



ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)
GRADO EN INGENIERÍA ELECTROMECÁNICA

SOLAR PATIO UMBRELLA

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Madrid

Junio 2016

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Director: Braedon Salz

Madrid
Junio 2016

To my family.

Thanks for your continued support and love through this process of becoming the person I am today. Without you all I could never have accomplished this.

I would also like to thank to Christian Ngeleza and Viren Mascarenhas, my partners during this second semester, for their hard work and dedication to this project and our team.

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RESUMEN DEL PROYECTO

1. Introducción

El objetivo principal de este proyecto es el diseño y la elaboración de una sombrilla de jardín, la cual es alimentada con energía solar. Este sistema consta de un panel fotovoltaico que utiliza un convertidor MPPT para transformar eficientemente la energía solar y almacenarla en una batería. Esta batería, más tarde, alimentará a los diferentes módulos que completan el diseño, cargador, seguidor solar y regulador de la intensidad lumínica. El módulo del cargador contiene un puerto USB, al cual se conecta un dispositivo electrónico para ser cargado. En cuanto al seguidor, posicionará el parasol en la dirección del sol para así captar la mayor energía posible. Finalmente, el regulador permitirá al usuario controlar la intensidad lumínica de los LEDs.

Actualmente, existen diferentes tipos de sombrillas de jardín que captan la energía solar, para más tarde utilizar esta para iluminar la zona justo debajo de la sombrilla o cargar diferentes dispositivos electrónicos. Sin embargo, no existe ningún sistema tan completo que incluya estas dos funciones y además incluya un seguidor solar para conseguir la mayor sombra posible. Asimismo, en la actualidad existe un auge imparable en el mundo de la energía fotovoltaica y se espera que en un futuro cercano el autoabastecimiento solar sea mucho más común debido a los últimos descubrimientos que han conseguido reducir el coste e incrementar la eficiencia de los paneles. Como conclusión, se puede apreciar que este producto es una alternativa económica y que competiría en un mercado en el cual no existen grandes competidores.

2. Diseño

2.1 Módulo de Energía

El objetivo de este módulo es absorber energía proveniente del sol a través de un panel fotovoltaico y convertirla, eficientemente, en electricidad almacenada en una batería de 12V y 7Ah. Para cargar la batería se utilizará un controlador MPPT.

2.2 Módulo de Ejecución

El propósito de este módulo es ejecutar las diferentes funciones de este parasol. Las tres funciones principales de este sistema son: una estación de carga a través de un puerto USB, un seguidor solar y un sistema de iluminación.

a) Estación de Carga

La estación de carga le permite al cliente la capacidad de cargar varios dispositivos a través de un puerto USB. El diseño de esta estación de carga incluye la elaboración de un reductor que se encargará de reducir el voltaje proveniente de la batería, 12 V, hasta 5 V, que es necesario para alimentar el cargador USB. La Figura 1 muestra el esquema utilizado para este diseño. Este convertidor funciona tal que cuando el interruptor está encendido, la energía es transferida directamente desde la entrada hasta la salida. En este caso, el diodo no permitiría el paso de corriente a través de él. Secuencialmente, cuando el interruptor está abierto, la energía, previamente almacenada en la bobina, produce una corriente que provoca que el diodo conduzca. El ciclo de trabajo determina el voltaje de salida. Existen dos modos de operación para un convertidor reductor, modo continuo y discontinuo. Este diseño está enfocado para que funcione en modo continuo. Este diseño también incluirá un control de lazo cerrado para mantener el voltaje de salida lo más cercano posible a 5 V.

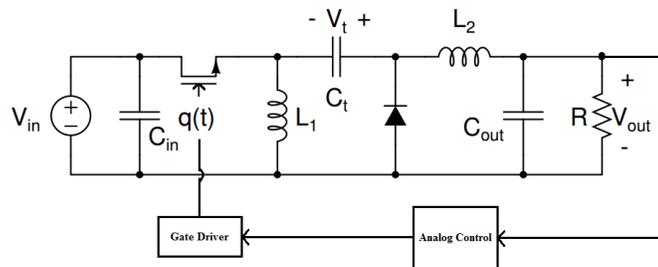


Figura 1: Esquema Base de un Convertidor Reductor

b) Seguidor Solar

La finalidad de este seguidor solar es monitorizar la posición del sol y posicionar el panel fotovoltaico para así captar la mayor cantidad de energía posible. Para este diseño se utilizarán foto-resistores cuya finalidad es localizar el sol basándose en la resistencia de estos, aquel que tenga una menor resistencia recibirá mayor intensidad solar. Esta resistencia se detecta utilizando un divisor de tensión. Esta información es enviada al micro-controlador que se encargará que posicionar la sombrilla enviando la energía necesaria a un motor de corriente continua, capaz de moverse en sentido horario y anti horario. Para este diseño, se utilizan 8 foto-sensores posicionados a 45° uno del otro. El panel está posicionado junto al sensor 1, el cual marca la posición de referencia para que reciba la mayor intensidad lumínica en todo momento.

c) Regulador lumínico

La meta de este regulador lumínico es ofrecer al usuario la capacidad de regular la intensidad de los LEDs, para lo cual se utilizará una señal PWM. Para este diseño, se utilizará un generador de PWM analógico, LM555. Este LM555 es un oscilador que produce una señal continua de onda cuadrada con un determinado ciclo y a una frecuencia fijada.

3. Resultados

3.1 Módulo de Energía

Basándose en los resultados obtenidos durante los diferentes experimentos llevados a cabo, ha sido estimado que el tiempo total para cargar la batería completamente es de 2.5 horas +/- 0.5 horas. El tiempo total que la batería es capaz de alimentar el proyecto entero, es de 4.5 horas +/- 0.5 horas.

1.2 Execution Module

a) Estación de Carga

Esta estación de carga contiene un convertidor reductor que es capaz de ofrecer un voltaje de salida de 5V +/- .05V y una corriente mayor de 1^a. Ha sido instalado un cargador tipo “Apple” capaz de cargar dispositivos Android e IOs.

Este convertidor, inicialmente fue diseñado en una proto-board. La salida deseada para este diseño era 5V +/- .25 V y 1A +/- 200mA. El rizado de la corriente de salida se mantuvo en el rango fijado, lo que significaba que el inductor utilizado era suficientemente grande; sin embargo se podría observar que en ocasiones había un desbarajuste en el valor del voltaje de salida lo que obligó a diseñar un control de lazo cerrado para ajustar el ciclo de trabajo y conseguir de nuevo un voltaje de salida de aproximadamente 5V. El circuito construido en dicha proto-board funcionaba perfectamente; no obstante al comprobar su eficiencia se observaba que no era muy alta lo que provocó que se diseñase este mismo convertidor en una PCB.

Tras soldar todos los componentes en la placa PCB y realizar varios experimentos, con carga y sin carga, se pudo comprobar que hay un incremento considerable, de alrededor de 15-20%, en la eficiencia de este convertidor. Este resultado fue algo esperado, ya que al desarrollar el reductor en un placa PCB se eliminan los cables, y por tanto sus pérdidas. El ciclo de trabajo es alrededor de 46% como fue predicho en el diseño y la eficiencia cercana a 90%. Finalmente, el rizado la señal del voltaje en la salida, cuando hay una carga conectada, es de 50 mVrms.

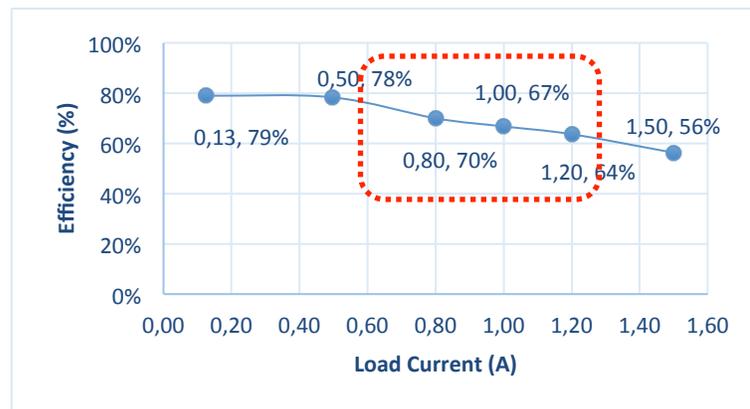


Figura 2: Eficiencia de un Convertidor Reductor diseñado en proto-board

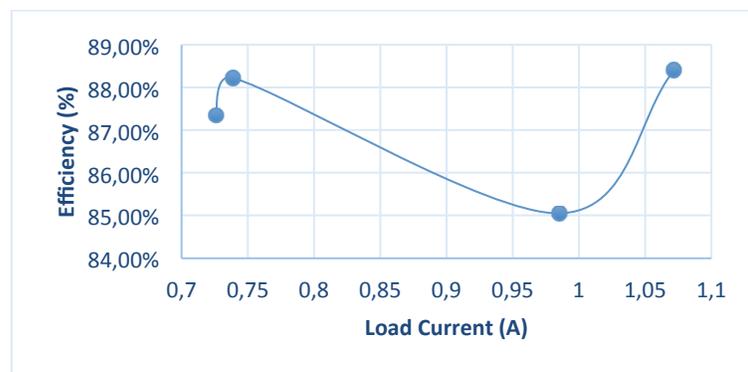


Figura 3: Eficiencia de un Convertidor Reductor diseñado en PCB

b) Seguidor Solar

Finalmente se ha conseguido que este seguidor solar posicione en la posición idónea, recibiendo la mayor intensidad posible, y una de precisión de ± 3 grados. El micro-controlador es capaz de leer los diferentes voltajes analógicos de los 8 sensores utilizados utilizando un A/D, comparar todos los valores entre si mismo y con una referencia, y rotar la sombrilla.

c) Regulador Lumínico

Este regulador lumínico ofrece al usuario la posibilidad de adaptar la intensidad de los LEDs a través de un potenciómetro, que ajusta el ciclo útil y que permite ajustar el voltaje de salida para lograr el output necesario. El ciclo de trabajo y la frecuencia son ajustados por R1 y la resistencia del potenciómetro.

4. Conclusiones

Este proyecto ha cumplido todos los objetivos fijados al inicio del semestre, excepto la incorporación, en la demostración final, de un micro-controlador independiente. En cuanto al desarrollo futuro de este proyecto incluiría depurar el diseño, y el cambio de algunos componentes. El primer paso sería construir el circuito del regulador lumínico en un PCB para así mejorar la eficiencia de este. Igualmente, se debería implementar un control, en el módulo del seguidor solar, que consiga posicionar con una mayor precisión la sombrilla y así absorber la mayor energía posible. Además, el circuito entero debería ser probado durante un periodo extenso de tiempo e implementado en una parasol de un tamaño acorde.

SOLAR PATIO UMBRELLA

EXECUTIVE SUMMARY OF THE PROJECT

1. Introduction

The project principally aims to design and build a Patio Umbrella that is solely powered by solar energy. The system consists of a solar panel that uses a Maximum Power Point Tracker (MPPT) converter to efficiently convert solar energy, which is then stored in the battery. The battery then powers up the lighting unit, the charging unit and the sun tracking unit. The charging module includes a USB port that can charge a phone. The lighting module consists of a dimming circuit that is used to dim and brighten LEDs, and lastly, the sun tracking module positions the solar panel to face maximum light from the sun. This paper details the design, requirements, results and findings.

Currently, there are several umbrellas already in existence that use the sun's energy in order to light up the area just below its roof or to charge an electronic device. However, there is not yet a single complete system that includes both of these two features in addition to tracking and following the direction of sun in order to create the largest shadow possible. Furthermore, solar energy is a developing energy and in a near future its use will be much more common since the latest discoveries allow cost to be reduced and an increased efficiency. The key takeaway is that this product is an economical alternative and competes in a market with numerous customers and few competing products. No product has been made yet that is as complete as this umbrella.

2. Design

2.1 Power Module

The purpose of this module is to absorb the sun's energy through a solar panel and efficiently convert that energy into electrical energy, using a maximum power point tracker (MPPT) controller, which charges a battery bank of 12V and 7Ah.

2.2 Execution Module

The purpose of this module is to execute the difference features of the solar-powered umbrella. The three features are the charging station, the sun tracking capability, and the lighting system.

sensor 1 which was designed to receive the most light at any given time. The motor is able to move the umbrella clockwise or anti-clockwise in order to reach the right position.

c) Lighting Module

This module is designed to control the light intensity of the LEDs, which is done through the use of Pulse Width Modulation (PWM). For this design, the PWM is generated by an LM555, which is an integrated circuit. The LM555 timer operates as an oscillator and outputs a continuous stream of rectangular pulses setting a specified frequency.

3. Results

3.1 Power Module

Based on the data collected during the different experiments, it was estimated that the time it took to fully charge the battery used is 2.5 hours +/- 0.5 hours. Additionally, using results from the consumption data, it was approximated that the battery is able to power the whole circuit throughout a time period of 4.5 hours +/- 0.5 hours.

3.2 Execution Module

a) Charging Module

The buck converter was finally able to accomplish 5V +/- .05V output and reach a current output up to 1A. The “Apple Charger” network check was implemented, optimized for 1A, and with this design, this module is able charge both the android and IOs devices.

The converter was first designed on the proto-board. The desired output current was 5V +/- .25 V and 1A +/- 200mA. The output ripple current was kept well within the desire range, meaning that the inductor of choice was large enough; however, it was quickly noted that the output voltage was vastly out of the desired range. In order to deal with this drop in voltage we needed to implement a control circuitry, which adjusted the duty cycle as needed, in order to maintain a certain range of voltage for the output load. The circuit on the proto-board was fully functional; however, the implementation of the converter on the proto-board was not very efficient.

Throughout the testing, there was a significant improvement in efficiency of the converter once it was on the PCB, for both with load and without a load. Although the increase in efficiency of about 15-20% may seem strikingly impressive, it is not completely unexpected. The reduction in the amount of wires connecting the components as well as the lengths of the component leads to a significant decrease in the overall parasitic in the system. The duty cycle was about 46% as it was predicted and the efficiency was about 90 percent. Finally, we looked at the output voltage ripple when the load was drawing about 1A., we can see that the peak ripple is about 50mVrms.

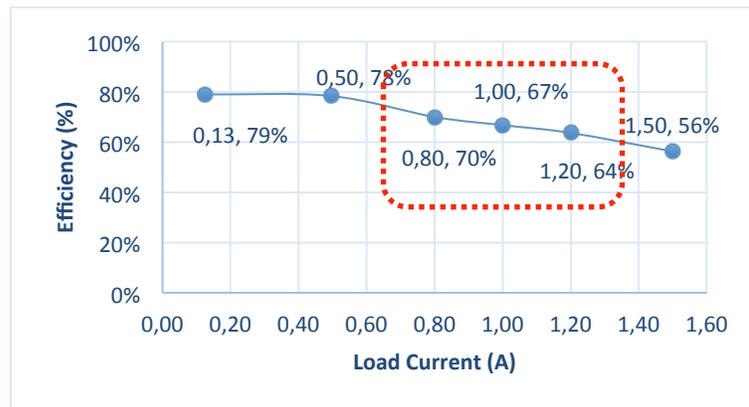


Figure 2: Proto-board Buck converter efficiency

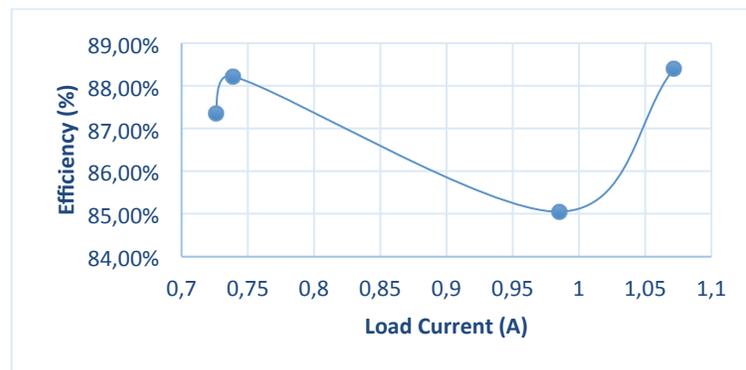


Figure 3: PCB Buck converter efficiency

b) Tracking Module

The sun tracking module accurately tracks the best position with the maximum amount of light with an accuracy of +/- 3 degrees. The micro-controller was finally able to receive the analog voltage from both the sensors network and using its A/D, provide the necessary output. It reads the analog voltages from all 8 sensors around the umbrella, converts these voltages from analog to digital, compares the obtained values, outputs the correct signal to rotate the umbrella, and finally stays in that positions for a set time depending on which sensor is reading the highest. The motor is able to rotate the umbrella based on the signal output from the micro-controller clockwise or anti-clockwise.

c) Lighting Module

Finally, the user has the possibility of adapting the intensity of the LEDs through a potentiometer. The potentiometer adjusts the PWM's duty cycle accordingly in order to provide the needed output voltage to the LEDs so that different intensities of light are generated. The duty cycle and the frequency may be precisely set by the ratio of the R1 and the resistance from the potentiometer.

4. Conclusions

This project has met all requirements initially set out at the beginning of the semester, only missing the incorporation in the final demonstration, of a standalone microcontroller.

Future work for this project involves refining the design and physical components. The first step would be to build the dimmer circuit on a Printed Circuit Board in order to improve the efficiency of this module. Furthermore, the Buck Converter PCB should be redesigned, since there are still some wires reducing its efficiency. In addition to this, an accurate control for the tracking module should be designed in order to reach to the exact position and absorb the greatest amount of energy possible. Lastly, the project as a whole should be tested for an extended period of time and implemented on an actual sized patio umbrella with all of the components mounted on, to ultimately test its long-term efficiency in realistic settings.

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1. Introduction

1.1 Statement of Purpose

In recent years, electricity prices have skyrocketed and will continue to increase in the future. What better way to save money than to use solar energy? In addition to financial benefits, the use of renewable energy, in particular, solar energy will benefit our environment. Nowadays, the majority of the world depends on electricity supply generated from fossil fuels. These means of electrical production have raised growing environmental concerns over the climate change risks. It is time to make a change and Go Green!

The goal of this project is to develop a solar powered patio umbrella that has a multitude of features that include USB ports in order to charge an electronic device, LED lighting system, and a solar tracking system for optimal power generation. This product is powered entirely on solar energy.

1.2 State of the Art

Solar technologies have evolved substantially in the last decades. While previously solar photovoltaic was seen as a thing of the future, nowadays, technological findings have located the solar industry for huge growth. Furthermore, latest advances have helped to become solar energy as one of the cheapest ways of obtaining power ^[19].

Both improving the efficiency and the cost-effectiveness of solar cells has always been the main purpose for scientists. A solar PV array includes thousands of solar cells, which individually convert the sunlight into electricity. The average efficiency of a solar cell is approximately 15%. Therefore, researchers have constantly been experimenting with new technologies to boost this light capture and conversion ^[19].

The majority of the solar panels are made of silicon, making up about 90% of the solar cell market. During the last years, several developing photovoltaic technologies have emerged. Dye-sensitized solar cells, organic photovoltaics, perovskite photovoltaics, and inorganic quantum dot solar cells are some examples of these emerging technologies. These new material solar cells

promise to be less expensive, thinner, more flexible, and amenable to a wide range of lighting conditions^[17].

An additional feature is included in this project is the sun tracking ability. This feature, which has several benefits, is quickly rising in popularity. Stationary solar panels, which are in a fixed position, can reduce their productivity when the sun is not located at an optimal position. Solar trackers maximize their output, automatically moving to “track” the sun among the sky. Solar panels that include a tracking ability generate more electricity since the direct exposure to the sun is being increased. There are different kind of solar trackers, such as single-axis and dual-axis trackers. This solar patio umbrella includes a single-axis solar tracker.

Currently, there are several umbrellas that use the sun energy to light up the area just below its roof or charge an electronic device, however there is not a single complete system that includes these two features and also tracks the sun in order to create the biggest shadow possible. In addition, as mentioned above, solar energy is a developing energy and in a near future its use will be much more common since the latest discoveries is reducing its cost and increasing its efficiency. The key takeaway is that this product is an economical alternative and competes in a market with numerous customers and few competing products. No product yet has been made that is as complete as this umbrella.

1.3 Objectives

1.3.1 Features

Unlike other commercially available solar powered umbrellas, this patio umbrella will include several other features as discussed below:

- 1- Maximum power point tracking (MPPT) built in
- 2- LED lighting system
- 3- USB ports
- 4- Sun tracking ability

1.3.2 Benefits

- 1- Save the environment by using renewable energy
- 2- Save money
- 3- Charge devices anytime using the USB hub
- 4- Optimize solar power using the sun tracking capability
- 5- Lighting system that is controllable through a dimmer
- 6- Optimize the charging capabilities for the battery by using an MPPT control

2. Design

This design is composed of two modules working together, as illustrated in Figure 1. The power module supplies the power to the execution module, which is further divided into sub-module. The sub-modules implement the features of the Solar Patio Umbrella.

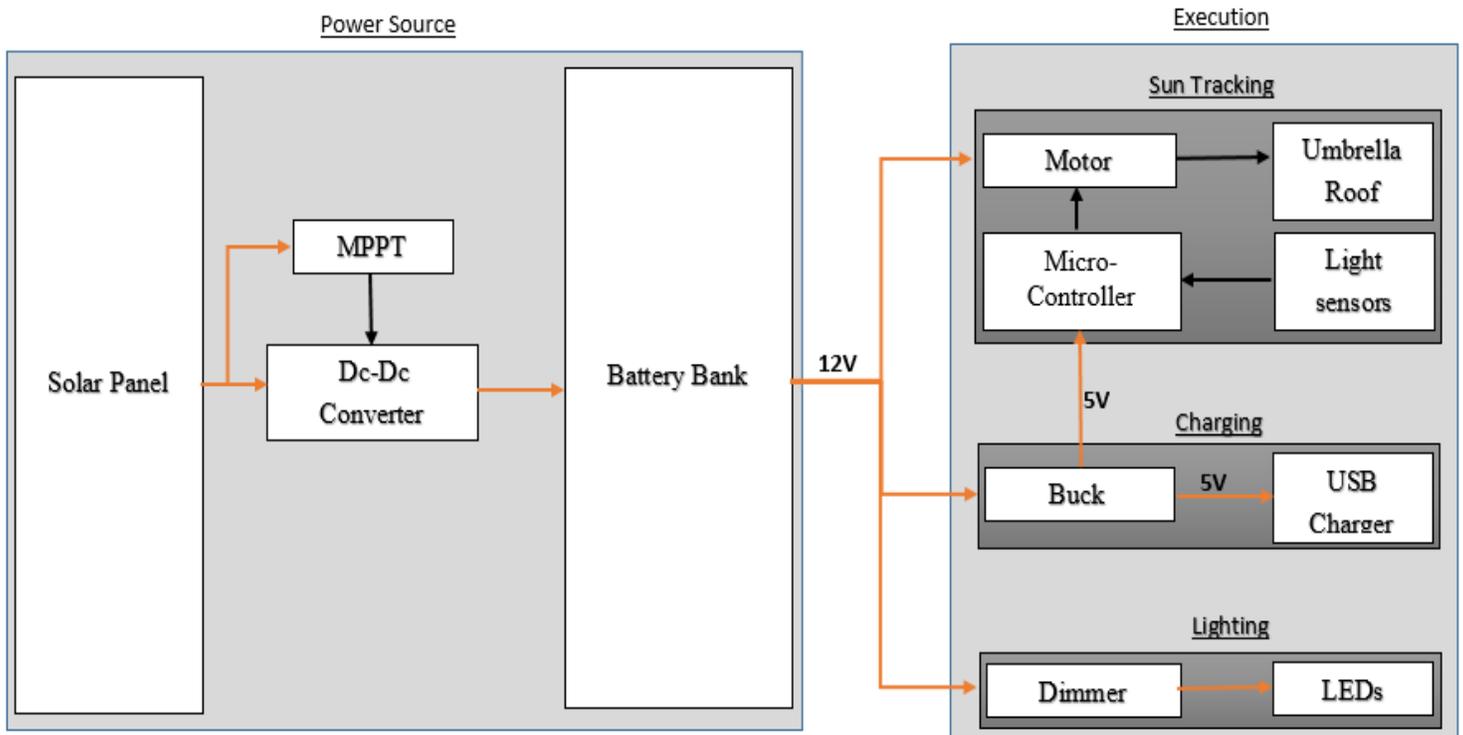
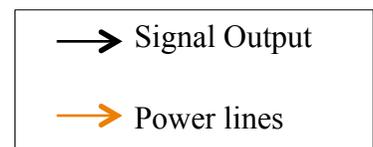


Figure 1: Modular Block Diagram



2.1 Power Module

The purpose of this module is to absorb the sun's energy through a solar panel and efficiently convert that energy into electrical energy, using a maximum power point tracker (MPPT) controller, which charges the battery bank.

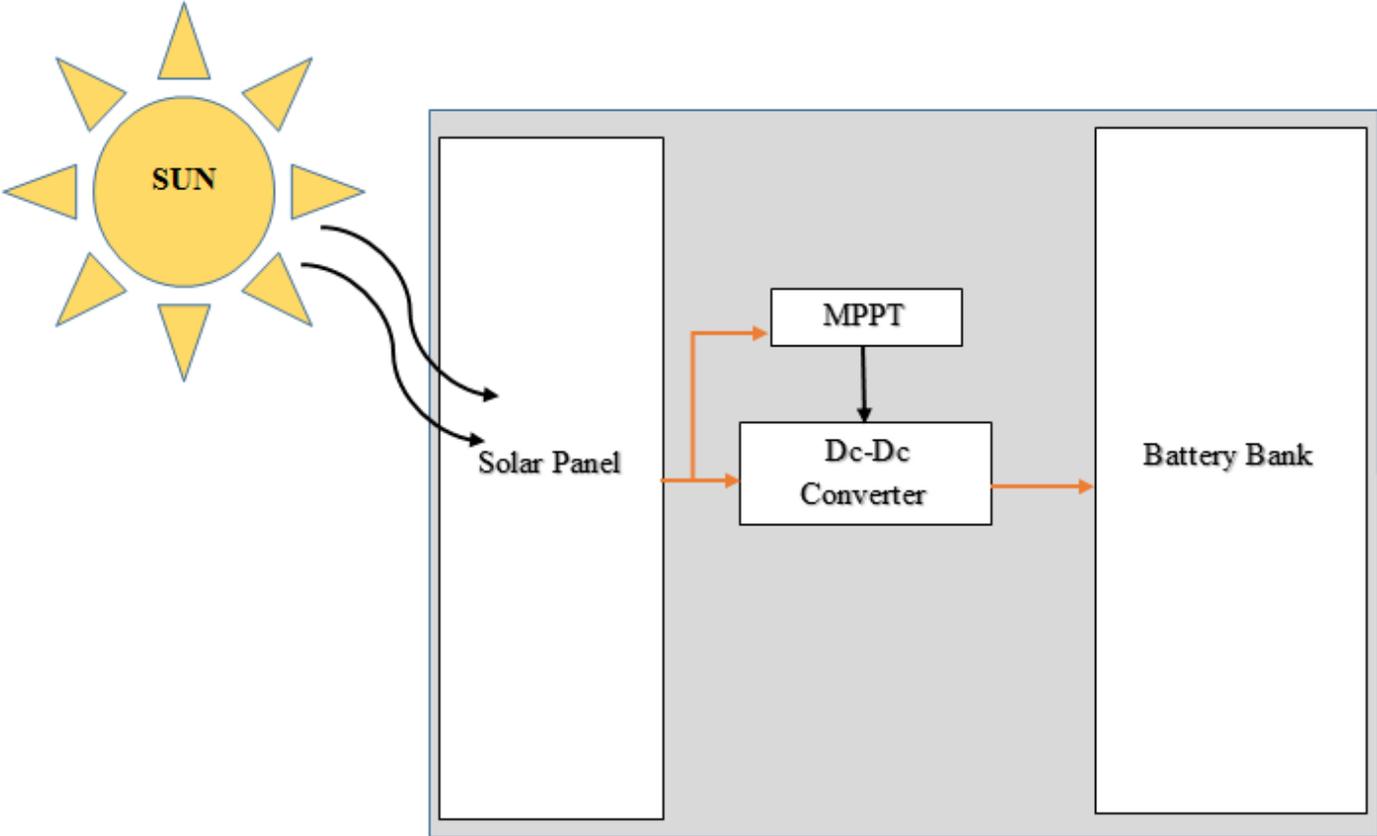
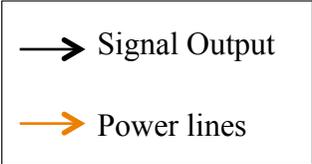


Figure 2: Power Module Block Diagram



2.1.1 Solar Panel

The Solar Panels are designed to absorb the sun's rays as a source of energy for generating electricity. This design makes use of one solar panel where it outputs 22V and 610mA to the MPPT controller. It is mounted on the roof of the umbrella. Its measures are 280mm*350mm*20mm.

2.1.2 MPPT

An MPPT, or maximum power point tracker, is an electronic DC-DC converter that optimizes the match between the PV panels and the battery bank. The controller looks at the output of the solar panel and compares it to the battery voltage. The controller then figures out what is the best power that the panel can output to charge the battery. Then it converts the higher voltage from the solar panel down to the lower voltage needed to charge the battery, in this case this voltage is 14.5V - 14.9V (Cycle Use Voltage).^[8]

The power point tracker works in a way in which it takes the DC input from the solar panels, inverts it to a high frequency AC and then converts it back to a different DC voltage and current that the battery needs for it to be optimized^[8]. The MPPT controller looks for maximum power point and then does the voltage/current conversion to change it to what the battery needs to charge.

