MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

EE 463- Static Power Conversion I - Hardware Project

2023-2024 Fall Term

Wind Turbine Battery Charger

Simulation Report of the team DoesNotHertz

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Introduction

Adjusting voltage levels is a common challenge in both power electronics and power systems. It's widely recognized that increasing transmission voltage enhances efficiency by reducing resistive losses. In our future professional endeavors, we may encounter systems where the initial voltage is high and needs to be lowered at the point of use for compatibility with low-voltage devices, such as microchips in data centers.

Moreover, aside from efficiency considerations, manipulating an input source to achieve a specific output voltage with a current limit is crucial in scenarios like charging a battery and motor driving. Additionally, there are situations where the input source is unknown, but the output specifications are well-defined, necessitating closed-loop voltage conversion in power electronics.

Recognizing the significance of these conversions, our project focuses on hands-on experience with DC/DC voltage conversion and current regulation. We'll achieve this by implementing a battery charging unit powered by a dynamic wind turbine model. Despite the variability in input voltage, our goal is to maintain well-regulated output voltage and current.

Specifications and Desirable Features

Table 1: Project specifications

Project Specifications		
Name	Value	Type
Input characteristics	The output of the 3-phase variac may exhibit potential unwanted line inductance. Due to the nature of the model, the voltage variation is significantly slower compared to the switching frequency of converters.	Educated guess
Input voltage	$15V_{ll}\ to\ 25V_{ll}$	Specification
Battery capacity	100 Ah	Specification
Battery nominal voltage	12V	Specification
Charging current	10A	Specification
Output current ripple	%20 of the mean output current	Specification

Table 2: Desirable Features

Desirable Features	
Name	Description
Efficiency	While there are no strict constraints on efficiency, the goal is to attain the highest possible level of efficiency.
Utilization	Select components in such a way that their operational conditions and ratings are closely aligned in magnitude.
Compactness	The aim is to attain a high power density.
Affordable design	Costs should be considered with equal importance as other parameters.
Analog Controller	Opting for a digital controller presents a simpler approach compared to analog controllers. However, analog solutions are likely to be more cost-effective, and their components can be readily replaced with equivalents, a task that can pose significant challenges in the digital approach. Consequently, an analog approach is highly
Constant current control	Rather than depending on manual input, it is more advantageous for the converter to autonomously adjust itself to maintain a constant charging current.
PCB design	Designing a PCB is crucial for eliminating errors associated with cabling, such as not connected cables, and it facilitates the scalability for mass production of the PCB.
Extra features	Additional features like temperature protection and power factor correction are highly welcomed.

Simplified Assumptions for Component Models Throughout the Project

Inductors

Inductors are accurately represented in the model as a combination of an inductor and a resistor connected in series.

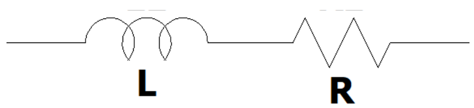

Figure 1: Simple model of the inductors

Capacitors

Capacitors are modeled as a capacitor in series with a resistor and an inductor. The series inductance will be approximated as 50nH. The rated voltage of the capacitor would be around 50V. The esr of the electrolytic capacitors are checked for different capacitance values at the Würth electronics webpage. The result is given in Table 3. When these results are fitted to a function, The approximation for capacitor ESR is simply represented as.

$$R_{ESR,50V}(C_{uF}) = 0.064 + \frac{3}{1+(\frac{C_{uF}}{15.33})^{1.474}}$$

Leakage is not incorporated into the model as it is deemed negligible in our specific scenario.

Figure 2: Simple model of the capacitors

Table 3: Würth Electronics radial Through-Hole Technology (THT) electrolytic capacitors.

Würth Electronics radial Through-Hole Technology (THT) electrolytic capacitors.			
Order Code	Rated Voltage (V)	Capacitance (μF)	ESR at 100kHz (Ω)
860010672004	50	0.47	3.000
860010672009	50	10	2.000
860010673012	50	47	0.500
860010674014	50	100	0.300
860010675020	50	470	0.100
860010678024	50	1000	0.060
860020680030	50	2200	0.003

Resistors

Resistors are simply modeled as resistors.

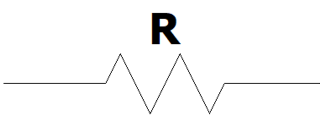

Figure 3: Simple model of the resistors

Wires

Wires are represented in the model as a combination of series resistance and inductance. While the wire resistance is unspecified, the inductor value is estimated by multiplying the wire length by a constant of 1.5uH/m. This constant is derived from information regarding wire self-inductance and aligns with real-life observations.

