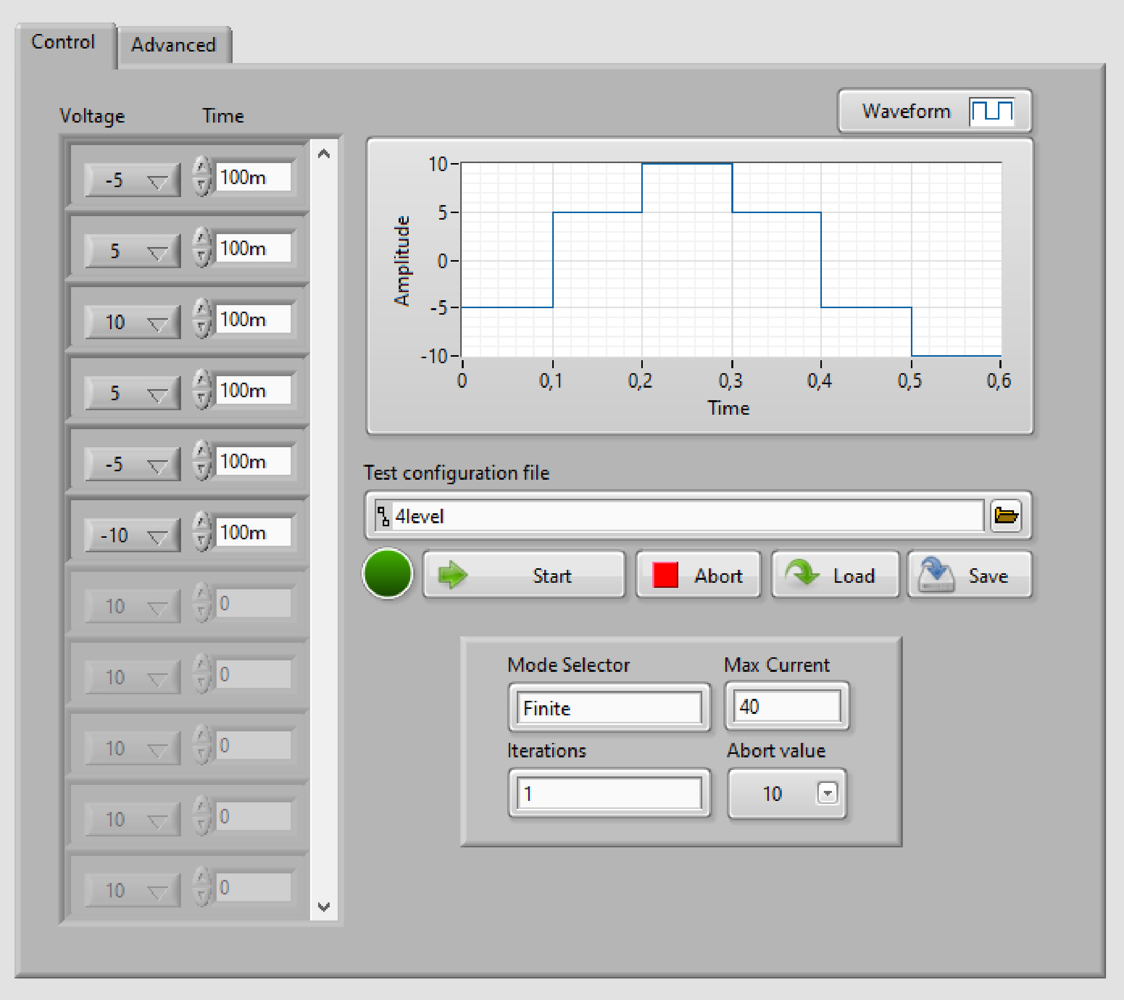

Voltage	Time
-5	100m
5	100m
10	100m
5	100m
-5	100m
-10	100m
10	0
10	0
10	0
10	0
10	0

Test configuration file: 4level

Mode Selector: Finite
Max Current: 40
Iterations: 1
Abort value: 10

Development of Test System for Motor Insulation

Bachelor's thesis in Electrical Engineering

Jesper Björklund & Markus Lennartsson

DEPARTMENT OF ELECTRICAL ENGINEERING
Chalmers University of Technology
Gothenburg, Sweden 2025
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Cover: The graphical user interface of the software solution developed in LabVIEW.

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Abstract

Modern pulse width modulated (PWM) inverters found in variable speed motor drives, while enhancing energy efficiency, introduce rapid switching transients and voltage overshoots that significantly increase electrical stress on motor insulation. The rapid switching triggers partial discharges (PDs) within the insulation, accelerating material degradation and ultimately causing insulation and motor failure. This thesis presents the design and validation of a programmable test platform that subjects motor winding insulation to electrical stresses commonly found in modern PWM drives. The system was implemented as a LabVIEW program that with the utilization of a PCI-6541 National Instrument (NI) digital I/O card controls multiple fast high voltage push-pull switches to generate arbitrary PWM signals in order to study PDs. To enable the NI card to deliver suitable current to control the switches, gate drivers were implemented. The software allows for save and load of test profiles, continuous or finite waveforms generation, and for stopping test sequences automatically if the current through the device under test (DUT) exceeds a user defined limit. Validation of the system was done through experimental testing with signal pulse widths ranging from 50 μs to 1 s. Tests were performed for three- and four-level signals that confirm accurate generation for signals with pulse widths above 500 μs and demonstrates the viability of NI I/O cards for generating square waveforms. The testing results indicate that the primary limitations of the system are imposed by the push-pull switching devices rather than the software. To enhance the system's testing capabilities, the use of faster switching components are proposed. Furthermore, future improvements could include the development of a custom PCB layout and a more refined user interface.

Acknowledgements

We would like to express our gratitude to Thomas Hammarström for giving us the opportunity to undertake this project and for his guidance and support throughout its course. We also extend our thanks to Chalmers University of Technology, not only for providing the equipment and resources that made this work possible but also for equipping us with the knowledge and skills necessary to carry out this project.

Jesper Björklund & Markus Lennartsson, Gothenburg, August 2025

Contents

1

Introduction

1.1 Background

Frequent use of modern pulse width modulated (PWM) inverters in variable speed motor drives has led to more efficient energy utilization but also to greater electrical stress on motor insulation. Rapid switching transients and voltage overshoots caused by these motor drives can cause partial discharges (PD) within weak points of the insulation material [1]. Repeated PD activity can lead to insulation breakdown, resulting in motor failure, unplanned downtime, and costly repairs.

It is essential to study insulation behavior under realistic electrical stress conditions to better understand and mitigate these effects. This requires a controlled test environment capable of reproducing the fast voltage transitions and high-voltage levels typically generated by modern power electronics.

1.2 Purpose

The primary purpose of this project is to develop a test system capable of generating a range of square waveforms that are commonly produced by modern power electronics. This system is designed to subject motor insulation to realistic electrical stresses that enable analysis of PD phenomena.

1.3 Goals

- Develop a LabVIEW-based software solution capable of controlling the test system and generating customizable output signals.
- Identify and implement a suitable National Instruments DIO card for signal generation.
- Design and construct a power amplification stage using gate drivers to interface the NI card with the high-voltage switches.
- Integrate real-time current monitoring of the device under test (DUT), with automatic signal interruption if a defined threshold is exceeded.
- Verify the system functionality through a series of practical tests, and document the resulting performance and limitations.

