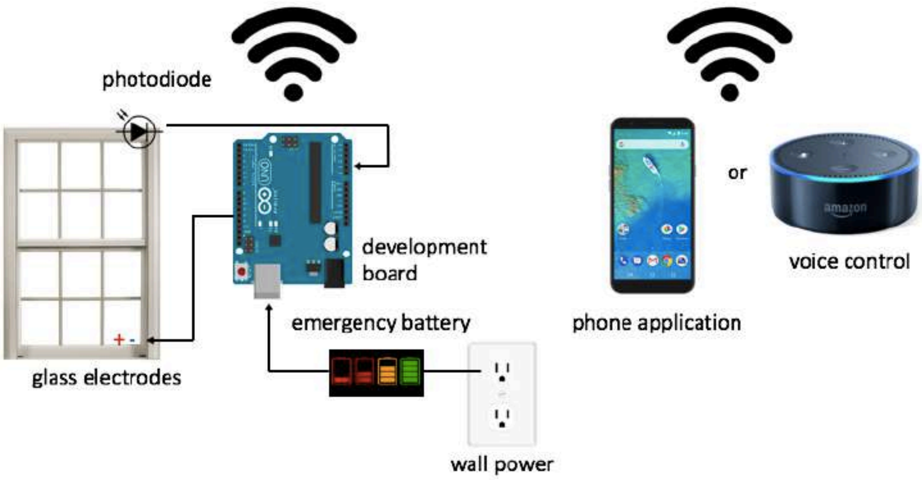


Figure 15. Initial design of communication structure

To improve this design, we replaced the Wi-Fi Shield with a Wi-Fi Module that has an IP address and is be able to communicate via Wi-Fi. This module can be programmed using the Arduino IDE. Instead of hosting the application on an Android phone, we instead chose to host a WebApp on an online server called Heroku. This cloud-based server is free to use up to a certain amount of storage. Through this server we were able to host our application both on desktop and phone and simplify the communication structure using socket.io methods in JavaScript. This improved design is shown in Figure 16.

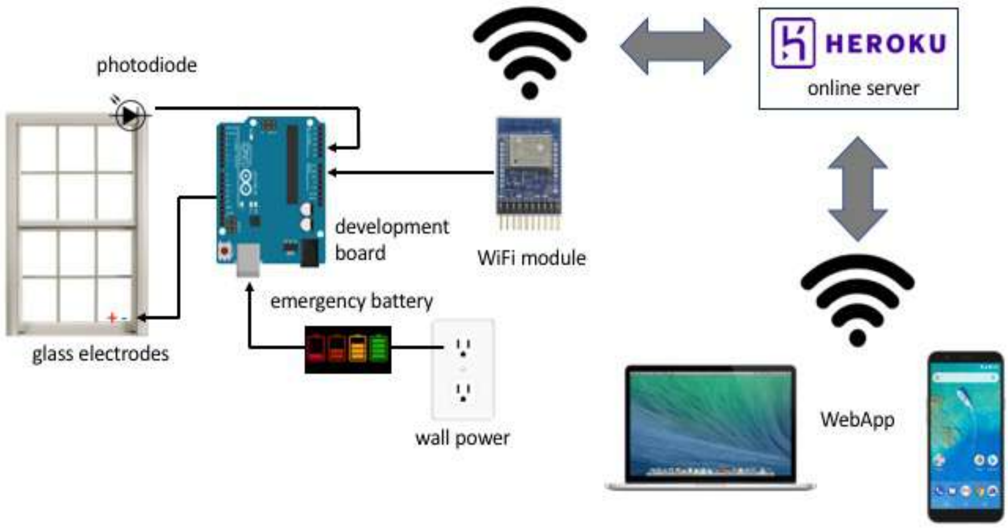


Figure 16. Final design of communication structure

2.3.2. App Design:

The application aesthetics were developed using basic HTML/CSS/JavaScript for both desktop and phone. The original app was going to be designed in Android Studio using MIT App Inventor, a platform which provides the higher-level base structure for Android apps to expedite and ease the coding process. Through this program, we came up with the baseline design, shown in Figure 17, which includes an alarm to be set by the user, communication with the clock on the users phone, a switch to determine whether the alarm is one, and a slider so the user can choose what percentage of the maximum light they would like the window to transmit.

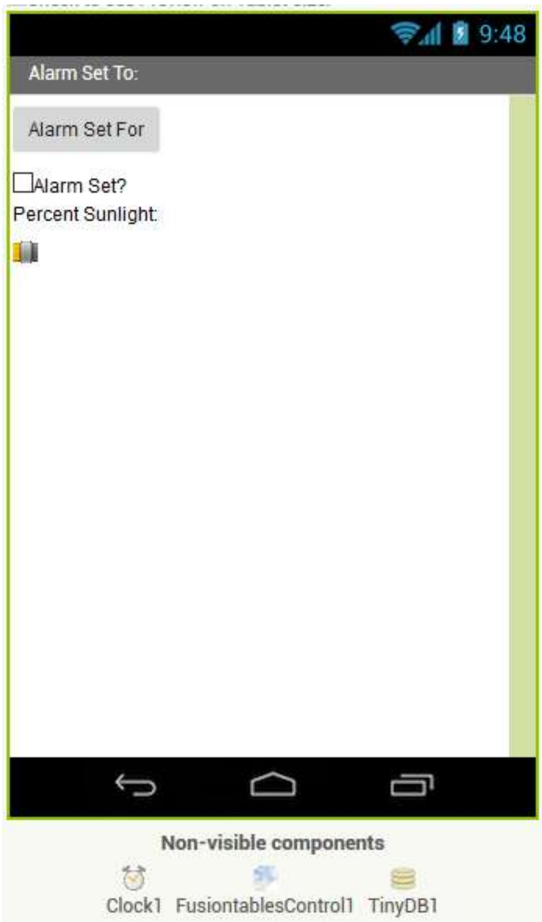


Figure 17. Image of the initial app design in MIT inventor

This design was translated into the HTML/CSS WebApp, previously shown in section 2.2.3.2, and again in Figure 18. The new design gives the user basic control of opacity and dimming of their window using slider controls as well as a module to set their alarm time. There are a lot of potential features that could be added to this design, such as an on/off for the alarm time and a log-in screen.

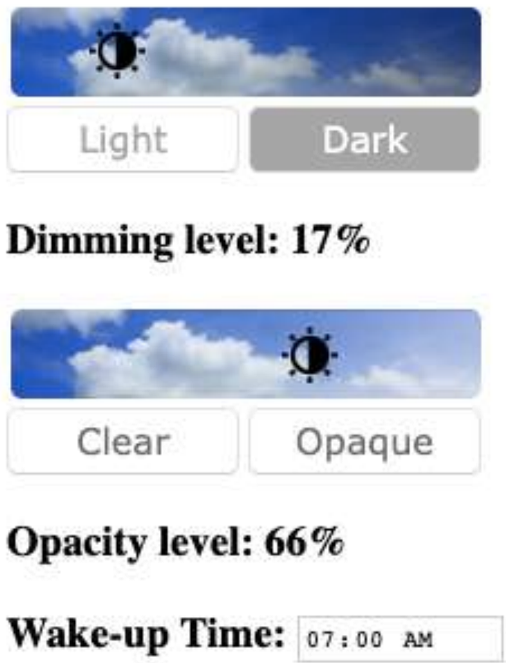


Figure 18. Image from a smartphone of the final app design

2.3.3. Server:

The server was deployed onto the Heroku platform using NodeJS. Heroku was chosen because it is both free and easy to use. The server's duties include posting the WebApp to phone/browser clients, communicating with these clients for information, storing this information and sending it to the Wi-Fi Module when requested. The client-server communication is accomplished using socket.io. It is also the role of the server to track the time of day and begin the window dimming when it is requested by the user.

3. CALCULATIONS:

3.1. Li-ion battery

Following the assumptions commented previously (section 2.2.2.1 of this report), we get the next equations that reflect the minimum capacitance needed with our working voltage so as to achieve a minimum time of supply of an hour:

$$Amperage\ consumed\ by\ the\ glass\ (from\ the\ specs): 9.3\frac{mA}{ft^2}$$

$$Dimension\ of\ the\ prototype: A4 = \ 8.27''x\ 11.69"{\sim}100\ in^2{\sim}0.7\ ft^2$$

$$t_{min} = 1h$$

$$C_{\min prototype} = 0.7\ ft^2 \cdot 9.3\frac{mA}{ft^2} \cdot 1\ h = 6.5\ mAh$$

As we see, the capacity needed to keep the circuit running for only an hour is minimal. Adding that we needed a nominal voltage battery of 3.7V to work with the charger module and a minimum value of 500 mAh capacity as well, we decided to use a 3.7V 500 mAh Li-ion battery purchased through the platform Adafruit, recommended by the producer of the charger module.

3.2. 555 Timer (Astable Mode)

The specifications required so as to design the most clean and simple square wave is to get f = 60 Hz and a duty cycle about 50%. The equations we are going to use in order to determine the values for the resistances and the capacitors are the following:

$$pulse_{high} = \ln(2) \cdot C \cdot (r1 + R2)$$

$$pulse_{low} = \ln(2) \cdot C \cdot R2$$

$$f = \frac{1}{\ln(2) \cdot C \cdot (R1 + 2 \cdot R2)}$$

By combining the requirements and the equations, we conclude with several theoretical values, which we tried individually, and the one that responded the better were the values used and shown in Figure 6.

We observed that increasing the value for R2, we could decrease the duty cycle, and decreasing the value of C, we increased the frequency of the square wave. All the circuits tried are shown in the following table:

Table 1. 555 timer astable mode test values

Circuit	C (μF)	R1 (kΩ)	R2 (kΩ)	f (Hz)
1	0.047	68	220	85
2	0.047	68	240	78
3	0.047	68	270	71.2
4	0.047	68	300	65.9
5	0.047	68	330	64.6

4. TECHNICAL REQUIREMENTS AND VERIFICATIONS:

Table 2. System requirements and verifications

Requirement	Verification
When connected to an outlet, the relay provides 120 V AC from the NO pins. If there is no voltage applied, connection must break.	1. Connect coil ins to 120V AC. 2. Verify connection by measuring the voltage between pins 9-12 (120V AC) with a multimeter AC. 3. Disconnect from the outlet. 4. Verify the disconnection by measuring again voltage between pins 9-12 (0 V) with the same multimeter.
In case of short circuit or over current, converter fuse (1A/400V) acts.	1. Create an artificial short-circuit (soldered in the breadboard). 2. Connect through a VARIAC to 120 VAC. 3. Turn on VARIAC. 4. Verify fuse acts and needs to be changed.
When low battery, red LED from the charger module lights up. While charging, yellow LED lights up. When done, green LED lights up and charging current to the battery stops.	1. Discharge the battery almost completely by using only the emergency power mode. Verify this way that the red LED works. 2. Connect through the converter to any outlet. Verify the yellow LED works. 3. Continue with the charge until the green LED lights up. 4. Measure the current that goes to the battery with a multimeter. Verify that the situation is an open circuit.

555-timer circuit is able to create a ~60Hz square wave when powered up at the same time as the Arduino microcontroller.	1. Connect parallelly both circuits to the output of the charger module. 2. Verify both inputs (Arduino and 555 timer) are around 5V. 3. Verify the output from the 555-timer circuit is the desired square wave.
The minimum time desired (t_{min} = 1h) for the circuit to be powered up with the external battery is exceeded.	1. Connect circuit to the load (window) and power it up through a full charged battery. 2. Let it work at full load (100% clarity percentage) for most of the time. Change this percentage while using it. 3. Repeat this for some time over the minimum. In this particular test, the circuit run for over two hours.
The values of the internal resistance change while varying the opacity percentage through the app.	1. Connect the whole circuit and run the software through the microcontroller. 2. By using a phone, scroll through several percentage values, while measuring the internal resistance values from the potentiometer using an ohmmeter. 3. Verify the range of resistance values are between [60, 10k] **Ω**, according to its personal specifications.
The setup from both the Web platform and the phone App display an alarm mode and a changing scroll so as to modify the opacity percentage .	1. Use a phone to verify the App setup. 2. Use a computer to verify the WebApp setup.

The setup from both the Web platform and the phone App are connected in a way that if both are being used and connected to a same load, if one's structure is modified, the other does as well.	1. Using both a phone and a computer, connect both devices to the same load using the Wi-Fi module. 2. Modify the percentage value from the WebApp on the computer. 3. Verify the same value changed in the phone App. 4. Repeat this process changing the order of the devices.
The microcontroller Arduino is capable of reading the values from the photodiode, and the software is capable to react according to them.	1. While everything is connected, using a flashlight, verify the input values that the Arduino read from the photodiode change. 2. While imposing a constant desired opacity percentage (like 70%), use the flashlight again to modify the incoming light from the photodiode. 3. Verify that the window maintains the opacity desired.
When all connected, the output signal from the transformer looks almost sinusoidal, and its frequency is 60 Hz.	1. Connect all the individual parts of the circuit. 2. With the help from an oscilloscope, measure the output from the transformer.

5. CIRCUIT COSTS:

5.1. Parts

Table 3. Parts list

Part description	Manufacturer	Part number	Number of units
Individual Sample Kit - Shading	Invisishade	-	1
Power Boost 500 Charger	Adafruit	-	1
Lithium Ion Polymer Battery	Adafruit	-	1
Power Supply Switching 5V 1W	CUI Inc.	VSK-S1-5U	1
Transformer 230/115VAC 16VCT	Signal Transformer	IF-6-16	1
Digi-Key 1885-1247-ND Relay	IDEC	1885-1247-ND	1
Digital Potentiometer Pmod DPOT	Digilent	-	1
1k	Yageo	1.0KQBK-ND	2
68k	Yageo	3.0QBK-ND	1
330k	Yageo	43KQBK-ND	1
0.047uF	VISHAY	1C25Z5U473M050B	1
0.1uF (400V)	nichicon	UVZ2G010MPD1TD	1
1uF (50V)	nichicon	UVP1H010MDD1TD	1
200uF	MULTICOMP	MCAX25V207K8X16	1
10nF	VISHAY	K103M15X7RF53L2	1
Fuse (1A/300V)	Littelfuse Inc.	2206001.MXP	1

5.2. Mass production

Table 4. Parts cost

Part description	Price (unit) $	Total	Price (10.000 units) $	Total
Power Boost 500 Charger	14,950	14,950	11,960	11,960
Lithium Ion Polymer Battery	7,950	7,950	7,160	7,160
Power Supply Switching 5V 1W	10,710	10,710	8,130	8,130
Transformer 230/115VAC 16VCT	12,890	12,890	10,650	10,650
Digi-Key 1885-1247-ND Relay	11,830	11,830	6,902	6,902
Digital Potentiometer Pmod DPOT	7,990	7,990	7,99	7,990
1k	0,100	0,200	0,009	0,018
68k	0,090	0,090	0,008	0,008
330k	0,090	0,090	0,008	0,008
0.047uF	0,488	0,488	0,121	0,121
0.1uF (400V)	0,444	0,444	0,168	0,168
1uF (50V)	0,206	0,206	0,084	0,084
200uF	0,772	0,772	0,162	0,162
10nF	0,313	0,313	0,065	0,065
Fuse (1A/300V)	0,770	0,770	0,319	0,319
		69,693		53,744

As we can see in the previous table, the total cost for the parts that compose the Power System circuit is \$69,70. This may look like a large amount for such a small circuit, but we have to take into account that just one circuit is able to power up several loads, several windows, and if the components are purchased in industrial quantities, the final cost reduce itself by almost a 23%, to \$53,75.

In order to completely analyze if the circuit is economically viable for mass production, we should take into care multiple estimations, such as how many workers are needed to develop this product, or if it could be an automotive process, Labor Costs, Production Costs, Maintenance Costs for the machinery, etc.

In order to complete this economic study, let's summarize the estimations that will be taking into account:

1) The leasing cost for the plant and space where the circuit would be stored and assembled is about 500\$/month.
2) Each circuit needs to be assembled by a worker.
3) Labor cost has an hourly rate of 15\$. Each day, each worker works 8 hours, and each hour mounts 3 circuits per hour, connects them to a load, downloads the program into the microcontroller and stores it.
4) We pay three workers.
5) There is no O&M Cost.
6) The total cost for the shipped product is shown in table 5. Each product is sold for 375\$.

Each month a total amount of 552 circuits are mounted and shipped (3 workers, 8 hours a day, 23 days a month), a total of 6624 circuits a year. When purchasing the items with the mass production price, there are a total of 3376 extra pieces that can be assembled the following year.

The total profit each month developing this product will be:

Total Present Worth Cost:

$$[\ (\$15 \cdot 8 \cdot 23) + (\$500) + (\$242.81 \cdot (10{,}000 / 12))\ ] = \$204{,}768.33$$

Total Present Worth Benefit:

$$[\ (\$375 \cdot 552)\ ] = \$207{,}000$$

Monthly profit = Benefit – Cost = \$2,231.67

Even though this example may be too simple to really understand the true economic viability of the project, we can sense that in a future it would be, as the numbers show us an initial profitability if the product catches the interest of the market.

Table 5. Full product cost

Item	Cost
Smart Glass (2) - **Invisishade Individual Sample Kit – Shading** - **SmartFilm Grey Sample 8x11'**	$158.00
Power System	$53.75
Sensors (2) **PHOTODIODE VTP9812FH-ND**	$3.12
Development Board (1) **Arduino Uno R3**	$8.99
WiFi Module (1) **Adafruit Feather HUZZAH ESP8266**	$18.95
Total	$242.81

6. ETHICAL CONSIDERATIONS:

Our product does not bear a lot of ethical implications, since it is more a product of convenience and leisure than anything else and affects only the user.

It was not difficult to find several patents that work with the same smart glass that our group is trying to implement in the Smart Window project (‘*Wanda, the Wake-Up window’*) we intend to prototype at the end of this year.

The first patent (PATENT 1) is a patent held by *Qualcomm, Inc* that details how the glass of the window actually works. This is a patent that we will not be violating because we will be using glass from a company that has rights to make that glass. In this way we will not need to avoid problems of intellectual property. This patent was filed in December of 2012, indicating that this is a relatively new concept of glass (less than 6 years old). A diagram of the glass from this patent is shown in Figure 19.

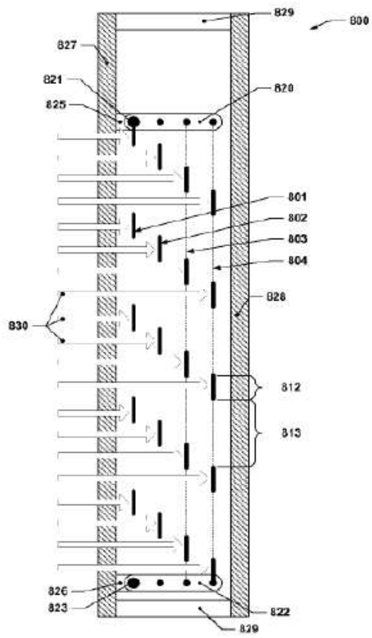


Figure 19. Smart Glass design patent by Qualcomm Inc.

A second patent develops the idea of this glass much further. The design shown in Figure 19 is a very simple idea of how the crystal implants block light. In Figure 20 we can now see how the layers can be further developed for an ideal light-blocking and allowing structure.

This patent was filed by *Sustainable Technologies Australia Ltd.*, a company from Australia. This patent includes not only the ability to darken the glass but also the ability to add color or tint. In this sense we will be using this technology for our frosting glass, since this merely colors the light to a white.

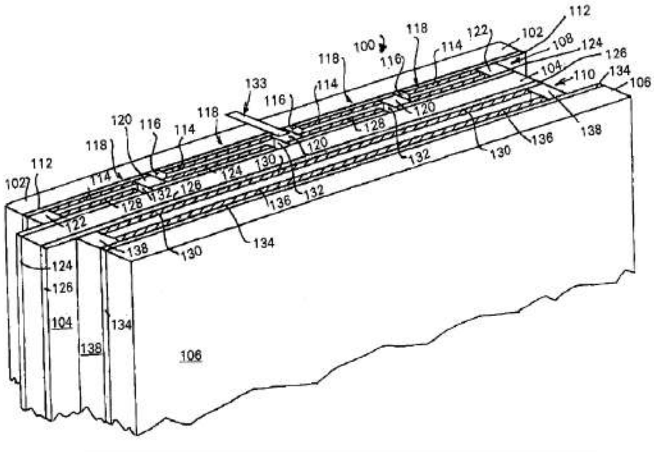


Figure 20. Layer Design by Sustainable Technologies Australia, Ltd.

There also exists a patent regarding a Smart Window and its management system from a small company called *E Ink Holdings Inc* that arranges a structure that includes a windowpane, at least one sensor, and a wireless signal transceiver, following the next scheme:

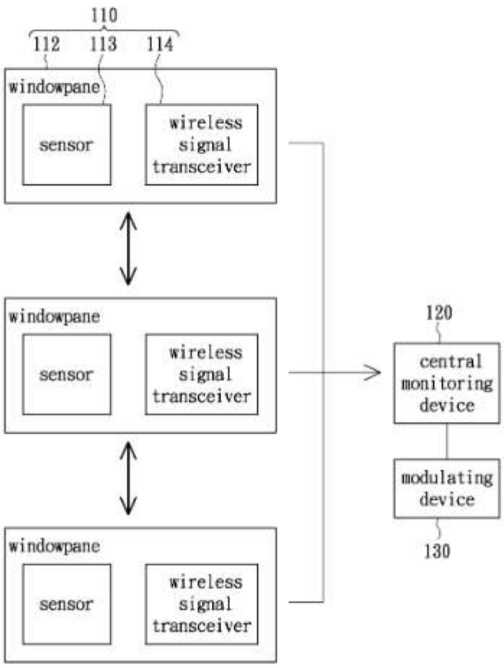


Figure 21. Scheme followed by E Ink Holdings Inc patent

Figure 21 shows a simple structure based on the idea of designing a control that enable the window itself to manage the modulation of the opacity of the glass with the data recovered from the sensors (at least one), which are configured to receive and collect the amount of light outside in order to perform an effectual intelligent modulation.

This patent is connected to our project as we intend to use sensors to collect data from the outside to control the transmission of light, but our goal is for the consumers themselves to be able to control the opacity of the window depending on how much natural light they want to enter their homes.

In our patent search we did not find any problems that we may run into regarding intellectual property other than the use of the most recent patent. For our smart window structure, however, we will be incorporating much more than the basics of this design.

As listed in the technical specification section, the window blocks UV exposure, making its users healthy and safe. The main environmental impact as far as we could find was that the smart windows would be consuming power, whereas normal windows do not consume electricity. However, the window runs on less than a Watt, and the power consumed to run the window will likely be offset by energy savings on heating and cooling. In fact, smart windows could be integrated with other smart home technologies such as lights, solar panels, etc. that could more effectively manage energy use. The minimal energy consumption also helps to avoid conflict with any government power regulations.

PART 2: FUTURE WORK

There are many potential improvements that can be made to this design to improve functionality and cater to the customer's desires. Firstly, Wanda the Window has the perfect potential to be integrated into the smart home structure, controlled by Alexa or any other voice control equivalent. A module such as the one created could be programmed to respond to smart home commands sent by a voice control module. Commands such as "Wanda, set my windows to 20% light" will be processed and sent to the window's hardware to set the window's electrical dimming percentage. As indicated by our survey results, this is a desirable control method and if integrated with the smart home will increase the attractiveness of this product for customers.

Another important step would be to create a native app accessible through any app store. Companies such as Lutron offer app control of their devices through a native app, and therefore it would be very desirable to offer this same feature. This app would be able to use the functionality of the phone itself, making it possible for Touch Id sign-in and possibly even integration with the alarm of the phone itself. Therefore, it would be possible for the user to set only one alarm. Additionally, as the user adds more Wanda Windows to their home, there will need to be an app feature to organize and control all of the windows separately in an intuitive manner.

There are also a variety of improvements that could be made on this prototype design. Firstly, the ESP8266 Wi-Fi Module was the greatest flaw in the final design due to its occasional hang-ups during operation. To reduce this error, it would be prudent to replace this module with a Wi-Fi Shield and replace the Uno R3 with a Mega to handle the increase in occupied pins. Or, if necessary, replace the Arduino itself with a Raspberry Pi to handle the internet interaction. The improvement of this hardware would increase the speed of response and ultimately create a better user experience.

Another consideration is that when multiple windows are connected, it must be possible to control them individually. Our design allows for control of one window currently. The app/server design would need to be expanded to handle and organize the opacity/dimming information for multiple windows. In the future, customers would also likely prefer windows that are able to both frost and dim. This design of two films that would be controlled with a separate voltage would need to be designed into the circuit and the communication structure.

PART 3: CONCLUSIONS

We should analyze if the objectives of both the Power System and the general product purposes have been accomplished during this past year work.

The main objectives for the power system were:

i. Power up the microcontroller and the whole circuit from any power outlet indefinitely.
ii. Power up the microcontroller and the whole circuit from the additional battery, in case of emergency for a specified time (t_{min} = 1h).
iii. Proof that the circuit would be able to power several loads, if necessary.
iv. Dimensionally small, acceptable to hide and move around.

All objectives have been achieved, as the circuit is able to work with power coming from any household outlet as well as the external battery, that lasts for at least two hours (checked during the test explained in Table 2), and that would be able, following that logic, to power up several loads at the same time for a smaller period. The charger module is capable to drawn over 1000 mA (usually 500 mA+) and each small load only consumes less than 9 mA.

When soldered altogether, the power circuit hardware is relatively compact and can easily be hidden within drywall or condensed into a small unassuming box.

The following objectives are referred to the final product.

I. Control the dimming of the glass through a phone App or web platform.
II. Connect both the App and desktop setup so if you change the specs from one, the other corrects it as well.
III. Design an intuitive App background.
IV. Design an external power system to power up the load in case of emergency.
V. Adapt the signal coming from the photodiode to respond correctly on the control.

The final result of this project is a fully-functional app control structure for an electronically dimming window. The power circuit hardware communicates with the app via Wi-Fi and responds almost immediately to the dimming percentage set on the app.

There are sporadic hang-ups with the ESP8266 module that could be improved by replacement with more reliable hardware. Otherwise, the window will respond in milliseconds providing the customer with the ideal amount of light for their room. This also affects the response time to the input from the photodiode.