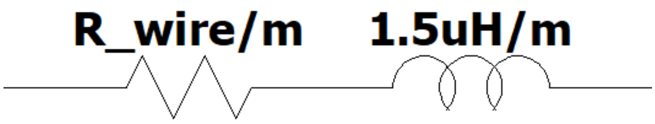

Figure 4: Simple model of the wires

Mosfets

MOSFETs will be treated as switches, activating when their gate-to-source capacitor accumulates a specific voltage, corresponding to a charge quantity of Q_gate. Once activated, the switch is substituted with a resistor model. Additionally, consideration is given to the body diode in this representation.

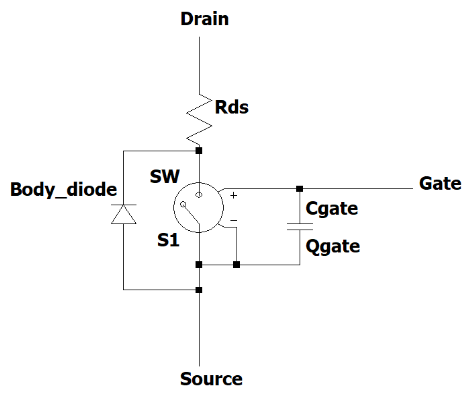

Figure 5: Simple model of the N-Channel MOSFETs

Diodes

Diodes are treated as components with a 0.7V voltage drop when in the on state. To account for reverse recovery, it is assumed that the diode maintains its state even when the polarity is briefly reversed. Preliminary designs will be based on this model, but the ultimate analysis will be conducted in accordance with the simulation results that use exact diode models.

Testing Procedures for Key Parameters of Purchased Components

Mosfet tests

Gate charge determining test procedure

1. Initially, Vsignal is zero
2. Apply a suitable Vsignal voltage
3. Measure Vgs and Vsignal by oscilloscope and determine gate current using the voltage drop on the 1kΩ resistor
4. Integrate this current.

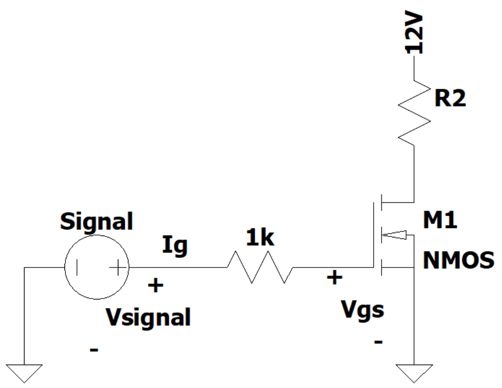

Figure 6: Simple test setup to measure MOSFET's gate charge

Rds(on) determining test procedure

1. Apply suitable Vsignal value. Multiple values can be tested.
2. Adjust Vsupply such that drain current is 10Amps DC.
3. Wait 5 minutes so that MOSFET heats up.
4. Measure the Vds voltage drop for the MOSFET.
5. Calculate Rds(on) using this voltage drop.

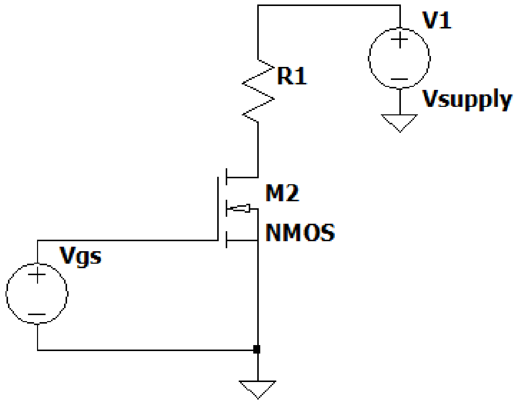

Figure 7: Simple test setup to measure MOSFET's Rds(on) value for different gate-to-source voltages

Inductor tests

Resistance or inductance determining test procedure.

Simply use an LCR meter to test those parameters.

Saturation current determining test procedure

1. Apply signal voltage.
2. Using voltage drop over the resistor, calculate drain current.
3. Note the current value where the slope of the current vs. time graph is very high compared to the initial slope
4. Given that this test exceeds the rated current values, it is important to promptly deactivate the signal to safeguard the components.

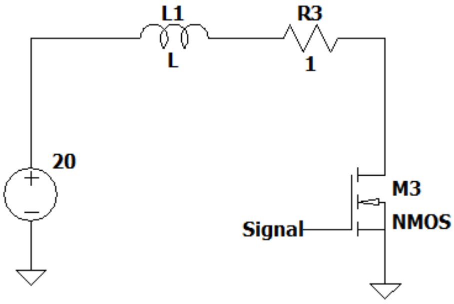

Figure 8: Simple test setup to determine the rough value of the saturation current of an inductor.

Capacitor tests

Simply use an LCR meter to measure capacitance.

Wire resistance calculation

Use a 1-meter wire carrying a 10-amp current and measure the voltage drop using a multimeter with at least three digits of precision. Then, calculate the resistance per meter value using Ohm's Law.

Topology to be used

Three-Phase Thyristor Rectifiers

Advantages

- Thyristors have high efficiency because they can control the power flow by adjusting the firing angle, allowing for optimal power transfer.
- The ability to control the firing angle enables variable speed operation, making it suitable for applications such as motor drives and speed control systems.
- Can reach 1.35 times the input line-line voltage.

