Wireless DC Motor Speed Control

Senior Design Review

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Contents

1. Introduction

The title of our project is High-performance low-cost low-loss wireless DC motor speed control unit. Nowadays, there are lots of good-quality motor speed controls on the market. However, their costs are relatively high. A speed control with both low cost and good performance will be highly marketable, especially for small mobility applications. On the other hand, the wireless connectivity has a nature of low cost and less environmental limitations. Combining these ideas together, we came up with this project.

Objectives

The wireless remote controller is simple: start, stop, accelerate and decelerate. The source of the speed control is a 12 V battery and control currents over a range of 0 to 50 A. The controller has a high efficiency for motor loads in the range of 50 to 150 W. It should deliver the nominal power continuously and be able to tolerate slight overloading for a short period of time. For strong overloading, it should protect the motor from being damaged for a few seconds, then shut down the motor and request a reset from the user simultaneously. Finally, the total parts cost of the converter does not to exceed $12.

Benefits

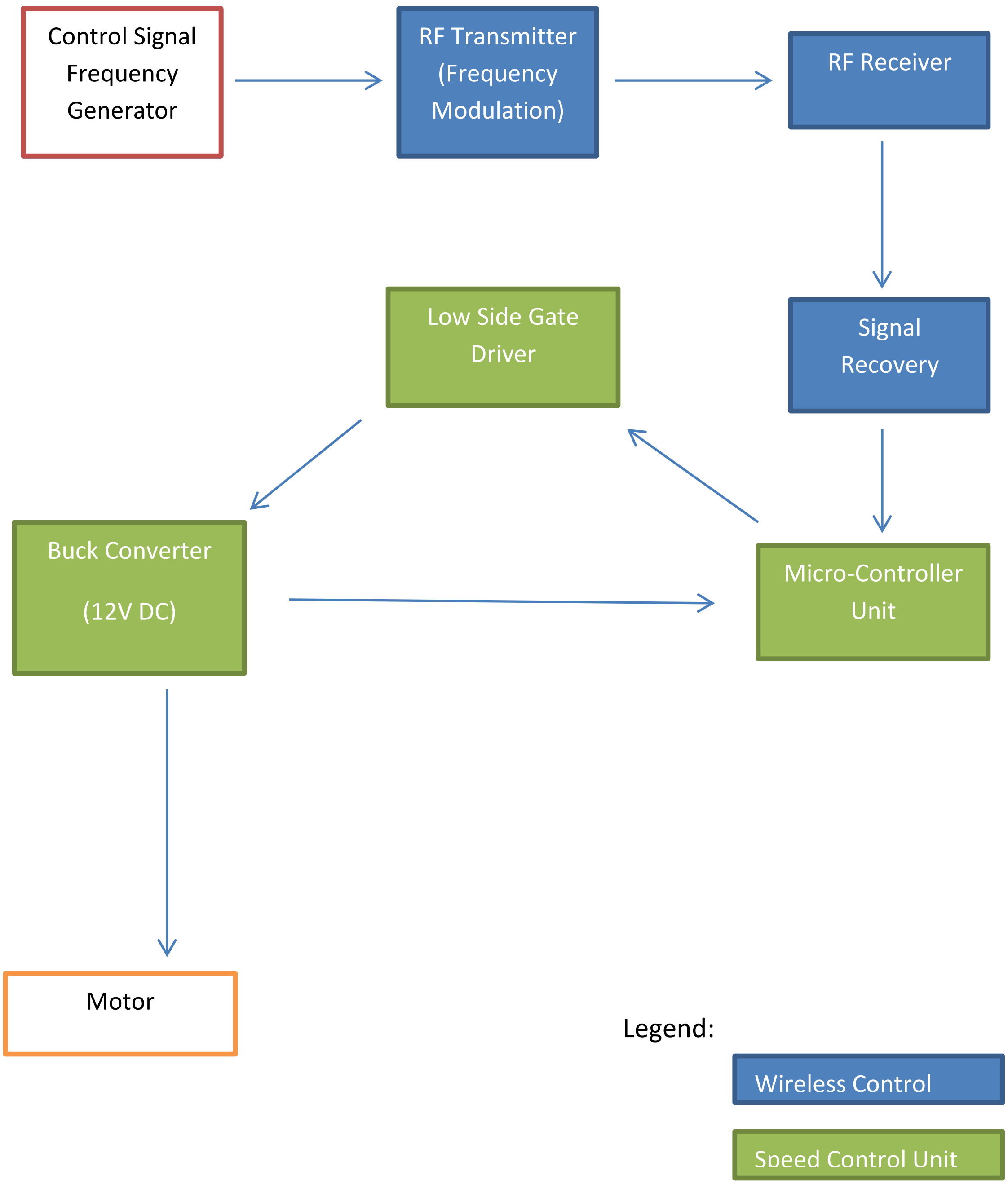
1. Low cost: each speed control unit costs no more than $12.
2. High performance: In standard input range, the motor has over 90% efficiency.
3. Self-protection: automatically shut down the motor when overloading is detected.
4. Less setup limitations: the wireless controller provides a high degree of freedom in terms of various range
5. Multiple unit control: one remote controller can control multiple motors if they are tuned to the same frequency channel.

Features

1. Small motorized shopping cart
2. Luggage cart
3. Electric golf bag cart
4. Easy to operate

2. Design

2.1 Block Diagram



2.2 Block Descriptions

Control Frequency Signal Generator:

This circuit generates a square wave whose frequency and duty ratio are controlled by two variable resistors.

RF transmitter:

The transceiver chip will take the output from the function generator (square wave) and frequency modulates it with the carrier signal. The modulated signal is then sent through an antenna. The chip we plan to use is TXM-315-LR, a high performance low power RF transmitter made by LINX.

RF receiver:

The receiver chip to be used is RXM-315-LR. It has a highly integrated signal recovery system which is able to pick up the desired signal, demodulate it and amplify it to the level powerful enough to drive the MCU.