The curve showed below in Figure 3 shows the PV module voltage vs the PV module power. The sharp peak to the right represents the maximum power point. The MPPT controller looks for this point and then does the voltage/current conversion to change it to what the battery needs to charge. An MPPT device typically provides a 20 to 45% power gain in winter and 10-15% in summer. This gain can vary widely depending on weather, temperature, battery state of charge, and other factors.^[11]

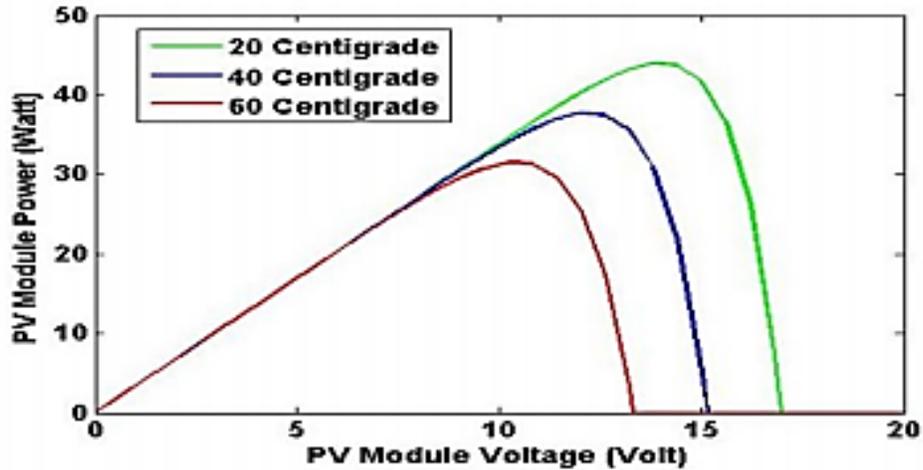


Figure 3: Power vs Voltage Curve for Solar Panel

A Genasun GV-5-PB-12V, 5A MPPT controller is used in this design. The Genasun has a peak efficiency from 96% to 99.85% with a built in DC-DC converter that stepped down the voltage to charge the battery and a smart controller for battery voltage monitoring. The specifications of the MPPT is given in Appendix F.

2.1.3 Battery Bank

The function of this device is initially designed to store up to 22Ah of energy that it receives from the MPPT converter and distributes 12V and up to 45W of power to the other devices within the system. However, finally a 12V 7Ah lead-acid battery is used for this design due to its availability.

2.1.4 Power Module Simulations

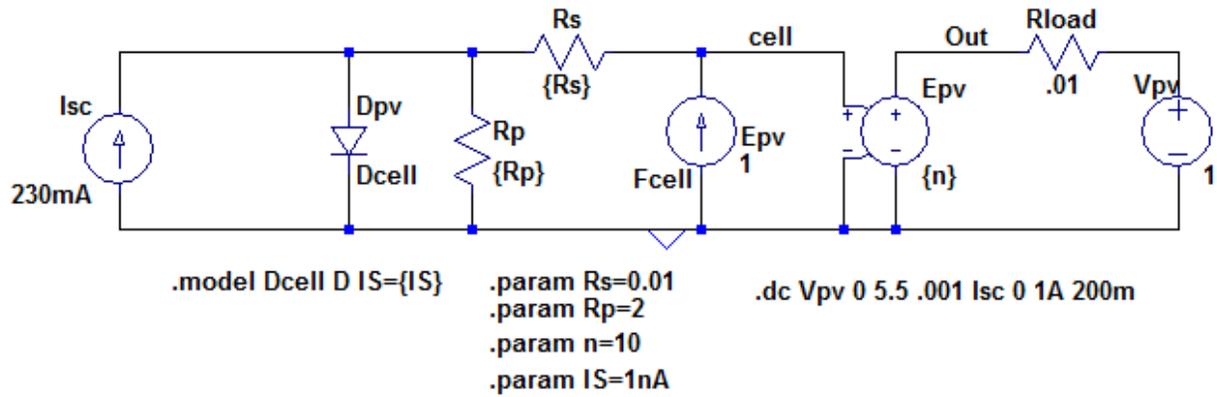


Figure 4: Ideal Model for PV System

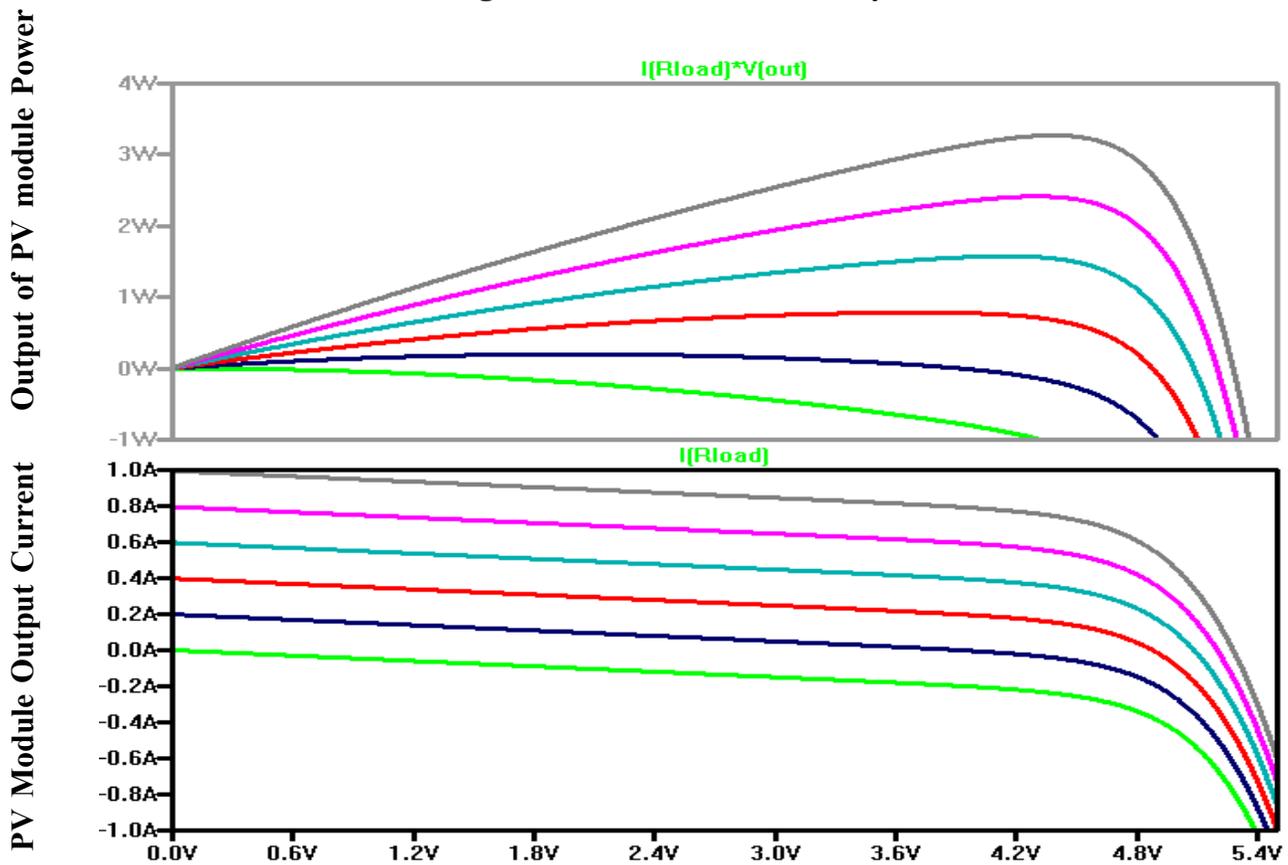


Figure 5: PV Output from Simulation. Output Power Curve on the Top and IV Curve on the Bottom

2.1.5 Power Module Results

Table 1: Power Module Results

Time	Luminous emittance (lx)	Solar Panel Output Voltage (V)	MPPT Output Voltage (V)	Current (A)	Power (W)
5min	35000	14,3	14,6	2,5	36,5
10 min	26600	14,14	14,6	2,4	35,04
15 min	26100	14,1	14,6	2,4	35,04
20 min	40000	14,53	14,7	2,6	38,22
25 min	45000	14,7	14,7	2,7	39,69
30 min	60000	16	14,8	3	44,4
35 min	70000	19	14,8	3,2	47,36
40 min	73000	19,8	14,8	3,3	48,84
Average	46962,5	15,82	14,7	2,76	40,64

Table 2: Consumption Results

	Voltage (V)	Current (A)	Power (W)
Dimming Module	13,2	0,8	9,6
Charging Module	13,2	2,2	6
Tracking Module	5	1	5
Total	-	4	20,6

Basing on the data recovered, showed on table 1, it is estimated that the time spent to totally charge the battery used is 2.5 hours +/- 0.5 hours. Furthermore, basing on the consumption data, table 2, it is approximated that the battery is able to power the whole circuit during 4.5 hours +/- 0.5 hours.

2.2 Charging Module

This module provides the user the ability to charge various devices through a USB port. In order to accomplish this, a buck converter was constructed such that it steps down the voltage from 12V, which is supplied from the battery box to 5V, which is needed to power up the USB charger. The implementation of the buck converter is displayed in Figure 6. The buck converter works such that when the switch is turned on, energy is transferred directly from the input to the output and the diode operates as a reverse biased element preventing the current to flow through it. Sequentially, when the switch is open, the energy stored in the inductor creates a current that needs to find a path to flow causing the diode to turn on. The duty cycle for this component determines the voltage obtained at the output as described in Equation 1. The buck converter has two operating modes, discontinuous conduction mode (DCM) and Continuous conduction mode (CCM). In this project, the design is focused on CCM. CCM produces a continuous current pulse. ^[5] Refer to Figure 8 for circuit layout.

2.2.1 Charging Module Calculations

All calculations for simulation purposes are made under the assumption that it is an ideal buck converter. However, for the actual circuit design that is implemented, it is assumed an approximately 90% efficiency will be achieved; hence, the calculations below have been adjusted accordingly.

In order to design the charging module's buck converter, we first begin by considering a various range of operating frequency. The switching frequency is inversely proportional to the converter efficiency, since a higher switching frequency translates to higher switching loss. However, switching frequency is also directly proportional to the component sizes such as the inductor and the capacitors at the input and output. With this factor in mind and the fact that the components need to be small such that this charger may be portable, it is decided to switch at the frequency shown below:

$$f_{sw} = 200 \text{ kHz}$$

In order to charge the phone, the converter should be able to give out the following outputs displayed below, where the cellphone (load) is represented as a 5Ω resistor load.

$$P_{in} = 5 \text{ W} \quad P_{out} = 5 \text{ W}$$

$$V_{in} = 12 \text{ V} \quad V_{out} = 5 \text{ V}$$

$$I_{in} = 0.417 \text{ A} \quad I_{out} = 1 \text{ A}$$

$$R_{Load} = 5 \Omega$$

Initially, it is needed to determine the component sizes of the buck converter. To do this, it is determined the duty ratio for the desired output voltage. Because the average inductor voltage has to be equal to zero, the volt-second balance to the inductor voltage is applied to obtain equation 1 below.

$$D = \frac{V_{out}}{\eta * V_{in}} = \frac{5}{12 * 0.9} * 100 = 46.3\% \quad (1)$$

Next, it is needed to determine the critical inductor; it is obtained the value of the inductor during boundary between CCM and DCM.

$$L_{crit} = \frac{R_{load} T (1-D)}{2} = 6.7 \mu H \quad (2)$$

$$\langle i_L \rangle = 1 \text{ A} = \frac{1}{2} i_{peak} \Rightarrow i_{peak} = \Delta i_{Lpp} = 2 \text{ A} \quad (MAX) \quad (3)$$

With this minimum value for the inductor and assuming that the output current ripple would be kept at +/- 200mA or less, it can be obtained an approximate inductor size of as it is the inductor that determines the output current ripple:

$$L = \frac{V_{out} * (V_{in} - V_{out})}{\Delta I_L * f_s * V_{in}} = \frac{5 * (12 - 5)}{.2 \text{ A} * (200 * 10^3) * 12} = 73 \mu H \quad (4)$$

The next step is to determine the input capacitance of the buck converter. Assuming an input voltage ripple of 1% of input voltage, it is obtained:

$$C_{in} = \frac{D_{max} * I_{out}}{\Delta V_{in} * f_{sw}} \quad (5)$$

$$C_{in} = \frac{.463 * 1}{.12 * 200 * 10^3} = 19.3 \mu F$$

For calculating, C_{out} it is assumed that $\langle i_c \rangle = 0$, so all the ripple voltage will go into the capacitor. Then, $\Delta V_{c_{pp}}$ is calculated without knowing the exact shape. Assuming a voltage capacitor ripple of 1%, it is obtained:

$$0.05 V = \Delta V_{c_{pp}} = \frac{\Delta i_{L_{pp}}}{8 C_{out} f_{sw}} \Rightarrow C_{out} = \frac{\Delta i_{L_{pp}}}{8 \Delta V_{c_{pp}} f_{sw}} = 25 \mu F \quad (6)$$

As previously stated, the above calculations are made under the assumption that 90% efficiency will be achieved. This estimation is made because the buck converter is not ideal because of the losses in its components such as the MOSFET, Power Diode and the Switching Losses. One particular component is the capacitor in the converter, more precisely the output capacitor. As a result, it is added a resistor in series commonly referred to as Equivalent Series Resistance (ESR) to the output capacitor because this ESR determined the ripple in the output voltage. The ESR for the input capacitor is not computed, as it is not very impactful. Looking at the datasheet, it is obtained the loss tangent based on the chosen frequency and output voltage to determine the ESR as follows:

$$ESR = \frac{\tan \delta}{C_{out} \omega} = 0.6 \Omega \quad (7)$$

2.2.2 Charging Module Schematic and Simulations

Charging Module Schematics

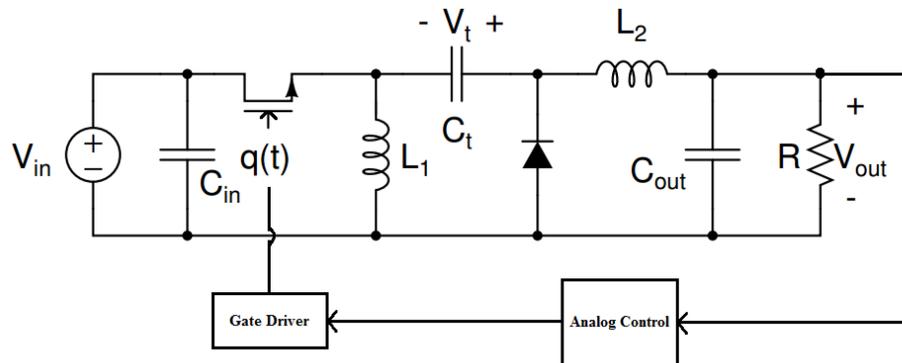


Figure 6: Top Level Schematic of a Buck Converter

Typical Connection

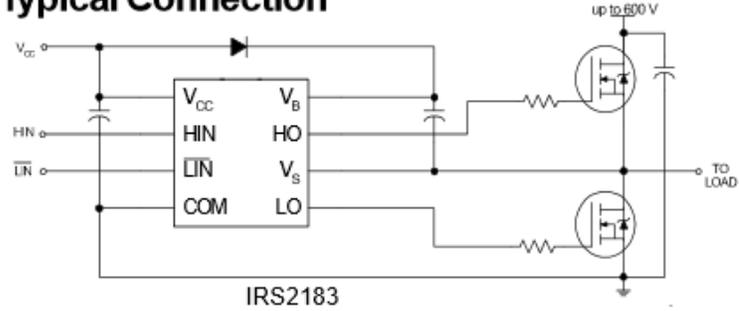


Figure 7: Typical Connection of a High Side Gate Driver

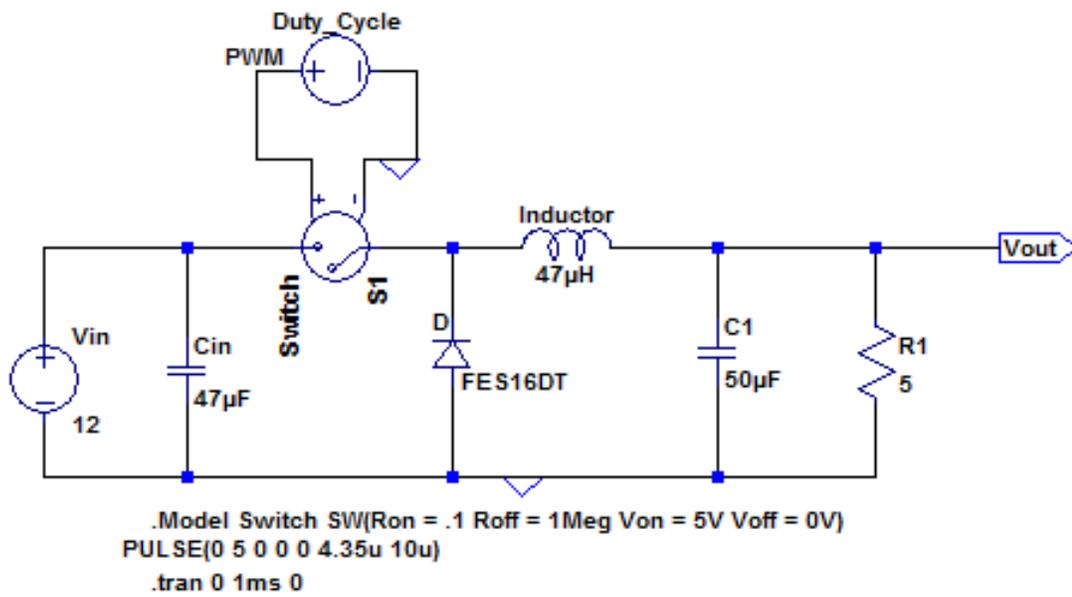


Figure 8: Buck Converter Circuit Design for CCM Operation

Charging Module Simulations

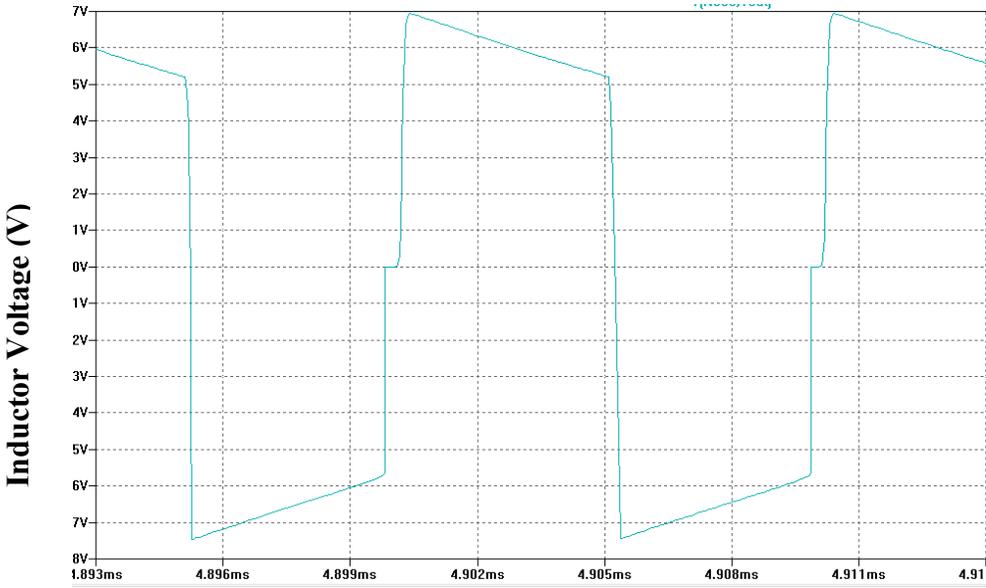


Figure 9: Simulation of Inductor voltage at DCM-CCM Boundary Vs. Time

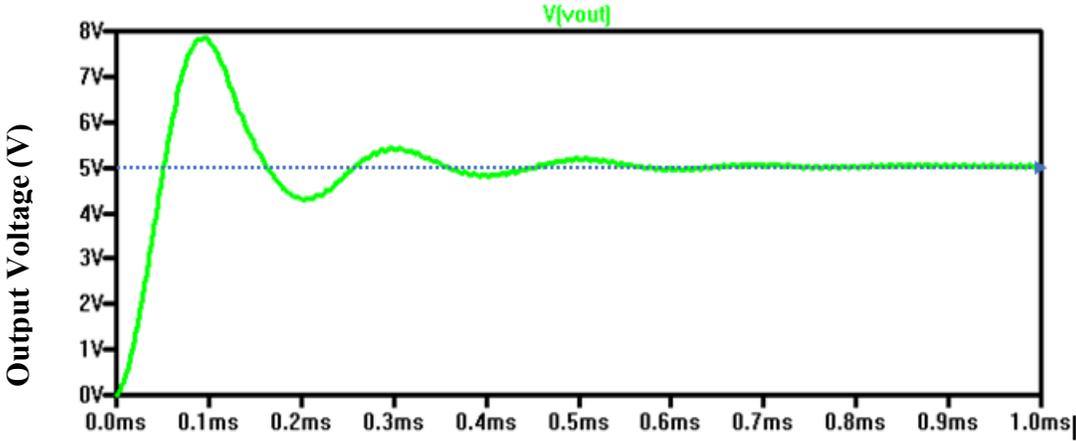


Figure 10: Output Voltage of Buck Converter vs. Time

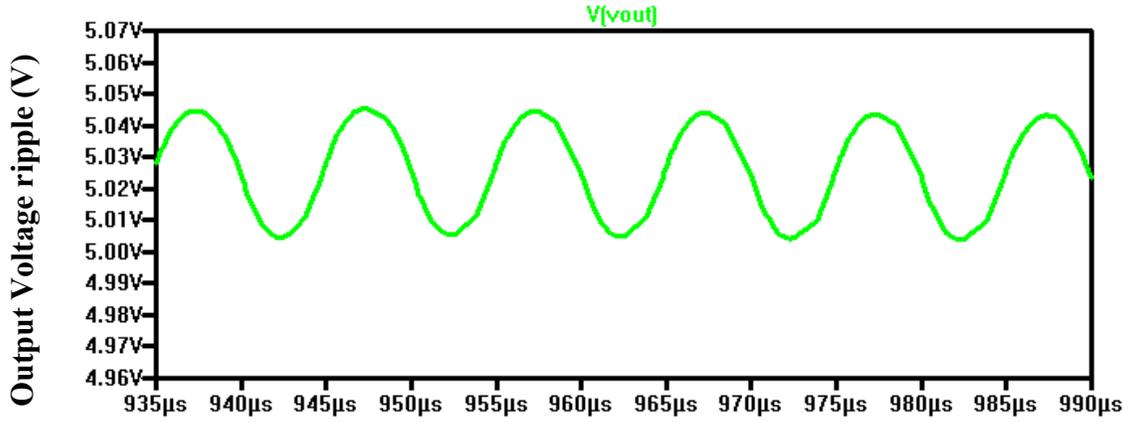


Figure 11: Output Voltage Ripple (< 50 mVrms) Vs. Time

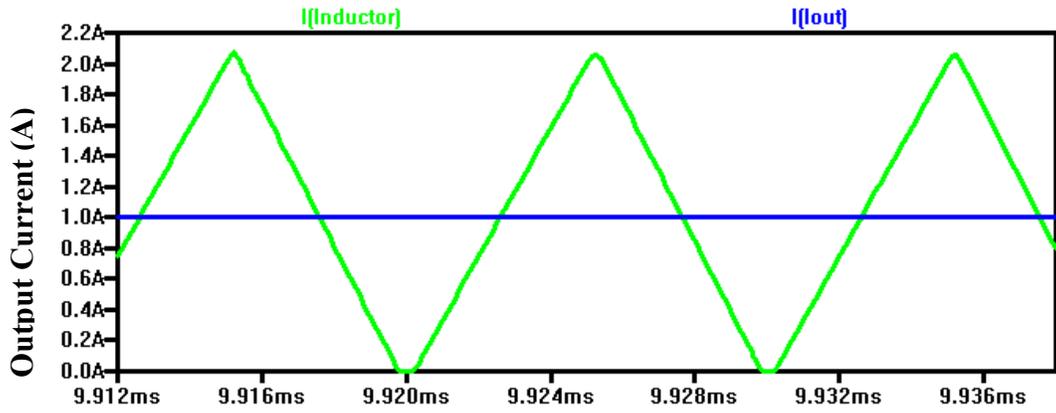


Figure 12: Output Inductor Current at CCM, DCM Boundary Vs. Time

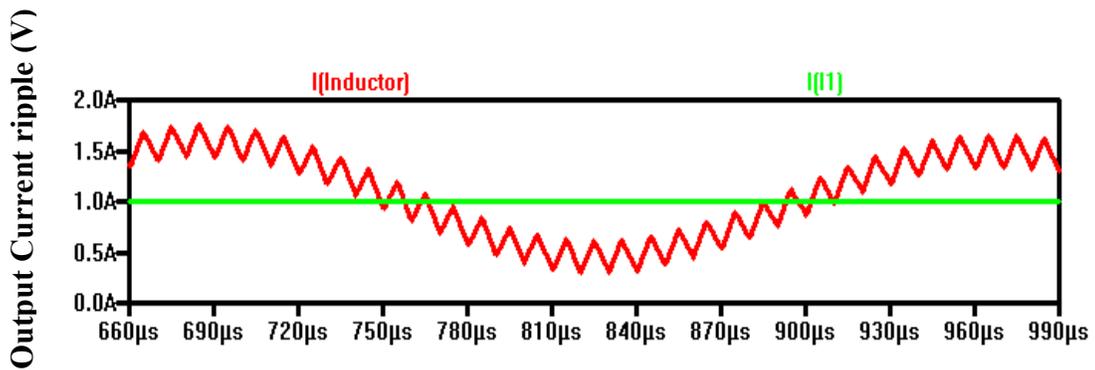


Figure 13: Output inductor current in CCM operation Vs. Time

2.2.3 Charging Module Parts

Finally, the components of the Buck Converter chosen for this design are:

- 1- Input Capacitor: A $47\mu\text{F}$ capacitor is placed in order to filter out the input voltage ripple from the battery bank. ^[13]
- 2- FET: A power MOSFET IRF520N is used due to its fast switching cycle and ultra-low on resistance ($.27\Omega$), since because this helps to reduce the switching losses and improve the efficiency.
- 3- Schottky Power Diode: In order to reduce losses in the diode when the switch is off, a Schottky diode MBRB1045 is added due to the fact that they have a small voltage drop across them. The diode is used to block the current when the MOSFET is conducting and provide an inductor current path when the MOSFET is not conducting. ^[12]
- 4- Inductor: Based on the calculations of the buck converter, it is determined that the minimum value of the inductor needed in order to keep the buck converter from operating in DCM was approximately $6.7\ \mu\text{H}$. The inductor is the key element in determining the boundary between DCM and CCM operation since it controls the output current. Therefore, in order to avoid having the core from saturating and to reduce the output current ripple, a larger inductor of $690\ \mu\text{H}$ is used instead.
- 5- Output Capacitor: A $47\mu\text{F}$ electrolytic capacitor is used in this design. The initial choice for the output capacitor is a parallel network of five ceramic capacitors because they have a low equivalent series resistance (ESR). Hence, this would reduce the output voltage ripple ($< 50\ \text{mVrms}$), therefore protecting the device being charged.
- 6- Micro-controller: A TI-MSP430 is used in the project in order to generate the system's PWM and P-Control for the buck converter to both lowers the duty cycle if the output voltage is higher than $5.25\ \text{V}$ or increase the duty cycle if the output voltage is lower than $4.75\ \text{V}$
- 7- Voltage Regulator: The LM337 voltage regulator is used to power the micro-controller on board.

2.2.4 Charging Module Results

With this design, it is able to accomplish $5V \pm .05V$ output and current output up to 1A. However, this is not enough to allow the phone to charge, as today's smartphones have to perform "network" checks to make sure that the device feeding it the voltage and current is truly a charge (See Figure 14). In order to overcome this, it is implemented the "Dedicated Charger" network, which works fine for android smartphone; however, this is rejected by the IOs devices. Then it is implemented the "Apple Charger" network check, optimized for 1A, and with this design, this module is able to charge both the android and IOs devices.

Shown below is the charging port circuit used in the design.

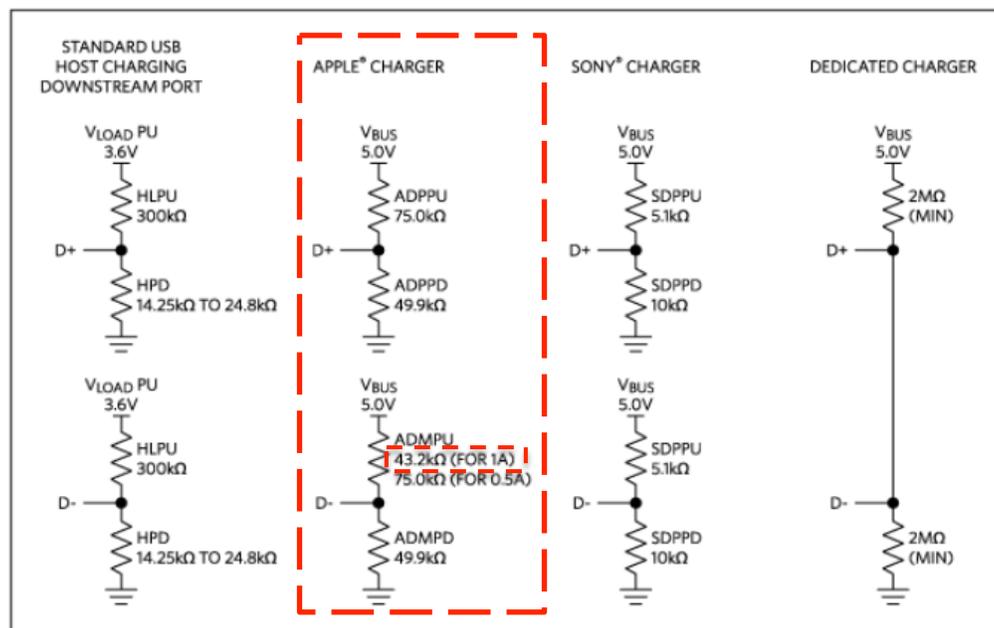


Figure 14: Dedicated charging ports for various manufacturers

The first iteration of the converter is first designed on the proto-board and the result of this is shown in Figure 15. In order to test the points of operations, it is used one of the provided electronic loads to apply various load current and see how the converter's efficiency and output current ripple changed. The results of this experiment are shown in Table 3. As previously stated, the desired output current is $5V \pm .25V$ and $1A \pm 200mA$, hence the highlighted points in the table shows the operating region. The output ripple current is kept well within the desire range, this means that the inductor of choice is large enough; however, one thing to note right away is

the output voltage which is way out of the desired range. In order to deal with this drop in voltage a control circuitry is implemented, which adjusted the duty cycle as needed, in order to maintain a certain range of voltage for the output load (See control flow Chart). The circuit on the proto-board is fully functional; however, by looking at Figure 16 and Table 3, one can quickly notice that the implementation of the converter on the board is not very efficient.

