MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL & ELECTRONICS ENGINEERING DEPARTMENT

# EE463 POWER ELECTRONICS – I

# HARDWARE PROJECT SIMULATION REPORT

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## INTRODUCTION

This report contains information about the preliminary design of the EE463 hardware project. The topology selection by comparing several solutions, the component selection for selected topology, risk mitigation activities and extra plan for bonus parts are provided. All analyses are tried to be supported by a simulation or literature findings.

## THE REQUIREMENTS

In that study, we aimed to build a wind turbine battery charger. Our target is to create a circuit that can control and manage the power coming from the wind turbine generator, ensuring that it effectively empowers the load and charges the battery. To achieve this, a circuit for converting AC to DC must be developed with necessary control. Furthermore, the battery as a load has a dynamic IV characteristic during charging and discharging events. This characteristic is shown in Figure 1 for a battery.

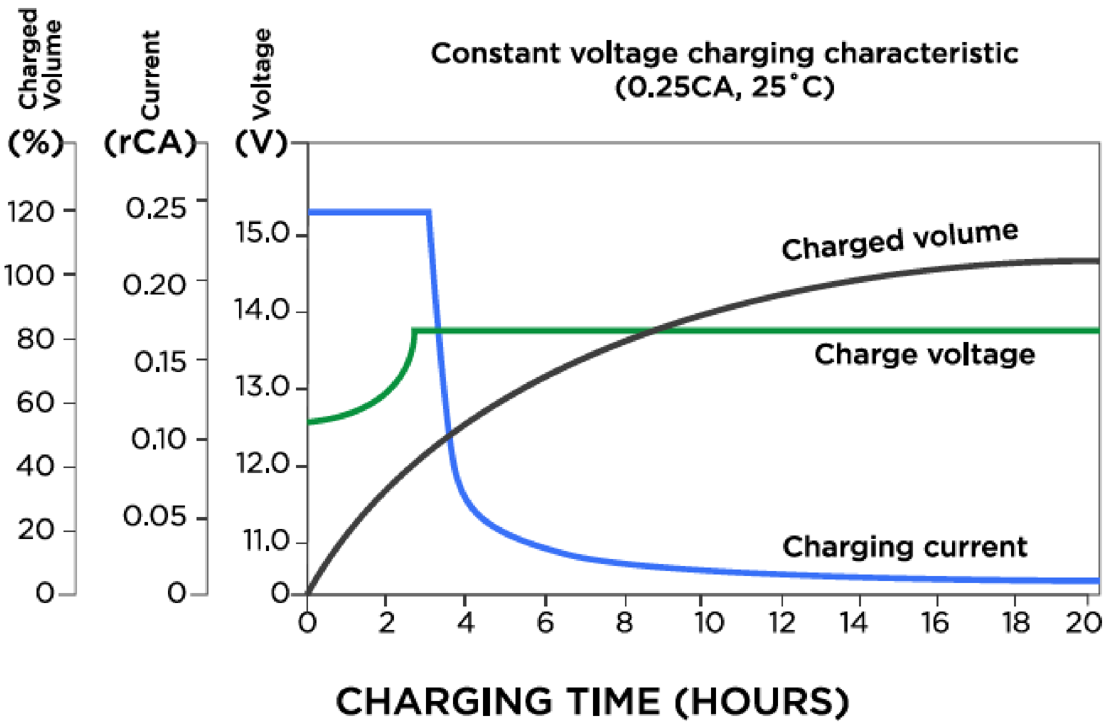



**Figure 1.** A Charging Characteristic of a Battery During Constant Voltage and Constant Current Event [1]

As shown in Figure 1, the controller must regulate the output voltage to have a fixed current when the battery is low. In the constant current regime, the current will be measured for generating feedback for relevelling output voltage. Similarly, a constant voltage operation is needed to be satisfied when the battery is high. A fully charged battery behaves like an open circuit such that it will not draw any current.

The input voltage and battery specification of this project is presented in Table 1.

**Table 1.** Project Specifications

| | **Value** |
|---|---|
| **Input voltage** | 15 $V_{line\text{-}to\text{-}line}$ to 25 $V_{line\text{-}to\text{-}line}$ |
| **Battery capacity** | 100 Ah |
| **Battery nominal voltage** | 12 V |
| **Output current** | 10 A |
| **Output current ripple** | %20 of average current |

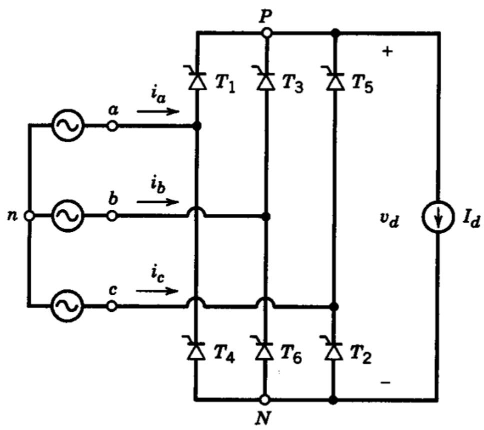
## TOPOLOGY SELECTION

There are several topology options for obtaining the above requirements. Topology selection is based on the rated current and voltage requirements and the complexity level. A linear charger with three-phase diode rectifier, flyback converter, three-phase thyristor rectifier and three-phase diode rectifier with buck converter are analyzed.

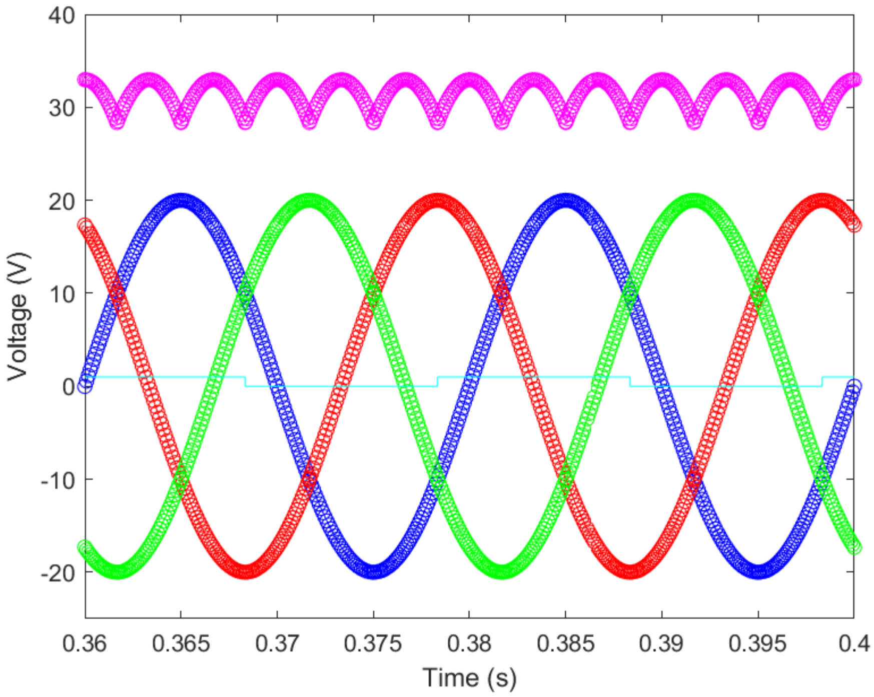
In a linear charger with three-phase diode rectifier, the output voltage and current are controlled by using a transistor as a voltage controlled resistor. The resistance of the transistor can be manipulated by adjusting the gate-source voltage, which can range from milliohms to megaohms. In that topology, the transistor is a certain power loss component; therefore, the efficiency is around 60%. This solution can be used for low voltage-current applications.

The buck converter is a better choice for our project compared to the flyback converter. It efficiently reduces high input voltage to a stable output voltage, which aligns with our goals. It's simpler, cost-effective, and has fewer parts, making it practical for our project. The buck converter is also more efficient at higher output currents, crucial for our constant current mode. Its smaller size and reduced weight are beneficial for projects with space and weight constraints. Additionally, the buck converter has less output voltage ripple, ensuring a stable output voltage during our constant voltage mode. It's easy control, especially with digital controllers like Arduino, allows precise regulation of output parameters, meeting our project requirements. While flyback converters have their uses, the buck converter is advantageous for our project's specific needs.

Three-phase thyristor rectifier is another proposed solution. This topology requires the synchronous control of the six thyristors with their firing angle. When the firing angle of the thyristor is set to zero, the circuit behaves like a full bridge diode rectifier; therefore maximum and minimum output voltage is 33.75V and 20.25V, respectively. A circuit schematic and output voltage of a three phase controlled thyristor rectifier are shown in Figure 2 when firing angle is zero..




(a)




(b)

Figure 2. Circuit topology (a) and Voltage Waveform (b) of Three PhaseThyristor Controlled Rectifiers (Firing angle is zero.)

The average output voltage of the rectifier with respect to iterated firing angle is shown in Figure 3 at 20V line-to-line voltage. If the input voltage is smaller than $20V_{ll}$, firing angle can be set to a smaller value.

