MIDDLE EAST TECHNICAL UNIVERSITY
ELECTRICAL-ELECTRONICS ENGINEERING DEPARTMENT

EE463

Wind Turbine Battery Charger

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1. INTRODUCTION

Our team is tasked on the design of a battery charger powered by a small wind turbine generator, with the goal of effectively regulating incoming power to charge a 12V, 100Ah battery. This collaborative project involves three individuals per group, with work documented in a publicly accessible repository. The specifications outline a voltage range of 15 $V_{line-to-line}$ to 25 $V_{line-to-line}$, a battery capacity of 100 Ah, a nominal battery voltage of 12 V, an output current of 10 A, and a 20% ripple allowance on the average current. Our strategic approach encompasses repository setup, topology evaluation, analytical calculations for circuit parameters, computer simulations to validate design choices, component selection, and the iterative implementation of a prototype. The ultimate objective was to present a functional prototype on the final demo day, demonstrating the charger's ability to sustainably charge the battery for a minimum of five minutes. Through these comprehensive steps, we aimed to create an efficient and reliable battery charger harnessing the power of wind energy.

2. PROJECT SPECIFICATION

The project specifications, important for the design and implementation of our battery charger, are outlined as follows and are tabulated in Table 1. The input voltage is expected to range from 15 $V_{line-to-line}$ to 25 $V_{line-to-line}$, aligning with the capabilities of a small wind turbine generator. The battery, with a substantial capacity of 100 Ah, operates at a nominal voltage of 12 V. The desired output is a steady current of 10 A, while allowing for a ripple of up to 20% of the average current. These specifications serve as the core parameters leading our team's design decisions, ensuring the charger meets the required performance criteria. Please refer to Table 1 for a detailed overview of these specifications.

Table 1. Design Specifications for the Battery Charger

	Value
Input Voltage	15 to 25 $V_{line-to-line}$
Battery Capacity	100 Ah
Nominal Voltage	12 V
Output Current	10 A
Output Current Ripple	%20 of average current

A battery can be represented as a DC voltage source accompanied by a series resistance typically within the milliohm range. During the charging process, the open circuit voltage of the battery rises, and it undergoes constant current charging at a specific voltage. At this juncture, the rate of the battery voltage increment diminishes due to a reduction in charging current magnitude. Figure 1 illustrates the voltage and current levels characteristic of a Ni-Cd battery during both constant current and constant voltage charging phases.

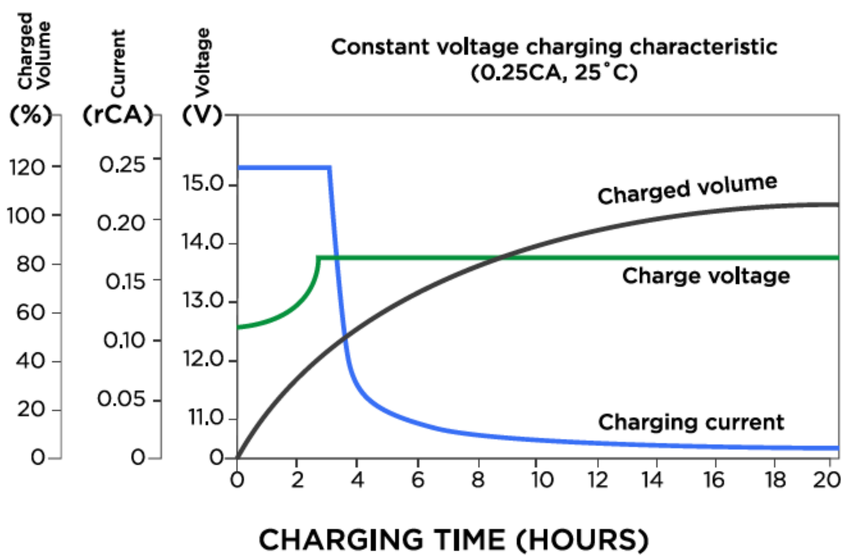


Figure 1. Typical Charging Characteristic of a Ni-Cd Battery

In the step in which we chose a topology for our charger's converter unit we made research about different topologies. Those involve: 3-phase diode rectifier with linear charger, 3-phase controlled thyristor rectifier, flyback converter and 3-phase diode rectifier with DC-DC buck converter. Among these designs, we chose a 3-phase diode rectifier with DC-DC buck converter.

A 3-phase diode rectifier with a linear charger is easy to construct but is not efficient and it is generally used in applications which need less power than ours.

3-phase controlled thyristor rectifiers can be used. However, it has more complexity and needs more time to work on. Moreover, it is usually used in higher power applications than ours and it is inefficient for our project.

Another possible topology is flyback converter. The reason we didn't choose this is that it would have more volume which we do not need, and it's more complex. On the other hand, it provides isolation which we do not need in our project.

Finally, we chose a 3 - phase diode rectifier - DC-DC buck converter, the simplified block diagram is shown in Figure 2, which fitted our design parameters. This topology provided us a solution having small size, high efficiency and good thermal performance.