1.3.1 System Concept

A LabVIEW-based program is used to control a National Instruments digital output card, enabling the generation of user-defined voltage signals. These digital outputs are used to control a set of high-voltage transistors, each connected to a fixed voltage level. By switching the transistors on and off in different combinations, the system can produce waveforms consisting of various voltages. These waveforms are then applied to a motor winding to simulate real-world electrical stress conditions.

1.4 Limitations

1.4.1 Hardware constrains

The configuration of the high-voltage transistors and the capabilities of the NI PCI-6541 card directly determine which voltage levels can be generated, and consequently, what test conditions the system can impose on the motor winding. The number of output levels is limited by the number of available transistors and voltage sources. Additionally, the overall system speed and response time are bounded by the physical switching characteristics of the components used, including the gate drivers and transistors themselves.

1.4.2 Measurements and validation limitations

The accuracy of the system's validation is inherently tied to the quality of the measurement equipment. In this project, current readings were obtained using a current probe and oscilloscope. While sufficient for general testing, more advanced instrumentation could provide higher precision, better noise rejection, and faster sampling, all of which would improve result fidelity.

1.4.3 Time constrains

The limited time available for the project restricted the scope of both implementation and testing. With more time, additional features could have been developed and integrated into the LabVIEW program, such as real-time data visualization, automatic report generation, or a more advanced signal editor. The existing code could also have been optimized further for performance and modularity, which would improve long-term maintainability and execution efficiency.

Additionally, extended development time would have allowed for broader testing scenarios. Including tests with higher voltage levels and the use of more high-voltage transistors in the switching grid. Testing the system at higher voltages would more accurately reflect its intended real-world application., and more switches would enable a higher number of voltage levels and support more advanced waveform generation.

2

Theory

2.1 Partial discharges

Partial discharges (PDs) are localized electrical discharges occurring within motor insulation that do not completely bridge the insulation between conductors. They occur when the electric field in a small region of the insulation exceeds the local dielectric strength. This excessive stress is typically caused by insulation defects. For example tiny voids or cracks in the insulation that provide a weak path for ionization. Each PD event releases heat and reactive elements that gradually erode the surrounding insulation material. PDs are considered a major contributor to reduced insulation lifetime in high-voltage or inverter-fed motors [1].

2.2 LabVIEW and Digital Measurement Systems

National Instruments (NI) provides a versatile hardware and software platform widely used in automated testing, measurement, and control applications. LabVIEW is an application offered by NI that serves as a graphical programming environment that integrates with instrumentation to enable control and data acquisition tasks [2]. This project utilizes an NI PCI-6541 digital measurement card for generating precise digital waveforms.

The NI PCI-6541 card is specifically designed for high-speed digital signal generation and acquisition. It allows users to write waveform data directly to onboard memory which is used to define digital output signals. These stored data points are sequentially output at defined intervals. By programming the card using LabVIEW, users can easily customize the frequency, duty cycle, and pattern sequences of the generated signals [3].

2.2.1 Producer/consumer framework

The producer/consumer framework is a design pattern in LabVIEW that separates fast input handling from slower processing tasks by using queues to coordinate between them. This pattern can be seen implemented in LabVIEW in Figure 2.1. This architecture enables multiple functions to operate concurrently without causing the program to become unresponsive. In this structure, the producer loop executes rapidly and is responsible for detecting user input and sending out queues that describe upcoming tasks. These tasks are then handled by one or more consumer loops, where the actual operations are carried out. Multiple consumer loops can run in parallel, allowing the program to efficiently manage different processes simultaneously [4].

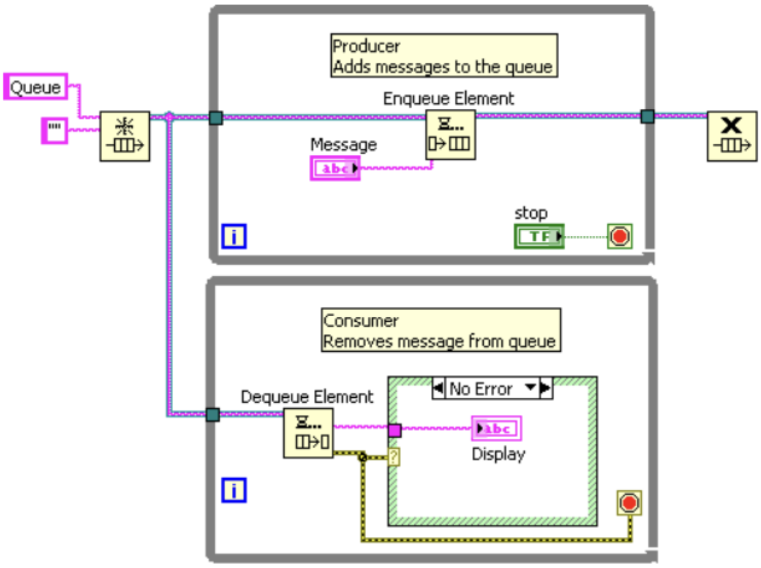


Figure 2.1: Producer/consumer design pattern implemented in LabVIEW.

2.3 Gate driver

Gate drivers are electronic circuits to control the gate of a transistor, such as a MOSFET. Their primary purpose is to ensure fast and efficient switching by delivering the appropriate voltage and current to the transistor gate within very short time intervals [5].

Power transistors often have significant input capacitance, which must be charged and discharged rapidly to switch the device on and off. A gate driver addresses this by providing high peak currents and low output impedance, ensuring fast transition times and minimizing switching losses. This is especially important in high-speed applications [5].

2.4 High voltage switch

High-voltage transistors are semiconductor switching devices designed to handle large voltages and currents while switching rapidly between on and off states. Common types include high-voltage MOSFETs and IGBTs, which are widely used in power electronics applications such as inverters, motor drives, and high-voltage testing systems [6].

In systems like the one developed in this project, high-voltage transistors are used to selectively connect different voltage levels to a shared output. The transistors are controlled via their gate terminals which require relatively low-power digital signals to operate. When a control signal is applied to the gate, the transistor switches on, allowing current to flow from drain to source, and effectively connecting the associated voltage to the output [6].

3

Methods

3.1 Structure and requirements

The project began by defining the general functional requirements for the test system. Based on these, an overview of the system architecture, see Figure 3.1, was developed to identify the components needed to meet the specified goals.