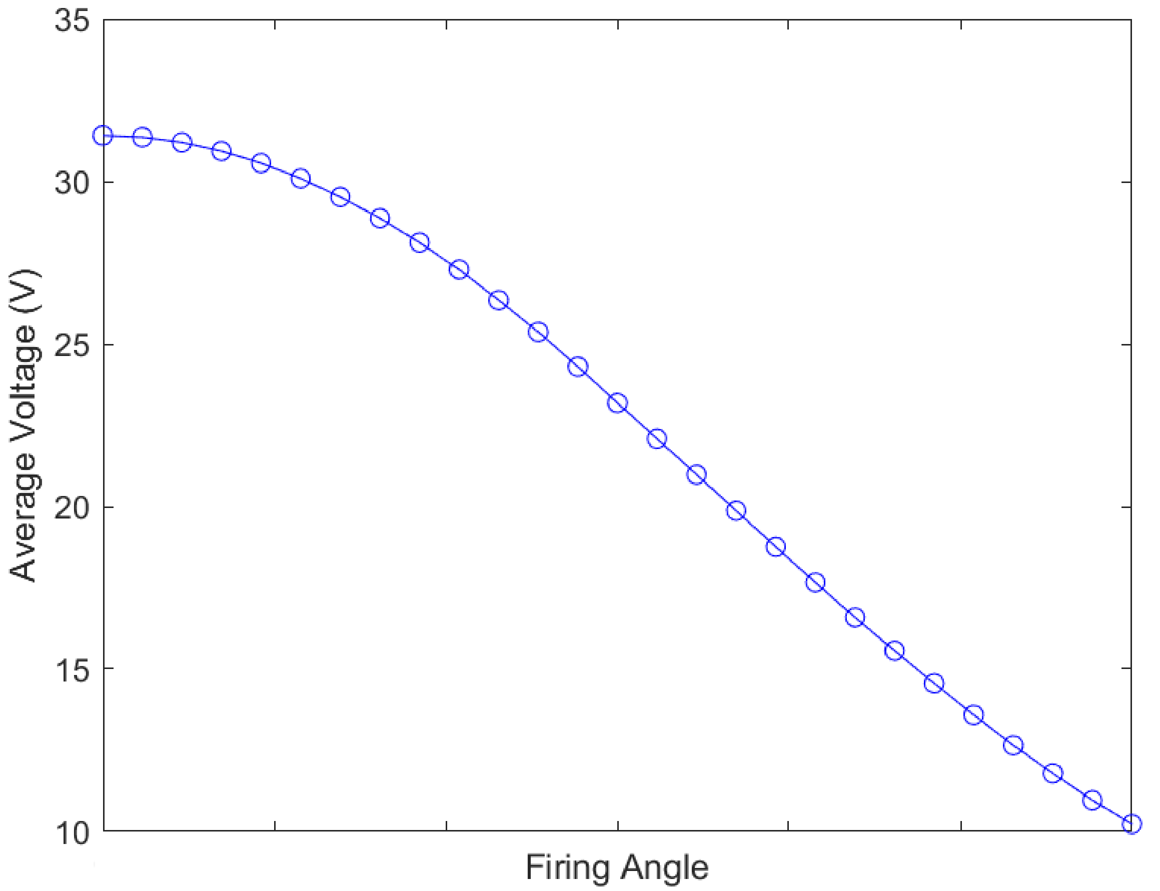



**Figure 3**. Average Voltage with Respect to Firing Angle for Three PhaseThyristor Controlled Rectifier (Resistive Load.)

Since the battery voltage will be around 13.2V and 10.8V as a characteristic of a lead-acid battery, the average output voltage of the controlled three phase thyristor rectifier must be around the voltage level of the battery. This can be achieved by setting a proper firing angle and a high enough output capacitor.

To mimic the constant current battery characteristic, firing angle is set to a value such that the average output voltage is 9.47V and the load is a constant current source which draws 10A. For the constant current regime, the output power is around 108W (10.8V X 10A). In the market, the forward-on voltage of a thyristor is in the range of 1 to 2 volts which leads to a high conduction losses compared to output power. Furthermore, the control of the six thyristors can be a complex problem, since there needs to be a minimum gate current supplied (in the order of mA) to the gate of the thyristor. We are planning to use digital controllers which generally have pins having a limited output current. To get a high amount of current, an additional current driving circuit will be needed. The combination of driving thyristor and their driving circuit makes the problem complicated and also it increases the possibility of failure. Additionally, the availability of thyristor is not as good as that of mosfet. Therefore, the three phase controlled thyristor rectifier will not be used.

We are planning to use a topology which contains AC to DC rectifier and DC to DC conversion. It can be named as the combination of three phase diode rectifiers and DC-DC converter. Our first aim is to get AC to DC rectification with a small output voltage ripple. The minimized ripple at the output of the AC-DC rectification indicates that the ripple at the output of DC-DC conversion is minimized. Therefore, DC-like output voltage is aimed for the rectifier. The obtained DC-like output voltage is always higher than the battery voltage; therefore, the buck converter is selected. In buck converter, driving only one mosfet is enough to get DC-DC conversion. Furthermore, the selection of low on-resistance and high speed mosfet creates an additional margin for thermal design. The availability of a mosfet also makes this topology more attractive. The details of the design are presented in the following sections.

## ANALYTIC ANALYSIS, SIMULATION and COMPONENT SELECTION

In this part, the analytic calculation for the circuit elements of the topology is presented. To gain a deeper understanding of the circuit dynamics and the ratings of the circuit elements, a simulation analysis was conducted. After that, the selected components were decided.

### Analytical Calculations of the Components' Parameters

In order to design the buck converter, firstly we calculated the maximum and minimum values of $V_{DC}$ which correspond to the output voltage of the three-phase full bridge rectifier. By using the formulas (1) and (2) shown below, $V_{DC-MIN}$ and $V_{DC-MAX}$ are calculated as 20.25V and 33.75V respectively.

| | |
|---|---|
| $V_{DC-MIN} = \frac{3\sqrt{2}\,V_{ll-min}}{\pi}$ | (1) |
| $V_{DC-MAX} = \frac{3\sqrt{2}\,V_{ll-max}}{\pi}$ | (2) |

After calculating the $V_{DC}$ values, we decided on the maximum and minimum duty cycle values. For obtaining the maximum duty cycle value we used the minimum $V_{DC}$ and maximum output voltage, and for obtaining the minimum duty cycle we used the maximum $V_{DC}$ and minimum output voltage values. $V_{OUT}$ is going to be between 13.1V and 10.8V due to the characteristic of lead-acid battery. Maximum and minimum $V_{DC}$ of full bridge diode rectifiers are calculated via Eq(1) & Eq(2) as 33.75V and 20.25V, respectively. We used the

Eq(3) for duty cycle calculations. Therefore, $D_{MIN}$ and $D_{MAX}$ values are calculated as 0.32 and 0.65 respectively.

$$D = \frac{V_{OUT}}{V_{DC}} \tag{3}$$

After calculating the D values, we calculated the parameters of the inductor and capacitor used in the buck converter. Although, according to the project limitations output current ripple ($\Delta I$) must not exceed 2A, we did our calculation to adjust the $\Delta I$ value to 1.5A. Even though the project does not have a specification on the output voltage ripple, we did our calculations fitting a 5% ripple for the output voltage. In order to calculate the L and C values in the Eq (4) and Eq(5), we assumed the $V_{OUT}(1 - D)$, values as their maximum, and $\Delta V_{OUT}$ value as its minimum. In order to determine the L and C values, first we had to determine the switching frequency. We chose the switching frequency as 100 kHz because choosing a larger switching frequency decreases the output ripple, and increases the frequency of the possible noises which can occur on the circuit. It also increases the switching losses but it can be eliminated by using high speed circuit components, which are relatively expensive. Also, 10A inductors are expensive so we decided to wind the coil by ourselves. Winding smaller inductance is easier. So, we chose the switching frequency as 100 kHz. As a result, 60µH and 3.75µF calculated as L and C respectively. To secure, we choose larger inductance and capacitance than calculated values as 100µH and 5.6µF respectively.

$$L = \frac{V_{OUT}\, x\, (1-D)}{f_s\, x\, \Delta I} \tag{4}$$

$$C = \frac{\Delta I}{8\, x\, f_s\, x\, \Delta V_{OUT}} \tag{5}$$

Finally, we decided to Cin capacitance value according to the following Eq(6). In order to reach a low ripple, we had to choose a very large capacitor. For simulation, we chose a 4 mF capacitor, but this value is large, and it can be revised during experimental procedure.

$$C = \frac{I_{av}\, t_{charging}}{\Delta V} \tag{6}$$

## Simulation Results of Full Bridge Diode Rectifier and Buck Converter

Figure 4 shows the simulink setup of the full bridge diode rectifier and buck converter. The circuit is in the form of subblocks.

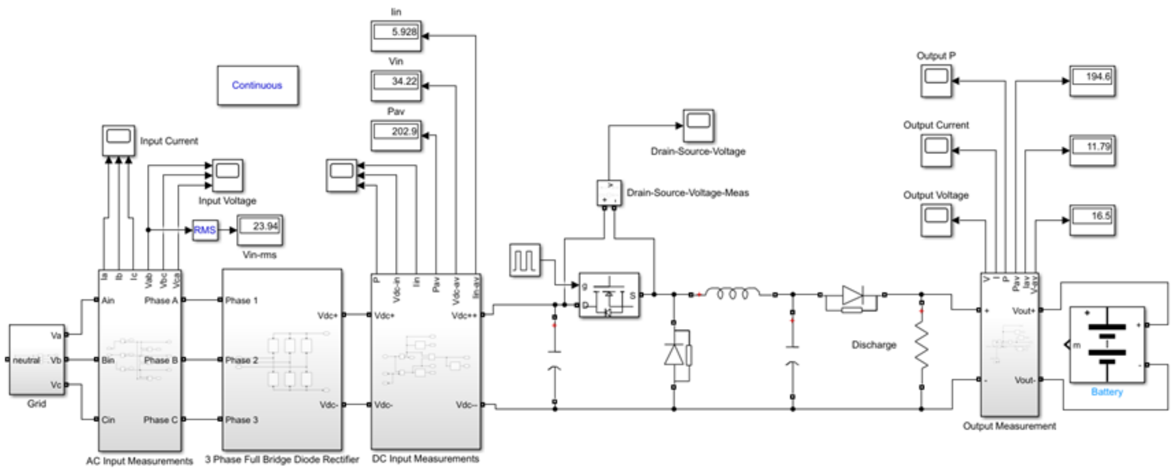



**Figure 4.** Schematic of the Design.

Figure 5 shows the inside of the grid subblock. This is the representation of the output voltage of a wind turbine. The line-to-line output voltage is between 15V and 25V.

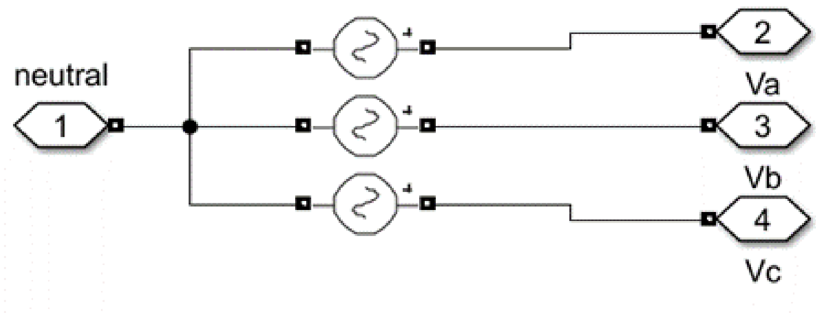



**Figure 5.** Inside of the Grid Block

The three phase diode rectifier is shown in Figure 6. The output of the rectifier is connected to the input of the buck converter.

