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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Submitted to the Undergraduate Research office at

Texas A&M University

in partial fulfillment of requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by

Faculty Research Advisor: Dr. Prasad Enjeti

May 2025

Major: Electrical Engineering

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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 scheme.

The device begins with a matrix converter, which accepts a low frequency three-phase (3**ϕ**) AC signal and outputs a high frequency 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 (LC) 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 relies on PowerSim to create the logic circuit, consisting of PLLs, sine wave generators, pulse-width-modulation (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

Contributors

We would like to thank our faculty advisor Dr. Prasad Enjeti, as well as Dr. Matthew Johnson and Peng-Hao Huang, for their knowledge and guidance throughout the course of this research.

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

Finally, a heartfelt thanks to all of our families for their constant love and support.

The data analyzed/used for WBG Devices-Based Matrix Converter for 3-Phase AC to DC Conversion in Industrial Computing Applications were provided by Jack Alagood, Kyle Bedrich, Ian Farrar, and Peng-Hao Huang. The analyses depicted in WBG Devices-Based Matrix Converter for 3-Phase AC to DC Conversion in Industrial Computing Applications were conducted in part by Power Electronics & Power Quality Laboratory at Texas A&M University and these data are unpublished.

All other work conducted for the thesis was completed by the student independently.

Funding Sources

This research received no external funding.

# Nomenclature

AC Alternating Current

ADC Analog-to-Digital Converter

BOM Bill of Materials

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

TH Through Hole

THD Total Harmonic Distortion

TI Texas Instruments

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 [1]. 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

The emergence of cloud computing and data centers in the field of information technology has sprouted a new demand for energy that’s expected to grow. To meet these demands, power engineers are responding with innovative energy delivery methods that promise to raise the ceiling on power conversion efficiency [2]. The aim of this research is to apply a 3x1 matrix converter topology for a more efficient step down conversion from 3-phase AC power to DC, thereby making better use of the electric grid through reducing losses associated with the conversion process. By increasing efficiency in energy conversion and delivery, carbon emissions can be reduced and economic growth will not be limited by the constraints of energy.

### Preexisting Research

Matrix converter based topographies have been around for some time, yet the extent of their application continues to evolve. In the realm of electric vehicles, higher expectations for DC fast charging is pushing automotive designers toward matrix converters due to their lack of electrolytic capacitors [1]. Moreover, bidirectional power flow allows for using the vehicle as a power source in cases where that’s important [3]. In high power telecommunications, matrix converters promise to reduce the total harmonic distortion (THD) present in typical telecom-rectifier schemes in addition to simplifying the number of power conversion stages [4].

### Scope and Limitations

The scope of this project is to provide a proof of concept and to see whether or not GaN FETs can outperform their more established SiC counterparts. As such, the objective is not to create a ready to implement device, but to create a functioning 3x1 matrix converter that, for the moment, doesn’t consider the thermal limitations that would result from prolonged operation. To fully implement a device similar to what is outlined in this paper, heat sinks and other cooling systems like cooling fans or liquid based systems would need to be implemented.

## Methods

The proposed topology is divided according to three subsystems: primary (3x1 matrix converter plus input LC filter), secondary (HF transformer, rectifier, and output LC filter), and controls to operate the FET switches on the primary and secondary sides.

### 3x1 Matrix Converter

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]**). Schematics and footprints for these elements were modeled in Altium Designer.

#### 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. 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 (230-650 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 positive and negative output voltages to be sent to the controls interface via an isolated amplifier with integrated DC/DC conversion. 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 physical board. These are given in further detail below.

Validation begins by testing the board design in power electronic systems simulation software, such as PLECS. Power from the grid is provided by an ideal source, and voltage and current meters determine whether or not the expected behavior is observed. In the case that the circuit does not function as intended, component parameters can be altered and tested once more. Also, the input power signal should be modeled with fluctuations and/or voltage spikes to verify the system integrity.

