High Performance Low Cost Low Loss Wireless DC Motor Speed Control

Senior Design Final Report

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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, decelerate and reset. 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 with over 90% efficiency and be able to tolerate slight overloading for at least one minute. For strong overloading, it should protect the motor from being damaged for at least six 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.

Performance Specifications:

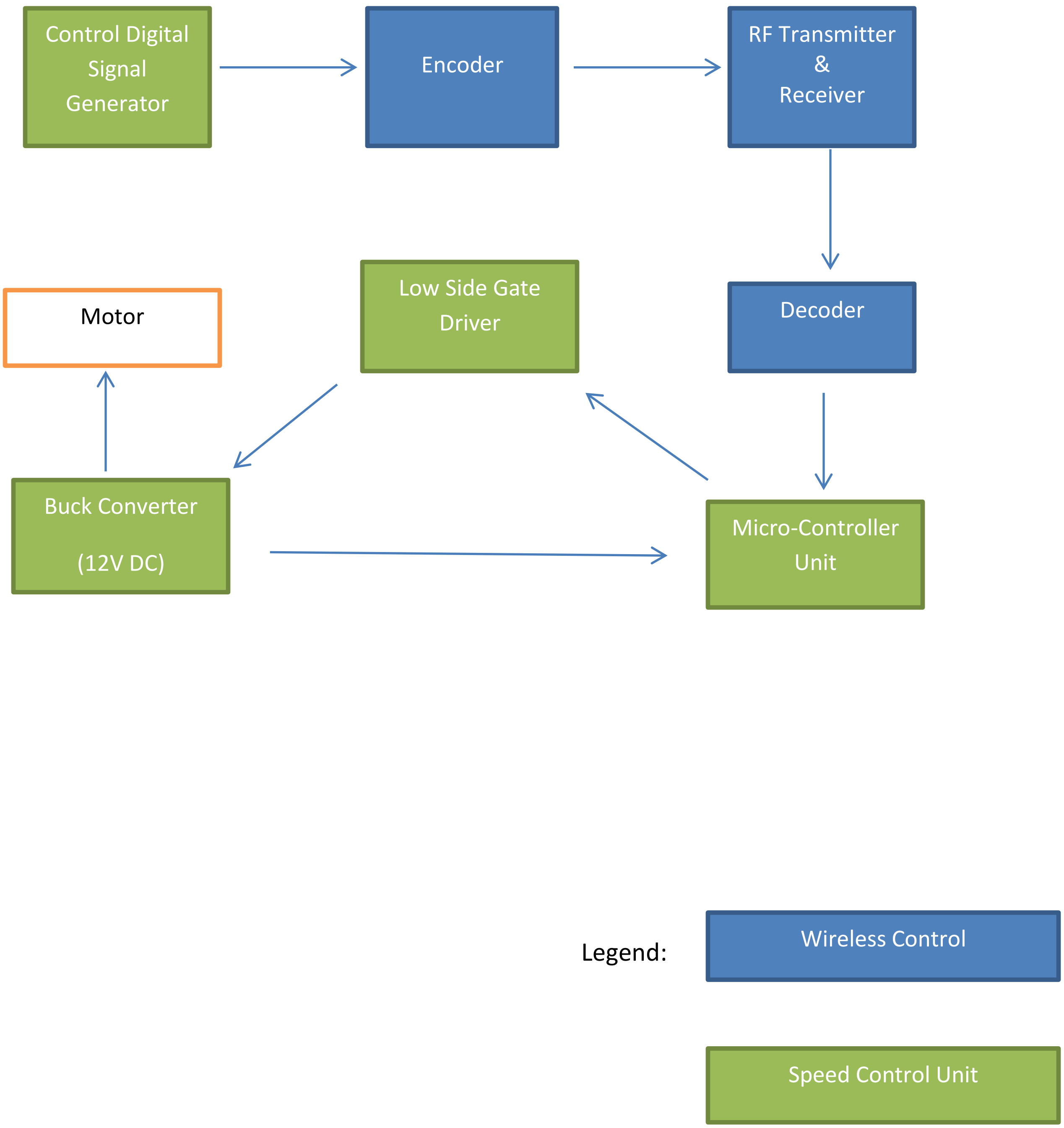
1. Wireless controller should be able to perform: start, stop, accelerate and decelerate commands.
2. The speed control has at least 90% efficiency for motor loads in the range of 50 to 150 W.
3. It should deliver 150 W continuously, 250 W for at least one minute, and up to 50 A at 10 V or more for at 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.

Applications

1. Small motorized shopping cart
2. Luggage cart
3. Electric golf bag cart

2. Design

2.1 Block Diagram



2.2 Block Descriptions

Control Signal Generator:

This unit is controlled by five push buttons and generate a 3-bit control code. The codes we assigned to each command is shown in the following table:

Commands	Codes
Start	110
Stop	111
Accelerate	100
Decelerate	010
Reset	001

We use a 3-input NAND gate to implement this encoding logic, here are the Boolean expression for each bit of the control codes:

Bit2 = (Reset AND Off)'
Bit1 = (Decelerate AND Start AND Off)'
Bit0 = (Increase AND Start AND OFF)'

Note: When each button is pushed, the corresponding signal is a logic 0

Encoder and Decoder

The 3-bit control code from the signal generator must be transformed in to serial data before it can be transmitted by the RF transmitter. Similarly, the received serial data output by the receiver must be transformed back to parallel form to complete the signal recovery process. This is done by a pair of encoder and decoder (LICAL-ENC-MS001 and LICAL-DEC-MS001).

RF Transmitter and Receiver

The transmitter chip will take the serial data output from the decoder and frequency modulates it with the carrier signal. The modulated signal is then sent through an antenna. The chip we are using is TXM-315-LR, a high performance low power RF transmitter made by LINX.

On the receiver end, the 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 decoder.

Buck Convertor:

The Buck Convertor takes a 12 V DC source as its input and output the DC voltage less than 12 V which is controlled by the gate driver signal. The higher output voltage causes the higher speed on the motor. Moreover, for a better control, we use low side gate driver to connect our buck convertor. 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 input current going through the motor by knowing the resistance and voltage. Since the input voltage of the circuit is constant at 12 V, we are able to calculate the input power.