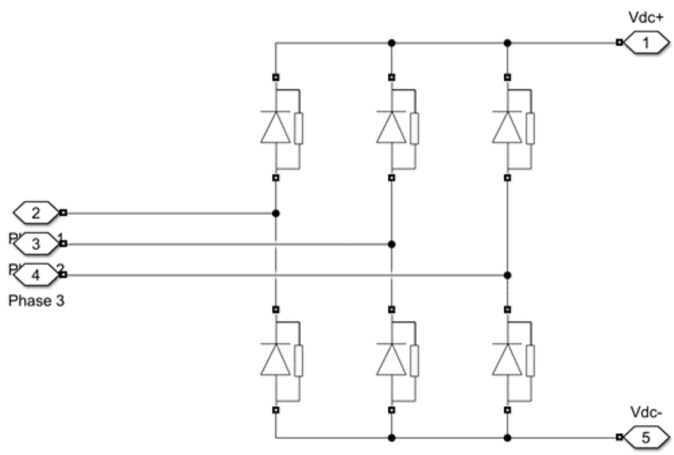



**Figure 6.** Inside of the 3-Phase Full Bridge Rectifier Block

Figure 7, 8 and 9 shows the inside of the measurement subblocks.

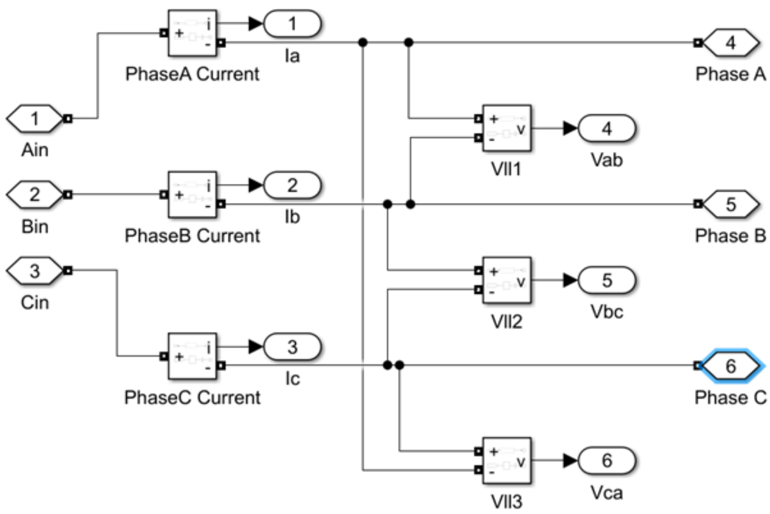



**Figure 7.** Inside of the AC Input Measurement Block

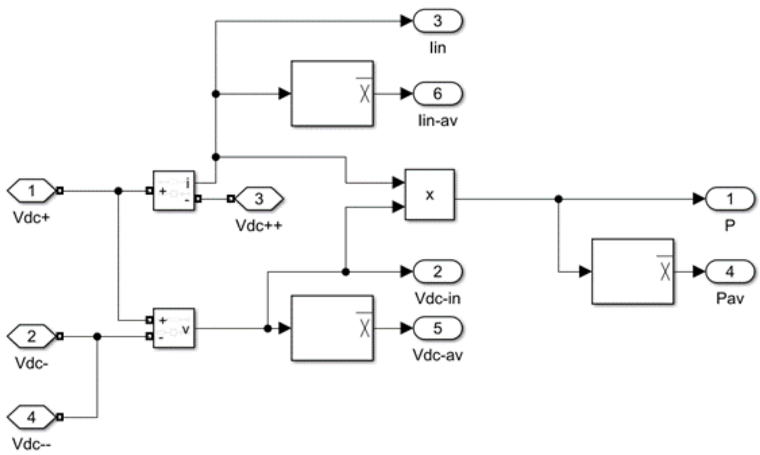



**Figure 8.** Inside of the DC Input Measurement Block

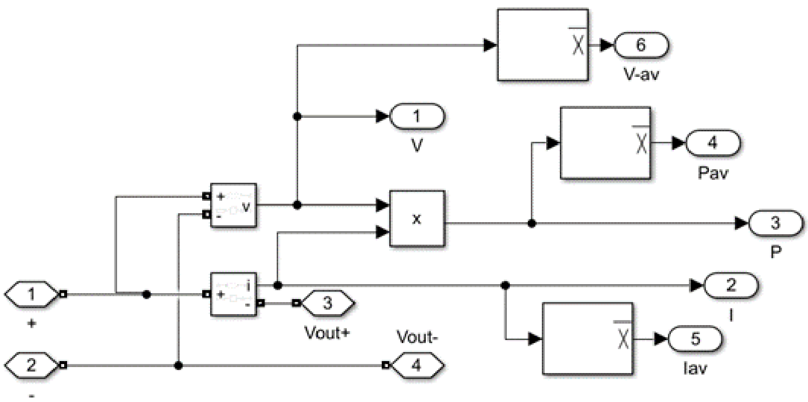



**Figure 9.** Inside of the Output Measurement Block

For simulation, we used the above schematics in the MATLAB SIMULINK. We used ideal components for the first simulation and then we thought about what the effects of real components might be. For the simulation period, we used a fixed duty cycle to control the gate of the MOSFET for different cases. While constructing the circuit on PCB, we are planning to use Arduino or analog PWM controller chip UC3843. Details of the controller will be determined later and the principle of the operation of the controller is explained in the coming section. Since we did not use a controller during simulation, we used a resistor, and we checked whether our converter could supply 10A output within the predicted duty cycle limits. Simulation results are shown in Figure 10 - 21.