Disadvantages

- More complicated structure.
- The control of thyristor rectifiers is more complex compared to diode rectifiers. Precise control of firing angles is necessary, and this complexity may increase the cost of the control system.
- Thyristors are generally more expensive than diodes, which can affect the overall cost of the rectifier system.

Three-Phase Diode Rectifier & Buck Converters

Advantages

- Diode rectifiers with buck converters are simpler to control compared to thyristor rectifiers. The absence of variable firing angles simplifies the control strategy.
- Diodes are less expensive than thyristors, contributing to a lower overall cost of the rectifier system.
- Can reach 1.35 times the input line-line voltage.

Disadvantages

- Compared to thyristor rectifiers, diode rectifiers may have slightly lower efficiency.
- Diode rectifiers can generate significant heat during operation, especially in high-power applications. Adequate cooling and heat dissipation measures must be implemented to prevent overheating and ensure the reliability of the system.

Why Diode Rectifier & Buck Converters

We chose a 3-phase diode rectifier and buck converter topology to charge the battery because

- Constructing a diode rectifier is easier.
- By using a 555 timer, it’s easier to control the buck converter. Thyristor rectifiers require more complex control.

Given the project specifications ensure a consistently higher input voltage compared to the battery voltage, the imperative lies in voltage reduction. Addressing this requirement, the optimal solution emerges in the form of a Buck converter. It's crucial to recognize that while the Buck converter excels in DC-to-DC conversion, our input source is three-phase AC. Therefore, a rectifier circuitry becomes an essential complement to seamlessly integrate these disparate elements. The comprehensive system architecture is visually depicted in Fig 9 through block diagrams, with detailed explanations of the internal operations provided in subsequent subsections.

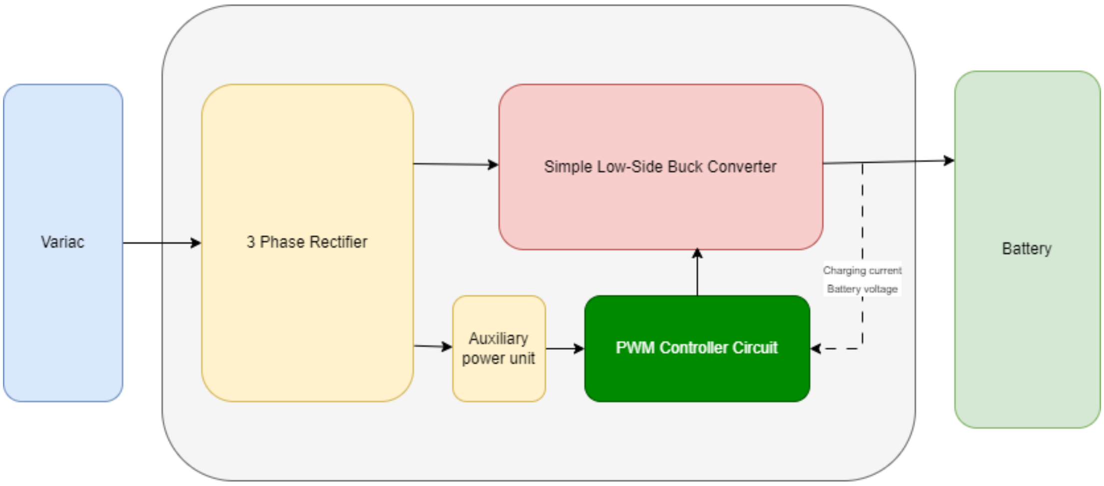

Figure 9: Simplified block diagram of the topology.

Three-phase rectifier block

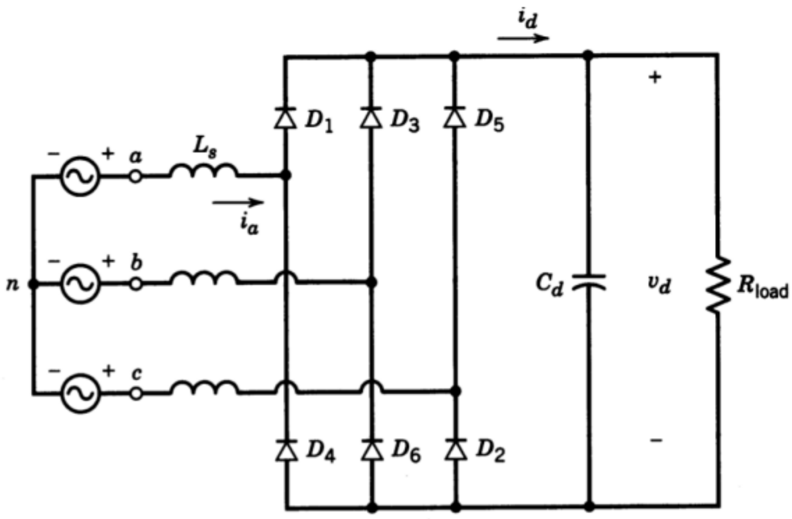

Figure 10: Three-phase full-wave rectifier circuit.