Buck Converter:

The Buck Converter takes a 12 V DC source as its input and output the DC voltage less than 12 V which controlled by the gate driver signal. The higher output voltage causes the higher speed on the motor. Moreover, for the better control, we use low side gate driver to connect our buck converter. As a result, we do not have to worry about the floating ground. On the other hand, we connect a 0.005 Ω current sense resistor between the source of the MOSFET and the ground. Therefore, we are able to calculate the current go thought the motor by knowing the resistance and voltage. Since the micro controller that we choose is just able to measure the voltage between 0 to 3.6 V and the voltage on motor is from 0 V to 12 V, we connect two resistor 60 kΩ and 20 kΩ parallel with the motor. For this reason, we can calculate the voltage on motor by knowing the voltage on the 20 kΩ resistor.

Micro Controller:

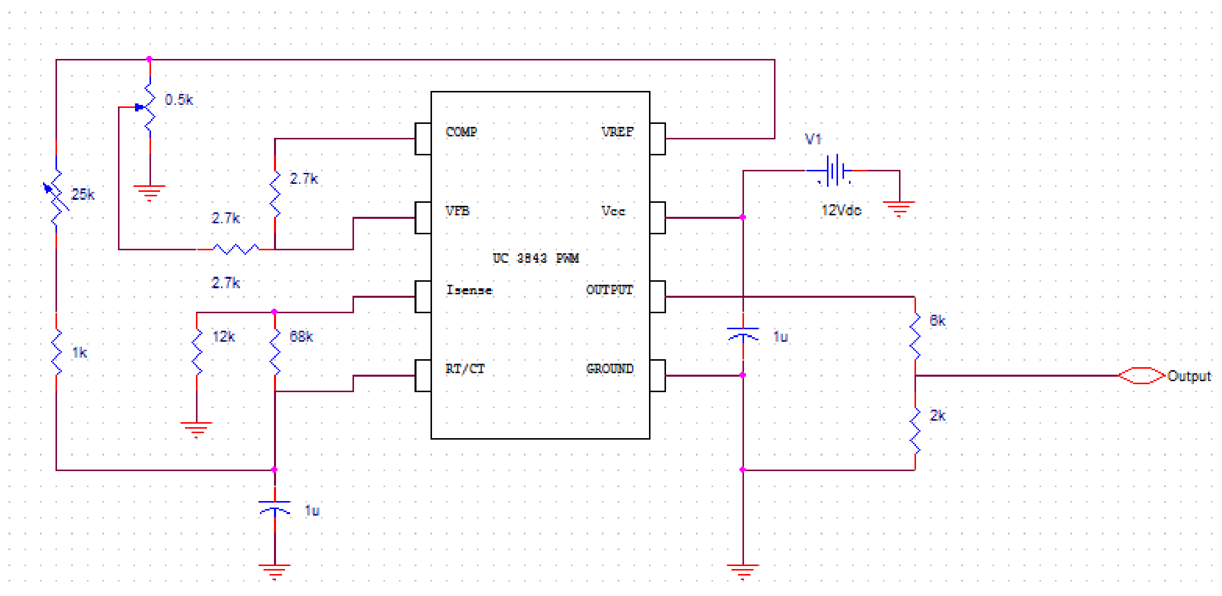
The micro controller that we choose is MSP430AFE233IPW. It has 12-MHz System clock, three 24-Bit Sigma-Delta Analog to Digital converters with differential PGA Inputs, 16 bits CPU, and PWM output generator. The micro controller has three inputs: the square signal from signal recover, the voltage on the current sense resistor and the voltage on 20 kΩ resistor from the buck converter. The micro controller has three functions: 1. Detecting if the motor overload; 2. Output 0 V to gate driver in order to shut down the motor when the motor overload for a long time period; 3. Reconnecting the signal from the signal recovery to the gate driver if the reset signal is detected.

Low Side Gate Driver:

We use IRS2117 to build the low side Gate driver circuit. It takes the digital signal from Micro controller as its input. Since the high of this digital is only 2.7 V which is not able to drive the MOSFET on buck converter, the gate driver would amplify the signal to 12 V which is strong enough to drive the MOSFET.

2.3 Schematics and Analysis

Control Frequency Signal Generator:



The output of the circuit would be a perfect square wave with amplitude 3V. Moreover, the 25k variable resistor is for controlling the frequency while the 0.5k one is for controlling the duty cycle.