PART 4: REFERENCES

[1] Carissa Johnson, "If you want to wake up happy, try this alarm clock trick"

https://www.mindbodygreen.com/0-28702/if-you-want-to-wake-up-happy-try-this-alarm-clock-t rick.html

[2] Invisishade, "Self-Adhesive Film Features and Specifications"

http://www.invisishade.com/

[3] Adafruit, "Miniature Single Cell, Fully Integrated Li-Ion, Li-Polymer Charge Management Controller"

DataSheet*: https://cdn-shop.adafruit.com/datasheets/MCP73831.pdf*

[4] Adafruit, "SYNCHRONOUS BOOST CONVERTER WITH 2A SWITCH"

DataSheet*: https://cdn-shop.adafruit.com/datasheets/tps61090.pdf*

[5] Belfuse, "International Flathead Low Profile Transformers"

DataSheet*: https://belfuse.com/resources/IF.pdf*

[6] Analog, "256-Position SPI-Compatible Digital Potentiometer"

DataSheet*: https://www.analog.com/media/en/technical-documentation/data-sheets/AD5160.pdf?_ga=2.189675691.1674535084.1555104651-1998442838.1555005985*

[7] IDEC, "RY/RM Series Miniature Relays"

DataSheet*: http://us.idec.com/Common/Download.aspx?d=33685*

[8] Cui Inc., "VSK-S1 Series"

DataSheet*: https://www.cui.com/product/power/ac-dc-power-supplies/board-mount/vsk-s1-series*

[9] Qualcomm Inc., "MECHANICAL SMART WINDOW WITH CONTINUOUSLY TUNABLE TRANSMISSION"

Datasheet:
https://patentimages.storage.googleapis.com/60/a3/ff/3a9bca0dd1bd23/WO2013096008A3.pdf

[10] E Ink Holdings Inc., "SMART WINDOW AND SMART WINDOW SYSTEM USING THE SAME"

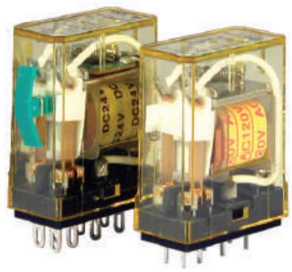
Datasheet: *https://patentimages.storage.googleapis.com/cf/24/8a/3e8bd7ea86ec49/US20120188627A1.pdf*

[11] Sustainable Technologies Australia Limited, "ELECTRO PHOTOCHROMIC SMART WINDOWS AND METHODS"

Datasheet: *https://patents.google.com/patent/JP4311876B2/en*

PART 5: DATASHEETS

RY/RM Series Miniature Relays



Key features:

- RY2 (3A), RY4 (5A), RM2 (5A)
- General purpose miniature relays
- 3A or 5A contact capacity
- Wide variety of terminal styles and coil voltages meet a wide range of applications
- All 4PDT types have arc barriers.

Part Number Selection

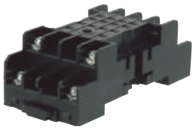
Contact	Model	Part Number: Plug-in Terminal	Part Number: PC Board Terminal	Coil Voltage Code
DPDT (Slim) 3A 	Standard	RY2S-U ☐	RY2V-U ☐	AC6V, AC12V, AC24V, AC110V, AC120V, AC220V, AC240V DC6V, DC12V, DC24V, DC48V, DC110V
	With Indicator	RY2S-UL ☐	RY2V-UL ☐	
	With Check Button	RY2S-UC ☐	—	
	With Indicator and Check Button	RY2S-ULC ☐		
	Top Bracket Mounting	RY2S-UT ☐		
	With Diode (DC coil only)	RY2S-UD ☐	RY2V-UD ☐	DC6V, DC12V, DC24V, DC48V, DC110V
DPDT (Wide) 5A 	Standard	RM2S-U ☐	RM2V-U ☐	RYAC6V, AC12V, AC24V, AC110-120V, AC220-240V DC6V, DC12V, DC24V, DC48V, DC100-110V
	With Indicator	RM2S-UL ☐	RM2V-UL ☐	
	With Check Button	RM2S-UC ☐	—	
	With Indicator and Check Button	RM2S-ULC ☐		
	Top Bracket Mounting	RM2S-UT ☐		
	With Diode (DC coil only)	RM2S-UD ☐		DC6V, DC12V, DC24V, DC48V, DC100-110V
	With Indicator and Diode (DC coil only)	RM2S-ULD ☐		
4PDT 5A 	Standard	RY4S-U ☐	RY4V-U ☐	AC6V, AC12V, AC24V, AC110-120V, AC220-240V DC6V, DC12V, DC24V, DC48V, DC100-110V
	With Indicator	RY4S-UL ☐	RY4V-UL ☐	
	With Check Button	RY4S-UC ☐	—	
	With Indicator and Check Button	RY4S-ULC ☐		
	Top Bracket Mounting	RY4S-UT ☐		
	With Diode (DC coil only)	RY4S-UD ☐		DC6V, DC12V, DC24V, DC48V, DC100-110V
	With Indicator and Diode (DC coil only)	RY4S-ULD ☐		

Top mount models are designed to mount directly to a panel and do not require a socket.

Ordering Information
When ordering, specify the Part No. and coil voltage code:

(example) **RY4S-U** **AC110-120V**
Part No. — Coil Voltage Code

Sockets

Relays	Standard DIN Rail Mount	Finger-safe DIN Rail Mount	Through Panel Mount	PCB Mount
RY2S	SY2S-05	SY2S-05C	SY2S-51	SY2S-61
RM2	SM2S-05	SM2S-05C	SM2S-51	SY4S-61 SY4S-62
RY4S	SY4S-05	SY4S-05C	SY4S-51	
				

Hold Down Springs & Clips

Appearance	Item	Relay	For DIN Mount Socket	For Through Panel & PCB Mount Socket
	Pullover Wire Spring	RY2S	SY2S-02F1	SY4S-51F1
		RM2	SY4S-51F1	SY4S-51F1
		RY4S		
	Leaf Spring [1] (side latch)	RY2S	SFA-202 [2]	SFA-302
		RM2, RY4S		
	Leaf Spring [1] (top latch)	RY2S	SFA-101 [2]	SFA-301
		RM2		
		RY4S		

1. Not available for PCB mount socket SY4S-62.
2. Order 2 pieces per relay.

Accessories

Item	Appearance	Use with	Part No.	Remarks
Aluminum DIN Rail (1 meter length)		All DIN rail sockets	BNDN1000	The BNDN1000 is designed to accommodate DIN mount sockets. Made of durable extruded aluminum, the BNDN1000 measures 0.413 (10.5mm) in height and 1.37 (35mm) in width (DIN standard). Standard length is 39" (1,000mm).
DIN Rail End Stop		DIN rail	BNL5	9.1 mm wide.
Replacement Hold-Down Spring Anchor		Horseshoe clip for all DIN rail sockets	Y778-011	For use on DIN rail mount socket when using pullover wire hold down spring. 2 pieces included with each socket.

Specifications

Contact Model	Standard Contact		
	RY2 - DPDT Slim	RM2 - DPDT Wide	RY4 - 4PDT
Contact Material	Gold-plated silver	Silver	Gold-plated silver
Contact Resistance [1]	50 mΩ maximum	30 mΩ maximum	50 mΩ maximum
Minimum Applicable Load	24V DC, 5 mA; 5V DC, 10 mA (reference value)	24V DC, 10 mA; 5V DC, 20 mA (reference value)	24V DC, 5 mA; 5V DC, 10 mA (reference value)
Operating Time [2]	20 ms maximum		
Release Time [2]	20 ms maximum		
Power Consumption (approx.)	AC: 1.1 VA (50 Hz), 1 VA (60 Hz) DC: 0.8W	AC: 1.4 VA (50 Hz), 1.2 VA (60 Hz) DC: 0.9W	AC: 1.4 VA (50 Hz), 1.2 VA (60 Hz) DC: 0.9W
Insulation Resistance	100 MΩ minimum (500V DC megger)		
Dielectric Strength	Between live and dead parts:		
	1500V AC, 1 minute	2000V AC, 1 minute	2000V AC, 1 minute
	Between contact and coil:		
	1500V AC, 1 minute	2000V AC, 1 minute	2000V AC, 1 minute
	Between contacts of different poles:		
	1500V AC, 1 minute	2000V AC, 1 minute	2000V AC, 1 minute
	Between contacts of the same pole:		
	1000V AC, 1 minute	1000V AC, 1 minute	1000V AC, 1 minute
Operating Frequency	Electrical: 1800 operations/h maximum Mechanical: 18,000 operations/h maximum		
Vibration Resistance	Damage limits: 10 to 55 Hz, amplitude 0.5 mm Operating extremes: 10 to 55 Hz, amplitude 0.5 mm		
Shock Resistance	Damage limits: 1000 m/s² Operating extremes: 100 m/s² (DPDT Slim), 200 m/s² (4PDT, DPDT Wide)		
Mechanical Life	50,000,000 operations		
Electrical Life	200,000 operations (220V AC, 3A)	500,000 operations (220V AC, 5A)	100,000 operations (220V AC, 5A) 200,000 operations (220V AC, 3A)
Operating Temperature [3]	–25 to +55°C (no freezing)	–25 to +45°C (no freezing)	–25 to +55°C (no freezing) [4]
Operating Humidity	45 to 85% RH (no condensation)		
Weight (approx.)	23g	35g	34g

Note: Above values are initial values.
1. Measured using 5V DC, 1A voltage drop method
2. Measured at the rated voltage (at 20°C), excluding contact bouncing
   Release time of relays with diode: 40 ms maximum
3. For use under different temperature conditions, refer to Continuous Load Current vs. Operating Temperature Curve. The operating temperature range of relays with indicator or diode is –25 to +40°C.
4. When the total current of 4 contacts is less than 15A, the operating temperature range is –25 to +70°C.

AC Coil Ratings

Voltage (V)	Rated Current (mA) ±15% at 20°C				Coil Resistance (Ω) ±10% at 20°C		Operation Characteristics (against rated values at 20°C)		
	AC 50Hz		AC 60Hz						
	DPDT Slim	DPDT Wide & 4PDT	DPDT Slim	DPDT Wide & 4PDT	DPDT Slim	DPDT Wide & 4PDT	Max. Continuous Applied Voltage	Pickup Voltage	Dropout Voltage
6	170	240	150	200	18.8	9.4	110%	80% maximum	30% minimum
12	86	121	75	100	76.8	39.3			
24	42	60.5	37	50	300	153			
110	9.6	—	8.4	—	6,950	—			
110-120	—	9.4-10.8	—	8.0-9.2	—	4,290			
120	8.6	—	7.5	—	8,100	—			
220	4.7	—	4.1	—	25,892	—			
220-240	—	4.7-5.4	—	4.0-4.6	—	18,820			
240	4.9	—	4.3	—	26,710	—			

DC Coil Ratings

Voltage (V)	Rated Current (mA) ±15% at 20°C		Coil Resistance (Ω) ±10% at 20°C		Operation Characteristics (against rated values at 20°C)		
	DPDT Slim	DPDT Wide & 4PDT	DPDT Slim	DPDT Wide & 4PDT	Max. Continuous Applied Voltage	Pickup Voltage	Dropout Voltage
6	128	150	47	40	110%	80% maximum	10% minimum
12	64	75	188	160			
24	32	36.9	750	650			
48	18	18.5	2,660	2,600			
100-110	—	8.2-9.0	—	12,250			
110	8	—	13,800	—			

Contact Ratings

Contact	Continuous Current	Maximum Contact Capacity				
		Allowable Contact Power		Rated Load		
		Resistive Load	Inductive Load	Voltage (V)	Res. Load	Ind. Load
DPDT Slim (RY2)	3A	660 VA AC 90W DC	176 VA AC 45W DC	110V AC	3A	1.5A
				220V AC	3A	0.8A
				30V DC	3A	1.5A
DPDT Wide (RM2)	5A	1100VA AC 150W DC	440VA AC 75W DC	110V AC	5A	2.5A
				220V AC	5A	2A
				30V DC	5A	2.5A
4PDT (RY4)	5A	1200 VA AC 150W DC	288 VA AC 60W DC	240V AC	5A	1.2A
				30V DC	5A	2A

Note: Inductive load for the rated load — cos ø = 0.3, L/R = 7 ms

TÜV Ratings

Voltage	DPDT Slim	DPDT Wide	4PDT
240V AC	3A	5A	5A
30V DC	3A	5A	5A

AC: cos ø = 1.0, DC: L/R = 0 ms

UL Ratings

Voltage	Resistive			General use		
	DPDT Slim	DPDT Wide	4PDT	DPDT Slim	DPDT Wide	4PDT
240V AC	3A	5A	5A	0.8A	2A	5A
120V AC	—	—	—	1.5A	2.5A	—
100V DC	0.2A	0.4A	0.2A	0.2A	—	0.2A
30V DC	3A	5A	5A	3A	—	5A

CSA Ratings

Voltage	Resistive			General use		
	DPDT Slim	DPDT Wide	4PDT	DPDT Slim	DPDT Wide	4PDT
240V AC	3A	5A	5A	0.8A	2A	5A
120V AC	3A	5A	—	1.5A	2.5A	—
100V DC	—	—	—	0.2A	0.4A	0.2A
30V DC	3A	5A	5A	1.5A	2.5A	1.5A

Socket Specifications

	Sockets	Terminal	Electrical Rating	Wire Size	Torque
DIN Rail Mount Sockets	SY2S-05	M3 screws with captive wire clamp	300V, 7A	Maximum up to 2–#14AWG	5.5 - 9 in•lbs
	SM2S-05	M3 screw with captive wire clamp	300V, 10A	Maximum up to 2–#14AWG	5.5 - 9 in•lbs
	SY4S-05	M3 screw with captive wire clamp	300V, 7A*	Maximum up to 2–#14AWG	5.5 - 9 in•lbs
Finger-safe DIN Rail Mount	SY2S-05C	M3 screws with captive wire clamp, fingersafe	300V, 7A	Maximum up to 2–#14AWG	5.5 - 9 in•lbs
	SM2S-05C	M3 screw with captive wire clamp, fingersafe	300V, 10A	Maximum up to 2–#14AWG	5.5 - 9 in•lbs
	SY4S-05C	M3 screw with captive wire clamp, fingersafe	300V, 7A*	Maximum up to 2–#14AWG	5.5 - 9 in•lbs
Through Panel Mount Socket	SY2S-51	Solder	250V, 7A	—	—
	SM2S-51	Solder	250V, 10A	—	—
	SY4S-51	Solder	250V, 7A*	—	—
PCB Mount Socket	SY2S-61	PCB Mount	300V, 7A	—	—
	SY4S-61	PCB Mount	300V, 7A	—	—
	SY4S-62	PCB Mount	250V, 7A	—	—

* When using only 2 poles of the 4-poles, the UL recognized current is 10A.

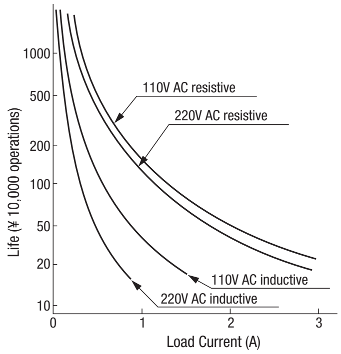
Switches & Pilot Lights
Signaling Lights
Relays & Sockets
Timers
Contactors
Terminal Blocks
Circuit Breakers

Characteristics (Reference Data)

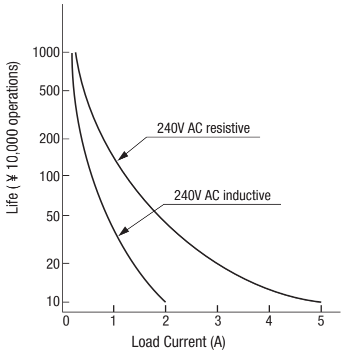
Electrical Life Curves

AC Load

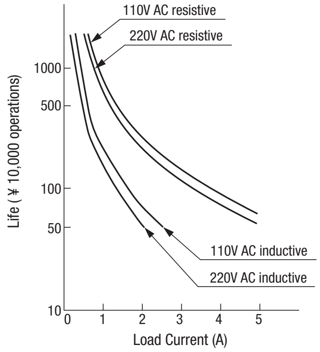
(RY2)



(RY4)

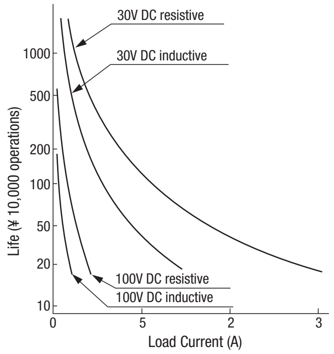


(RM2)

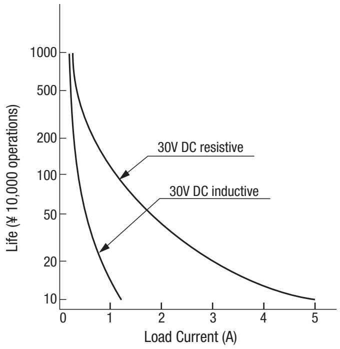


DC Load

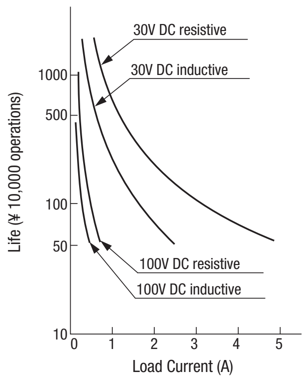
(RY2)



(RY4)

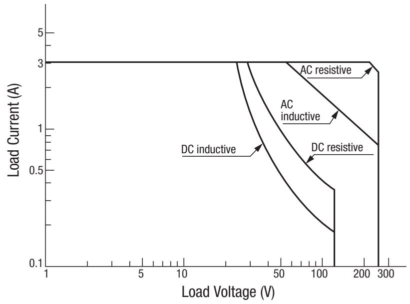


(RM2)

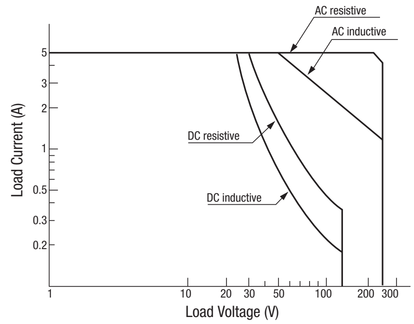


Maximum Switching Capacity

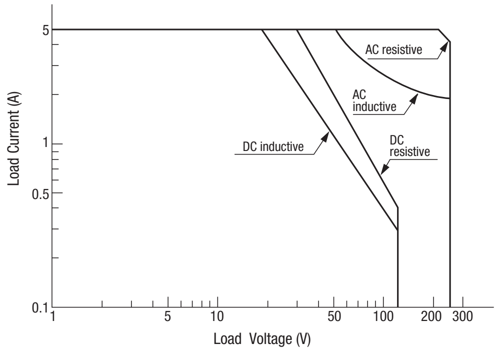
(RY2)



(RY4)

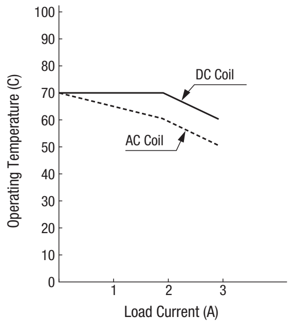


(RM2)

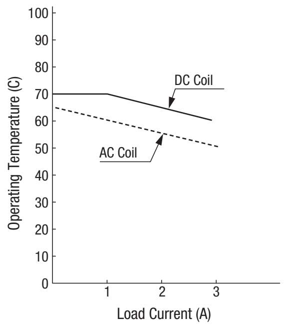


Continuous Load Current vs. Operating Temperature Curve (Standard Type, With Check Button, and Top Bracket Mounting Type)

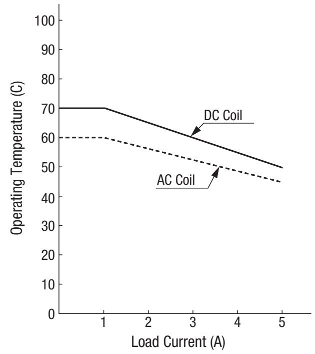
(RY2)



(RY4)



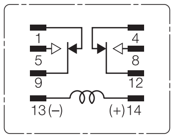
(RM2)



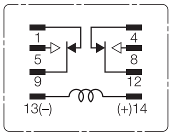
Internal Connection (View from Bottom)

Standard Type

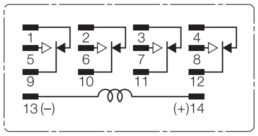
DPDT Slim (RY2)



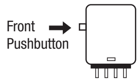
DPDT Wide (RM2)



4PDT (RY4)

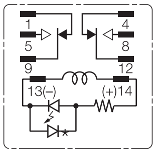
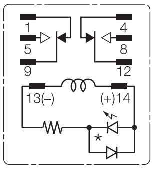
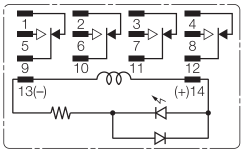
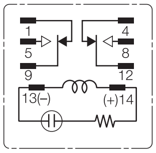
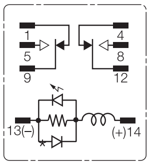
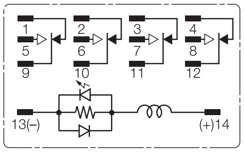


With Check Button



Contacts can be operated by pressing the check button.

With Indicator (-L type)

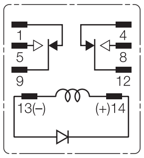
	DPDT Slim (RY2)		DPDT Wide (RM2)	4PDT (RY4)
Coil Below 100V AC/DC		Coil Below 24V AC/DC		
Coil 100V AC/DC and over		Coil 24V AC/DC and over		

When the relay is energized, the indicator goes on.

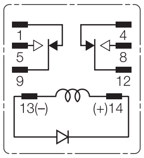
- An LED protection diode is not contained in DPDT relays for coils below 100V DC.
- If coil polarity is reversed LED will not light.

With Diode (-D type)

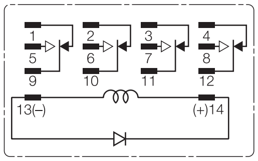
DPDT Slim (RY2)



DPDT Wide (RM2)



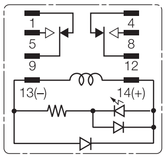
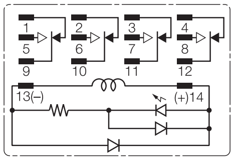
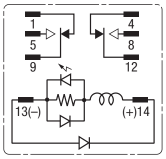
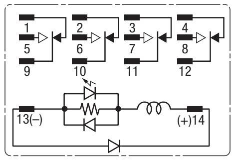
4PDT (RY4)



Contains a diode to absorb the back emf generated when the coil is de-energized. The release time is slightly longer.

- Diode Characteristics
  Reverse withstand voltage: 1,000V
  Forward current: 1A

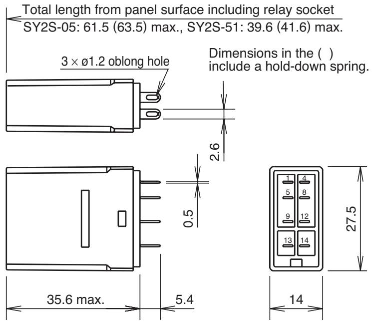
With Indicator and Diode (-LD type)

	DPDT Wide (RM2)	4PDT (RY4)		DPDT Wide (RM2)	4PDT (RY4)
Coil Below 24V DC			Coil 24V DC and over		

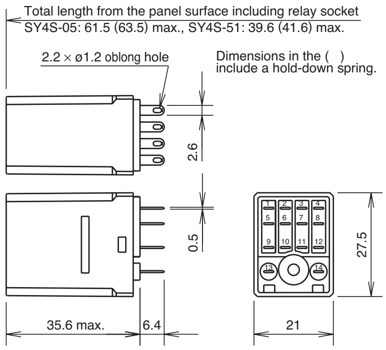
Contains an LED indicator and a surge absorber.

Dimensions (mm)