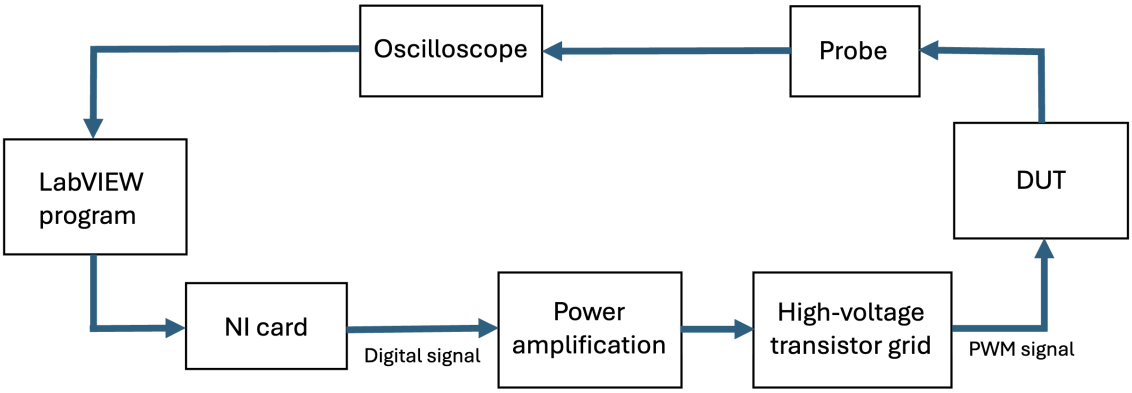


Figure 3.1: Complete system overview.

From the project requirements a set of features for the program was decided:
- Square waveform input and display
- Continuous or finite waveform generation
- Save and Load test configuration
- Automatic test stop when current goes over threshold
- Data logging and display

The LabVIEW IDE was chosen for program development primarily because it is developed by National Instruments and offers seamless integration with their hardware. Since the project involved selecting between two National Instruments digital output cards, using LabVIEW ensured easy integration and support for high-level control through a graphical programming environment tailored for NI devices.

3.2 Selection of NI card

Initially, two different National Instruments digital I/O cards were available for the project: the NI PCI-6503 and the NI PCI-6541. At first, the PCI-6503 appeared to be the more suitable option due to its simpler interface. However, after developing an early-stage LabVIEW program that successfully transmitted a user-defined signal, it became evident that the PCI-6503 could not deliver an output with the time precision needed. This limitation was caused by the card's lack of an internal clock. Instead, it relied on the host computer's system clock, which was simultaneously handling other processes. As a result, the output signal became inconsistent and unusable for the intended application.

The NI PCI-6541 card, in contrast, is equipped with its own internal hardware clock, allowing it to generate precise and reliable digital signals independently of the host computer's operating system. This made it well suited for the requirements of the project. Therefore the PCI-6541 was chosen and the LabVIEW program was adapted to use its internal clock and National instruments NI-HSDIO driver for all signal generation.

3.3 Development of the LabVIEW program and digital signal generation

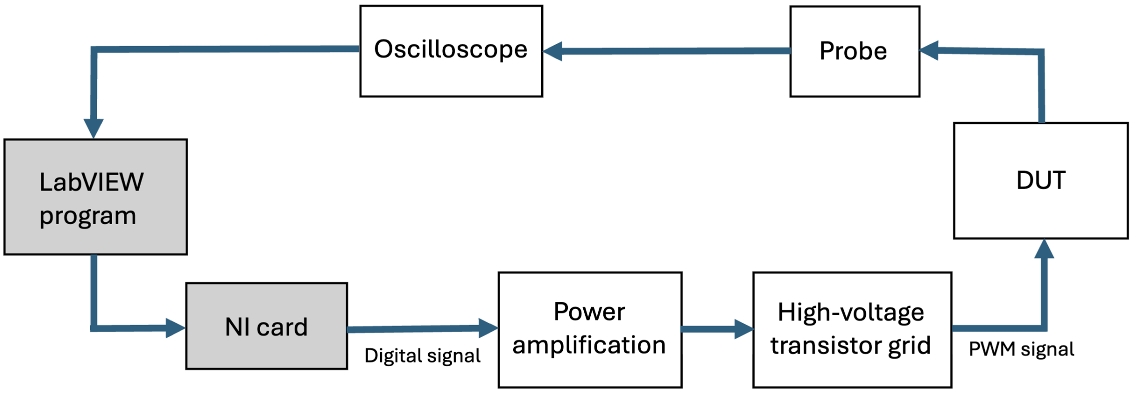


Figure 3.2: Highlighted subsystem for the software and digital signal generation.

As shown in Figure 3.2, the first task to address was the software and the digital signal generation. The primary purpose of the LabVIEW program is to generate a signal for output via the NI card, while also monitoring measurement data from the DUT and interrupting the signal if a specified threshold is exceeded. Additionally, features such as signal loading and saving were implemented to improve user-friendliness. The output signal is defined as a sequence of digital values, where each sample represents a specific bit pattern distributed across the pins on the PCI-6541 card. Each bit is either high or low, and the combination of these states corresponds to a predefined voltage level that is later produced by the high-voltage transistor grid. This mapping enables the system to translate binary control data into actual high-voltage waveforms for insulation testing. The complete LabVIEW code can be found in Appendix B.

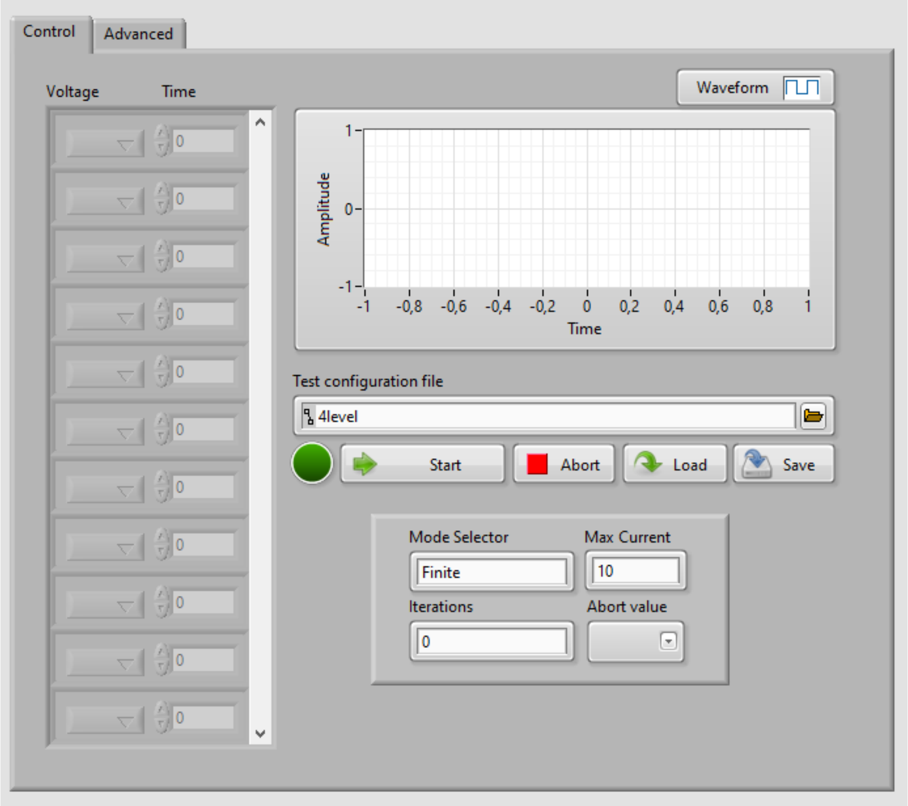
3.3.1 Program overview

The LabVIEW program was designed using the producer/consumer framework to enable parallel execution of independent tasks. This structure was chosen to ensure that the user interface remained responsive while other operations where executed in the background.