**Simulation 1: (Battery Charge = 100%, Battery Voltage = 13.09V, Vll-rms = 25.1V, D = 37.25 %)**

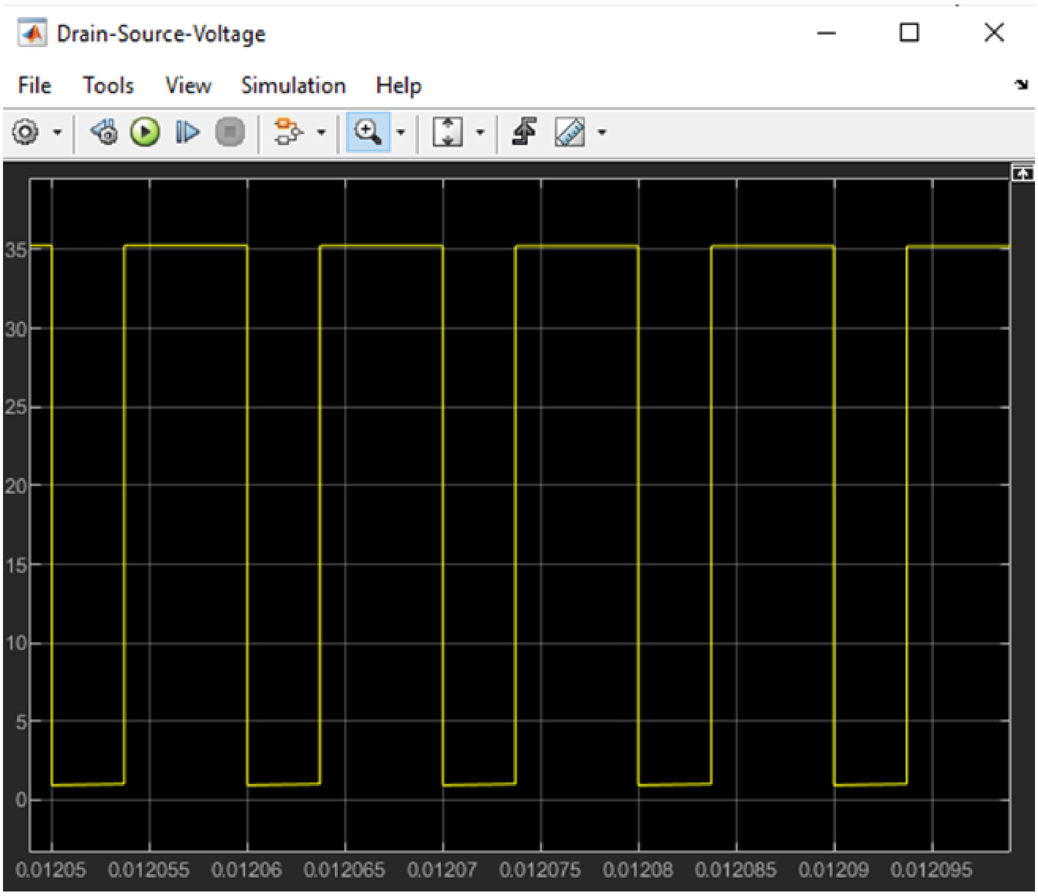



**Figure 10.** $V_{DS}$ of the Switching MOSFET for $V_{LL}$ = 25.1V and D = 37.25%

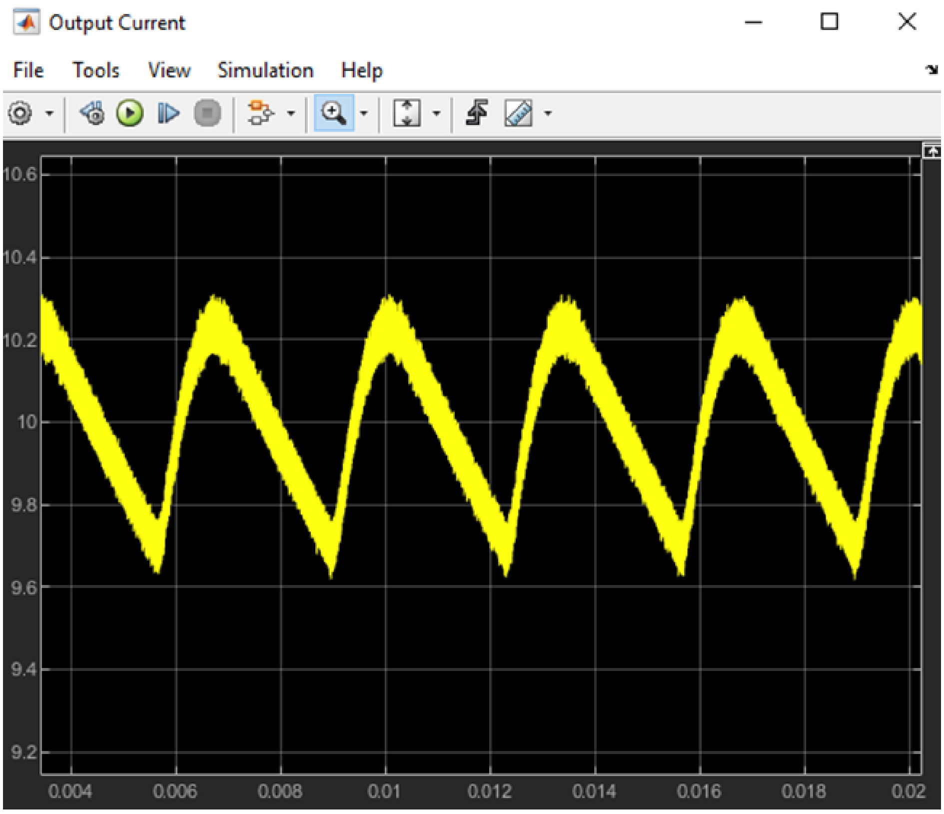



**Figure 11.** Output Current for $V_{LL}$ = 25.1V and D = 37.25%

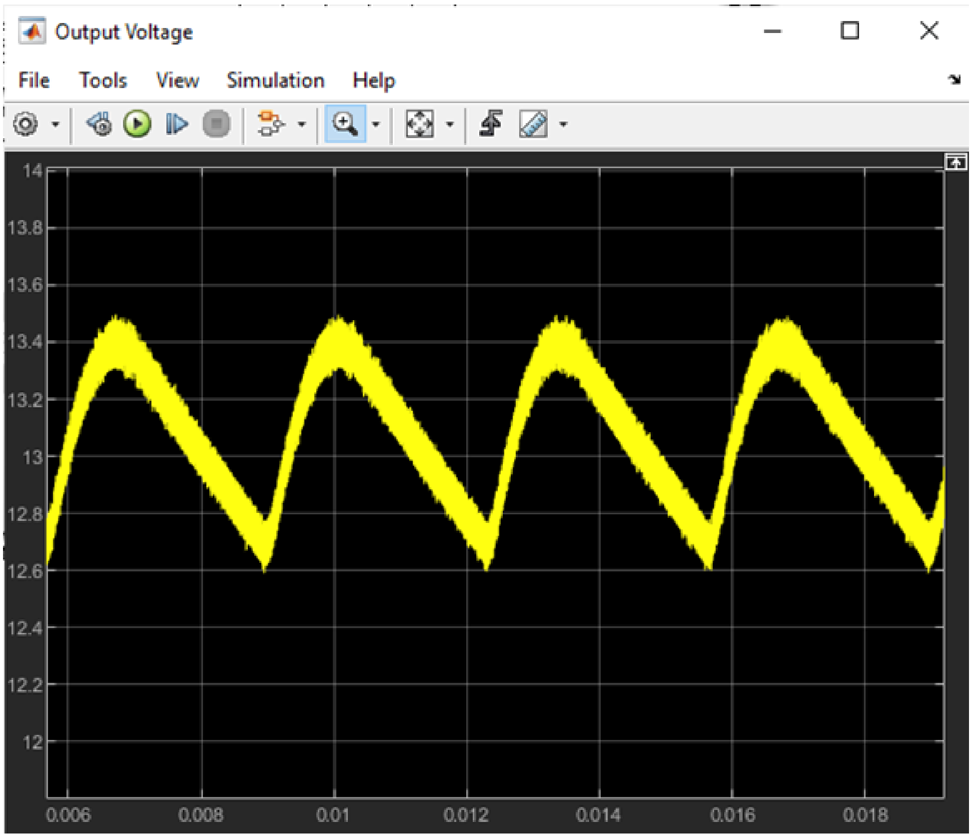



**Figure 12.** Output Voltage for $V_{LL}$ = 25.1V and D = 37.25%

**Simulation 2: (Battery Charge = 10%, Battery Voltage = 10.5V, Vll-rms = 25.1V, D = 29.88 %)**

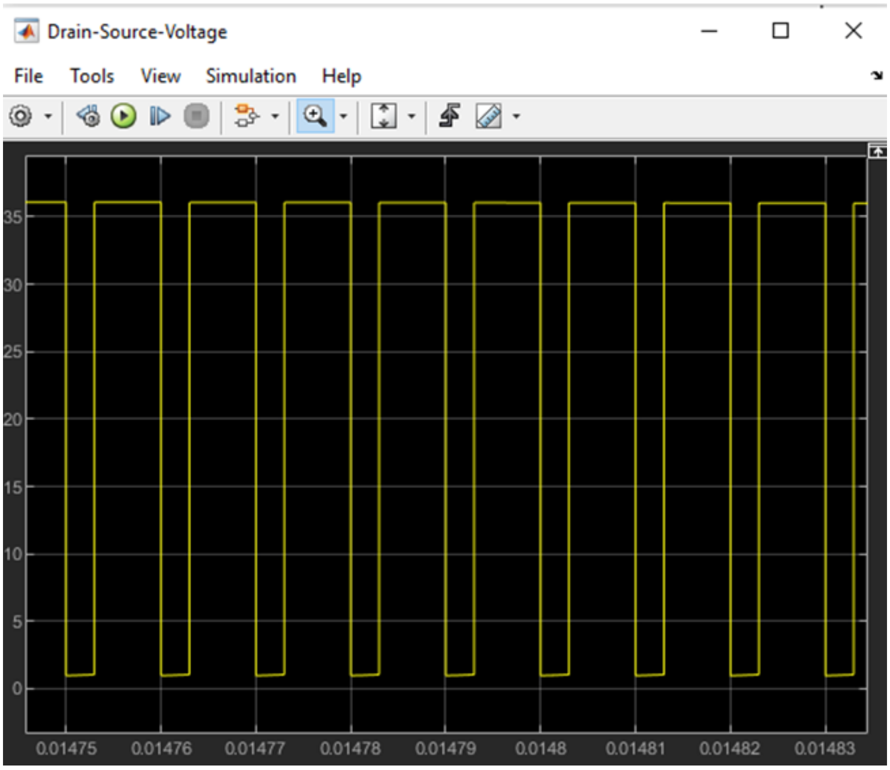



**Figure 13.** $V_{DS}$ of the Switching MOSFET for $V_{LL}$ = 25.1V and D = 29.88%

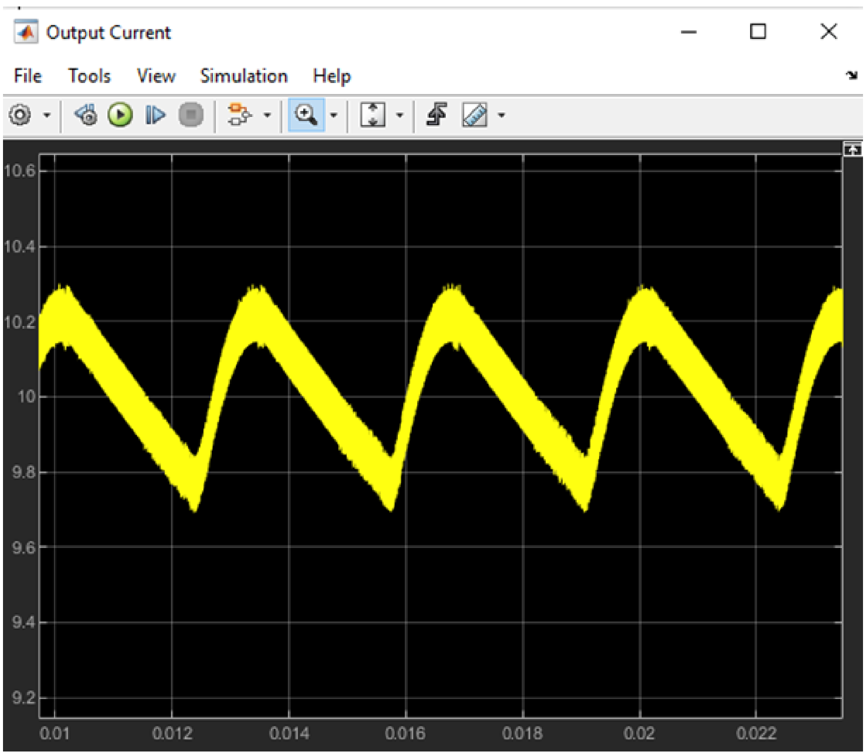



**Figure 14.** Output Current for $V_{LL}$ = 25.1V and D = 29.88%

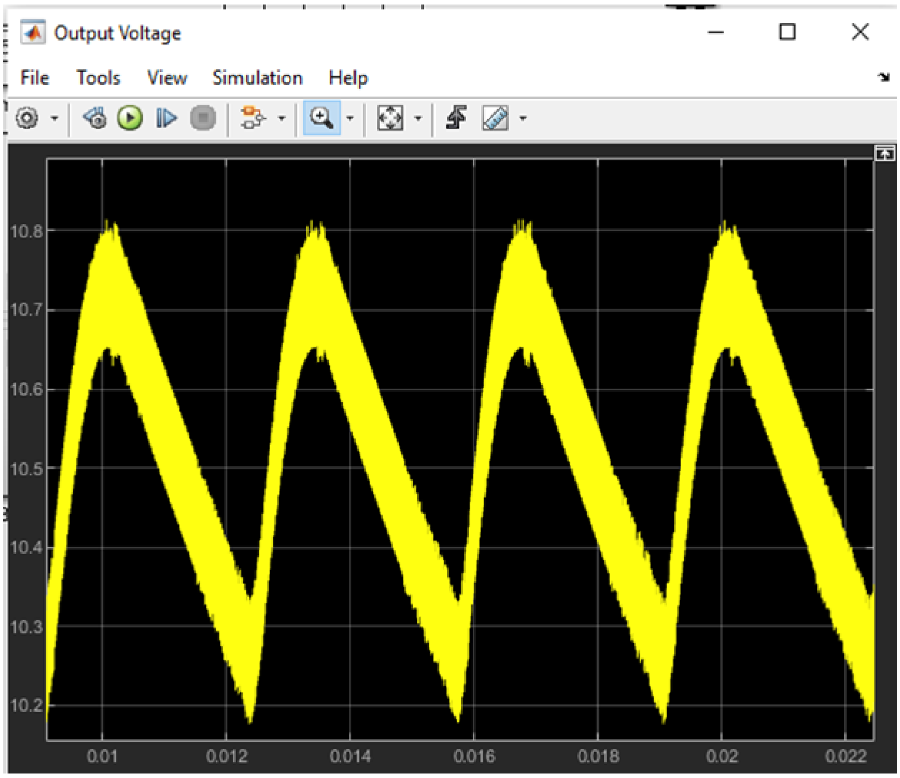



**Figure 15.** Output Voltage for $V_{LL}$ = 25.1V and D = 29.88%

**Simulation 3. (Battery Charge = 100%, Battery Voltage = 13.09V, Vll-rms = 15.01V, D = 64.7 %)**

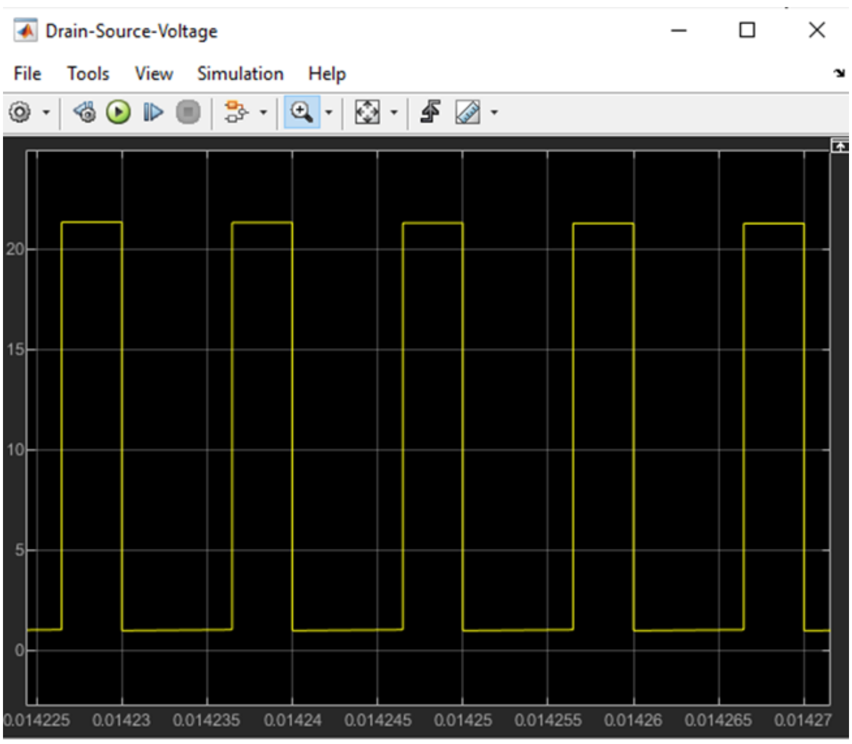



**Figure 16.** $V_{DS}$ of the Switching MOSFET for $V_{LL}$ = 15.01V and D = 64.7%

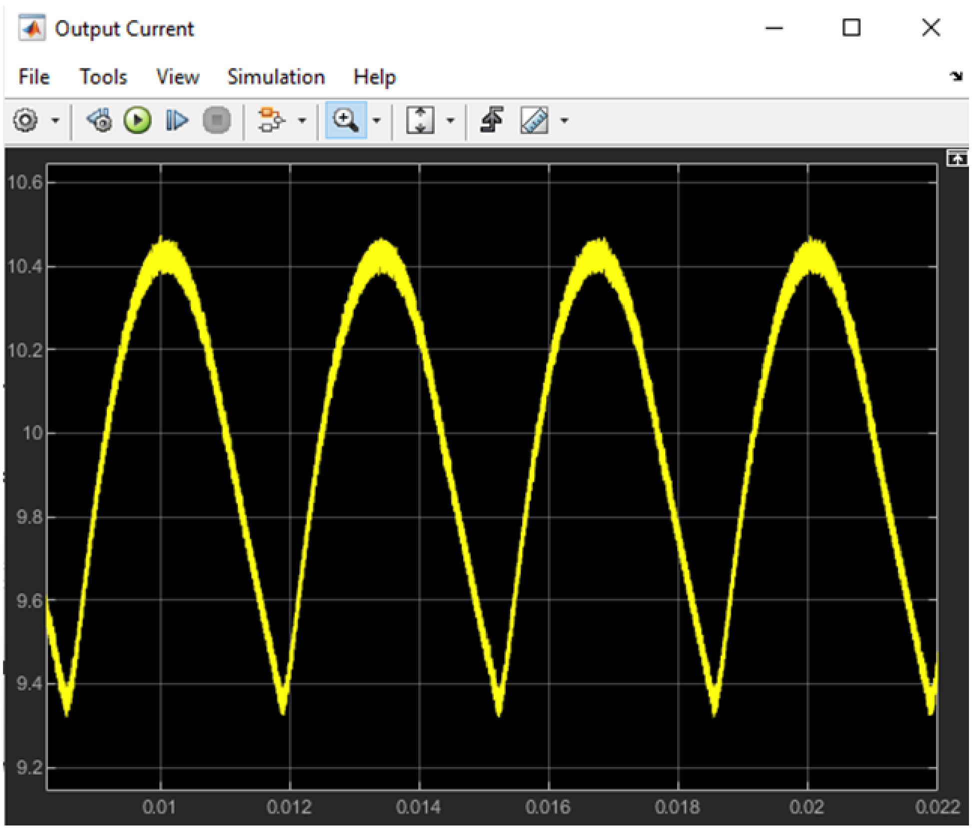



**Figure 17.** Output Current for $V_{LL}$ = 15.01V and D = 64.7%

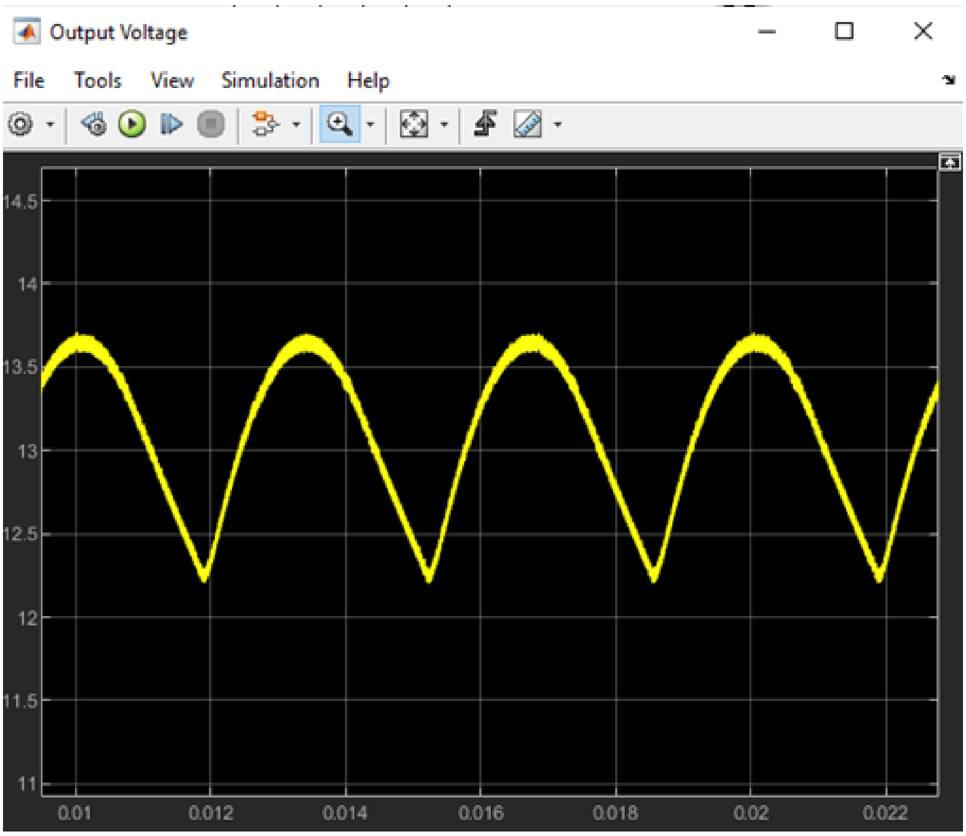



**Figure 18.** Output Voltage for $V_{LL}$ = 15.01V and D = 64.7%

**Simulation 4. (Battery Charge = 10%, Battery Voltage = 10.5V, Vll-rms = 15.1V, D = 51.84 %)**

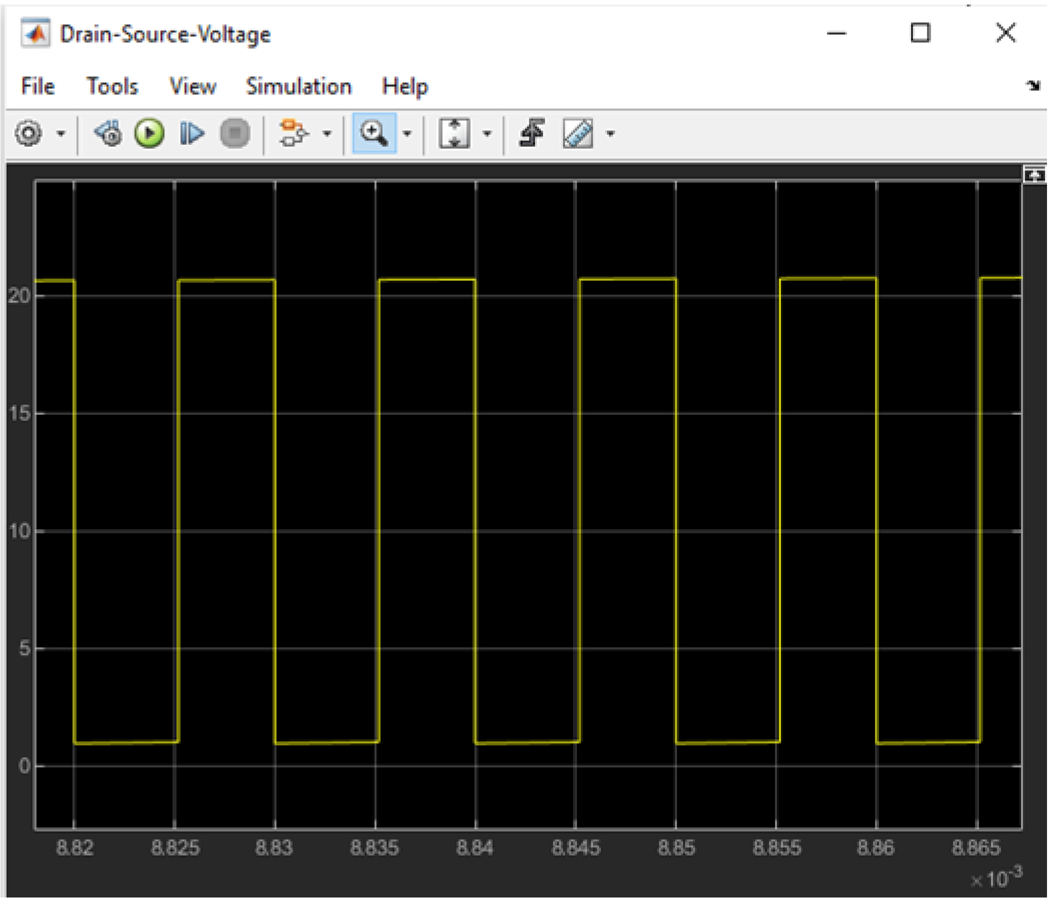



