GaN-Based Modular DC-DC Converter for EV Auxiliary Systems

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INTRODUCTION

Objective and Background

Goals: Electric Vehicle auxiliary systems such as air conditioning (up to 30% range reduction) and heating system (up to 35% range reduction) severely reduce the vehicles range [10]. DC-DC converters are used to go from 200-800V battery to 48V or 12V battery to power these systems in EVs [2][3]. Most converters are rated for high currents hence are inefficient for lower current operation[6]. This means that during various situations such as when the high power auxiliary systems are idle, there is power wastage. Additionally, many modern electric vehicles use the high voltage to power some of their auxiliary systems. As such, different electric vehicles may have widely different auxiliary power requirements, which does not lend itself to using premade DC-DC converters, as they are generally designed for high power [7]. This means that car manufacturers either use preexisting high power converters at lower powers, which is inefficient [6] or they must design their own converters. By using multiple GaN converters we increase the efficiency and save power, while allowing car manufacturers more flexibility in choosing the size and power of their DC-DC converters.

Functions: We believe the solution is to use a modular DC-DC converter design. Each converter will be designed for a specific low power requirement (138W, 13.8V at 10A) and multiple modules can be connected together to achieve the desired power output. Using control logic a given number of converters will be turned off, based on the current draw, to ensure that the converters are always running at high efficiency. The outputs will be connected to the loads in parallel. Generally, testing would be done at 200-400V[3]; however, due to the tools we have available to us we will be using 80V to simulate the car's propulsion battery. The converters will output 13.8 V to be supplied to auxiliary components. For testing purposes only 2 converters will be used. This modular DC-DC converter is applicable to a wide range of applications and could potentially be used as a universal DC-DC conversion system; however, for the purposes of this project we will be focusing its application in electric vehicles.

Benefits: This design will allow for high efficiency at all power bands above 50W and will allow for complete customizability of power output for different applications. This means that for low power applications few modules can be used allowing for a smaller design.

Features:

Power Converters: Used to convert the high voltage input into a low voltage output, consists of multiple parallel GaN down converters.

Controls: A control circuit which decides when each converter will be on . This module will take in inputs from the current sensor.

Current Sensor: A circuit that senses whether the amount of current that is being drawn by the auxiliary systems and checks if it has exceeded the defined threshold level. This module will send control information to the switching interface.