In this implementation, the producer loop continuously monitors the graphical user interface. Each button press or parameter change is interpreted as an event and placed in a queue along with its associated data. These events are then processed in one of several consumer loops, each dedicated to a specific type of task. For example, one consumer loop handles signal generation and communication with the NI PCI-6541 card, while another is responsible for saving and loading the signal waveform to memory.

3.3.2 Graphical user interface

A graphical user interface (GUI) was developed in LabVIEW to operate and configure the test system. The GUI was structured with two tabs: Control and Advanced, to separate signal handling and system configuration tasks. A complete software configuration guide for setting up a test is provided in Appendix A.



Voltage	Time
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0
	0

Test configuration file: 4level

Mode Selector: Finite

Max Current: 10

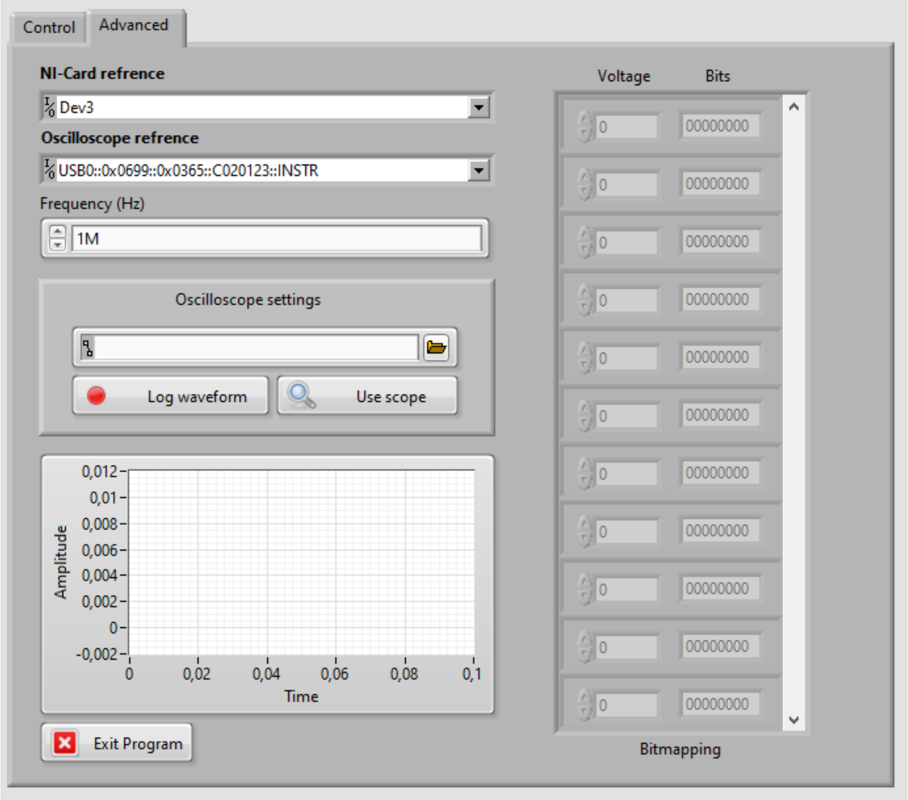
Iterations: 0

Abort value:

Figure 3.3: GUI control tab.

In the control tab (Figure 3.3), the following functions were implemented:

- Manual input of voltage signal.
- Option to run the signal continuously until aborted, or for a set number of iterations specified by the user.
- Previewing the signal waveform (one iteration) prior to transmission.
- Load signal.
- Save signal.
- Aborting signal when running.
- Set max current, the signal will abort if this value is exceeded.



NI-Card refrence: Dev3
Oscilloscope refrence: USB0::0x0699::0x0365::C020123::INSTR
Frequency (Hz): 1M

Voltage	Bits
0	00000000
0	00000000
0	00000000
0	00000000
0	00000000
0	00000000
0	00000000
0	00000000
0	00000000
0	00000000
0	00000000

Figure 3.4: GUI advanced tab.

The Advanced tab (Figure 3.4) provides access to settings required for system configuration:

- Management of the bit-to-voltage mapping used for signal generation.
- Definition of the voltage levels available for selection in the Control tab.
- Configure the oscilloscope, see input waveform and log values in a file.
- Adjustment of system clock rate.
- Selection of the connected NI device.

3.3.3 Save and load function

The system includes a save and load feature to allow the user to save a test setup and also reuse the same test configurations at a later date without having to reconfigure the software again. The feature works by saving a ".ini" file to the LabVIEW project directory. This file can then be accessed either through the computers file explorer or by pressing the "Load" button in the GUI's control tab. The user specifies what configuration file to use and presses the "Load" button, which populates all the control fields in the GUI. This eliminates manual re-entry and ensures that identical test conditions are maintained across test runs.

3.3.4 Waveform generation function

The digital output signals generated by the NI card are dynamically controlled through a LabVIEW function. The digital waveform generation occurs within a dedicated consumer loop that receives commands and configuration parameters from the GUI producer loop. The Communication with the NI card is then managed through the National Instruments High-Speed Digital I/O (NI-HSDIO) drivers. These drivers require waveform data to be provided as a 1D array where each element represents a single byte (8 bits). Each byte corresponds to the digital state of the first eight DIO pins on the card and are outputted at a user specified frequency. Figure 3.5 shows a waveform array of three bits whose output forms a four-level PWM signal.

Waveform array

Voltage	b2	b1	b0
+10	1	1	-
+5	0	1	-
-5	-	0	1
-10	-	0	0
-5	-	0	1
+5	0	1	-

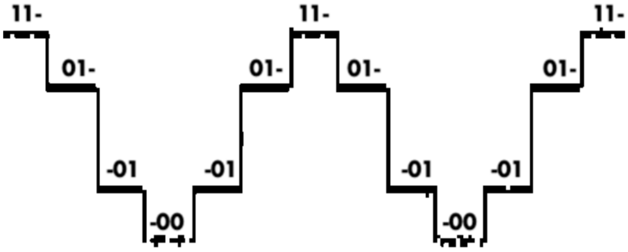


Figure 3.5: Visualization of waveform data converted to multi-level PWM waveform.

The waveform array is dynamically generated based on voltage and timing specifications entered by the user through the GUI. Initially, an empty waveform array is created in order for LabVIEW to allocate the required memory. The software then iterates through the voltage-time array provided by the user. For each specified voltage level, the program references a predefined lookup array that maps each voltage level to its corresponding bit pattern. The matching bit pattern is repeatedly inserted into the waveform array according to the duration specified by the user.