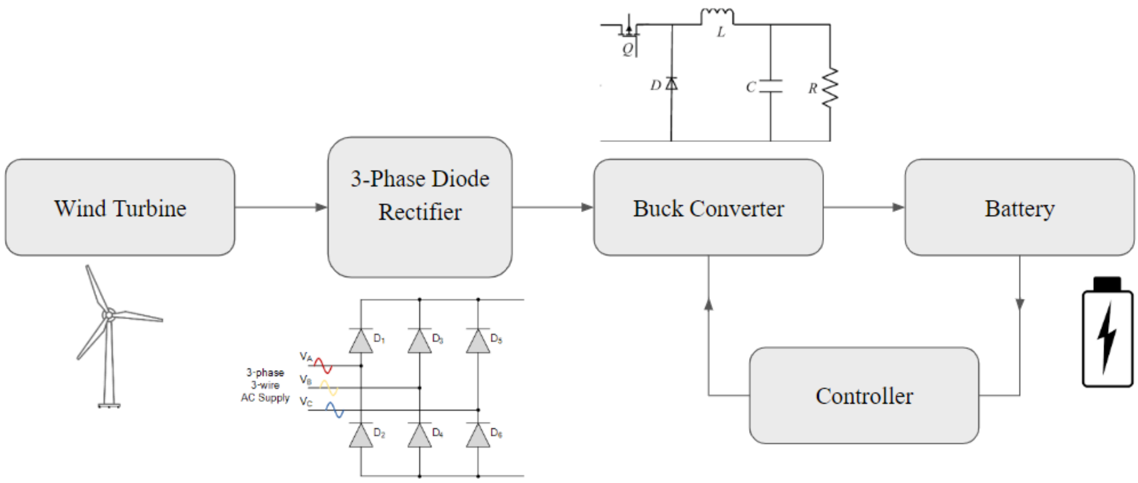


Figure 2. The Block Diagram of the 3 Phase Diode Rectifier - DC-DC Buck Converter

3. COMPONENT SELECTION AND DESIGN DECISIONS

Simulation programs like LTSpice and MATLAB Simulink are used to understand the circuit in a detailed manner. These programs help us to determine device rating and to find any abnormality in the circuit.

Figure 3 shows the schematic of the 3-phase diode rectifier simulated in LTSpice.

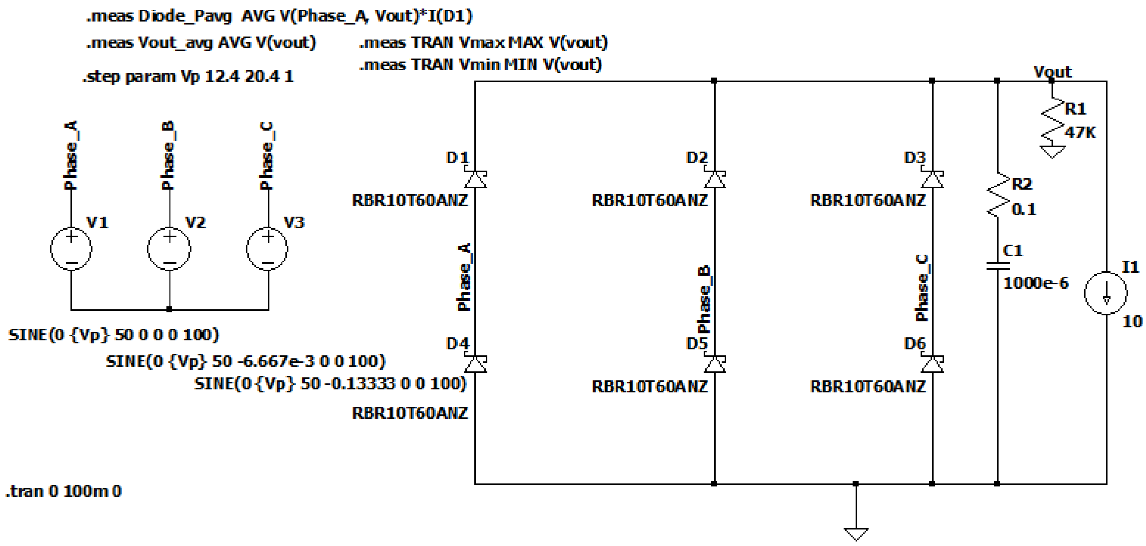
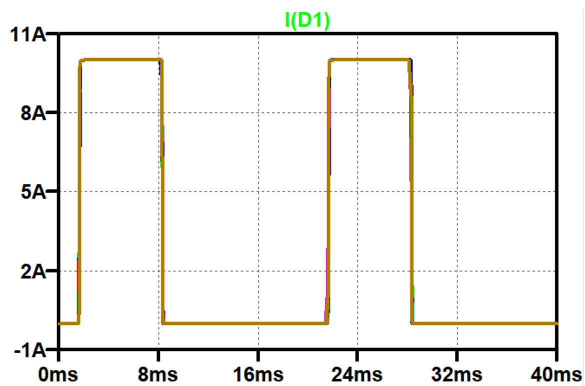
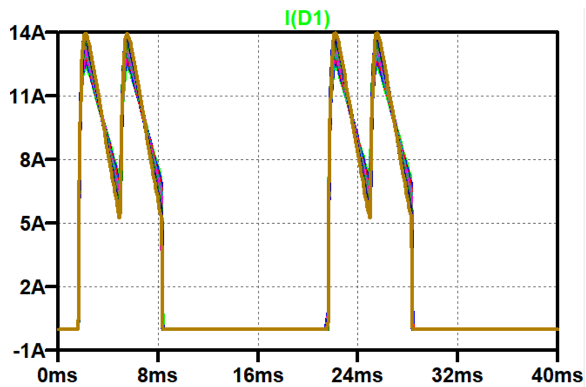