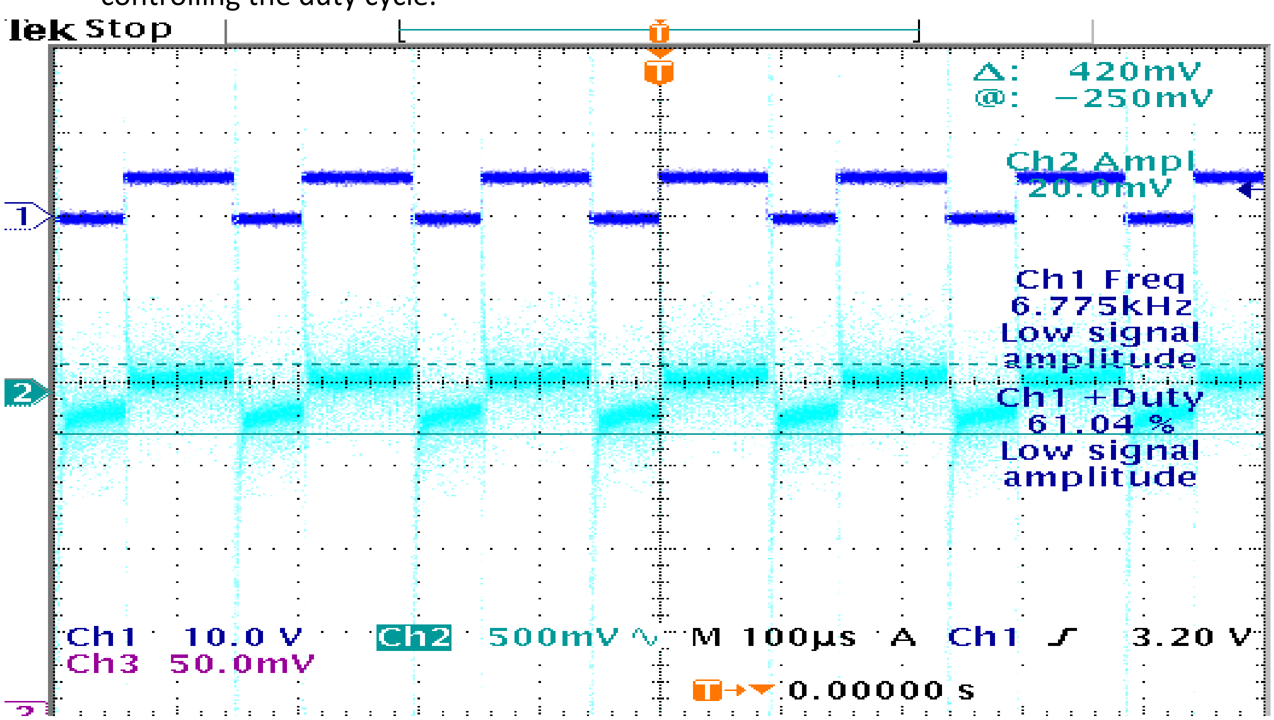
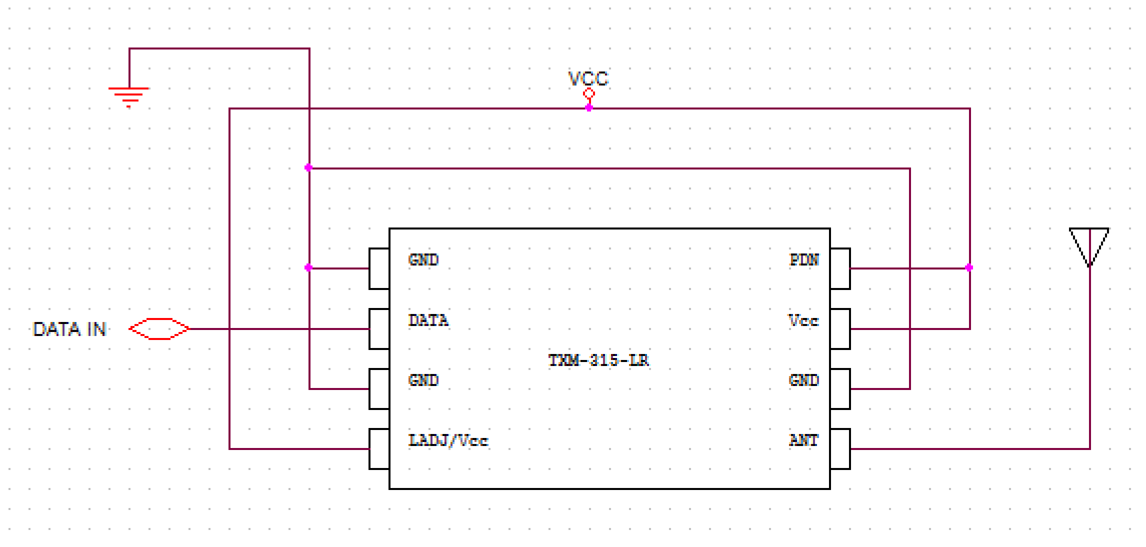


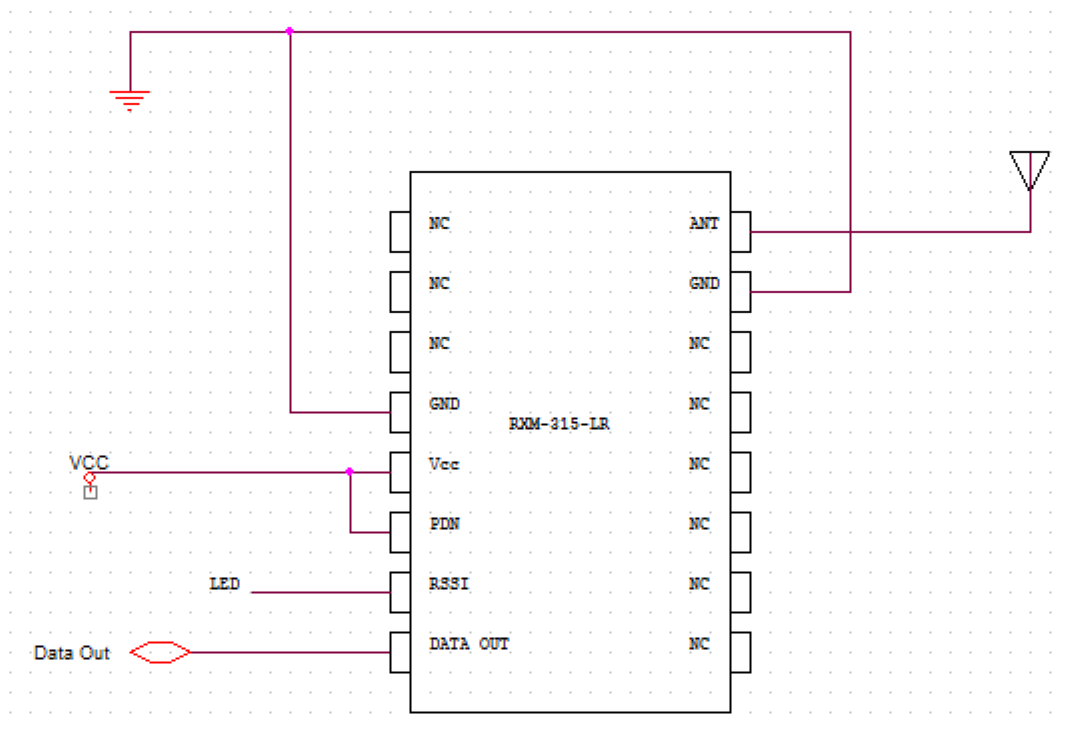
Figure 1 . channel 1: the switch frequency from the frequency generator

RF transmitter:



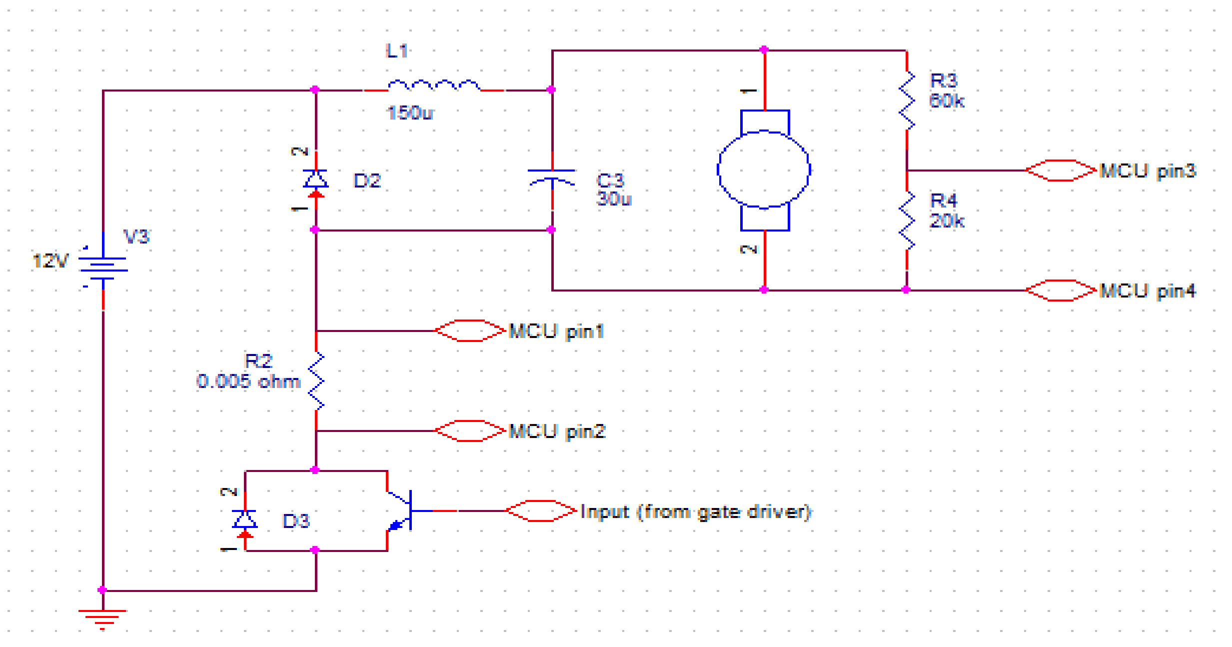
The carrier signal is generated by the built-in VCO which is controlled by a frequency generator. A high precision crystal is used as a reference for the frequency generator. The carrier frequency is fixed at 315 MHz in this case. The carrier signal is then amplified by the power amplifier whose switch is controlled by the DATA input. Therefore, the message signal is digitally modulated and ready to be sent to the antenna after the final filter stage.

RF receiver:



The first stage of the receiver is a band select filter which is fixed at 315 MHz. It picks up the desired signal and filters out the image. The signal is then passed through a low noise amplifier. The amplified signal is down converted to an intermediate frequency by mixing with a local oscillator. The IF signal is then further amplified, demodulated and filtered to recover the original message signal.

Buck Converter:



Since the circuit is required to stay at 250W input for at least 60 seconds and 3 seconds for 500W input, we need to focus at the 250W input case.

Choosing MOSFET:

Since V_{in} = 12V, we have

$$I = \frac{250W}{12V} \approx 21\ A \quad (1)$$

Since efficiency is at least 90%, we assume the power loss on the MOSFET cannot higher than 2% of the total power. Therefore, the thermal resistance is one of the requirement.

$$R_{Mos} \leq \frac{250W \times 2\%}{(21A)^2} = 0.011\ \Omega \quad (2)$$

According to the calculation results from (1) and (2), the MOSFET CSD16415Q5 is picked. It has I_{D_max} = 100 A and R_{on} = 0.99 mΩ. As a result, it is able handle the 250W case and even the 500W case. Moreover, we have:

$$P_{Mos} = I^2 \times R_{on} \times D = (13A)^2 \times 0.99m\Omega = 0.169W \text{ @150W} \quad (3)$$

Where D ≤ 1.

Choosing Inductor:

Assume f_{switch} =100 KHz and D = 50%, we have

$$\Delta T = \frac{D}{f_{switch}} = \frac{50\%}{100KHz} = 5us \quad (4)$$

$$V_L = L \times \frac{di}{dt} = L \times \frac{\Delta I}{\Delta T} = V_{in} - V_{out} = 12V - 6V = 6\ V \quad (5)$$

Assume there is 2% ripple current, we have

$$I_{ripple} = \Delta i = 2\% * 12.5A = 0.25A \quad (6)$$

Combining (5) and (6), we have $L \geq 120\ uh$.

$$P_L = {I_{load}}^2 \times ESR \quad (7)$$

Since I_{load} is very large, we need a very small ESR to decrease the power loss.

Choosing Capacitor:

Assume there is 2% ripple voltage, ESR=0.05Ω and ESL= 0, we have

$$\Delta V = 6V \times 2\% = 0.12V$$

$$\Delta V = \Delta I \times (ESR + \frac{\Delta T}{C} + ESL) \quad (8)$$

From (8), we have C ≥ 12uF

$$P_C = {I_{ripple}}^2 \times ESR = 0.003W \quad (9)$$

Choosing Diode:

$$I_D = (1 - D) \times I_{load} = 42A \text{ @250W} \quad (10)$$

Where $D \leq 1$

As a result, we choose MBRB40250TG which I_{D_MAX}=60A and V_F=0.76V

$$P_D = I_D \times V_F = 9.5W \quad (11)$$

$$P_{loss} = P_{Mos} + P_L + P_C + P_D = 3.125W \quad (12)$$

$$Efficiency = \frac{P_{loss}}{P_{in}} \times 100\% = 91.57\% \quad (13)$$

Which the 90% requirement is met

According to the equation (7), the buck converter circuit has a large power loss on the inductor due to its ESR. For this reason, the buck converter needs to be redesign.