Physical Design

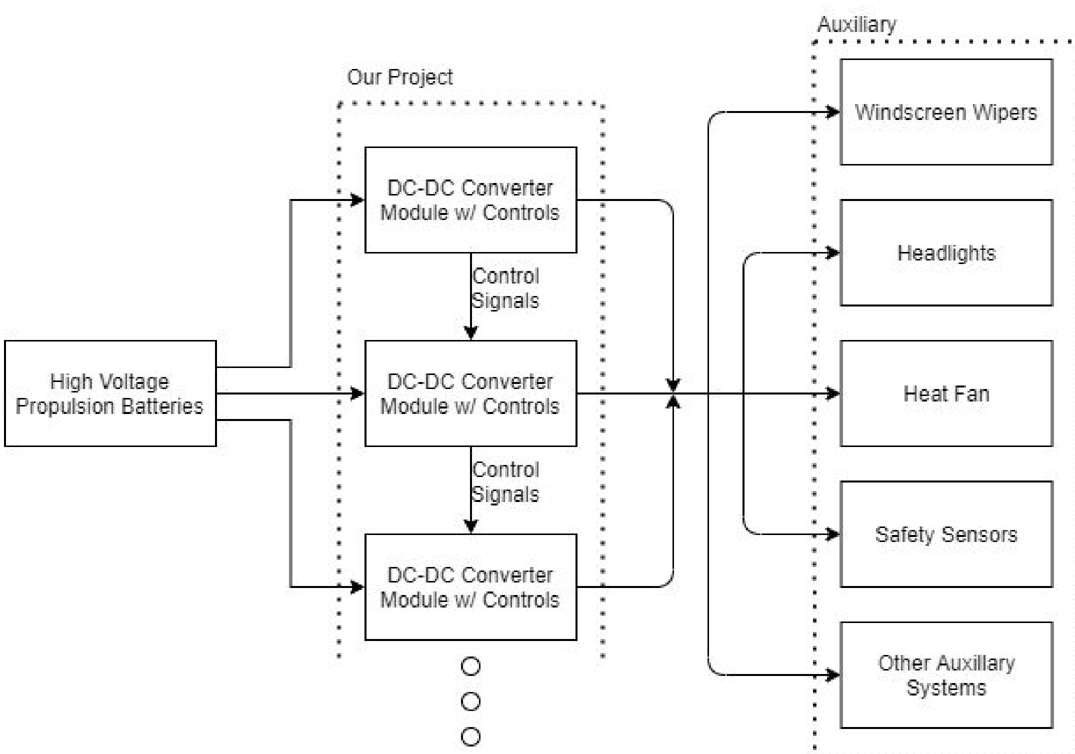

Figure 1: Physical Design

High-Level Requirements

- The converter's output voltage has minimal variation from desired output even when additional converters are powering up
- The converter operates at high efficiency at all operating points
- The converter has non-destructive failure modes