The voltage coming from the wind turbine will change between 15-25V line to line. The voltage output formula of the three-phase full bridge rectifier is:

$$V_o = \frac{3\sqrt{2}}{\pi} V_{l-l} = 1.35 * 25 = 33.75V$$

As a result, the maximum output voltage will be around 35V. For the buck converter design, this voltage value must be considered.

Low-side buck converter

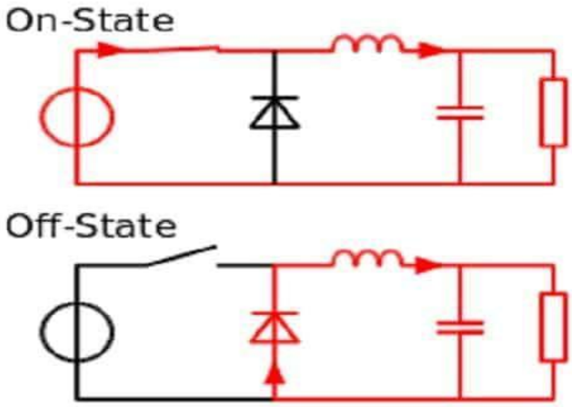

Figure 11: Basic buck converter circuit.

We prefer to use a MOSFET in the buck converter as a switch. It has a Low ON-State Resistance (RDSon), leading to minimal conduction losses, and it has low switching losses compared to other switching devices. MOSFETs are voltage-driven devices that simplify the drive circuitry.

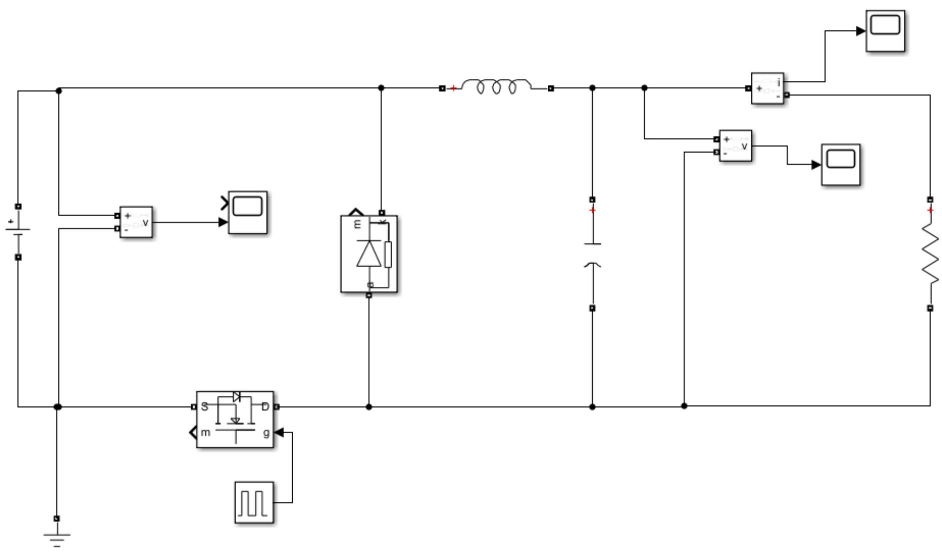

Figure 12: Low-side buck converter simulink circuit.

In the design of our battery charging unit, we chose to use a low-side buck converter instead of a high-side buck converter. With low-side buck converters, N-type MOSFETs, which are easier to find and cheaper compared to P-type MOSFETs, can be used. And we preferred to use N-type MOSFETs.
Despite the inherent capability of N-MOSFETs to be driven directly by a PWM (Pulse Width Modulation) signal, our design includes a dedicated gate drive. Utilizing a gate drive allows for precise control over the switching of the N-MOSFET, ensuring optimal performance and efficiency in our low-side buck converter.

Auxiliary power unit

The controller unit requires power, albeit relatively small compared to the charging power. Insufficient power supply can lead to unexpected circuit behavior. Therefore, it's crucial to design a power unit with low power but high stability. We've proposed four methods for achieving this. The first method involves using linear voltage regulators, which provide constant voltages with minimal loss to the overall system. Another option is employing zener diodes and resistor division, though it's not as effective as linear regulators. The third approach is using an off-the-shelf and compact buck converter to power the controller unit. The fourth method is to use battery voltage directly.

PWM 555 timer circuit

The NE555 timer will be used to generate the PWM. It will be used in its stable mode. This means that the output will never be stable and will keep switching between HIGH and LOW. The basic 555 timer structure can be found below.