Table 3: Buck converter (on Proto-board) operation for various load currents

V _{in} (V)	I _{in} (A)	V _{out} (V)	I _{out} (A)	I _{out} ripple (mA)	P _{in} (W)	P _{out} (W)	η (%)
12.00	0.066	4.97	0.13	-	0.79	0.627	79%
12.01	0.240	4.57	0.50	42.75	2.88	2.260	78%
12.03	0.390	4.10	0.80	49.00	4.69	3.284	70%
12.04	0.490	3.94	1.00	120.00	5.90	3.940	67%
12.04	0.580	3.71	1.20	160.00	6.98	4.447	64%
12.04	0.730	3.30	1.50	236.30	8.79	4.950	56%

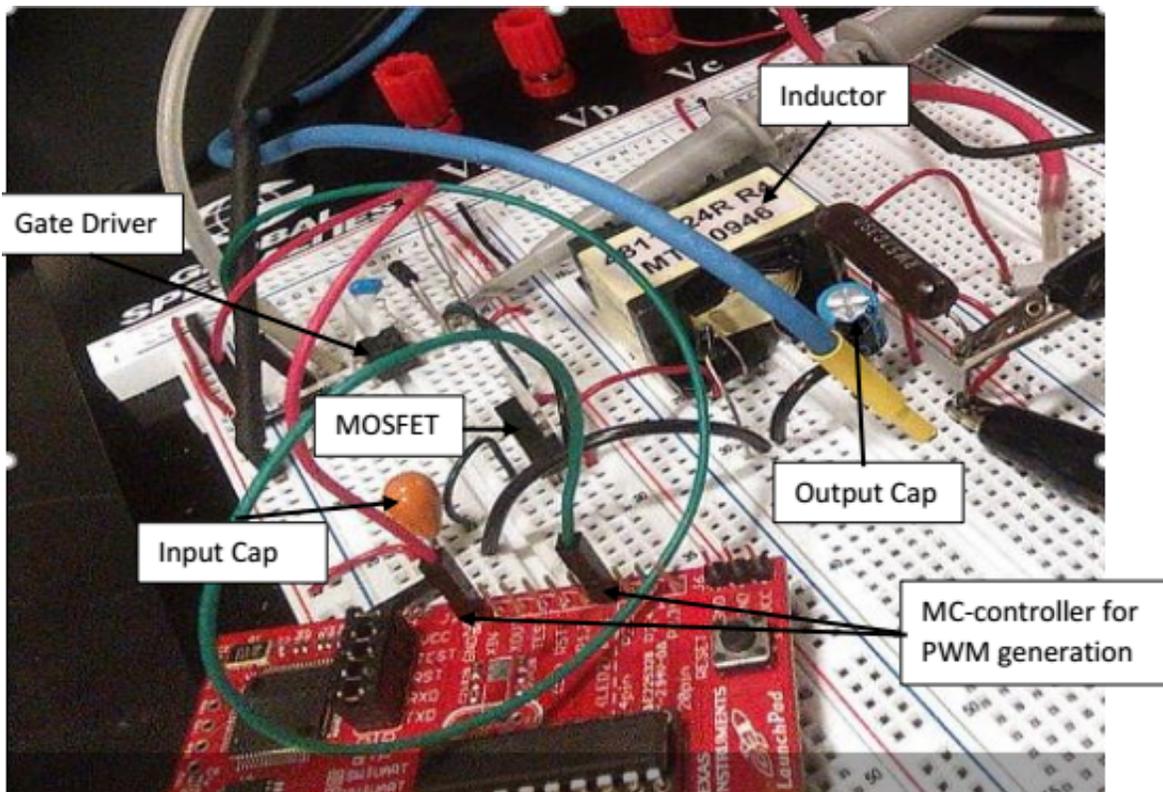


Figure 15: Fully Functional Buck Converter built on a proto-board

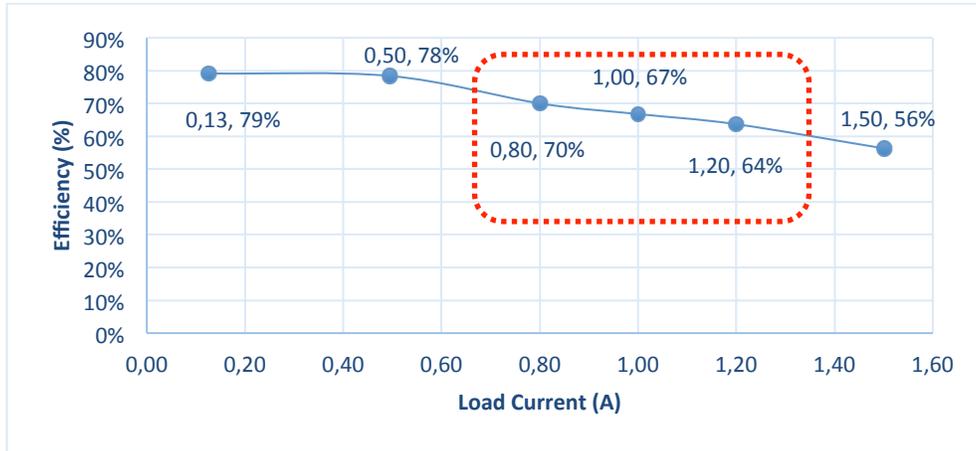


Figure 16: Buck converter efficiency

As it can be seen from both Table 3 and Figure 16, the efficiency of the buck converter decreases quite a bit with the change in load current being drawn. Therefore, it is needed to provide a limit inside control such that if too much current is being drawn then the system will shut off or reset (See Equation 3). One way to detect this surge in current demand is to monitor the output voltage. As shown in table 3, the larger the current demand, the lower the output voltage that means a higher duty cycle was needed in order to raise the output voltage. However, if the duty cycle raises all the way to nearly 100% this would run the risk of damaging the system. A snippet of the flowchart for the PWM control, the code for the PWM generation as well as the control circuitry are shown in Figure 17.

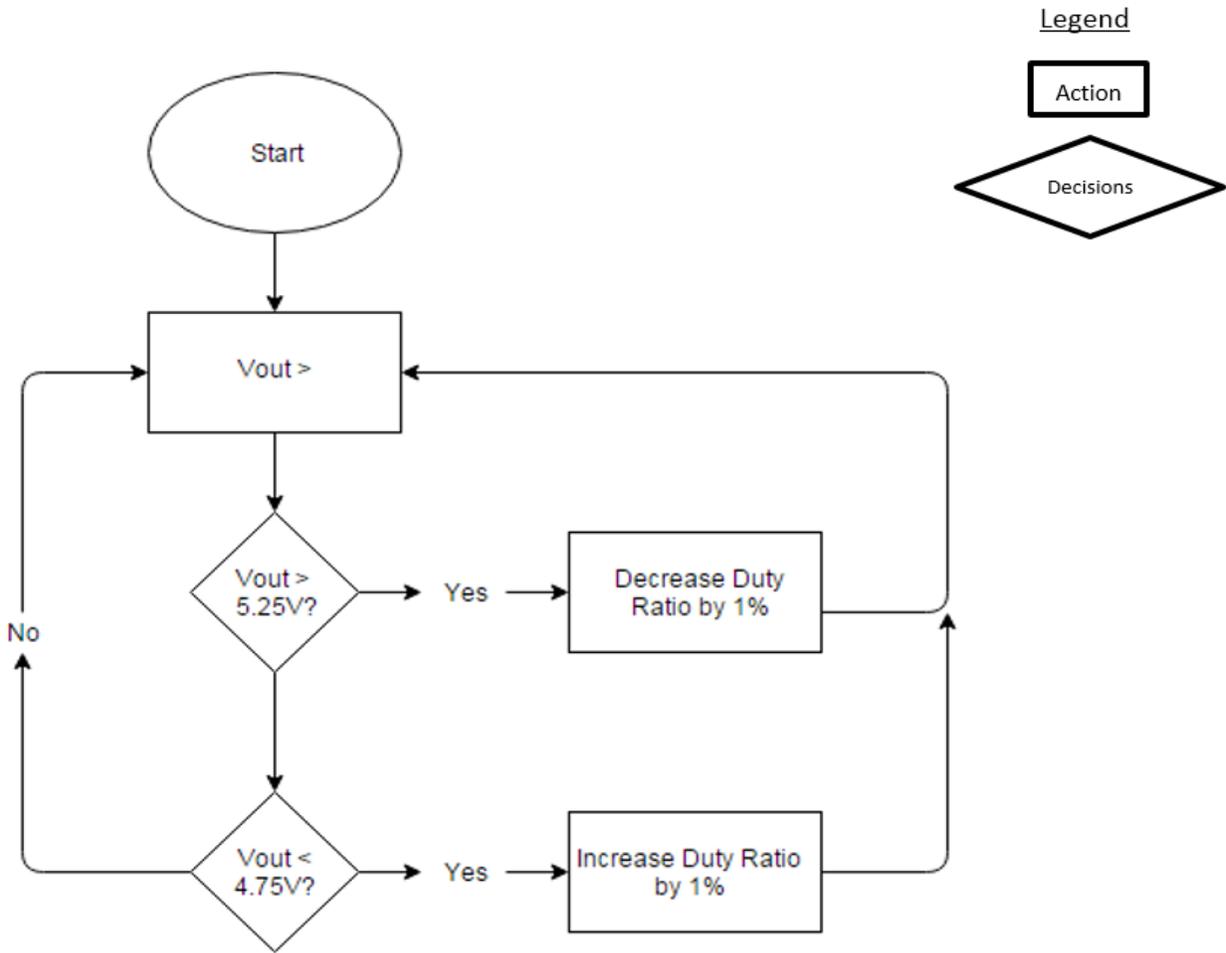


Figure 17: Flow Chart for Buck Converter P-Control

In addition, in order to improve the system's efficiency, it is figured that it will be imperative that moving the system from proto-board to a PCB, as this would greatly reduce parasitic in the wires and hence improving the overall system's efficiency. The circuit for the PCB layout is shown in Figure 18.

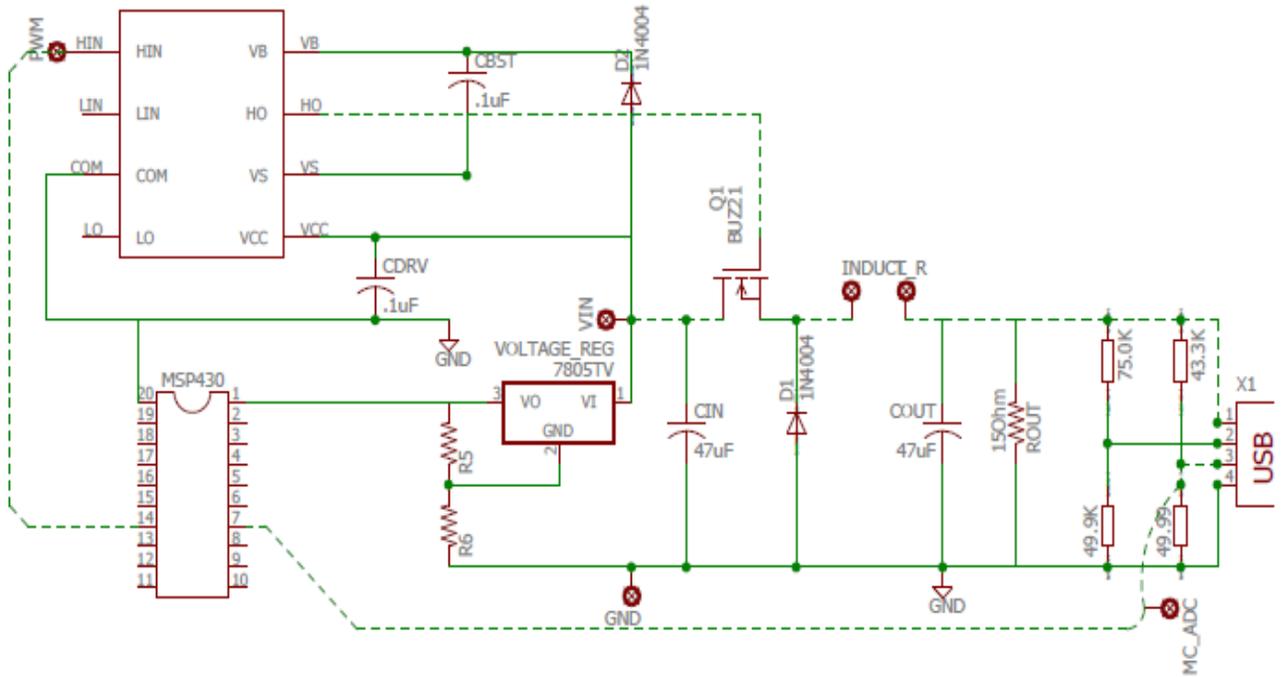


Figure 18: Charging circuit

This PCB shows all the components of the buck converter working as one close loop circuit. First, the Micro-controller is programmed to output a PWM of frequency 200 kHz and a duty cycle of 47%. This information is then communicated to the gate driver, which controls the switching cycle of the converter's MOSFET [2]. If 12V is applied at the input of the converter, then an expected output of 5V should be read at the load side. However, if the output falls outside the required range, then the micro-controller's A/D read this and adjust the PWM accordingly.

Based on the buck converter values and the requirements for building a PCB, it is looked for the appropriate elements on Mouser Electronics website [1], it is additionally used another website, Digi-Key Electronics [3], to find other items such as the gate driver or resistors. After analyzing the maximum current that will go through the buck converter, it is chosen a trace width of 30 mm since it will be running about 2 to 3 A in the circuit.

Once the converter is ready on the PCB, the testing begins. One thing that is quickly noticed is that 15-30 sec after the load was connected to the converter; the output current ramped up to a new steady state output current and each time this value changed. The reason for this occurrence is that it takes the phone about 15-30 second to establish how much current it needs to draw in

order to optimally charge. The lower the phone's battery level, the more current it needs to draw. This effect is best shown in video; however, it is attempted to show this by looking the waveform when no load is connected and when a load as been connected. See Figure 20 and Figure 21 showed below.

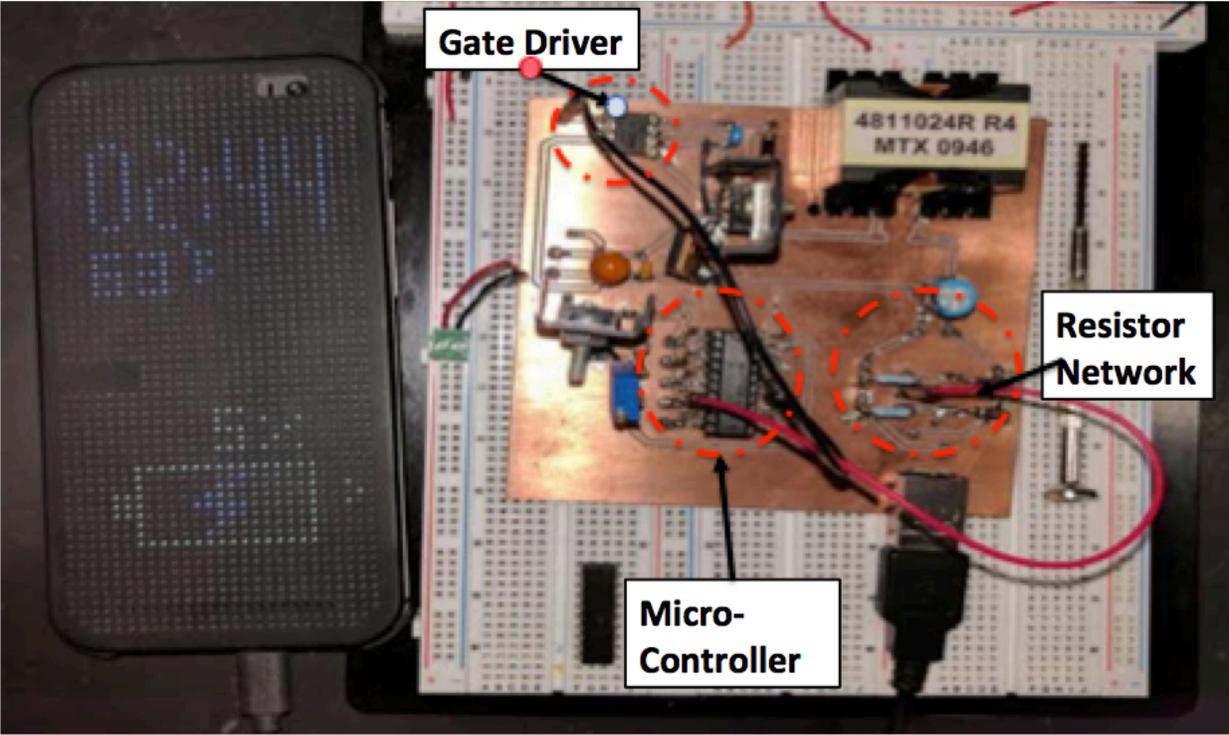


Figure 19: Buck Converter built on a PCB charging a Phone.

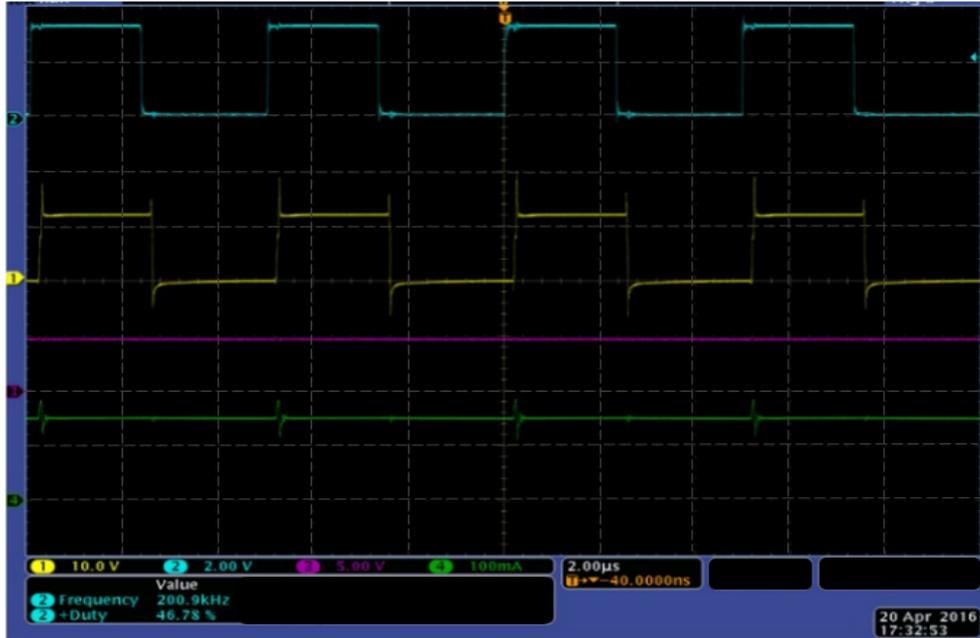


Figure 20: Converter Operation With load 20% battery life (12V input – 5V output). (From top to bottom – PWM output, Gate Driver Output, Output Voltage (4.98V), Input Current (495mA)).

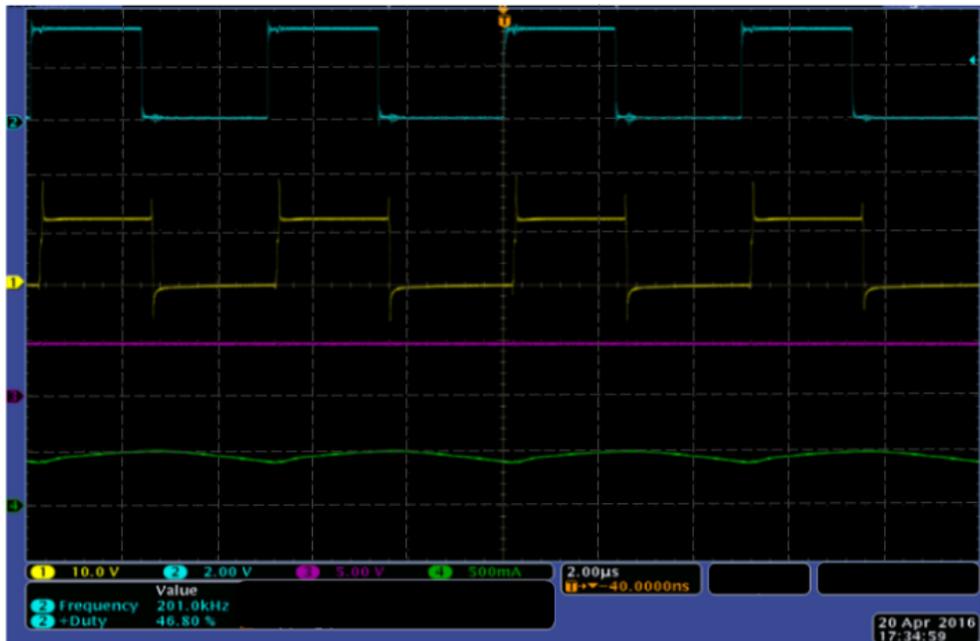


Figure 21: Converter Operation With no load (12V input – 5V output). (From top to bottom – PWM output, Gate Driver Output, Output Voltage (5.01V), Input Current (150mA))

Throughout the testing, it is also noticed that there is a significant improvement in efficiency of the converter once it is on the PCB, for both with load and without a load. These results are displayed in Table 4 and Table 5 as well as Figure 22 and Figure 23 respectively. Although the increase in efficiency of about 15-20% might seem strikingly impressive, it is not completely unexpected. The reduction in amount of wires connecting the components as well as the lengths of the component leads themselves significantly decrease the overall parasitic in the system. The result of these observations are shown in Figure 20, where it can be also notice that the duty cycle is about 46% as predicted before and the efficiency is about 90 percent (see Table 5).

Table 4: Buck converter operation with no load (on PCB)

Duty Cycle (%)	V _{in} (V)	I _{in} (A)	V _{out} (V)	I _{out} (A)	P _{in} (W)	P _{out} (W)	η (%)
45.60	12.00	0.11	5.27	0.25	1.36	1.31	96.31
46.00	12.00	0.12	5.11	0.27	1.48	1.37	92.57
46.00	12.00	0.16	5.03	0.34	1.88	1.72	91.16
47.00	12.01	0.16	5.16	0.34	1.92	1.75	91.32

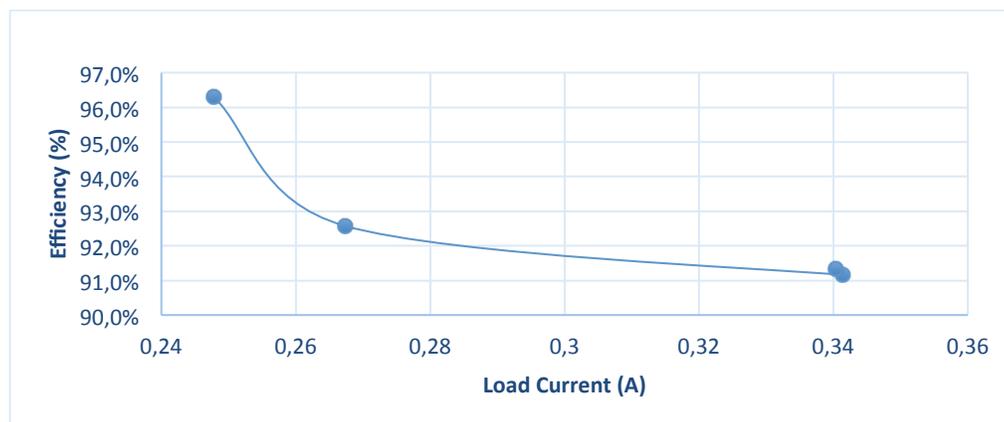


Figure 22: Buck converter efficiency with No Load

Table 5: Buck converter operation with load (on PCB)

Duty Cycle (%)	V _{in} (V)	I _{in} (A)	V _{out} (V)	I _{out} (A)	P _{in} (W)	P _{out} (W)	Efficiency (%)
45.60	12.00	0.33	4.78	0.73	3.97	3.47	87.35
49.00	12.01	0.36	5.19	0.74	4.35	3.84	88.23
46.50	12.01	0.46	4.75	0.98	5.50	4.68	85.05
46.00	12.00	0.49	4.88	1.07	5.92	5.23	88.41

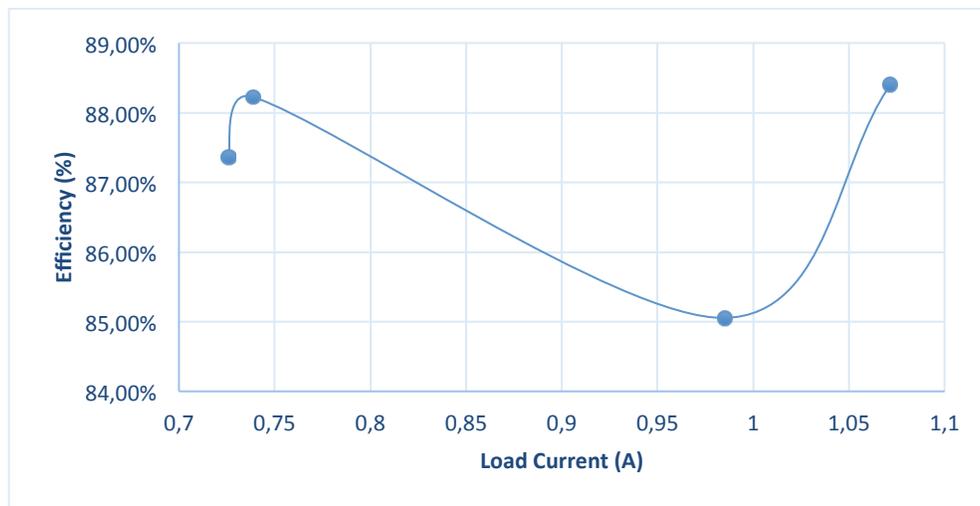


Figure 23: Buck converter efficiency with Load

Finally, looking at the output voltage ripple when the load is drawing about 1A. Figure 24 below shows this result and by looking at the measurements shown on the top right side of the figure, it can be observed that the peak-peak ripple was about 100mV. This is as expected considering the fact that the converter is designed for obtaining a peak ripple of about 50 mVrms.

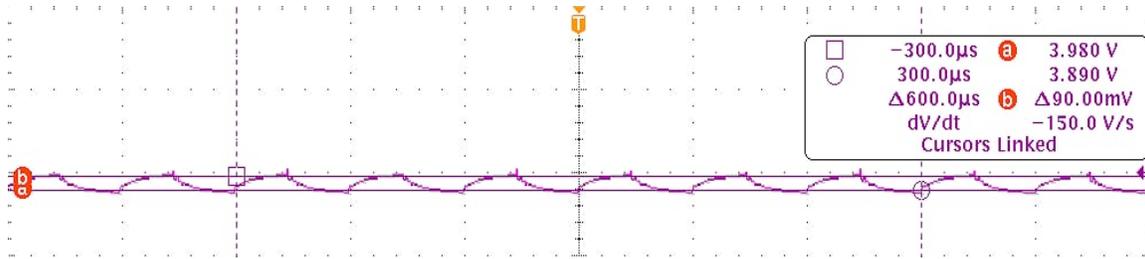


Figure 24: Output voltage ripple at 1A load current

2.3 Sun Tracking Module

The purpose of this module is to be able to track the sun and position the solar panel towards the most light at all times.

2.3.1 Light Dependent Resistors

The Light Dependent Resistors (LDRs) are used to keep track of the position on the umbrella that received the most light from the sun. This information is sent to the microcontroller which positioned the umbrella such that the solar panel on the roof of the umbrella is facing the sun.

LDR works in the way that when the light is shown on the resistor, the resistance of the sensor decreases, allowing current to pass through it. This drop in resistance is then communicated to the microcontroller, which in turns activates the motor to position the roof of the umbrella towards the sun. In this design, the LDRs are powered by the 5V and a reference resistor in series with the LDR. The voltage drop between the reference resistors is what is sent to the microcontroller's ADC. Refer to Figure 25 for LDR circuit setup.

The design includes 8 sensors in 8 different positions (labelled 1-8 in Figure 26). They are positioned 45° away from each other. The solar panel (Red box in Figure 26) is placed in front of sensor 1 which is designed to receive the most light at any given time. The flowchart for the design is shown in Figure 29.

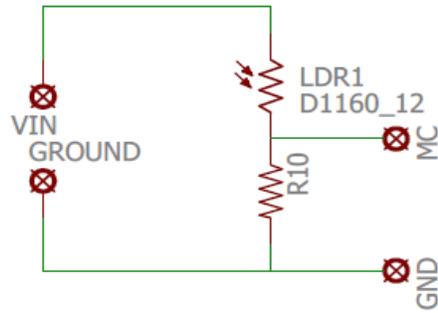


Figure 25: LDR circuit setup

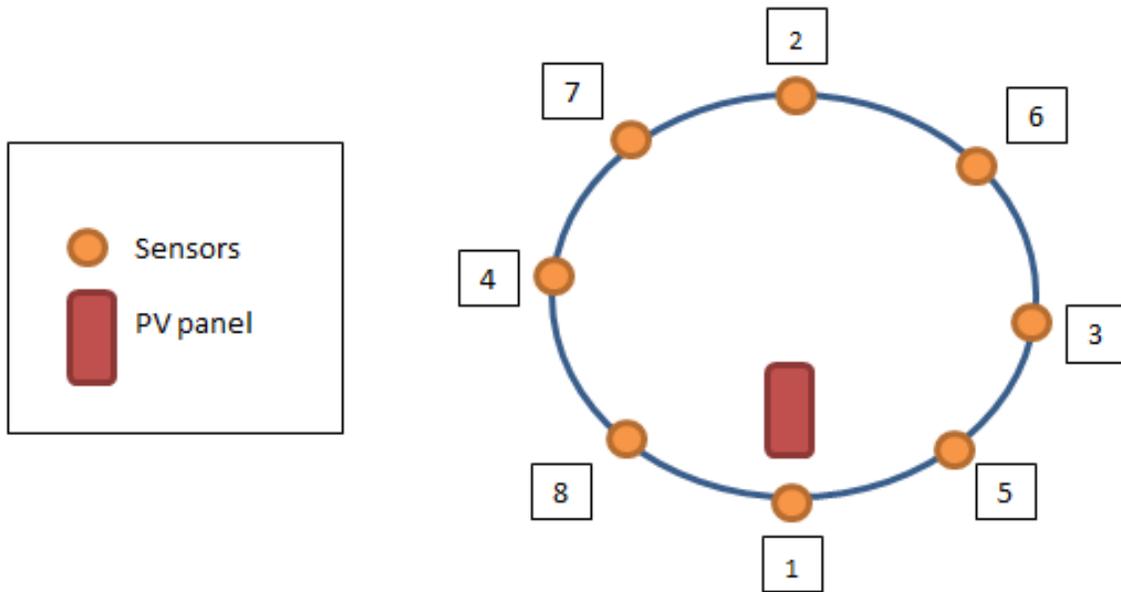


Figure 26: Sun Tracking Sensor Setup

The LDRs used in this design are Photo cell (CdS photoresistor) from adafruit. They had a dark room resistance (10 lux) of $10\text{k}\Omega$ and a maximum illuminated resistance at full daylight (10,000 lux) of 100Ω . The data of the LDR is given in Figure 27.

