wbg devices-based matrix converter for 3-phase ac to dc conversion in industrial computing applications

An Undergraduate Research Scholars Thesis

by

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# Abstract

WBG Devices-Based Matrix Converter for 3-Phase AC to DC Conversion in Industrial Computing Applications

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A devices-based 3x1 matrix converter (MC) is proposed for high voltage (HV) power delivery to industrial-scale computing operations such as AI model training, cloud computing, and crypto mining. The system described in this report aims to reduce the energy burden of these loads by improving the power distribution efficiency. The project can be split into three key parts: a primary side matrix converter, secondary side transformer, and an external controls system.

The device begins with a matrix converter, which accepts a low frequency three-phase (3**ϕ**) AC signal and outputs a high frequency ([x] kHz) one-phase AC signal. The matrix converter is controlled by a digital signal processor (DSP) connected to the gate drivers. A high frequency (HF) transformer then transitions the signal to DC and outputs 48 V.

The matrix converter consists of three wide-bandgap (WBG) bidirectional switches with gallium nitride (GaN) FETs. Using GaN technology provides greater power density over silicon carbide components, as does using a matrix converter over traditional rectifiers due to the lack of DC-link capacitors. The experimental results of this report are from providing the matrix converter with 230 V.

A high frequency step down transformer is used in the power transfer from the 3x1 matrix converter on the primary side to the secondary side. The secondary side is composed of WBG, Silicon Carbide (SiC) semiconductors operating as switches in a rectifier. An inductor-capacitor filter is used to reduce ripple in the rectified output.

The controls subsystem contains the logic and hardware necessary to switch the gate drivers for the GaN FETs. It utilizes PowerSim to create the logic circuit, consisting of PLLs, sine wave generators, PWM signal generators, and digital logic. For control I/O, a TI F28397D controlCARD is used to handle the switching algorithm and output the PWM signal to the gate drivers.

# Acknowledgements

[PAGE INSTRUCTIONS] [see comment]

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Contributors

[I would like to thank my faculty advisor, Dr. [XXXX], and my [XXXX], [XXXX], for their guidance and support throughout the course of this research.

Thanks also go to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience.

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Funding Sources

This research received no external funding.

# Nomenclature

AC Alternating Current

ADC Analog-to-Digital Converter

CMOS Complementary Metal Oxide Transistor

CPU Central Processing Unit

DAC Digital-to-Analog Converter

DC Direct Current

DSP Digital Signal Processor

EN Enable

FET Field Effect Transistor

FPGA Field Programmable Gate Array

GaN Gallium Nitride

GPIO General-Purpose Input/Ouput

HF High Frequency

HIL Hardware-In-The-Loop

HPRC High Performance Research Computing

HV High Voltage

IC Integrated Circuit

IMS Insulated Metal Substrate

I/O Input/Output

LC Inductor-Capacitor

MC Matrix Converter

PCB Printed Circuit Board

PLL Phase-Locked Loop

PWM Pulse Width Modulation

RC Resistor-Capacitor

RMS Root Mean Squared

SiC Silicon Carbide

SMT Surface Mount

SR Slew Rate

TIM Thermal Interface Material

TH Through Hole

THD Total Harmonic Distortion

TI Texas Instruments

TTL Transistor-Transistor Logic

V Voltage

WBG Wide Bandgap

3x1 Three-to-one

3**ϕ** Three phase

## Introduction

With today’s remarkable demand for computing power, data storage, and implementing artificial intelligence, there’s no question our aging energy infrastructure is in dire need of upgrades. Fortunately, the necessary technology to develop said upgrades exists and is becoming more commercially viable with every passing day. Matrix converters, though not quite cutting edge, are a modern method for achieving high efficiency power conversion while improving power density and overall functionality. Even more recently, the development of gallium nitride (GaN) FETs has the potential to surpass silicon carbide as the premiere semiconductor material in several spaces, including industrial computing.

### Problem Statement

[text]

### Preexisting Research

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## Methods

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The proposed topology is divided according to three subsystems: primary, secondary, and controls.

### Primary Subsystem

The primary (front-end) subsystem refers to the 3x1 matrix converter responsible for converting a low frequency three-phase AC signal to high frequency one-phase AC signal, as well as its I/O filters and voltage sensors (**Figure [x]**). These circuit elements are explained in detail below.

#### Subsystem Description

The 3x1 MC is equipped with six digitally controlled bidirectional switches (two per phase), each of which are paired with an RC snubber to suppress potential voltage spikes. LC filters are placed before and after the switching array to limit the bandgap.

Each of the six switches contains two GaN FETs whose gate terminals share a gate driver circuit (**Figure [x]**). The gate driver switches the FETs to their ON or OFF state according to the PWM control signal. When operating within the voltage limits of the FETs (<650 V), the result is a consolidation of phases, from three to one, along with an increase in the signal frequency.

In order to verify the matrix converter is functioning as intended, voltage sensors monitor the input and output signal voltages and send them to the controls interface. This also acts as a precaution to avoid damaging the more sensitive circuit components in the primary and secondary subsystems.

#### Subsystem Design and Validation

Primary subsystem validation requires (1) running simulations with various inputs to test edge cases, (2) confirming the controls subsystem is being provided with the necessary parameters (ie. I/O voltages), (3) verifying the connection between the gate drivers and controls, and (4) testing the actual board.

#### Subsystem Conclusion

[text]

### Secondary Subsystem

The secondary subsystem refers to the high frequency step down transformer and the rectifier producing a DC output.