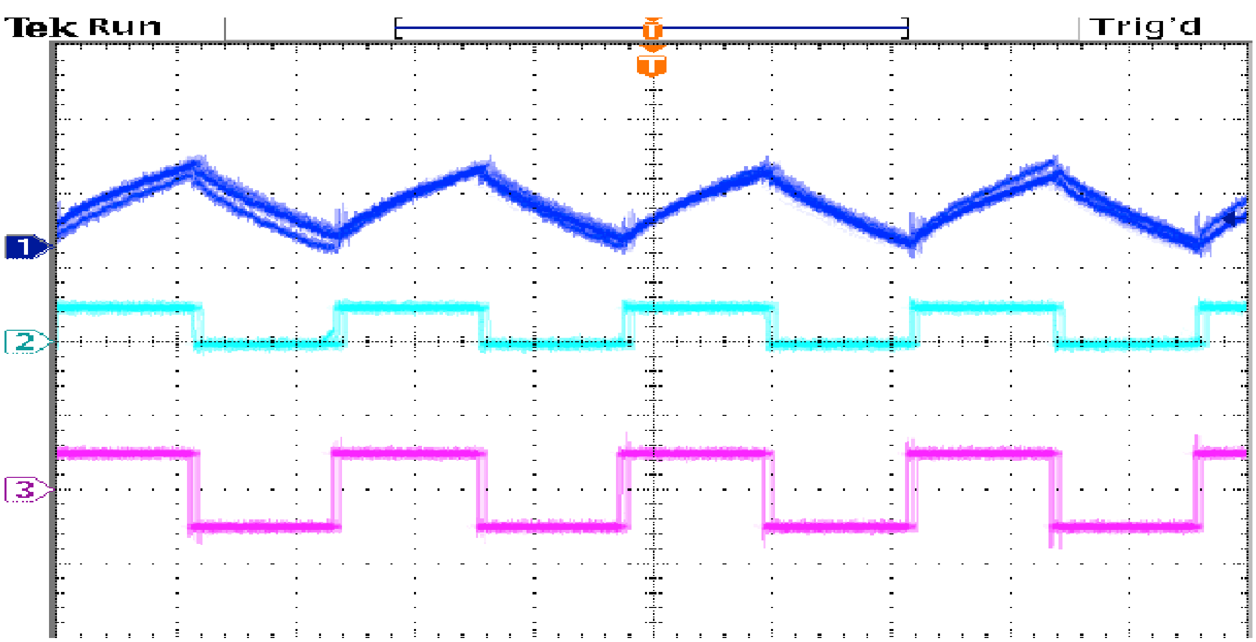
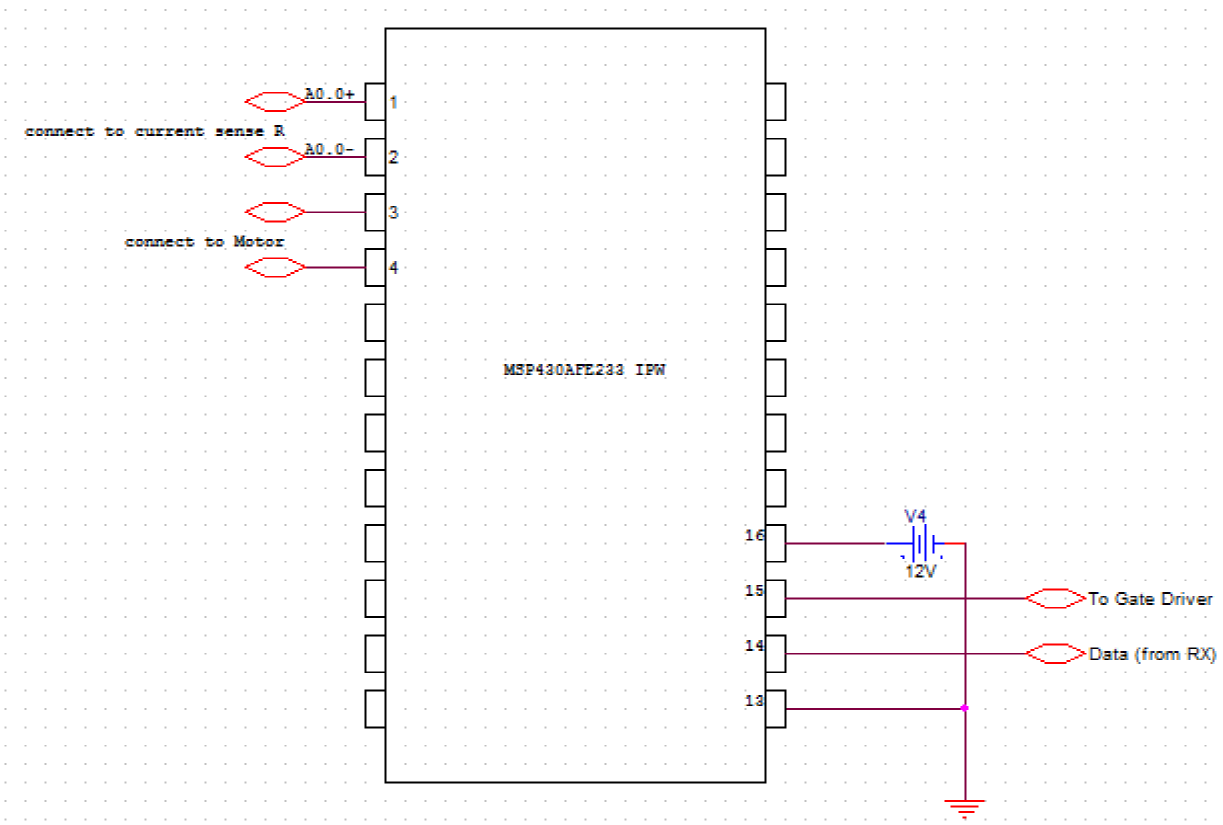


Figure 2. Channel 1: current on the motor; Channel 2: voltage on the motor; Channel 3. Switch frequency

The results above are based on the Class-C chopper circuit which is the same as our previous buck converter but without capacitor and inductor. According to the results, the Class-C chopper circuit meets our motor speed controller requirements since we do not have ripple requirement in our design. Moreover, to improve our output, the out capacitor is need. Form the calculation above, the capacitor only has very small amount power loss which would meet our low power loss requirement.