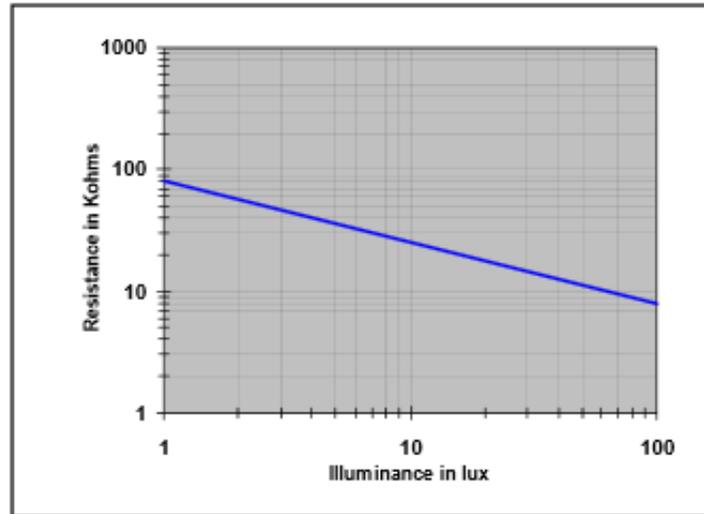


Figure 27: Characteristic Operation of the PDV-P8103 Showing the Cell Resistance Vs Illuminance ^[1]

2.3.2 Micro Controller

This design uses a TIMSP430 micro-controller, powered by the 5V Voltage regulator (LM7805) which dropped the battery's voltage to 5V to track the position that received the most light.

Each sensor is placed in series with a reference resistor as shown in Figure 25 to simulate a potentiometer like behavior. That is, the voltage across the LDR is compared to the voltage across the reference resistor. Since the LDRs resistance decreases as the intensity of light increased, the voltage drop across it decreases as well. If the voltage drop is at a certain voltage (2.5V in this design), the microcontroller compares the sensor to all other sensors and activates the motor if it is in fact receiving the most light. (See Figure 29 for flow chart).

2.3.3 Motor

The purpose for the motor is to move the roof of umbrella towards the sun in order to maximize solar radiation captured by the solar panel. The motor used for this design was a 5 W DC Motor.

As mentioned above, the main purpose in this case is positioning the umbrella such that the solar panel on the roof of the umbrella is facing the sun in order to capture the greatest amount of energy possible. This is achieved by using an open loop control, calculating the amount of time needed to change the position of the solar panel from the position 1 to any other position

determined in Figure 26. It uses a PWM signal sent by the microcontroller in order to control the motor speed.

The direction of rotation needs to be controlled, either clockwise or anti-clockwise, in order to reach the position where the sun is facing as fast as possible. An H-Bridge is used, similar to the one shown in Figures 28 and 28.1. It has four switching elements, and when these switches were turned on, in pairs, the motor changed its direction accordingly. If high side left and low side right are turned on, the motor rotates in forward direction, in this case, the current flow from the power supply through the motor coil to ground. Similarly, when you switch on low side left and high side right, the current flow in opposite direction and the motor rotates in backward direction ^[18].

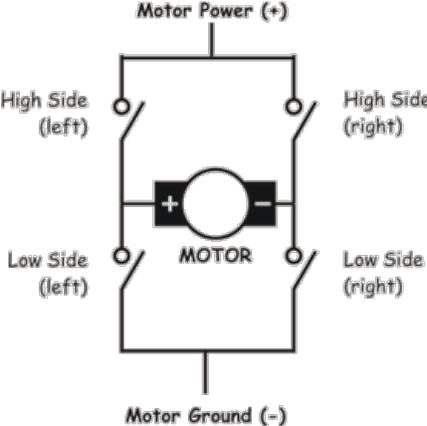


Figure 28: Basic H-Bridge ^[18]

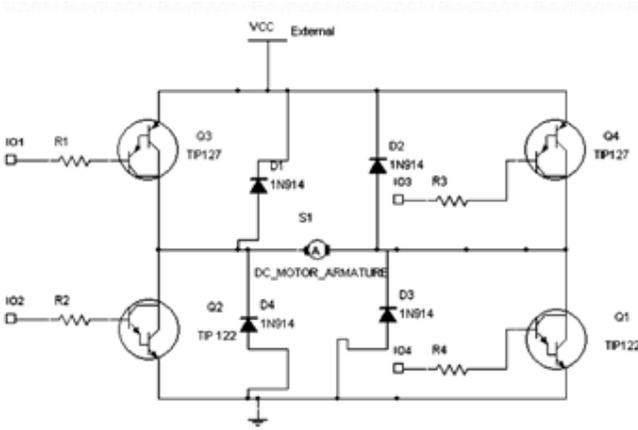


Figure 28.1: Motor Drive Schematic ^[18]

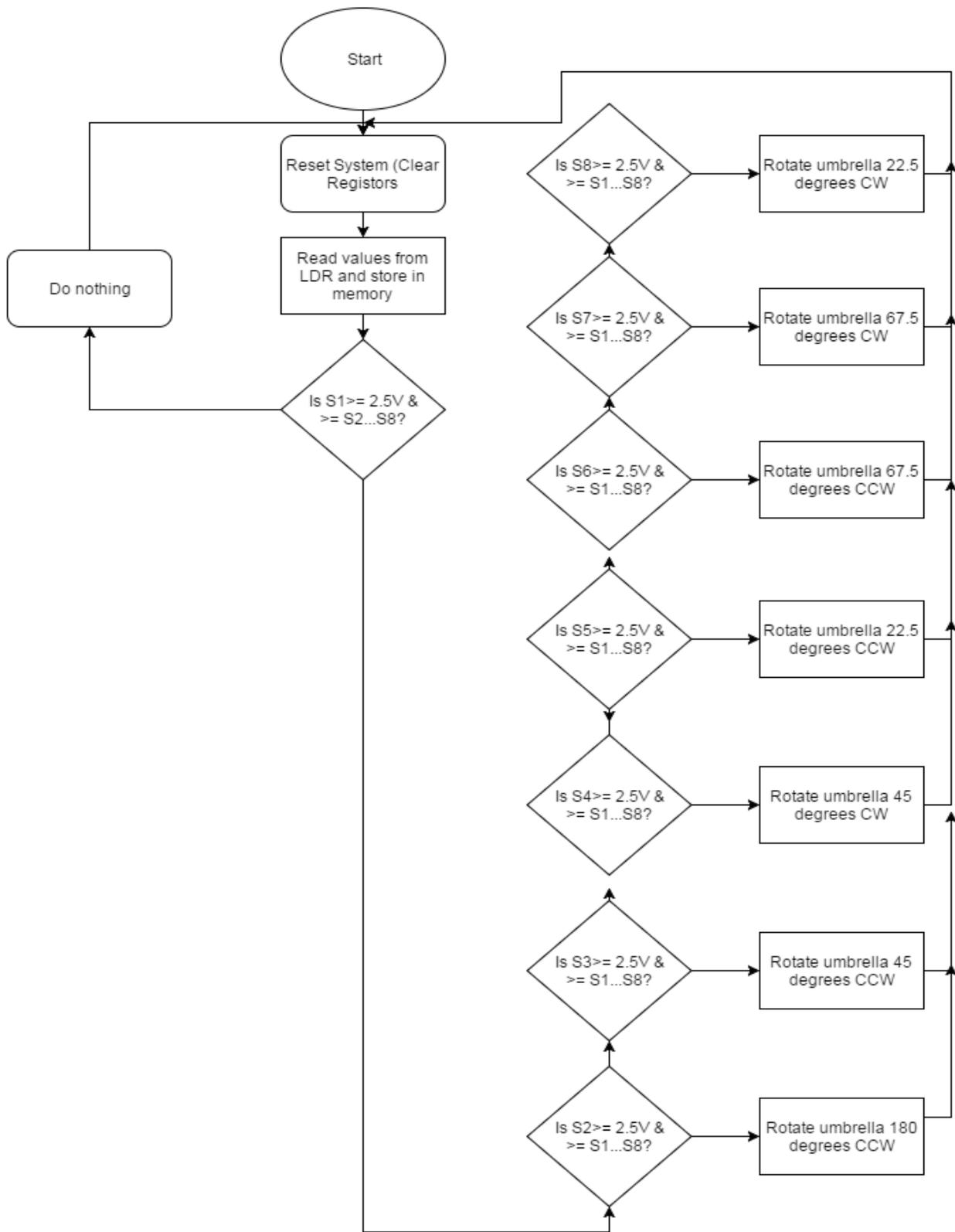


Figure 29: Flow Chart for Micro-controller tracking

2.4 Lighting Module

This module is designed to control the light intensity of the LEDs, which is done by using Pulse Width Modulation (PWM). For this design, the PWM is generated by an LM555, which is an integrated circuit. The LM555 timer operates as an oscillator and outputs a continuous stream of rectangular pulses setting a specified frequency.

The user adapts the intensity of the LEDs through a potentiometer, which adjusts the PWM's duty cycle accordingly in order to provide the needed output voltage to the LEDs, so that different intensities of light are generated. The duty cycle might be precisely set by the ratio of the R1 and the resistance from the potentiometer.

Furthermore, a vital factor in this design is the turn on time or 'duration'. That is, if the light was turned on and off too slowly the viewer will see the flickering of the LED and not a constant light output which appeared dimmer. Therefore, when using PWM, it is important to consider how slowly the LED could 'flash' so that the viewer does not perceive the oscillation. In this design, basing on the information from the LEDs datasheet and results obtained in the laboratory, the limit frequency for not observing the flickering in the LEDs is 200 Hz. Since the frequency of the pulse stream depends on the values of C1, R1, the resistor output by the potentiometer. Therefore, a 1K resistor (R1), and 0.1 μ F (C1) are included that set the frequency from 268 Hz to 320 Hz.

Please refer to Figure 30 for the lighting circuit.

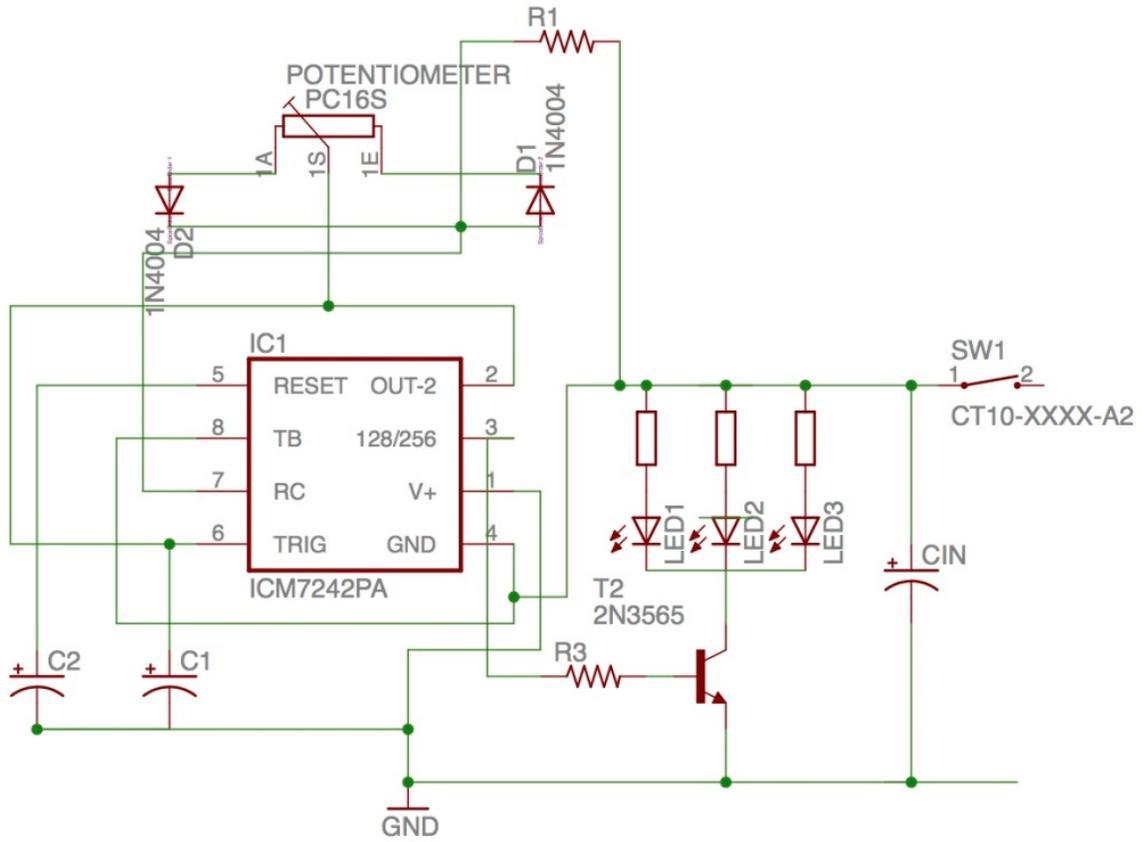


Figure 30: Lighting module circuit

2.4.1 Lighting Module Simulations

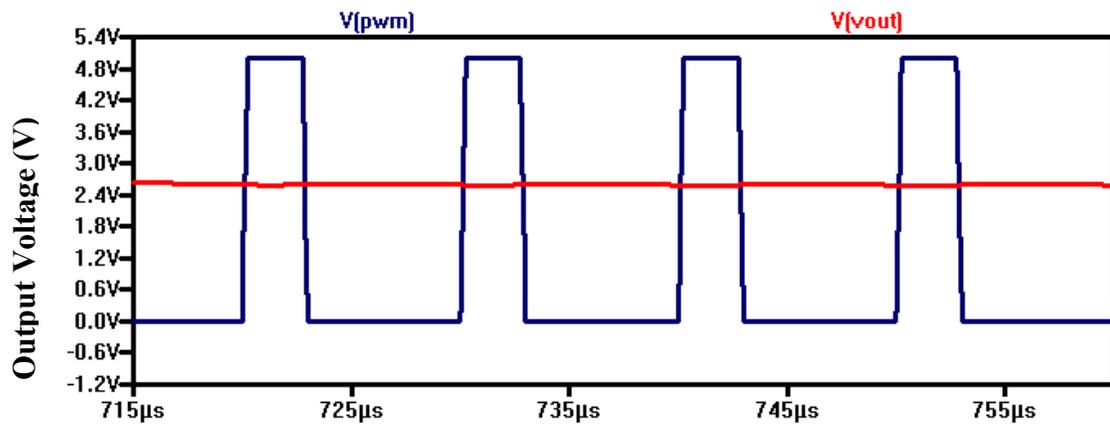


Figure 31: PWM output at 25% Duty Cycle Vs. Time

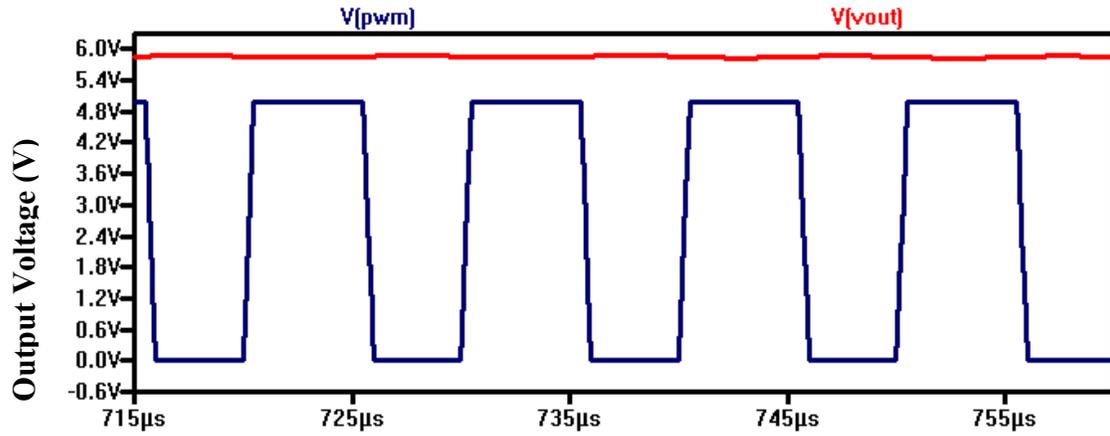


Figure 32: PWM output at 50% Duty Cycle Vs. Time

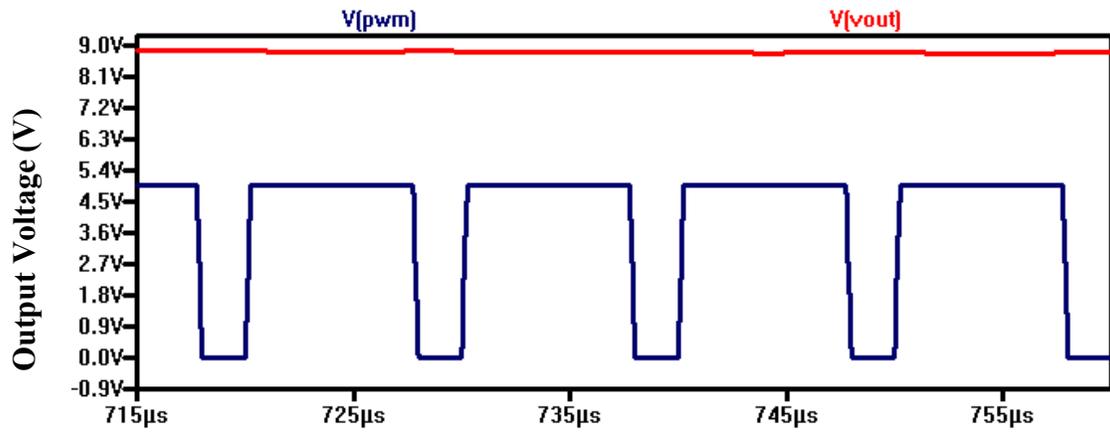


Figure 33: PWM Output at 75% Duty Cycle Vs. Time

2.4.2 Lighting Module Results

The following figures show the PWM output from the LM555 chip that is used to control the intensity of the LEDs. It can be observed that the duty cycle and the frequency are changing as mentioned before.

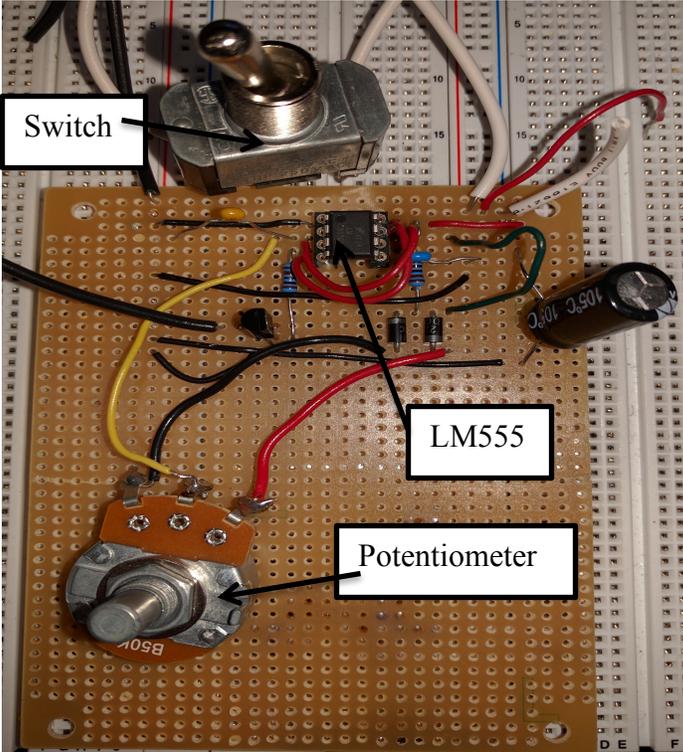


Figure 34: Lighting dimmer built on a prototype circuit board



Figure 35: PWM Output from Timer (LM 555) at Duty Cycle 0% vs Time

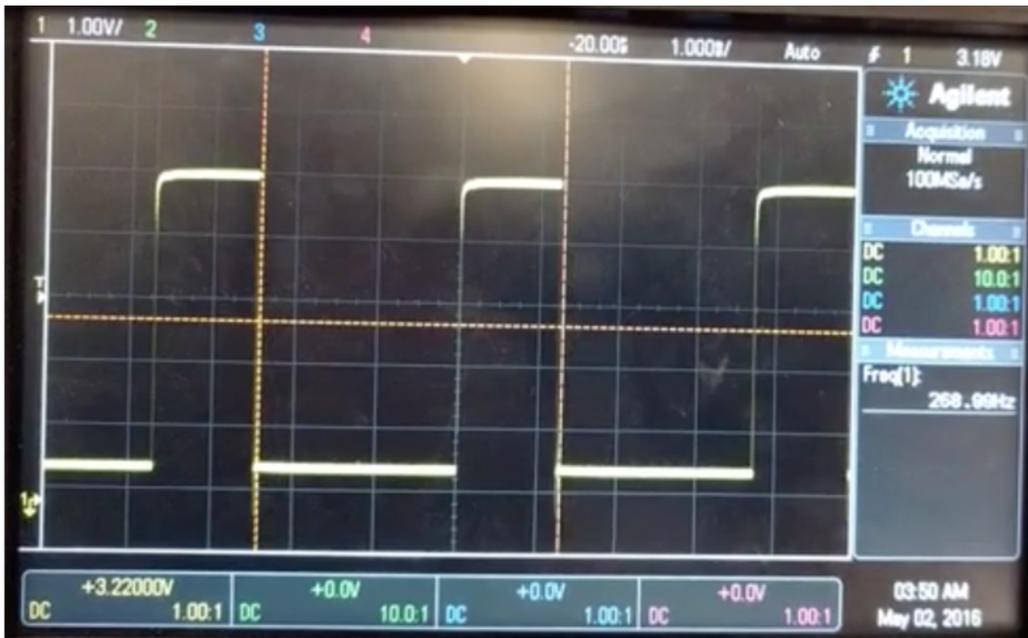


Figure 36: PWM Output from Timer (LM 555) at Duty Cycle 50% vs Time



Figure 37: PWM Output from Timer (LM 555) at Duty Cycle 100% vs Time

3. Design Verification

3.1 Solar Panel

A working solar panel should be able to absorb sun radiation and depending on the intensity of this radiation, it should provide a range of output voltages. For details on the specific requirements and testing procedures, please see Appendix A.

3.2 MPPT Controller (Genasun GV-5)

A working MPPT controller should be able to optimize the output from the Solar panel and provide this to charge the battery bank at its optimal state. For details on the specific requirements and testing procedures, please see Appendix A.

3.3 Battery Bank

The battery bank needed to be able to supply with $12V \pm 2V$ at up to 2.5 A at all times to the rest of the system. For details on the specific requirements and testing procedures, please see Appendix A.

3.4 Light Sensors

The resistance of the light sensors should be able to vary depending on the light intensity with a reasonable accuracy. For details on the specific requirements and testing procedures, please see Appendix A.

3.5 Micro controller

A working micro-controller should be able to receive the analog voltage from both the sensors network and the buck converts and using its A/D, provide the necessary outputs. A working micro-controller reads the analog voltages from all 8 sensors around the umbrella, converts these voltages from analog to digital, compares the obtained values and output the correct signal to rotate the umbrella and for how long based on which sensor reading was the highest. A working micro-controller should be able to receive the analog voltage from the buck converter, convert this reading from analog to digital, and accurately adjusts the pulse width modulation (PWM)

duty cycle and output the PWM signal. For details on the specific requirements and testing procedures, please see Appendix A.

3.6 Motor

The motor should be able to rotate the umbrella based on the signal output from the micro-controller clockwise or anti-clockwise. For details on the specific requirements and testing procedures, please see Appendix A.

3.7 DC-DC buck converter

A working converter should be able to receive the voltage from the battery and step down this voltage such that it may then be used to charge a phone. For details on the specific requirements and testing procedures, please see Appendix A.

4. Budget

4.1 Parts Cost

Table 6: Parts Cost

Item		Quantity	Cost
Patio Umbrella		1	\$56.99
Solar Panel		5	\$49.75
Battery		1	\$44.89
MPPT		1	\$67.50
LDRs		4	\$3.16
Microcontroller		1	\$10.37
Motor		1	\$10.50
Buck Converter	Capacitor	4	\$2.20
	Diode	2	\$0.34
	High side gate driver	1	\$3.19
	Inductor(47 μ H)	2	\$2.20
	Resistor(.5 Ω)	2	\$1.50
	Resistor(.1 Ω)	2	\$1.50
USB		1	\$9.66
LEDs		1 strip	\$6.99
		TOTAL	\$270.74

4.2 Labor Cost

Table 7: Labor Cost

Name	Hourly Rate	Hours Invested	Total
Viren Mascarenhas	\$ 35.00	200	\$ 17,500.00
Christian Ngeleza	\$ 35.00	200	\$ 17,500.00
Luis Pe-Ferrer	\$ 35.00	200	\$ 17,500.00
TOTAL	-	600	\$ 52,500.00

4.3 Total Costs

Table 8: Total Cost

Section	Total
Labor	\$ 52,500.00
Parts	\$ 270.74
Grand Total	\$ 52,770.74

5. Conclusions

5.1 Accomplishments

This project met all requirements initially set out at the beginning of the semester, only missing the incorporation in the final demonstration, of a standalone microcontroller. However, the standalone microcontroller works on individual modules. The sun tracking module accurately tracks the best position with the maximum amount of light with an accuracy of +/- 3 degrees. The charging unit is able to charge a phone with both Android and Apple operating systems with a buck efficiency of approximately 90%. Lastly, the user is able to dim the LED lighting system in this patio umbrella. All these modules are powered by a 12 V battery that is charged by a solar panel using a MPPT charging device.

5.2 Uncertainties

There are a few uncertainties present in this project. For example, the time it will take the charging unit to fully charge a phone from 0% to 100% is not yet concrete. In addition, another uncertainty present is the time the battery will last on a full charge. The completed calculations, based on the data collected during a cloudy day, show a final result of it lasting for 2.5 hours, however it was not tested it with the design. Furthermore, the exact time that the battery would be able to power the whole circuit would also need to be checked. The estimated time is 4.5 hours.

5.3 Ethical Considerations

Since this product is a commercial product that will be used by consumers in hotels etc., it is important that it meets all safety requirements and its 100% safe to use. Therefore, since the project continued to move forward and was completed, the 1st code of ethics in IEEE Code of Ethics was thus complied to,^[21]

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

Knowledge was also gained about the microcontroller code, voltage and current sensing circuitry and increased the understanding of the operation and behavior of physical systems, as opposed to theoretical behavior. This correlates to the 5th IEEE Code of Ethics:

5. To improve the understanding of technology; its appropriate application, and potential consequences.

Solar panels were heavily studied, in addition to MPPT, power converters and control mechanisms for solar tracking. This relates to the 6th IEEE Code of Ethics

6. To maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations.

In this class, it was required to peer review other groups and give our opinion on things. Also, help was needed from other groups and TA's to complete the project. This correlated to the 7th IEEE Code of Ethics.

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

The main objective was to stay safe and to ensure that everyone using this product remained safe as well. This correlated to the 9th IEEE Code of Ethics.

9. To avoid injuring others, their property, reputation, or employment by false or malicious action.

Lastly, that being said, it was promised to comply to all the IEEE Code of Ethics regardless if its mentioned in the above statement or not.

5.4 Future work

Future work for this project would involve refining the design and physical components. The first step would be to build the lightning module on a Printed Circuit Board, which was already designed (See Appendix C-B), in order to improve the efficiency of this module. Furthermore, the Buck Converter PCB should be redesigned, since there were still some wires, which reduces its efficiency. Both changes would make both systems more attractive for a possible future sale.

A future revision of the project would also include a design of an accurate control for the tracking module in order to reach to the exact position and absorbing the greatest amount of energy possible. Furthermore, the whole project should be tested for an extended period of time, and check how long the mobile phone spends to be fully charged or how long the battery can be used.

The last step would be to implement the project on an actual sized patio umbrella with all the components mounted on.