The duration for which a particular voltage level is outputted depends on the number of repetitions of its corresponding bit pattern in the waveform array. The shortest possible voltage duration is determined by the period time for the specified frequency. Longer durations are achieved by repeating the bit pattern multiple times where the duration is a multiple of the period, as shown in (3.1) where N is the number of times the certain voltage is outputted. Once the waveform array is populated it is transferred via the NI-HSDIO driver onto the onboard memory of the NI card. After loading, the card outputs the waveform sequentially at the frequency specified by the user.

$$N = t_{\text{signal}} \cdot f_{\text{clk}} \tag{3.1}$$

3.3.5 Aborted signal ends on ’aborted value’

Originally, when a signal is aborted, the output pins on the NI card remain at the values they held at the moment the abort command was pressed. However, setting all output bits to 0 does not necessarily result in a 0 V output from the switching grid. This is due to the way voltage levels are mapped to bit combinations. To address this, an "aborted value" control was implemented. It is provided as a ring selector in the user interface, allowing the user to choose the desired output voltage that should be applied when the signal is aborted.

3.3.6 Oscilloscope function

The waveform acquisition functionality is implemented in a while loop that can run in parallel with the waveform generation loop. Its purpose is to handle communication with the Tektronix TDS 2004B oscilloscope that has a current probe connected on channel 1. Communication with the oscilloscope is managed by third party LabVIEW drivers specifically designed for Tektronix TDS 200, 1000 and 2000 series devices.

The function is called at the beginning of program execution if the user has selected to use the oscilloscope, trough the "Use scope" button seen in Figure 3.4. The function then initializes communication with the oscilloscope and executes an automatic setup routine. Following this initialization step the function begins continuous acquisition of waveform data from the oscilloscope. The user can then decide to log waveform data by selecting this option in the GUI. Additionally, the function will automatically terminate an ongoing test if the measured current surpasses a maximum threshold defined by the user.

3.4 Signal generation hardware

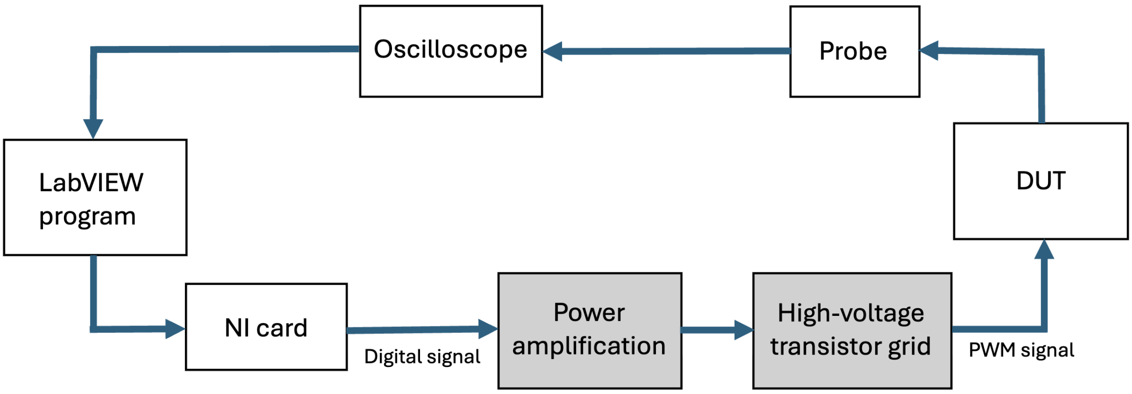


Figure 3.6: Highlighted subsystem for signal generation hardware.

Between the PCI-6541 card and the DUT, as seen in Figure 3.6, the system required additional hardware components. Specifically, a gate driver and a grid of high-voltage switches.

The high-voltage switches used in the system have a 50 Ω pull-down resistor connected to each gate, resulting in a constant current draw when driven high. This load exceeds the maximum drive current of the NI PCI-6541 card, which is limited to 32 mA per output. To handle this, a power amplification stage was necessary between the NI card and the switches gates to ensure that the control signals could be delivered without overloading the output channels.

3.4.1 Power amplification using the TC4427 gate driver

To drive the switches in the test system, the TC4427 gate driver was used. The TC4427 is a dual non-inverting MOSFET driver capable of sourcing and sinking peak currents up to 1.5 A. It is designed for high-speed applications and provides short propagation delays (typically 40 ns) and matched rise and fall times of approximately 25–30 ns, making it suitable for fast switching of capacitive loads such as transistor gates. At 25 °C, the TC4427's maximum on-to-off "turnaround" time for continuous square-wave operation is 140 ns. This corresponds to a theoretical maximum toggle rate of about 7.1 MHz [7].

The choice of the TC4427 was based on several key advantages. Its current output capacity meets the demands imposed by the gate input and pull-down resistance of the high-voltage switches. The matched transition times help maintain clean and predictable switching behavior, which is important for signal fidelity. Additionally, the driver provides protection against reverse current, preventing potential damage to the NI PCI-6541 card. Since each TC4427 IC includes two independent drivers, a single device can control two switches, which contributes to a more compact and efficient circuit design.

As can be seen in Figure 3.7, the TC4427 has two inputs and two outputs, meaning that one TC4427 IC was used to drive two high voltage switches. Its outputs were directly connected to the TTL input terminal of the switch.

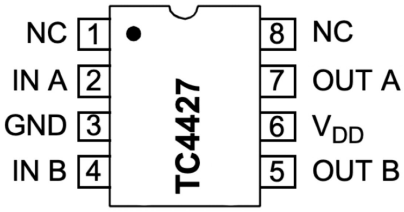


Figure 3.7: TC4427 pin configuration.

In the implemented circuit seen in Figure 3.8, the TC4427 was powered with a supply voltage of 5 V, which is within its recommended range of 4.5 to 18 V. At each gate driver's input a 1 kΩ series resistance was connected. The added resistance dampens high frequency parasitic noise, ringing and slowed down the edges which would otherwise trigger the switches internal protection circuitry that protects against switching frequencies that are outside its operating range.

To ensure stable operation during switching, two capacitors were connected in parallel between the V_{DD} pin and ground: one with a value of 4.7 μF to provide bulk decoupling, and another with a value of 0.1 μF to filter high-frequency transients. This combination allowed the gate driver to supply the necessary current for fast switching on both output channels without causing voltage dips or instability.

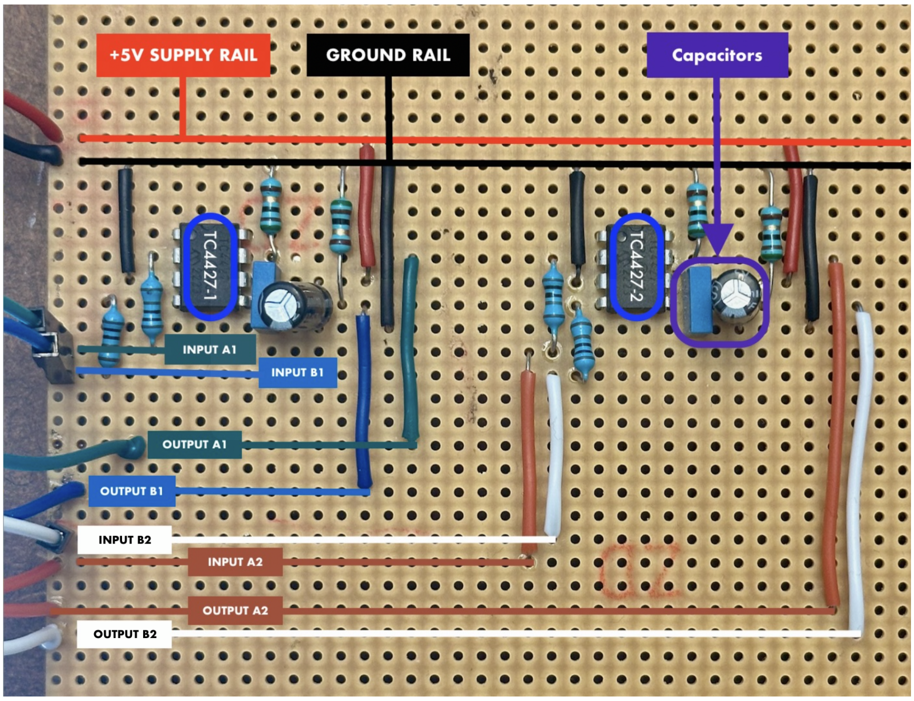


Figure 3.8: Complete amplification stage circuit on prototype board.