With a working simulation (and all line currents well-within part limitations), we then make sure the controls hardware (TI controlCARD) is receiving the voltage sensor outputs. This is best accomplished through intentional debugging while referencing the relevant manuals. To avoid damaging equipment, seek help from experienced faculty for directions.

Once the controls hardware is up and running and the state of the matrix converter is being actively monitored, we move to the final and most comprehensive validation step: testing the board. The PCB has built-in test points for recording voltages, so as each portion of the product is soldered, use a multimeter or oscilloscope for measurement, and compare those values to the simulation. It’s best to assemble and test the board sequentially so as to identify and resolve issues the moment they arise.

#### Subsystem Conclusion

The 3x1 matrix converter heavily relies on the modulation from the controls subsystem. As such, the subsystem team members should frequently communicate updates and changes to their work. The gallium nitride FETs should be tested for power efficiency and contrasted with silicon carbide components. The LC input filter should be rated to handle anomalous voltage behavior such as that experienced during power surges, and the RC snubbers should be proven as sufficient protection.

### High Frequency Transformer

The high frequency transformer facilitates the transfer of power between the 3X1 matrix converter and the rectifier while stepping the voltage down from 240 VRMS line to line to 90 VRMS.

#### 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 High Frequency 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.

Litz wire is used in the transformer coil windings to minimize copper losses. Selection of Litz wire configuration is elaborated on in section 2.4.2.

#### 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. The selected core shape was an E core due to the difficulty of winding other shapes and relatively low core losses when compared to other shapes.

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 transient simulation type in ANSYS Maxwell 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.

An initial analysis of the change in simulation results as a result of changing the mesh size and time step was done. Once the point of diminishing returns was determined, the rest of the simulations to evaluate performance was done using these mesh size and time step settings.

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.

Litz wire with a strand size of 0.05 mm in diameter and a strand count of 1000 is used to carry the rated current of 12 amps on the primary coil of the transformer. On the secondary coil, Litz wire with a strand size of 0.2 mm in diameter and a strand count of 100 is used to carry the rated current of 20 amps. These wires were selected by their capacity to carry the desired current, strand size, and availability of the wire as is without need for custom design and order. Litz wire reduces the copper losses resulting from the skin depth effect taking place at higher frequencies of AC current flowing through a wire. The maximum strand size was determined using the following equation for skin depth where is the resistivity of copper at room temperature (20 degrees Celsius) and is the frequency of operation (100 kHz):

|  |  |  |
| --- | --- | --- |
|  |  | (2) |

Different rules of thumb are used to determine the desired strand size from calculated skin depth; in this paper, the strand diameter was limited to the calculated skin depth of 0.2mm. The Litz wire material was modelled in simulation using Ansys Maxwell’s built-in Litz wire model in the custom material build tool. Strand size, count, and the material properties of copper were taken as inputs to the model.

For simulation purposes, the windings were wound in a circular spiral pattern around the core’s center leg. The primary coil was wound first from one end of the leg until its end, and then the secondary winding was wound from where primary winding ended to the other end of the core’s middle leg. This was deemed sufficient for simulation to validate the design and determine the best core to select.

When the coils were wound around the actual transformer, the coils were interleaved to reduce proximity effect losses, leakage inductance, and interwinding capacitance. This was avoided in simulation due to the added complexity of modeling the transformer in a parametric model outweighing the benefit of a slightly more accurate model that would likely not affect the final core selection when all cores are limited in accuracy in the same manner, particularly when these effects are relatively insignificant.

### Controls Scheme

The controls include the logic, circuitry, and hardware parts managing the gate drivers of the 3x1 matrix converter on the primary side of the board. The subsystem is crucial in controlling the operation of the matrix converter to ensure correct and efficient power conversion. It includes hardware and embedded control logic necessary to transform a 3-phase input signal into a stable AC output signal to facilitate smooth and reliable power transfer.  
 The primary objective of the control system design is to deliver a specified voltage level and reduce electrical noise and distortion. To accomplish this, the subsystem includes an open-loop feedback circuit utilizing pulse-width modulation (PWM) techniques and logic circuitry used to tell the gate drivers exactly when to switch on and off. The control system is also designed to ensure maximum efficiency, improve power factor correction, and offer safe operation in varying load conditions. The controls subsystem is fully responsible for the performance of the power conversion process.