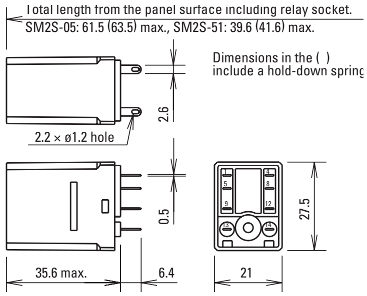
RY2S



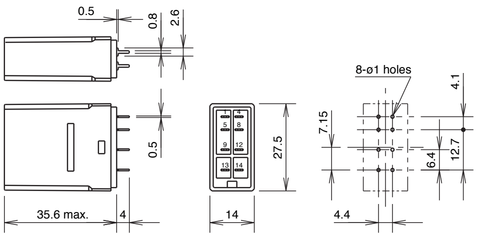
RY4S



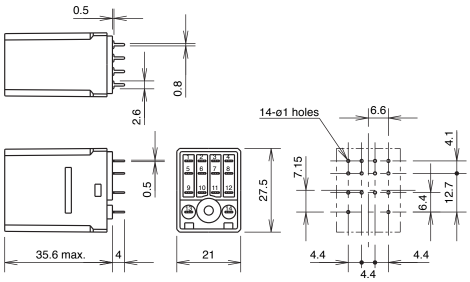
RM2S



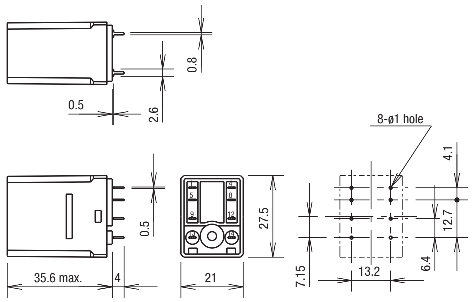
RY2V



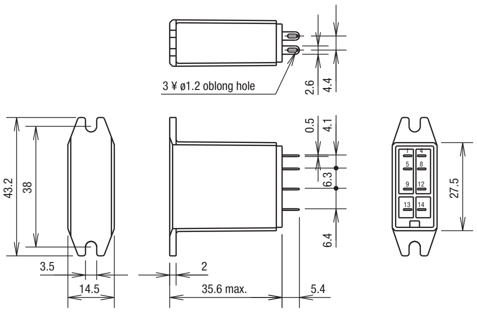
RY4V



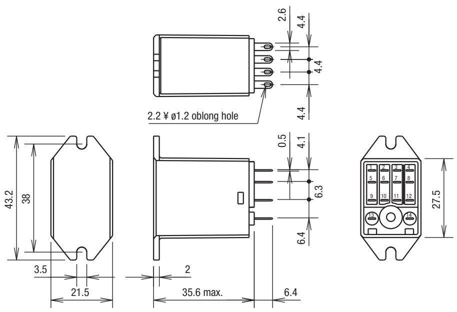
RM2V



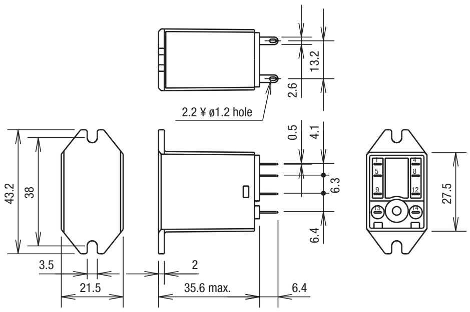
RY2S-UT



RY4S-UT



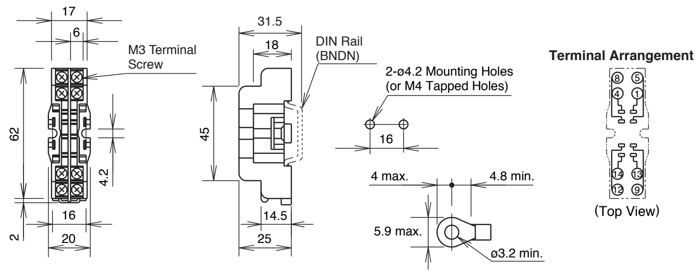
RM2S-UT



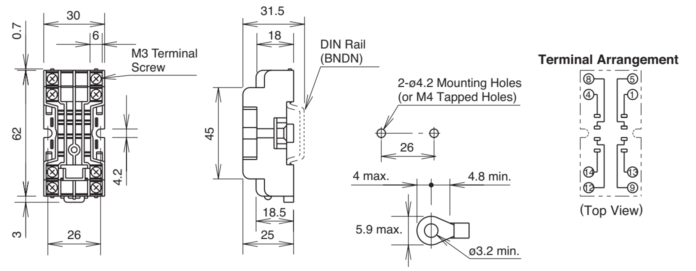
Dimensions

Standard DIN Rail Mount Sockets

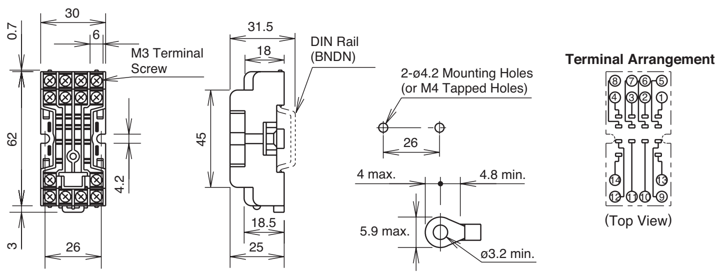
SY2S-05



SM2S-05

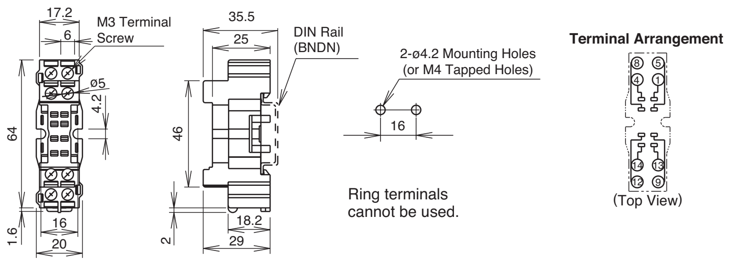


SY4S-05

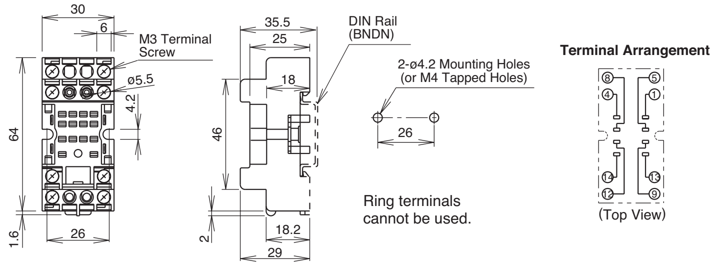


Finger-safe DIN Rail Mount Sockets

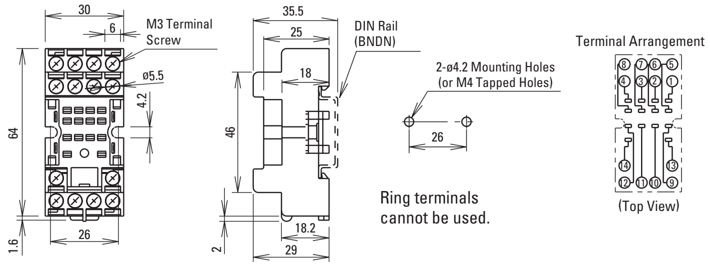
SY2S-05C



SM2S-05C

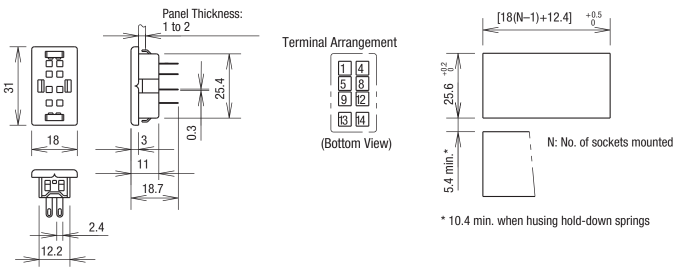


SY4S-05C

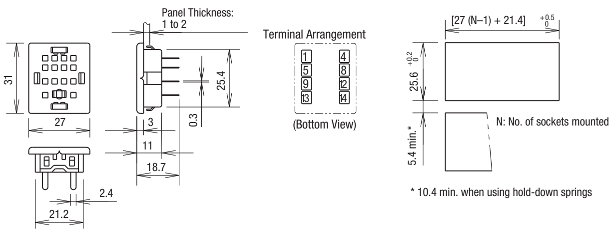


Through Panel Mount Socket

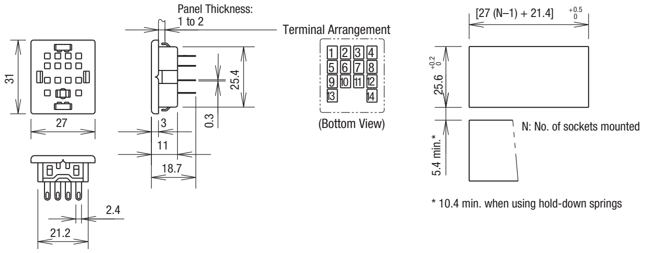
SY2S-51



SM2S-51

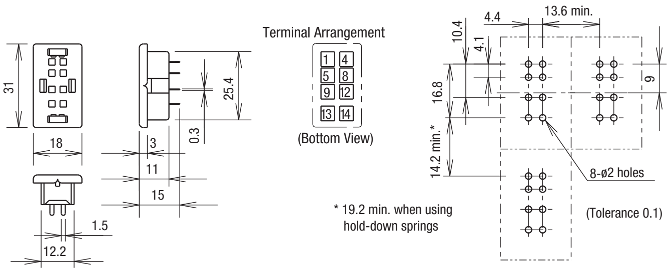


SY4S-51

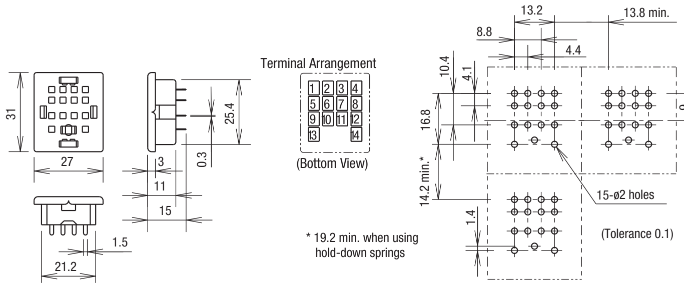


PCB Mount Sockets

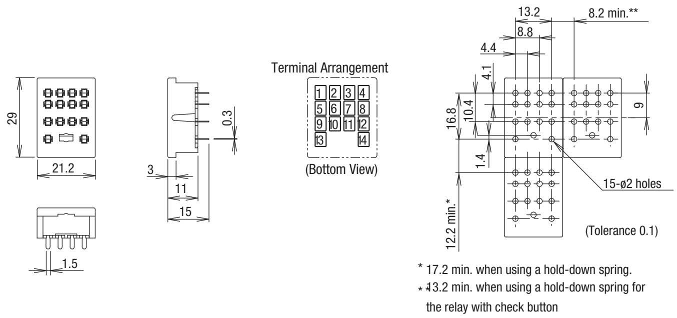
SY2S-61



SY4S-61



SY4S-62



For more information, please visit the product page.

CUI INC

SERIES: VSK-S1 | DESCRIPTION: AC-DC POWER SUPPLY

FEATURES
- up to 1 W continuous power
- compact board mount design
- universal input (85~305 Vac / 120~430 Vdc)
- single output from 3.3~24 Vdc
- over current and short circuit protection
- UL/cUL and CE safety approvals
- efficiency up to 75%

MODEL	output voltage (Vdc)	output current max (mA)	output power max (W)	ripple and noise[1] max (mVp-p)	efficiency typ (%)
VSK-S1-3R3U	3.3	300	1	200	63
VSK-S1-5U	5	200	1	200	68
VSK-S1-9U	9	111	1	200	72
VSK-S1-12U	12	83	1	200	73
VSK-S1-15U	15	67	1	200	74
VSK-S1-24U	24	42	1	200	75

Notes: 1. At full load 20 MHz bandwidth oscilloscope, see Test Configuration section.

PART NUMBER KEY

VSK-S1 - XX U

Base Number (VSK-S1)
Output Voltage (XX)

INPUT

parameter	conditions/description	min	typ	max	units
voltage		85 120		305 430	Vac Vdc
frequency		47		63	Hz
current	at 115 Vac at 230 Vac			37 21	mA mA
inrush current	at 115 Vac at 230 Vac		7 14		A A
leakage current				0.15	mA
no load power consumption				0.2	W

OUTPUT

parameter	conditions/description	min	typ	max	units
maximum capacitive load	3.3 and 5 Vdc output models 9 and 12 Vdc output models 15 Vdc output model 24 Vdc output model			4,000 2,200 1,000 680	μF μF μF μF
line regulation	at full load		±2		%
load regulation	at 10 ~ 100% load		±5		%
voltage accuracy	3.3 Vdc model all other models		±6 ±5		% %
switching frequency				100	kHz

PROTECTIONS

parameter	conditions/description	min	typ	max	units
over current protection	auto restart	110			%
short circuit protection	continuous, auto restart				

SAFETY & COMPLIANCE

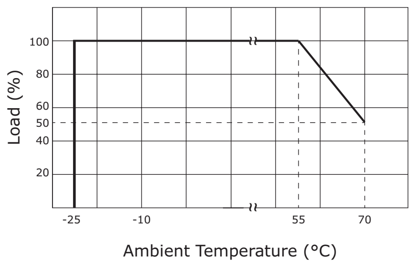
parameter	conditions/description	min	typ	max	units
isolation voltage	input to output for 1 minute	3,000			Vac
safety approvals	UL 60950-1				
safety class	class II				
conducted/radiated emissions	CISPR22/EN55022 Class B				
ESD	IEC/EN61000-4-2 class B, contact ±4kV, air ±8kV				
radiated immunity	IEC/EN61000-4-3 class A, 10V/m				
EFT/burst	IEC/EN61000-4-4 class B, ±2kV (external circuit required, see figure 3)				
surge	IEC/EN61000-4-5 class B, ±2kV (external circuit required, see figure 3)				
conducted immunity	IEC/EN61000-4-6 class A, 10 Vr.m.s				
PFM	IEC/EN61000-4-8 class A, 10 A/m				
voltage dips & interruptions	IEC/EN61000-4-11 class B, 0%-70%				
MTBF	as per MIL-HDBK-217F, 25°C	300,000			hours
RoHS	2011/65/EU				

ENVIRONMENTAL

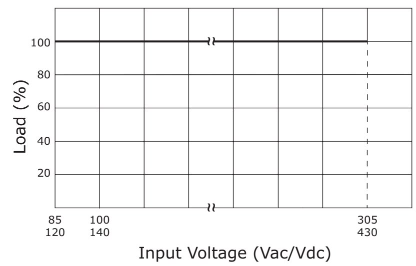
parameter	conditions/description	min	typ	max	units
operating temperature	see derating curves	-25		70	°C
storage temperature		-25		85	°C
operating humidity	non-condensing			90	%
storage humidity	non-condensing			95	%

DERATING/EFFICIENCY CURVES

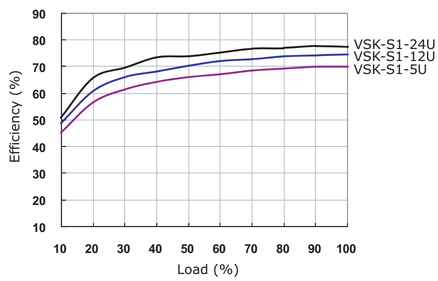
output power vs. ambient temperature
(85~305 Vac; 120~430 Vdc)



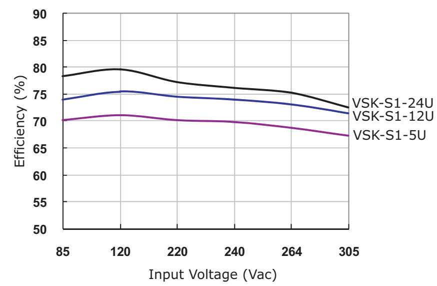
output power vs. input voltage
(25°C)



efficiency vs. output power
(Vin=230 Vac)



efficiency vs. input voltage
(full load)



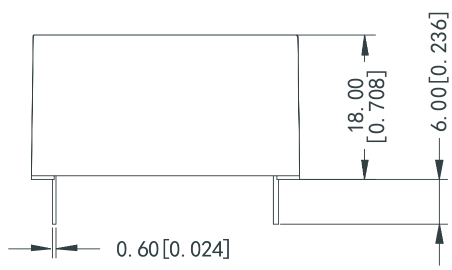
MECHANICAL

parameter	conditions/description	min	typ	max	units
dimensions	33.70 x 22.20 x 18.00 (1.327 x 0.874 x 0.708 inch)				mm
case material	UL94V-0				
weight			20		g

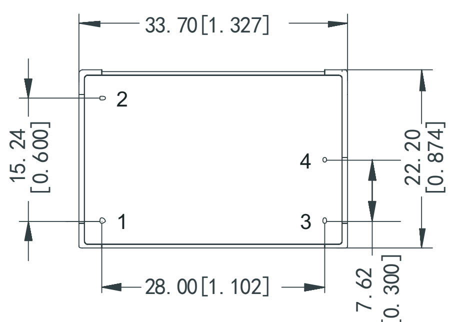
MECHANICAL DRAWING

units: mm [inches]
tolerance: ±0.50 [±0.020]
pin section tolerance: ±0.10 mm [±0.004]

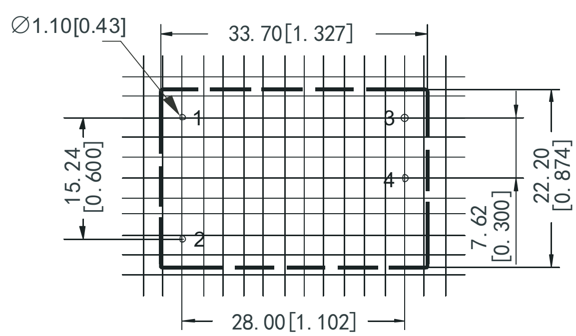
PIN CONNECTIONS	
PIN	FUNCTION
1	AC(N)
2	AC(L)
3	-Vo
4	+Vo



Front view



Bottom view



Recommended PCB Layout
Top View

TEST CONFIGURATION

Figure 1

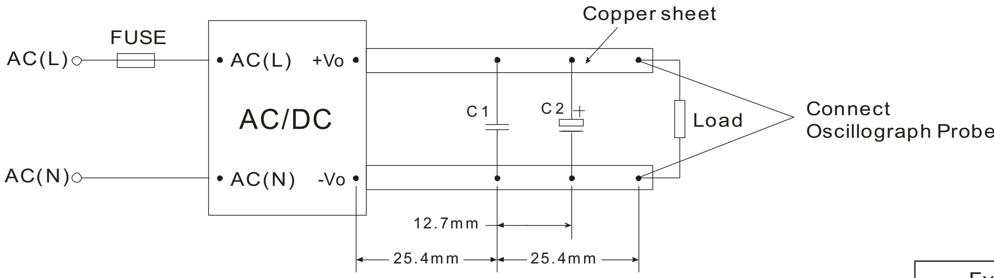


Table 1

External components	
C1	1μF ceramic
C2	10μF electrolytic

TYPICAL APPLICATION CIRCUIT

Figure 2

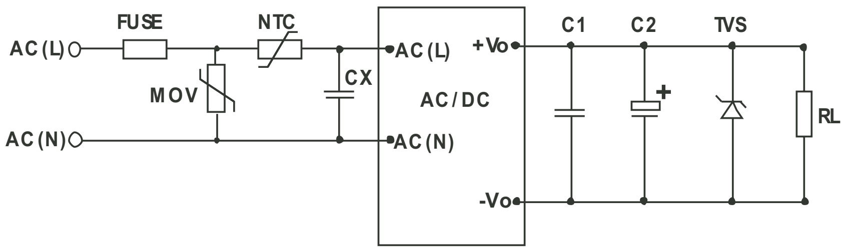
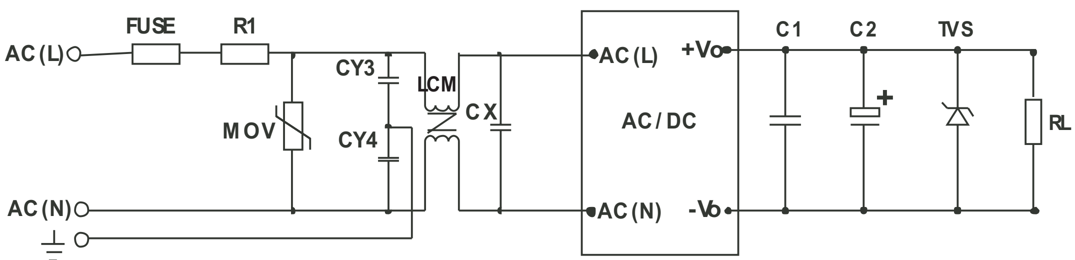


Table 2

Recommended external circuit components										
Model	FUSE	MOV	NTC	R1	CY3, CY4	CX	LCM	TVS[1]	C1[2]	C2[3]
VSK-S1-3R3U	1A/300V, slow blow	S14K350	10D-11	47Ω/3W	2.2nF/400V	0.4μF/305Vac	10 mH	SMBJ7.0A	1μF/50V	220μF
VSK-S1-5U	1A/300V, slow blow	S14K350	10D-11	47Ω/3W	2.2nF/400V	0.1μF/305Vac	10 mH	SMBJ7.0A	1μF/50V	220μF
VSK-S1-9U	1A/300V, slow blow	S14K350	10D-11	47Ω/3W	2.2nF/400V	0.1μF/305Vac	10 mH	SMBJ12A	1μF/50V	120μF
VSK-S1-12U	1A/300V, slow blow	S14K350	10D-11	47Ω/3W	2.2nF/400V	0.1μF/305Vac	10 mH	SMBJ20A	1μF/50V	120μF
VSK-S1-15U	1A/300V, slow blow	S14K350	10D-11	47Ω/3W	2.2nF/400V	0.1μF/305Vac	10 mH	SMBJ20A	1μF/50V	120μF
VSK-S1-24U	1A/300V, slow blow	S14K350	10D-11	47Ω/3W	2.2nF/400V	0.1μF/305Vac	10 mH	SMBJ30A	1μF/50V	68μF

EMC RECOMMENDED CIRCUIT

Figure 3



Notes:
1. See Table 2 for EMC components.
2. TVS is a recommended component to protect post-circuits if converter fails.
3. C1 is a ceramic capacitor used to filter high frequency noise.
4. C2 is an electrolytic capacitor. We recommend using high frequency and low impedence electrolytic capacitors. For capacitance and current of capacitor please refer to the manufacture's datasheet. Voltage derating of capacitor should be 80% or above.
5. All specifications are measured at rated input voltage, rated output load, TA=25°C, and humidity < 75% unless otherwise specified.

REVISION HISTORY

rev.	description	date
1.0	initial release	06/04/2012
1.01	picture updated	09/06/2012
1.02	updated derating curves and spec	11/12/2013
1.03	internal inductor & PCB structure changed	10/26/2015

The revision history provided is for informational purposes only and is believed to be accurate.

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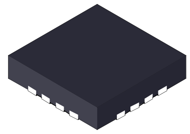
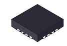
cui.com
techsupport@cui.com





Actual Size
(4,15 mm x 4,15 mm)

SYNCHRONOUS BOOST CONVERTER WITH 2A SWITCH

FEATURES

- **Synchronous (96% Efficient) Boost Converter With 500-mA Output Current From 1.8-V Input**
- **Available in a 16-Pin QFN 4 x 4 Package**
- **Device Quiescent Current: 20-μA (Typ)**
- **Input Voltage Range: 1.8-V to 5.5-V**
- **Adjustable Output Voltage Up to 5.5-V Fixed Output Voltage Options**
- **Power Save Mode for Improved Efficiency at Low Output Power**
- **Low Battery Comparator**
- **Low EMI-Converter (Integrated Antiringing Switch)**
- **Load Disconnect During Shutdown**
- **Over-Temperature Protection**

APPLICATIONS

- **All Single Cell Li or Dual Cell Battery, or USB Powered Operated Products as MP-3 Player, PDAs, and Other Portable Equipment**

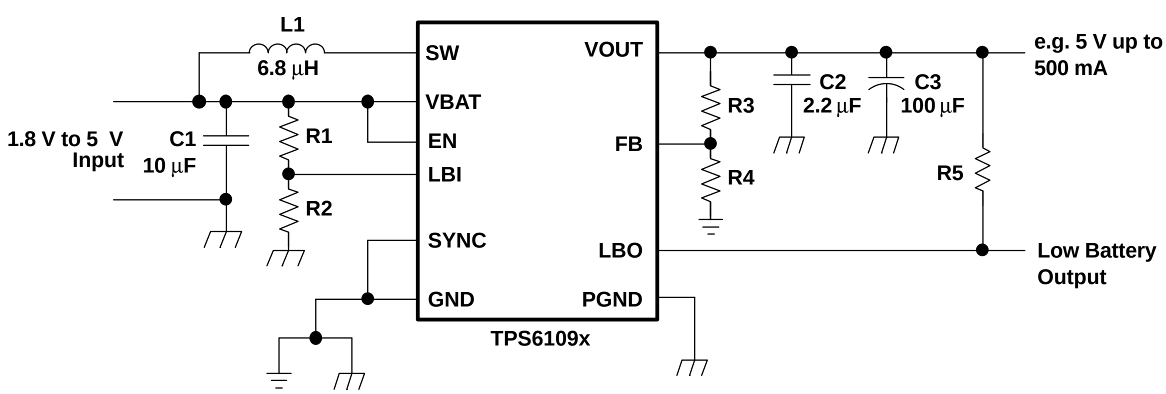
DESCRIPTION

The TPS6109x devices provide a power supply solution for products powered by either a one-cell Li-Ion or Li-polymer, or a two-cell alkaline, NiCd or NiMH battery and required supply currents up to or higher than 1 A. The converter generates a stable output voltage that is either adjusted by an external resistor divider or fixed internally on the chip. It provides high efficient power conversion and is capable of delivering output currents up to 0.5 A at 5 V at a supply voltage down to 1.8 V. The implemented boost converter is based on a fixed frequency, pulse-width- modulation (PWM) controller using a synchronous rectifier to obtain maximum efficiency. Boost switch and rectifier switch are connected internally to provide the lowest leakage inductance and best EMI behavior possible. The maximum peak current in the boost switch is limited to a value of 2500 mA.

The converter can be disabled to minimize battery drain. During shutdown, the load is completely disconnected from the battery. A low-EMI mode is implemented to reduce ringing and, in effect, lower radiated electromagnetic energy when the converter enters the discontinuous conduction mode.

The output voltage can be programmed by an external resistor divider or is fixed internally on the chip.

The device is packaged in a 16-pin QFN 4 x 4 mm (16 RSA) package.



These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

AVAILABLE OUTPUT VOLTAGE OPTIONS[1]

T_A	OUTPUT VOLTAGE DC/DC	PACKAGE	Part Number[2]
40°C to 85°C	Adjustable	16-Pin QFN 4x4mm	TPS61090RSA
	3.3 V	16-Pin QFN 4x4mm	TPS61091RSA
	5 V	16-Pin QFN 4x4mm	TPS61092RSA

(1) Contact the factory to check availability of other fixed output voltage versions.
(2) The RSA package is available taped and reeled. Add R suffix to device type (e.g., TPS61090RSAR) to order quantities of 3000 devices per reel.

ABSOLUTE MAXIMUM RATINGS

over operating free-air temperature range (unless otherwise noted)[1]

	TPS6109x
Input voltage range on LBI	-0.3 V to 3.6 V
Input voltage range on SW, VOUT, LBO, VBAT, SYNC, EN, FB	-0.3 V to 7 V
Operating free air temperature range T_A	-40°C to 85°C
Maximum junction temperature T_J	150°C
Storage temperature range T_{stg}	-65°C to 150°C

(1) Stresses beyond those listed under "absolute maximum ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under "recommended operating conditions" is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.

RECOMMENDED OPERATING CONDITIONS

	MIN	NOM	MAX	UNIT
Supply voltage at VBAT, V_I	1.8		5.5	V
Inductance, L	2.2	6.8		μH
Input, capacitance, C_i		10		μF
Output capacitance, C_o	22	100		μF
Operating free air temperature, T_A	-40		85	°C
Operating virtual junction temperature, T_J	-40		125	°C

ELECTRICAL CHARACTERISTICS

over recommended free-air temperature range and over recommended input voltage range (typical values are at an ambient temperature range of 25°C) (unless otherwise noted)

DC/DC STAGE						
PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
V_I	Input voltage range		1.8		5.5	V
V_O	TPS61090 output voltage range		1.8		5.5	V
V_{FB}	TPS61090 feedback voltage		490	500	510	mV
f	Oscillator frequency		500	600	700	kHz
	Frequency range for synchronization		500		700	kHz
I_{SW}	Switch current limit	VOUT= 5 V	2000	2200	2500	mA
	Start-up current limit			0.4 x I_{SW}		mA
	Boost switch on resistance	VOUT= 5 V		55		mΩ
	Rectifying switch on resistance	VOUT= 5 V		55		mΩ
	Total accuracy		-3%		3%	
	Line regulation				0.6%	

Electrical Characteristics (continued)

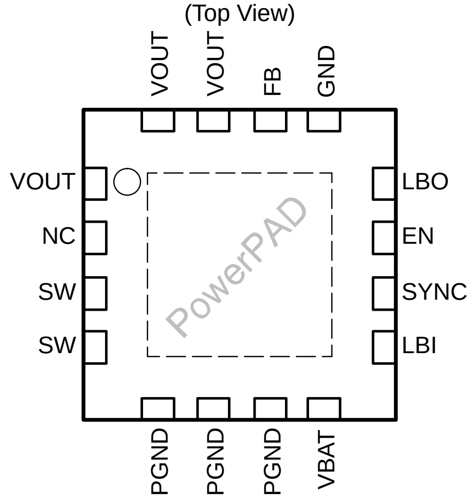
over recommended free-air temperature range and over recommended input voltage range (typical values are at an ambient temperature range of 25°C) (unless otherwise noted)

DC/DC STAGE						
PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
Load regulation					0.6%	
Quiescent current	into VBAT	I_O = 0 mA, V_{EN} = VBAT = 1.8 V, VOUT =5 V		10	25	µA
	into VOUT	I_O = 0 mA, V_{EN} = VBAT = 1.8 V, VOUT = 5 V		10	20	µA
Shutdown current		V_{EN}= 0 V, VBAT = 2.4 V		0.1	1	µA

CONTROL STAGE						
PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
V_{UVLO}	Under voltage lockout threshold	V_{LBI} voltage decreasing		1.5		V
V_{IL}	LBI voltage threshold	V_{LBI} voltage decreasing	490	500	510	mV
	LBI input hysteresis			10		mV
	LBI input current	EN = VBAT or GND		0.01	0.1	µA
	LBO output low voltage	V_O = 3.3 V, I_{OI} = 100 µA		0.04	0.4	V
	LBO output low current			100		µA
	LBO output leakage current	V_{LBO} = 7 V		0.01	0.1	µA
V_{IL}	EN, SYNC input low voltage				0.2 × VBAT	V
V_{IH}	EN, SYNC input high voltage		0.8 × VBAT			V
	EN, SYNC input current	Clamped on GND or VBAT		0.01	0.1	µA
	Overtemperature protection			140		°C
	Overtemperature hysteresis			20		°C

PIN ASSIGNMENTS

RSA Package
(Top View)



Terminal Functions

TERMINAL		I/O	DESCRIPTION
NAME	NO.		
EN	11	I	Enable input. (1/VBAT enabled, 0/GND disabled)
FB	14	I	Voltage feedback of adjustable versions