Figure 3. The Simulation Setup of 3-Phase Diode Rectifier with Non-ideal Filtering Capacitor



(a)

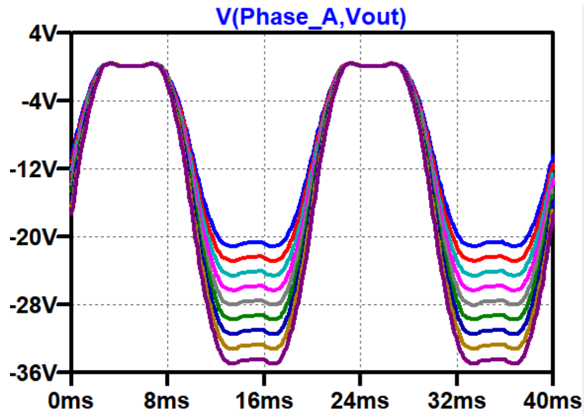


(b)

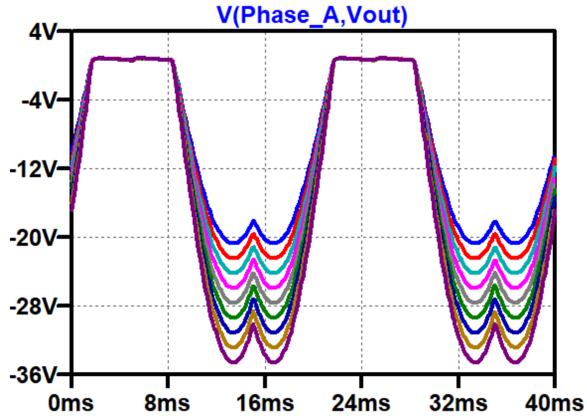
Figure 4. The Current Waveform of the D1 (a) with and without (b) Filtering Capacitance

The peak current of the 3-phase diode rectifier is affected by the existence of the filtering capacitor. Since the filtering capacitor is feeding the load such that it is needed to charge it up again. Charging the filtering capacitor ends up with a higher peak current. Figure 4 shows the current waveform of the D1 with and without a filtering capacitor. It can be seen in Figure 4 (b) that the peak current can reach 14A while drawing 10A constant current at the load. By considering the waveform in Figure 4, the diodes in the rectifier should have a current rating higher than 13A.

Figure 5 represents the voltage waveform of a diode during rectification. It shows that the diode needs to handle 36V reverse voltage in the rectifier. Figure 5 also indicated that the voltage ripple at the rectifier is observed at heavy load.



(a)



(b)

Figure 5. The Voltage Waveform of the D1 (a) with 0.1 A and (b) 10A. The effect of filtering capacitors vanishes at high load current.

Similar methodology is used for MOSFET and diode selection in the buck converter. The output of the 3 phase diode rectifier is in the range between 14V and 25V. The duty cycle of the gate PWM is controlled such that the batter is charged with constant voltage or constant current. Figure 6 shows the drain current and drain-source voltage waveform of the MOSFET while driving 10A load current at 12.7V output voltage. These figures indicate that the MOSFET experiences 11.6A during ON period and 25V during OFF period. However, the simulation considers almost ideal components; therefore voltage and current rating of the components must be higher than the values observed in the simulation.