Micro Controller:



First, we need to store the inputs to three variables: s_in, v_sen, and v_mot. Then, create three counters: c_low, c_high, and reset. The c_low counts from x0000 to xFFFF, then go back to x0000 again. Whenever c_low reach xFFFF, c_high increases by 1. It will go back to x0000 again when it reach to xFFFF. Since the system clock is 12 MHz, the time when c_high reach xFFFF from x0000 is: $\frac{2^{33}-1}{12000000} = 715.828\ seconds$. As a result, we can use these two counters to count how long the motor has been overloaded. For the reset commend, the system is reset when the user turn the wireless control off. As a result, the micro controller needs to be able to detect when the s_in signal is off. Since

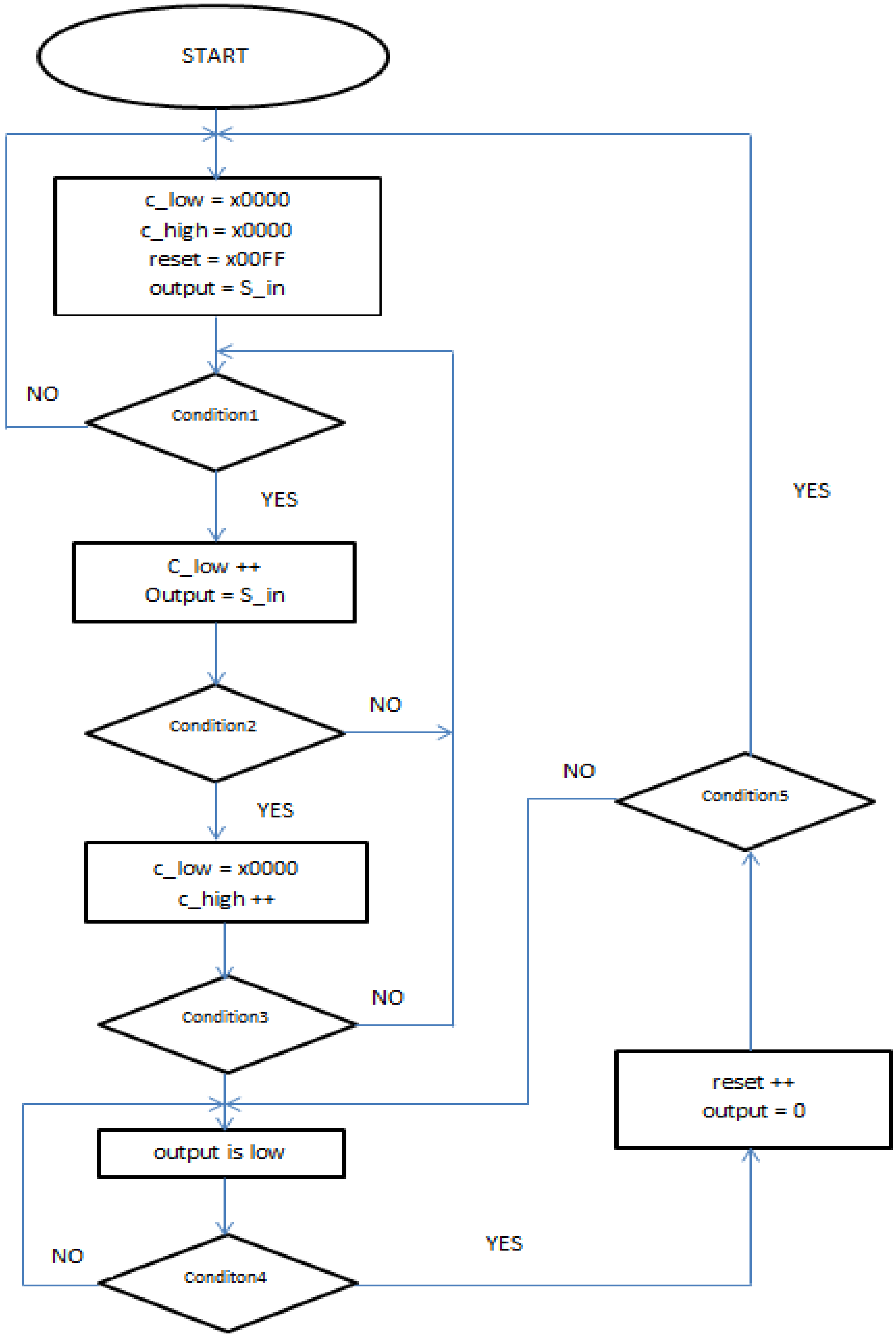
f_{switch} =100KHz and system clock is 12MHz, we are able to calculate the minimum number of clock cycle needed to detect s_in is off.

$$\frac{T_{switch}}{T_{clock}} = \frac{f_{clock}}{f_{switch}} = 120 = \text{x0078}$$