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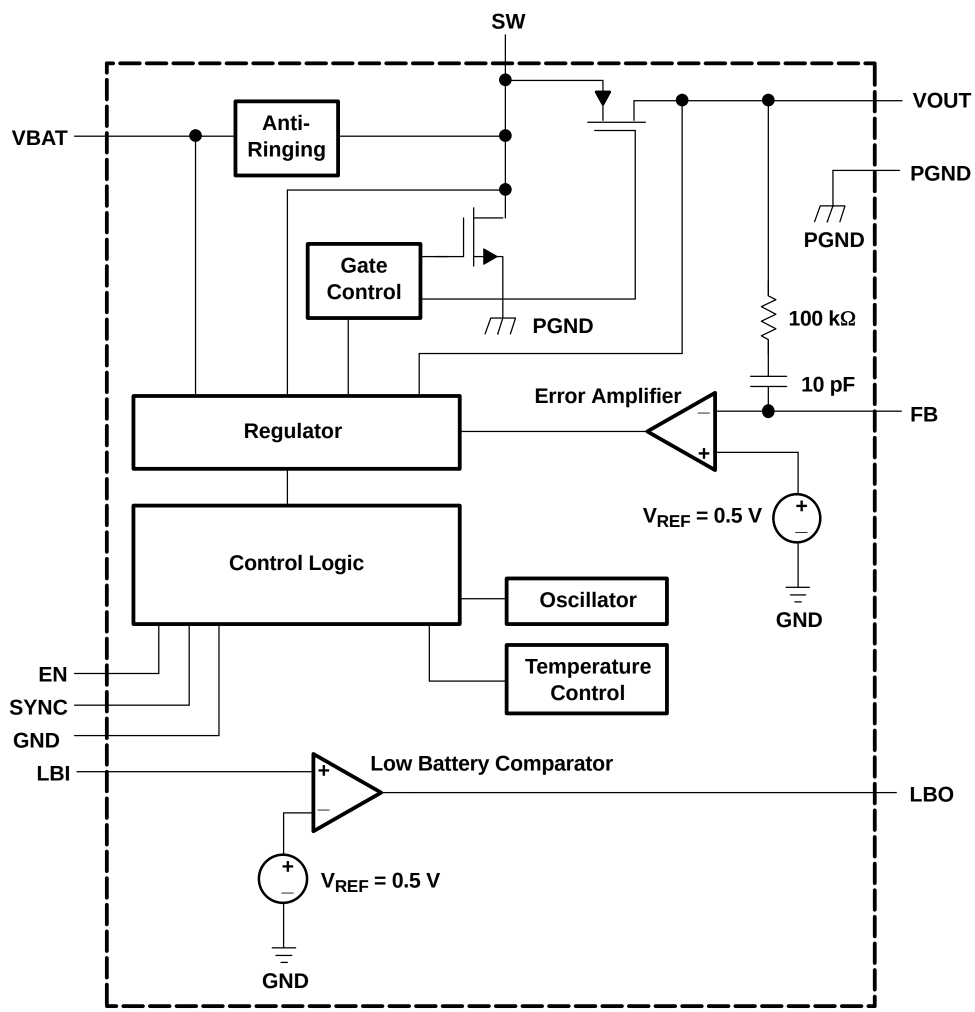
Pin Assignments (continued)

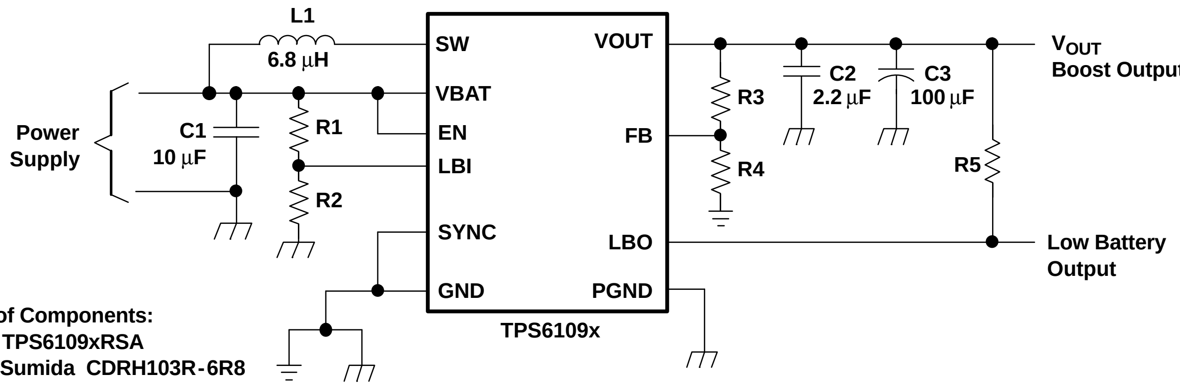
Terminal Functions (continued)

TERMINAL		I/O	DESCRIPTION
NAME	NO.		
GND	13	I/O	Control/logic ground
LBI	9	I	Low battery comparator input (comparator enabled with EN)
LBO	12	O	Low battery comparator output (open drain)
NC	2		Not connected
SYNC	10	I	Enable/disable power save mode (1: VBAT disabled, 0: GND enabled, clock signal for synchronization)
SW	3, 4	I	Boost and rectifying switch input
PGND	5, 6, 7	I/O	Power ground
VBAT	8	I	Supply voltage
VOUT	1, 15, 16	O	DC/DC output
PowerPAD™			Must be soldered to achieve appropriate power dissipation. Should be connected to PGND.

FUNCTIONAL BLOCK DIAGRAM



PARAMETER MEASUREMENT INFORMATION



List of Components:
U1 = TPS6109xRSA
L1 = Sumida CDRH103R-6R8
C1, C2 = X7R/X5R Ceramic
C3 = Low ESR Tantalum

TYPICAL CHARACTERISTICS

Table of Graphs

DC/DC Converter		Figure
Maximum output current	vs Input voltage	1, 2
Efficiency	vs Output current (TPS61090) (V_O = 2.5 V, V_I = 1.8 V, VSYNC = 0 V)	3
	vs Output current (TPS61091) (V_O = 3.3 V, V_I = 1.8 V, 2.4 V, VSYNC = 0 V)	4
	vs Output current (TPS61092) (V_O = 5.0 V, V_I = 2.4 V, 3.3 V, VSYNC = 0 V)	5
	vs Input voltage (TPS61091) (I_O = 10 mA, 100 mA, 500 mA, VSYNC = 0 V)	6
	vs Input voltage (TPS61092) (I_O = 10 mA, 100 mA, 500 mA, VSYNC = 0 V)	7
Output voltage	vs Output current (TPS61091) (V_I = 2.4 V)	8
	vs Output current (TPS61092) (V_I = 3.3 V)	9
No-load supply current into VBAT	vs Input voltage (TPS61092)	10
No-load supply current into VOUT	vs Input voltage (TPS61092)	11
Waveforms	Output voltage in continuous mode (TPS61092)	12
	Output voltage in power save mode (TPS61092)	13
	Load transient response (TPS61092)	14
	Line transient response (TPS61092)	15
	DC/DC converter start-up after enable (TPS61092)	16

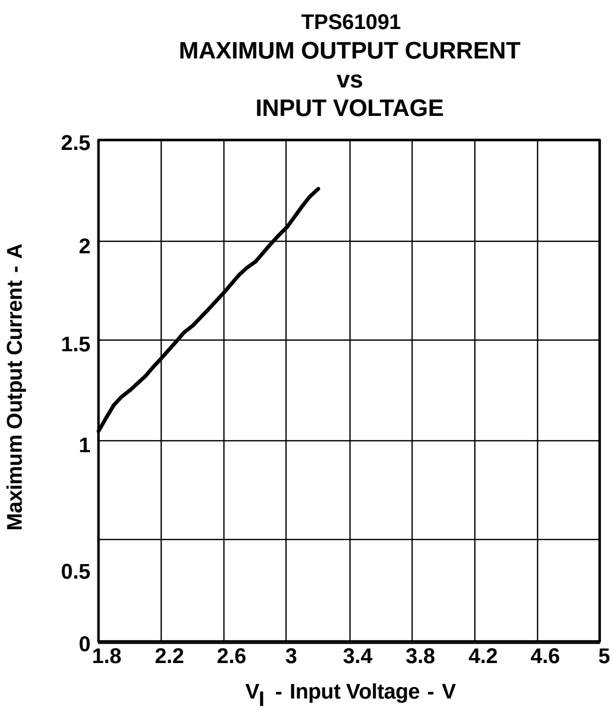


Figure 1.

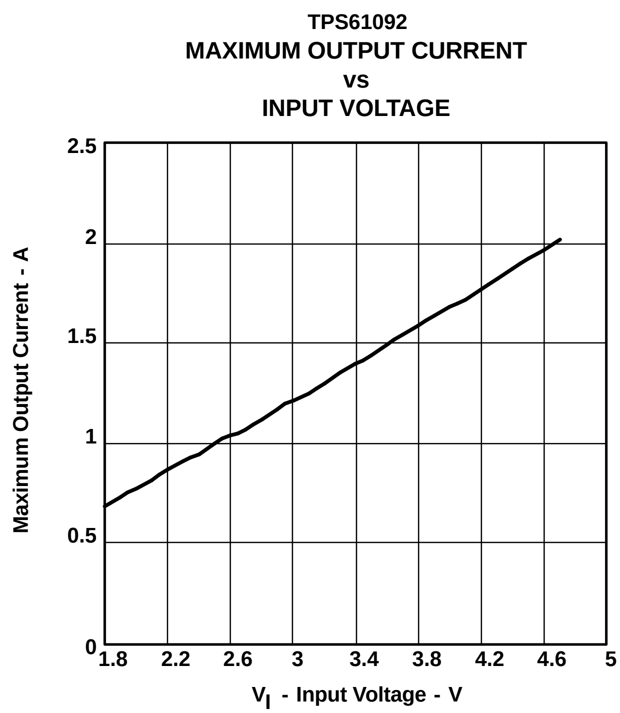


Figure 2.

TYPICAL CHARACTERISTICS (continued)

TPS61090
EFFICIENCY
vs
OUTPUT CURRENT

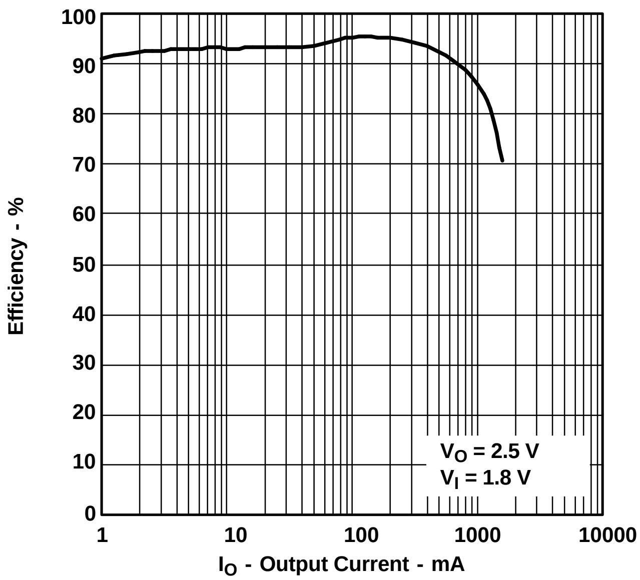


Figure 3.

TPS61091
EFFICIENCY
vs
OUTPUT CURRENT

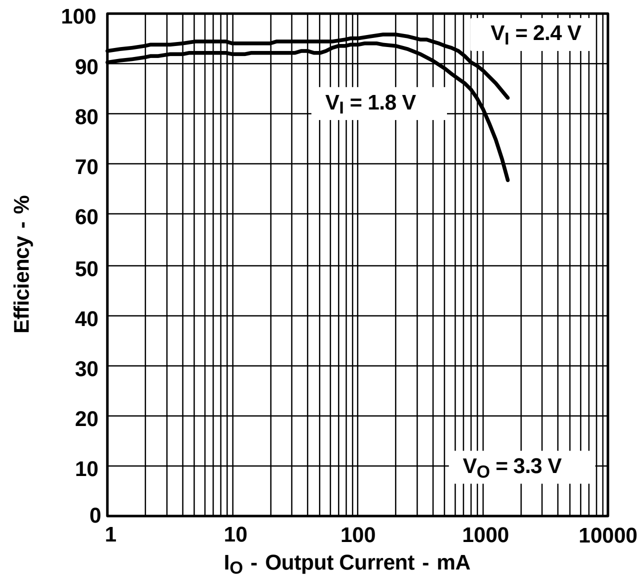


Figure 4.

TPS61092
EFFICIENCY
vs
OUTPUT CURRENT

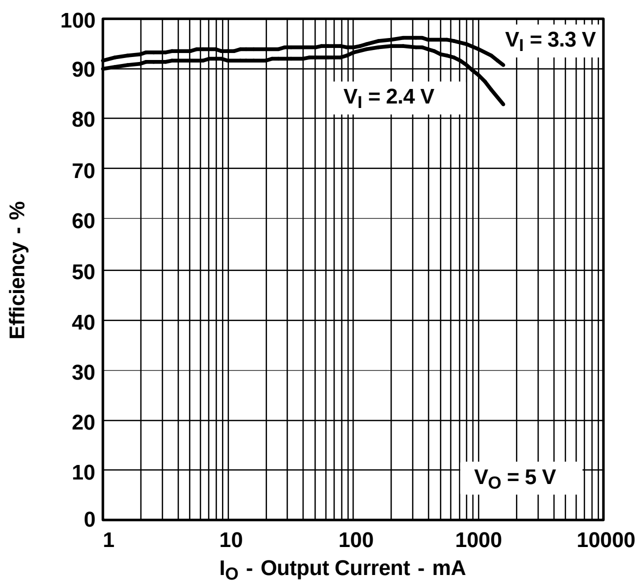


Figure 5.

TPS61091
EFFICIENCY
vs
INPUT VOLTAGE

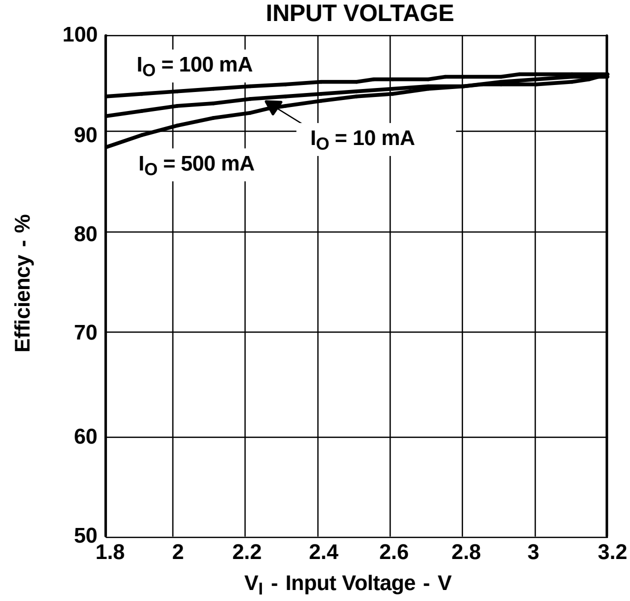


Figure 6.

TYPICAL CHARACTERISTICS (continued)

TPS61092
EFFICIENCY
vs
INPUT VOLTAGE

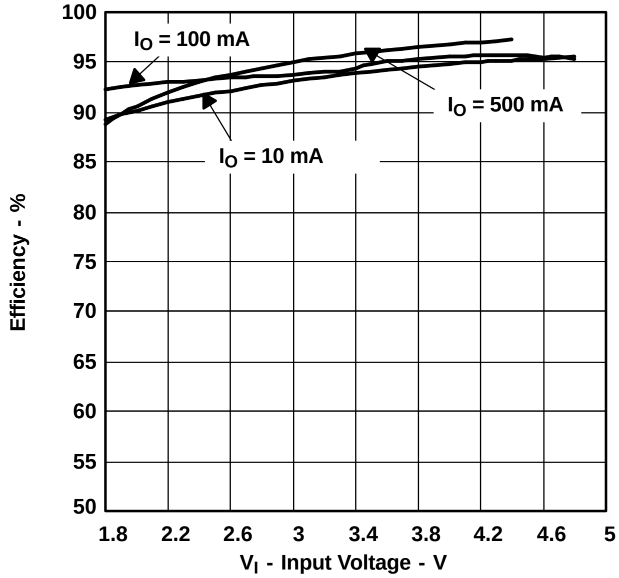


Figure 7.

TPS61091
OUTPUT VOLTAGE
vs
OUTPUT CURRENT

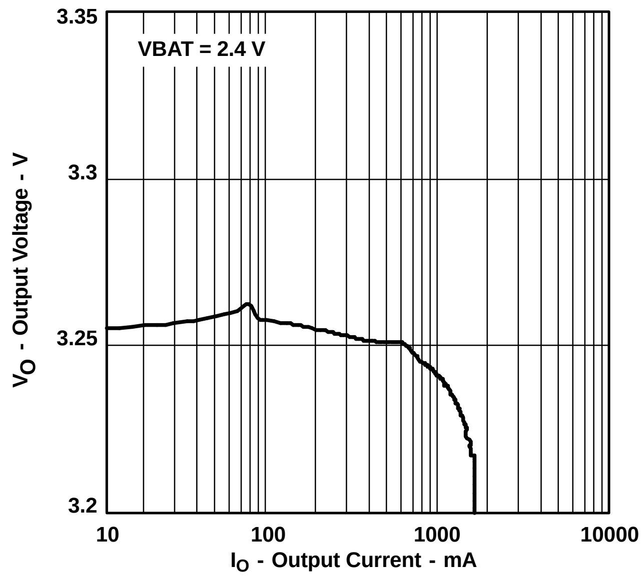


Figure 8.

TPS61092
OUTPUT VOLTAGE
vs
OUTPUT CURRENT

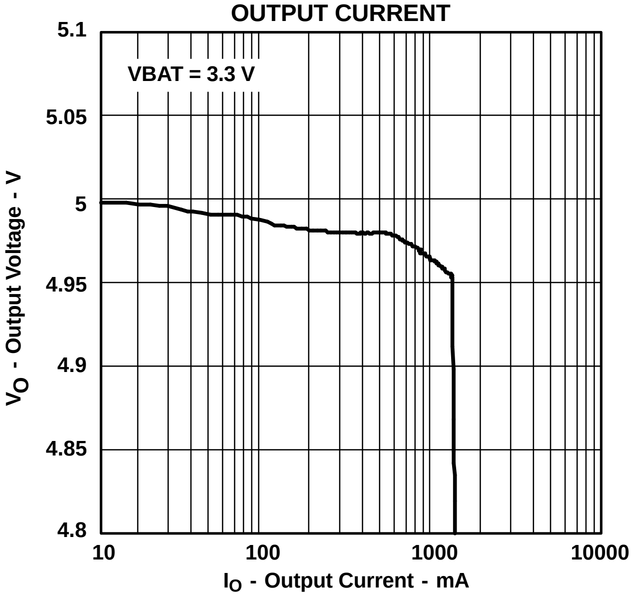


Figure 9.

TPS61092
NO-LOAD SUPPLY CURRENT INTO VBAT
vs
INPUT VOLTAGE

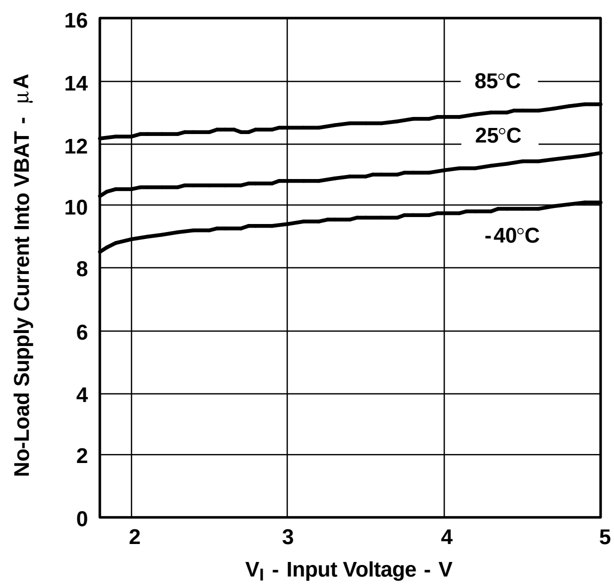


Figure 10.

TYPICAL CHARACTERISTICS (continued)

TPS61092
NO-LOAD SUPPLY CURRENT INTO VOUT
vs
INPUT VOLTAGE

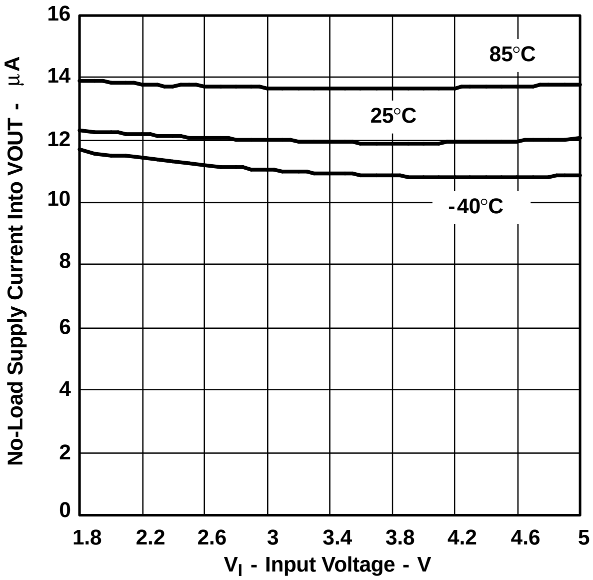


Figure 11.

MINIMUM LOAD RESISTANCE AT STARTUP
vs
INPUT VOLTAGE

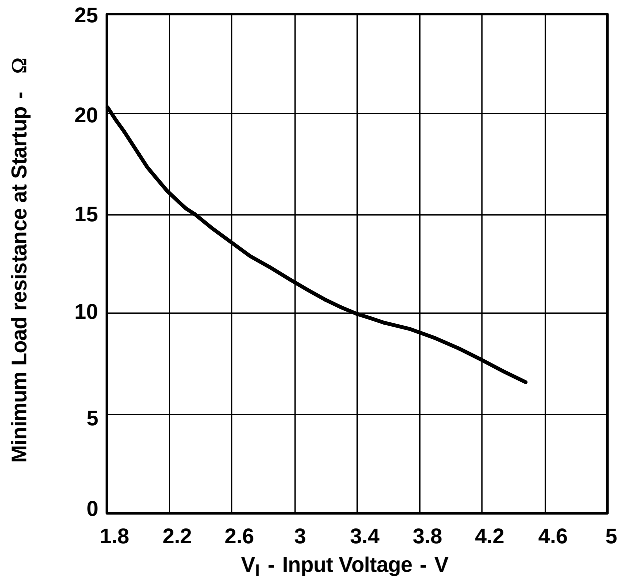


Figure 12.

TPS61092
OUTPUT VOLTAGE IN CONTINUOUS MODE

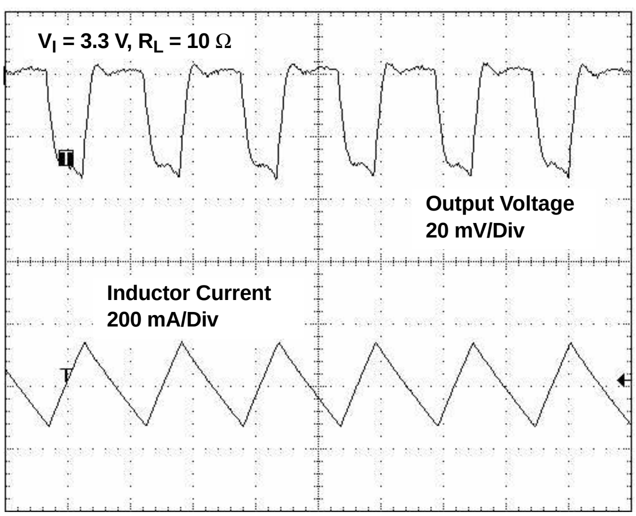


Figure 13.

TPS61092
OUTPUT VOLTAGE IN POWER SAVE MODE

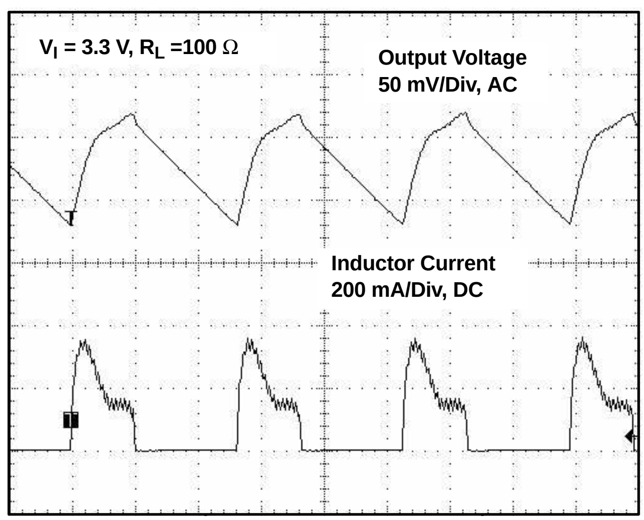
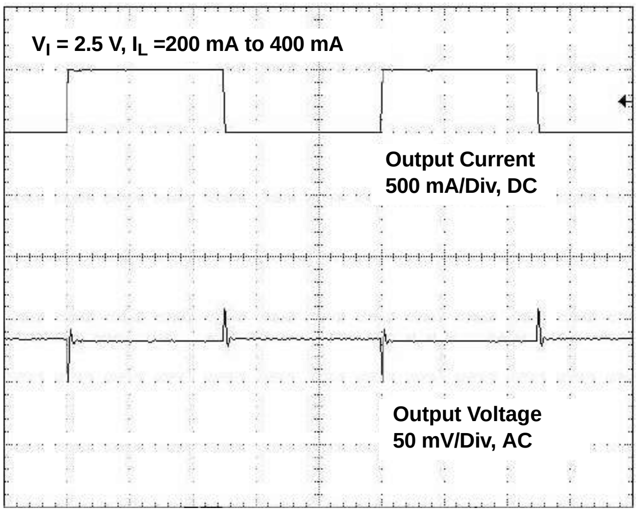


Figure 14.

TYPICAL CHARACTERISTICS (continued)

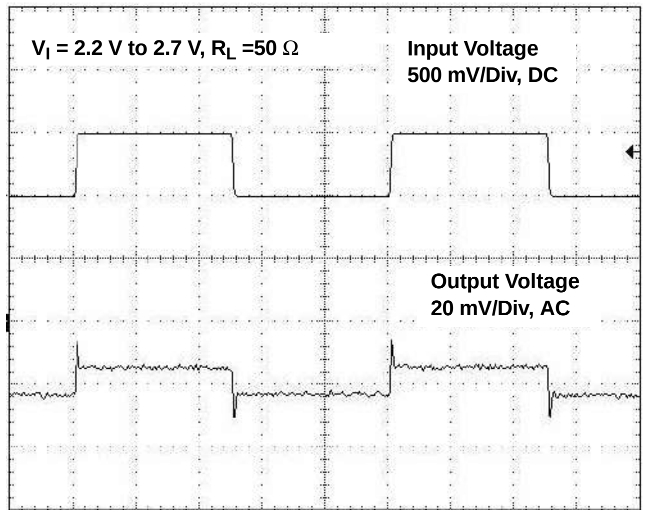
TPS61092
LOAD TRANSIENT RESPONSE



Timebase - 2 ms/Div

Figure 15.