Micro Controller Unit:

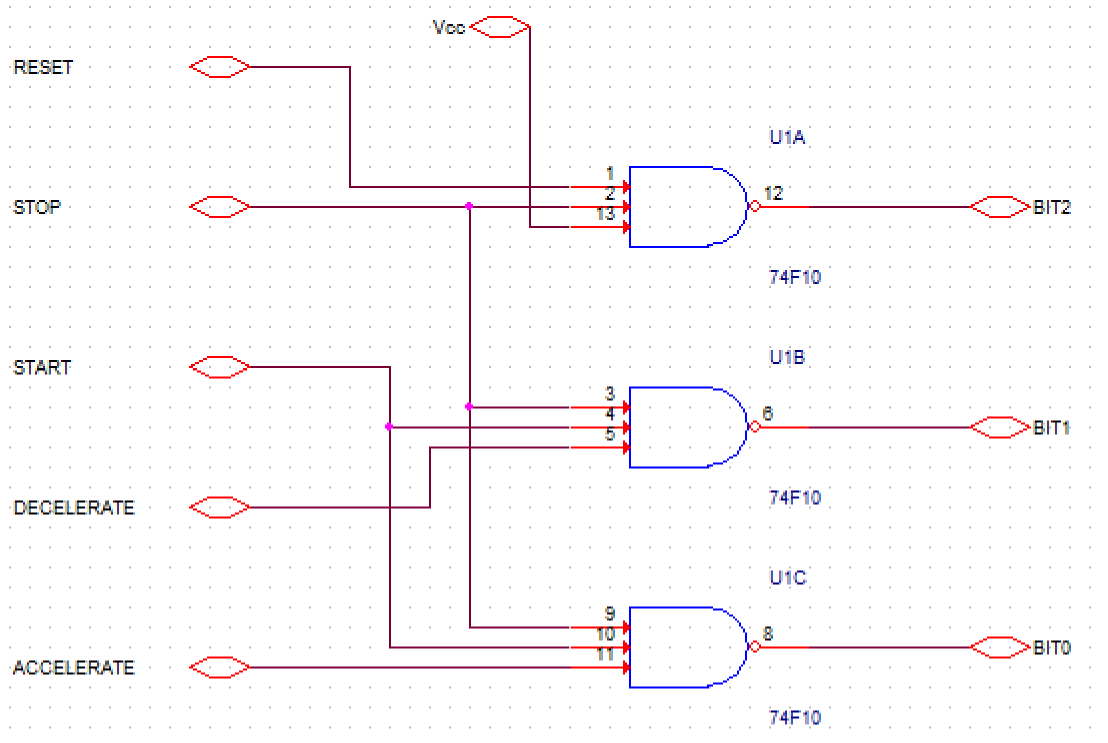
This unit contains two micro controller chips, both of them are MSP430G2152 from TI. One chip is used as the PWM generator and the other one is for overload detection and circuit protection. The PWM generator takes the 3-bit command code from the decoder and generates the PWM signal based on the input. The overload detector is going to measure the voltage between the current sense resistor and detect an overloading. There are three connections between these two chips. When an overloading is detected, the detector chip will output a "detected" signal to the PWM generator. When the overloading has last for a longer period, the detector outputs an OFF signal to the PWM generator to shut down the circuit. When the RESET signal is received from the user, the PWM generator will output a RESET signal to the detector to reinitialize it.

Low Side Gate Driver:

We use UCC27424 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 3.2 V which is not strong enough to drive the MOSFET on buck convertor, the gate driver would amplify the signal to 10 V which is strong enough to drive the MOSFET.

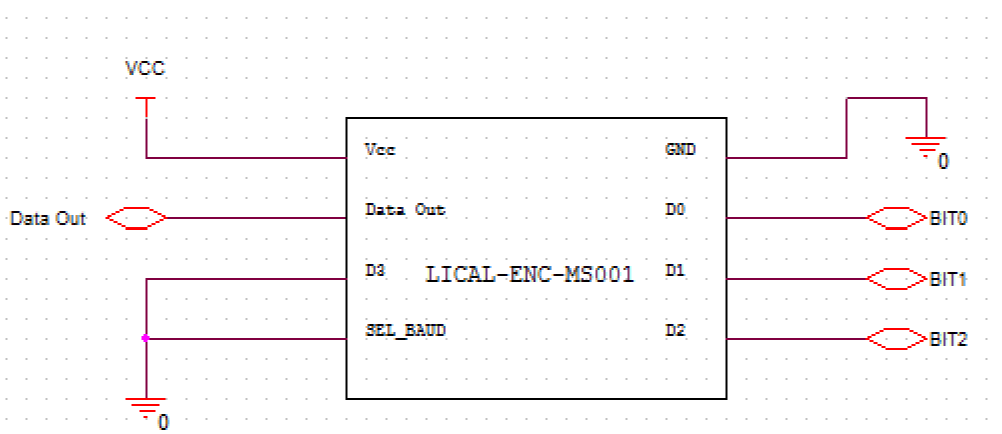
2.3 Schematics and Analysis

Control Signal Generator:



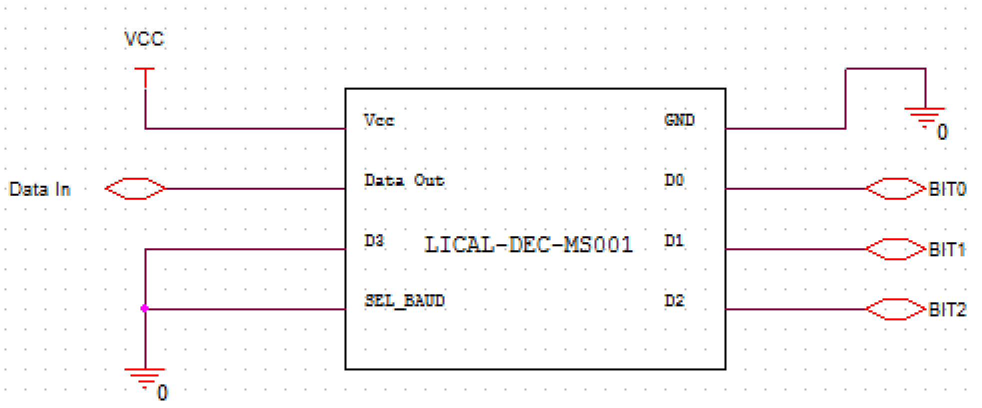
A simple 3-input NAND gate will complete the task.