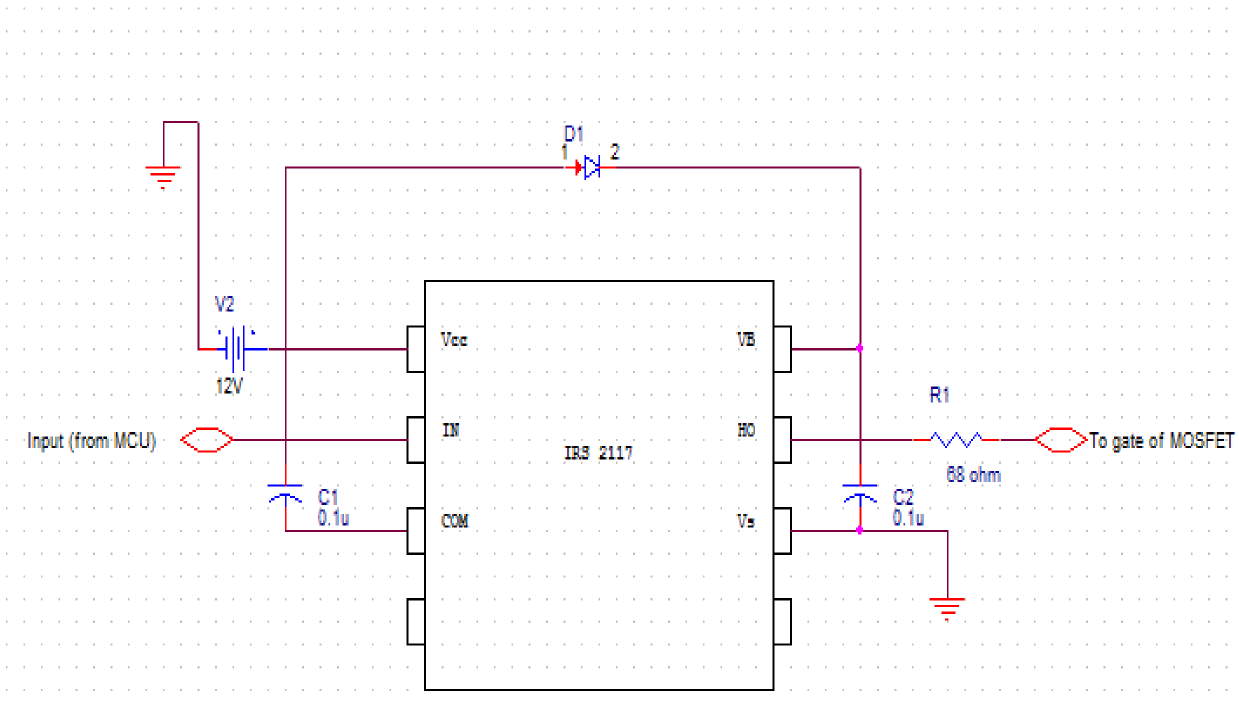
As a result, we could use the counter reset to count from x0000 to x0078. Whenever s_in is low, the counter reset increase by one. Else reset goes back to x0000.
To make the micro controller meet all the function, it need to detect the conditions blow.

Condition 1: $4 \times v\_mot \times \frac{v\_sen}{0.005} \geq 200W$; Condition 2: c_low = xFFFF

Condition 3: c_high = XFFFF; Condition 4: s_in is low; Condition 5: reset = x0078



Low Side Gate Driver:



Since it is low side switch control, the source of the MOSFET is connected on the ground. Therefore, the pin V_s is connected to ground.

2.4 Performance Specifications:

1. Wireless controller should be able to perform: start, stop, accelerate and decelerate commands.
2. The speed control has at least 90% efficiency for motor loads in the range of 50 to 150 W.
3. It should deliver 150 W continuously, 250 W for at least one minute, and up to 50 A at 10 V or more for at least 5 seconds without damage.
4. If it is overloaded for a longer period, it should shut off automatically and require a reset by the user.

3. Performance Requirement and Verification

Requirements	Verification
Control Frequency Signal Generator 1. The generator should be able to output a stable square wave function. 2. The frequency and duty cycle of the square wave function are controlled by changing the value of the variable resistor.	1. Connecting the output to an oscilloscope and observe if the output is a stable square wave. 2. Changing the variable resistance and check if the duty cycle and frequency of the square wave from oscilloscope change. Moreover, check if the frequency can remain the same when the duty cycle is changing.
Low Side Gate Driver 1. The Driver is able to output a square wave signal which has the same frequency and duty cycle as the input square wave. 2. The square wave from the driver is 0V to 12V.	1. Connect the function generator from the lab to the low side gate driver. Select the output of the function generator to square wave. Connect the channel 1 and 2 of an oscilloscope to the outputs of low side gate driver and function generator Check if the channel 1 of the oscilloscope has the same frequency and duty cycle as channel 2. 2. Measure the high and low of the square wave function of gate driver. Check if they are 12V and 0V.
Buck Converter 1. The converter is able to convert the signal whose magnitude controlled by the duty cycle of the gate driver signal from 0V to 11V. 2. The efficiency of the converter is at less 90% at 150W input. 3. Extreme case at 250W and 500W power supply. The converter is able to stay at the 250W and 500W power supply at less 60 seconds and 3 seconds without any damages.	1. Connect the motor to a power resistor and also connect the channel 1 of an oscilloscope to the power resistor. Connect a function generator which is able to output a 0V to 12V square wave to the gate of the buck converter. Verify if magnitude of the signal in channel 1 control by the duty ratio of the gate driver signal 2. Connect the power meter to the power load to the power resistor. Select the power supply in 150 W. Calculate the efficiency base on the result from power meter. Disconnect the power load and use a DC motor and check if the efficiency still at less 90%. 3. For safety reason, we use a power resistor instead the DC motor. Connect a fuse in the circuit. Select the power supply at 12V and 21A. check if the circuit can stay at 60 seconds without burn the fuse. If it pass the 150W case, check with the 12V 42A power supply case.

Requirements	Verification
<u>Micro Controller</u> 1. Detecting if the converter overload. 2. Turn off the motor if overload over 715 seconds. 3. Turn the motor after the reset signal from the user is detected	1. Connect 0.1 V between pin1 and pin2, and 2.5V between pin3 and pin4. Check if those two values are recorded in the registers in micro controller correctly. If so, check if the reset is counting. 2. Connecting the output of the micro controller to an oscilloscope and a 3V high signal to pin14. Check if the signals in the oscilloscope change to low after 715 seconds. 3. After the verification 2 is observed, turn on the signal on pin14. Then, turn back it on. Check if the output of the micro controller output the same signal as the signal on pin14.
<u>RF transmitter</u> 1. The transmitter has to provide an almost perfect modulation. 2. The transmitter must preserve the signal quality over a range of at least 25m.	1. Setup a function generator to output a square wave with 100 kHz frequency. Connect the output of the function generator to both the DATA IN port of the transmitter and the channel 1 of an oscilloscope. Then connect the antenna port of the transmitter to channel 2 of the oscilloscope. Adjust and overlap the waveform of both channels on the oscilloscope and compare the difference. 2. Select another work station which has the largest possible distance away from the transmitter and function generator. Setup a vector analyzer and connect an antenna to one of the input port. Tune the center frequency of detection to 315 MHz on the vector analyzer. Examine the received waveform and record the SINAD value. The waveform should be the same as in the transmission end and the SINAD value should not go below -20 dB.