3.4.2 Fast high voltage push-pull switch

The high-voltage switching in the test system was performed by the HTS 81-06-GSM fast high voltage push-pull switch, which can be seen in Figure 3.9. This component is specifically designed for fast high voltage applications and was selected for its ability to handle up to 8 kV DC and peak currents of 60 A. The maximum continuous switching speed is 10 kHz [6].

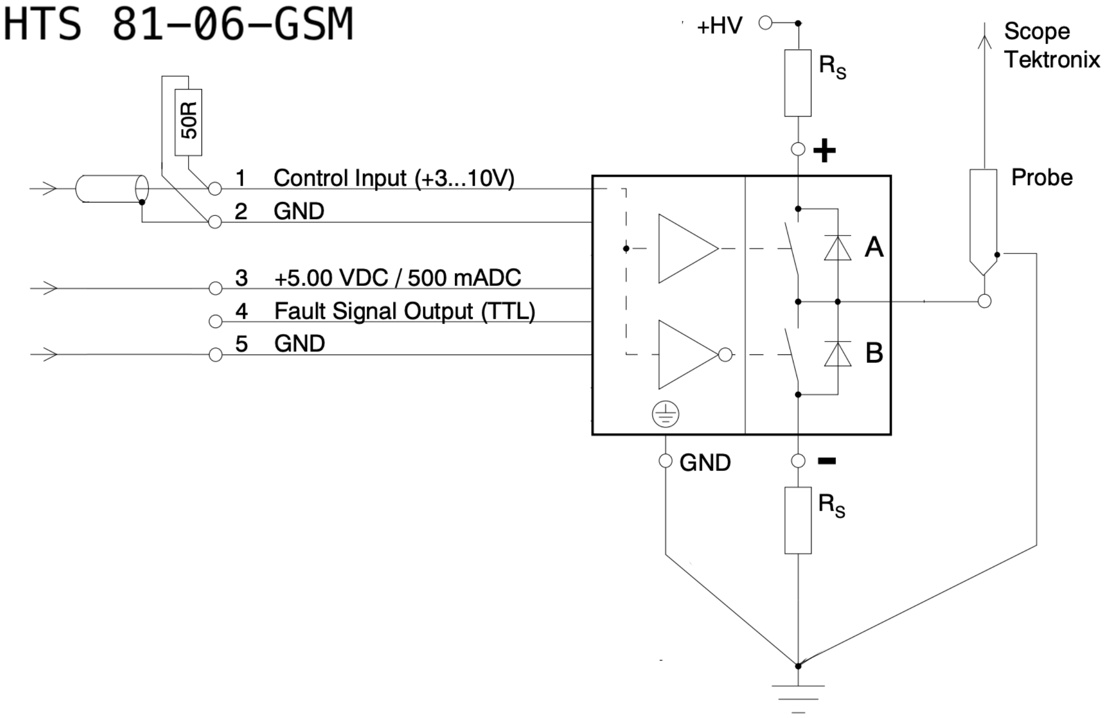


Figure 3.9: Pin configuration for HTS 81-06-GSM switch

The Switches are controlled by applying a signal at the TTL control input. Signals in the range of 3 to 10 V are interpreted as a logical high. An input voltage between 0 and 3 V is interpreted as a logical low. When a high signal is applied to the input, the device outputs the voltage present at the positive supply terminal. Conversely, when a low input signal is applied, the voltage at the negative supply terminal is outputted [6]. As seen in Figure 3.9, the switch has a 50 Ω pull-down resistor to ground at the control input. This is to prevent the input from becoming floating in the absence of a signal. R_S selected to 75 Ω.

3.5 Signal acquisition from device under test

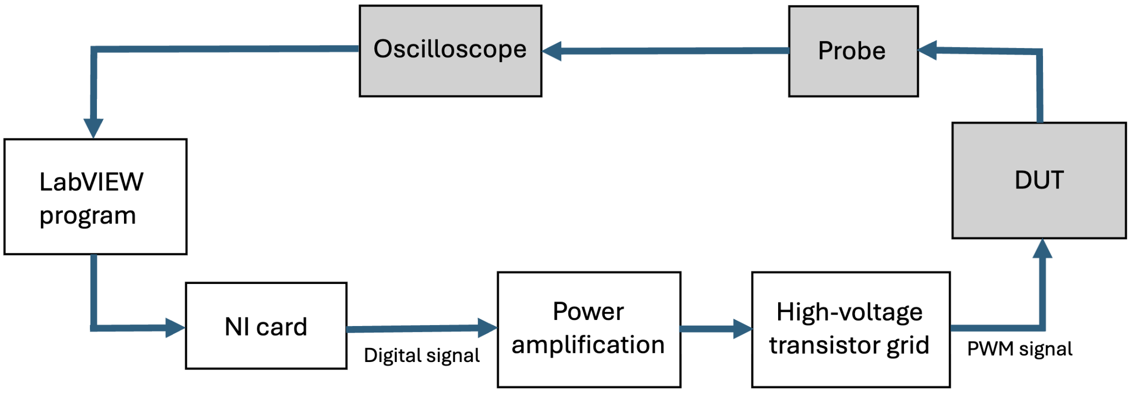


Figure 3.10: Highlighted subsystem for the reading of the DUT.

The data acquisition process is illustrated in Figure 3.10, which shows how the current from the DUT is measured and returned to the LabVIEW program for analysis.

3.5.1 DUT and current measurement setup

A motor winding, seen in Figure 3.11, was utilized as the device under test. The motor winding exhibits primarily capacitive behavior and can be approximated by the equivalent circuit illustrated in Figure 3.12, consisting of a capacitor C1 and resistor R1. The component values of C1 and R1 are estimates, not derived from precise measurements. To facilitate reliable current measurement, a 1.5 kΩ resistor was connected in parallel with the motor winding to emulate a motor breakdown scenario and ensure sufficient current flow.

The current was monitored using a Pearson current monitor (model 8585C), clamped around the cable connecting the DUT to ground. The current monitor operates as a current transformer, which means it detects changes in current by sensing the changing magnetic field around a conductor [8]. This changing field induces a voltage in the transformer's winding that is proportional to the rate of change of current (di/dt), not the current itself [9]. The Pearson current monitor has a voltage-to-current ratio of 1:1, meaning the voltage waveform observed on the oscilloscope directly corresponds to the measured current in amperes [8]. This simplifies the interpretation of the signal.