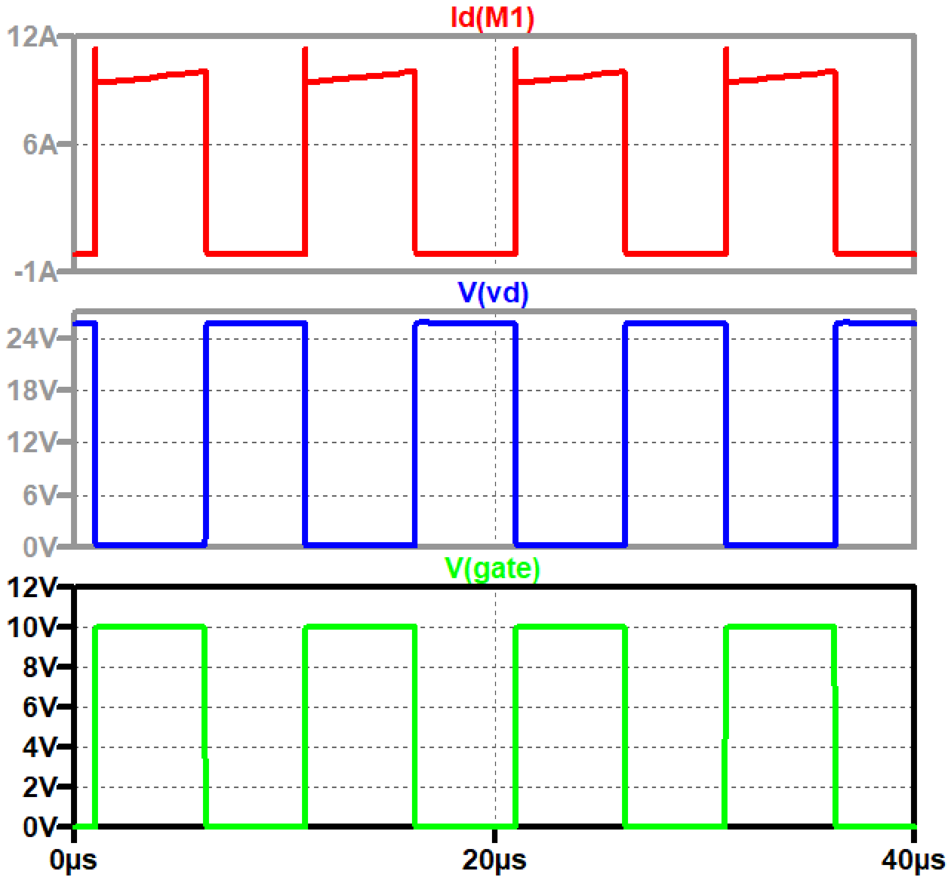


Figure 6. The Voltage Waveform of the MOSFET in Buck Converter.
(Input Voltage 25V, DC 0.52, Output Voltage 12.7V, Output Current 9.7A)

Similar to Figure 6, the diode current and voltage waveforms are shown in Figure 7. The diode in the buck converter observes -25V and 11.6A as a peak value. It is necessary to put a margin between the rating of the devices and the obtained values in the simulation.

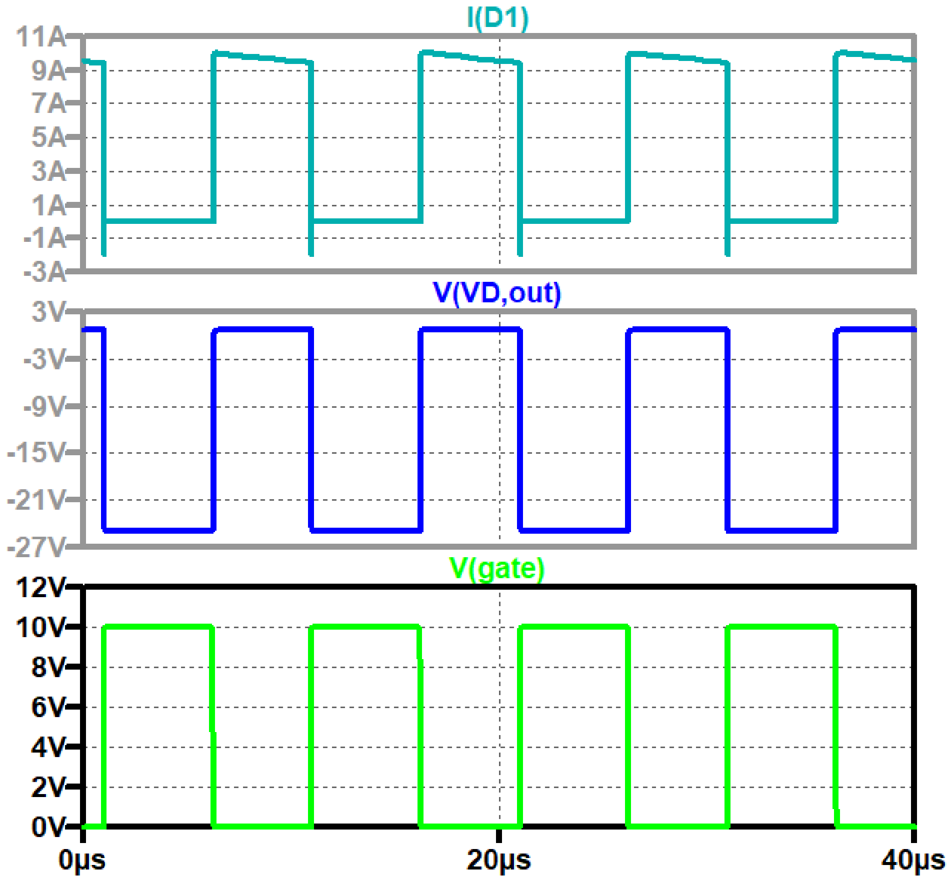


Figure 7. The Voltage Waveform of the Diode in Buck Converter.
(Input Voltage 25V, DC 0.52, Output Voltage 12.7V, Output Current 9.7A)

Table 2 (a) & (b) summarizes specification of the selected MOSFET and diode. Note that the diode in the simulation has a similar rating with the one used in the circuit.

Table 2 The Component Specification of the (a) MOSFET and (b) Diode in the Buck Converter

(a)	**Vds (V)**	**Ron (mΩ)**	**Ids (A)**	**Gate Charge (nC)**	**Vgs,th (V)**	**Cost ($) (1000 unit)**
IRFZ44N	55V	17.5	49A	63	2V, 4V	$0.58

(b)	**Vbr(V)**	**If (A)**	**Cost ($)**
DSS16-0045A	45	16A	$0.82

4. INDUCTOR AND CAPACITOR SIZING IN THE BUCK CONVERTER

In a rectifier circuit, the inclusion of an output inductor, often part of an LC filter with a capacitor, serves to smooth the pulsating DC output by its nature. This reduces output ripple, enhances voltage regulation against load variations, and minimizes harmonic distortion for a cleaner power supply. Acting as a filter, the inductor also blocks high-frequency noise, contributing to the overall stability and reliability of the rectifier circuit. Careful selection of the inductor, considering factors like inductance, current rating, and saturation, is crucial to meeting the specific requirements of the circuit and load.