Another main objective of the control system design is to thoroughly test and validate the proper operation of the system before its integration into the overall system. It is extremely important to ensure all components of the system operate as they should and lower the possibility of failure or malfunction when implemented within the final system. By finding and resolving issues sooner in the development phase, we can prevent errors in the subsystem and simplify and accelerate troubleshooting.

In order to achieve this level of dependability, we designed a comprehensive testing regimen specifically for the control subsystem. It entails rigorous testing on multiple levels: software validation through simulation and code verification, hardware testing to confirm all physical components function correctly, and hardware-in-the-loop (HIL) simulations to simulate real-time behavior under realistic operating conditions. These tests allow us to fine-tune the system, optimize its efficiency, and confirm its stability before moving to full integration. With the help of this structured process of testing, we are able to verify that the control subsystem would perform as desired, avoiding potential unwanted issues and ensuring smooth functionality when implemented within the framework of the overall system.

#### Subsystem Description

The control subsystem governs all hardware and software elements involved in switching gate drivers for the 3x1 matrix converter to influencing correct power conversion on the primary side of the system. The controls subsystem has the central role to play in assisting the efficient and reliable operation of the matrix converter under conditions of varying loads. The entire system is regulated by a Texas Instruments C2000 microcontroller, which was chosen because of its high performance as well as real-time control capabilities. Specifically, the TI Delfino F28379D controlCARD is utilized to interface with the hardware, providing the required input and output interfaces needed for the control of the matrix converter.

The controlCARD is the core hardware platform, offering a wide range of analog and digital I/O functions. These include analog-to-digital converter (ADC) inputs to monitor voltage and current sensor signals and general-purpose input/output (GPIO) pins to deliver digital switching signals for driving gates. The ADC inputs are needed for continuous monitoring of system performance, and the digital outputs enable precise control of the switching states of the converter.

In case a stable output voltage is desired, the control system contains an open loop feedback circuit and sensors to detect the input voltage, output voltage and other electrical parameters. Based on sensor data of the input voltage, the system dynamically alters the switching patterns in order to operate correctly at a setpoint using a phase-locked-loop logic circuit. In addition, the sensors are utilized for zero-voltage switching (ZVS), a technique that minimizes switching losses and improves the efficiency of the system as a whole by having switches turn on only when voltage levels are at or near zero.

While the current design utilizes the TI controlCARD as the source of control and signal processing, the final design can utilize a custom PCB to host the control electronics. The custom PCB would integrate the microcontroller, power electronics, and the signal conditioning circuits needed in an integrated and optimized design with increased reliability and performance of the control system.

The control subsystem consists of both logic and hardware components that work together to regulate the switching of the 3x1 matrix converter, enabling the conversion of a 3-phase input signal into a stable AC output signal. The logic is implemented in software and is responsible for executing a switching algorithm that precisely controls the converter’s operation. This algorithm is designed using PowerSim, a specialized power electronics simulation software that allows for detailed modeling and validation of the control logic before generating the necessary embedded code for the TI Delfino F28379D controlCARD.

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

Validation of the subsystem is an important development step since it ensures that each subsystem will function as required once it has been incorporated into the entire system. It is a step that is required to verify the performance, reliability, and stability of the subsystem before full implementation. The process of control subsystem validation is divided into three distinct phases: software validation, hardware validation, and combined logic and hardware validation, which is conducted with the assistance of hardware-in-the-loop (HIL) testing. All three phases are essential to the guarantee of correct operation of the control subsystem in real conditions.