DESIGN

Block Diagram

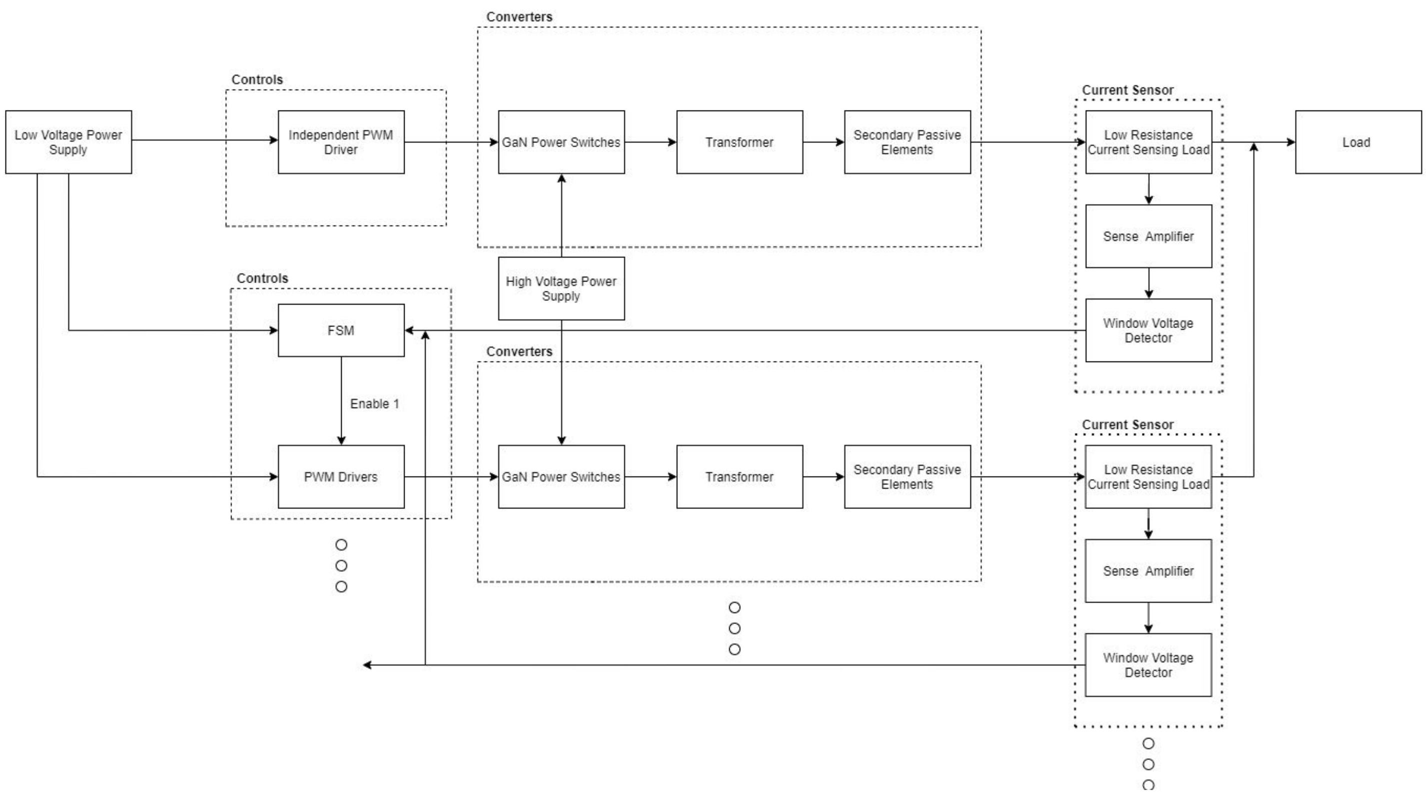

Figure 2: Block Diagram

Functional Overview

FSM

This state machine will control the logic so that the proper PWM drivers are on. When the current sensor module detects that the auxiliary units are taking in a high or low current, this circuit will direct the specific PWM drivers to be switched on and allow for proper operation of our power converter modules. If more converter modules are needed, then the FSM will send signals to those drivers. This unit will consist of logic ICs that will send a signal directly to the gate drivers of the power converter. The determination of whether the high or low power converter should be used is dependent on the current levels sensed by the current sensor.

PWM Drivers

The drivers will be ICs that will be able to drive the gates of our switches. These drivers will receive power from a low voltage power supply, which will be taken from an external power supply in the power electronics laboratory. These drivers will be controlled by our FSM in the control unit.

Transformer

The transformer will be used in our converter to provide both galvanic isolation for safety purposes and bring the voltage down from 80 V. The transformer will be a large enough conversion ratio so that our duty cycle for the converters would not need to be very small because that would cause inefficiencies. This transformer will include windings made of litz wire and copper foil in order to reduce DC and AC resistance. As we will be testing with 80V, we will use a reduce turn ratio in the transformer. To convert our design to one that can be used commercially in an electric vehicle the only thing that would be changed is a higher turn ratio will be used to ensure that 200V is stepped down sufficiently.

Power Converter Module

The power converter will be a GaN two-switch single-ended forward converter. This converter will take our 80V input and convert it to 13.8V. This converter will also feature ports that can allow us to create a modular design where multiple converters can be stacked in parallel if we need a larger current output for the load.

Sense Amplifier/Low Resistance Current Sensing Load

The sense amplifier detects current through the low resistance current sensing load and feeds it to our window detector IC. This allows us to see if our load is pulling large currents or low currents, and then we can feed the signal from our window detector into our controller unit to then decide how many converter modules to turn on.

Window Voltage Detector

The window voltage detector takes the output from the Sense Amplifier as an input and switches into digital value. There is a threshold voltage used that distinguishes between the digital values[5].

GaN Power FETs

The GaN power switches are used as our transistors in the converter topology. These switches are selected because of it's high electron mobility and bandgap, allowing for a smaller on resistance, higher voltage tolerance, and faster switching[9].

Low Voltage Power Supply

The low voltage power supply will be taken from bench equipment, and will power our PWM drivers as well as logic circuits.

High Voltage Power Supply

The high voltage power supply will be set to 80V and simulate an electric vehicle's main battery.

Load

The load will be taken from bench equipment and will simulate between an auxiliary unit taking in large amounts of current 10A or higher depending on how many modular converters are needed.