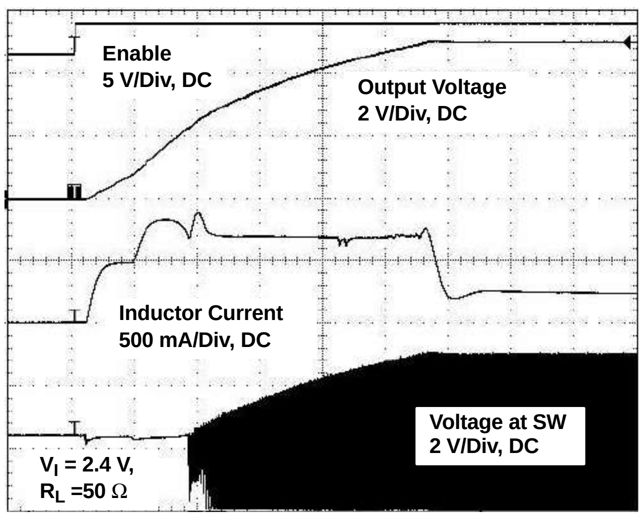
TPS61092
LINE TRANSIENT RESPONSE



Timebase - 2 ms/Div

Figure 16.

TPS61092
DC/DC CONVERTER START-UP AFTER ENABLE



Timebase - 200 μs/Div

Figure 17.

APPLICATION INFORMATION

DESIGN PROCEDURE

The TPS6109x dc/dc converters are intended for systems powered by a dual or triple cell NiCd or NiMH battery with a typical terminal voltage between 1.8 V and 5.5 V. They can also be used in systems powered by one-cell Li-Ion with a typical stack voltage between 2.5 V and 4.2 V. Additionally, two or three primary and secondary alkaline battery cells can be the power source in systems where the TPS6109x is used.

Programming the Output Voltage

The output voltage of the TPS61090 dc/dc converter section can be adjusted with an external resistor divider. The typical value of the voltage on the FB pin is 500 mV. The maximum allowed value for the output voltage is 5.5 V. The current through the resistive divider should be about 100 times greater than the current into the FB pin. The typical current into the FB pin is 0.01 µA, and the voltage across R4 is typically 500 mV. Based on those two values, the recommended value for R4 should be lower than 500 kΩ, in order to set the divider current at 1 µA or higher. Because of internal compensation circuitry the value for this resistor should be in the range of 200 kΩ. From that, the value of resistor R3, depending on the needed output voltage (V_O), can be calculated using Equation 1:

$$R3 = R4 \times \left(\frac{V_O}{V_{FB}} - 1\right) = 200\ k\Omega \times \left(\frac{V_O}{500\ mV} - 1\right) \tag{1}$$

If as an example, an output voltage of 5.0 V is needed, a 1.8-MΩ resistor should be chosen for R3. If for any reason the value for R4 is chosen significantly lower than 200 kΩ additional capacitance in parallel to R3 is recommended. The required capacitance value can be easily calculated using Equation 2

$$C_{parR3} = 10\ pF \times \left(\frac{200\ k\Omega}{R4} - 1\right) \tag{2}$$

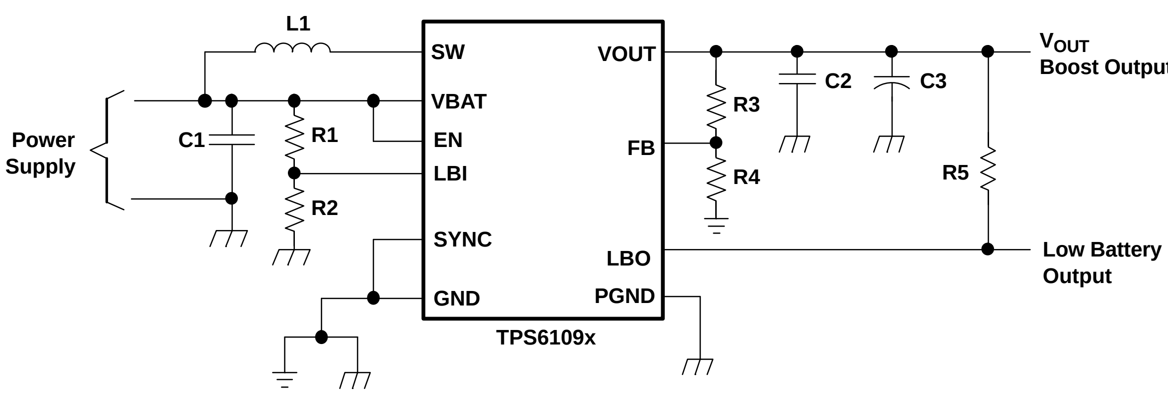


Figure 18. Typical Application Circuit for Adjustable Output Voltage Option

Programming the LBI/LBO Threshold Voltage

The current through the resistive divider should be about 100 times greater than the current into the LBI pin. The typical current into the LBI pin is 0.01 µA, and the voltage across R2 is equal to the LBI voltage threshold that is generated on-chip, which has a value of 500 mV. The recommended value for R2is therefore in the range of 500 kΩ. From that, the value of resistor R1, depending on the desired minimum battery voltage $V_{BAT,}$ can be calculated using Equation 3.

APPLICATION INFORMATION (continued)

$$R1 = R2 \times \left(\frac{V_{BAT}}{V_{LBI-threshold}} - 1 \right) = 390\ k\Omega \times \left(\frac{V_{BAT}}{500\ mV} - 1 \right) \tag{3}$$

The output of the low battery supervisor is a simple open-drain output that goes active low if the dedicated battery voltage drops below the programmed threshold voltage on LBI. The output requires a pullup resistor with a recommended value of 1 MΩ. The maximum voltage which is used to pull up the LBO outputs should not exceed the output voltage of the dc/dc converter. If not used, the LBO pin can be left floating or tied to GND.

Inductor Selection

A boost converter normally requires two main passive components for storing energy during the conversion. A boost inductor and a storage capacitor at the output are required. To select the boost inductor, it is recommended to keep the possible peak inductor current below the current limit threshold of the power switch in the chosen configuration. For example, the current limit threshold of the TPS6109x's switch is 2500 mA at an output voltage of 5 V. The highest peak current through the inductor and the switch depends on the output load, the input (V_{BAT}), and the output voltage (V_{OUT}). Estimation of the maximum average inductor current can be done using Equation 4:

$$I_L = I_{OUT} \times \frac{V_{OUT}}{V_{BAT} \times 0.8} \tag{4}$$

For example, for an output current of 500 mA at 5 V, at least 1750 mA of average current flows through the inductor at a minimum input voltage of 1.8 V.

The second parameter for choosing the inductor is the desired current ripple in the inductor. Normally, it is advisable to work with a ripple of less than 20% of the average inductor current. A smaller ripple reduces the magnetic hysteresis losses in the inductor, as well as output voltage ripple and EMI. But in the same way, regulation time at load changes rises. In addition, a larger inductor increases the total system costs. With those parameters, it is possible to calculate the value for the inductor by using Equation 5:

$$L = \frac{V_{BAT} \times \left(V_{OUT} - V_{BAT}\right)}{\Delta I_L \times f \times V_{OUT}} \tag{5}$$

Parameter f is the switching frequency and ΔI_L is the ripple current in the inductor, i.e., 20% × I_L. In this example, the desired inductor has the value of 5.5 µH. With this calculated value and the calculated currents, it is possible to choose a suitable inductor. Care has to be taken that load transients and losses in the circuit can lead to higher currents as estimated in equation 4. Also, the losses in the inductor caused by magnetic hysteresis losses and copper losses are a major parameter for total circuit efficiency.

The following inductor series from different suppliers have been used with the TPS6109x converters:

List of Inductors

VENDOR	INDUCTOR SERIES
Sumida	CDRH6D28
	CDRH6D38
	CDRH103R
Wurth Elektronik	WE-PD type L
	WE-PD type XL
EPCOS	B82464G

Capacitor Selection

Input Capacitor

At least a 10-µF input capacitor is recommended to improve transient behavior of the regulator and EMI behavior of the total power supply circuit. A ceramic capacitor or a tantalum capacitor with a 100-nF ceramic capacitor in parallel, placed close to the IC, is recommended.

Output Capacitor DC/DC Converter

The major parameter necessary to define the minimum value of the output capacitor is the maximum allowed output voltage ripple in steady state operation of the converter. This ripple is determined by two parameters of the capacitor, the capacitance and the ESR. It is possible to calculate the minimum capacitance needed for the defined ripple, supposing that the ESR is zero, by using equation Equation 6:

$$C_{min} = \frac{I_{OUT} \times \left(V_{OUT} - V_{BAT}\right)}{f \times \Delta V \times V_{OUT}} \qquad (6)$$

Parameter f is the switching frequency and ΔV is the maximum allowed ripple.

With a chosen ripple voltage of 10 mV, a minimum capacitance of 53 µF is needed. The total ripple is larger due to the ESR of the output capacitor. This additional component of the ripple can be calculated using Equation 7:

$$\Delta V_{ESR} = I_{OUT} \times R_{ESR} \qquad (7)$$

An additional ripple of 40 mV is the result of using a tantalum capacitor with a low ESR of 80 mΩ. The total ripple is the sum of the ripple caused by the capacitance and the ripple caused by the ESR of the capacitor. In this example, the total ripple is 50 mV. Additional ripple is caused by load transients. This means that the output capacitance needs to be larger than calculated above to meet the total ripple requirements. The output capacitor has to completely supply the load during the charging phase of the inductor. A reasonable value of the output capacitance depends on the speed of the load transients and the load current during the load change. With the calculated minimum value of 53 µF and load transient considerations, a reasonable output capacitance value is in a 100 µF range. For economical reasons this usually is a tantalum capacitor. Because of this the control loop has been optimized for using output capacitors with an ESR of above 30 mΩ.

Small Signal Stability

When using output capacitors with lower ESR, like ceramics, it is recommended to use the adjustable voltage version. The missing ESR can be easily compensated there in the feedback divider. Typically a capacitor in the range of 10 pF in parallel to R3 helps to obtain small signal stability with lowest ESR output capacitors. For more detailed analysis the small signal transfer function of the error amplifier and regulator, which is given is Equation 8, can be used.

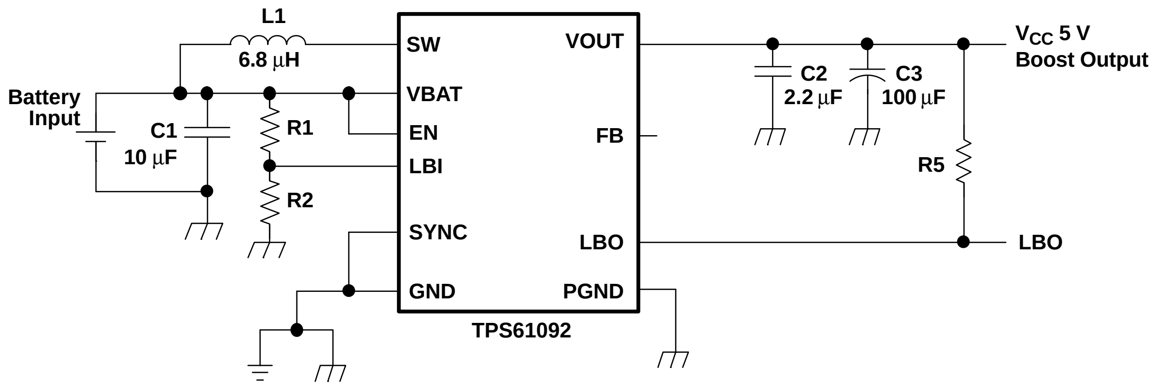
$$A_{REG} = \frac{d}{V_{FB}} \qquad A_{REG} = \frac{d5(R3 + R4)}{R4 \times (1 + i \times \omega \times 2.3\ \mu s)} \qquad (8)$$

LAYOUT CONSIDERATIONS

As for all switching power supplies, the layout is an important step in the design, especially at high peak currents and high switching frequencies. If the layout is not carefully done, the regulator could show stability problems as well as EMI problems. Therefore, use wide and short traces for the main current path and for the power ground tracks. The input capacitor, output capacitor, and the inductor should be placed as close as possible to the IC. Use a common ground node for power ground and a different one for control ground to minimize the effects of ground noise. Connect these ground nodes at any place close to one of the ground pins of the IC.

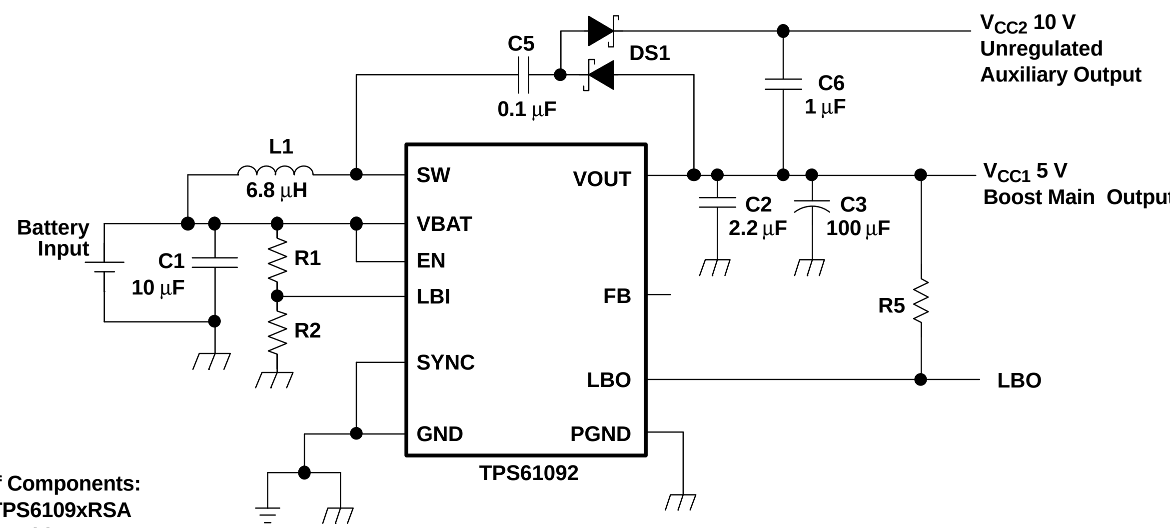
The feedback divider should be placed as close as possible to the control ground pin of the IC. To lay out the control ground, it is recommended to use short traces as well, separated from the power ground traces. This avoids ground shift problems, which can occur due to superimposition of power ground current and control ground current.

APPLICATION INFORMATION



List of Components:
U1 = TPS6109xRSA
L1 = Sumida CDRH103R-6R8
C1, C2 = X7R,X5R Ceramic
C3 = Low ESR Tantalum

Figure 19. Power Supply Solution for Maximum Output Power



List of Components:
U1 = TPS6109xRSA
L1 = Sumida CDRH103R-6R8
C1, C2, C5, C6, = X7R,X5R Ceramic
C3 = Low ESR Tantalum
DS1 = BAT54S

Figure 20. Power Supply Solution With Auxiliary Positive Output Voltage

Application Information (continued)

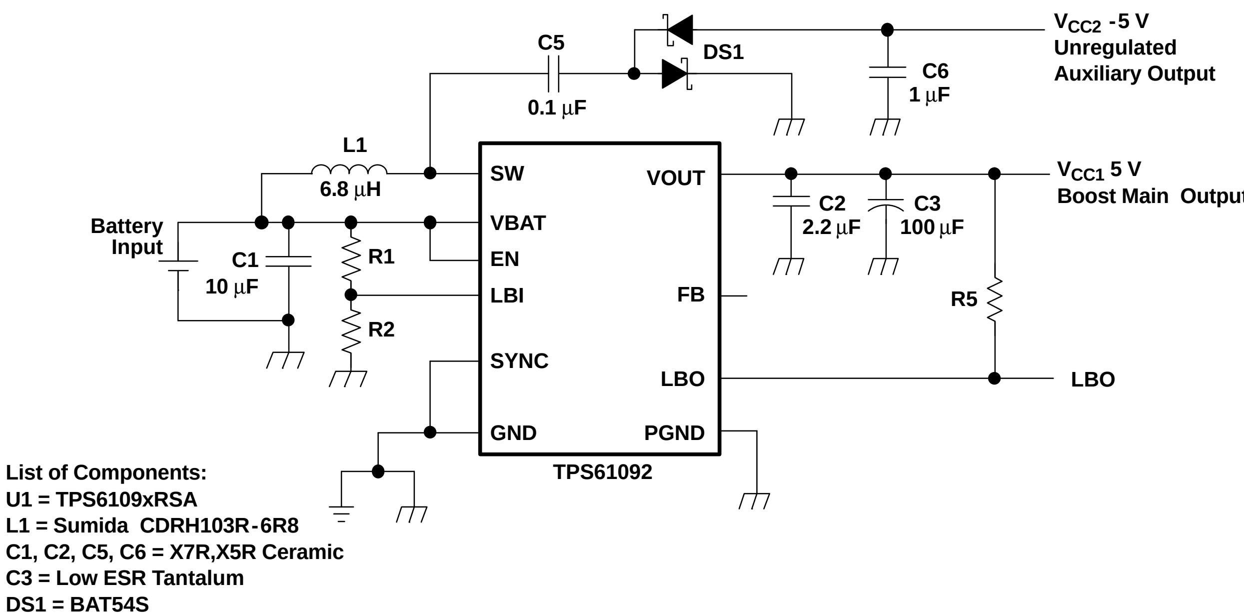


Figure 21. Power Supply Solution With Auxiliary Negative Output Voltage

DETAILED DESCRIPTION

Synchronous Rectifier

The device integrates an N-channel and a P-channel MOSFET transistor to realize a synchronous rectifier. Because the commonly used discrete Schottky rectifier is replaced with a low RDS(ON) PMOS switch, the power conversion efficiency reaches 96%. To avoid ground shift due to the high currents in the NMOS switch, two separate ground pins are used. The reference for all control functions is the GND pin. The source of the NMOS switch is connected to PGND. Both grounds must be connected on the PCB at only one point close to the GND pin. A special circuit is applied to disconnect the load from the input during shutdown of the converter. In conventional synchronous rectifier circuits, the backgate diode of the high-side PMOS is forward biased in shutdown and allows current flowing from the battery to the output. This device however uses a special circuit which takes the cathode of the backgate diode of the high-side PMOS and disconnects it from the source when the regulator is not enabled (EN = low).

The benefit of this feature for the system design engineer is that the battery is not depleted during shutdown of the converter. No additional components have to be added to the design to make sure that the battery is disconnected from the output of the converter.

Controller Circuit

The controller circuit of the device is based on a fixed frequency multiple feedforward controller topology. Input voltage, output voltage, and voltage drop on the NMOS switch are monitored and forwarded to the regulator. So changes in the operating conditions of the converter directly affect the duty cycle and must not take the indirect and slow way through the control loop and the error amplifier. The control loop, determined by the error amplifier, only has to handle small signal errors. The input for it is the feedback voltage on the FB pin or, at fixed output voltage versions, the voltage on the internal resistor divider. It is compared with the internal reference voltage to generate an accurate and stable output voltage.

The peak current of the NMOS switch is also sensed to limit the maximum current flowing through the switch and the inductor. The typical peak current limit is set to 2200 mA.

An internal temperature sensor prevents the device from getting overheated in case of excessive power dissipation.

Detailed Description (continued)

Device Enable

The device is put into operation when EN is set high. It is put into a shutdown mode when EN is set to GND. In shutdown mode, the regulator stops switching, all internal control circuitry including the low-battery comparator is switched off, and the load is isolated from the input (as described in the Synchronous Rectifier Section). This also means that the output voltage can drop below the input voltage during shutdown. During start-up of the converter, the duty cycle and the peak current are limited in order to avoid high peak currents drawn from the battery.

Undervoltage Lockout

An undervoltage lockout function prevents device start-up if the supply voltage on VBAT is lower than typically 1.6 V. When in operation and the battery is being discharged, the device automatically enters the shutdown mode if the voltage on VBAT drops below approximately 1.6 V. This undervoltage lockout function is implemented in order to prevent the malfunctioning of the converter.

Softstart

When the device enables the internal startup cycle starts with the first step, the precharge phase. During precharge, the rectifying switch is turned on until the output capacitor is charged to a value close to the input voltage. The rectifying switch current is limited in that phase. This also limits the output current under short-circuit conditions at the output. After charging the output capacitor to the input voltage the device starts switching. Until the output voltage is reached, the boost switch current limit is set to 40% of its nominal value to avoid high peak currents at the battery during startup. When the output voltage is reached, the regulator takes control and the switch current limit is set back to 100%.

Power Save Mode and Synchronization

The SYNC pin can be used to select different operation modes. To enable power save, SYNC must be set low. Power save mode is used to improve efficiency at light load. In power save mode the converter only operates when the output voltage trips below a set threshold voltage. It ramps up the output voltage with one or several pulses and goes again into power save mode once the output voltage exceeds the set threshold voltage. This power save mode can be disabled by setting the SYNC to VBAT.

Applying an external clock with a duty cycle between 30% and 70% at the SYNC pin forces the converter to operate at the applied clock frequency. The external frequency has to be in the range of about ±20% of the nominal internal frequency. Detailed values are shown in the electrical characteristic section of the data sheet.

Low Battery Detector Circuit—LBI/LBO

The low-battery detector circuit is typically used to supervise the battery voltage and to generate an error flag when the battery voltage drops below a user-set threshold voltage. The function is active only when the device is enabled. When the device is disabled, the LBO pin is high-impedance. The switching threshold is 500 mV at LBI. During normal operation, LBO stays at high impedance when the voltage, applied at LBI, is above the threshold. It is active low when the voltage at LBI goes below 500 mV.

The battery voltage, at which the detection circuit switches, can be programmed with a resistive divider connected to the LBI pin. The resistive divider scales down the battery voltage to a voltage level of 500 mV, which is then compared to the LBI threshold voltage. The LBI pin has a built-in hysteresis of 10 mV. See the application section for more details about the programming of the LBI threshold. If the low-battery detection circuit is not used, the LBI pin should be connected to GND (or to VBAT) and the LBO pin can be left unconnected. Do not let the LBI pin float.

Low-EMI Switch

The device integrates a circuit that removes the ringing that typically appears on the SW node when the converter enters discontinuous current mode. In this case, the current through the inductor ramps to zero and the rectifying PMOS switch is turned off to prevent a reverse current flowing from the output capacitors back to the battery. Due to the remaining energy that is stored in parasitic components of the semiconductor and the inductor, a ringing on the SW pin is induced. The integrated antiringing switch clamps this voltage to VBAT and therefore dampens ringing.

THERMAL INFORMATION

Implementation of integrated circuits in low-profile and fine-pitch surface-mount packages typically requires special attention to power dissipation. Many system-dependent issues such as thermal coupling, airflow, added heat sinks and convection surfaces, and the presence of other heat-generating components affect the power-dissipation limits of a given component.

Three basic approaches for enhancing thermal performance are listed below.

- Improving the power dissipation capability of the PCB design
- Improving the thermal coupling of the component to the PCB
- Introducing airflow in the system

The maximum junction temperature (T_J) of the TPS6109x devices is 150°C. The thermal resistance of the 16-pin QFN PowerPAD package (RSA) is$R_{\Theta JA}$ = 38.1 °C/W, if the PowerPAD is soldered and the board layout is optimized. Specified regulator operation is assured to a maximum ambient temperature T_A of 85°C. Therefore, the maximum power dissipation is about 1700 mW. More power can be dissipated if the maximum ambient temperature of the application is lower.

$$P_{D(MAX)} = \frac{T_{J(MAX)} - T_A}{R_{\theta JA}} = \frac{150°C - 85°C}{38.1\ k/W} = 1700\ mW$$

If designing for a lower junction temperature of 125°C, which is recommended, maximum heat dissipation is lower. Using the above equation (8) results in 1050 mW power dissipation.

PACKAGING INFORMATION

Orderable Device	Status (1)	Package Type	Package Drawing	Pins	Package Qty	Eco Plan (2)	Lead/Ball Finish (6)	MSL Peak Temp (3)	Op Temp (°C)	Device Marking (4/5)	Samples
TPS61090RSAR	ACTIVE	QFN	RSA	16	3000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-40 to 85	TPS6 1090	Samples
TPS61090RSARG4	ACTIVE	QFN	RSA	16	3000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-40 to 85	TPS6 1090	Samples
TPS61091RSAR	ACTIVE	QFN	RSA	16	3000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-40 to 85	TPS6 1091	Samples
TPS61091RSARG4	ACTIVE	QFN	RSA	16		TBD	Call TI	Call TI	-40 to 85		Samples
TPS61092RSAR	ACTIVE	QFN	RSA	16	3000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-40 to 85	TPS6 1092	Samples
TPS61092RSARG4	ACTIVE	QFN	RSA	16	3000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-40 to 85	TPS6 1092	Samples

(1) The marketing status values are defined as follows:
ACTIVE: Product device recommended for new designs.
LIFEBUY: TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.
NRND: Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.
PREVIEW: Device has been announced but is not in production. Samples may or may not be available.
OBSOLETE: TI has discontinued the production of the device.

(2) Eco Plan - The planned eco-friendly classification: Pb-Free (RoHS), Pb-Free (RoHS Exempt), or Green (RoHS & no Sb/Br) - please check http://www.ti.com/productcontent for the latest availability information and additional product content details.
TBD: The Pb-Free/Green conversion plan has not been defined.
Pb-Free (RoHS): TI's terms "Lead-Free" or "Pb-Free" mean semiconductor products that are compatible with the current RoHS requirements for all 6 substances, including the requirement that lead not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, TI Pb-Free products are suitable for use in specified lead-free processes.
Pb-Free (RoHS Exempt): This component has a RoHS exemption for either 1) lead-based flip-chip solder bumps used between the die and package, or 2) lead-based die adhesive used between the die and leadframe. The component is otherwise considered Pb-Free (RoHS compatible) as defined above.
Green (RoHS & no Sb/Br): TI defines "Green" to mean Pb-Free (RoHS compatible), and free of Bromine (Br) and Antimony (Sb) based flame retardants (Br or Sb do not exceed 0.1% by weight in homogeneous material)

(3) MSL, Peak Temp. - The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

(4) There may be additional marking, which relates to the logo, the lot trace code information, or the environmental category on the device.

(5) Multiple Device Markings will be inside parentheses. Only one Device Marking contained in parentheses and separated by a "~" will appear on a device. If a line is indented then it is a continuation of the previous line and the two combined represent the entire Device Marking for that device.

(6) Lead/Ball Finish - Orderable Devices may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead/Ball Finish values may wrap to two lines if the finish value exceeds the maximum column width.