Requirements	Verification
<u>RF receiver</u> 1. The receiver has to recover a square wave swinging between 0 to 3V. Also, the signal must have the same duty cycle and frequency as the generated signal. 2. The LED connected to the RSSI pin must be able to indicate the presence and absence of the desired signal.	1. Connect the function generator, transmitter and receiver in cascade mode with two 50 ohms coaxial cable. Setup the same square wave as in the transmitter testing procedure. Connect both the output of function generator and receiver to channel 1 and 2 of the oscilloscope respectively. Compare the waveform to check the quality of demodulation and amplification. 2. Keep the instrument setup as above. Disconnect the cable between transmitter and receiver. Terminate both of them with 50 ohm antennas. Transfer the receiver to another workstation 25m away from the receiver. Connect the RSSI pin to the LED (with additional current divider circuit). Turn on and off the transmitter and see if the LED gives the correct indication.

Tolerance Analysis

Since we have to deal with two overload cases which may damage our components. We have to setup up a specific testing plan for it. First, connect a thermometer on transistors in the Buck converter. Then, start on the 150W loading and run it for 5 minutes and record the temperature. Calculate the power lost on the transistors. Gradually increase the input power, record the temperature and calculate the power lost on the transistor for every 10W power increase. If the temperature rises too quickly, shut down the circuit immediately and modify components to achieve higher overloading tolerance. By testing the 500W case, replace the motor by power resistor and see if the circuit meets the requirement because in this case, there will be 50A of current going through the load which may damage the motor.

4. Cost and Schedule

4.1 Cost Analysis

1. Labor
   Jing Y. Guo: ($30/hr) x (15hr/week) x (9weeks) = $4050
   Yu Qiao: ($30/hr) x (15hr/week) x (9weeks) = $4050

2. Parts
   Table 1. Cost for speed controller

Parts	Quantity	Unit Cost	Total
UC3843	1	1	1.32
IRS2117	1	0.96	0.96
CSD16415Q5	1	1.05	1.05
MBRB40250TG	1	0.90	0.90
CW20C393K(39uF)	1	0.23	0.23
0.005Ω current sense resistor	1	0.90	0.90
0.1uF, 1uf, capacitor	4	0.20	0.80
12kΩ,1 kΩ,2.7 kΩ,12 kΩ,68 kΩ resistors	7	0.02	0.14
Variable resistor	1	0.79	0.79
MSP430AFE233IPW	1	2.10	2.10
1N4002	2	0.10	0.20
Total			9.39

According to the total cost in table 1 above, the total cost of the speed controller is $9.39 which is lower than the requirement $12. The cost requirement is met.

Table 2. Cost for RF components

Parts	Quantity	Unit Cost	Total
ANT-315-PW-RA	2	4.00	8.00
TXM-315-LR	1	7.46	7.46
RXM-315-LR	1	13.56	13.56
RG-174	2	8.52	17.04
Total			46.06

3. Grand Total

Grand Total = $4050 * 2 + $55.45= $8155.45

4.2 Schedule

Date	Tasks	Person
2/6	Prepare for proposal	Yu Qiao
	Prepare for proposal	Jing Guo
2/13	Design schematics	Yu Qiao
	Calculate the value of component	Jing Guo
2/20	Complete all the initial design and prepare for design review	Yu Qiao
	Order parts	Jing Guo
2/27	Implement RF transmitter and receiver circuits	Yu Qiao
	Built the control frequency circuit and test if the receiver can receive the same waveform as the frequency circuit output.	Jing Guo
3/5	Test the quality of the TX and RX signal	Yu Qiao
	Built the buck converter and also check if the efficiency meet the requirement.	Jing Guo
3/12	Programming the MCU, check if the MCU A/D converter can store the voltage in the register	Yu Qiao
	Programming the MCU, check if the MCU can detect the overload, and the time counter is working	Jing Guo
3/19	Spring Break	Yu Qiao
	Spring Break	Jing Guo
3/26	Sign up for Mock presentation Testing and debugging the MCU	Yu Qiao
	Testing and debugging the MCU	Jing Guo
4/2	Connect the MCU to the circuit and check if the function is working or not	Yu Qiao Jing Guo
4/9	Testing and improving	Yu Qiao
	Combine the top level circuit	Jing Guo
4/16	Assemble the product	Yu Qiao
	Test the requirements and change part if necessary	Jing Guo
4/23	Demo and prepare for presentation	Yu Qiao
	Prepare presentation materials	Jing Guo

5. Ethical Assessment

Our project has no conflict with the IEEE Code of Ethics. Most of the ideas that support the development of this project are from our studies in the last couple of years. Any references that helped us with our design have been given credits. We would like to thank Professor Krein for providing critical information to improve our design. Due to the special requirements of our design such as handling overloaded motors which may cause danger to potential users. We will perform thorough theoretical analysis before going in to the real testing phase. For safety reasons, any abnormal situations we encountered in the lab will be reported to our TA immediately.

6. References

"Buck Converter Design Example." *Simon's SatCom Page*. N.p., n.d. Web. 20 Feb. 2012. <satcom.tonnarelli.com/files/smps/SMPSBuckDesign_031809.pdf>.

Krein, Philip. *Power Electronics Laboratary*. 2.4a ed. Urbana: Department of Electrical and Computer Engineering, University of Illinois at Urbana Champaign, 2011. Print.