#### Subsystem Description

Isolated power transfer from the primary to secondary side of the 3x1 matrix converter is facilitated using a high frequency transformer. The high frequency transformer utilizes a Kool Mu core from Magnetics, Inc. due to its high saturation level and low core losses, making the transformer more efficient and capable of handling the input and output loads.

The transformer feeds the stepped down voltage into an AC-DC rectifier. Like the primary side, the secondary side will use WBG semiconductors as switches in the rectifier. An inductor and capacitor filter follows the rectifier to produce a more stable output and to minimize ripple.

#### Subsystem Design and Validation

The high frequency transformer is designed using Ansys Maxwell, an electromagnetics simulation and modelling software. Core models are designed parametrically, allowing for the simple and quick adjustment of core dimensions by changing variable values.

Due to the lengthy runtime and computationally expensive simulation process in Ansys Maxwell, the HPRC provided by Texas A&M University is used to simulate different core model dimensions and windings. The simulation provides information on magnetic flux density in the core to determine if saturation is occurring. The simulation also provides information on the losses occurring when the transformer is in operation.

Two simulations are run for each core model: one with a sinusoidal voltage excitation applied to the primary winding and one with a sinusoidal current excitation applied to the primary winding. The magnitudes of the excitations are set to the desired max rating for the 3x1 matrix converter to ensure that the system can handle the maximum rated load. The frequencies of the excitations are set to 100 kHz to match the switching frequency set by the controls subsection.

The core model with the best performance and efficiency as evaluated using the above simulation process was selected for the final design.

### Controls Subsystem

The controls subsystem contains the logic and circuitry that controls the gate drivers for the 3x1 matrix converter on the primary side of the PCB. It contains the hardware and logic needed to convert a 3-phase signal into an AC signal. The goal of the control system’s design is to maintain a specified voltage and minimize noise.

#### Subsystem Description

The system is controlled using a Texas Instruments C2000 microcontroller. The TI Delfino F28379D controlCARD houses the software and hardware I/O needed to control the 3-1 matrix converter on the primary side. Sensors are implemented in the control scheme to maintain a desired output. The sensors are also used to implement zero-voltage switching to improve efficiency. The final design may include a custom PCB to house the electronics for the control system.

The control subsystem is comprised of logic and hardware. The logic converts a 3-phase signal to an AC signal using a logic circuit consisting of a PLL, sine wave generators, PWM generators, and digital logic. The logic is created using PowerSim, a power electronics simulation software that can easily output generated code for the controlCARD.

The PLL is a circuit that can capture the phase angle of any AC signal. This is then used to create a sine wave using a sine wave generator. These sine waves go through a mix of PWM generators and digital logic to create a switching algorithm capable of switching a 3-1 matrix converter.

To create the signal in real life, a TI F28379D controlCARD in conjunction with a expansion board with a built-in ADC, DAC, and GPIO is used. The input to the control logic is inputted to the ADC, and the switching signal for the gate drivers is outputted from the GPIO pins.

#### Subsystem Design and Validation

Control subsystem validation will occur in 3 stages: logic validation, hardware validation, and logic + hardware validation. Logic validation consists of implementing the control logic along with the power circuitry in PowerSim and simulating how the logic controls the simulated circuit. Hardware validation consists of testing code generation, compiling, uploading, and testing on the TI F28379D controlCard. This ensures that the board is able to handle the logic and successfully input and output signals.

Logic + hardware validation consists of implementing the control logic, code generation, and hardware together and testing the entire system. In this validation, hardware-in-the-loop (HIL) testing is conducted using the entire controls subsystem to validate the functionality of the subsystem before it is fully implemented with the other subsystems.

#### Subsystem Conclusion

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## Results

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### Results Subheading

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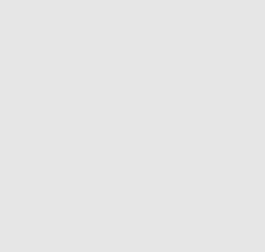


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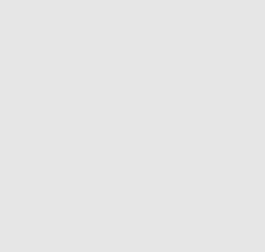


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## Conclusion

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# References

[1] H. S. Krishnamoorthy, P. Garg and P. N. Enjeti, “A matrix converter-based topology for high power electric vehicle battery charging and V2G application,” *IECON 2012 – 38th Annual Conference on IEEE Industrial Electronics Society*,Montreal, QC, Canada, 2012, pp. 2866-2871, doi: 10.1109/IECON.2012.6389440.

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[4] V. Vlatkovic, D. Borojevic and F. C. Lee, “A zero-voltage switched, three-phase isolated PWM buck rectifier,” in *IEEE Transactions on Power Electronics*,vol. 10, no. 2, pp. 148-157, March 1995, doi: 10.1109/63.372599.

# Appendix: TITLE

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* If including multiple Appendices, label them as Appendix A: Title, Appendix B: Title, etc.
* Label figures, tables, and equations consecutively starting with A.1, A.2, etc. For additional Appendices (B, C, etc.), label figures, tables, and equations as B.1, B.2, etc.
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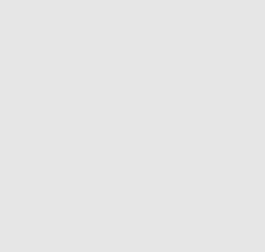


Figure A.: Type a descriptive caption for the figure.

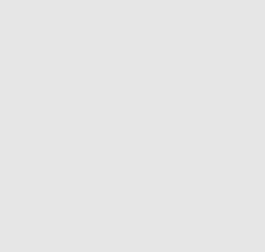


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Table A.: Type a Descriptive Title for the Table.

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