Software validation is the first step in the process, in which the control logic is designed and tested alongside the power circuitry within a simulation framework. It involves implementing the control algorithms, setting up system parameters, and modeling the desired system performance. The primary purpose of this step is to simulate how the control logic interacts with the power electronics such that the designed algorithms will respond as intended.

In order to achieve this, PowerSim was selected as the primary software for the verification of the software since it is capable of carrying out precise and fast simulations of power electronic circuits and control schemes. Using this software, the control logic was coded, and the simulated system was observed under different conditions. As a result of simulations, potential issues such as phase misalignments or incorrect control output were identified and corrected before moving ahead with the hardware realization. This is a critical phase because it offers quick iteration and debugging within a risk-free simulated environment before moving to physical hardware testing.

Following software validation, the next step is hardware validation, which seeks to confirm that the control logic can be compiled, uploaded, and executed on the target hardware platform without any issues. This process verifies if the microcontroller can execute the control logic in real time and manage signal inputs and outputs at the desired frequency.

For hardware validation, the TI F28379D controlCARD was used due to its powerful processing capability and support for control applications. The methodology began by generating code via PowerSim's code generation facility, which is capable of seamless integration with TI controlCARDs. This facility allowed for automatic conversion of the validated software model to executable code to reduce the likelihood of error caused by manual coding. Once the code had been generated, it was subsequently imported into TI Code Composer Studio, compiled and uploaded onto the controlCARD. The uploaded code was then subjected to testing on the actual hardware.

The final step of the validation process is the logic + hardware validation, wherein both the control logic and hardware are combined into an actual real-time test environment. Hardware-in-the-loop (HIL) testing is conducted in this step to simulate real-world conditions using actual hardware components. This is a critical step to ensure that the complete subsystem functions properly before integrating it with the rest of the subsystems in the complete system.

For HIL testing, a Typhoon HIL 602+ box was utilized along with Typhoon HIL Control Center software. This setup enabled a high-fidelity simulation of the system where the best circuit topology was created within the software and actual switching and control logic were implemented using the hardware. Under the use of the HIL system, communication under real time among the control algorithms and hardware components was practiced within real operating conditions to confirm that the control subsystem performed as predicted.

HIL configuration allowed exhaustive testing of multiple scenarios, including transient response, faults, and varying load profiles, allowing the engineers to identify and rectify any potential errors before final deployment. This process significantly reduces the chance of failures at the last stage of integration.

#### Subsystem Conclusion

[text]

### Secondary Side Rectifier

The secondary side rectifier is composed of four wide bandgap silicon carbide MOSFETs being operated by the control system defined earlier. Following the rectifier is an LC filter to minimize voltage ripple effects.

#### Subsystem Description

The rectifier uses silicon carbide instead of gallium nitride MOSFETs since it receives a lower voltage than the 3x1 matrix converter due to the step-down transformer, so there is no need for the gallium nitride to handle the higher voltages as in the 3X1 matrix converter side of the circuit. The LC filter aids in creating a more pure DC output in the final stage of the topology.

#### Subsystem Design and Validation

The output rectifier is designed to accept the transformer’s high frequency step-down AC voltage and convert it to 48 volts DC. Much like the matrix converter, this is validated through simulating the power in and recording the power out, then comparing actual values once the prior subsystems have been installed on the physical board.

### System Integration and Testing

#### Integration

After each subsystem is complete and tested in isolation, the transformer coils will be soldered to the primary side and secondary side PCBs to facilitate power transfer between the two stages. The MCU will receive the sensor outputs and provide the control pulse width modulation signals via header pins on both PCBs.

#### Overall System Testing

The completely integrated system must be validated after assembly and after each subsystem passed the testing procedure outlined in its respective section above. The rated primary voltage of 240 VRMS line to line will be applied to the input of the 3X1 Matrix Converter PCB. Oscilloscopes and multimeters were used to validate expected signals and voltage and current levels throughout the circuit. Measured points of interest include output of gate drivers, PWM signals, primary and secondary windings of the transformer, and final DC output.