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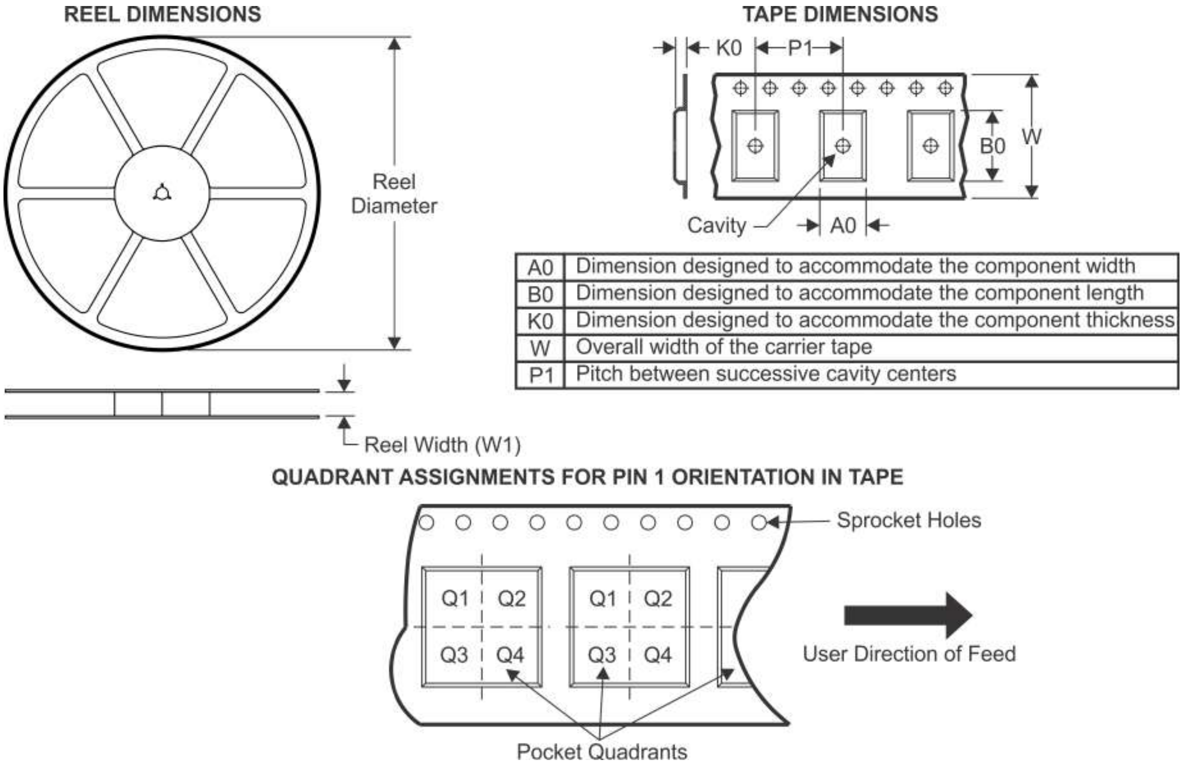
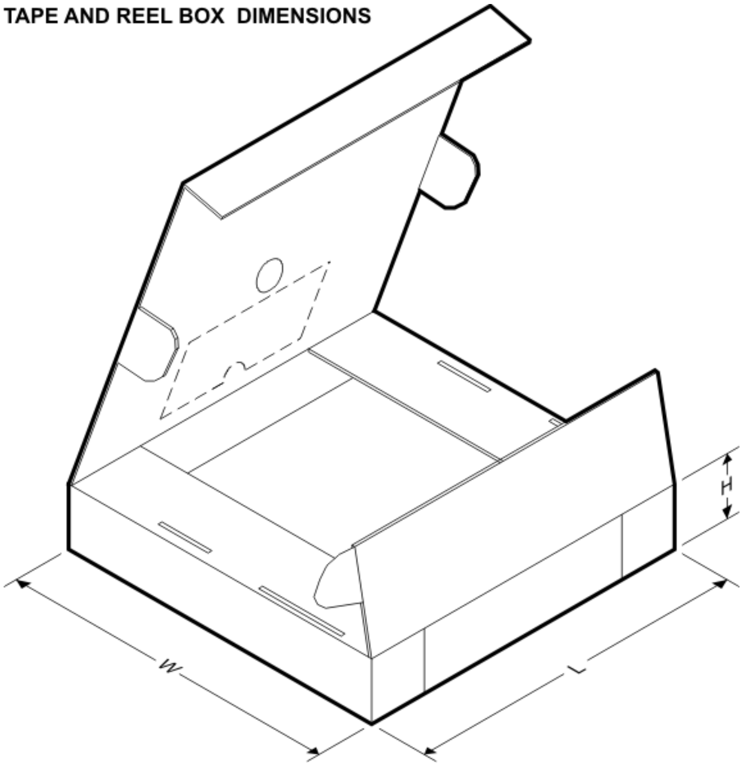
TAPE AND REEL INFORMATION



*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Reel Diameter (mm)	Reel Width W1 (mm)	A0 (mm)	B0 (mm)	K0 (mm)	P1 (mm)	W (mm)	Pin1 Quadrant
TPS61090RSAR	QFN	RSA	16	3000	330.0	12.4	4.3	4.3	1.5	8.0	12.0	Q2
TPS61091RSAR	QFN	RSA	16	3000	330.0	12.4	4.3	4.3	1.5	8.0	12.0	Q2
TPS61092RSAR	QFN	RSA	16	3000	330.0	12.4	4.3	4.3	1.5	8.0	12.0	Q2

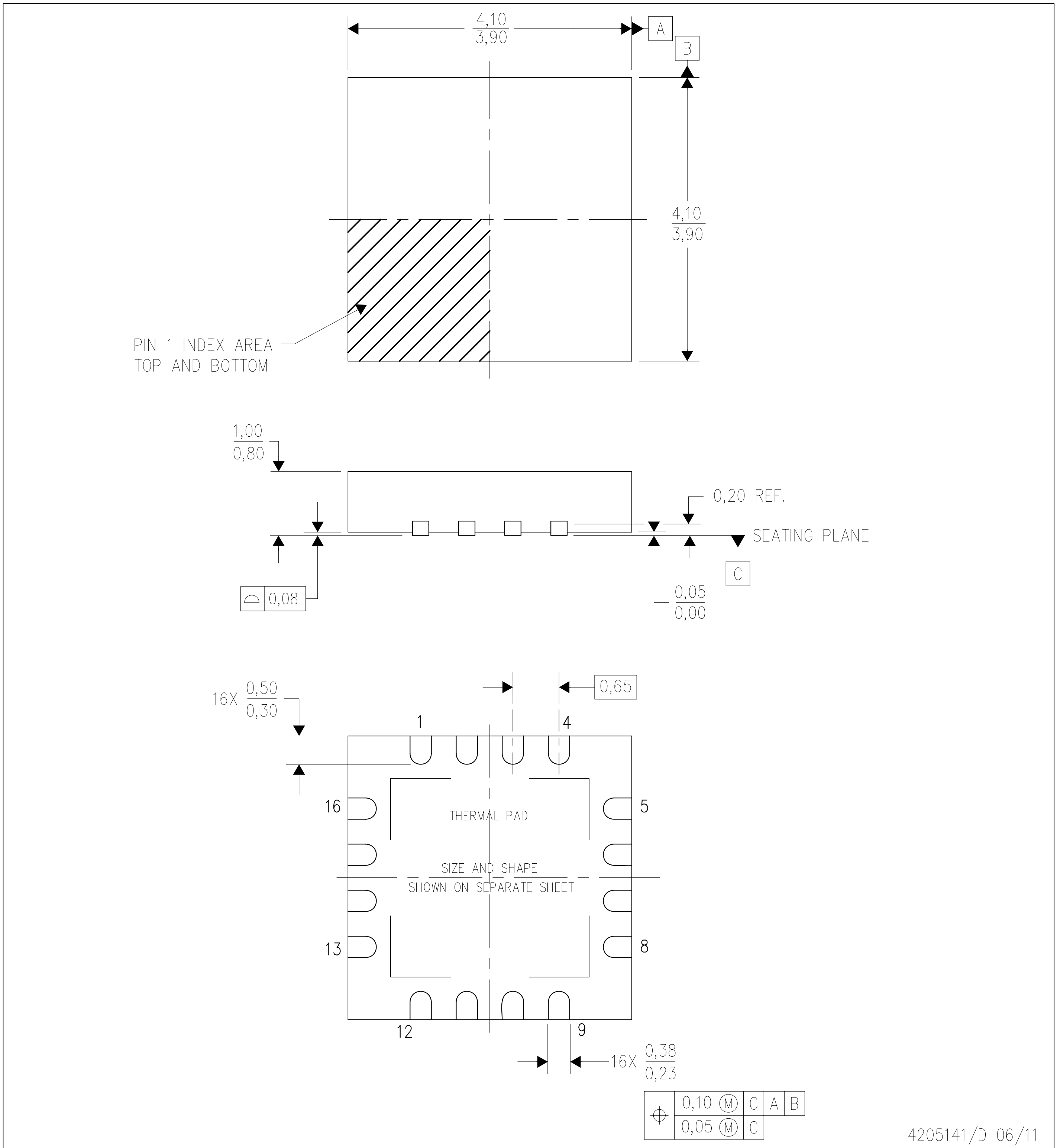
TAPE AND REEL BOX DIMENSIONS



*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
TPS61090RSAR	QFN	RSA	16	3000	338.1	338.1	20.6
TPS61091RSAR	QFN	RSA	16	3000	338.1	338.1	20.6
TPS61092RSAR	QFN	RSA	16	3000	338.1	338.1	20.6

RSA (S–PVQFN–N16) PLASTIC QUAD FLATPACK NO–LEAD



NOTES:
A. All linear dimensions are in millimeters. Dimensioning and tolerancing per ASME Y14.5M–1994.
B. This drawing is subject to change without notice.
C. Quad Flatpack, No–leads (QFN) package configuration.
D. The package thermal pad must be soldered to the board for thermal and mechanical performance.
E. See the additional figure in the Product Data Sheet for details regarding the exposed thermal pad features and dimensions.
F. Falls within JEDEC MO–220.

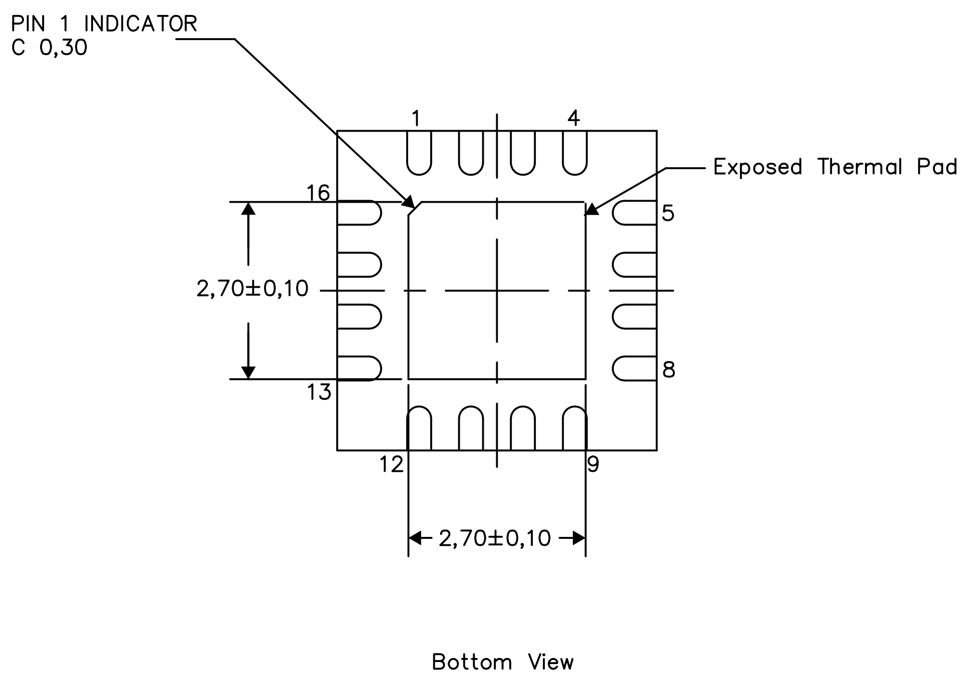
RSA (S-PVQFN-N16) PLASTIC QUAD FLATPACK NO-LEAD

THERMAL INFORMATION

This package incorporates an exposed thermal pad that is designed to be attached directly to an external heatsink. The thermal pad must be soldered directly to the printed circuit board (PCB). After soldering, the PCB can be used as a heatsink. In addition, through the use of thermal vias, the thermal pad can be attached directly to the appropriate copper plane shown in the electrical schematic for the device, or alternatively, can be attached to a special heatsink structure designed into the PCB. This design optimizes the heat transfer from the integrated circuit (IC).

For information on the Quad Flatpack No-Lead (QFN) package and its advantages, refer to Application Report, QFN/SON PCB Attachment, Texas Instruments Literature No. SLUA271. This document is available at www.ti.com.

The exposed thermal pad dimensions for this package are shown in the following illustration.

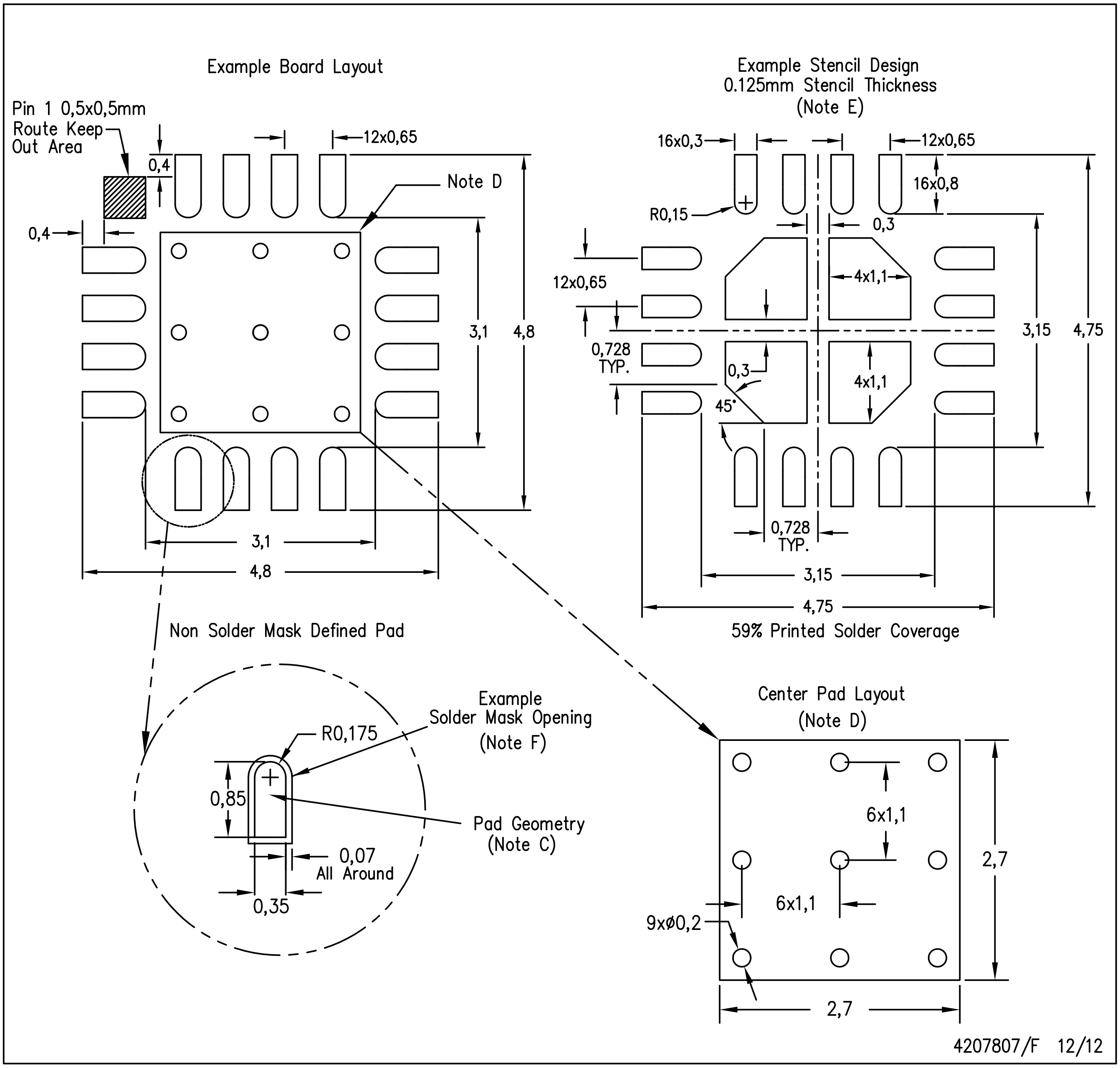


Exposed Thermal Pad Dimensions

4206364/N 07/13

NOTES:
A. All linear dimensions are in millimeters

RSA (S-PVQFN-N16) PLASTIC QUAD FLATPACK NO-LEAD



NOTES:
A. All linear dimensions are in millimeters.
B. This drawing is subject to change without notice.
C. Publication IPC-7351 is recommended for alternate designs.
D. This package is designed to be soldered to a thermal pad on the board. Refer to Application Note, QFN Packages, Texas Instruments Literature No. SLUA271, and also the Product Data Sheets for specific thermal information, via requirements, and recommended board layout. These documents are available at www.ti.com <http: //www.ti.com>.
E. Laser cutting apertures with trapezoidal walls and also rounding corners will offer better paste release. Customers should contact their board assembly site for stencil design recommendations. Refer to IPC 7525 for stencil design considerations.
F. Customers should contact their board fabrication site for solder mask tolerances.

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256-Position SPI-Compatible Digital Potentiometer

Data Sheet **AD5160**

FEATURES

256-position
End-to-end resistance: 5 kΩ, 10 kΩ, 50 kΩ, 100 kΩ
Compact SOT-23-8 (2.9 mm × 3 mm) package
SPI-compatible interface
Power-on preset to midscale
Single supply: 2.7 V to 5.5 V
Low temperature coefficient: 45 ppm/°C
Low power, I_{DD} = 8 µA
Wide operating temperature: –40°C to +125°C
Evaluation board available

APPLICATIONS

Mechanical potentiometer replacement in new designs
Transducer adjustment of pressure, temperature, position, chemical, and optical sensors
RF amplifier biasing
Gain control and offset adjustment

FUNCTIONAL BLOCK DIAGRAM

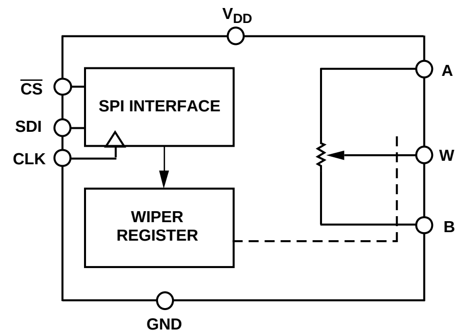

Figure 1.

PIN CONFIGURATION

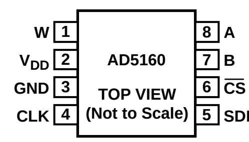

Figure 2.

GENERAL DESCRIPTION

The AD5160 provides a compact 2.9 mm × 3 mm packaged solution for 256-position adjustment applications. These devices perform the same electronic adjustment function as mechanical potentiometers[1] or variable resistors but with enhanced resolution, solid-state reliability, and superior low temperature coefficient performance.

The wiper settings are controllable through an SPI-compatible digital interface. The resistance between the wiper and either end point of the fixed resistor varies linearly with respect to the digital code transferred into the RDAC latch.

Operating from a 2.7 V to 5.5 V power supply and consuming less than 5 µA allows for usage in portable battery-operated applications.

[1] The terms digital potentiometer, VR, and RDAC are used interchangeably.

Rev. C Document Feedback

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Technical Support www.analog.com

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Changes to Ordering Guide 16

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Deleted Shutdown Supply Current Parameter and Endnote 7, Table 1 3
Changes to Resistor Noise Voltage Density Parameter, Table 1 3
Deleted Shutdown Supply Current Parameter and Endnote 7, Table 2 4
Changes to Resistor Noise Voltage Density Parameter, Table 2 4
Added Endnote to Table 3 5
Changes to Table 4 6
Changes to the Rheostat Operation Section 14
Deleted Terminal Voltage Operating Range Section and Figure 41, Renumbered Figures Sequentially 13
Changes to Figure 40 and Figure 41 15
Changes to Ordering Guide 16

5/03—Revision 0: Initial Version

SPECIFICATIONS

ELECTRICAL CHARACTERISTICS—5 kΩ VERSION

V_{DD} = 5 V ± 10%, or 3 V ± 10%; V_A = +V_{DD}; V_B = 0 V; −40°C < T_A < +125°C; unless otherwise noted.

Table 1.

Parameter	Symbol	Conditions	Min	Typ[1]	Max	Unit
DC CHARACTERISTICS						
Rheostat Mode						
Resistor Differential Nonlinearity[2]	R-DNL	R_{WB}, V_A = no connect	−1.5	±0.1	+1.5	LSB
Resistor Integral Nonlinearity[2]	R-INL	R_{WB}, V_A = no connect	−4	±0.75	+4	LSB
Nominal Resistor Tolerance[3]	ΔR_{AB}	T_A = 25°C	−20		+20	%
Resistance Temperature Coefficient	$\Delta R_{AB}/\Delta T$	V_{AB} = V_{DD}, wiper = no connect		45		ppm/°C
Wiper Resistance	R_W			50	120	Ω
Potentiometer Divider Mode		Specifications apply to all VRs				
Resolution	N				8	Bits
Differential Nonlinearity[4]	DNL		−1.5	±0.1	+1.5	LSB
Integral Nonlinearity[4]	INL		−1.5	±0.6	+1.5	LSB
Voltage Divider Temperature Coefficient	$\Delta V_W/\Delta T$	Code = 0x80		15		ppm/°C
Full-Scale Error	V_{WFSE}	Code = 0xFF	−6	−2.5	0	LSB
Zero-Scale Error	V_{WZSE}	Code = 0x00	0	+2	+6	LSB
RESISTOR TERMINALS						
Voltage Range[5]	V_A, V_B, V_W		GND		V_{DD}	V
Capacitance A, Capacitance B[6]	$C_{A,B}$	f = 1 MHz, measured to GND, code = 0x80		45		pF
Capacitance W[6]	C_W	f = 1 MHz, measured to GND, code = 0x80		60		pF
Common-Mode Leakage	I_{CM}	V_A = V_B = V_{DD}/2		1		nA
DIGITAL INPUTS						
Input Logic High	V_{IH}		2.4			V
Input Logic Low	V_{IL}				0.8	V
Input Logic High	V_{IH}	V_{DD} = 3 V	2.1			V
Input Logic Low	V_{IL}	V_{DD} = 3 V			0.6	V
Input Current	I_{IL}	V_{IN} = 0 V or 5 V			±1	µA
Input Capacitance[6]	C_{IL}			5		pF
POWER SUPPLIES						
Power Supply Range	$V_{DD\ RANGE}$		2.7		5.5	V
Supply Current	I_{DD}	V_{IH} = 5 V or V_{IL} = 0 V		3	8	µA
Power Dissipation[7]	P_{DISS}	V_{IH} = 5 V or V_{IL} = 0 V, V_{DD} = 5 V			0.2	mW
Power Supply Sensitivity	PSS	ΔV_{DD} = +5 V ± 10%, code = midscale		±0.02	±0.05	%/%
DYNAMIC CHARACTERISTICS[6, 8]						
Bandwidth −3 dB	BW_5K	R_{AB} = 5 kΩ, code = 0x80		1.2		MHz
Total Harmonic Distortion	THD_W	V_A = 1 V rms, V_B = 0 V, f = 1 kHz		0.05		%
V_W Settling Time	t_S	V_A = 5 V, V_B = 0 V, ±1 LSB error band		1		µs
Resistor Noise Voltage Density	e_{N_WB}	R_{WB} = 2.5 kΩ		6		nV/√Hz

[1] Typical specifications represent average readings at +25°C and V_{DD} = 5 V.
[2] Resistor position nonlinearity error (R-INL) is the deviation from an ideal value measured between the maximum resistance and the minimum resistance wiper positions. R-DNL measures the relative step change from ideal between successive tap positions. Parts are guaranteed monotonic.
[3] V_{AB} = V_{DD}, wiper (V_W) = no connect.
[4] INL and DNL are measured at V_W with the RDAC configured as a potentiometer divider similar to a voltage output digital-to-analog converter (DAC). V_A = V_{DD} and V_B = 0 V. DNL specification limits of ±1 LSB maximum are guaranteed monotonic operating conditions.
[5] Resistor Terminal A, Resistor Terminal B, and Resistor Terminal W have no limitations on polarity with respect to each other.
[6] Guaranteed by design and not subject to production test.
[7] P_{DISS} is calculated from (I_{DD} × V_{DD}). CMOS logic level inputs result in minimum power dissipation.
[8] All dynamic characteristics use V_{DD} = 5 V.

10 kΩ, 50 kΩ, 100 kΩ VERSIONS

V_{DD} = 5 V ± 10%, or 3 V ± 10%; $V_A = V_{DD}$; V_B = 0 V; −40°C < T_A < +125°C; unless otherwise noted.

Table 2.

Parameter	Symbol	Conditions	Min	Typ[1]	Max	Unit
DC CHARACTERISTICS						
Rheostat Mode						
Resistor Differential Nonlinearity[2]	R-DNL	R_{WB}, V_A = no connect	−1	±0.1	+1	LSB
Resistor Integral Nonlinearity[2]	R-INL	R_{WB}, V_A = no connect	−2	±0.25	+2	LSB
Nominal Resistor Tolerance[3]	ΔR_{AB}	T_A = 25°C	−15		+15	%
Resistance Temperature Coefficient	$\Delta R_{AB}/\Delta T$	$V_{AB} = V_{DD}$, Wiper = no connect		45		ppm/°C
Wiper Resistance	R_W	V_{DD} = 5 V		50	120	Ω
Potentiometer Divider Mode		Specifications apply to all VRs				
Resolution	N				8	Bits
Differential Nonlinearity[4]	DNL		−1	±0.1	+1	LSB
Integral Nonlinearity[4]	INL		−1	±0.3	+1	LSB
Voltage Divider Temperature Coefficient	$\Delta V_W/\Delta T$	Code = 0x80		15		ppm/°C
Full-Scale Error	V_{WFSE}	Code = 0xFF	−3	−1	0	LSB
Zero-Scale Error	V_{WZSE}	Code = 0x00	0	1	3	LSB
RESISTOR TERMINALS						
Voltage Range[5]	$V_{A,B,W}$		GND		V_{DD}	V
Capacitance A, Capacitance B[6]	$C_{A,B}$	f = 1 MHz, measured to GND, code = 0x80		45		pF
Capacitance W[6]	C_W	f = 1 MHz, measured to GND, code = 0x80		60		pF
Common-Mode Leakage	I_{CM}	$V_A = V_B = V_{DD}/2$		1		nA
DIGITAL INPUTS						
Input Logic High	V_{IH}		2.4			V
Input Logic Low	V_{IL}				0.8	V
Input Logic High	V_{IH}	V_{DD} = 3 V	2.1			V
Input Logic Low	V_{IL}	V_{DD} = 3 V			0.6	V
Input Current	I_{IL}	V_{IN} = 0 V or 5 V			±1	µA
Input Capacitance[6]	C_{IL}			5		pF
POWER SUPPLIES						
Power Supply Range	$V_{DD\ RANGE}$		2.7		5.5	V
Supply Current	I_{DD}	V_{IH} = 5 V or V_{IL} = 0 V		3	8	µA
Power Dissipation[7]	P_{DISS}	V_{IH} = 5 V or V_{IL} = 0 V, V_{DD} = 5 V			0.2	mW
Power Supply Sensitivity	PSS	ΔV_{DD} = +5 V ± 10%, code = midscale		±0.02	±0.05	%/%
DYNAMIC CHARACTERISTICS[6, 8]						
Bandwidth −3 dB	BW	R_{AB} = 10 kΩ/50 kΩ/100 kΩ, Code = 0x80		600/100/40		kHz
Total Harmonic Distortion	THD_W	V_A = 1 V rms, V_B = 0 V, f = 1 kHz, R_{AB} = 10 kΩ		0.05		%
V_W Settling Time (10 kΩ/50 kΩ/100 kΩ)	t_S	V_A = 5 V, V_B = 0 V, ±1 LSB error band		2		µs
Resistor Noise Voltage Density	e_{N_WB}	R_{WB} = 5 kΩ		9		nV/√Hz

[1] Typical specifications represent average readings at +25°C and V_{DD} = 5 V.
[2] Resistor position nonlinearity error (R-INL) is the deviation from an ideal value measured between the maximum resistance and the minimum resistance wiper positions. R-DNL measures the relative step change from ideal between successive tap positions. Parts are guaranteed monotonic.
[3] $V_{AB} = V_{DD}$, wiper (V_W) = no connect.
[4] INL and DNL are measured at V_W with the RDAC configured as a potentiometer divider similar to a voltage output digital-to-analog converter (DAC). $V_A = V_{DD}$ and V_B = 0 V. DNL specification limits of ±1 LSB maximum are guaranteed monotonic operating conditions.
[5] Resistor Terminal A, Resistor Terminal B, and Resistor Terminal W have no limitations on polarity with respect to each other.
[6] Guaranteed by design and not subject to production test.
[7] P_{DISS} is calculated from ($I_{DD} \times V_{DD}$). CMOS logic level inputs result in minimum power dissipation.
[8] All dynamic characteristics use V_{DD} = 5 V.