**Figure 19.** $V_{DS}$ of the Switching MOSFET for $V_{LL}$ = 15.01V and D = 51.84%

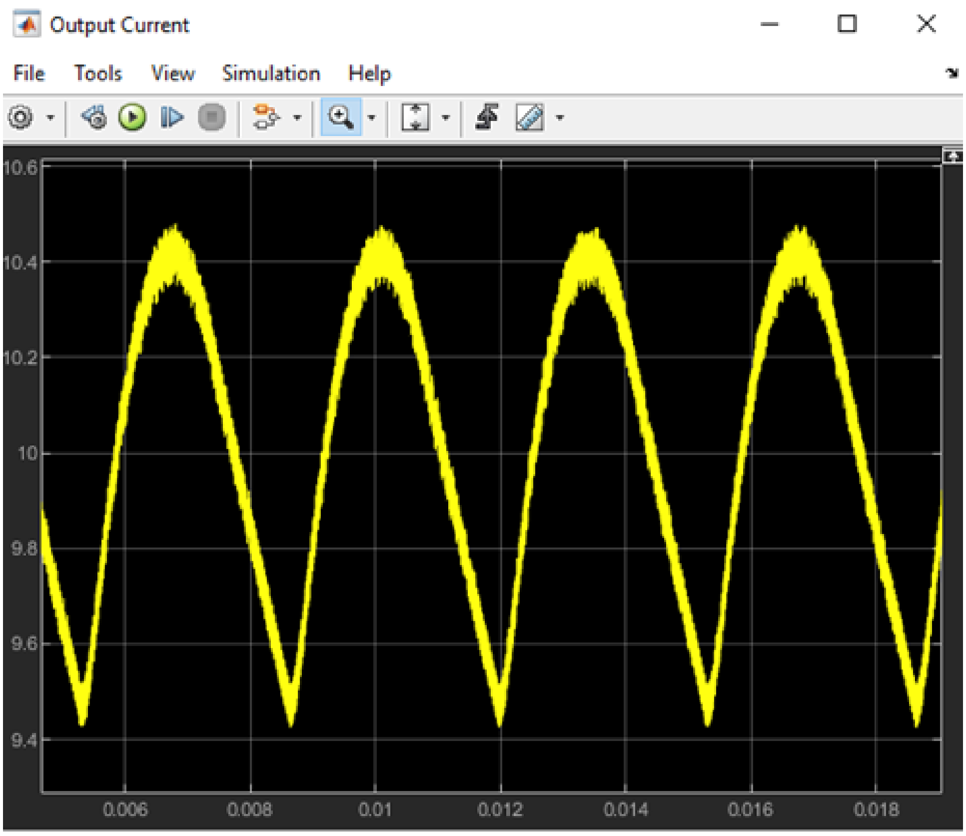



**Figure 20.** Output Current for $V_{LL}$ = 15.01V and D = 51.84%

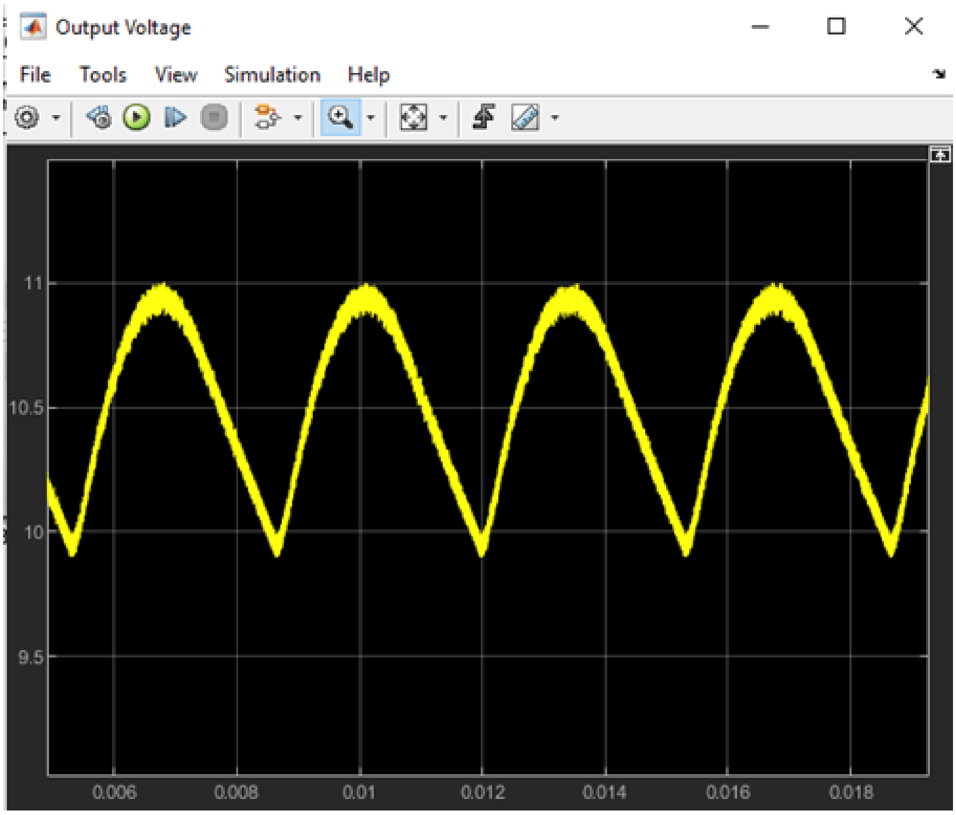



**Figure 21.** Output Voltage for $V_{LL}$ = 15.01V and D = 51.84%

As shown in Figure 10-21, the switching mosfet can handle 35V as drain-source voltage and 13A as drain current. Since there will be parasitic inductance in our circuit, the breakdown voltage of the mosfet can be selected by considering parasitic inductor related voltage spikes. Similarly, self-heating of the mosfet degrades the drain-source current or on-resistance. Therefore, drain-source current of the mosfet must be larger than 13A.

We will use %40 safety design margin for our mosfet. Therefore, the selected mosfet should have >50V breakdown voltage and >20A drain-source current. Note that switching mosfets are used in linear region (on-state) or cut-off region (off-state). Therefore, the voltage drop on the mosfet during on state is related to the on-resistance. The transition from on-off state or off-state can be controlled by the driving circuit. If the device is forced to change state when there is a current flow, the switching is known as a hard switch. Hard switching results in more stressful conditions for the mosfet and it generates ringing in the voltage and the current. To minimize its effect, the snubber circuit