As the core in our inductor, we used 0077442A7 which is provided in the laboratory. According to our calculations we needed an inductor of 60 μH.

$$L = \frac{V_{OUT}(1-D)}{\Delta I f_S} \qquad \text{Eq. (1)}$$

The most important part is that while carrying current, the inductor's inductance value doesn't stay constant, it decreases if the current increases. Moreover, in order to guarantee our inductor carries 10A, we connected two cables in parallel and then made 32 turns on our core. This turn number is higher than the needed inductance value. To calculate the inductance of the inductor, we need to use the datasheet of the inductor. In the datasheet we are provided the inductance created by the square of turn number. This number is 202 nH for the square of the turn number for our core. By iteration;

$$30^2\, x\, 0.202 \ = 181.2\, uH$$

when our turn number is 30. However, when there is 10A passing through the inductor, according to the datasheet of the core, our inductance value decreases to 136 uH. Even though this value is higher than our need, we constructed this inductor because if we had constructed an inductor with fewer turns, our core's size couldn't change and there would not be any change in our inductor's size. The only disadvantage of using an oversize inductor is that because of the longer cable, we had more loss because of the increasing resistance value. However, these losses were negligibly small.

In a buck converter, capacitors are placed at the output for various purposes. Firstly, they contribute to voltage regulation by smoothing out the output voltage, reducing the fluctuations induced by the rapid switching action of the converter. Secondly, capacitors serve to reduce voltage ripple, acting as effective filters to provide a more stable and clean DC output. Additionally, these components function as energy storage devices during the switching cycles, releasing stored energy during off periods to maintain a continuous output voltage. The presence of capacitors also enhances the transient response of the buck converter. Furthermore, capacitors reduce the effective output impedance, improving the converter's ability to handle dynamic loads and ensuring output voltage stability. Lastly, they act as low-pass filters, attenuating high-frequency noise from the output voltage. The careful selection of capacitor values, considering factors such as load regulation, output voltage ripple, and transient response, is crucial for optimizing the performance of the buck converter in diverse applications.

$$C = \frac{\Delta I}{8 f_S \Delta V_{OUT}} \qquad \text{Eq. (2)}$$

According to our aimed input frequency and output voltage ripple values, our capacitance could be 5.6 uF. However, we made an overdesign here, and we used a capacitor which has 47 uF capacitance. The reason for that was that we aimed to reduce our output current ripple. Unfortunately we couldn't achieve our goal perfectly and we could reduce our output current ripple up to 10%. In order to decrease the output current to better values, instead of using such an overdesign capacitor, we could have connected more capacitors in parallel which would still increase our capacitance value. Furthermore, in the parallel connection of capacitors, our ESR value would be smaller which will help our output current become more stable, and would decrease our losses because of the decrease of the resistance value.

5. BILL OF MATERIAL

Table 3 shows the list of the material used in the battery charger and their cost. Note that the complete schematic is provided in Appendix A.

Table 3. Used Components and Prices

6 x DSS16-0045A Diode for the Rectifier	34.66 x 6 = 207.96 TRY
2200 uF Electrolytic Capacitor for the Rectifier	12.89 TRY
6800 uF Electrolytic Capacitor for the Rectifier	70.73 TRY
DSS16-0045A Diode for the Buck Converter	34.66 TRY
IRLZ44N Mosfet for the Buck Converter	20.05 TRY
47 uF Electrolytic Capacitor for the Buck Converter	0.64 TRY
LM338 Voltage Regulator	45.39 TRY
Arduino Uno Klon	145.35 TRY
TLP250 Gate Driver	51.95 TRY
LM358 Opamp	3.66 TRY
ACS712 Current Sensor	70 TRY
Pertinaks	50 TRY
Resistors (100 kΩ, 10 kΩ, 2.2 kΩ, 270 Ω, 100 Ω, 22 Ω)	0.5 TRY
5 x Input Output Sockets	Taken from the lab
0077442A7 Toroid Core	Taken from the lab
2 x Heatsink	20 x 2 = 40 TRY
TOTAL COST	753.78 TRY (24,88$)

6. TEST RESULTS

The test procedure consists of mainly two parts namely resistive load tests and battery charging tests. For safety and not to damage the circuit, output current is limited to 1A first, and incremented after checking the thermal result at each step. Before testing with load, the no load test is done in order to test the voltage control of the circuit. Test results are below.

Figure 8. No Load Test for Both Vll = 15V and Vll = 25V

The steady state test result for no load condition is given in Figure 8. As can be seen from Figure 8, our voltage control is successfully working at steady state. However, when there is a sudden change in the input voltage, the response of the controller is slow which results in sudden voltage changes at the output. Note that the code block of the controller is provided in Appendix B. When the Vin-ll changes from 15V to 25V, the output voltage reaches 18V for an instant and drops to 13V again. Similarly, when the Vin-ll changes from 25V to 15V, the output voltage drops to 8V and increases to 13V again. As a result, our voltage controller can regulate the output voltage to the desired level, however it cannot react fast enough to the sudden changes in the input voltage.

After no load test is completed, resistive load test is realized. The aim of this test is to check the voltage control and the current control and thermal issues before connecting the circuit to the battery. This test is done with DC power supply. Resistive load test results are below.