Encoder



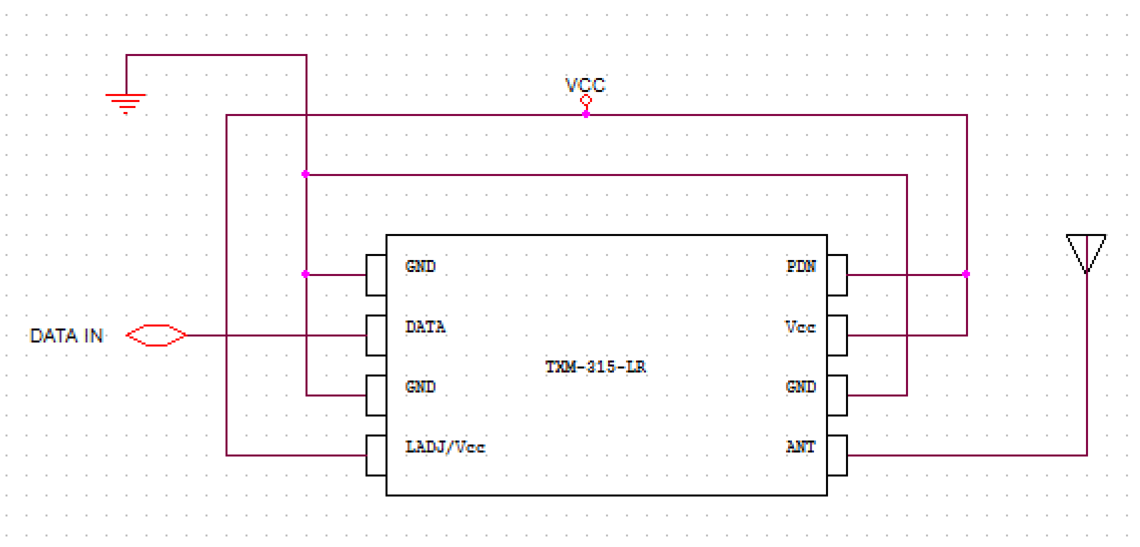
The 3-bit input is fed into D0, D1 and D2. D3 is pulled to ground since it is not used. The SEL_BAUD pin is used to set the serial data generation rate. When it is pulled high, the rate is set at 9600 bps. When it is pulled low, the rate is set at 2400 bps. Since we are not sending too much information, we selected the lower rate.

Decoder



The decoder has almost the same configuration as the encoder but reversed input and output setup. The D0, D1 and D2 pins are outputs to the PWM generator. Here we also connect the SEL_BAUD pin to ground to ensure the data rate is the same as we selected before on the encoder.

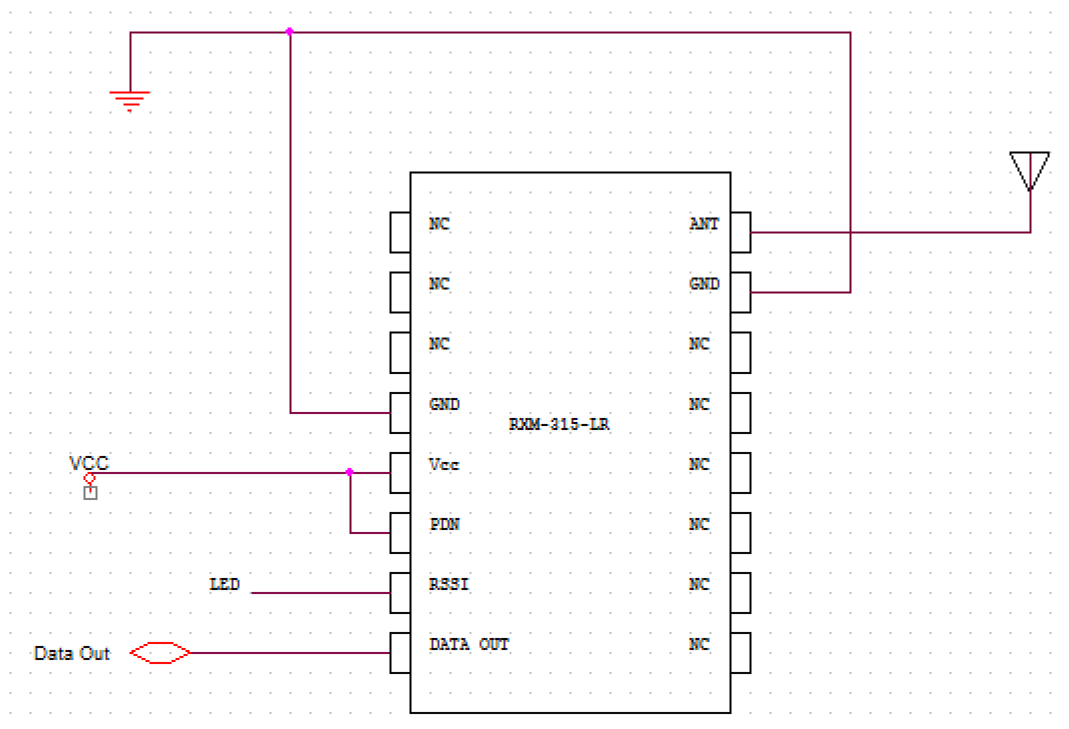
RF transmitter:



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.