is implemented. Another switching characteristic is soft switching. Soft switching can also be used by setting a dead time for switching mosfets in a synchronous converter. The dead time eliminates the short-through risk between rail voltage to the ground, but it harms the efficiency of the conversion. Note that hard/soft switching is valid for synchronous converters. As a risk mitigation activity, we are planning to use an asynchronous converter which contains a diode and a mosfet as a switching element. A synchronous converter will be reconsidered after the completion of asynchronous converter to get higher conversion efficiency. The diode type will be Schottky diode to minimize switching losses and having low forward voltage drop.

The selected mosfet and Schottky diodes are presented in Table 2.

**Table 8. The Selected Power Diodes and MOSFETs**

| **MOSFET Code** | **Vds (V)** | **Ron (mΩ)** | **Gate Charge (nC)** | **Vgs,th (V)** | **Cost ($) ( 1000 unit)** | **Availability** |
|---|---|---|---|---|---|---|
| **IRFZN44N** | 55V | 13 | 63 | 2-4V | $0.58 | Yes |
| **IRFZ46NPbF** | 55V | 16.5 | 72 | 2-4V | $0.51 | Yes |

| **Schottky Diode Code** | **Vbr(V)** | **I (A)** | **Cost ($) ( 1000 unit)** | **Availability** |
|---|---|---|---|---|
| **RB215T-90NZC9** | 90 | 20A | $0.58 | Yes |
| **RB205T-60NZC9** | 60 | 15 A | $1.22 | Yes |

The spice simulation of a DC-DC converter with IRFZN44N mosfet and RB215T-90NZC9 Schottky diode are provided.