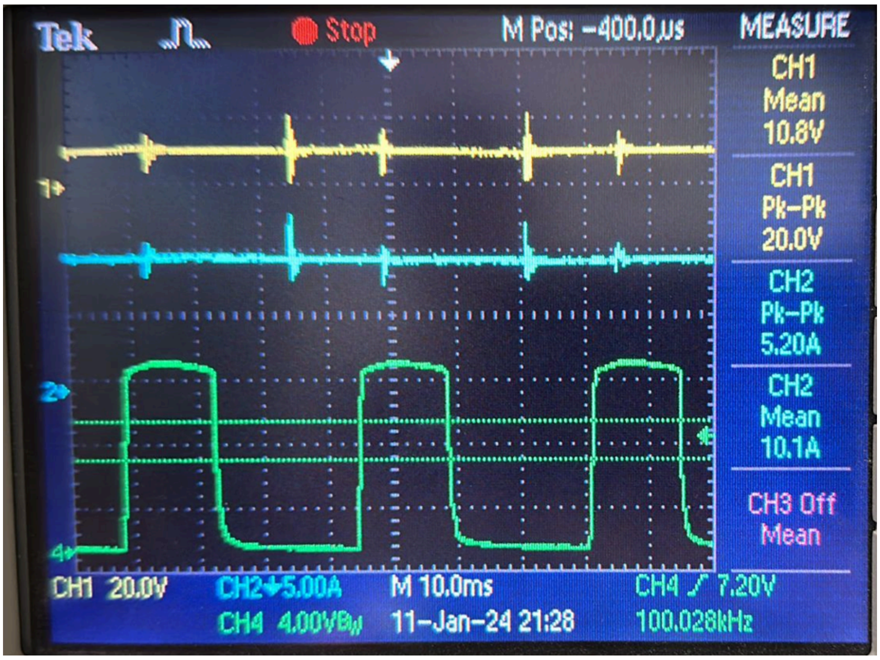


Figure 9. Resistive Load Test Waveforms for VDC = 25V

Figure 10. Resistive Load Test Current Ripple for VDC = 25V

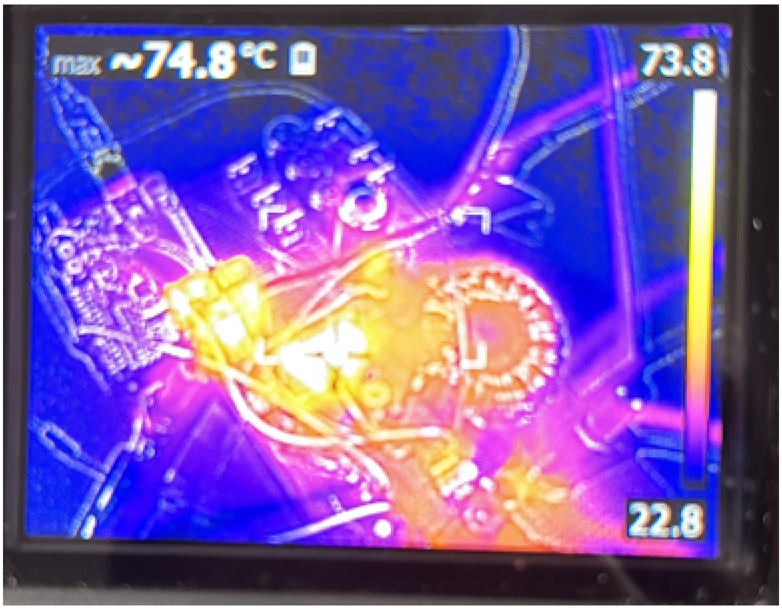


Figure 11. Resistive Load Test Thermal Camera Results for VDC = 25V

10A test results for resistive load are given in the above figures. Before testing with 10A, similar tests are done with lower currents and at each step thermal results are checked. In Figure 10, current ripple can be seen for the average 10A current output 420 mA, which is far below the current ripple limitations of the project which is 2A. In Figure 11, thermal camera view of the circuit while supplying 10 A can be seen. The hottest component is the diode of the buck converter and it is at 74.8 °C.

Finally the battery charging test which is the purpose of the project is done. Test results are below.