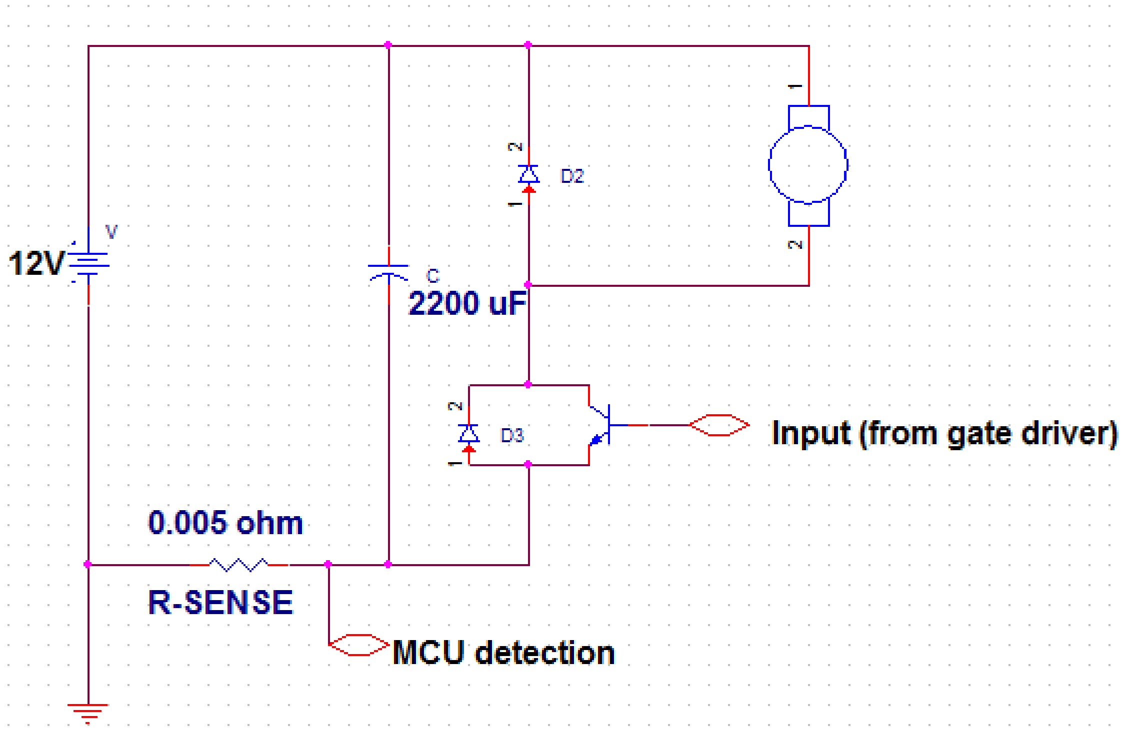
The carrier frequency is fixed at 315 MHz in this case. The carrier signal is then amplified by the power amplifier whose switch is controlled by the DATA input. Therefore, the message signal is digitally modulated and ready to be sent to the antenna after the final filter stage.

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 Convertor:



Since the circuit is required to stay at 250W input for at least 60 seconds and 6 seconds for 500W input, we need to focus at the 250W input case.
Choosing MOSFET:
Since V_{in} = 12V, we have

$$I = \frac{250W}{12V} \approx 21\ A \tag{1}$$

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.

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

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:

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

Where D ≤ 1.

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

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

$$\Delta V = \Delta I \times (ESR + \frac{\Delta T}{C} + ESL) \tag{4}$$

From (8), we have C ≥ 12uF

$$P_C = {I_{ripple}}^2 \times ESR = 0.003W \tag{5}$$

Choosing Diode:

$$I_D = (1 - D) \times I_{load} = 42A \text{ @250W} \quad (6)$$

Where $D \leq 1$

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

$$P_D = I_D \times V_F = 9.5W \quad (7)$$

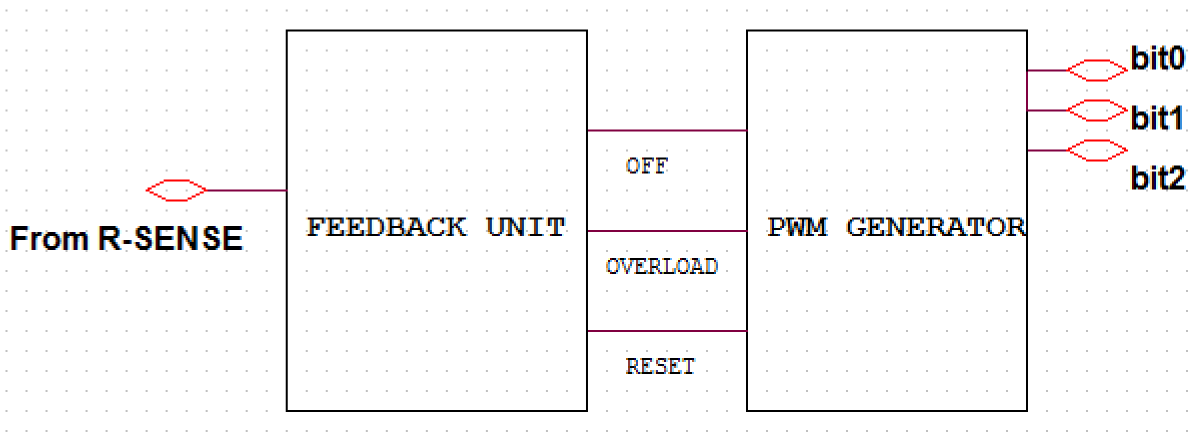
$$P_{sen} = {I_{in}}^2 \times R_{sen} = 2.205\text{W} \quad (8)$$

$$P_{loss} = P_{Mos} + P_C + P_D + P_{sen} = 11.88W \quad (9)$$

$$Efficiency = \left(\frac{P_{in} - P_{loss}}{P_{in}}\right) \times 100\% = 92.08\% \quad (10)$$

Which the 90% requirement is met

Micro Controller:



On the PWM generator, the up mode is used to generate the PWM signal. The specific detail of the up-mode is show on the appendix figure 1. In order to improve the performance of the circuit and protect the circuit, two frequency modes are used. The high frequency mode is 160 kHz which is used for the normal operation (200W input power or less). The low frequency mode is 1.6 kHz which is used for the overload case (over 200W input power). The clock signal of this MCU is 16MHz. As a result, we are able to calculate the value of CCR0 correspond to the frequency modes.

$$CCR0 = \frac{f_{clock}}{f_{mode}} \quad (11)$$

According to the equation (11) above, we have

$$CCR0 = 100@High\ frequency\ mode$$

$$CCR0 = 10000@Low\ frequency\ mode$$

The value of the CCR1 is depended on the 3 bit digital input signal from the decoder side; whenever the reset signal is received, it output a reset signal to the feedback unit and reset to the high frequency mode with 50% duty radio. Whenever the overload signal from the feedback unit change from low to high, it sets the low frequency mode and multiplies the current CCR1 by 100. When the off signal from the feedback unit is received, it change the value of CCR1 to 0.