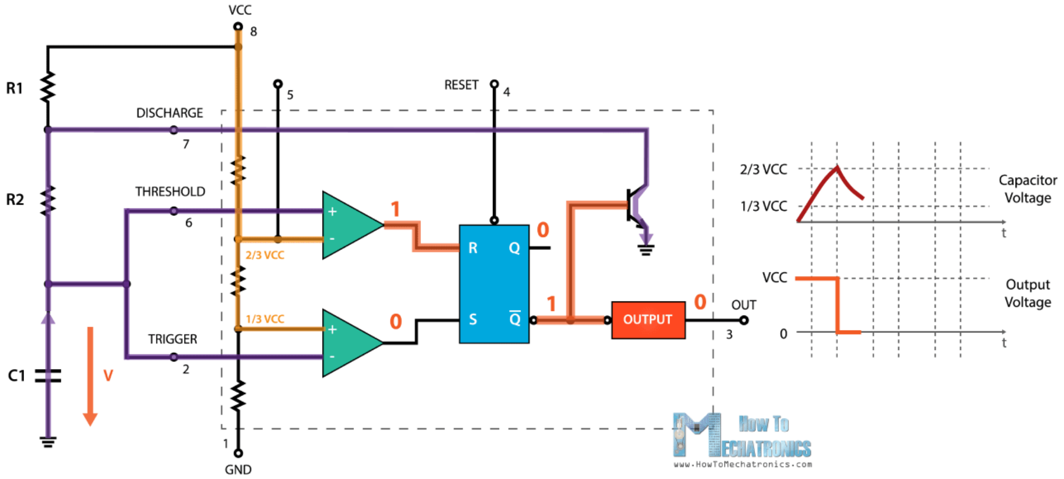

Figure 13: Example schematic of 555 timer.

It checks if the voltage on the Trigger pin is below 1/3 of VCC. If it is, the Output pin becomes high. And it checks if the voltage on the Threshold pin is above 2/3 of VCC. If it is, the Output pin becomes low.

Formulas for the duty cycle and frequency,

$$T_{on} = 0.693 * (R_1 + R_2)C_1$$

$$T_{of} = 0.693 * R_2 C_1$$

$$T_{total} = 0.693 * (R_1 + 2R_2)C_1$$

$$f = 1.44/(R_1 + 2R_2)C_1$$

$$PWM(\%) = \frac{T_{on}}{T_{total}} = \frac{(R_1+R_2)}{(R_1+2R_2)} * 100$$

In our buck converter design, the switching frequency is chosen between 70-80kHz. The 555 timer circuit parameters must be chosen according to this switching frequency.

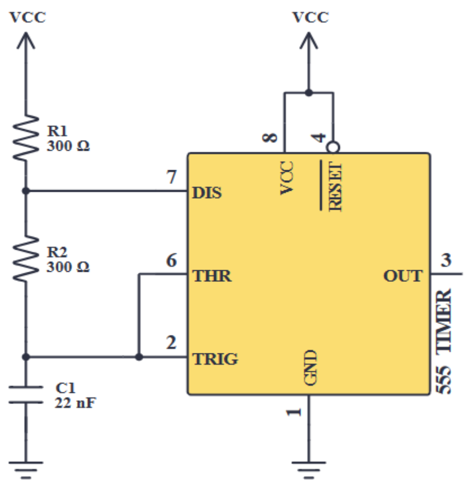

Figure 14: 555 timer circuit diagram.

Calculations,

$$T_{on} = 0.693 * (300 + 300) * 22 * 10^{-9} = 9.15\ \mu s$$

$$T_{off} = 0.693 * (300) * 22 * 10^{-9} = 4.57\,\mu s$$

$$f = 1.44/(300 + 2 * 300) * 22 * 10^{-9} = 72.7kHz$$

We have used 300Ω and 300Ω resistance, respectively, for R1 and R2. We will use a feedback circuit to maintain a constant output current from your buck converter while the input voltage varies. The duty cycle of the MOSFET is adjusted based on the sensed output current.
An operational amplifier (op-amp) as an error amplifier will compare the sensed current with a reference voltage. The output of this amplifier represents the error signal. Connect the output of the error amplifier to the control voltage input (CV) of the 555 timer. The CV input of the 555 timer is used to adjust the threshold voltage, which in turn affects the timing and duty cycle of the output PWM signal.

Components to buy

Rectifier Diode

KBPC3510 35A 1000V bridge rectifier

Table 4: Critical parameter values of selected rectifier diode.

PEAK REPETITIVE REVERSE VOLTAGE	1000V
AVERAGE RECTIFIED FORWARD CURRENT	35A
PEAK REVERSE CURRENT	10uA
FORWARD VOLTAGE(IFM=17.5A)	1.2V

According to our simulations, a diode must carry around 10A. We will use 2 single-phase bridge rectifiers rather than using 6 diodes diodes separately. Two legs and One of the legs of the other single-phase rectifier will be used to obtain a three-phase bridge rectifier. It has a smaller size, is cheaper, and the implementation is much easier. Thus, we chose two single-phase bridge rectifier diodes. Each can carry 35A for 1000V.