6. References

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Appendix A Requirement and Verification Table

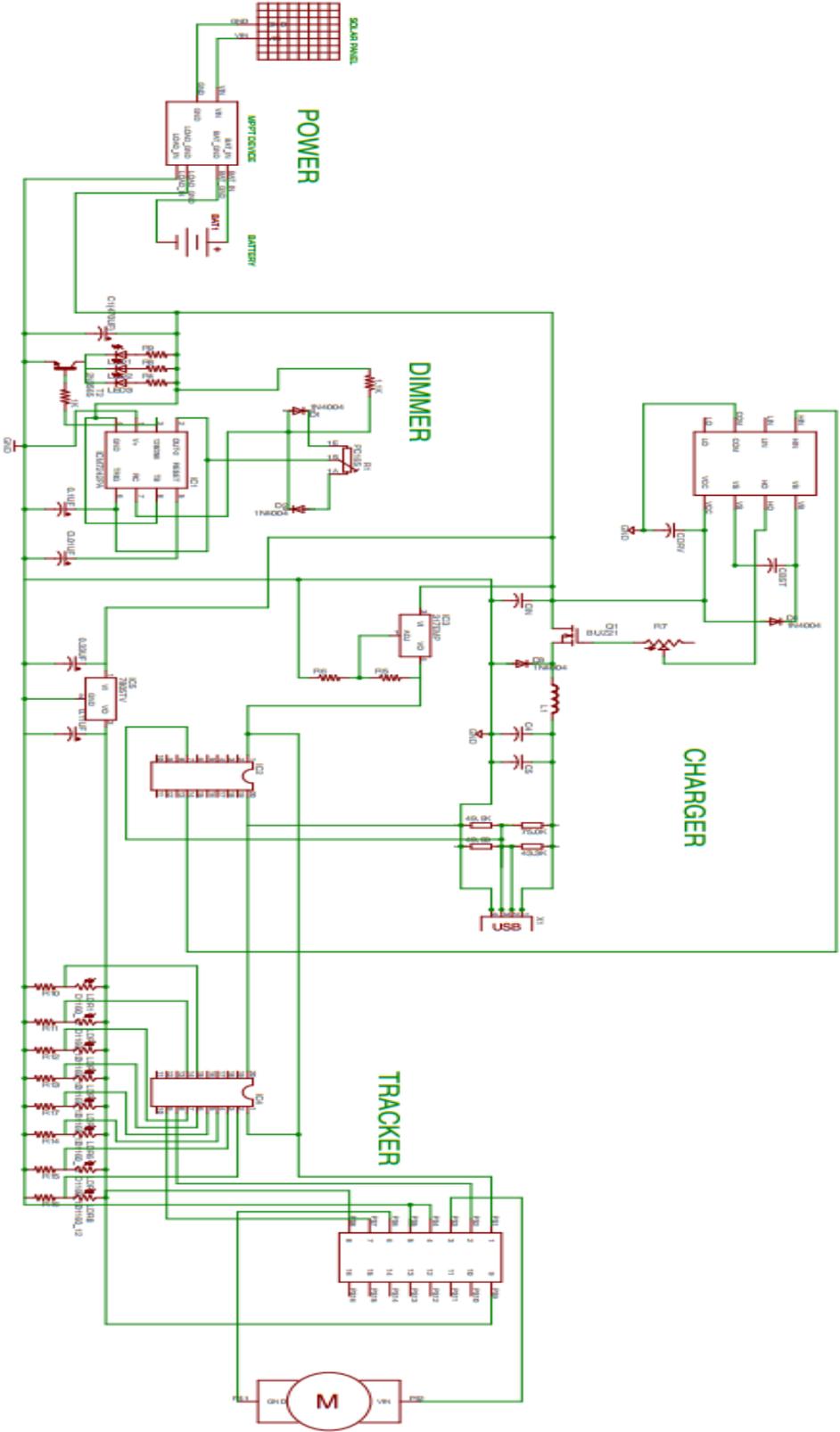
	Requirement	Verification	Verification Status
Solar Panel	1- Output a voltage 22V +/- 2V	1- Connect a multi-meter in parallel with the output terminals of the solar panel and verify the output be 22V +/- 2V.	1- Yes
Genasun MPPT	1- Supply the battery with 12 V +/- 0.5V 2- Outputs maximum power point voltage	1- Change the input voltage of the MPPT using a voltage source and observe to see if we are still getting 12 V +/- 0.5 V on the battery 2- Plot the output (P vs V) curve of the solar panel on an oscilloscope. Make sure the MPPT output the Maximum power point as displayed on the oscilloscope	1- Yes
Battery	1- Output a constant 12 VDC +/- 1 V	1- Connect a multi-meter in parallel with the output terminals of the battery and verify the output voltage to read 12V +/- 1V	1- Yes
Sensors	1- When light is shown directly into the LDR, the resistance will decrease to 150 Ω +/- 25 Ω . When no light is	1- Measure the resistance outputted by the sensors with a multi-meter and make sure that that the resistance is 150 Ω +/- 25 Ω	1- Yes

	shown to the LDR, the resistance will increase to $4\text{kk}\Omega \pm 0.2\text{kk}\Omega$.	and the 'dark room' to be $4\text{kk}\Omega \pm 0.2\text{kk}\Omega$.	
Micro-controller Voltage Sensing	<ol style="list-style-type: none"> 1- Microcontroller's AD converter takes an analog voltage between $0-3.5\text{V} \pm .1\text{V}$ and converts to digital data in range 0-1023. 2- Controller senses input voltage in the range of $0-3.5\text{V}$. If $V_{\text{ref}} > 3\text{V} \pm .3\text{V}$, the controller activates motor to rotate the umbrella's roof-top with appropriate duty cycle. If $V_{\text{ref}} < 3 \pm .3\text{V}$, the controller disables motor. 	<ol style="list-style-type: none"> 1- Power microcontroller with 5V. Sweep the input to the ADC from 0-5V. Record the digital data being outputted by the microcontroller and make sure it corresponds to the analog data with a tolerance of 2%. 2- Power microcontroller with 5V. Provide the sensor circuit with 5V Vdd. Simulate shading on the sensor by covering the top and slowly removing the hand. Observer with a multi-meter that the reference voltage is fluctuating. If $V_{\text{ref}} > 3\text{V}$, with a tolerance of 5%, then motor must be activated. If $V_{\text{ref}} < 3\text{V}$, with also a tolerance of 5%, then the motor is not activated. 	1- Yes
Micro-controller Dimmer	<ol style="list-style-type: none"> 1- Outputs a voltage of $11\text{V} \pm .2\text{V}$ when the LEDs are at full brightness. 2- Outputs a voltage of $5.5\text{V} \pm .2\text{V}$ when the LEDs are at full brightness. 3- Outputs 0V when switch is turned off. 	<ol style="list-style-type: none"> 1- Provide the circuit with 12V. Adjust potentiometer such that the duty cycle is at 99% (max brightness). Measure voltage across the LEDs to be $11\text{V} \pm .2\text{V}$. 2- Provide the circuit with 12V. Adjust potentiometer such that the duty cycle is at 2% (least brightness). Measure voltage across the LEDs to be $5.5\text{V} \pm .2\text{V}$. 3- Turn the switch off and use a voltmeter to measure the voltage of 0V. 	1- Yes

Micro-controller Buck converter	1- Provide a PWM with a duty cycle of 47% +/- 5%	1- Power microcontroller with 5V. Using an oscilloscope, observe the period of the duty cycle the generated is 47% with a tolerance of 5%.	1- Yes
Motors	1- Motor spins umbrella 2- When the voltage at reference sensor is greater than the other sensors, the motor stops spinning	1- When 5V is provided to the motor, the motor spins the umbrella. 2- Set up the motor control circuitry and observe 0V +/- .1 V across the motor's input voltage.	1- Yes
Buck Converter	1- Outputs 5V +/- 0.5V and 1 A +/- 0.3A 2- Ensure Inductor does not saturate and send the buck converter into DCM 3- Gate driver is operational	1- Connect a multi-meter in parallel with the output terminals of the buck converter and verify the output voltage to be 5V +/- 0.5V. 2- Connect a multi-meter 1-in series with the output terminals of the buck converter and verify the output current to 1A +/- 0.3A. 3- Send in a signal into pin 2 of IRS2183 and vary the duty cycle. Observe the output in pin 7 using a oscilloscope and make sure the output is switching accordingly	1- Yes
USB	1- Outputs 5V +/- .5V and 1A +/- .2A	1- Using a multi-meter, observe the voltage being outputted by the USB port and ensure	1- Yes

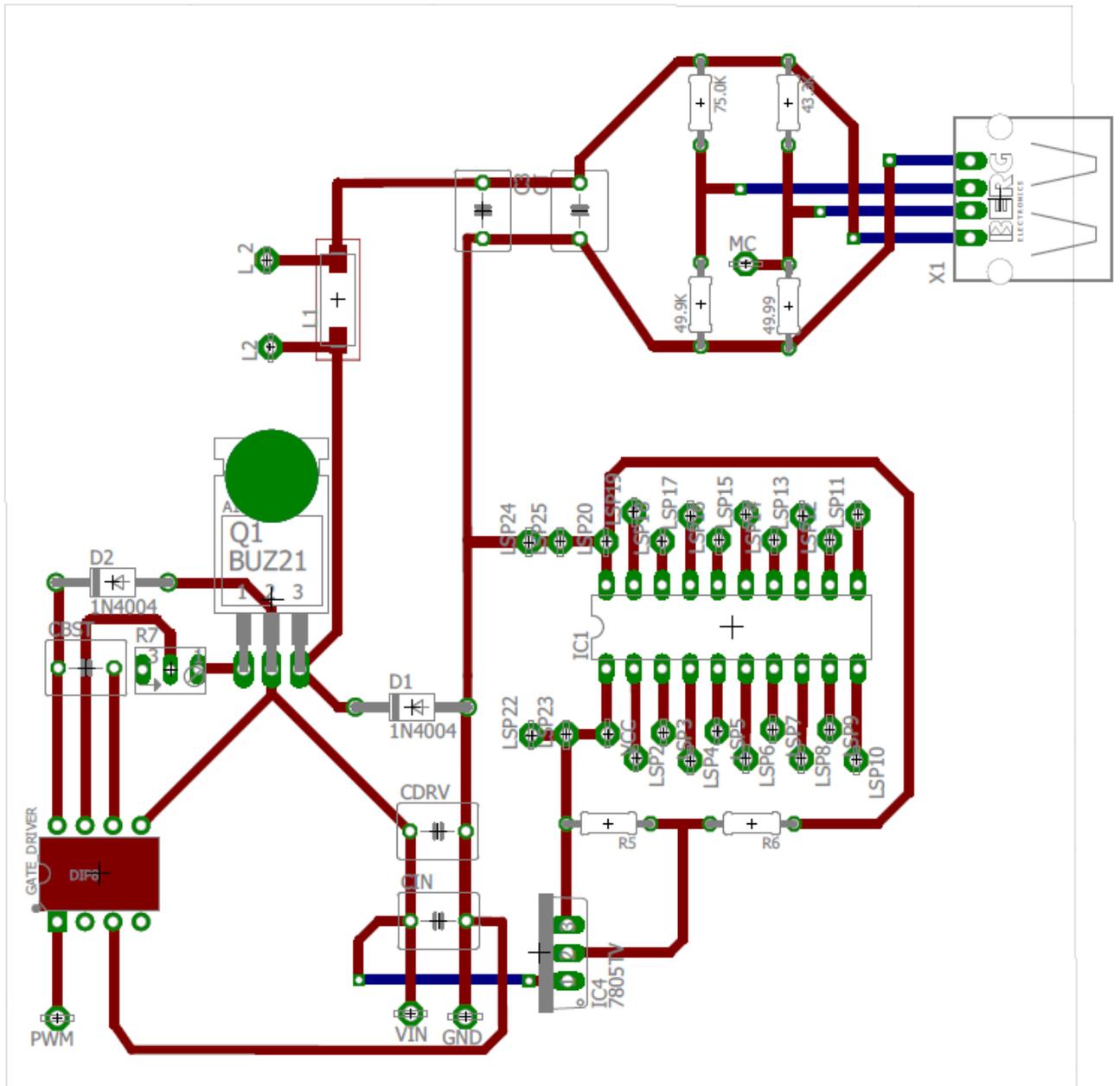
	2- Charges phone	that 5V, 1A is being outputted with a tolerance of 5% and 20% accordingly. 2- Plug in phone and see that it is charging.	
Dimmer	1- Outputs Voltages (5.5V +/- .2V to 11 +/- .2V) based on duty cycle of PWM varying from 2% to 99%.	1- Observe the PWM output on the oscilloscope as well as the output voltage of the dimmer. It should be seen that the output voltage of the dimmer changes from 5.5V +/- .2V to 11 +/- .2V	1- Yes
LED	1- Brightness increases with different voltages	1- Adjust potentiometer and see if the LEDs change brightness.	1- Yes

Appendix B Full System Circuit Diagram

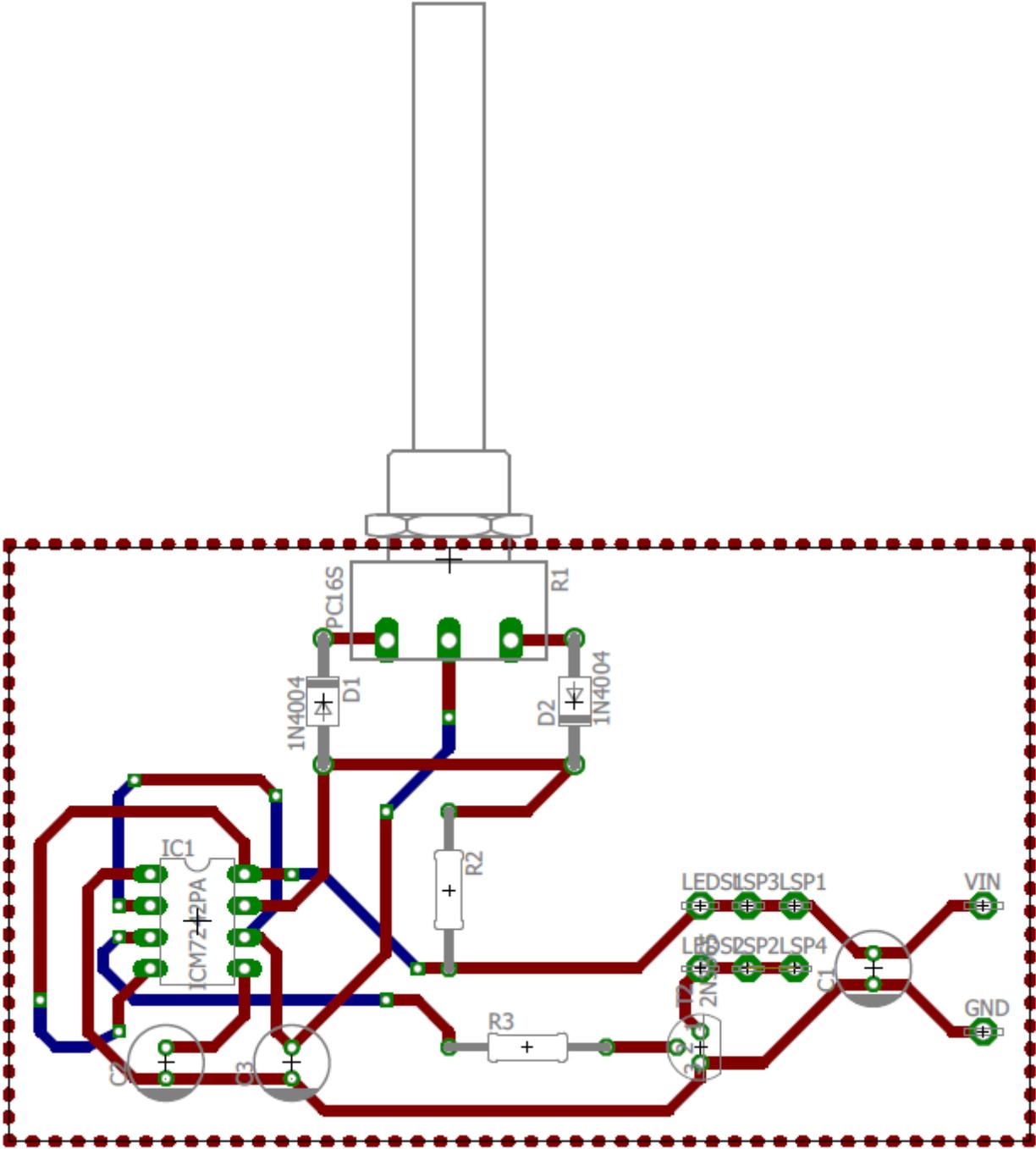


Appendix C PCB Layouts

C-A: Buck Converter Layout



C-B Lighting Circuit Layout



Appendix D Micro-Controller Code

D-A: Sun Tracking Module Code

```
\
#include <msp430.h>
#define LED0 BIT0
#define LED1 BIT6
unsigned int value = 0;
unsigned int value2 = 0;
unsigned int value3 = 0;
unsigned int value4 = 0;
unsigned int value5 = 0;
unsigned int value6 = 0;
unsigned int value7 = 0;
unsigned int value8 = 0;

#define ADC_CHANNELS 8
unsigned int samples[ADC_CHANNELS];

void ConfigureAdc(void)
{
    ADC10CTL1 = INCH_7 + ADC10DIV_0 + CONSEQ_3 + SHS_0; //Multi-channel
repeated conversion starting from channel 5
    ADC10CTL0 = SREF_0 + ADC10SHT_2 + MSC + ADC10ON + ADC10IE;
    ADC10AEO = BIT7 + BIT6 + BIT5 + BIT4 + BIT3 + BIT2 + BIT1 + BIT0;
    ADC10DTC1 = ADC_CHANNELS; //ADC_CHANNELS defined to 5
}

void main(void)
{
    WDTCTL = WDTPW + WDTHOLD; // Stop WDT
    BCSCTL1 = CALBC1_1MHZ; // Set range
    DCOCTL = CALDCO_1MHZ;
    BCSCTL2 &= ~(DIVS_3); // SMCLK = DCO = 1MHz

    P2DIR |= BIT0 + BIT1;
    // P1SEL |= BIT5; //ADC Input pin P1.5
    P2OUT &= ~(BIT0 + BIT1); //bit0 ccw, bit1 cw
    ConfigureAdc();
    __enable_interrupt(); // Enable interrupts.

    while(1)
    {
        __delay_cycles(1000); // Wait for ADC Ref to settle
        ADC10CTL0 &= ~ENC;
        while (ADC10CTL1 & BUSY);
        ADC10SA = (unsigned int)samples;
        ADC10CTL0 |= ENC + ADC10SC; // Sampling and conversion start
        __bis_SR_register(CPUOFF + GIE); // LPM0 with interrupts enabled
    }
}
```

```

// value = ADC10MEM;

value = samples[0];
value2 = samples[1];
value3 = samples[2];
value4 = samples[3];
value5 = samples[4];
value6 = samples[5];
value7 = samples[6];
value8 = samples[7];

if (value2>650 && value2 >= value && value2 >= value3 && value2 >= value4 &&
value2 >= value5 && value2 >= value6 && value2 >= value7 && value2 >= value8) //if
sensor 2 has the most light, spin 90 CCW
{
    P2OUT &= ~(BIT0 + BIT1);
    P2OUT |= BIT0;
    __delay_cycles(7500000);
}
else if (value3>650 && value3 >= value && value3 > value2 && value3 >= value4
&& value3 >= value5 && value3 >= value6 && value3 >= value7 && value3 >= value8) //if
sensor 3 has the most light, spin 45 CCW
{
    P2OUT &= ~(BIT0 + BIT1);
    P2OUT |= BIT1;
    __delay_cycles(3500000);
}
else if(value4> 650 && value4 >= value && value4 > value2 && value4 > value3 &&
value4 >= value5 && value4 >= value6 && value4 >= value7 && value4 >= value8)
{
    P2OUT &= ~(BIT0 + BIT1);
    P2OUT |= BIT0;
    __delay_cycles(3500000);
}
else if(value5> 650 && value5 >= value && value5 > value2 && value5 > value3 &&
value5 > value4 && value5 >= value6 && value5 >= value7 && value5 >= value8)
{
    P2OUT &= ~(BIT0 + BIT1);
    P2OUT |= BIT1;
    __delay_cycles(1750000);
}
else if(value6> 650 && value6 >= value && value6 > value2 && value6 > value3 &&
value6 >> value4 && value6 >> value5 && value6 >= value7 && value6 >= value8)
{
    P2OUT &= ~(BIT0 + BIT1);
    P2OUT |= BIT1;
    __delay_cycles(5100000);
}
else if(value7> 650 && value7 >= value && value7 > value2 && value7 > value3 &&
value7 >> value4 && value7 >> value5 && value7 >> value6 && value7 >= value8)
{
    P2OUT &= ~(BIT0 + BIT1);
    P2OUT |= BIT0;
    __delay_cycles(5100000);
}

```

```

    }
    else if(value8 > 650 && value8 > value && value8 > value2 && value8 > value3 &&
value8 >> value4 && value8 >> value5 && value8 >> value6 && value8 >> value7)
    {
        P2OUT &= ~(BIT0 + BIT1);
        P2OUT |= BIT0;
        __delay_cycles(1750000);
    }

    else
    {
        P2OUT &= ~(BIT0 + BIT1);
    }

}

}

```

```

#pragma vector=ADC10_VECTOR
__interrupt void ADC10_ISR (void)
{
    __bic_SR_register_on_exit(CPUOFF); // Return to active mode
}

```

D-B Charging Module PWM output and control Code

```

#include <msp430.h>
#include <msp430g2253.h>

/** Global Variable */
int IncDec_PWM = 0;
unsigned int n = 0;

void main(void){

    /** Watchdog timer and clock Set-Up */
    WDTCTL = WDTPW + WDTXLD; // Stop watchdog timer

    // configure the CPU clock (MCLK)
    // to run from DCO @ 16MHz and SMCLK = DCO
    BCSCTL1 = CALBC1_16MHZ; // Set DCO
    DCOCTL = CALDCO_16MHZ;
    BCSCTL2 = DIVS_0 + DIVM_0; // divider=1 for SMCLK and 1 for MCLK

    /** GPIO Set-Up */
    P1DIR |= BIT6; // P1.6 set as output (Green LED)
}

```

```

P1SEL |= BIT6; // P1.6 selected Timer0_A Out1 output

    /*** Timer0_A Set-Up ***/
    TA0CCR0 |= 78; // PWM period (us)
    IncDec_PWM = 36;
    TA0CCR1 |= IncDec_PWM; // TA0CCR1 PWM duty cycle
    TA0CCTL1 |= OUTMOD_6; // TA0CCR1 output mode = reset/set
    TA0CTL |= TASSEL_2 + MC_1; // SMCLK, Up Mode (Counts to TA0CCR0)

    /*** Timer1_A Set-Up ***/
    TA1CCR0 |= 4000; // Counter value
    TA1CCTL0 |= CCIE; // Enable Timer1_A interrupts
    TA1CTL |= TASSEL_2 + MC_1; // SMCLK, Up Mode (Counts to TA1CCR0)

    __enable_interrupt(); // Enable interrupts.
    _BIS_SR(LPM0_bits + GIE); // Enter Low power mode 0 with interrupts
enabled
}

#pragma vector=TIMER1_A0_VECTOR // Timer1 A0 interrupt service routine
__interrupt void Timer1_A0 (void) {

    ADC10CTL1 |= INCH_5 + CONSEQ_2;
    ADC10CTL0 |= ADC10SHT_3 + ADC10ON + MSC;
    ADC10AE0 |= BIT5;
    //Adc input pin P1.0
    __delay_cycles(1000); // Wait for ADC Ref to settle
    ADC10CTL0 |= ADC10SC + ENC;
    //
    __bis_SR_register(CPUOFF + GIE); // LPM0 with interrupts enabled
    n = ADC10MEM;

    if(n < 780){ //if the
output voltage is too low increase the duty cycle

        if (IncDec_PWM == 40){
            IncDec_PWM = 36;
        }
        IncDec_PWM +=1;
        TA0CCR1 = IncDec_PWM;
        TA0CCTL1 = OUTMOD_6;
        TA0CTL = TASSEL_2 + MC_1;
    }

    else if(n > 800){ //If
the output voltage is too high, decrease the duty cycle

        if (IncDec_PWM == 20){
            IncDec_PWM = 36;
        }
        IncDec_PWM -=1;
        TA0CCR1 = IncDec_PWM;
        TA0CCTL1 = OUTMOD_6;
        TA0CTL = TASSEL_2 + MC_1;
    }
}

```

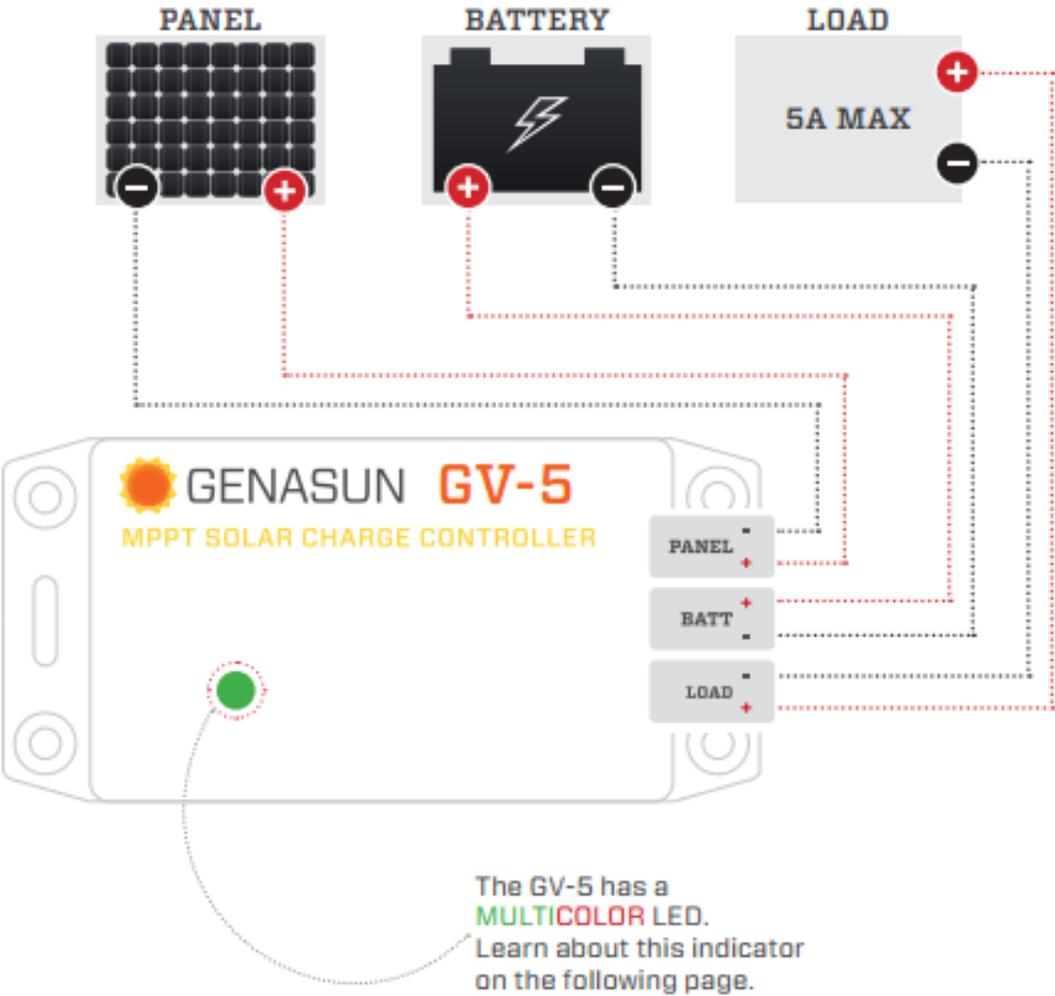
```

/*
    if (n < 100) {
        //Lower limit check, if gate driver stops driving.
        //ie.
input voltage to gate drops below 8V, Reset system by outputing ideal duty cycle

        TA0CCR0 |= 78;           // PWM period (us)
        TA0CCR1 |= 37;           // TA0CCR1 PWM duty
cycle
        TA0CCTL1 |= OUTMOD_6;    // TA0CCR1 output mode =
reset/set
        TA0CTL |= TASSEL_2 + MC_1; // SMCLK, Up Mode (Counts
to TA0CCR0)
        }*/
}

```


Appendix E Solar Panel, MPPT and Battery Connection



Appendix F Genasun MPPT Specifications

Model: GV-5-Pb-12V	
Max. Recommended Panel Power	65W
Rated Battery (Output) Current	5A
Nominal Battery Voltage	12V
Max Panel Voltage	27V
Recommended Max Voc at STC	22V
Min. Battery Voltage for Operation	7.2V
Input Voltage Range	0-27V
Recommended Max. Input Short Circuit Current (for Solar Use)	5A
Continuous Rated Load Current	5A
Maximum Input Current (that could be drawn from an unlimited source)	9A
Absorption Voltage	14.2V
Absorption Time	2 hours
Float Voltage	13.8V
Load (LVD) Disconnect/Reconnect Voltage	11.4V / 12.5V

Appendix G Schedule

Week	Task	Responsibility
2/8	<ul style="list-style-type: none"> Set up Meeting With Solar Expert 	Christian Ngeleza
	<ul style="list-style-type: none"> Look Up Parts for Project 	Luis Pe-Ferrer
	<ul style="list-style-type: none"> Complete Proposal 	Viren Mascarenhas
2/15	<ul style="list-style-type: none"> Design interaction between sun tracking modules 	Christian Ngeleza
	<ul style="list-style-type: none"> Order Parts 	Luis Pe-Ferrer
	<ul style="list-style-type: none"> Design Test Environment for Power Source 	Viren Mascarenhas
2/22	<ul style="list-style-type: none"> Assemble Charging modules 	Christian Ngeleza
	<ul style="list-style-type: none"> Assemble Lighting modules 	Luis Pe-Ferrer
	<ul style="list-style-type: none"> Start PCB Design 	Viren Mascarenhas
2/29	<ul style="list-style-type: none"> Begin Writing logic code for sun tracking modules 	Christian Ngeleza
	<ul style="list-style-type: none"> Assemble Power Source Modules 	Luis Pe-Ferrer
	<ul style="list-style-type: none"> Continue PCB Design 	Viren Mascarenhas
3/7	<ul style="list-style-type: none"> Continue writing Logic code for sun tracking module 	Christian Ngeleza
	<ul style="list-style-type: none"> Start Test for Power Source 	Luis Pe-Ferrer
	<ul style="list-style-type: none"> Finalize PCB Design 	Viren Mascarenhas
3/14	<ul style="list-style-type: none"> Finalize logic code for sun tracking module 	Christian Ngeleza
	<ul style="list-style-type: none"> Optimize Power Source Interaction based on test results 	Luis Pe-Ferrer
	<ul style="list-style-type: none"> Assemble Motor, LDR, Micro-controller and Umbrella Interface 	Viren Mascarenhas
3/21	<ul style="list-style-type: none"> Optimization of dimmer PWM code based on results 	Christian Ngeleza

Spring Break	<ul style="list-style-type: none"> • Optimization of tracking code based on suggestions. 	Luis Pe-Ferrer
	<ul style="list-style-type: none"> • PCB design for LDR and Dimmer 	Viren Mascarenhas
3/28	<ul style="list-style-type: none"> • Starting test of sun tracking modules based on code 	Christian Ngeleza
	<ul style="list-style-type: none"> • Start testing interaction between power source and Execution modules 	Luis Pe-Ferrer
	<ul style="list-style-type: none"> • Start assembling modules together 	Viren Mascarenhas
4/4	<ul style="list-style-type: none"> • Modular Testing for lighting modules 	Christian Ngeleza
	<ul style="list-style-type: none"> • Final optimization of Power Source and Execution modules interface 	Luis Pe-Ferrer
	<ul style="list-style-type: none"> • Modular Testing for charging modules 	Viren Mascarenhas
4/11	<ul style="list-style-type: none"> • Assemble all modules 	Christian Ngeleza
	<ul style="list-style-type: none"> • Prepare Demos 	Luis Pe-Ferrer
	<ul style="list-style-type: none"> • Optimize code based on test results 	Viren Mascarenhas
4/18	<ul style="list-style-type: none"> • Finish Demos preparation 	Christian Ngeleza
	<ul style="list-style-type: none"> • Finalize debugging of code 	Luis Pe-Ferrer
	<ul style="list-style-type: none"> • Finalize circuit optimization 	Viren Mascarenhas
4/25	<ul style="list-style-type: none"> • Start Final Paper 	Christian Ngeleza
	<ul style="list-style-type: none"> • Make sure Demonstration is ready 	Luis Pe-Ferrer
	<ul style="list-style-type: none"> • Start Presentation 	Viren Mascarenhas
5/2	<ul style="list-style-type: none"> • Finish Final Paper 	Christian Ngeleza
	<ul style="list-style-type: none"> • Finish Presentation 	Luis Pe-Ferrer
	<ul style="list-style-type: none"> • Proof read all documentation 	Viren Mascarenhas

Appendix H Safety Statement

The solar power umbrella designed in this project uses a battery bank which will be providing 45 W, with a maximum of 3.7 A. According to OSHA standards, the effect of current on the human body is shown in Table 1. Because of this, necessary safety precautions will be needed when assembling the system due to the fact that these conditions can be deadly.