The probe's output was fed to a Tektronix TDS 2004B oscilloscope, which was interfaced with the LabVIEW program to enable real-time current monitoring. This current reading was used to allow the user to define a maximum allowable current threshold in the software, and if the threshold is exceeded the program will terminate signal transmission. Additionally, a Tektronix DPO 4043 oscilloscope was used for analyzing the current waveform due to its superior signal averaging capabilities.

Figure 3.11: Motor winding.

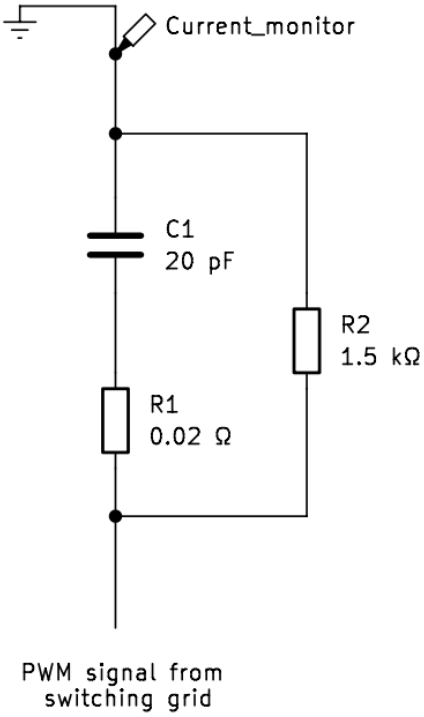


Figure 3.12: Motor winding equivalent scheme, along with R2 to emulate motor breakdown.

3.6 Test configurations

To verify the functionality of the system, two tests were performed. The first test used two switches to generate a three-level output, while the second test used three switches to achieve a four-level output. Both tests were performed multiple times with different pulse widths to test the systems boundaries. The pulse widths selected for documentation and analysis of the test system were: 50 µs, 500 µs, 5 ms and 1 s.

3.6.1 Three-level output test configuration

Two switches were wired as in Figure 3.13. The high-side switch was powered with +10 V on its positive supply terminal and the output from the low-side switch to the the negative terminal. The low-side switch was supplied with –10 V on its negative terminal, with ground connected to the positive terminal. Their gates were controlled by two separate DIO pins, allowing each possible 2-bit combination to produce an output voltage at the output node connected to the DUT. A single TC4427 gate driver was used to drive both switches simultaneously by utilizing its two independent output channels (A and B).

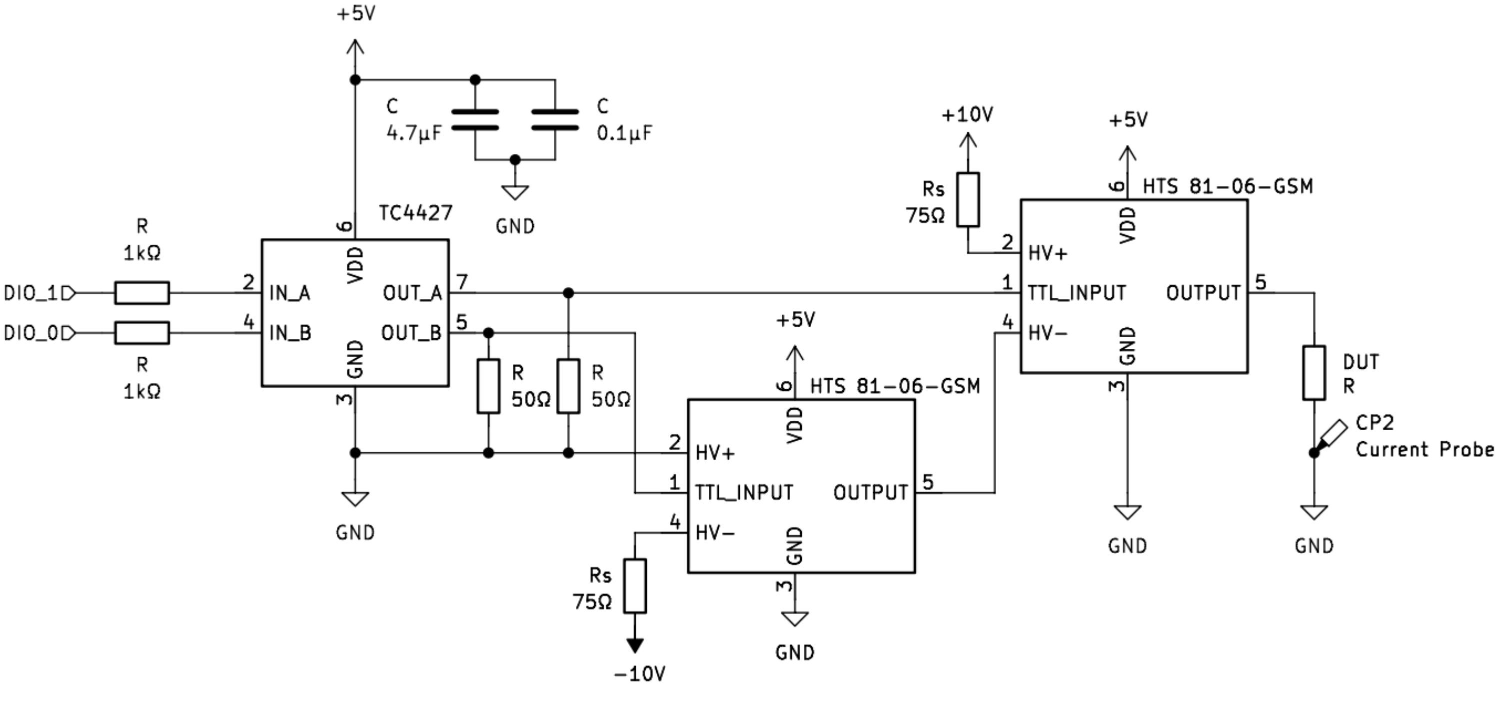


Figure 3.13: Configuration for 3-level PWM signal generation and current measurement.

- **1-:** When the high-side switch receives a logic-1 it connects the output node to the +10V rail regardless of the state of the low-side switch. The bit controlling the the state of the low-side switch is therefore considered a "do not care"
- **01:** With the high-side switch held at logic-0 and the low-side at logic-1, The output node is left un-driven and set to goes to ground potential of 0V.
- **00:** Holding both gates low allows the negative terminal on both switches to conduct which outputs the -10V from the railing.

As a result, these bits {bit 1, bit 0} directly maps to three discrete output levels: {+10V, 0V, -10V}, as summarized in Table 3.1.

Table 3.1: Bit patterns corresponding to three-level output voltage.

Voltage	**b1**	**b0**
$+10$	1	-
0	0	1
-10	0	0

3.6.2 Four-level output test configuration

To generate a four-level output, three high-voltage switches were required, each controlled by a separate digital output bit. Since each TC4427 gate driver provides only two output channels, an additional gate driver was added to accommodate the third switch.