Figure 12. Battery Charging Test Wattmeter Vll = 16.9V

Figure 13. Battery Charging Test Waveforms and Current Ripple for Vll = 16.9V

Figure 14. Battery Charging Test Waveforms and Output Power for Vll = 16.9V

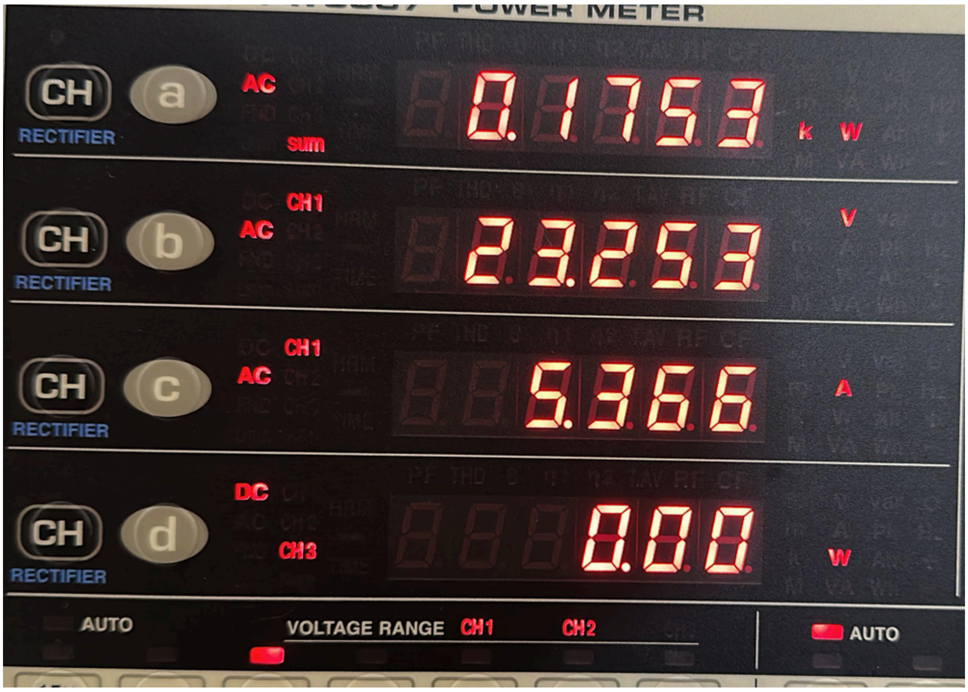


Figure 15. Battery Charging Test Wattmeter Vll = 23V

Figure 16. Battery Charging Test Waveforms and Current Ripple for Vll = 23V

Figure 17. Battery Charging Test Waveforms and Output Power for Vll = 23V

Figure 18. Battery Charging Test Thermal Camera View

In Figure 13, current waveform, output voltage waveform and switching waveform for 16.9V Vll can be seen. As can be seen from the same figure, current ripple is 2A with 10A mean which satisfies the project requirements. Similarly, the same waveforms for 23V Vll can be seen in Figure 16. As can be seen from Figure 16, output current ripple is 1.84A with 10A mean which satisfies the project requirements. As a result, our buck converter can supply 10A current within the 20% ripple limit to the battery in the given Vll voltage limits. However, when the input voltage is increased rapidly, the output current can reach very high levels such as 20A for an instant and reaches its steady state 10A again. This can be dangerous and it shows that our controller can not respond fast enough.

After waiting for 5 min while the Vin-ll equals 23V, thermal camera view is recorded which can be seen in Figure 18. As can be seen from Figure 18, The switching mosfet reaches 108 °C. Since the mosfet and the diode can operate up to 175 °C and voltage regulator can operate up to 125 °C, our circuit can operate safely at the rated conditions.

7. POWER ANALYSIS

In Figure 12, 166.25W input power is shown for the Vin-ll = 16.9V. In Figure 14, 146W output power is shown for the same input. As a result 146/166.25 = 87.8% efficiency is obtained for the Vin-ll = 16.9V.

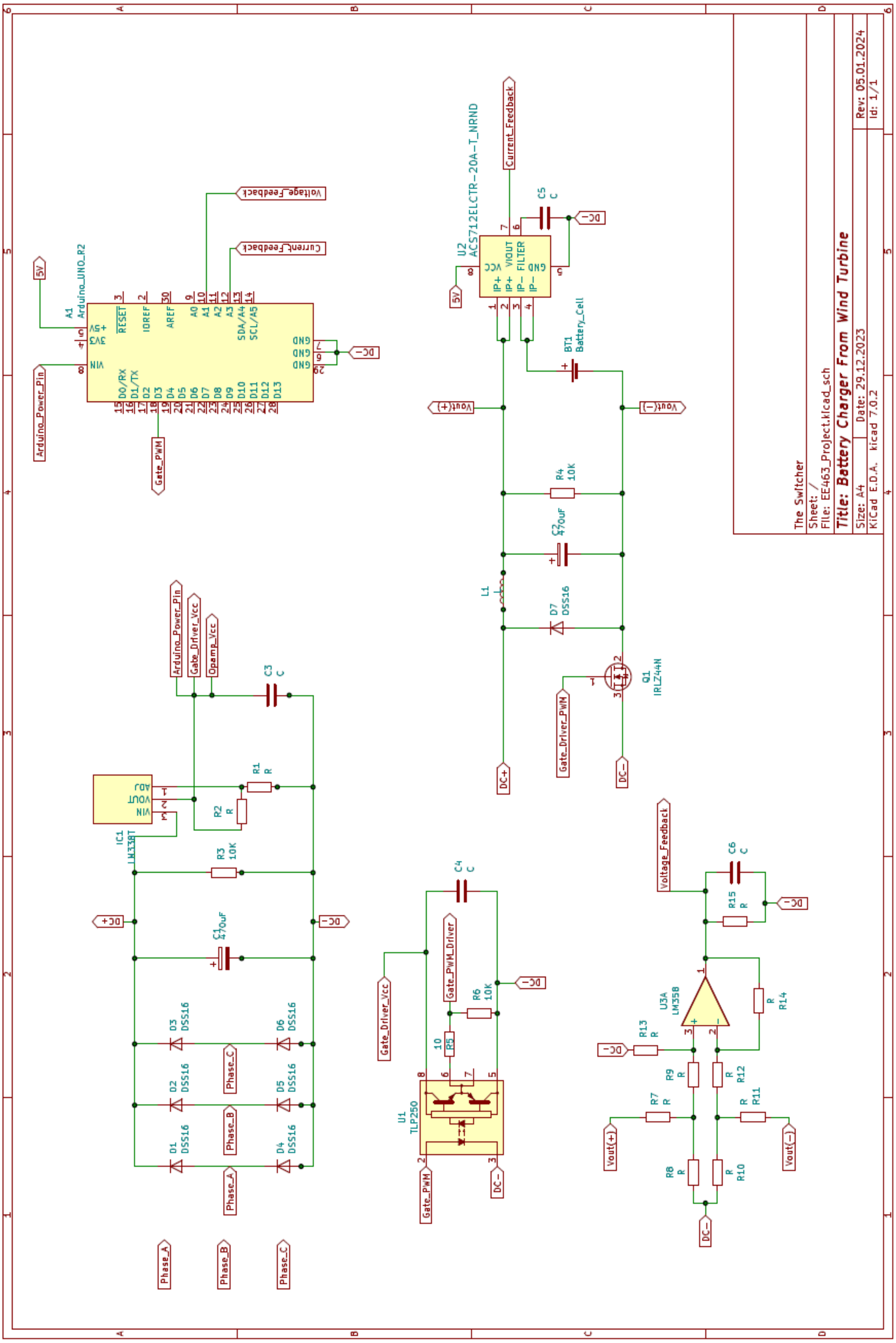
Similarly in Figure 15, 175W input power is shown for the Vin-ll = 23V. In Figure 17, 147W output power is shown for the same input. As a result 147/175 = 84% efficiency is obtained for the Vin-ll = 23V.