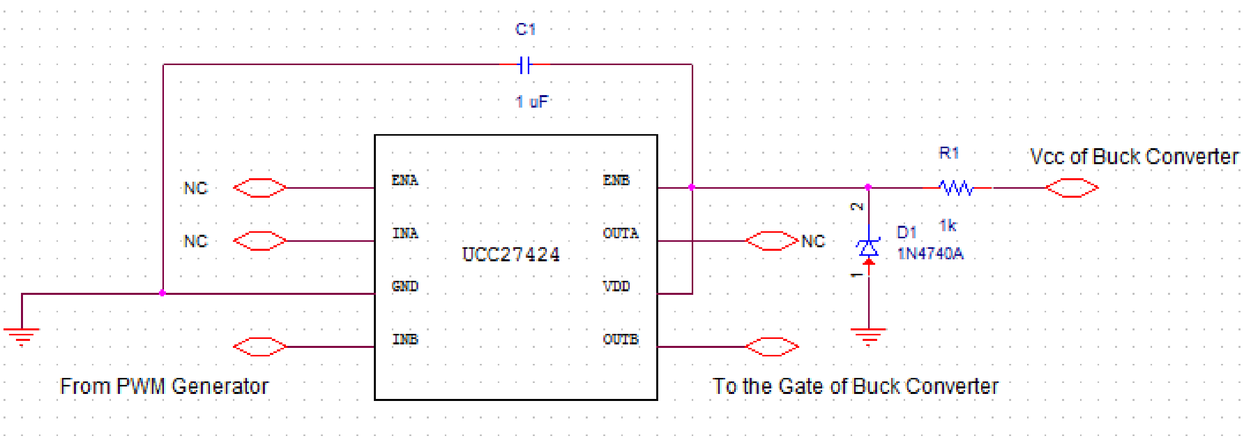
On the feedback unit, we set the overload input power is 200W. Therefore, we have:

$$I_{in} = \frac{P_{in}}{V_{in}} = 16.67\ A \tag{12}$$

$$V_{sen} = I_{in} \times R_{sen} = 83\ mV \tag{13}$$

Since the input voltage and the resistance of the current sense resistor are constant, we are able to detect the input power. In order to calculate the average input power, the Simpson's rule to do the approximation. That means adding the value of (V_{detect} - V_{sen}) to one register if (V_{detect} - V_{sen}) is positive or the value of this register is greater than (V_{detect} - V_{sen}). As a result, the Value of the register is R_{SEN}*(P_{AVG} - 200)/12. In order to avoid the overflow case, we use two register to store this value instead of one. When the value of the low register is over a specific value, the detector unit outputs high on the overload signal. When the value of the high register is over a specific value, the detector unit outputs high on the off signal and the value of the high register remain the same. When the reset signal is high, both registers overload signal and off signal reset to zero.

Low Side Gate Driver:



The low side gate driver take the PWM signal as its input and then boost the voltage to 10V. Moreover, there is a voltage divider circuit to get a 10V voltage to the V_{DD} from the source of the buck converter.

3. Performance Requirement and Verification

Requirements	Verification	Result
<u>Control Signal Generator</u> 1. The output combination from the NAND gate should correspond to the assigned command code when each button is pressed	1. Connect the 3 outputs to an LED array and see if the LEDs light up correctly	Checked
<u>Low Side Gate Driver</u> 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 10V.	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 10V and 0V.	Checked
<u>Buck Converter</u> 1. The convertor 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 convertor 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	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	Checked

without any damages.	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 passes the 150W case, check with the 12V 42A power supply case.	
<u>Micro Controller</u> 1. Detecting if the converter overload. 2. Tune of the motor if overload over 715 seconds. 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. 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.	Checked
<u>RF Transmitter & Receiver</u> 1. Test the two chips together, see if the output from the receiver duplicates the input to the transmitter	1. Setup a function generator to output a square wave with 3 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 output port of the receiver to channel 2 of the oscilloscope. Adjust and overlap the waveform of both channels on the oscilloscope. Vary the duty cycle of the function generator and compare the difference. Small time delay should be tolerable.	Checked
<u>Encoder & Decoder</u> 1. Test them together, the input combination to	1. Connect the 3-input pins of the encoder to the control signal generator. Connect the output of	Checked

	the encoder should be the same as the output from the decoder	the encoder to the input of the decoder. The output of the decoder is then connected to the LED array. Check if the LEDs still give the correct indication.	

For the overall performance of the final product, please see the appendix for detailed result of each testing case. According to the results on the appendix, our circuit can handle the 250W case very well without the low frequency protection mode because the temperature is 91 degree and the maximum operation temperature is 120 degree. As a result, it should not have any problem to last over 60 seconds. Moreover, with the protection mode, the temperature of the circuit drops to room temperature. That means our circuit can work on 250W as its normal operation with the low frequency mode. On the 500W case, the circuit stays on for 60 seconds while the temperature raise up to 120 degree and the circuit shut down automatically. That means the 500W input power can damage the circuit, but it is not a problem to stay for just 6 seconds.

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

Buck Converter

Parts	Quantity	Unit Price	Total Price
Copper slab	x1	$0.50	$0.50
Heat Sink	x4	$0.25	$1.00
Diode (MBR2545P)	x2	$0.66	$1.32
Power MOSFET (CSD16415Q5)	x1	$0.95	$0.95
Current sense resistor (WSH28185)	x1	$1.50	$1.50
Capacitor (2200uF)	x1	$0.45	$0.45
Electroboard	x1	$1.50	$1.50

Main Circuit

Parts	Quantity	Unit Price	Total Price
Resistors (100 ohms, 330 ohms)	x2	$0.016	$0.032
Zener diode (1N4740, 1N4728)	x2	$0.14	$0.28
Capacitor (1uF)	x2	$0.02	$0.04
MCU (MSP430G2452)	x2	$0.70	$1.40

Low side gate driver (UCC27424)	x1	$1.01	$1.01
Decoder (LICAL-DEC-MS001)	x1	$3.72	$3.72
Receiver (RXM-315-LR)	x1	$13.56	$13.56
SMA connector (A97594)	x1	$2.85	$2.85
Antenna (ANT-315-CW-HWR-SMA)	x1	$10.14	$10.14

Controller

Part	Quantity	Unit Price	Total Price
Push buttons	x5	$0.16	$0.80
3-input NAND gate (SN74F10N)	x1	$0.22	$0.22
Encoder (LICAL-ENC-MS001)	x1	$3.72	$3.72
Transmitter (TXM-315-LR)	x1	$7.46	$7.46
SMA connector ((A97594)	x1	$2.85	$2.85
Antenna (ANT-315-CW-HWR-SMA)	x1	$10.14	$10.14
Batter holder	x1	$1.00	$1.00

Note: the underlined parts contribute to wireless controlling feature, which is not limited by the low price requirement.