Table 1: Effects of electrical shock

Dc Current Level (mA)	Probable Effects
0-4	Perception
4-15	Surprise, Slight shock felt
15-80	Reflex Action, “let-go” range, Painful shock
80 - 160	Muscular Inhibition, Extreme Pain
160 - 300	Respiratory Block, Ventricular fibrillation
Over 300	Cardiac Arrest, Sever Burns, Usually Fatal

From the Table 1, it can be observed that will be working with nearly 12 times the needed current to cause fatal injuries. It must be ensured that all the necessary safety precautions are taken when performing experiments as well as making sure the final built can withstand the various outdoor environments it will be subjected too.

In order to reduce the risk of injuries it was followed this set of rules already imposed by the power electronic lab (ECE Building 4024) as listed below ^[9]:

Please follow the safety precautions to avoid injury, discomfort, lost lab time, and expensive repairs.

- **GROUND!** Be aware of which connections are grounded, and which are not. The most common cause of equipment damage is unintended shorts to ground. Remember that oscilloscopes are designed to measure voltage relative to ground, not between two arbitrary points.
- **RATINGS!** Before applying power, check that the voltage, current, and power levels you expect to see do not violate any ratings. What is the power you expect in a given resistor?

- **HEAT!** Small parts can become hot enough to cause burns with as little as one watt applied to them. Even large resistors will become hot if five watts or so are applied.
- **CAREFUL WORKMANSHIP!** Check and recheck all connections before applying power. Plan ahead: consider the effects of a circuit change before trying it. Use the right wires and connectors for the job, and keep your bench neat.
- **WHEN IN DOUBT, SHUT IT OFF!** Do not manipulate circuits or make changes with power applied.
- **LIVE PARTS!** Most semiconductor devices have an electrical connection to the case. Assume that anything touching the case is part of the circuit and is connected. Avoid tools and other metallic objects around live circuits. Keep beverage containers away from your bench.
- **Neckties and loose clothing should not be worn when working with motors.** Be sure motors are not free to move about or come in contact with circuitry.
- Remember the effects of inductive circuits -high voltages can occur if you attempt to disconnect an inductor when current is flowing.
- EMERGENCY PHONE NUMBER: 9-911

The laboratory was equipped with an emergency electrical shutoff system. When any red button (located throughout the room) is pushed, power is disconnected from all room panels. Room lights and the wall duplex outlets used for instrument power and low-power experiments are not affected. If the emergency system operates, and you are without power, inform your instructor. It is your instructor's task to restore power when it is safe to do so. Each workbench is connected to power through a set of line cords. The large line cords are connected to two front panel switches labelled “3 ϕ mains” and “dc mains.” The standard ac line cord is connected to the switch on the bench outlet column. Your bench can be de-energized by shutting off these three switches. ^[9]

Additionally, there are more protocols that must be followed, especially when working with the motor, as giving by the Electric machine laboratory safety manual ^[9]:

1. Do not make circuit changes or perform any wiring when power is on.
2. Assume that panel jacks on your bench are electrically live unless power is off.
3. Be sure you understand the function and wiring of an instrument before using it in a circuit.
4. Do not repeat the same mistake.

5. Do not guess — know! If in doubt, see 2 above.
6. Do not wear loose - fitting clothing or jewelry in the lab. Rings and necklaces are usually excellent conductors in excellent contact with your skin.
7. It is wise in electrical labs to wear pants rather than shorts or skirts. Ties are also dangerous.
8. Powered equipment can be hot! Use caution when handling equipment after it has been operating.

Additional key precautions

1. Acquaint yourself with disconnect switches, especially those at your bench.
2. Work slowly and deliberately. Think as you act.
3. Do your wiring, setup, and a careful circuit checkout before applying power.
4. Use wires of appropriate length. Do not allow them to drape over your equipment. Avoid splices, which create live surfaces. When running a pair of wires to adjacent terminals, twist the wires together so they do not dangle. This also neatens your work and will save time.
5. Keep your bench organized and neat. It should be clear of coats, extra books and papers, and unused equipment.
6. Use your bench. Avoid long connections by using the bench transfer wires. Plug instruments
7. Into the bench, not into the wall. This gives you the protection of the bench switches.
8. No smoking in the lab, and no food or beverages on or near the workbenches. If you smell smoke, turn off power.
9. Do not touch anything if your hands are wet. The “one-hand” approach is safest.
10. Do not pull wires out until you are absolutely sure that the circuit is completely dead. Shocks can occur if an inductive load (motor or transformer) is disconnected while conducting.

In the event of an accident or emergency:

- Do not panic.
- Shut off all power.
- Call for assistance. Fire Department and emergency services 9 - 911

Finally, more precautions were needed in order to insure that the final built can withstand the various weather conditions it may encounter. That is, it was need to pick the components carefully and make sure that proper wiring procedures are followed, as well as the right amount of insulations. One way to account for this was that it was planned on using a waterproof USB hub.

Furthermore, it was ensured to watch out for ourselves, our peers, professors and everyone who will be working on this project.

Appendix I Solar Patio Umbrella, Whole System



Appendix J Datasheets

LM555 Timer

1 Features

- Direct Replacement for SE555/NE555
- Timing from Microseconds through Hours
- Operates in Both Astable and Monostable Modes
- Adjustable Duty Cycle
- Output Can Source or Sink 200 mA
- Output and Supply TTL Compatible
- Temperature Stability Better than 0.005% per °C
- Normally On and Normally Off Output
- Available in 8-pin VSSOP Package

2 Applications

- Precision Timing
- Pulse Generation
- Sequential Timing
- Time Delay Generation
- Pulse Width Modulation
- Pulse Position Modulation
- Linear Ramp Generator

3 Description

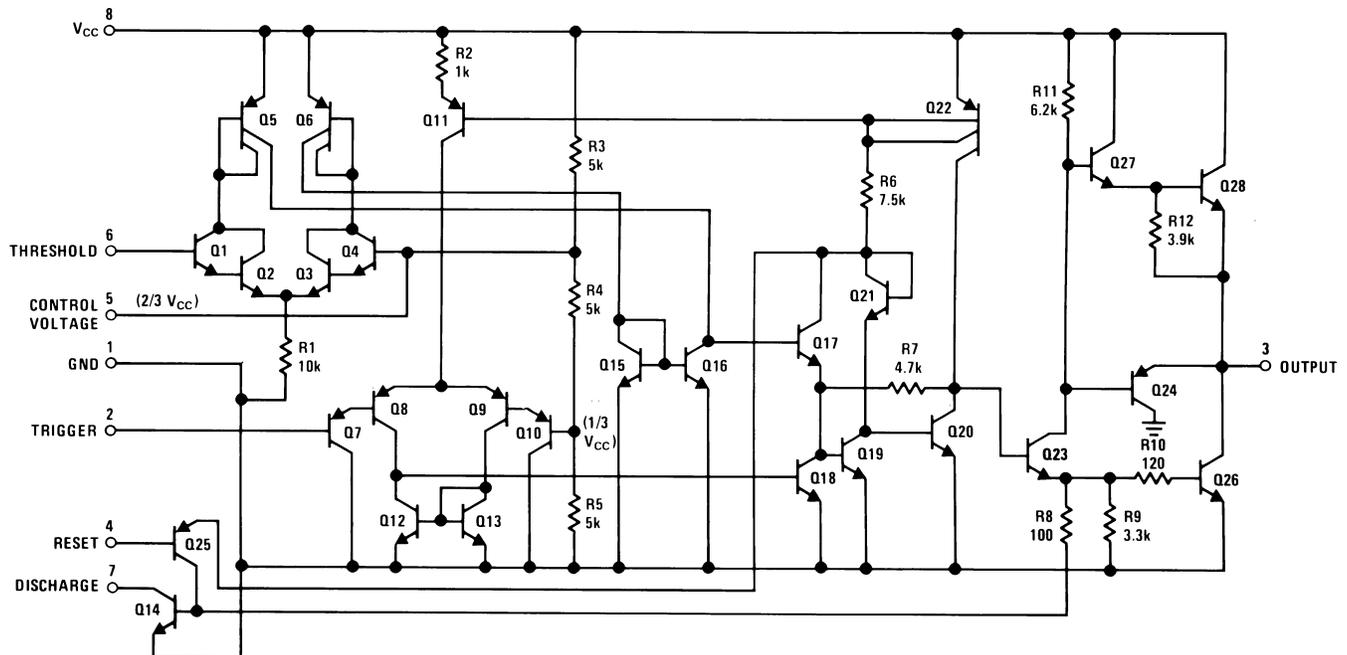
The LM555 is a highly stable device for generating accurate time delays or oscillation. Additional terminals are provided for triggering or resetting if desired. In the time delay mode of operation, the time is precisely controlled by one external resistor and capacitor. For a stable operation as an oscillator, the free running frequency and duty cycle are accurately controlled with two external resistors and one capacitor. The circuit may be triggered and reset on falling waveforms, and the output circuit can source or sink up to 200 mA or drive TTL circuits.

Device Information⁽¹⁾

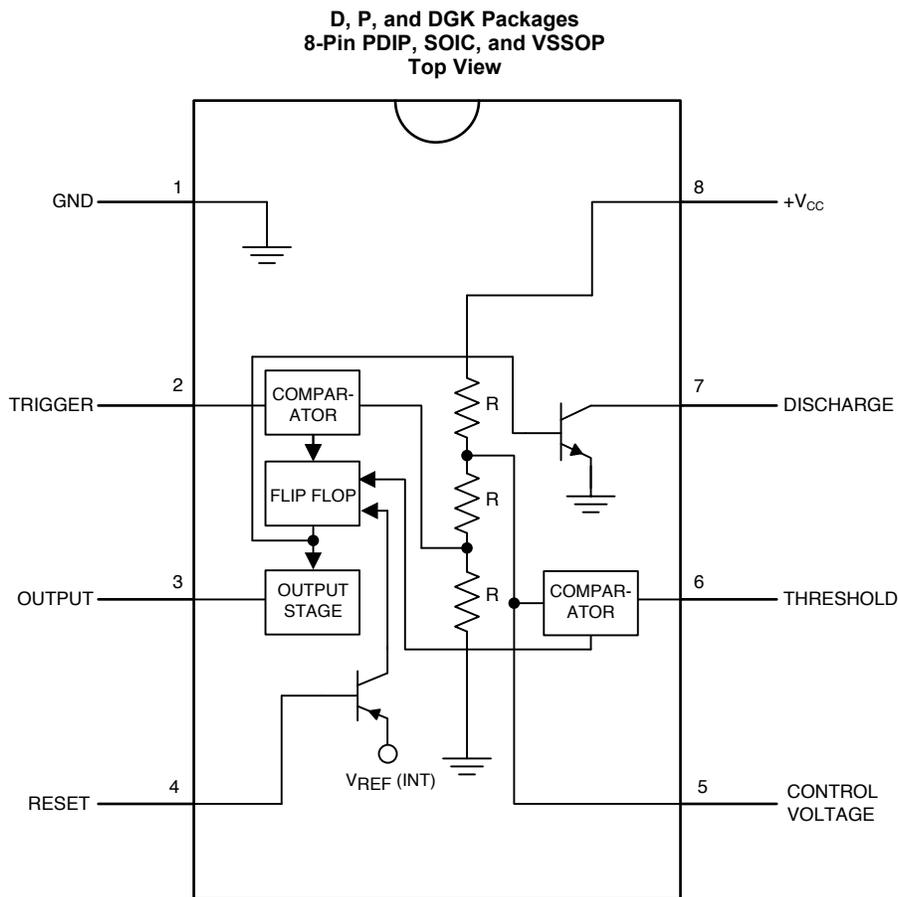
PART NUMBER	PACKAGE	BODY SIZE (NOM)
LM555	SOIC (8)	4.90 mm × 3.91 mm
	PDIP (8)	9.81 mm × 6.35 mm
	VSSOP (8)	3.00 mm × 3.00 mm

(1) For all available packages, see the orderable addendum at the end of the datasheet.

Schematic Diagram



5 Pin Configuration and Functions



Pin Functions

PIN		I/O	DESCRIPTION
NO.	NAME		
5	Control Voltage	I	Controls the threshold and trigger levels. It determines the pulse width of the output waveform. An external voltage applied to this pin can also be used to modulate the output waveform
7	Discharge	I	Open collector output which discharges a capacitor between intervals (in phase with output). It toggles the output from high to low when voltage reaches 2/3 of the supply voltage
1	GND	O	Ground reference voltage
3	Output	O	Output driven waveform
4	Reset	I	Negative pulse applied to this pin to disable or reset the timer. When not used for reset purposes, it should be connected to VCC to avoid false triggering
6	Threshold	I	Compares the voltage applied to the terminal with a reference voltage of 2/3 Vcc. The amplitude of voltage applied to this terminal is responsible for the set state of the flip-flop
2	Trigger	I	Responsible for transition of the flip-flop from set to reset. The output of the timer depends on the amplitude of the external trigger pulse applied to this pin
8	V ⁺	I	Supply voltage with respect to GND

6 Specifications

6.1 Absolute Maximum Ratings

 over operating free-air temperature range (unless otherwise noted)⁽¹⁾⁽²⁾

		MIN	MAX	UNIT	
Power Dissipation ⁽³⁾		LM555CM, LM555CN ⁽⁴⁾		1180	mW
		LM555CMM		613	mW
Soldering Information	PDIP Package	Soldering (10 Seconds)		260	°C
	Small Outline Packages (SOIC and VSSOP)	Vapor Phase (60 Seconds)		215	°C
		Infrared (15 Seconds)		220	°C
Storage temperature, T _{stg}		-65	150	°C	

- (1) Stresses beyond those listed under *Absolute Maximum Ratings* may cause permanent damage to the device. These are stress ratings only, which do not imply functional operation of the device at these or any other conditions beyond those indicated under *Recommended Operating Conditions*. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
- (2) If Military/Aerospace specified devices are required, please contact the TI Sales Office/Distributors for availability and specifications.
- (3) For operating at elevated temperatures the device must be derated above 25°C based on a 150°C maximum junction temperature and a thermal resistance of 106°C/W (PDIP), 170°C/W (SOIC-8), and 204°C/W (VSSOP) junction to ambient.
- (4) Refer to RETS555X drawing of military LM555H and LM555J versions for specifications.

6.2 ESD Ratings

		VALUE	UNIT	
V _(ESD)	Electrostatic discharge	Human-body model (HBM), per ANSI/ESDA/JEDEC JS-001 ⁽¹⁾	±500 ⁽²⁾	V

- (1) JEDEC document JEP155 states that 500-V HBM allows safe manufacturing with a standard ESD control process.
- (2) The ESD information listed is for the SOIC package.

6.3 Recommended Operating Conditions

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

		MIN	MAX	UNIT
Supply Voltage			18	V
Temperature, T _A		0	70	°C
Operating junction temperature, T _J			70	°C

6.4 Thermal Information

THERMAL METRIC ⁽¹⁾	LM555			UNIT
	PDIP	SOIC	VSSOP	
	8 PINS			
R _{θJA} Junction-to-ambient thermal resistance	106	170	204	°C/W

- (1) For more information about traditional and new thermal metrics, see the *IC Package Thermal Metrics* application report, [SPRA953](#).

6.5 Electrical Characteristics

 $(T_A = 25^\circ\text{C}, V_{CC} = 5\text{ V to } 15\text{ V}, \text{ unless otherwise specified})^{(1)(2)}$

PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
Supply Voltage		4.5		16	V
Supply Current	$V_{CC} = 5\text{ V}, R_L = \infty$		3	6	mA
	$V_{CC} = 15\text{ V}, R_L = \infty$ (Low State) ⁽³⁾		10	15	
Timing Error, Monostable					
Initial Accuracy			1 %		
Drift with Temperature	$R_A = 1\text{ k to } 100\text{ k}\Omega,$		50		ppm/°C
	$C = 0.1\ \mu\text{F},$ ⁽⁴⁾				
Accuracy over Temperature			1.5 %		
Drift with Supply			0.1 %		V
Timing Error, Astable					
Initial Accuracy			2.25		
Drift with Temperature	$R_A, R_B = 1\text{ k to } 100\text{ k}\Omega,$		150		ppm/°C
	$C = 0.1\ \mu\text{F},$ ⁽⁴⁾				
Accuracy over Temperature			3.0%		
Drift with Supply			0.30 %		V
Threshold Voltage			0.667		$\times V_{CC}$
Trigger Voltage	$V_{CC} = 15\text{ V}$		5		V
	$V_{CC} = 5\text{ V}$		1.67		V
Trigger Current			0.5	0.9	μA
Reset Voltage		0.4	0.5	1	V
Reset Current			0.1	0.4	mA
Threshold Current	⁽⁵⁾		0.1	0.25	μA
Control Voltage Level	$V_{CC} = 15\text{ V}$	9	10	11	V
	$V_{CC} = 5\text{ V}$	2.6	3.33	4	
Pin 7 Leakage Output High			1	100	nA
Pin 7 Sat ⁽⁶⁾					
Output Low	$V_{CC} = 15\text{ V}, I_T = 15\text{ mA}$		180		mV
Output Low	$V_{CC} = 4.5\text{ V}, I_T = 4.5\text{ mA}$		80	200	mV
Output Voltage Drop (Low)	$V_{CC} = 15\text{ V}$				
	$I_{SINK} = 10\text{ mA}$		0.1	0.25	V
	$I_{SINK} = 50\text{ mA}$		0.4	0.75	V
	$I_{SINK} = 100\text{ mA}$		2	2.5	V
	$I_{SINK} = 200\text{ mA}$		2.5		V
	$V_{CC} = 5\text{ V}$				
	$I_{SINK} = 8\text{ mA}$				V
$I_{SINK} = 5\text{ mA}$		0.25	0.35	V	

(1) All voltages are measured with respect to the ground pin, unless otherwise specified.

(2) **Absolute Maximum Ratings** indicate limits beyond which damage to the device may occur. **Recommended Operating Conditions** indicate conditions for which the device is functional, but do not ensure specific performance limits. **Electrical Characteristics** state DC and AC electrical specifications under particular test conditions which ensures specific performance limits. This assumes that the device is within the **Recommended Operating Conditions**. Specifications are not ensured for parameters where no limit is given, however, the typical value is a good indication of device performance.

(3) Supply current when output high typically 1 mA less at $V_{CC} = 5\text{ V}$.

(4) Tested at $V_{CC} = 5\text{ V}$ and $V_{CC} = 15\text{ V}$.

(5) This will determine the maximum value of $R_A + R_B$ for 15 V operation. The maximum total ($R_A + R_B$) is 20 M Ω .

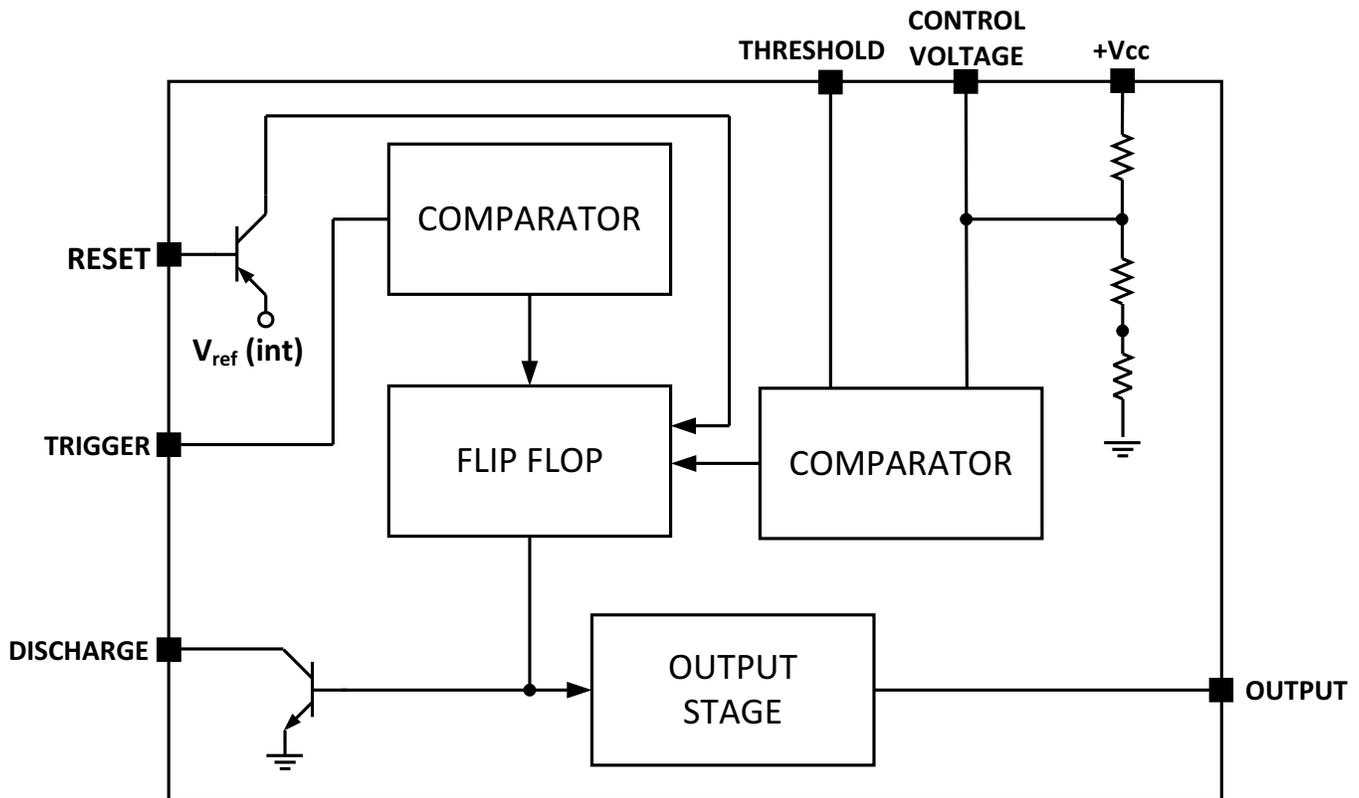
(6) No protection against excessive pin 7 current is necessary providing the package dissipation rating will not be exceeded.

7 Detailed Description

7.1 Overview

The LM555 is a highly stable device for generating accurate time delays or oscillation. Additional terminals are provided for triggering or resetting if desired. In the time delay mode of operation, the time is precisely controlled by one external resistor and capacitor. For astable operation as an oscillator, the free running frequency and duty cycle are accurately controlled with two external resistors and one capacitor. The circuit may be triggered and reset on falling waveforms, and the output circuit can source or sink up to 200mA or driver TTL circuits. The LM555 are available in 8-pin PDIP, SOIC, and VSSOP packages and is a direct replacement for SE555/NE555.

7.2 Functional Block Diagram



7.3 Feature Description

7.3.1 Direct Replacement for SE555/NE555

The LM555 timer is a direct replacement for SE555 and NE555. It is pin-to-pin compatible so that no schematic or layout changes are necessary. The LM555 come in an 8-pin PDIP, SOIC, and VSSOP package.

7.3.2 Timing From Microseconds Through Hours

The LM555 has the ability to have timing parameters from the microseconds range to hours. The time delay of the system can be determined by the time constant of the R and C value used for either the monostable or astable configuration. A nomograph is available for easy determination of R and C values for various time delays.

7.3.3 Operates in Both Astable and Monostable Mode

The LM555 can operate in both astable and monostable mode depending on the application requirements.

- Monostable mode: The LM555 timer acts as a “one-shot” pulse generator. The pulse begins when the LM555 timer receives a signal at the trigger input that falls below a 1/3 of the voltage supply. The width of the output pulse is determined by the time constant of an RC network. The output pulse ends when the voltage on the

Feature Description (continued)

capacitor equals $2/3$ of the supply voltage. The output pulse width can be extended or shortened depending on the application by adjusting the R and C values.

- Astable (free-running) mode: The LM555 timer can operate as an oscillator and puts out a continuous stream of rectangular pulses having a specified frequency. The frequency of the pulse stream depends on the values of R_A , R_B , and C.

7.4 Device Functional Modes

7.4.1 Monostable Operation

In this mode of operation, the timer functions as a one-shot (Figure 11). The external capacitor is initially held discharged by a transistor inside the timer. Upon application of a negative trigger pulse of less than $1/3 V_{CC}$ to pin 2, the flip-flop is set which both releases the short circuit across the capacitor and drives the output high.

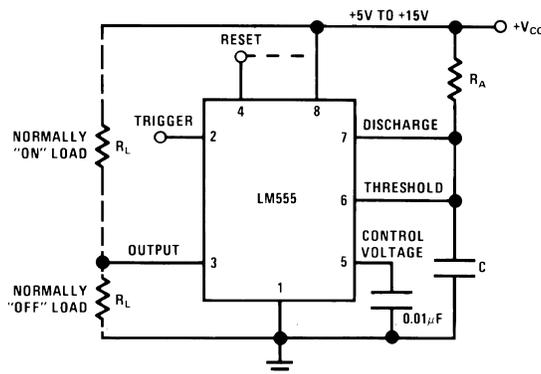
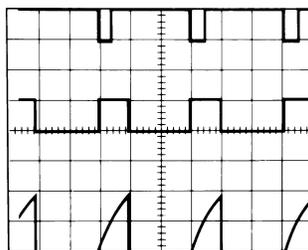


Figure 11. Monostable

The voltage across the capacitor then increases exponentially for a period of $t = 1.1 R_A C$, at the end of which time the voltage equals $2/3 V_{CC}$. The comparator then resets the flip-flop which in turn discharges the capacitor and drives the output to its low state. Figure 12 shows the waveforms generated in this mode of operation. Since the charge and the threshold level of the comparator are both directly proportional to supply voltage, the timing interval is independent of supply.



$V_{CC} = 5\text{ V}$
 TIME = 0.1 ms/DIV.
 $R_A = 9.1\text{ k}\Omega$
 $C = 0.01\text{ }\mu\text{F}$

Top Trace: Input 5V/Div.
 Middle Trace: Output 5V/Div.
 Bottom Trace: Capacitor Voltage 2V/Div.

Figure 12. Monostable Waveforms

During the timing cycle when the output is high, the further application of a trigger pulse will not effect the circuit so long as the trigger input is returned high at least $10\text{ }\mu\text{s}$ before the end of the timing interval. However the circuit can be reset during this time by the application of a negative pulse to the reset terminal (pin 4). The output will then remain in the low state until a trigger pulse is again applied.

When the reset function is not in use, TI recommends connecting the Reset pin to V_{CC} to avoid any possibility of false triggering.

Device Functional Modes (continued)

Figure 13 is a nomograph for easy determination of R, C values for various time delays.

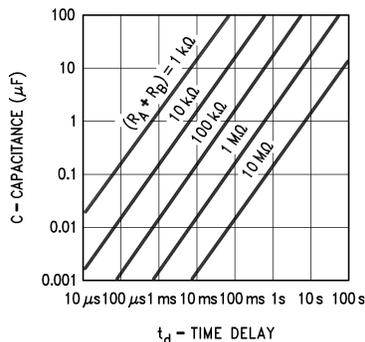


Figure 13. Time Delay

7.4.2 Astable Operation

If the circuit is connected as shown in Figure 14 (pins 2 and 6 connected) it will trigger itself and free run as a multivibrator. The external capacitor charges through $R_A + R_B$ and discharges through R_B . Thus the duty cycle may be precisely set by the ratio of these two resistors.

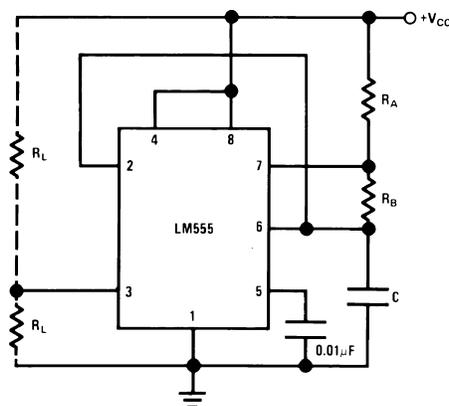
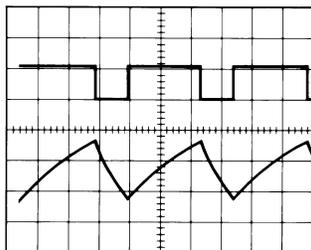


Figure 14. Astable

In this mode of operation, the capacitor charges and discharges between $1/3 V_{CC}$ and $2/3 V_{CC}$. As in the triggered mode, the charge and discharge times, and therefore the frequency are independent of the supply voltage.

Figure 15 shows the waveforms generated in this mode of operation.

Device Functional Modes (continued)



$V_{CC} = 5\text{ V}$
 $\text{TIME} = 20\mu\text{s}/\text{DIV.}$
 $R_A = 3.9\text{ k}\Omega$
 $R_B = 3\text{ k}\Omega$
 $C = 0.01\text{ }\mu\text{F}$

Top Trace: Output 5V/Div.
 Bottom Trace: Capacitor Voltage 1V/Div.

Figure 15. Astable Waveforms

The charge time (output high) is given by:

$$t_1 = 0.693 (R_A + R_B) C \tag{1}$$

And the discharge time (output low) by:

$$t_2 = 0.693 R_B C \tag{2}$$

Thus the total period is:

$$T = t_1 + t_2 = 0.693 (R_A + 2R_B) C \tag{3}$$

The frequency of oscillation is:

$$f = \frac{1}{T} = \frac{1.44}{(R_A + 2R_B) C} \tag{4}$$

Figure 16 may be used for quick determination of these RC values.

The duty cycle is:

$$D = \frac{R_B}{R_A + 2R_B} \tag{5}$$

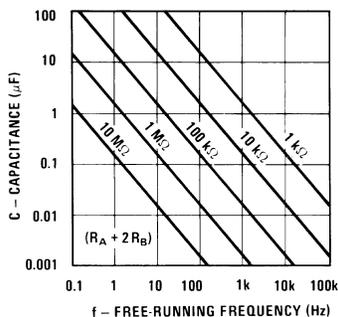


Figure 16. Free Running Frequency

9 Power Supply Recommendations

The LM555 requires a voltage supply within 4.5 V to 16 V. Adequate power supply bypassing is necessary to protect associated circuitry. The minimum recommended capacitor value is 0.1 μF in parallel with a 1- μF electrolytic capacitor. Place the bypass capacitors as close as possible to the LM555 and minimize the trace length.