The input and output voltages and currents are measured to determine the input and output powers from equation 2. Efficiency is then found from the calculated power in and power out values.

|  |  |  |
| --- | --- | --- |
|  |  | (2) |

The heat being produced by the system is also observed. As the aim of this paper is proof of concept, the device aims to only operate for a limited period of time and thus heat generation is not a practical concern beyond its relation to loss and efficiency. The monitoring of temperature is used to prevent damage to the device while collecting under test to collect data.

## Results

### 3x1 Matrix Converter Design Implementation

In order to quickly become proficient in using the Altium Designer interface while simultaneously providing expandable models for the three-phase matrix converter, we began by creating a single-phase prototype. By shrinking the number of circuit elements to a third, unexpected changes to the design rules or bill of materials (BOM) could be implemented faster. Since no limitations on size or dimension were given, initial drawings for the prototype could take any form, so long as the following design rules were respected:

1. Minimum part dimensions set at 1206
2. Low and high voltage systems must be far enough apart to prevent risk of shorting
3. Where copper pours are not appropriate, HV traces must be very thick (>50 mils)
4. Traces should be as short as possible
5. Decoupling capacitors must be directly adjacent to their respective power supply

The result of following these guidelines gives a rough outline of the final product. High voltage components are contained in a central area surrounded by low voltage traces and pours that reach around connecting the voltage sensors back to their designated pins (**Figure 1**). Note that several improvements still need to be made, such as bringing the two switches closer to one another, resizing the traces to the left of the GaN FETs, and adjusting the position and orientation of the LC filters to better align with the RC snubbers.

A computer screen shot of a computer chip

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Figure 1: Single-phase matrix converter PCB prototype. Low and high voltage elements connect through gate drivers (gold) and voltage sensors (green).

A diagram of a circuit

AI-generated content may be incorrect.

Figure 2: 3-phase matrix converter schematic with RC snubbers in parallel with bidirectional GaN switches. Each switch receives high and low signals from a corresponding gate driver.

A diagram of a circuit

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Figure 3: One of six gate driver schematics with its designated power supply. Each driver accepts a PWM signal from a GPIO pin and outputs gate and Kelvin source voltages to a FET.

A screen shot of a computer code

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Figure 4: One of three voltage sensor schematics. Each sensor reads a positive and negative voltage across two phases of the input power and sends correlated outputs to a pin header.

### [Ian’s Results Section]

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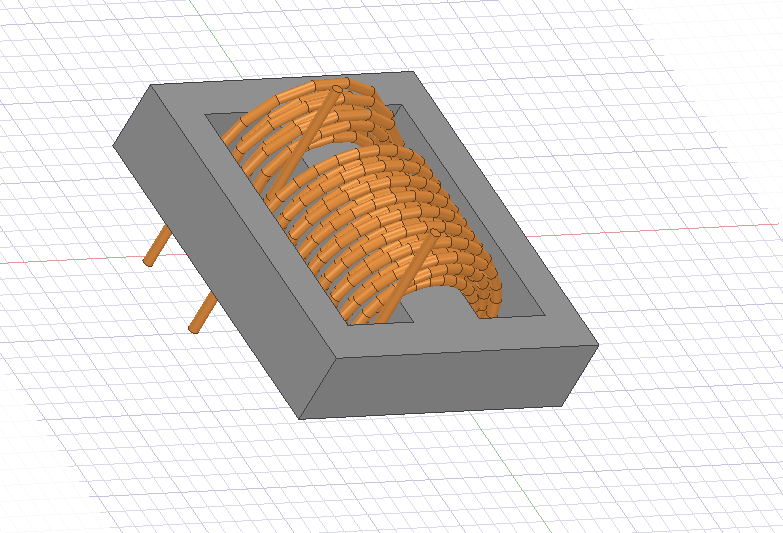


Figure 6: Transformer undergoing testing isolated from rest of system. Input voltage is applied to the primary coil, and a resistive load closes the secondary coil.

[text]

## Conclusion

### Measured versus Expected Performance

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