TIMING CHARACTERISTICS—ALL VERSIONS

V_{DD} = +5V ± 10%, or +3V ± 10%; $V_A = V_{DD}$; V_B = 0 V; −40°C < T_A < +125°C; unless otherwise noted.

Table 3.

Parameter	Symbol	Conditions	Min	Typ[1]	Max	Unit
SPI INTERFACE TIMING CHARACTERISTICS[1, 2]		Specifications apply to all parts				
Clock Frequency	f_{CLK}				25	MHz
Input Clock Pulse Width	t_{CH}, t_{CL}	Clock level high or low	20			ns
Data Setup Time	t_{DS}		5			ns
Data Hold Time	t_{DH}		5			ns
$\overline{CS}$ Setup Time	t_{CSS}		15			ns
$\overline{CS}$ High Pulse Width	t_{CSW}		40			ns
CLK Fall to $\overline{CS}$ Fall Hold Time	t_{CSH0}		0			ns
CLK Fall to $\overline{CS}$ Rise Hold Time	t_{CSH1}		0			ns

[1] See the timing diagram, Figure 38, for location of measured values. All input control voltages are specified with $t_R = t_F$ = 2 ns (10% to 90% of 3 V) and timed from a voltage level of 1.5 V.
[2] Guaranteed by design and not subject to production test.

ABSOLUTE MAXIMUM RATINGS

T_A = +25°C, unless otherwise noted.

Table 4.

Parameter	Rating
V_{DD} to GND	−0.3 V to +7 V
V_A, V_B, V_W to GND	V_{DD}
Maximum Current I_{MAX}[1]	
I_{WB}, I_{WA} Pulsed	±20 mA
I_{WB}, I_{WA} Continuous	
5 kΩ, 10 kΩ	4.7 mA
50 kΩ	0.95 mA
100 kΩ	0.48 mA
Digital Inputs and Output Voltage to GND	0 V to +7 V
Temperature	
Operating Temperature Range	−40°C to +125°C
Maximum Junction Temperature (T_{JMAX})	150°C
Storage Temperature	−65°C to +150°C
Thermal Resistance (SOT-23 Package)[2]	
θ_{JA} Thermal Impedance	206°C/W
θ_{JC} Thermal Impedance	91°C/W
Reflow Soldering (Pb-Free)	
Peak Temperature	260°C
Time at Peak Temperature	10 sec to 40 sec

[1] Maximum terminal current is bounded by the maximum current handling of the switches, maximum power dissipation of the package, and applied voltage across any two of the A, B, and W terminals at a given resistance.
[2] Package power dissipation = $(T_{JMAX} - T_A)/\theta_{JA}$.

Stresses at or above those listed under Absolute Maximum Ratings may cause permanent damage to the product. This is a stress rating only; functional operation of the product at these or any other conditions above those indicated in the operational section of this specification is not implied. Operation beyond the maximum operating conditions for extended periods may affect product reliability.

ESD CAUTION

ESD (electrostatic discharge) sensitive device. Charged devices and circuit boards can discharge without detection. Although this product features patented or proprietary protection circuitry, damage may occur on devices subjected to high energy ESD. Therefore, proper ESD precautions should be taken to avoid performance degradation or loss of functionality.

PIN CONFIGURATION AND FUNCTION DESCRIPTIONS

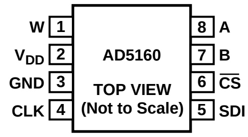

Figure 3. Pin Configuration

Table 5. Pin Function Descriptions

Pin	Mnemonic	Description
1	W	W Terminal.
2	V_{DD}	Positive Power Supply.
3	GND	Digital Ground.
4	CLK	Serial Clock Input. Positive edge triggered.
5	SDI	Serial Data Input.
6	$\overline{CS}$	Chip Select Input, Active Low. When $\overline{CS}$ returns high, data loads into the DAC register.
7	B	B Terminal.
8	A	A Terminal.

TYPICAL PERFORMANCE CHARACTERISTICS

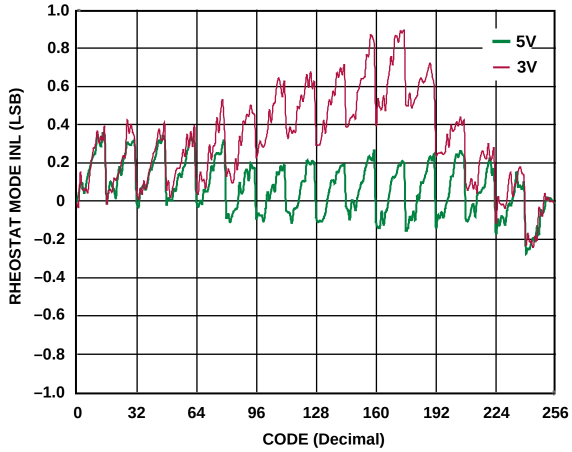

Figure 4. R-INL vs. Code vs. Supply Voltages

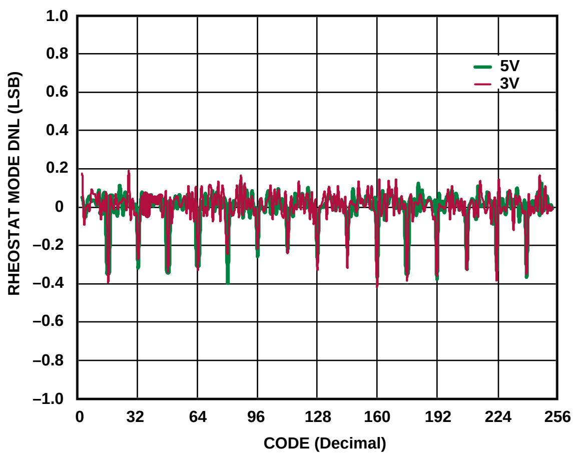

Figure 5. R-DNL vs. Code vs. Supply Voltages

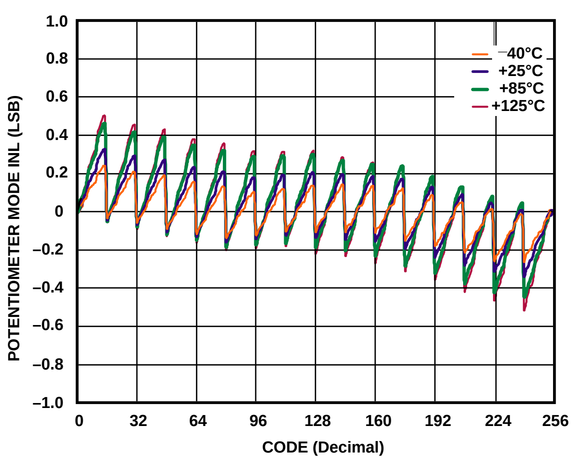

Figure 6. INL vs. Code, V_{DD} = 5 V

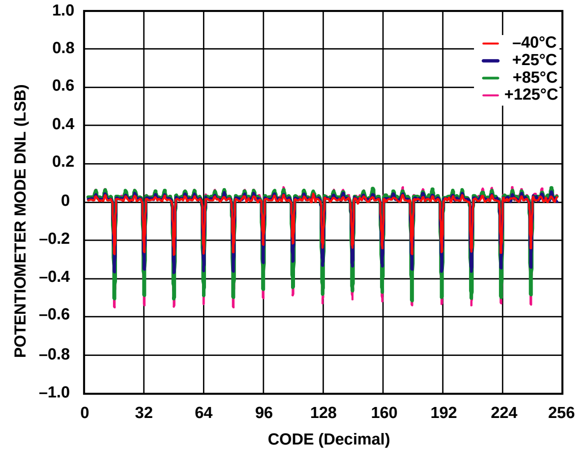

Figure 7. DNL vs. Code, V_{DD} = 5 V

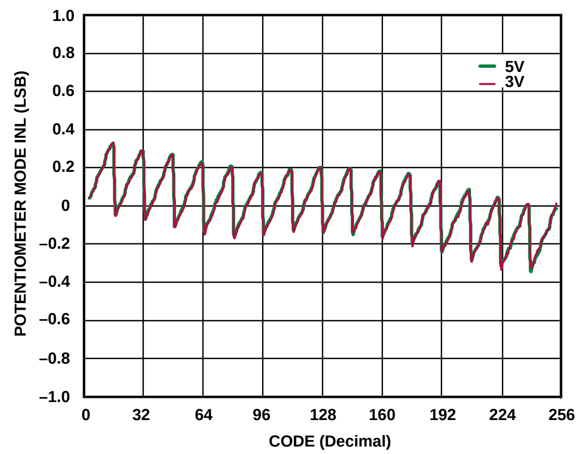

Figure 8. INL vs. Code vs. Supply Voltages

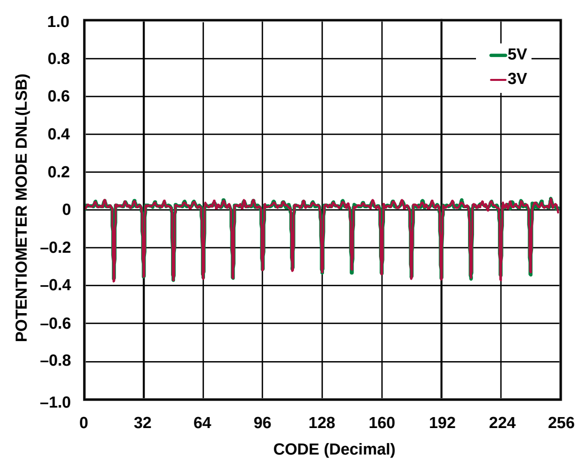

Figure 9. DNL vs. Code vs. Supply Voltages

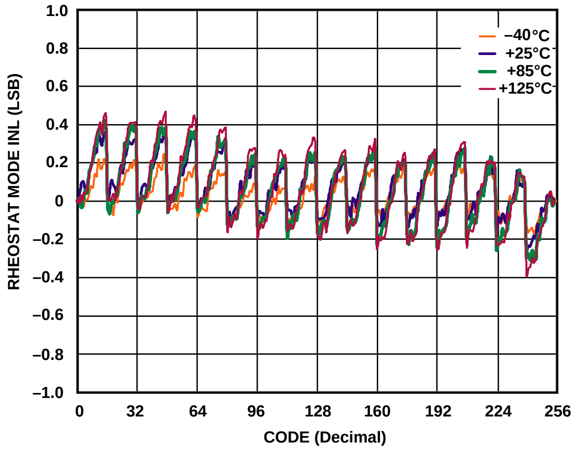

Figure 10. R-INL vs. Code, V_{DD} = 5 V

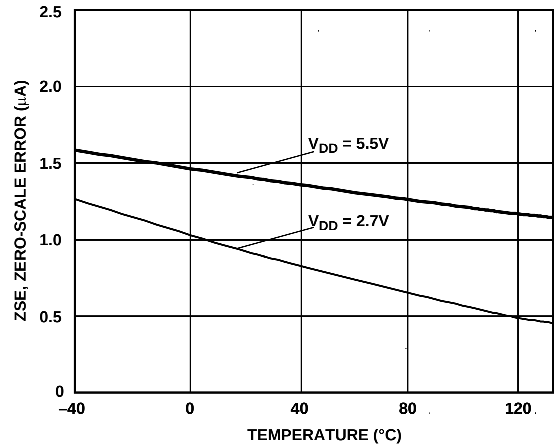

Figure 13. Zero-Scale Error vs. Temperature

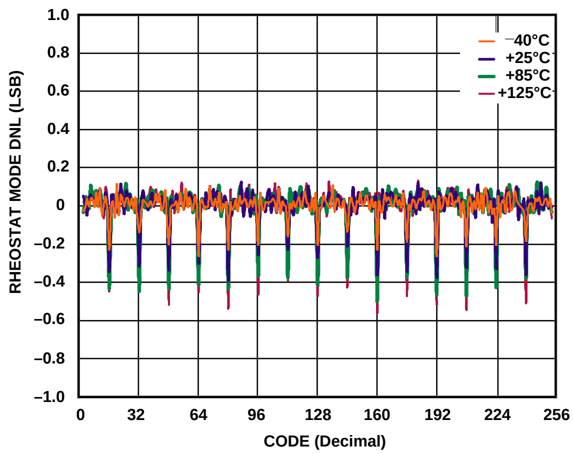

Figure 11. R-DNL vs. Code, V_{DD} = 5 V

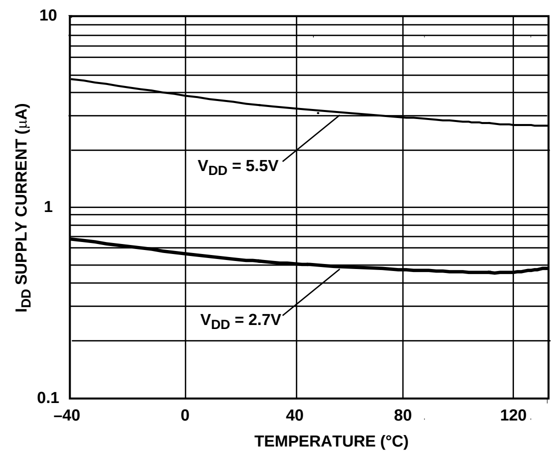

Figure 14. Supply Current vs. Temperature

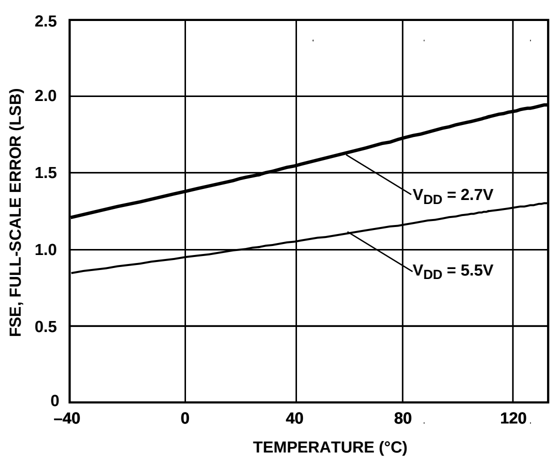

Figure 12. Full-Scale Error vs. Temperature

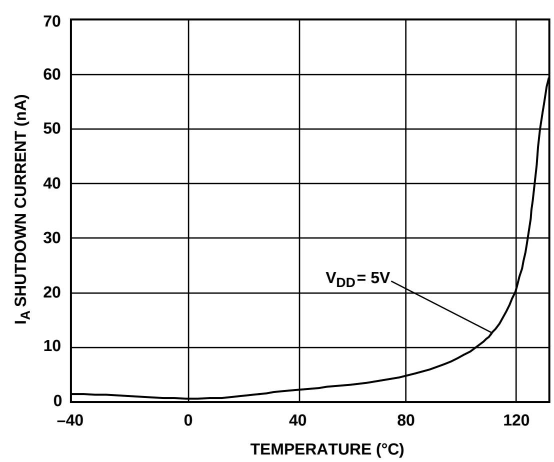

Figure 15. Shutdown Current vs. Temperature

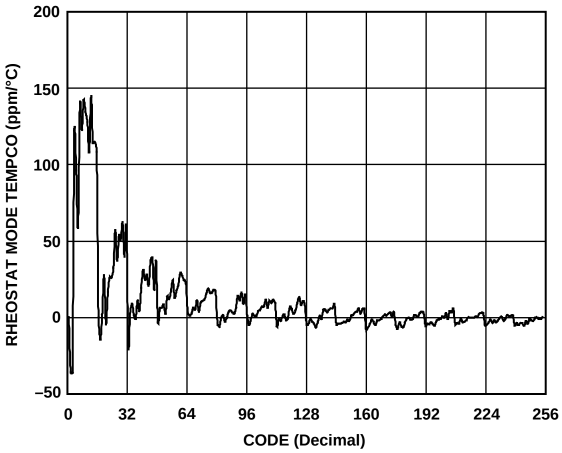

Figure 16. Rheostat Mode Tempco $\Delta R_{WB}/\Delta T$ vs. Code

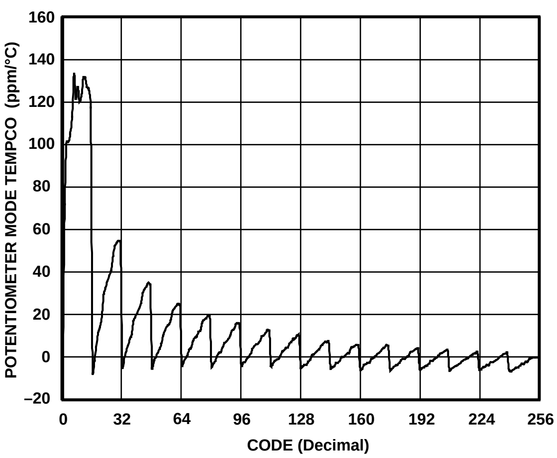

Figure 17. Potentiometer Mode Tempco $\Delta V_{WB}/\Delta T$ vs. Code

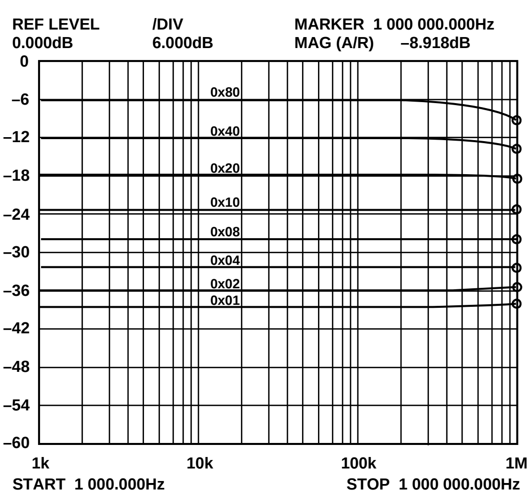

Figure 18. Gain vs. Frequency vs. Code, R_{AB} = 5 kΩ

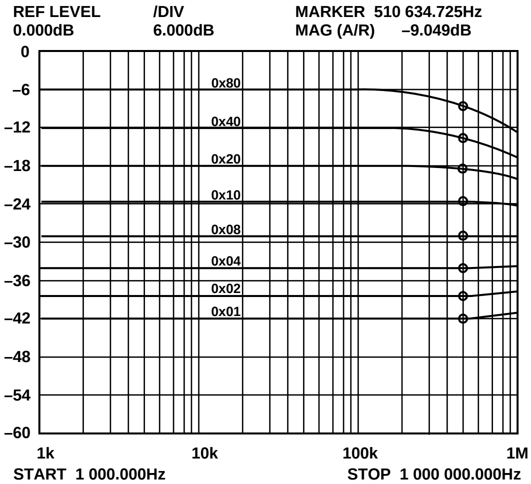

Figure 19. Gain vs. Frequency vs. Code, R_{AB} = 10 kΩ

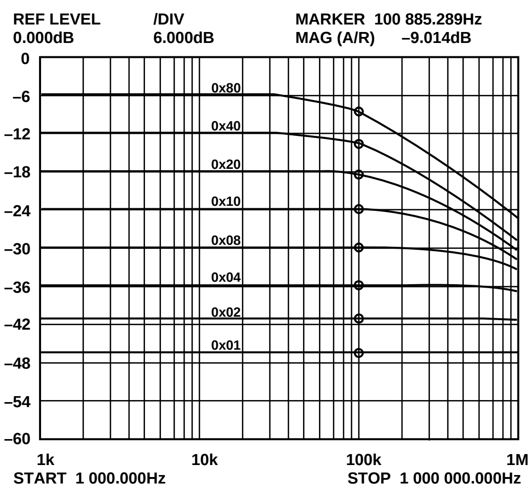

Figure 20. Gain vs. Frequency vs. Code, R_{AB} = 50 kΩ

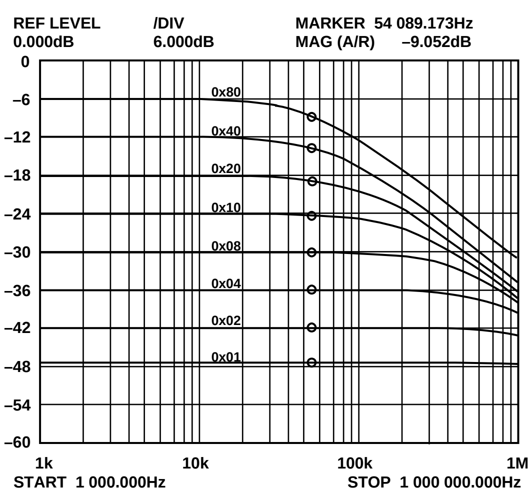

Figure 21. Gain vs. Frequency vs. Code, R_{AB} = 100 kΩ

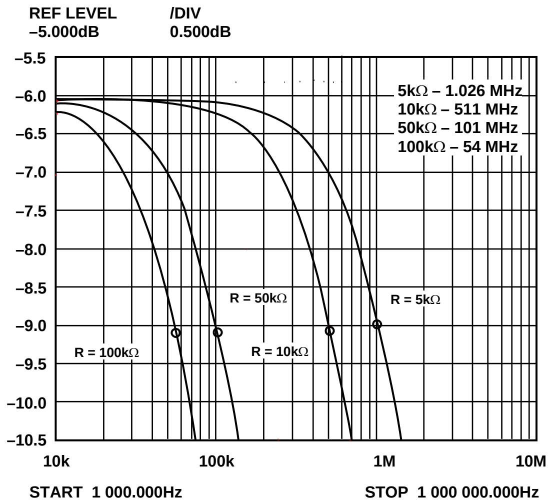

Figure 22. −3 dB Bandwidth @ Code = 0x80

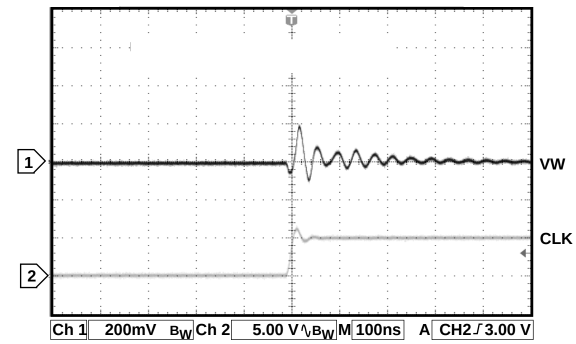

Figure 25. Digital Feedthrough

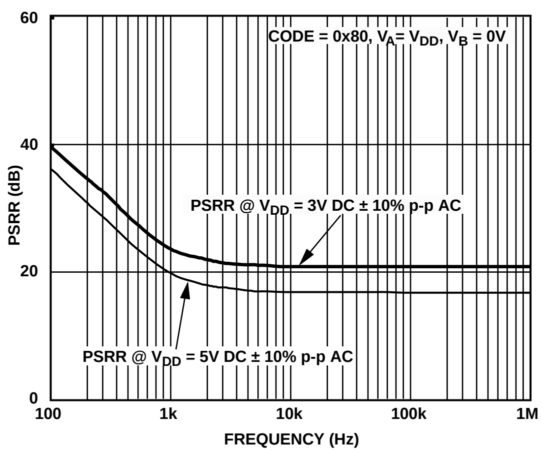

Figure 23. PSRR vs. Frequency

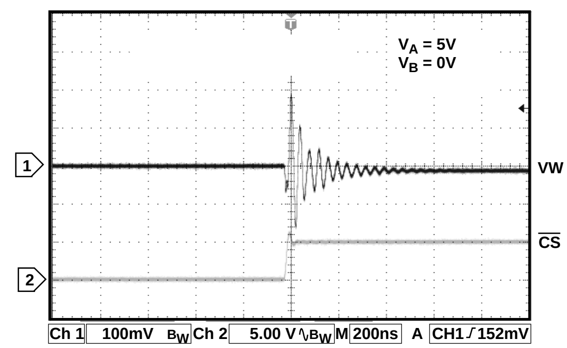

Figure 26. Midscale Glitch, Code 0x80 to Code 0x7F

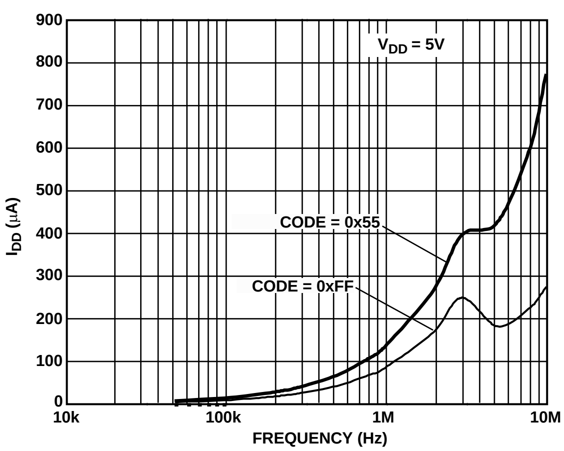

Figure 24. I_{DD} vs. Frequency

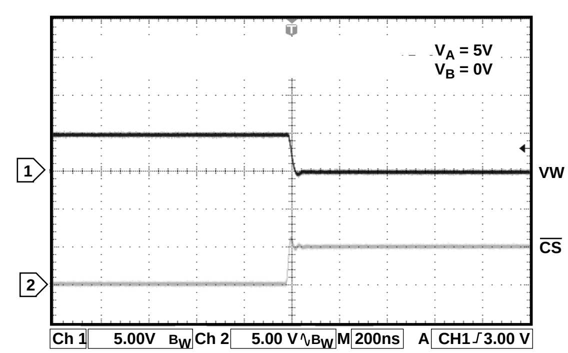

Figure 27. Large Signal Settling Time, Code 0xFF to Code 0x00

TEST CIRCUITS

Figure 28 to Figure 36 illustrate the test circuits that define the test conditions used in the product specification tables.