10 Layout

10.1 Layout Guidelines

Standard PCB rules apply to routing the LM555. The 0.1- μF capacitor in parallel with a 1- μF electrolytic capacitor should be as close as possible to the LM555. The capacitor used for the time delay should also be placed as close to the discharge pin. A ground plane on the bottom layer can be used to provide better noise immunity and signal integrity.

Figure 20 is the basic layout for various applications.

- C1 – based on time delay calculations
- C2 – 0.01- μF bypass capacitor for control voltage pin
- C3 – 0.1- μF bypass ceramic capacitor
- C4 – 1- μF electrolytic bypass capacitor
- R1 – based on time delay calculations
- U1 – LMC555

10.2 Layout Example

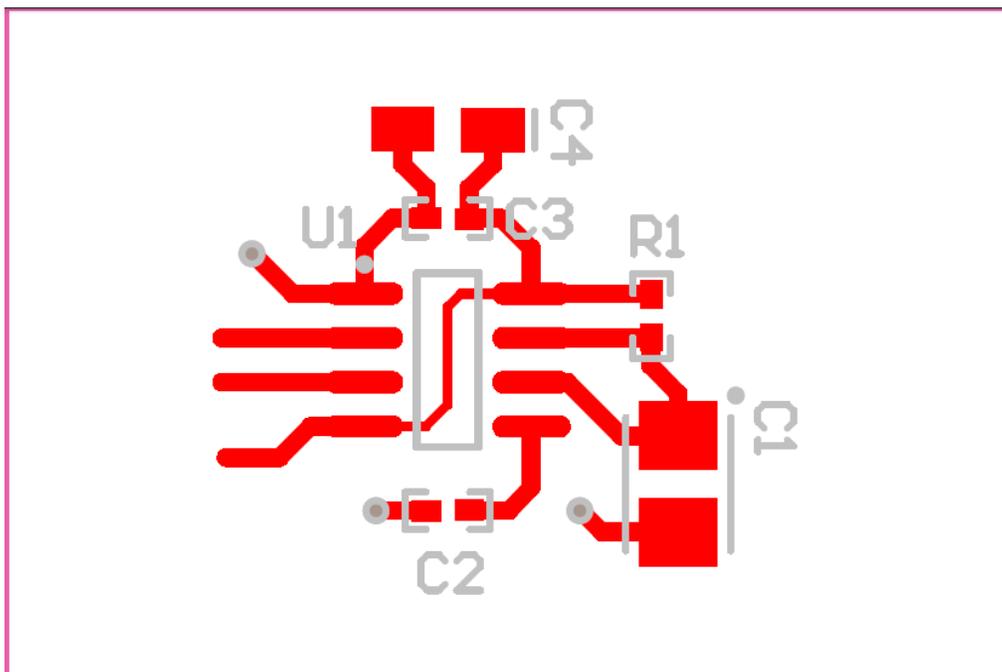


Figure 20. Layout Example

MIXED SIGNAL MICROCONTROLLER

FEATURES

- **Low Supply-Voltage Range: 1.8 V to 3.6 V**
- **Ultra-Low Power Consumption**
 - **Active Mode: 230 μ A at 1 MHz, 2.2 V**
 - **Standby Mode: 0.5 μ A**
 - **Off Mode (RAM Retention): 0.1 μ A**
- **Five Power-Saving Modes**
- **Ultra-Fast Wake-Up From Standby Mode in Less Than 1 μ s**
- **16-Bit RISC Architecture, 62.5-ns Instruction Cycle Time**
- **Basic Clock Module Configurations**
 - **Internal Frequencies up to 16 MHz With Four Calibrated Frequency**
 - **Internal Very-Low-Power Low-Frequency (LF) Oscillator**
 - **32-kHz Crystal**
 - **External Digital Clock Source**
- **Two 16-Bit Timer_A With Three Capture/Compare Registers**
- **Up to 24 Capacitive-Touch Enabled I/O Pins**
- **Universal Serial Communication Interface (USCI)**
 - **Enhanced UART Supporting Auto Baudrate Detection (LIN)**
 - **IrDA Encoder and Decoder**
 - **Synchronous SPI**
 - **I²C™**
- **On-Chip Comparator for Analog Signal Compare Function or Slope Analog-to-Digital (A/D) Conversion**
- **10-Bit 200-kSPS Analog-to-Digital (A/D) Converter With Internal Reference, Sample-and-Hold, and Autoscan (See [Table 1](#))**
- **Brownout Detector**
- **Serial Onboard Programming, No External Programming Voltage Needed, Programmable Code Protection by Security Fuse**
- **On-Chip Emulation Logic With Spy-Bi-Wire Interface**
- **Family Members are Summarized in [Table 1](#)**
- **Package Options**
 - **TSSOP: 20 Pin, 28 Pin**
 - **PDIP: 20 Pin**
 - **QFN: 32 Pin**
- **For Complete Module Descriptions, See the *MSP430x2xx Family User's Guide (SLAU144)***

DESCRIPTION

The Texas Instruments MSP430 family of ultra-low-power microcontrollers consists of several devices featuring different sets of peripherals targeted for various applications. The architecture, combined with five low-power modes, is optimized to achieve extended battery life in portable measurement applications. The device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows wake-up from low-power modes to active mode in less than 1 μ s.

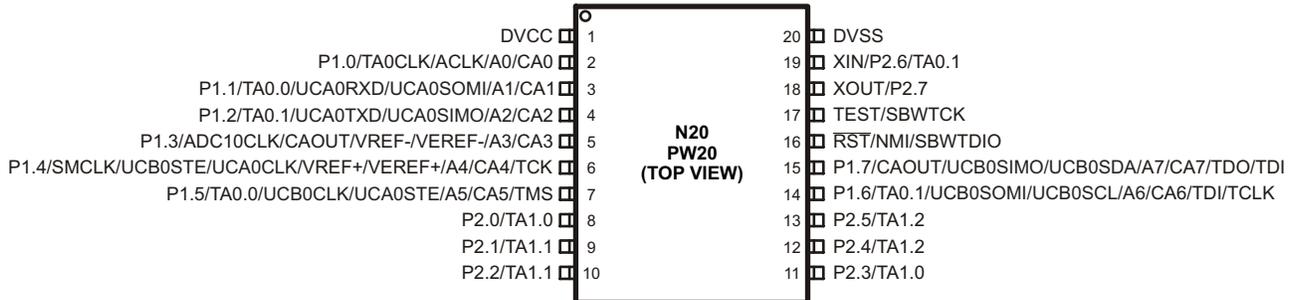
The MSP430G2x13 and MSP430G2x53 series are ultra-low-power mixed signal microcontrollers with built-in 16-bit timers, up to 24 I/O capacitive-touch enabled pins, a versatile analog comparator, and built-in communication capability using the universal serial communication interface. In addition the MSP430G2x53 family members have a 10-bit analog-to-digital (A/D) converter. For configuration details see [Table 1](#).

Typical applications include low-cost sensor systems that capture analog signals, convert them to digital values, and then process the data for display or for transmission to a host system.



Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this data sheet.

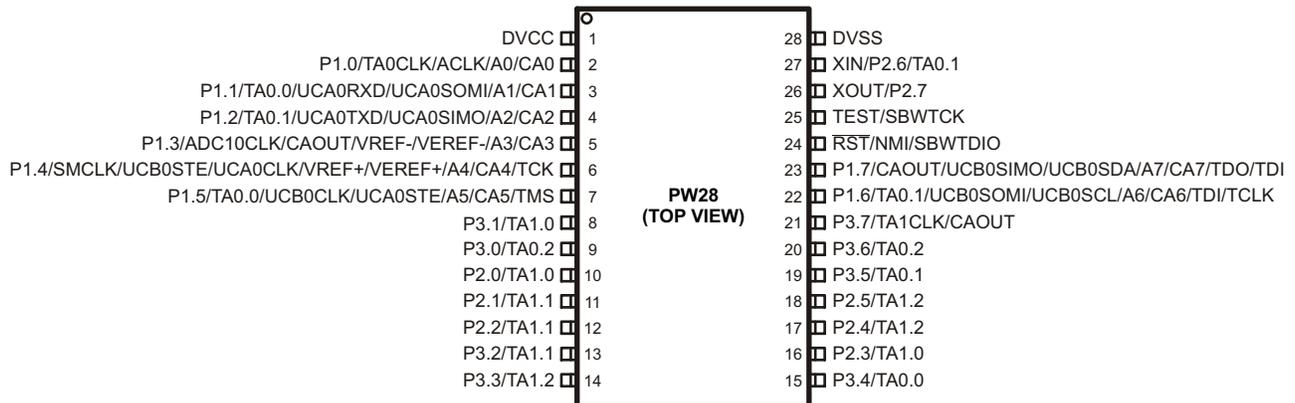
Device Pinout, MSP430G2x13 and MSP430G2x53, 20-Pin Devices, TSSOP and PDIP



NOTE: ADC10 is available on MSP430G2x53 devices only.

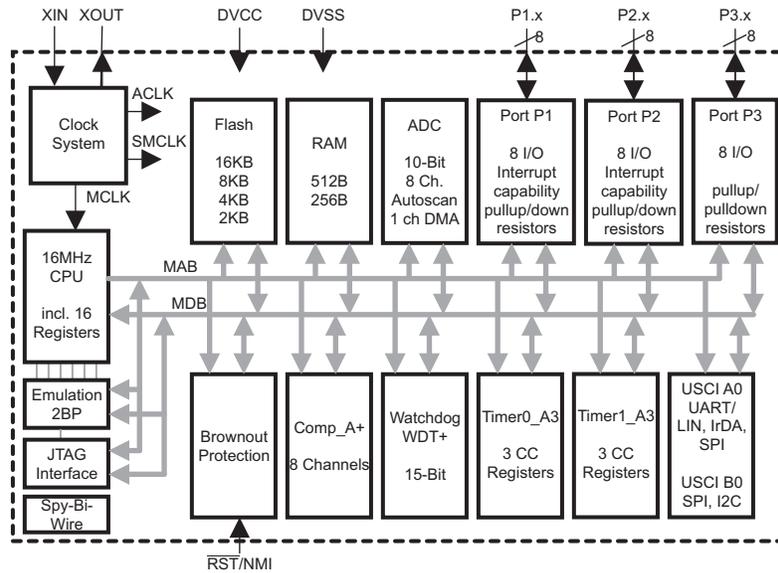
NOTE: The pulldown resistors of port P3 should be enabled by setting P3REN.x = 1.

Device Pinout, MSP430G2x13 and MSP430G2x53, 28-Pin Devices, TSSOP



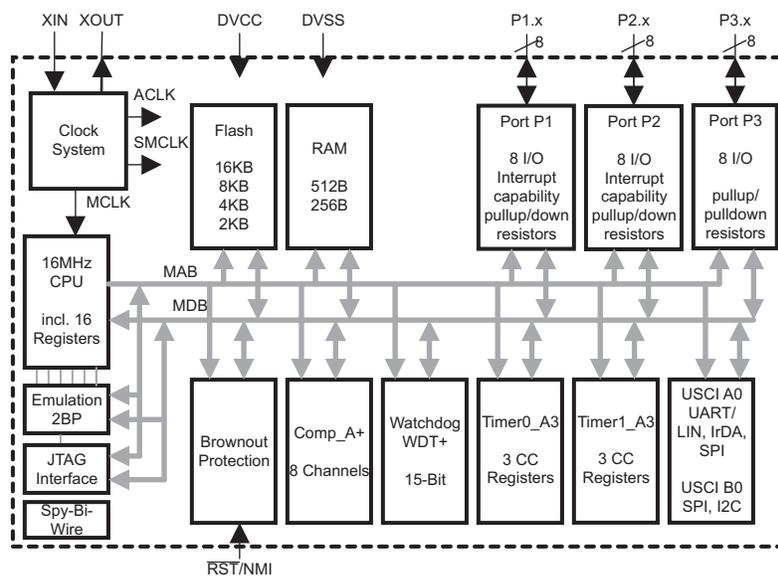
NOTE: ADC10 is available on MSP430G2x53 devices only.

Functional Block Diagram, MSP430G2x53



NOTE: Port P3 is available on 28-pin and 32-pin devices only.

Functional Block Diagram, MSP430G2x13



NOTE: Port P3 is available on 28-pin and 32-pin devices only.

Table 2. Terminal Functions

NAME	TERMINAL			I/O	DESCRIPTION
	NO.				
	PW20, N20	PW28	RHB32		
P1.0/ TA0CLK/ ACLK/ A0 CA0	2	2	31	I/O	General-purpose digital I/O pin Timer0_A, clock signal TACLK input ACLK signal output ADC10 analog input A0 ⁽¹⁾ Comparator_A+, CA0 input
P1.1/ TA0.0/ UCA0RXD/ UCA0SOMI/ A1/ CA1	3	3	1	I/O	General-purpose digital I/O pin Timer0_A, capture: CC10A input, compare: Out0 output / BSL transmit USCI_A0 UART mode: receive data input USCI_A0 SPI mode: slave data out/master in ADC10 analog input A1 ⁽¹⁾ Comparator_A+, CA1 input
P1.2/ TA0.1/ UCA0TXD/ UCA0SIMO/ A2/ CA2	4	4	2	I/O	General-purpose digital I/O pin Timer0_A, capture: CC11A input, compare: Out1 output USCI_A0 UART mode: transmit data output USCI_A0 SPI mode: slave data in/master out ADC10 analog input A2 ⁽¹⁾ Comparator_A+, CA2 input
P1.3/ ADC10CLK/ A3/ VREF-/VEREF-/ CA3/ CAOUT	5	5	3	I/O	General-purpose digital I/O pin ADC10, conversion clock output ⁽¹⁾ ADC10 analog input A3 ⁽¹⁾ ADC10 negative reference voltage ⁽¹⁾ Comparator_A+, CA3 input Comparator_A+, output
P1.4/ SMCLK/ UCB0STE/ UCA0CLK/ A4/ VREF+/VEREF+/ CA4/ TCK	6	6	4	I/O	General-purpose digital I/O pin SMCLK signal output USCI_B0 slave transmit enable USCI_A0 clock input/output ADC10 analog input A4 ⁽¹⁾ ADC10 positive reference voltage ⁽¹⁾ Comparator_A+, CA4 input JTAG test clock, input terminal for device programming and test
P1.5/ TA0.0/ UCB0CLK/ UCA0STE/ A5/ CA5/ TMS	7	7	5	I/O	General-purpose digital I/O pin Timer0_A, compare: Out0 output / BSL receive USCI_B0 clock input/output USCI_A0 slave transmit enable ADC10 analog input A5 ⁽¹⁾ Comparator_A+, CA5 input JTAG test mode select, input terminal for device programming and test

(1) MSP430G2x53 devices only

Table 2. Terminal Functions (continued)

NAME	TERMINAL			I/O	DESCRIPTION
	NO.				
	PW20, N20	PW28	RHB32		
P1.6/ TA0.1/ A6/ CA6/ UCB0SOMI/ UCB0SCL/ TDI/TCLK	14	22	21	I/O	General-purpose digital I/O pin Timer0_A, compare: Out1 output ADC10 analog input A6 ⁽¹⁾ Comparator_A+, CA6 input USCI_B0 SPI mode: slave out master in USCI_B0 I2C mode: SCL I2C clock JTAG test data input or test clock input during programming and test
P1.7/ A7/ CA7/ CAOUT/ UCB0SIMO/ UCB0SDA/ TDO/TDI	15	23	22	I/O	General-purpose digital I/O pin ADC10 analog input A7 ⁽¹⁾ Comparator_A+, CA7 input Comparator_A+, output USCI_B0 SPI mode: slave in master out USCI_B0 I2C mode: SDA I2C data JTAG test data output terminal or test data input during programming and test ⁽²⁾
P2.0/ TA1.0	8	10	9	I/O	General-purpose digital I/O pin Timer1_A, capture: CCI0A input, compare: Out0 output
P2.1/ TA1.1	9	11	10	I/O	General-purpose digital I/O pin Timer1_A, capture: CCI1A input, compare: Out1 output
P2.2/ TA1.1	10	12	11	I/O	General-purpose digital I/O pin Timer1_A, capture: CCI1B input, compare: Out1 output
P2.3/ TA1.0	11	16	15	I/O	General-purpose digital I/O pin Timer1_A, capture: CCI0B input, compare: Out0 output
P2.4/ TA1.2	12	17	16	I/O	General-purpose digital I/O pin Timer1_A, capture: CCI2A input, compare: Out2 output
P2.5/ TA1.2	13	18	17	I/O	General-purpose digital I/O pin Timer1_A, capture: CCI2B input, compare: Out2 output
XIN/ P2.6/ TA0.1	19	27	26	I/O	Input terminal of crystal oscillator General-purpose digital I/O pin Timer0_A, compare: Out1 output
XOUT/ P2.7	18	26	25	I/O	Output terminal of crystal oscillator ⁽³⁾ General-purpose digital I/O pin
P3.0/ TA0.2	-	9	7	I/O	General-purpose digital I/O pin Timer0_A, capture: CCI2A input, compare: Out2 output
P3.1/ TA1.0	-	8	6	I/O	General-purpose digital I/O pin Timer1_A, compare: Out0 output
P3.2/ TA1.1	-	13	12	I/O	General-purpose digital I/O pin Timer1_A, compare: Out1 output
P3.3/ TA1.2	-	14	13	I/O	General-purpose digital I/O Timer1_A, compare: Out2 output
P3.4/ TA0.0	-	15	14	I/O	General-purpose digital I/O Timer0_A, compare: Out0 output

(2) TDO or TDI is selected via JTAG instruction.

(3) If XOUT/P2.7 is used as an input, excess current flows until P2SEL.7 is cleared. This is due to the oscillator output driver connection to this pad after reset.

Table 2. Terminal Functions (continued)

NAME	TERMINAL			I/O	DESCRIPTION
	NO.				
	PW20, N20	PW28	RHB32		
P3.5/ TA0.1	-	19	18	I/O	General-purpose digital I/O Timer0_A, compare: Out1 output
P3.6/ TA0.2	-	20	19	I/O	General-purpose digital I/O Timer0_A, compare: Out2 output
P3.7/ TA1CLK/ CAOUT	-	21	20	I/O	General-purpose digital I/O Timer1_A, clock signal TACLK input Comparator_A+, output
$\overline{\text{RST}}$ / NMI/ SBWTDIO	16	24	23	I	Reset Nonmaskable interrupt input Spy-Bi-Wire test data input/output during programming and test
TEST/ SBWTCK	17	25	24	I	Selects test mode for JTAG pins on Port 1. The device protection fuse is connected to TEST. Spy-Bi-Wire test clock input during programming and test
AVCC	NA	NA	29	NA	Analog supply voltage
DVCC	1	1	30	NA	Digital supply voltage
DVSS	20	28	27, 28	NA	Ground reference
NC	NA	NA	8, 32	NA	Not connected
QFN Pad	NA	NA	Pad	NA	QFN package pad. Connection to VSS is recommended.

SHORT-FORM DESCRIPTION

CPU

The MSP430 CPU has a 16-bit RISC architecture that is highly transparent to the application. All operations, other than program-flow instructions, are performed as register operations in conjunction with seven addressing modes for source operand and four addressing modes for destination operand.

The CPU is integrated with 16 registers that provide reduced instruction execution time. The register-to-register operation execution time is one cycle of the CPU clock.

Four of the registers, R0 to R3, are dedicated as program counter, stack pointer, status register, and constant generator, respectively. The remaining registers are general-purpose registers.

Peripherals are connected to the CPU using data, address, and control buses, and can be handled with all instructions.

The instruction set consists of the original 51 instructions with three formats and seven address modes and additional instructions for the expanded address range. Each instruction can operate on word and byte data.

Instruction Set

The instruction set consists of 51 instructions with three formats and seven address modes. Each instruction can operate on word and byte data. [Table 3](#) shows examples of the three types of instruction formats; [Table 4](#) shows the address modes.

Program Counter	PC/R0
Stack Pointer	SP/R1
Status Register	SR/CG1/R2
Constant Generator	CG2/R3
General-Purpose Register	R4
General-Purpose Register	R5
General-Purpose Register	R6
General-Purpose Register	R7
General-Purpose Register	R8
General-Purpose Register	R9
General-Purpose Register	R10
General-Purpose Register	R11
General-Purpose Register	R12
General-Purpose Register	R13
General-Purpose Register	R14
General-Purpose Register	R15

Table 3. Instruction Word Formats

INSTRUCTION FORMAT	EXAMPLE	OPERATION
Dual operands, source-destination	ADD R4,R5	R4 + R5 --> R5
Single operands, destination only	CALL R8	PC -->(TOS), R8-> PC
Relative jump, un/conditional	JNE	Jump-on-equal bit = 0

Table 4. Address Mode Descriptions⁽¹⁾

ADDRESS MODE	S	D	SYNTAX	EXAMPLE	OPERATION
Register	✓	✓	MOV Rs,Rd	MOV R10,R11	R10 -- --> R11
Indexed	✓	✓	MOV X(Rn),Y(Rm)	MOV 2(R5),6(R6)	M(2+R5) -- --> M(6+R6)
Symbolic (PC relative)	✓	✓	MOV EDE,TONI		M(EDE) -- --> M(TONI)
Absolute	✓	✓	MOV &MEM,&TCDAT		M(MEM) -- --> M(TCDAT)
Indirect	✓		MOV @Rn,Y(Rm)	MOV @R10,Tab(R6)	M(R10) -- --> M(Tab+R6)
Indirect autoincrement	✓		MOV @Rn+,Rm	MOV @R10+,R11	M(R10) -- --> R11 R10 + 2-- --> R10
Immediate	✓		MOV #X,TONI	MOV #45,TONI	#45 -- --> M(TONI)

(1) S = source, D = destination

Operating Modes

The MSP430 has one active mode and five software selectable low-power modes of operation. An interrupt event can wake up the device from any of the low-power modes, service the request, and restore back to the low-power mode on return from the interrupt program.

The following six operating modes can be configured by software:

- Active mode (AM)
 - All clocks are active
- Low-power mode 0 (LPM0)
 - CPU is disabled
 - ACLK and SMCLK remain active, MCLK is disabled
- Low-power mode 1 (LPM1)
 - CPU is disabled
 - ACLK and SMCLK remain active, MCLK is disabled
 - DCO's dc generator is disabled if DCO not used in active mode
- Low-power mode 2 (LPM2)
 - CPU is disabled
 - MCLK and SMCLK are disabled
 - DCO's dc generator remains enabled
 - ACLK remains active
- Low-power mode 3 (LPM3)
 - CPU is disabled
 - MCLK and SMCLK are disabled
 - DCO's dc generator is disabled
 - ACLK remains active
- Low-power mode 4 (LPM4)
 - CPU is disabled
 - ACLK is disabled
 - MCLK and SMCLK are disabled
 - DCO's dc generator is disabled
 - Crystal oscillator is stopped

Absolute Maximum Ratings⁽¹⁾

Voltage applied at V_{CC} to V_{SS}		-0.3 V to 4.1 V
Voltage applied to any pin ⁽²⁾		-0.3 V to $V_{CC} + 0.3$ V
Diode current at any device pin		± 2 mA
Storage temperature range, T_{stg} ⁽³⁾	Unprogrammed device	-55°C to 150°C
	Programmed device	-55°C to 150°C

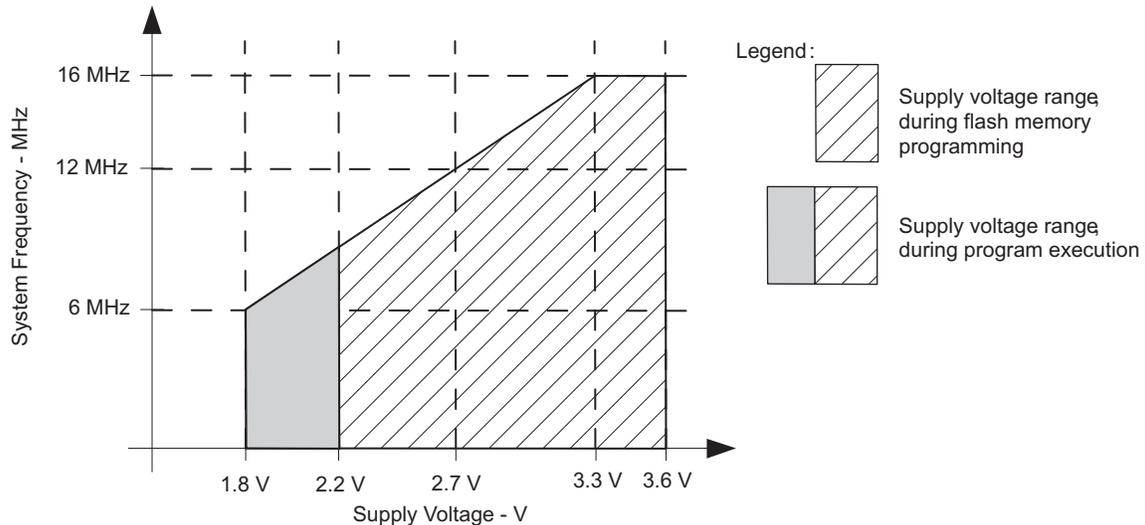
- (1) Stresses beyond those listed under "absolute maximum ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under "recommended operating conditions" is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
- (2) All voltages referenced to V_{SS} . The JTAG fuse-blow voltage, V_{FB} , is allowed to exceed the absolute maximum rating. The voltage is applied to the TEST pin when blowing the JTAG fuse.
- (3) Higher temperature may be applied during board soldering according to the current JEDEC J-STD-020 specification with peak reflow temperatures not higher than classified on the device label on the shipping boxes or reels.

Recommended Operating Conditions

Typical values are specified at $V_{CC} = 3.3$ V and $T_A = 25^\circ\text{C}$ (unless otherwise noted)

		MIN	NOM	MAX	UNIT	
V_{CC}	Supply voltage	During program execution		1.8	V	
		During flash programming or erase		2.2		
V_{SS}	Supply voltage			0	V	
T_A	Operating free-air temperature	I version		-40	85	°C
f_{SYSTEM}	Processor frequency (maximum MCLK frequency) ⁽¹⁾⁽²⁾	$V_{CC} = 1.8$ V, Duty cycle = 50% \pm 10%		dc	6	MHz
		$V_{CC} = 2.7$ V, Duty cycle = 50% \pm 10%		dc	12	
		$V_{CC} = 3.3$ V, Duty cycle = 50% \pm 10%		dc	16	

- (1) The MSP430 CPU is clocked directly with MCLK. Both the high and low phase of MCLK must not exceed the pulse duration of the specified maximum frequency.
- (2) Modules might have a different maximum input clock specification. See the specification of the respective module in this data sheet.



Note: Minimum processor frequency is defined by system clock. Flash program or erase operations require a minimum V_{CC} of 2.2 V.

Figure 1. Safe Operating Area

Electrical Characteristics

Active Mode Supply Current Into V_{CC} Excluding External Current

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)⁽¹⁾⁽²⁾

PARAMETER	TEST CONDITIONS	T_A	V_{CC}	MIN	TYP	MAX	UNIT
$I_{AM,1MHz}$ Active mode (AM) current at 1 MHz	$f_{DCO} = f_{MCLK} = f_{SMCLK} = 1\text{ MHz}$, $f_{ACLK} = 0\text{ Hz}$, Program executes in flash, $BCSCTL1 = CALBC1_1MHz$, $DCOCTL = CALDCO_1MHz$, $CPUOFF = 0$, $SCG0 = 0$, $SCG1 = 0$, $OSCOFF = 0$		2.2 V		230		μA
			3 V		330	420	

(1) All inputs are tied to 0 V or to V_{CC} . Outputs do not source or sink any current.

(2) The currents are characterized with a Micro Crystal CC4V-T1A SMD crystal with a load capacitance of 9 pF. The internal and external load capacitance is chosen to closely match the required 9 pF.

Typical Characteristics, Active Mode Supply Current (Into V_{CC})

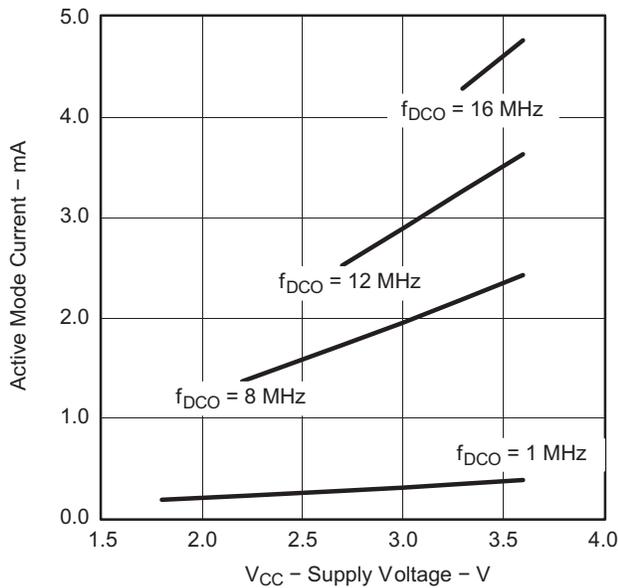


Figure 2. Active Mode Current vs V_{CC} , $T_A = 25^\circ C$

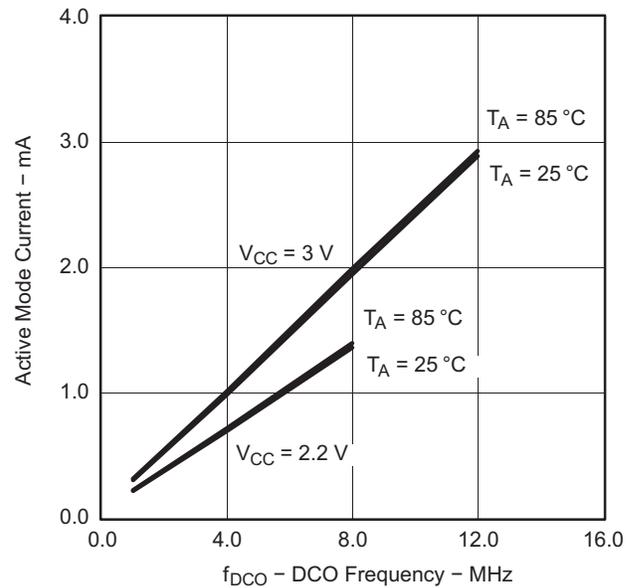


Figure 3. Active Mode Current vs DCO Frequency

Low-Power Mode Supply Currents (Into V_{CC}) Excluding External Current

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)^{(1) (2)}

PARAMETER	TEST CONDITIONS	T_A	V_{CC}	MIN	TYP	MAX	UNIT
$I_{LPM0,1MHz}$ Low-power mode 0 (LPM0) current ⁽³⁾	$f_{MCLK} = 0$ MHz, $f_{SMCLK} = f_{DCO} = 1$ MHz, $f_{ACLK} = 32768$ Hz, BCSCTL1 = CALBC1_1MHZ, DCOCTL = CALDCO_1MHZ, CPUOFF = 1, SCG0 = 0, SCG1 = 0, OSCOFF = 0	25°C	2.2 V		56		μA
I_{LPM2} Low-power mode 2 (LPM2) current ⁽⁴⁾	$f_{MCLK} = f_{SMCLK} = 0$ MHz, $f_{DCO} = 1$ MHz, $f_{ACLK} = 32768$ Hz, BCSCTL1 = CALBC1_1MHZ, DCOCTL = CALDCO_1MHZ, CPUOFF = 1, SCG0 = 0, SCG1 = 1, OSCOFF = 0	25°C	2.2 V		22		μA
$I_{LPM3,LFXT1}$ Low-power mode 3 (LPM3) current ⁽⁴⁾	$f_{DCO} = f_{MCLK} = f_{SMCLK} = 0$ MHz, $f_{ACLK} = 32768$ Hz, CPUOFF = 1, SCG0 = 1, SCG1 = 1, OSCOFF = 0	25°C	2.2 V		0.7	1.5	μA
$I_{LPM3,VLO}$ Low-power mode 3 current, (LPM3) ⁽⁴⁾	$f_{DCO} = f_{MCLK} = f_{SMCLK} = 0$ MHz, f_{ACLK} from internal LF oscillator (VLO), CPUOFF = 1, SCG0 = 1, SCG1 = 1, OSCOFF = 0	25°C	2.2 V		0.5	0.7	μA
I_{LPM4} Low-power mode 4 (LPM4) current ⁽⁵⁾	$f_{DCO} = f_{MCLK} = f_{SMCLK} = 0$ MHz, $f_{ACLK} = 0$ Hz, CPUOFF = 1, SCG0 = 1, SCG1 = 1, OSCOFF = 1	25°C	2.2 V		0.1	0.5	μA
		85°C			0.8	1.7	

- (1) All inputs are tied to 0 V or to V_{CC} . Outputs do not source or sink any current.
- (2) The currents are characterized with a Micro Crystal CC4V-T1A SMD crystal with a load capacitance of 9 pF. The internal and external load capacitance is chosen to closely match the required 9 pF.
- (3) Current for brownout and WDT clocked by SMCLK included.
- (4) Current for brownout and WDT clocked by ACLK included.
- (5) Current for brownout included.