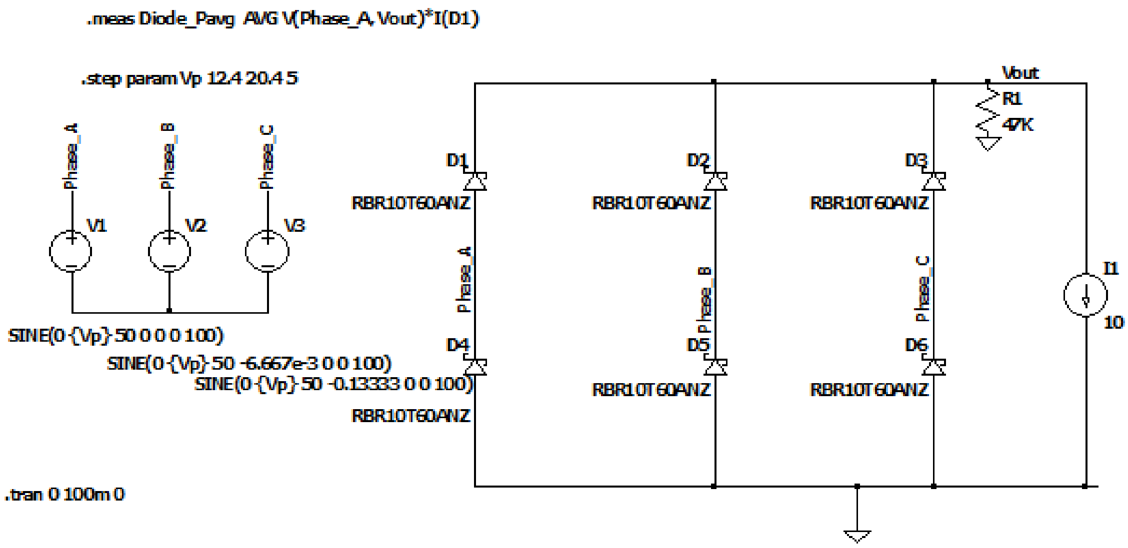



**Figure 22.** A circuit schematic of Three Phase Full Bridge Rectifier with RBR10T60ANZ When the Battery is in Constant Current Regime

An average dissipated power for one of RB215T-90NZC9 in diode rectifiers is 2.43W. The junction-to-case thermal resistance is 2.43C/W. By adding the thermal resistance of TIM and heatsink, the equivalent resistance will be around 22C/W., which increases the temperature to 52.8C. The device temperature can be calculated as 77.8C which is completely safe for this device. Note the six of the diodes will consume 14.4W in total. This results shows that using a diode having smaller rating can also be functional.

Note that the power dissipation in the diode is not continuous. During 6.67ms on period, the power dissipation is around 8W, shown in Figure 23. This means that the junction of the diode will be heated for a finite amount of time but it has a larger time for cooling. It is important to note that the connection of a diode to a heatsink can cause problems. Since the heat sink conducts heat from a diode in on-state to a diode in off- state. A separated but small size heat sink can be utilized.

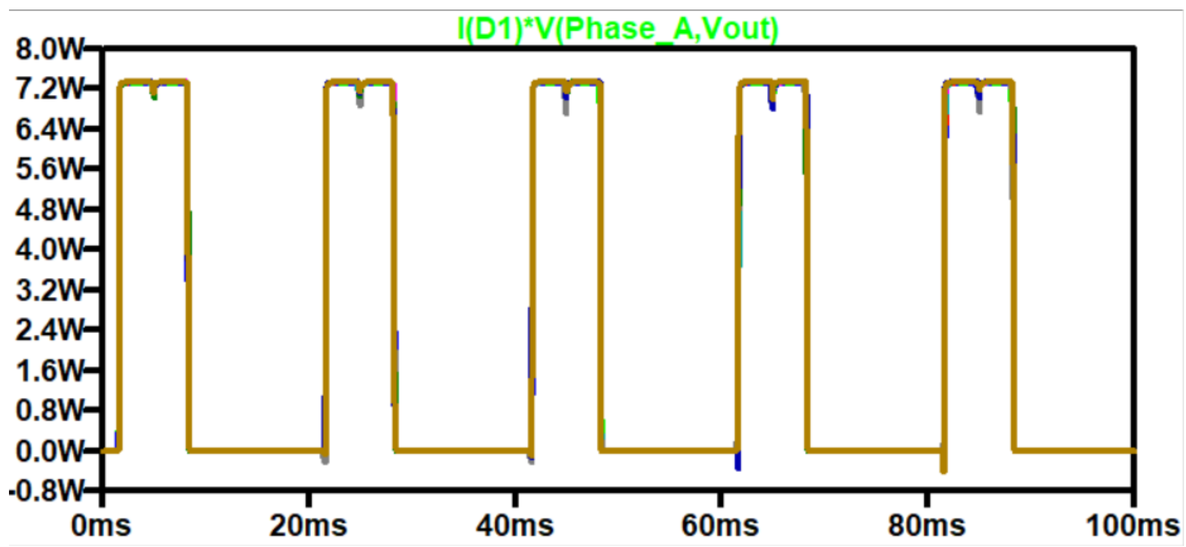



**Figure 23.** The Transient Power Dissipation of a Schottky Diode for Several Input Voltage. Note that the conduction loss of a diode does not depend on the input voltage.

Figure 24 shows the output voltage of the rectifier for several input voltages. Note that the capacitance at the output of the capacitor is not high enough to hold the output voltage of the rectifier until the next charging cycle is valid for constant current charging event..

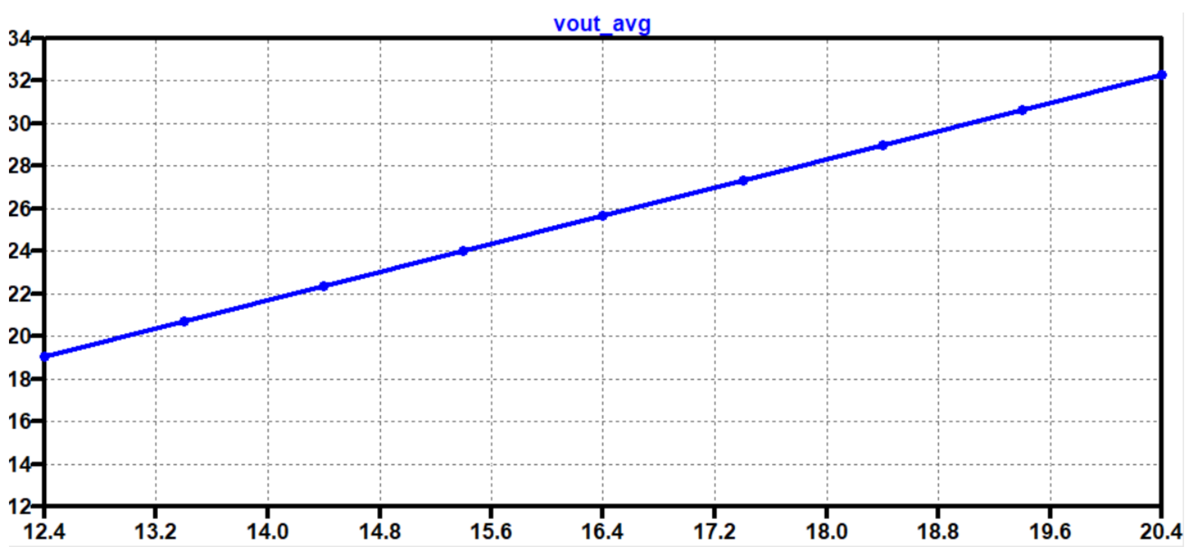



**Figure 24.** The Output Voltage of the Three Phase Diode Rectifier for Several Input Peak Voltage.

Figure 25 illustrates the circuit topology of the DC-DC buck converter, containing IRFZN44N mosfet, RB215T-90NZC9 Schottky diode, 100uH inductor and 5.6uF capacitor. The switching frequency is set to 100KHz. The spice circuit is shown in Figure 25.

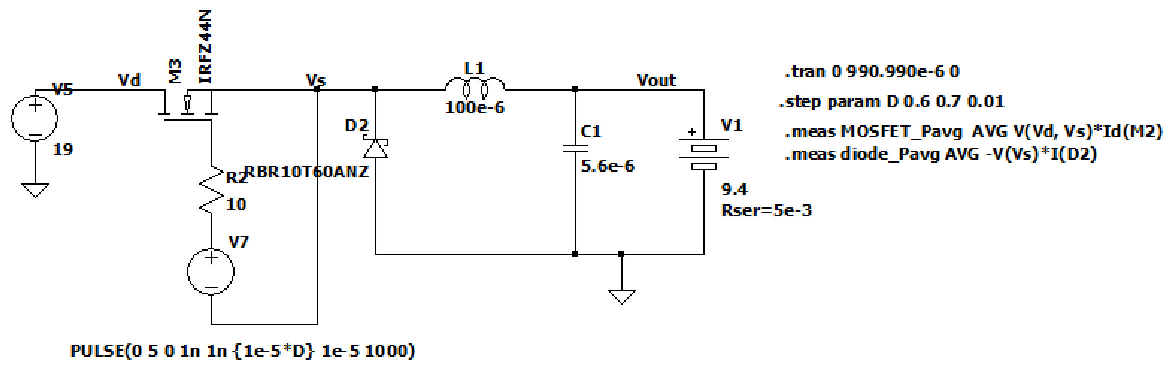



**Figure 25.** The Circuit Schematic for DC-DC Buck Converter

The duty cycle of the switching mosfet is a control parameter for the constant voltage and constant current operation. Figure 26 is shown the charging event of the circuit for duty cycle ranging from 0.55 to 0.58 with 0.04 step. Note that these values are selected when the rectifier voltage is at its minimum value. It can be seen that the higher duty cycle provides a shorter amount of time to reach steady state for charging events. This is the case since the duty cycle is an indication of the amount of time to store energy into the inductor.