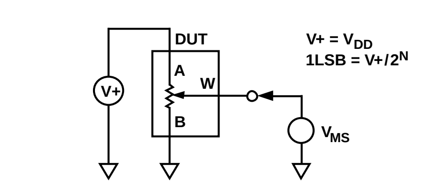

Figure 28. Test Circuit for Potentiometer Divider Nonlinearity Error (INL, DNL)

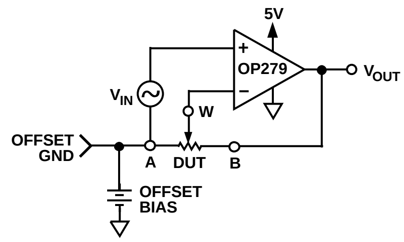

Figure 33. Test Circuit for Noninverting Gain

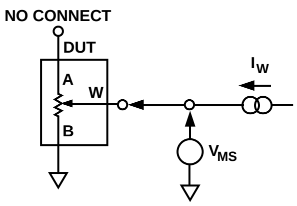

Figure 29. Test Circuit for Resistor Position Nonlinearity Error (Rheostat Operation; R-INL, R-DNL)

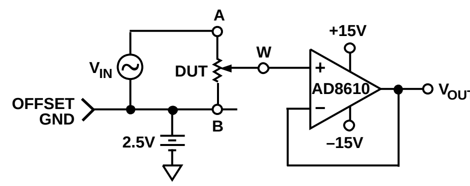

Figure 34. Test Circuit for Gain vs. Frequency

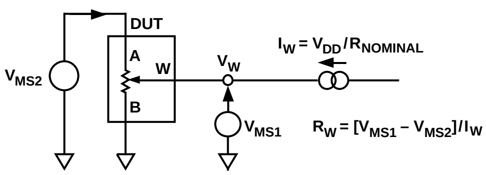

Figure 30. Test Circuit for Wiper Resistance

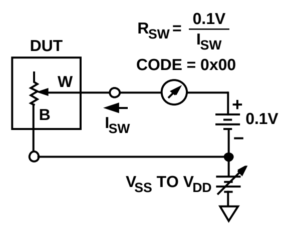

Figure 35. Test Circuit for Incremental On Resistance

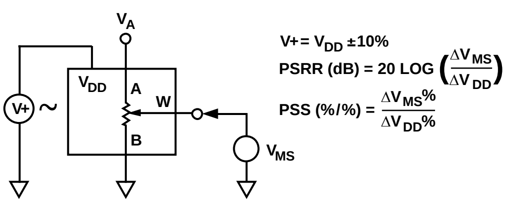

Figure 31. Test Circuit for Power Supply Sensitivity (PSS, PSSR)

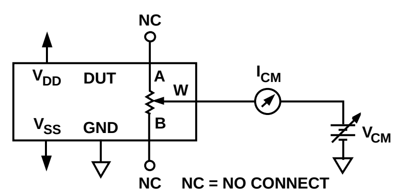

Figure 36. Test Circuit for Common-Mode Leakage Current

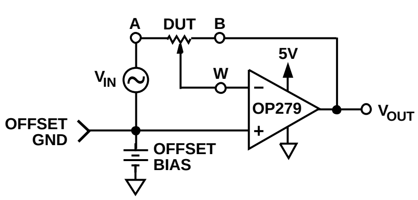

Figure 32. Test Circuit for Inverting Gain

SPI INTERFACE

Table 6. Serial Data-Word Format

B7	B6	B5	B4	B3	B2	B1	B0
D7 MSB 2^7	D6	D5	D4	D3	D2	D1	D0 LSB 2^0

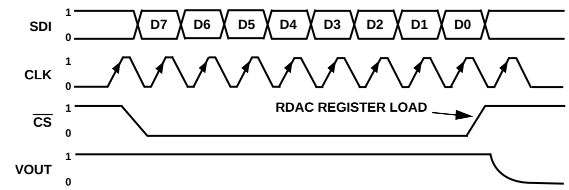

Figure 37. SPI Interface Timing Diagram (V_A = 5 V, V_B = 0 V, V_W = V_{OUT})

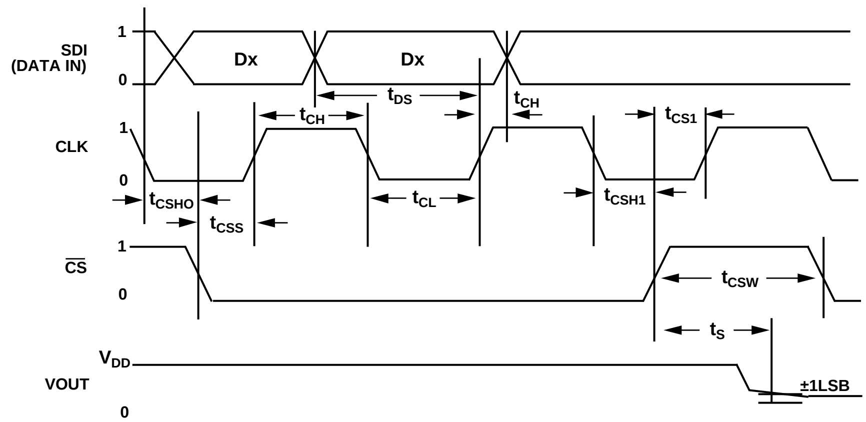

Figure 38. SPI Interface Detailed Timing Diagram (V_A = 5 V, V_B = 0 V, V_W = V_{OUT})

THEORY OF OPERATION

The AD5160 is a 256-position digitally controlled variable resistor (VR) device.

An internal power-on preset places the wiper at midscale during power-on, which simplifies the fault condition recovery at power-up.

PROGRAMMING THE VARIABLE RESISTOR

Rheostat Operation

The nominal resistance of the RDAC between Terminal A and Terminal B is available in 5 kΩ, 10 kΩ, 50 kΩ, and 100 kΩ. The final two or three digits of the model number as listed in the Ordering Guide section determine the nominal resistance value, for example, in model AD5160BRJZ10, the 10 represents 10 kΩ; and in AD5160BRJZ50, the 50 represents 50 kΩ.

The nominal resistance (R_{AB}) of the VR has 256 contact points accessed by the wiper terminal, plus the B terminal contact. The 8-bit data in the RDAC latch is decoded to select one of the 256 possible settings.

Assuming a 10 kΩ part is used, the first connection of the wiper starts at the B terminal for Data 0x00. Because there is a 60 Ω wiper contact resistance, such connection yields a minimum of 60 Ω resistance between Terminal W and Terminal B.

The second connection is the first tap point, which corresponds to 99 Ω ($R_{WB} = R_{AB}/256 + R_W = 39\ \Omega + 60\ \Omega$) for Data 0x01.

The third connection is the next tap point, representing 138 Ω (2 × 39 Ω + 60 Ω) for Data 0x02, and so on. Each LSB data value increase moves the wiper up the resistor ladder until the last tap point is reached at 9961 Ω (R_{AB} – 1 LSB + R_W). Figure 39 shows a simplified diagram of the equivalent RDAC circuit where the last resistor string is not accessed; therefore, there is 1 LSB less of the nominal resistance at full scale in addition to the wiper resistance.

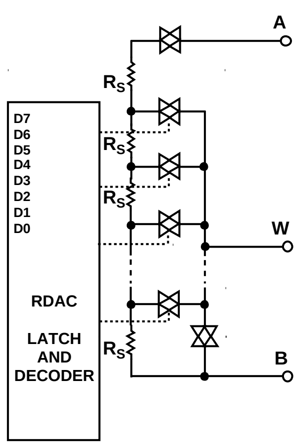

Figure 39. Equivalent RDAC Circuit

The general equation determining the digitally programmed output resistance between W and B is

$$R_{WB}(D) = \frac{D}{256} \times R_{AB} + R_W \tag{1}$$

where:
D is the decimal equivalent of the binary code loaded in the 8-bit RDAC register.
R_{AB} is the end-to-end resistance.
R_W is the wiper resistance contributed by the on resistance of the internal switch.

In summary, if R_{AB} = 10 kΩ and the A terminal is open circuited, the following output resistance R_{WB} is set for the indicated RDAC latch codes.

Table 7. Codes and Corresponding R_{WB} Resistance

D (Dec.)	R_{WB} (Ω)	Output State
255	9961	Full Scale (R_{AB} – 1 LSB + R_W)
128	5060	Midscale
1	99	1 LSB
0	60	Zero Scale (Wiper Contact Resistance)

Note that in the zero-scale condition, a finite wiper resistance of 60 Ω is present. Take care to limit the current flow between W and B in this state to a maximum pulse current of no more than 20 mA. Otherwise, degradation or possible destruction of the internal switch contact can occur.

Similar to the mechanical potentiometer, the resistance of the RDAC between the Wiper W and Terminal A also produces a digitally controlled complementary resistance (R_{WA}). When these terminals are used, the B terminal can be opened. Setting the resistance value for R_{WA} starts at a maximum value of resistance and decreases as the data loaded in the latch increases in value. The general equation for this operation is

$$R_{WA}(D) = \frac{256 - D}{256} \times R_{AB} + R_W \tag{2}$$

For R_{AB} = 10 kΩ and the B terminal is open circuited, the following output resistance R_{WA} is set for the indicated RDAC latch codes.

Table 8. Codes and Corresponding R_{WA} Resistance

D (Dec.)	R_{WA} (Ω)	Output State
255	99	Full Scale
128	5060	Midscale
1	9961	1 LSB
0	10,060	Zero Scale

Typical device-to-device matching is process lot dependent and may vary by up to ±30%. Because the resistance element is processed in thin film technology, the change in R_{AB} with temperature has a very low 45 ppm/°C temperature coefficient.

PROGRAMMING THE POTENTIOMETER DIVIDER

Voltage Output Operation

The digital potentiometer easily generates a voltage divider at wiper-to-B and wiper-to-A proportional to the input voltage at A-to-B. Unlike the polarity of V_{DD} to GND, which must be positive, voltage across A to B, W to A, and W to B can be at either polarity.

If ignoring the effect of the wiper resistance for approximation, connecting the A terminal to 5 V and the B terminal to ground produces an output voltage at the wiper-to-B starting at 0 V up to 1 LSB less than 5 V. Each LSB of voltage is equal to the voltage applied across Terminal A and Terminal B divided by the 256 positions of the potentiometer divider. The general equation defining the output voltage at V_W with respect to ground for any valid input voltage applied to Terminal A and Terminal B is

$$V_W(D) = \frac{D}{256} V_A + \frac{256 - D}{256} V_B \quad (3)$$

For a more accurate calculation, which includes the effect of wiper resistance, V_W can be found as

$$V_W(D) = \frac{R_{WB}(D)}{256} V_A + \frac{R_{WA}(D)}{256} V_B \quad (4)$$

Operation of the digital potentiometer in the divider mode results in a more accurate operation over temperature. Unlike the rheostat mode, the output voltage is dependent mainly on the ratio of the internal resistors (R_{WA} and R_{WB}) and not the absolute values. Therefore, the temperature drift reduces to 15 ppm/°C.

SPI-COMPATIBLE 3-WIRE SERIAL BUS

The AD5160 contains a 3-wire SPI-compatible digital interface (SDI, $\overline{CS}$, and CLK). The 8-bit serial word must be loaded MSB first. The format of the word is shown in Table 6.

The positive-edge sensitive CLK input requires clean transitions to avoid clocking incorrect data into the serial input register. Standard logic families work well. If mechanical switches are used for product evaluation, they should be debounced by a flip-flop or other suitable means. When $\overline{CS}$ is low, the clock loads data into the serial register on each positive clock edge (see Figure 37).

The data setup and data hold times in the specification table determine the valid timing requirements. The AD5160 uses an 8-bit serial input data register word that is transferred to the internal RDAC register when the $\overline{CS}$ line returns to logic high. Extra MSB bits are ignored.

ESD PROTECTION

All digital inputs are protected with a series input resistor and parallel Zener ESD structures are shown in Figure 40 and Figure 41. This applies to SDI, CLK, and $\overline{CS}$, which are the digital input pins.

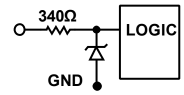

Figure 40. ESD Protection of Digital Pins

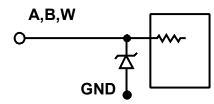

Figure 41. ESD Protection of Resistor Terminals

POWER-UP SEQUENCE

Because the ESD protection diodes limit the voltage compliance at the A, B, and W terminals, it is important to power V_{DD}/GND before applying any voltage to the A, B, and W terminals; otherwise, the diode forward biases such that V_{DD} is powered unintentionally and may affect the rest of the user's circuit. The ideal power-up sequence is in the following order: GND, V_{DD}, digital inputs, and then $V_{A/B/W}$. The relative order of powering V_A, V_B, V_W, and the digital inputs is not important as long as they are powered after V_{DD}/GND.

LAYOUT AND POWER SUPPLY BYPASSING

It is a good practice to employ compact, minimum lead length layout design. Keep the leads to the inputs as direct as possible with a minimum conductor length. Ground paths should have low resistance and low inductance.

Similarly, it is also a good practice to bypass the power supplies with quality capacitors for optimum stability. Bypass supply leads to the device with disc or chip ceramic capacitors of 0.01 µF to 0.1 µF. To minimize any transient disturbance and low frequency ripple, apply low ESR 1 µF to 10 µF tantalum or electrolytic capacitors at the supplies (see Figure 42). To minimize the ground bounce, join the digital ground remotely to the analog ground at a single point.

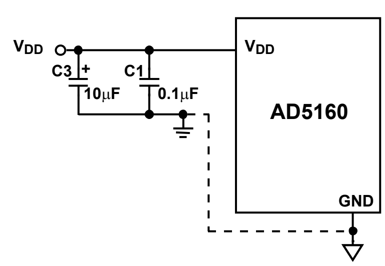

Figure 42. Power Supply Bypassing

OUTLINE DIMENSIONS

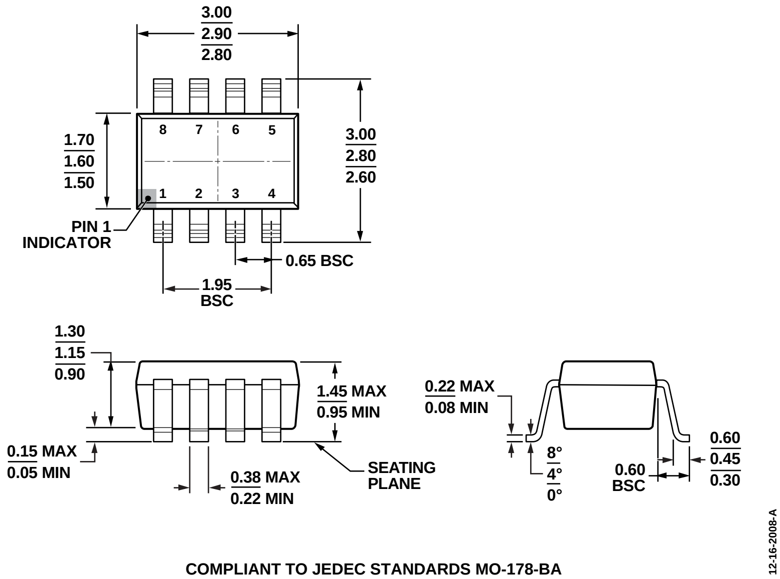

Figure 43. 8-Lead Small Outline Transistor Package [SOT-23] (RJ-8)
Dimensions shown in millimeters

ORDERING GUIDE

Model[1, 2, 3]	R_{AB} (Ω)	Temperature	Package Description	Package Option	Branding
AD5160BRJZ5-R2	5 k	−40°C to +125°C	8-Lead SOT-23	RJ-8	D6Q
AD5160BRJZ5-RL7	5 k	−40°C to +125°C	8-Lead SOT-23	RJ-8	D6Q
AD5160BRJZ10-R2	10 k	−40°C to +125°C	8-Lead SOT-23	RJ-8	D09
AD5160BRJZ10-RL7	10 k	−40°C to +125°C	8-Lead SOT-23	RJ-8	D09
AD5160BRJZ50-R2	50 k	−40°C to +125°C	8-Lead SOT-23	RJ-8	D8J
AD5160BRJZ50-RL7	50 k	−40°C to +125°C	8-Lead SOT-23	RJ-8	D8J
AD5160BRJZ100-R2	100 k	−40°C to +125°C	8-Lead SOT-23	RJ-8	D0B
AD5160BRJZ100-RL7	100 k	−40°C to +125°C	8-Lead SOT-23	RJ-8	D0B
EVAL-AD5160DBZ			Evaluation Board		

[1] The AD5160 contains 2532 transistors. Die size: 30.7 mil × 76.8 mil = 2358 sq. mil.
[2] Z = RoHS Compliant Part.
[3] The EVAL-AD5160DBZ board is shipped with the 10 kΩ R_{AB} resistor option; however, the board is compatible with all available resistor value options.

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International Flathead™ Low Profile Transformers • Printed Circuit Mount

For Critical Height and International Safety Requirements

Signal's IF transformers utilize unique insulating techniques including full encapsulation to meet international safety requirements. These transformers are ideal for low power applications where minimum height and reduced magnetic radiation are required.

General Specifications

- Power - 2 VA to 30 VA
- Dielectric Strength - 4000 Vrms Hipot
- Dual Primaries - 115/230 V, 50/60 Hz
- Dual Secondaries - Series or parallel
- Height - 0.69" to 1.39" (17.5 mm to 35.3 mm) height
- Insulation System - Class B, 130º C

Agency Certifications

- UL 1446 (E66312)
- UL recognized to UL 506 / UL 5085-2, File # E63829
- CSA certified to C22.2 #66.1, File # 221070
- VDE certified to VDE 0805 / EN 60950, File # 8325

RoHS 2002/95/EC

Part Number	VA	Secondary RMS Rating	
	Size	Series	Parallel
IF-2-10	2	10VCT @ 200mA	5V @ 400mA
IF-2-12	2	12VCT @ 170mA	6V @ 340mA
IF-2-16	2	16VCT @ 125mA	8V @ 250mA
IF-2-20	2	20VCT @ 100mA	10V @ 200mA
IF-2-24	2	24VCT @ 85mA	12V @ 170mA
IF-2-30	2	30VCT @ 70mA	15V @ 140mA
IF-2-34	2	34VCT @ 60mA	17V @ 120mA
IF-2-40	2	40VCT @ 50mA	20V @ 100mA
IF-2-56	2	56VCT @ 40mA	28V @ 80mA
IF-2-230	2	230VCT @ 9 mA	115V @ 18mA
IF-4-10	4	10VCT @ 400 mA	5V @ 800mA
IF-4-12	4	12VCT @ 335mA	6V @ 670mA
IF-4-16	4	16VCT @ 250mA	8V @ 500mA
IF-4-20	4	20VCT @ 200mA	10V @ 400mA
IF-4-24	4	24VCT @ 170mA	12V @ 340mA
IF-4-30	4	30VCT @ 135mA	15V @ 270mA
IF-4-34	4	34VCT @ 120mA	17V @ 240mA
IF-4-40	4	40VCT @ 100mA	20V @ 200mA
IF-4-56	4	56VCT @ 70mA	28V @ 140mA
IF-4-230	4	230VCT @ 18mA	115V @ 36mA
IF-6-10	6	10VCT @ 600mA	5V @ 1.20A
IF-6-12	6	12VCT @ 500mA	6V @ 1.00A
IF-6-16	6	16VCT @ 375mA	8V @ 750mA
IF-6-20	6	20VCT @ 300mA	10V @ 600mA
IF-6-24	6	24VCT @ 250mA	12V @ 500mA
IF-6-30	6	30VCT @ 200mA	15V @ 400mA
IF-6-34	6	34VCT @ 180mA	17V @ 360mA
IF-6-40	6	40VCT @ 150mA	20V @ 300mA
IF-6-56	6	56VCT @ 110mA	28V @ 220mA
IF-6-230	6	230VCT @ 25mA	115V @ 50mA
IF-10-10	10	10VCT @ 1.00A	5V @ 2.00A
IF-10-12	10	12VCT @ 835mA	6V @ 1.67A
IF-10-16	10	16VCT @ 625mA	8V @ 1.25A
IF-10-20	10	20VCT @ 500mA	10V @ 1.00A
IF-10-24	10	24VCT @ 420mA	12V @ 840mA
IF-10-30	10	30VCT @ 335mA	15V @ 670mA
IF-10-34	10	34VCT @ 300mA	17V @ 600mA
IF-10-40	10	40VCT @ 250mA	20V @ 500mA
IF-10-56	10	56VCT @ 180mA	28V @ 360mA
IF-10-230	10	230VCT @ 45mA	115V @ 90mA

Part Number	VA	Secondary RMS Rating	
	Size	Series	Parallel
IF-14-10	14	10VCT @ 1.40A	5V @ 2.80A
IF-14-12	14	12VCT @ 1.20A	6V @ 2.40A
IF-14-16	14	16VCT @ 875mA	8V @ 1.75A
IF-14-20	14	20VCT @ 700mA	10V @ 1.40A
IF-14-24	14	24VCT @ 600mA	12V @ 1.20A
IF-14-30	14	30VCT @ 470mA	15V @ 940mA
IF-14-34	14	34VCT @ 415mA	17V @ 830mA
IF-14-40	14	40VCT @ 350mA	20V @ 700mA
IF-14-56	14	56VCT @ 250mA	28V @ 500mA
IF-14-230	14	230VCT @ 60mA	115V @ 120mA
IF-18-10	18	10VCT @ 1.80A	5V @ 3.60A
IF-18-12	18	12VCT @ 1.50A	6V @ 3.00A
IF-18-16	18	16VCT @ 1.15A	8V @ 2.30A
IF-18-20	18	20VCT @ 900mA	10V @ 1.80A
IF-18-24	18	24VCT @ 750mA	12V @ 1.50A
IF-18-30	18	30VCT @ 600mA	15V @ 1.20A
IF-18-34	18	34VCT @ 530mA	17V @ 1.06A
IF-18-40	18	40VCT @ 450mA	20V @ 900mA
IF-18-56	18	56VCT @ 320mA	28V @ 640mA
IF-18-230	18	230VCT @ 80mA	115V @ 160mA
IF-24-10	24	10VCT @ 2.40A	5V @ 4.80A
IF-24-12	24	12VCT @ 2.00A	6V @ 4.00A
IF-24-16	24	16VCT @ 1.50A	8V @ 3.00A
IF-24-20	24	20VCT @ 1.20A	10V @ 2.40A
IF-24-24	24	24VCT @ 1.00A	12V @ 2.00A
IF-24-30	24	30VCT @ 800mA	15V @ 1.60A
IF-24-34	24	34VCT @ 700mA	17V @ 1.40A
IF-24-40	24	40VCT @ 600mA	20V @ 1.20A
IF-24-56	24	56VCT @ 430mA	28V @ 860mA
IF-24-230	24	230VCT @ 105mA	115V @ 210mA
IF-30-10	30	10VCT @ 3.00A	5V @ 6.00A
IF-30-12	30	12VCT @ 2.50A	6V @ 5.00A
IF-30-16	30	16VCT @ 1.90A	8V @ 3.80A
IF-30-20	30	20VCT @ 1.50A	10V @ 3.00A
IF-30-24	30	24VCT @ 1.25A	12V @ 2.50A
IF-30-30	30	30VCT @ 1.00A	15V @ 2.00A
IF-30-34	30	34VCT @ 900mA	17V @ 1.80A
IF-30-40	30	40VCT @ 750mA	20V @ 1.50A
IF-30-56	30	56VCT @ 550mA	28V @ 1.10A
IF-30-230	30	230VCT @ 130mA	115V @ 260mA

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For Critical Height and International Safety Requirements

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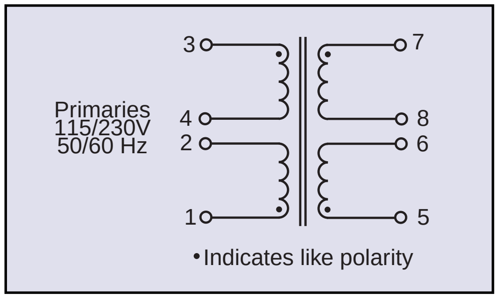

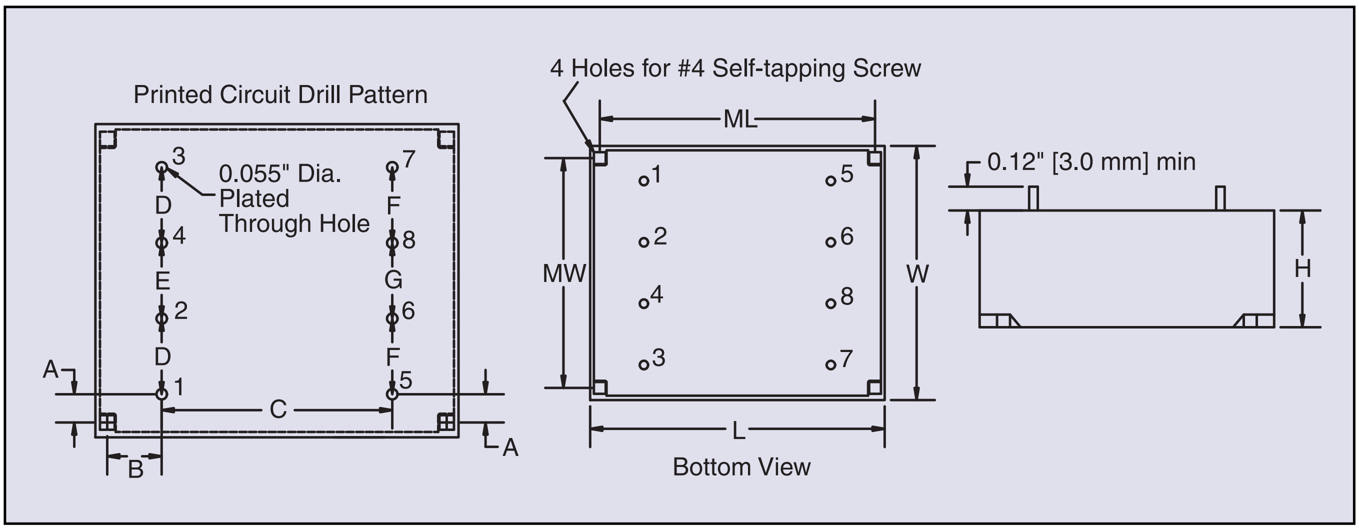

VA	L	W	H	ML	MW	A	B	C	D	E	F	G	Weight
Size	Inches (mm)												oz (kg)
2	2.09 (53.0)	1.73 (44.0)	0.69 (17.6)	1.87 (47.5)	1.48 (37.5)	0.05 (1.3)	0.25 (6.3)	1.38 (35.0)	0.39 (10.0)	0.39 (10.0)	0.59 (15.0)	0.19 (5.0)	4.6 (0.13)
4	2.09 (53.0)	1.73 (44.0)	0.77 (19.6)	1.87 (47.5)	1.48 (37.5)	0.05 (1.3)	0.25 (6.3)	1.38 (35.0)	0.39 (10.0)	0.39 (10.0)	0.59 (15.0)	0.19 (5.0)	5.4 (0.15)
6	2.09 (53.0)	1.73 (44.0)	0.89 (22.6)	1.87 (47.5)	1.48 (37.5)	0.05 (1.3)	0.25 (6.3)	1.38 (35.0)	0.39 (10.0)	0.39 (10.0)	0.59 (15.0)	0.19 (5.0)	6.9 (0.20)
10	2.66 (67.6)	2.24 (57.0)	0.89 (22.6)	2.46 (62.5)	1.97 (50.0)	0.28 (7.1)	0.34 (8.8)	1.77 (45.0)	0.59 (15.0)	0.43 (10.9)	0.39 (10.0)	0.63 (15.9)	10.3 (0.29)
14	2.66 (67.6)	2.24 (57.0)	0.96 (24.3)	2.46 (62.5)	1.97 (50.0)	0.28 (7.1)	0.34 (8.8)	1.77 (45.0)	0.59 (15.0)	0.43 (10.9)	0.39 (10.0)	0.63 (15.9)	11.9 (0.34)
18	2.66 (67.6)	2.24 (57.0)	1.09 (27.6)	2.46 (62.5)	1.97 (50.0)	0.28 (7.1)	0.34 (8.8)	1.77 (45.0)	0.59 (15.0)	0.43 (10.9)	0.39 (10.0)	0.63 (15.9)	14.1 (0.40)
24	2.68 (68.0)	2.26 (57.5)	1.23 (31.3)	2.46 (62.5)	1.97 (50.0)	0.28 (7.2)	0.34 (8.8)	1.77 (45.0)	0.59 (15.0)	0.43 (10.9)	0.39 (10.0)	0.63 (15.9)	16.5 (0.47)
30	2.68 (68.0)	2.26 (57.5)	1.39 (35.3)	2.46 (62.5)	1.97 (50.0)	0.28 (7.2)	0.34 (8.8)	1.77 (45.0)	0.59 (15.0)	0.43 (10.9)	0.39 (10.0)	0.63 (15.9)	19.7 (0.58)

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