In the second case, the duty cycle decreases and the time that diode is ON increases. Since the diode losses are higher than the mosfet losses our power loss increases. Moreover, as the input voltage increases losses on the voltage regulator increases too. Therefore our efficiency dropped 3.8 percent while input voltage increased from 16.8V to 23V. As a result, this buck converter operates in between 84% and 87.8% efficiency.

8. CONCLUSION

In this project, we aimed to construct a battery charger which charges a Ni-Cd battery with 10A constant current with a maximum of 20% ripple. The main problem was that when the battery is being charged, its voltage increases and in order to provide a constant current of 10A, we need to use a controller which increases the voltage of our charger output while the battery's voltage increases. Our application basically involves 3 units which are our 3 - phase rectifier, low side buck converter, and our controller. The rectifier rectified our AC signal which we obtained from the VARIAC to DC. In order to do that, we used Arduino Uno as a microcontroller and at the output of the microcontroller we set up a gate driver which drives our mosfet. Then, with the mosfet, we obtained the voltage required by the microcontroller. The microcontroller worked basically with hysteresis control which gets our output current as feedback (by the usage of current sensor connected to our microcontroller) and as our current exceeds 10A, our microcontroller decreases the current step by step in every loop, and when our current is below 10A, our current increases step by step in every loop as well. The way for doing that is to play with the duty cycle of our buck converter which we made changeable between 20% and 80%. When constructing our charger, we paid attention in the selection of the components which require our specifications. The most heating components were the voltage regulator and our mosfet. In order to overcome this problem, we used heat sinks on these components. However, in steady state operation, these components' temperature was at most 110 °C which didn't exceed their upper limit which is 170 °C. In the end, we obtained 10A output and our current ripple was around 10% which is enough for the project's aspects. Although the project fulfills the aspect, in order to optimize it we could make some upgradings. One of them is to reduce the output ripple. In order to make this, we could add some parallel capacitors to the output of our buck converter. It would provide a better current output because of the reducing ESR value and increasing output capacitance value as well. Moreover, our inductor and capacitor which is located at the output of the rectifier were an overdesign, we could use smaller inductors and capacitors there which would optimize our charger's size. Another optimization could be done in the controller. Our controller doesn't work rapidly which in real life we do not need. However, when we change the VARIAC level fastly, we couldn't have encountered a jumping current value if we had done a controller which works with PID control principle instead of hysteresis control.

APPENDIX A



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Size: A4
Date: 29.12.2023
Rev: 05.01.2024
KiCad E.D.A. kicad 7.0.2
Id: 1/1

APPENDIX B

```
int analogPin1 = A1;
int analogPin3 = A3;
int Isns = 0;  // variable to store the value read
int vload = 0; // variable load voltage

double Icrit = 645;  //526 1A, 580 5A, 600 6.4A, 650 9.5A, 655 10.1A
double Vcrit = 145; // Critical voltage value (div 4, Vmax 13.2, Vcrit = 675.84 (out of 1024))
                              // 1024 at output voltage correspond 20V
double DC_step = 1; // 0.01*160/100 ; //%100 DC = 160,

void setup ()
{
  Serial.begin(600);
  pinMode (3, OUTPUT) ;
  TCCR2A = 0x23 ;
  TCCR2B = 0x09 ; // mode 7, clock prescale by 1
  OCR2A = 160-1 ;  // 160 clock periods = 10us per cycle
  OCR2B =0 ;
  TCNT2 =0 ;
  delay(5000);
}
void loop ()
{
  // here you can set the duty cycle by writing values between 0 and 160 to
  //OCR2B = 80;

  vload = analogRead(analogPin1); // read the input pin - VOLTAGE SENSE
  Isns = analogRead(analogPin3);  // read the input pin - CURRENT SENSE (512 -> 2.5V voltage offset)

  Serial.println("Current");   Serial.println(Isns);          // debugging purpose
  Serial.println("Voltage");   Serial.println(vload);         // debugging purpose
  Serial.println(OCR2B);                                      // debugging purpose

  if ((Isns<=Icrit) & (vload<=Vcrit)) {
    Serial.println("Safe");
    if (OCR2B <144){
      OCR2B = OCR2B + DC_step;
    }
  }
  else if (OCR2B > 0) {
    Serial.println("Fail");
    OCR2B = OCR2B - 1;
 }
}
```