Total cost for the motor speed control parts = $11.002

Total cost for the wireless control parts = $55.44

Total cost for the parts = $66.442

Total cost for the entire project = $9166.442

5. Conclusion

Accomplishments

1. Transmitting and receiving control signals wirelessly
2. Successfully protecting the circuit by lowering frequency
3. Properly setup shut down point to protect the motor
4. Keeping the cost low

Ethical Considerations

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.

Appendix

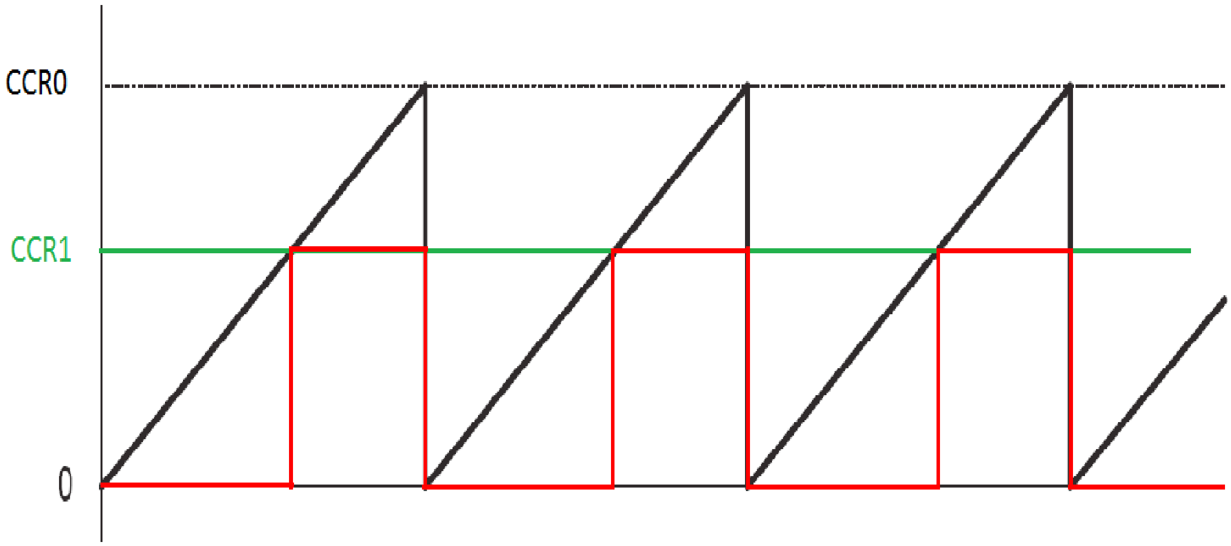


Figure 1: Up-Mode PWM Generation

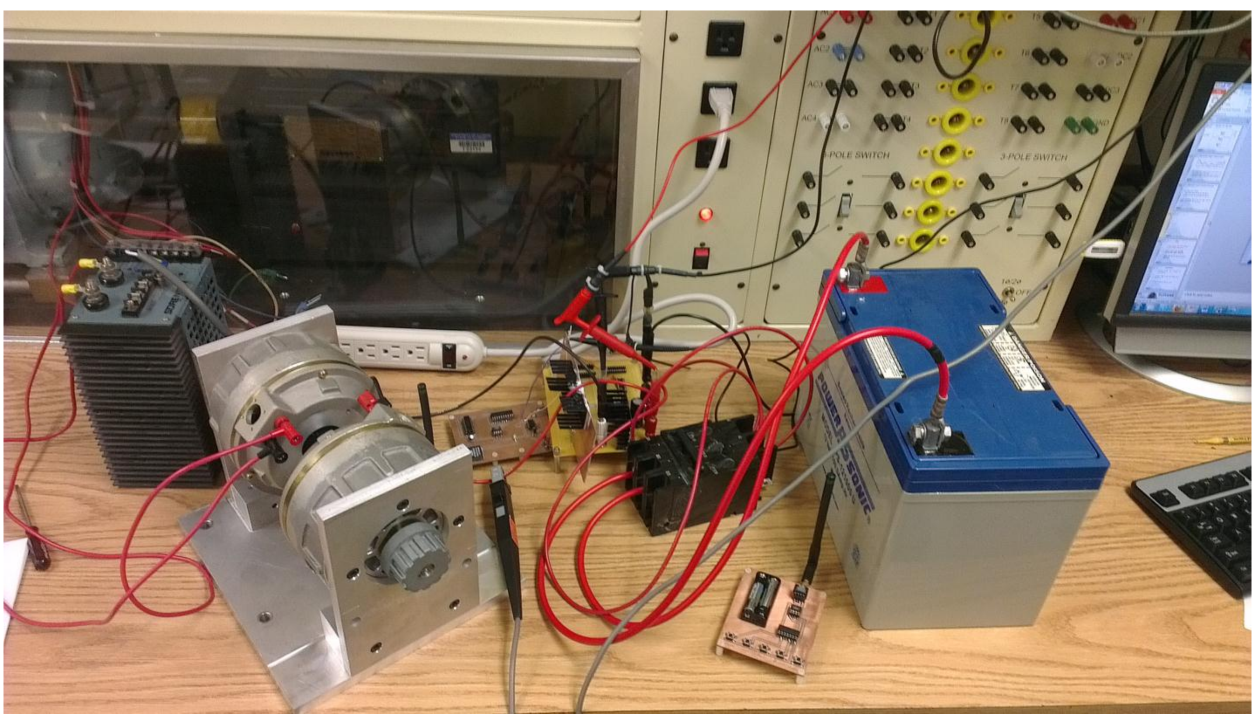


Figure 2: 150W Test Case Set Up

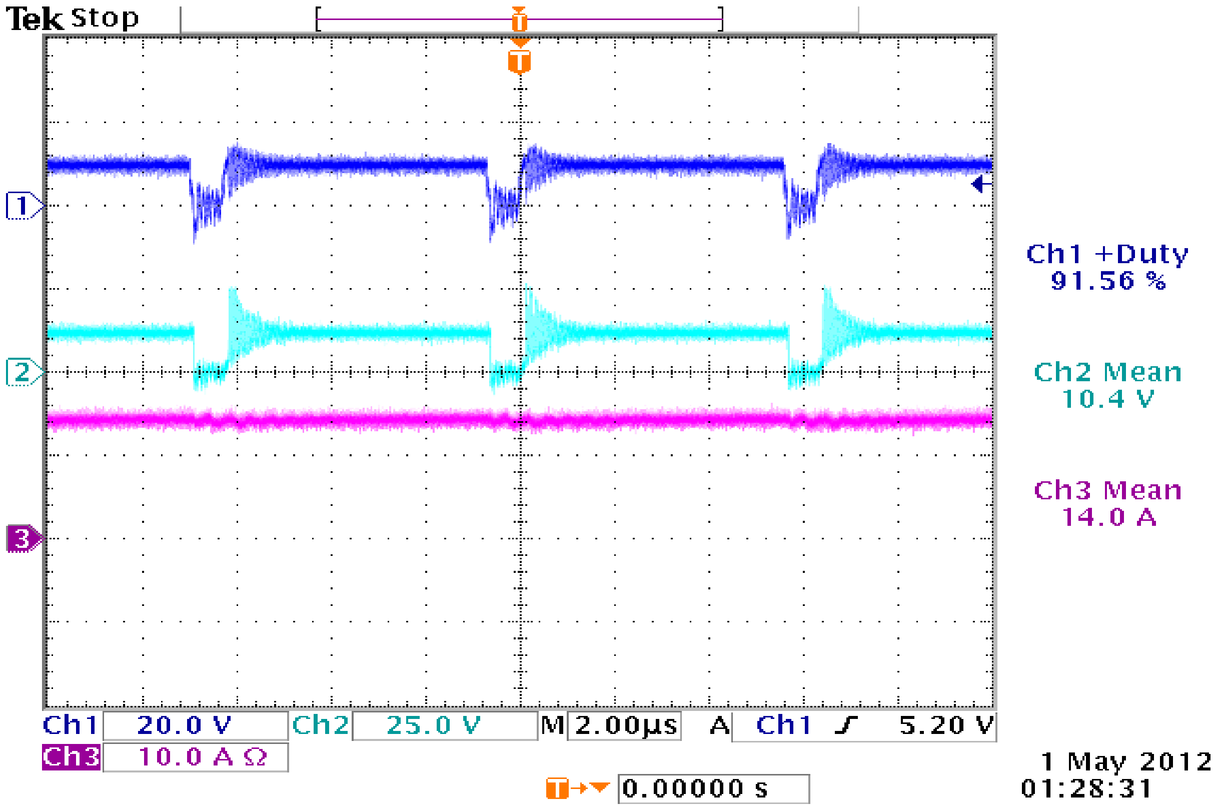


Figure 3: 150W test case result
Ch1: switch frequency Ch2: output voltage Ch3: output current