Timer

NE555

Since we need to generate a PWM for the MOSFET in our buck converter, we will use the NE555 Timer. This timer can generate PWM in a very wide frequency range. We aim to produce a 70-80kHz frequency PWM signal.

MOSFET

IRFZ44 N Channel MOSFET 60V 50A

Table 5: Critical parameter values of selected MOSFET.

COLLECTOR-EMITTER VOLTAGE	*60V*
GATE-SOURCE VOLTAGE	*+/- 20V*
COLLECTOR CURRENT	*48 A @ 25°*
POWER DISSIPATION	*110 W*
OPERATING TEMPERATURE	*-55°C / +175°C*

Buck Converter Diode

MBR1560CT 60V 15A Schottky Diode

Table 6: Critical parameter values of selected diode at buck converter side.

RATED REPETITIVE REVERSE VOLTAGE	60V
AVERAGE RECTIFIED FORWARD CURRENT	15A
MAXIMUM REVERSE CURRENT	50mA
REVERSE RECOVERY TIME	50ns

Capacitor & Inductor

We chose some capacitance and inductor values according to our requirements and simulation results. We tried to choose capacitances that existed in the component list or were easy to find. The values can be changed after the lab tests.

Fuse

15A Fuse

According to our component current rates, the current value should not exceed some limits. To prevent damage to the circuit during testing, we will use fuses.

Gate Driver

IR2102 MOSFET High and Low side driver

Table 7: Critical parameter values of the selected gate driver.

MINIMUM PEAK OUTPUT CURRENT	210mA
VOLTAGE OUTPUT	10-20V
TEMPERATURE RANGE	150°C
MAXIMUM SWITCHING SPEED	160ns

Things to be careful about

Inductor Saturation: Monitor for potential inductor saturation issues.

Closed Loop Current Detection: Take precautions to prevent the duty cycle from reaching 100% in the absence of a connected battery. Maintain a duty cycle of 0 if the output voltage falls below a specified threshold.

Capacitor and Inductor Nonideal Models: Address challenges associated with nonideal capacitor and inductor models, particularly at high frequencies.

MOSFETs Turn On/Off Times: Be mindful that MOSFET turn-on/off times may be comparable to duty cycles at 100kHz.

Thermal Management: Ensure effective cooling for inductors and MOSFETs to prevent overheating.

Controller Circuitry Voltage Stability: Supply a stable voltage to the controller circuitry through a reliable auxiliary power supply.

Diode Reverse Recovery Time: Account for the reverse recovery time of diodes, as it may lead to an increase in the drain-to-source voltage of the MOSFETs.

Preliminary simulations of the topology

The simulated circuit and the simulation results are given in Figures 15, 16, and 17, respectively.