Typical Characteristics, Low-Power Mode Supply Currents

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

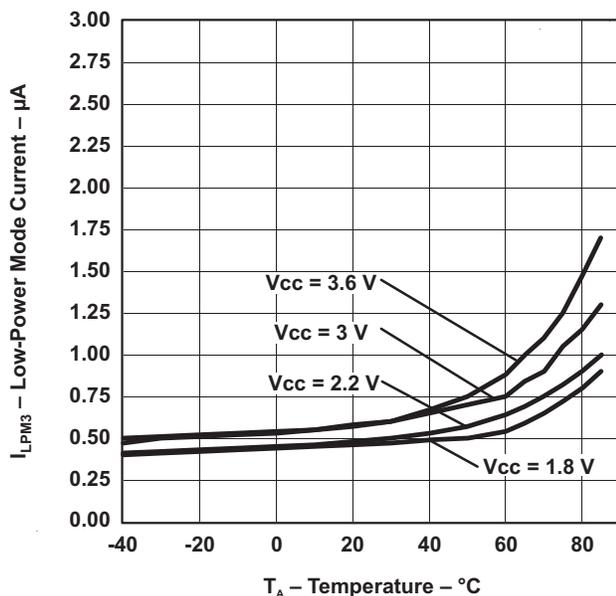


Figure 4. LPM3 Current vs Temperature

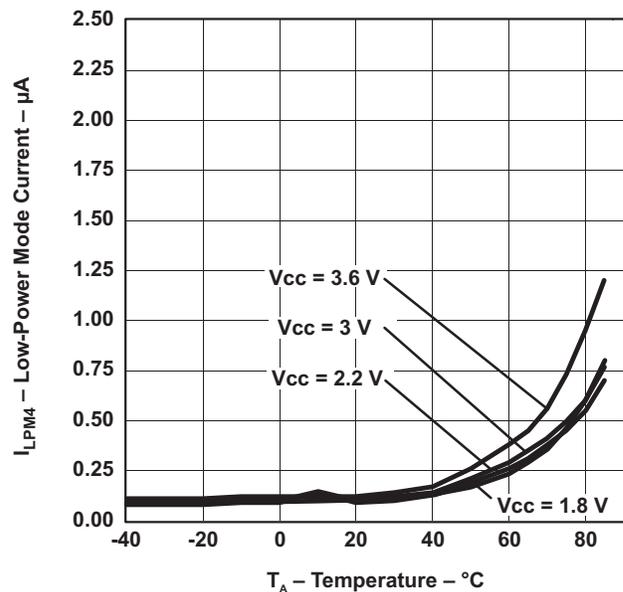


Figure 5. LPM4 Current vs Temperature

Schmitt-Trigger Inputs, Ports Px

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER		TEST CONDITIONS	V _{CC}	MIN	TYP	MAX	UNIT
V _{IT+}	Positive-going input threshold voltage			0.45 V _{CC}		0.75 V _{CC}	V
			3 V	1.35		2.25	
V _{IT-}	Negative-going input threshold voltage			0.25 V _{CC}		0.55 V _{CC}	V
			3 V	0.75		1.65	
V _{hys}	Input voltage hysteresis (V _{IT+} – V _{IT-})		3 V	0.3		1	V
R _{Pull}	Pullup/pulldown resistor	For pullup: V _{IN} = V _{SS} For pulldown: V _{IN} = V _{CC}	3 V	20	35	50	kΩ
C _I	Input capacitance	V _{IN} = V _{SS} or V _{CC}			5		pF

Leakage Current, Ports Px

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER		TEST CONDITIONS	V _{CC}	MIN	MAX	UNIT
I _{lkg(Px.y)}	High-impedance leakage current	(1) (2)	3 V		±50	nA

- (1) The leakage current is measured with V_{SS} or V_{CC} applied to the corresponding pin(s), unless otherwise noted.
- (2) The leakage of the digital port pins is measured individually. The port pin is selected for input and the pullup/pulldown resistor is disabled.

Outputs, Ports Px

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER		TEST CONDITIONS	V _{CC}	MIN	TYP	MAX	UNIT
V _{OH}	High-level output voltage	I _(OHmax) = –6 mA ⁽¹⁾	3 V		V _{CC} – 0.3		V
V _{OL}	Low-level output voltage	I _(OLmax) = 6 mA ⁽¹⁾	3 V		V _{SS} + 0.3		V

- (1) The maximum total current, I_(OHmax) and I_(OLmax), for all outputs combined should not exceed ±48 mA to hold the maximum voltage drop specified.

Output Frequency, Ports Px

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER		TEST CONDITIONS	V _{CC}	MIN	TYP	MAX	UNIT
f _{Px.y}	Port output frequency (with load)	Px.y, C _L = 20 pF, R _L = 1 kΩ ⁽¹⁾ (2)	3 V		12		MHz
f _{Port_CLK}	Clock output frequency	Px.y, C _L = 20 pF ⁽²⁾	3 V		16		MHz

- (1) A resistive divider with two 0.5-kΩ resistors between V_{CC} and V_{SS} is used as load. The output is connected to the center tap of the divider.
- (2) The output voltage reaches at least 10% and 90% V_{CC} at the specified toggle frequency.

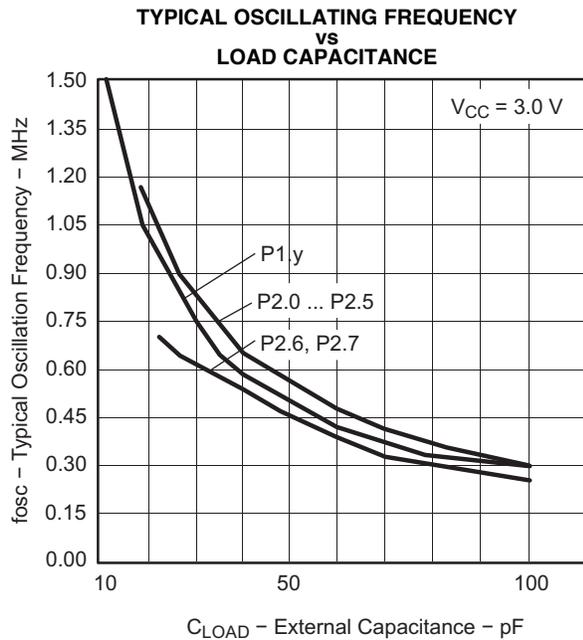
Pin-Oscillator Frequency – Ports Px

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER	TEST CONDITIONS	V _{CC}	MIN	TYP	MAX	UNIT
f _{OP1,x} Port output oscillation frequency	P1.y, C _L = 10 pF, R _L = 100 kΩ ⁽¹⁾⁽²⁾	3 V		1400		kHz
	P1.y, C _L = 20 pF, R _L = 100 kΩ ⁽¹⁾⁽²⁾			900		
f _{OP2,x} Port output oscillation frequency	P2.0 to P2.5, C _L = 10 pF, R _L = 100 kΩ ⁽¹⁾⁽²⁾	3 V		1800		kHz
	P2.0 to P2.5, C _L = 20 pF, R _L = 100 kΩ ⁽¹⁾⁽²⁾			1000		
f _{OP2,6/7} Port output oscillation frequency	P2.6 and P2.7, C _L = 20 pF, R _L = 100 kΩ ⁽¹⁾⁽²⁾	3 V		700		kHz
f _{OP3,x} Port output oscillation frequency	P3.y, C _L = 10 pF, R _L = 100 kΩ ⁽¹⁾⁽²⁾			1800		kHz
	P3.y, C _L = 20 pF, R _L = 100 kΩ ⁽¹⁾⁽²⁾			1000		

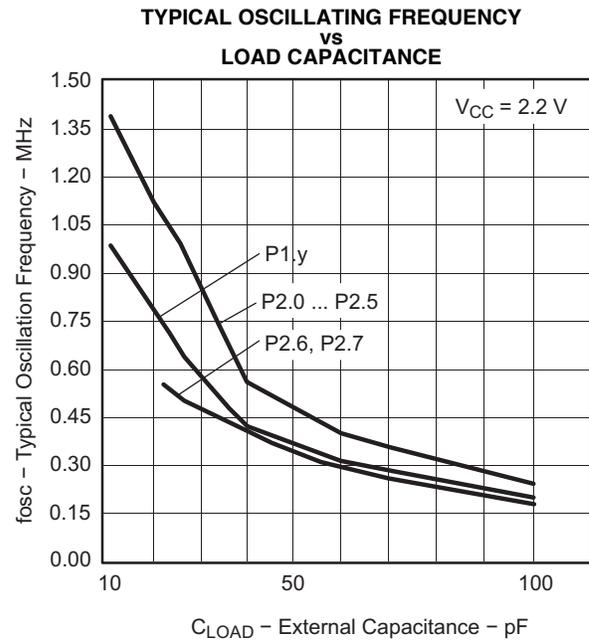
- (1) A resistive divider with two 50-kΩ resistors between V_{CC} and V_{SS} is used as load. The output is connected to the center tap of the divider.
- (2) The output voltage reaches at least 10% and 90% V_{CC} at the specified toggle frequency.

Typical Characteristics, Pin-Oscillator Frequency



A. One output active at a time.

Figure 10.



A. One output active at a time.

Figure 11.

POR, BOR⁽¹⁾⁽²⁾

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER		TEST CONDITIONS	V _{CC}	MIN	TYP	MAX	UNIT
V _{CC(start)}	See Figure 12	dV _{CC} /dt ≤ 3 V/s			0.7 × V _(B_IT-)		V
V _(B_IT-)	See Figure 12 through Figure 14	dV _{CC} /dt ≤ 3 V/s			1.35		V
V _{hys(B_IT-)}	See Figure 12	dV _{CC} /dt ≤ 3 V/s			140		mV
t _{d(BOR)}	See Figure 12				2000		μs
t _(reset)	Pulse duration needed at $\overline{\text{RST/NMI}}$ pin to accepted reset internally		2.2 V	2			μs

- (1) The current consumption of the brownout module is already included in the I_{CC} current consumption data. The voltage level V_(B_IT-) + V_{hys(B_IT-)} is ≤ 1.8 V.
- (2) During power up, the CPU begins code execution following a period of t_{d(BOR)} after V_{CC} = V_(B_IT-) + V_{hys(B_IT-)}. The default DCO settings must not be changed until V_{CC} ≥ V_{CC(min)}, where V_{CC(min)} is the minimum supply voltage for the desired operating frequency.

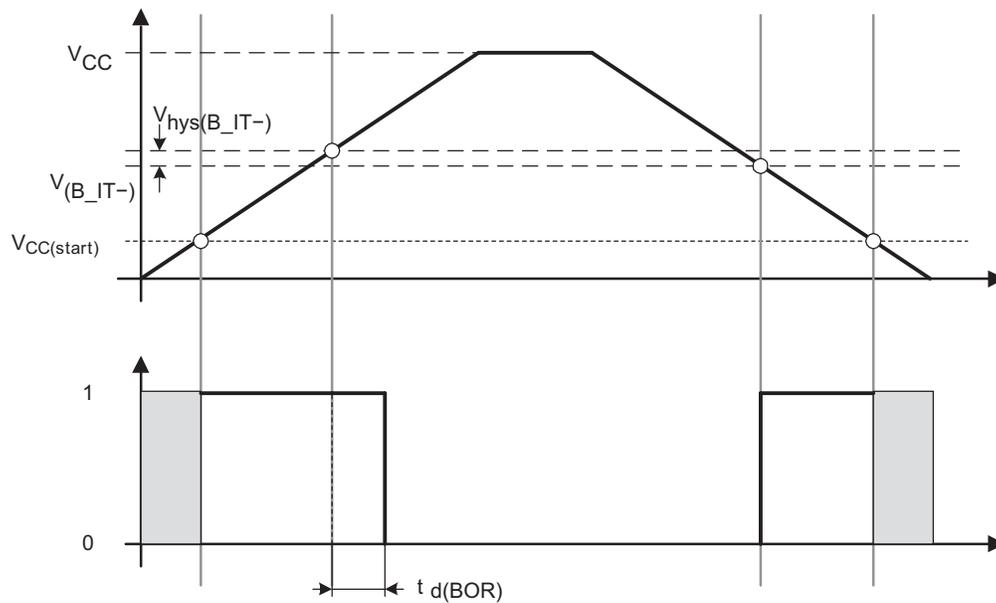


Figure 12. POR and BOR vs Supply Voltage

Typical Characteristics, POR and BOR

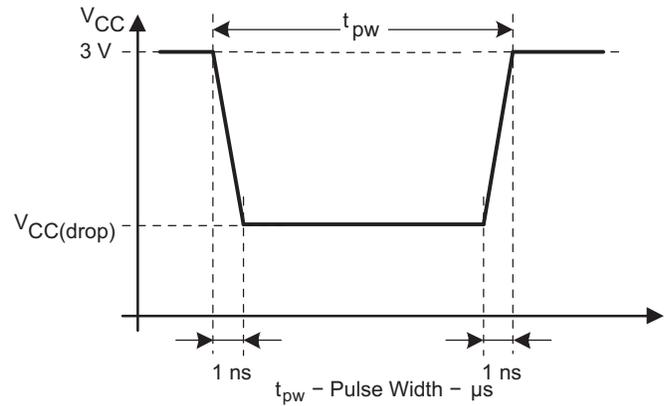
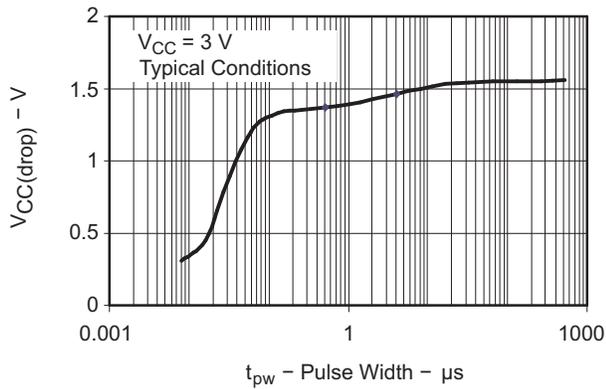


Figure 13. $V_{CC(drop)}$ Level With a Square Voltage Drop to Generate a POR or BOR Signal

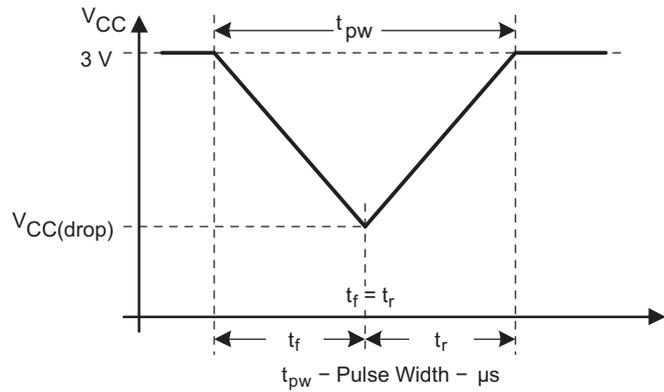
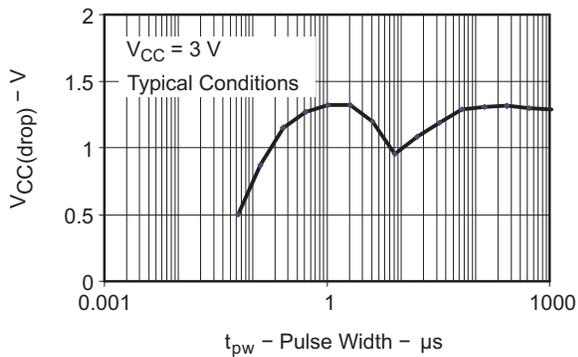


Figure 14. $V_{CC(drop)}$ Level With a Triangle Voltage Drop to Generate a POR or BOR Signal

DCO Frequency

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER		TEST CONDITIONS	V _{CC}	MIN	TYP	MAX	UNIT
V _{CC}	Supply voltage	RSELx < 14		1.8		3.6	V
		RSELx = 14		2.2		3.6	
		RSELx = 15		3		3.6	
f _{DCO(0,0)}	DCO frequency (0, 0)	RSELx = 0, DCOx = 0, MODx = 0	3 V	0.06		0.14	MHz
f _{DCO(0,3)}	DCO frequency (0, 3)	RSELx = 0, DCOx = 3, MODx = 0	3 V	0.07		0.17	MHz
f _{DCO(1,3)}	DCO frequency (1, 3)	RSELx = 1, DCOx = 3, MODx = 0	3 V		0.15		MHz
f _{DCO(2,3)}	DCO frequency (2, 3)	RSELx = 2, DCOx = 3, MODx = 0	3 V		0.21		MHz
f _{DCO(3,3)}	DCO frequency (3, 3)	RSELx = 3, DCOx = 3, MODx = 0	3 V		0.30		MHz
f _{DCO(4,3)}	DCO frequency (4, 3)	RSELx = 4, DCOx = 3, MODx = 0	3 V		0.41		MHz
f _{DCO(5,3)}	DCO frequency (5, 3)	RSELx = 5, DCOx = 3, MODx = 0	3 V		0.58		MHz
f _{DCO(6,3)}	DCO frequency (6, 3)	RSELx = 6, DCOx = 3, MODx = 0	3 V	0.54		1.06	MHz
f _{DCO(7,3)}	DCO frequency (7, 3)	RSELx = 7, DCOx = 3, MODx = 0	3 V	0.80		1.50	MHz
f _{DCO(8,3)}	DCO frequency (8, 3)	RSELx = 8, DCOx = 3, MODx = 0	3 V		1.6		MHz
f _{DCO(9,3)}	DCO frequency (9, 3)	RSELx = 9, DCOx = 3, MODx = 0	3 V		2.3		MHz
f _{DCO(10,3)}	DCO frequency (10, 3)	RSELx = 10, DCOx = 3, MODx = 0	3 V		3.4		MHz
f _{DCO(11,3)}	DCO frequency (11, 3)	RSELx = 11, DCOx = 3, MODx = 0	3 V		4.25		MHz
f _{DCO(12,3)}	DCO frequency (12, 3)	RSELx = 12, DCOx = 3, MODx = 0	3 V	4.30		7.30	MHz
f _{DCO(13,3)}	DCO frequency (13, 3)	RSELx = 13, DCOx = 3, MODx = 0	3 V	6.00	7.8	9.60	MHz
f _{DCO(14,3)}	DCO frequency (14, 3)	RSELx = 14, DCOx = 3, MODx = 0	3 V	8.60		13.9	MHz
f _{DCO(15,3)}	DCO frequency (15, 3)	RSELx = 15, DCOx = 3, MODx = 0	3 V	12.0		18.5	MHz
f _{DCO(15,7)}	DCO frequency (15, 7)	RSELx = 15, DCOx = 7, MODx = 0	3 V	16.0		26.0	MHz
S _{RSEL}	Frequency step between range RSEL and RSEL+1	$S_{RSEL} = f_{DCO(RSEL+1,DCO)} / f_{DCO(RSEL,DCO)}$	3 V		1.35		ratio
S _{DCO}	Frequency step between tap DCO and DCO+1	$S_{DCO} = f_{DCO(RSEL,DCO+1)} / f_{DCO(RSEL,DCO)}$	3 V		1.08		ratio
	Duty cycle	Measured at SMCLK output	3 V		50		%

Calibrated DCO Frequencies, Tolerance

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER	TEST CONDITIONS	T _A	V _{CC}	MIN	TYP	MAX	UNIT
1-MHz tolerance over temperature ⁽¹⁾	BCSCTL1 = CALBC1_1MHZ, DCOCTL = CALDCO_1MHZ, calibrated at 30°C and 3 V	0°C to 85°C	3 V	-3	±0.5	+3	%
1-MHz tolerance over V _{CC}	BCSCTL1 = CALBC1_1MHZ, DCOCTL = CALDCO_1MHZ, calibrated at 30°C and 3 V	30°C	1.8 V to 3.6 V	-3	±2	+3	%
1-MHz tolerance overall	BCSCTL1 = CALBC1_1MHZ, DCOCTL = CALDCO_1MHZ, calibrated at 30°C and 3 V	-40°C to 85°C	1.8 V to 3.6 V	-6	±3	+6	%
8-MHz tolerance over temperature ⁽¹⁾	BCSCTL1 = CALBC1_8MHZ, DCOCTL = CALDCO_8MHZ, calibrated at 30°C and 3 V	0°C to 85°C	3 V	-3	±0.5	+3	%
8-MHz tolerance over V _{CC}	BCSCTL1 = CALBC1_8MHZ, DCOCTL = CALDCO_8MHZ, calibrated at 30°C and 3 V	30°C	2.2 V to 3.6 V	-3	±2	+3	%
8-MHz tolerance overall	BCSCTL1 = CALBC1_8MHZ, DCOCTL = CALDCO_8MHZ, calibrated at 30°C and 3 V	-40°C to 85°C	2.2 V to 3.6 V	-6	±3	+6	%
12-MHz tolerance over temperature ⁽¹⁾	BCSCTL1 = CALBC1_12MHZ, DCOCTL = CALDCO_12MHZ, calibrated at 30°C and 3 V	0°C to 85°C	3 V	-3	±0.5	+3	%
12-MHz tolerance over V _{CC}	BCSCTL1 = CALBC1_12MHZ, DCOCTL = CALDCO_12MHZ, calibrated at 30°C and 3 V	30°C	2.7 V to 3.6 V	-3	±2	+3	%
12-MHz tolerance overall	BCSCTL1 = CALBC1_12MHZ, DCOCTL = CALDCO_12MHZ, calibrated at 30°C and 3 V	-40°C to 85°C	2.7 V to 3.6 V	-6	±3	+6	%
16-MHz tolerance over temperature ⁽¹⁾	BCSCTL1 = CALBC1_16MHZ, DCOCTL = CALDCO_16MHZ, calibrated at 30°C and 3 V	0°C to 85°C	3 V	-3	±0.5	+3	%
16-MHz tolerance over V _{CC}	BCSCTL1 = CALBC1_16MHZ, DCOCTL = CALDCO_16MHZ, calibrated at 30°C and 3 V	30°C	3.3 V to 3.6 V	-3	±2	+3	%
16-MHz tolerance overall	BCSCTL1 = CALBC1_16MHZ, DCOCTL = CALDCO_16MHZ, calibrated at 30°C and 3 V	-40°C to 85°C	3.3 V to 3.6 V	-6	±3	+6	%

(1) This is the frequency change from the measured frequency at 30°C over temperature.

Wake-Up From Lower-Power Modes (LPM3/4)

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER	TEST CONDITIONS	V _{CC}	MIN	TYP	MAX	UNIT
t _{DCO,LPM3/4}	DCO clock wake-up time from LPM3/4 ⁽¹⁾	BCSCTL1 = CALBC1_1MHz, DCOCTL = CALDCO_1MHz	3 V	1.5		μs
t _{CPU,LPM3/4}	CPU wake-up time from LPM3/4 ⁽²⁾			1/f _{MCLK} + t _{Clock,LPM3/4}		

- (1) The DCO clock wake-up time is measured from the edge of an external wake-up signal (e.g., port interrupt) to the first clock edge observable externally on a clock pin (MCLK or SMCLK).
- (2) Parameter applicable only if DCOCLK is used for MCLK.

Typical Characteristics, DCO Clock Wake-Up Time From LPM3/4

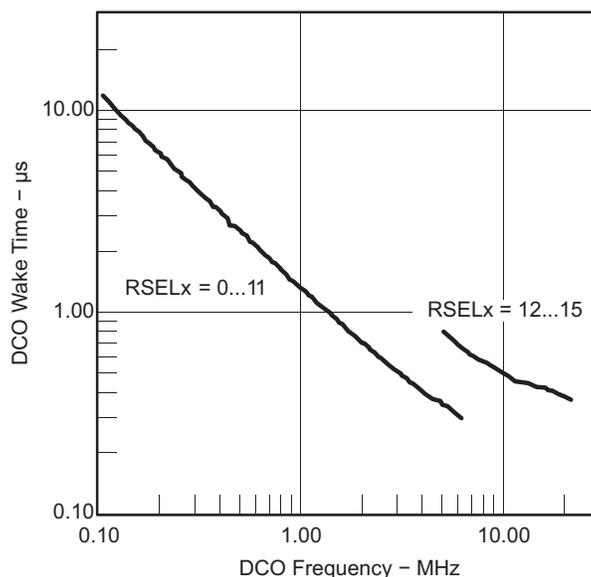


Figure 15. DCO Wake-Up Time From LPM3 vs DCO Frequency

Crystal Oscillator, XT1, Low-Frequency Mode⁽¹⁾

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER		TEST CONDITIONS	V _{CC}	MIN	TYP	MAX	UNIT
f _{LFXT1,LF}	LFXT1 oscillator crystal frequency, LF mode 0, 1	XTS = 0, LFXT1Sx = 0 or 1	1.8 V to 3.6 V		32768		Hz
f _{LFXT1,LF,logic}	LFXT1 oscillator logic level square wave input frequency, LF mode	XTS = 0, XCAPx = 0, LFXT1Sx = 3	1.8 V to 3.6 V	10000	32768	50000	Hz
O _{A,LF}	Oscillation allowance for LF crystals	XTS = 0, LFXT1Sx = 0, f _{LFXT1,LF} = 32768 Hz, C _{L,eff} = 6 pF			500		kΩ
		XTS = 0, LFXT1Sx = 0, f _{LFXT1,LF} = 32768 Hz, C _{L,eff} = 12 pF			200		
C _{L,eff}	Integrated effective load capacitance, LF mode ⁽²⁾	XTS = 0, XCAPx = 0			1		pF
		XTS = 0, XCAPx = 1			5.5		
		XTS = 0, XCAPx = 2			8.5		
		XTS = 0, XCAPx = 3			11		
	Duty cycle, LF mode	XTS = 0, Measured at P2.0/ACLK, f _{LFXT1,LF} = 32768 Hz	2.2 V	30	50	70	%
f _{Fault,LF}	Oscillator fault frequency, LF mode ⁽³⁾	XTS = 0, XCAPx = 0, LFXT1Sx = 3 ⁽⁴⁾	2.2 V	10		10000	Hz

- (1) To improve EMI on the XT1 oscillator, the following guidelines should be observed.
 - (a) Keep the trace between the device and the crystal as short as possible.
 - (b) Design a good ground plane around the oscillator pins.
 - (c) Prevent crosstalk from other clock or data lines into oscillator pins XIN and XOUT.
 - (d) Avoid running PCB traces underneath or adjacent to the XIN and XOUT pins.
 - (e) Use assembly materials and process that avoid any parasitic load on the oscillator XIN and XOUT pins.
 - (f) If a conformal coating is used, ensure that it does not induce capacitive or resistive leakage between the oscillator pins.
 - (g) Do not route the XOUT line to the JTAG header to support the serial programming adapter as shown in other documentation. This signal is no longer required for the serial programming adapter.
- (2) Includes parasitic bond and package capacitance (approximately 2 pF per pin).
Because the PCB adds additional capacitance, it is recommended to verify the correct load by measuring the ACLK frequency. For a correct setup, the effective load capacitance should always match the specification of the used crystal.
- (3) Frequencies below the MIN specification set the fault flag. Frequencies above the MAX specification do not set the fault flag. Frequencies in between might set the flag.
- (4) Measured with logic-level input frequency but also applies to operation with crystals.

Internal Very-Low-Power Low-Frequency Oscillator (VLO)

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER		T _A	V _{CC}	MIN	TYP	MAX	UNIT
f _{VLO}	VLO frequency	-40°C to 85°C	3 V	4	12	20	kHz
df _{VLO} /dT	VLO frequency temperature drift	-40°C to 85°C	3 V		0.5		%/°C
df _{VLO} /dV _{CC}	VLO frequency supply voltage drift	25°C	1.8 V to 3.6 V		4		%/V

Timer_A

over recommended ranges of supply voltage and operating free-air temperature (unless otherwise noted)

PARAMETER		TEST CONDITIONS	V _{CC}	MIN	TYP	MAX	UNIT
f _{TA}	Timer_A input clock frequency	SMCLK, duty cycle = 50% ± 10%			f _{SYSTEM}		MHz
t _{TA,cap}	Timer_A capture timing	TA0, TA1	3 V	20			ns