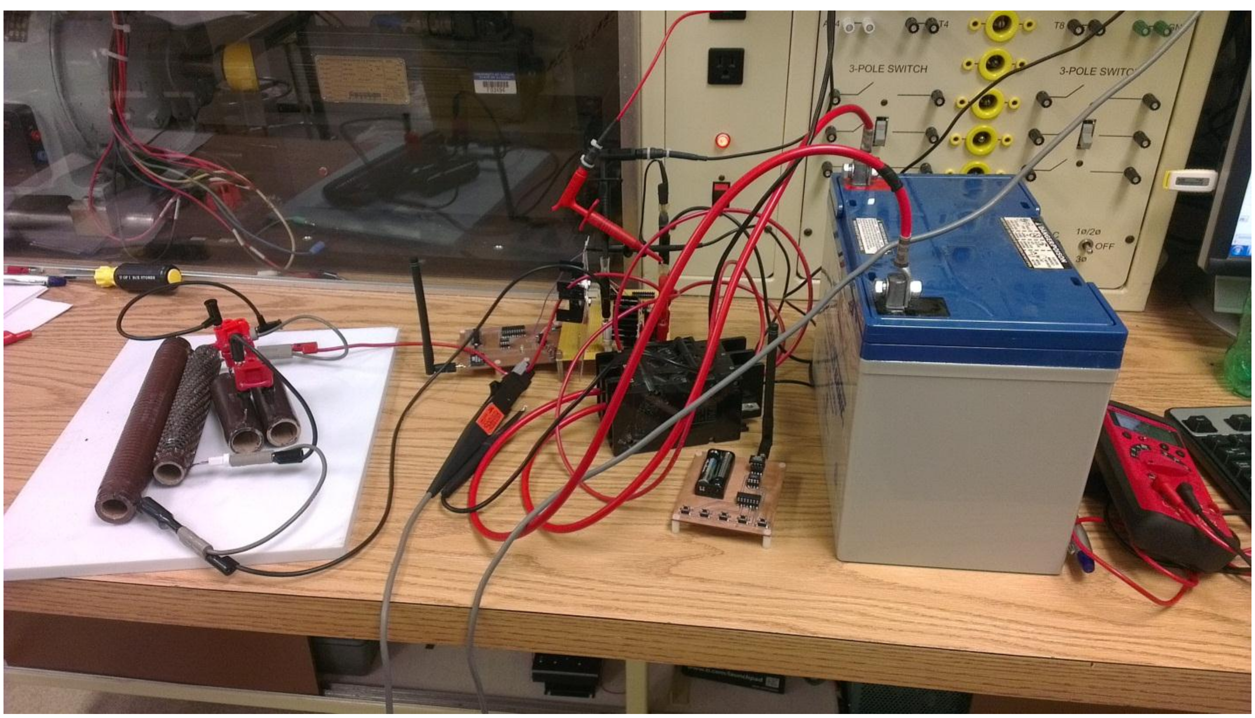


Figure 4: 250W test case set up

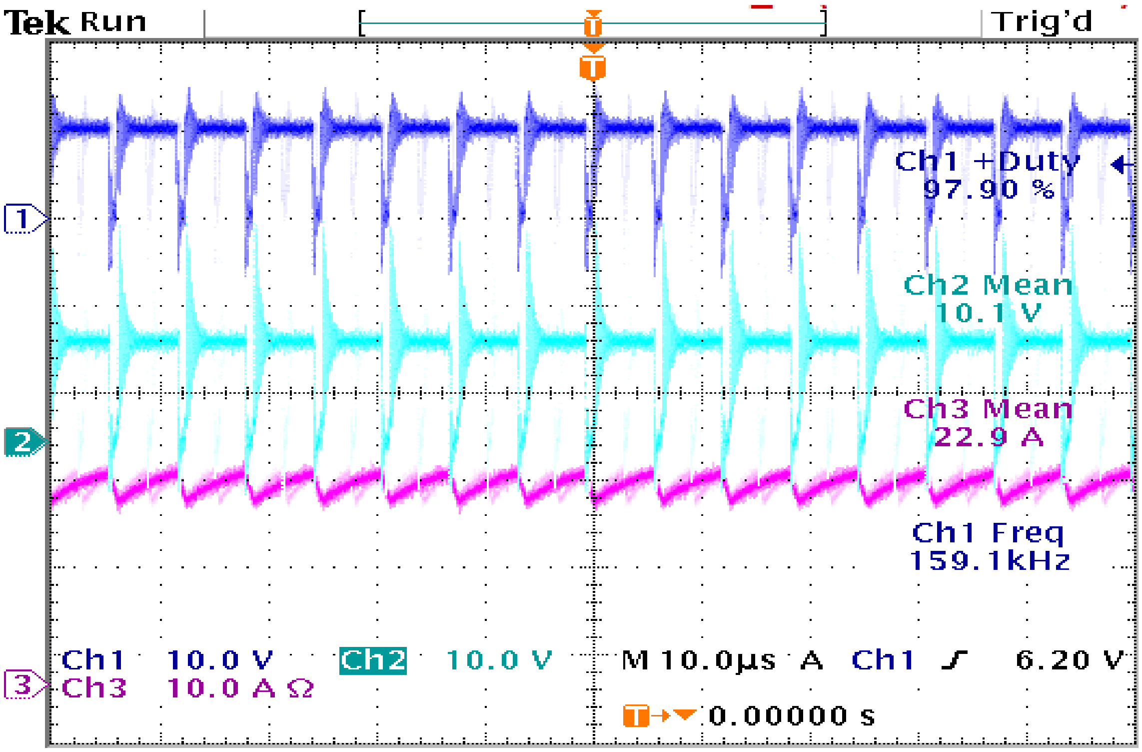


Figure 5: results of 250W test case with high frequency mode
Ch1: switch frequency Ch2: output voltage Ch3: output current

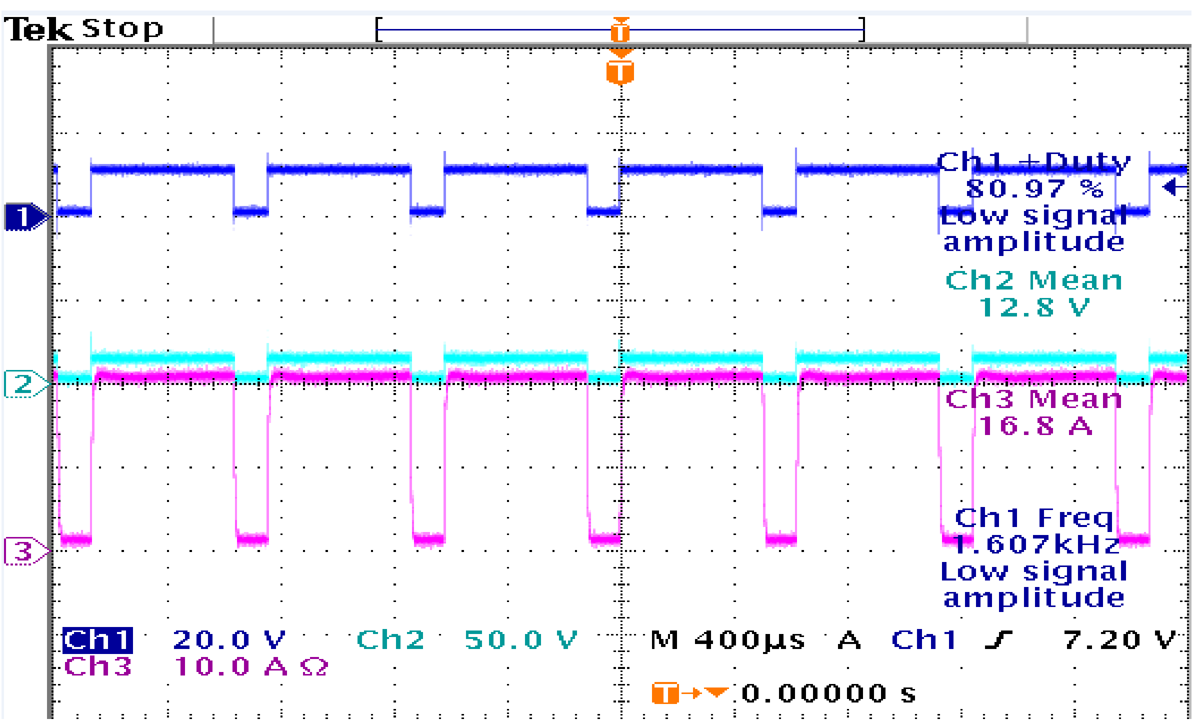


Figure 6: results of 250W test case with low frequency mode
Ch1: switch frequency Ch2: output voltage Ch3: output current

	I_{in}(A)	V_{in}(V)	P_{in}(W)	I_{out}(A)	V_{out}(V)	P_{out}(W)	Efficiency(%)	Temperature(℃)
150W test case	12.41	12.1	150.04	14.0	10.4	145.6	97	34
250W test case (low frequency)	21.5	11.97	257.35	16.8	12.8	215.04	83.5	31
250W test case (high frequency)	21.3	11.97	254.96	22.9	10.1	231.29	90.7	91

Table 1: results of the test cases