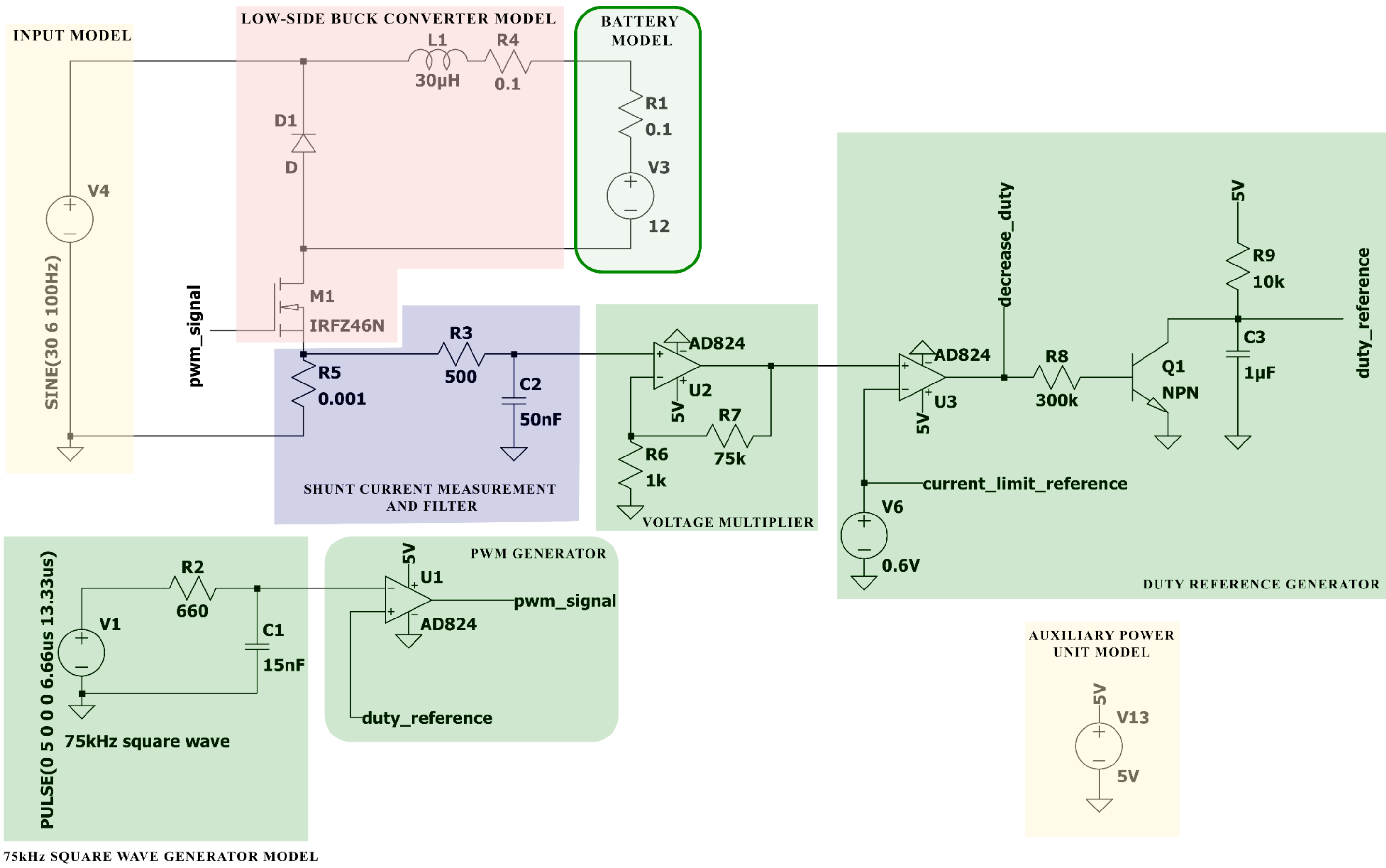

Figure 15: Buck converter with analog feedback topology.

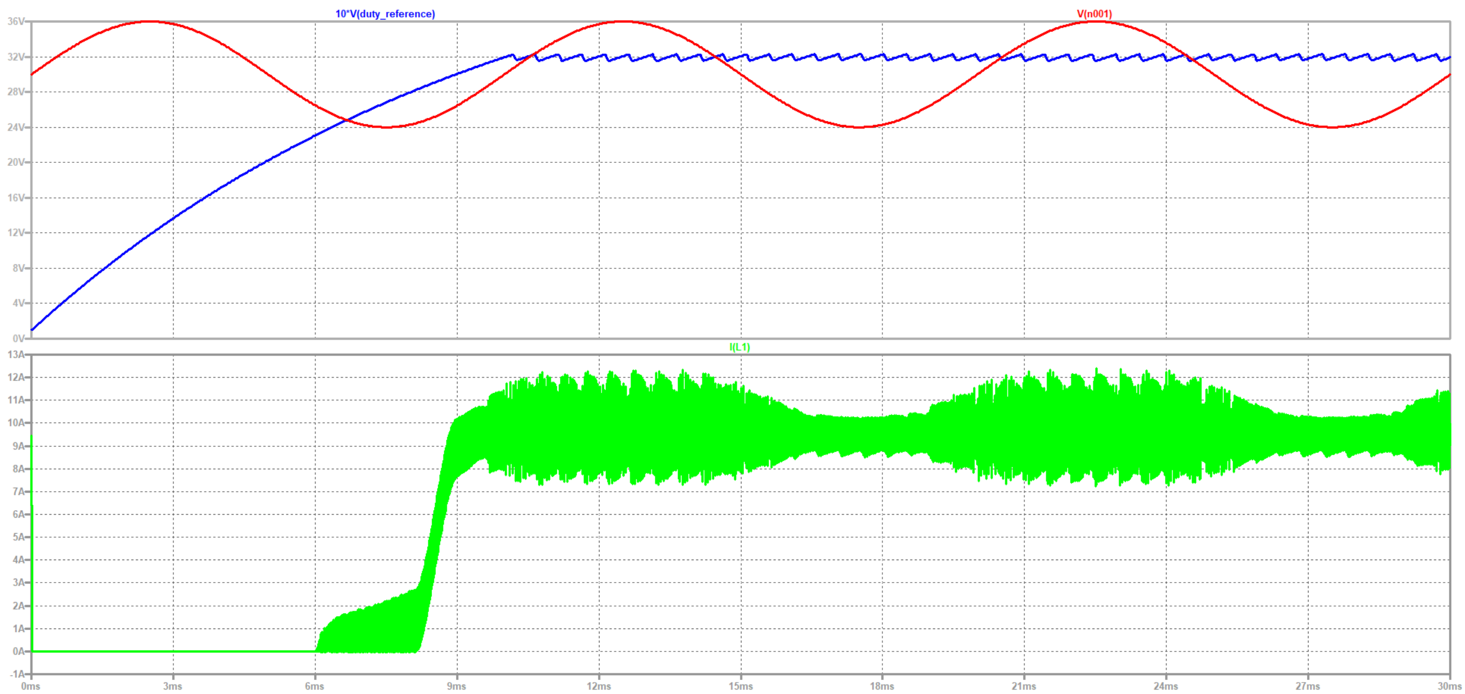

Figure 16: Validating Effective Current Regulation with Transient period included.