Block Requirements

Control Subsystem

Requirements	Verification
1. Gate driver must provide 3-6V to drive the GaN FETs during operation of circuit 2. FSM holds correct state based on current sensor output	1A. Measure voltage at the gate of FETs with multimeter 2A. Measure voltages at different points in the logic of FSM using multimeter

3. FSM is able to drive PWM Drivers 4. Current Sensor output switches from 0 to 1 at correct current level 5. Components maintain thermal stability below 90 degrees celsius	2B. View proper switching at output of logic gates with oscilloscope 3A. Measure voltage using multimeter 4A. Measure the output of the current sensor using multimeter 4B. Adjust output load to adjust current pull and see how current sensor output varies with current 5A. Measure temperature using infrared thermometer

Table 1: Control Subsystem Requirements and Verification

Power Converter Subsystem

Requirements	Verification
1. Voltage at output must remain within 5% of desired output (13.8 V), during single converter operation 2. Voltage at output must remain within 10% of desired output (13.8 V), turning or off additional converters. 3. Efficiency above 85% for all reasonable operating points	1A. Measure the loaded voltage output with different loads to emulate different power draws, ensuring sufficient number of data points within both the high power and low power bands 1B. View the maximum output variations with an oscilloscope 2A. Measure the loaded voltage output, while emulating the control signals to turn on or off a converter 2B. View the output voltage variation with an oscilloscope. 3A. Measure the loaded current output with different loads to emulate different power draws, ensuring sufficient number of data points within multiple power bands 3B. Calculating the efficiency to ensure that the converters remain within specifications.

Table 2: Power Converter Subsystem Requirements and Verification

Current Sensor Subsystem

Requirements	Verification
1. 400mV (window detector threshold) [5] should be detected at input of the window detector at 10A 2. Window detector outputs a high value at above 10A and low value at below 10A.	1A. Measure voltage using a multimeter at different current draws 2A. Measure voltage using a multimeter at different current draws

Table 3: Current Sensor Subsystem Requirements and Verification

Risk Analysis

The component that poses the greatest risk to the completion of our project is the Current Sensor Subsystem. The controls and logic components are heavily dependent on the sense amplifier which if doesn't work properly, the digitization will not be implemented properly leading to the logic and PWM drivers malfunctioning. This would jeopardize our controls which provide inputs to the converters and thus risking any functionality of our project all-together. This is also particularly important since the load needs to be provided power at all times, and there could be larger consequences stemming from the hindrance of the current sensing ability.

ETHICS AND SAFETY

The ethical concerns with our project mainly deal with the safety and handling when using or attaching this product onto another machine. Although our project is mainly a proof of concept to show a highly efficient way of powering auxiliary systems in an EV, this project could be applied to a multitude of devices or machines that use power electronics. Because of these applications, the safety of the passengers who are in vehicles that use this device or people who own appliances that might use this device is extremely important. The IEEE code of ethics holds paramount the safety of those involved in any way with this project. There should not be any electrical damage to the equipment that the public uses when this product is involved, and this will be done through extensive design and testing, as well as consultation with course staff. The IEEE code of ethics also states that we should seek to improve our technical competence and undertake tasks only if we are competent. This is especially important since we are dealing with high voltages; we will study and refresh our knowledge on how to work with high power electronics so that we are safe and our product is safe for others to use.

There are multiple safety precautions that we will require during the testing and verification part of the project. Specifically, using a very high voltage/power source requires extensive safety measures and we will take any safety training required by the instructors and lab technicians. During our design process, we will ensure that our implementation will be practical for use in an EV and for testing. The output is high current/power which makes it critical for us to ensure that we follow the required rules and regulations. We will inspect and test each component separately and carefully to ensure that there are no faulty components which might lead to any issues. Furthermore, we will dawn any PPE required to work with the components that we plan to use/build. We will cover all high voltage areas to ensure no direct contact in any case is possible.

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