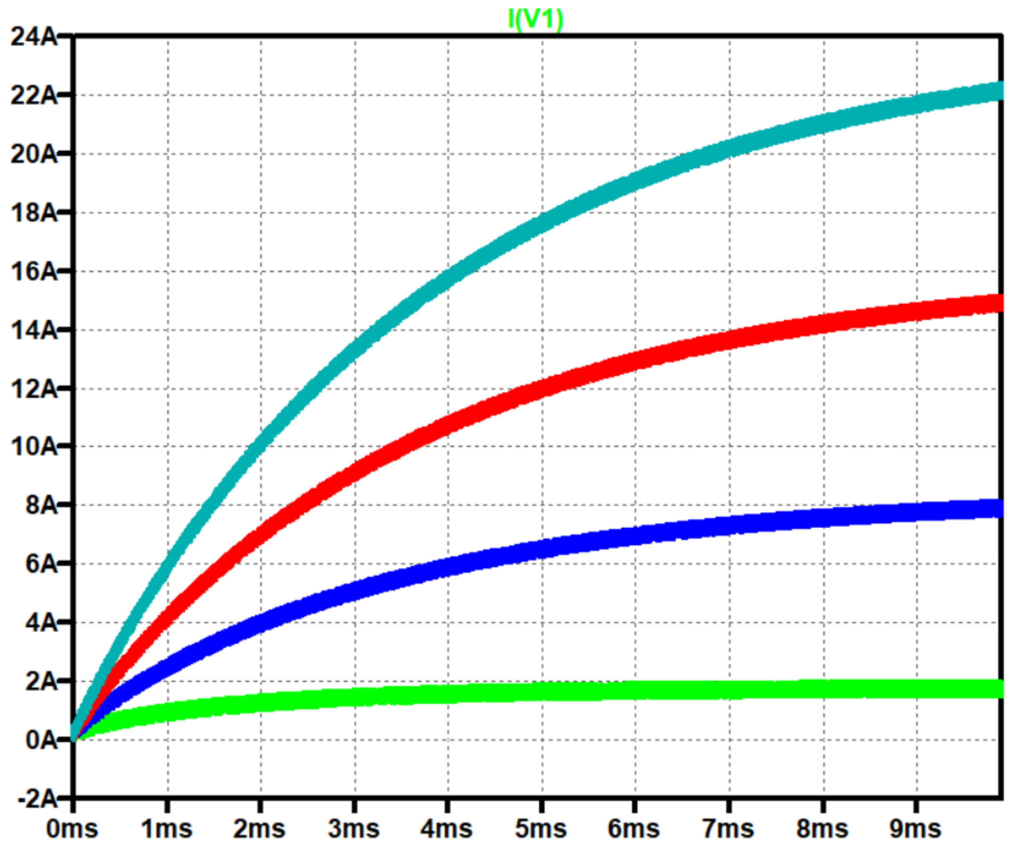



**Figure 26.** The Transient Analysis of Battery Current for DC-DC Buck Converter When Constant Current Regime is Active. (Duty Cycle: From 0.55 to 0.58 with 0.01 step)

For a given 20V input DC voltage, 0.55 duty cycle can not generate high enough output voltage to charge the battery with 10A constant current. The higher duty cycle results in higher charging current. For safety, a fuse must be implemented to the input and output.

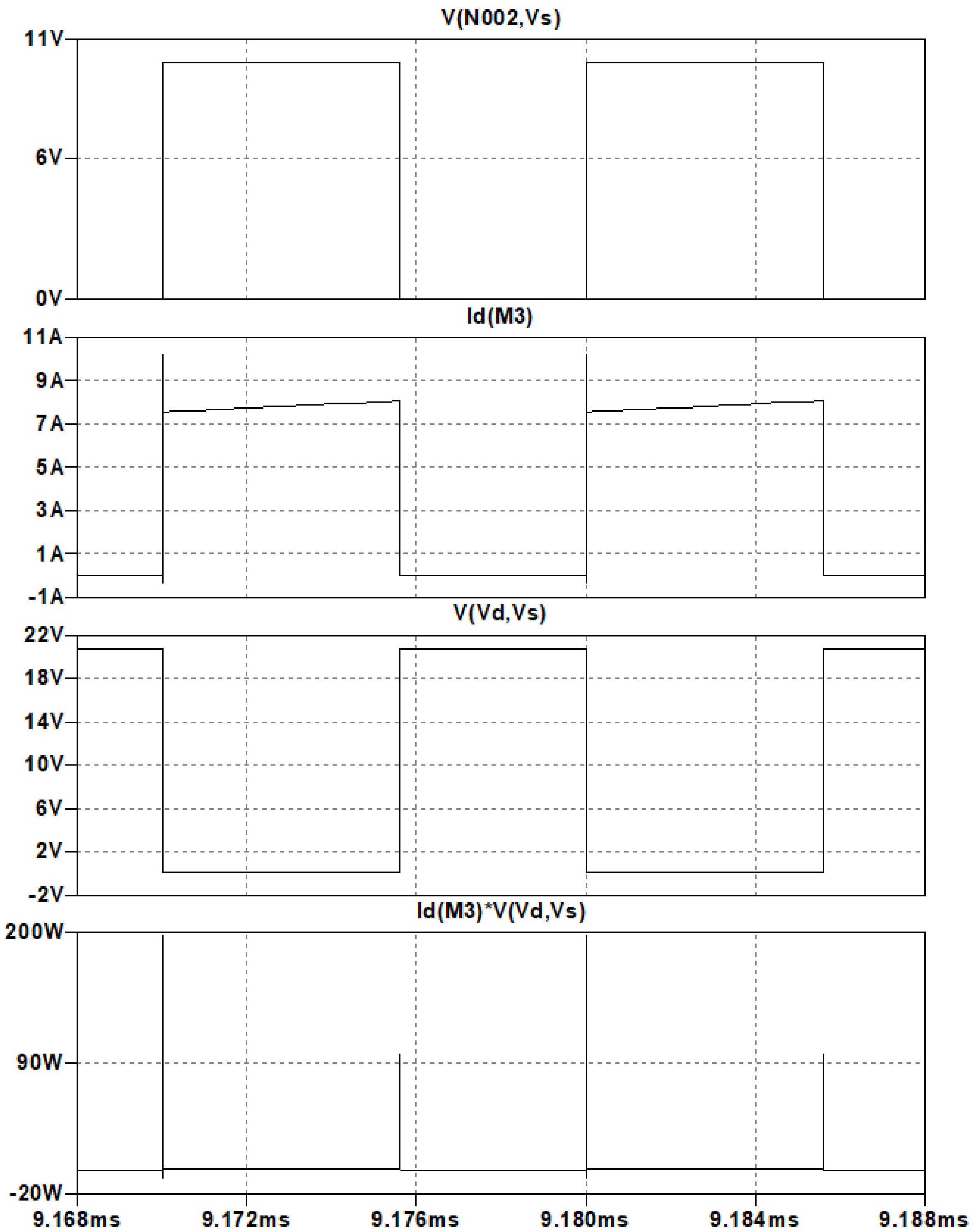



**Figure 27.** The Transient Voltage, Current and Power Analysis of Switching MOSFET for DC-DC Buck Converter When Constant Current Regime is Active. (Duty Cycle: 0.56)

Figure 27 shows the power dissipation on the mosfet and the diode when duty cycle is 0.56. This simulation in Figure 27 represents one of the worst cases. It can be seen that during switching event and conduction event there is a significant power dissipation of the mosfet. The average power dissipation of the mosfet is 0.5W It can give more space for junction to ambient thermal resistance without considering the increase in on-resistance. Therefore, the cooling capacity or switching speed of the transistor will be reconsidered. For the sake of voltage transient analysis, the device breakdown voltage is in acceptable range. Note that average power dissipation of the diode is 2.4W, which is located in quite a safe region.

To sum up, voltage and current ratings of the switching device will be reconsidered after detailed analysis of the thermal limitation.

## CONTROLLER

The controller unit of the project is going to continuously measure the output voltage and current, and it is going to adjust the duty cycle of the MOSFET. Our buck converter has 2 operating regions which are constant current and constant voltage modes. During the constant current operation, our controller is going to try to adjust our output current as 10A. In order to measure the output current, we are going to use an output series connected output resistor which has a very low value (around 0.5 mΩ) and we measure the voltage drop across this resistor. As the battery voltage increases, our controller is going to increase duty cycle and output voltage in order to keep the constant 10A output current. Until the output voltage reaches 13.1V, this constant current operation is going to continue. After the output voltage reaches the 13.1V, controller operation mode is going to switch to the constant voltage mode. During constant voltage operation, output current is going to decrease.

For the controller operations mentioned above, we have two possible solutions which are digital controller with Arduino and analog controller with UC3843 PWM Controller IC. For the digital controller solution, we are going to measure the output current and voltage as described above and insert these values into Arduino. By processing these measurements with a PID controller embedded inside the Arduino, we are going to control the duty cycle. For the analog controller we need extra elements which are optocoupler, shunt regulator and passive elements. In that solution, we are going to construct two control loops for both voltage and current. We are going to measure the output voltage and voltage drop on the output series resistance and connect that measured voltages to shunt regulators. When the output current or output voltage exceeds the predefined reference values, shunt regulators start conducting and it will generate a signal through optocouplers. This signal is going to result in a decreasing duty cycle in the output of the PWM controller IC.

In summary, the proposed buck converter project operates in two key phases: maintaining a constant current and achieving a constant voltage. The controller, responsible for regulating the output, adopts a dynamic approach to ensure a stable power supply. Whether implemented through a digital controller with Arduino or an analog counterpart with the

UC3843 PWM Controller IC, the controller actively sustains the output current at 10A during the constant current phase by adjusting the duty cycle based on battery voltage variations. Upon reaching 13.1V output voltage, a smooth transition to the constant voltage phase occurs, leading to a controlled reduction in output current, showcasing the converter's adaptability to different loads. The flexibility in choosing between a digital or analog controller allows for a customized solution tailored to specific project needs. Although the controller unit's design is not finalized, the thorough exploration of digital and analog options lays a strong groundwork for the subsequent phases of project development and implementation.

## CONCLUSION

In conclusion, this report outlines the initial design of the EE463 hardware project, specifically focused on developing a wind turbine battery charger. The project's requirements were detailed, emphasizing the necessity for a circuit capable of efficiently controlling power from a wind turbine generator to charge a battery and power a load. The chosen topology, involving a combination of three-phase diode rectifiers and a buck converter, underwent thorough analysis against alternative options.

The analytical analysis, simulation, and component selection were discussed in detail, presenting the calculations for key circuit elements and their simulation results. The chosen MOSFET and Schottky diodes were scrutinized, taking into consideration power dissipation and thermal limitations. The simulations illustrated the circuit's performance under various scenarios, aiding in the selection of suitable components for the final design.

Furthermore, the report delved into the crucial role of the controller unit, outlining its operation in both constant current and constant voltage modes. Two potential solutions, a digital controller with Arduino and an analog controller with the UC3843 PWM Controller IC, were proposed, each offering distinct advantages. The digital solution involves measuring and processing output parameters with a PID controller, while the analog solution employs optocouplers, shunt regulators, and passive elements for control loops.

In essence, the proposed buck converter project promises a versatile solution capable of seamlessly transitioning between constant current and constant voltage modes. The ongoing exploration of digital and analog controller options ensures adaptability to specific project requirements, setting the stage for the subsequent phases of development and implementation.

## REFERENCES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