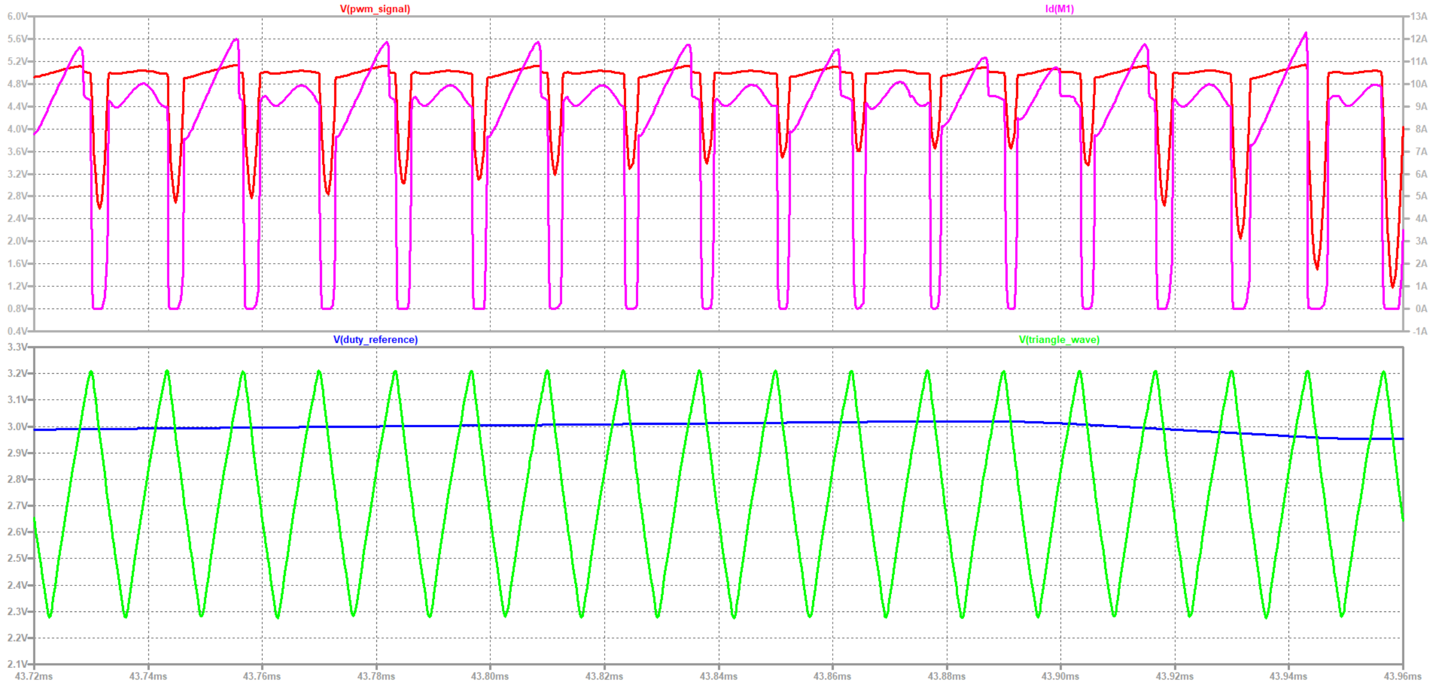

Figure 17: Verification of Shunt-Feedback Effectiveness: Simulation Results

The current regulation is evidently successful, as indicated by the ripple is less than 20% of the mean value. However, the impact of varying input voltage on inductor current is noticeable, as seen in Fig. 16. This is attributed to the gradual changes in our duty reference circuitry. Fine-tuning is underway to enhance response times, with refinements expected in the coming weeks.

Conclusion

In summary, our project focuses on creating a reliable battery charging unit powered by a dynamic wind turbine model. Despite dealing with varying input voltages, our main goal is to maintain a steady output voltage and current. We chose a three-phase bridge rectifier and buck converter for their cost-effectiveness and easy control.

We conducted simulations and hand calculations for key components like the three-phase rectifier circuit, buck converter, and 555 timer. Testing procedures for components such as Mosfets, inductors, capacitors, and wires were established to ensure reliability.

When selecting components, we balanced hand calculations with simulation results, considering safety margins and cost-effectiveness. Our approach emphasized not only technical specifications but also practical factors.

To validate our design, we performed power loss simulations, integrating the results into our final setup. Our project combines theory, simulation, and practical considerations to create an optimized battery charging unit. It addresses challenges posed by dynamic wind energy sources, aiming for reliability, efficiency, and cost-effectiveness in our engineering solution.