To enable the four distinct voltage levels, the supply voltages to the switches were adjusted. The high-side switch was connected with +10 V on its positive terminal and +5 V on its negative terminal, allowing it to control the output for all positive voltage levels. The low-side switch was configured with –5 V on its positive terminal and –10 V on its negative terminal, making it responsible for generating the negative voltage levels.

The outputs from the high-side and low-side switches were then connected to the supply inputs of the third switch, which acted as the final stage in delivering the desired voltage to the load. The complete circuit configuration is shown in Figure 3.14.

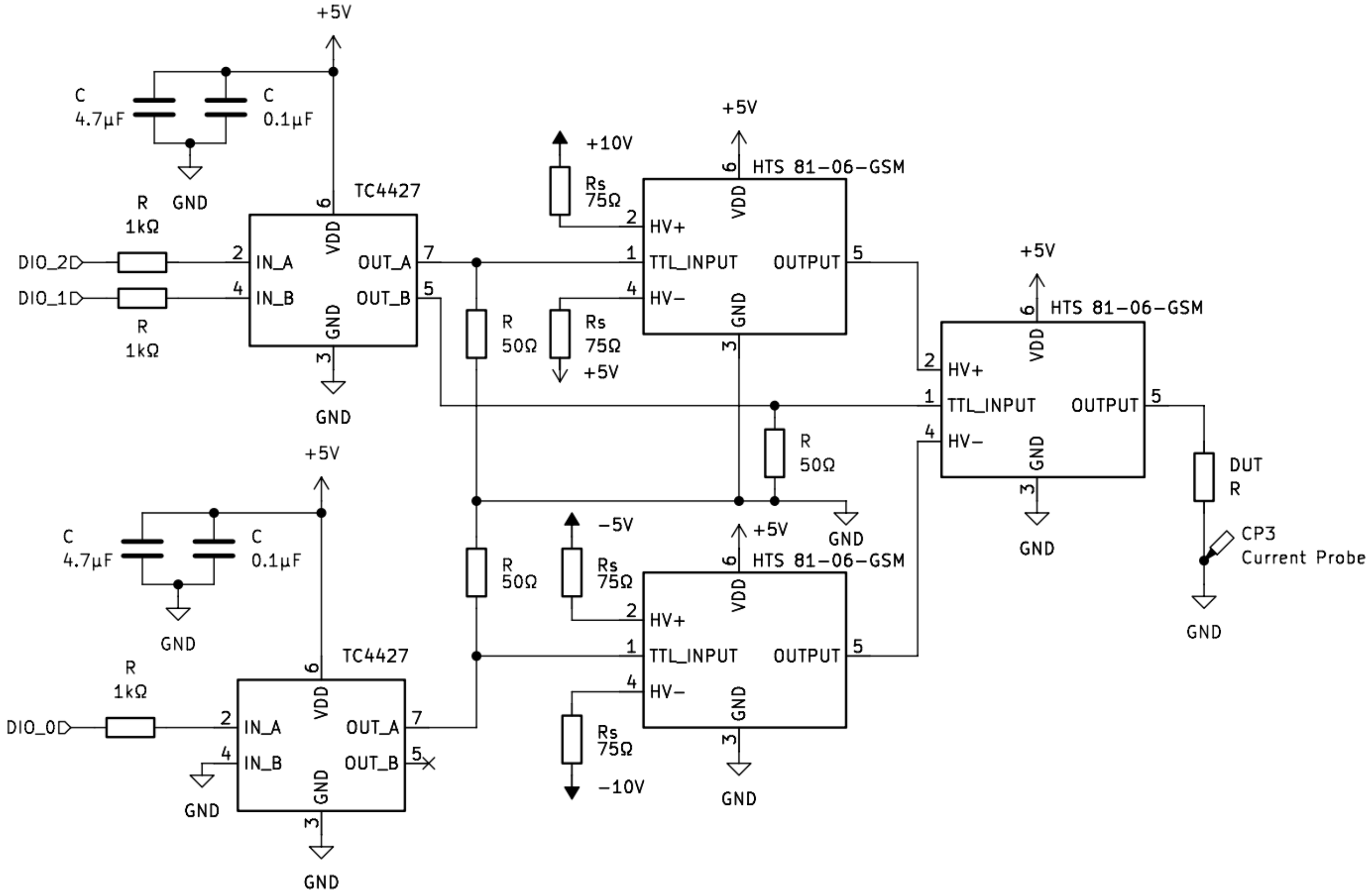


Figure 3.14: Configuration for 4-level PWM signal generation and current measurement.

- **11-:** When both b2 and b1 are high, the output is connected to the +10 V rail via the uppermost high-side switch. In this case, the state of b0 is irrelevant (a "don't care"), since the +10 V switch dominates the output.
- **01-:** When b2 is low and b1 is high, the +5 V switch is enabled while the others remain off. This ties the output to +5 V, again regardless of the state of b0.
- **-01:** When b1 is low and b0 is high, the +5 V and +10 V switches are off, and the –5 V switch is enabled. This connects the output to –5 V.
- **-00:** When all three bits are low, the –10 V switch is enabled, and the output is pulled to –10 V.

Thus the control word {bit 2, bit 1, bit 0} maps directly to four output levels {+10 V, +5 V, -5 V, -10 V}, as summarized in Table 3.2.

Table 3.2: Bit patterns corresponding to four-level output voltage.

Voltage	**b2**	**b1**	**b0**
+10	1	1	-
+5	0	1	-
-5	-	0	1
-10	-	0	0

4

Results

4.1 System specifications

The developed motor insulation test system successfully integrated with the NI PCI-6541 high-speed digital I/O card and the HTS 81-06-GSM switches to generate arbitrary PWM signals for insulation testing. The software developed as part of this thesis enables control over the signal characteristics.

4.2 Three- and four-level test results

4.2.1 Generated PWM signals

The system performed reliably in generating both three-level and four-level output signals. The user-defined waveforms created in the LabVIEW program, shown in Figures 4.1 and 4.2, were accurately reproduced at the output of the high-voltage transistor grid. These figures, which were captured directly from the GUI, also confirming that the graphical preview functionality within the interface works as intended. Note that Figure 4.1 and 4.2 illustrate the waveform generated during a single signal period.

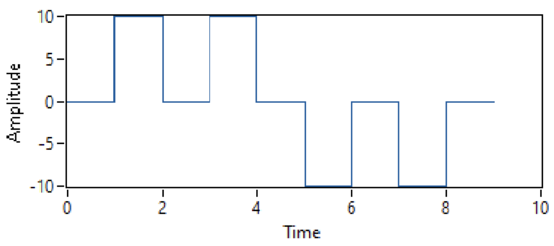


Figure 4.1: 3-level input waveform

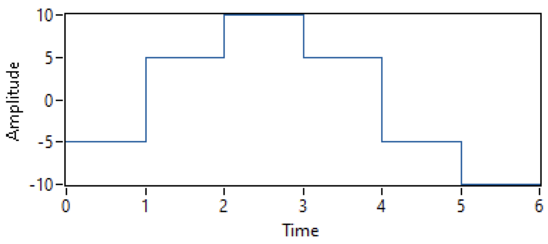


Figure 4.2: 4-level input waveform

4.2.2 Observed digital signals

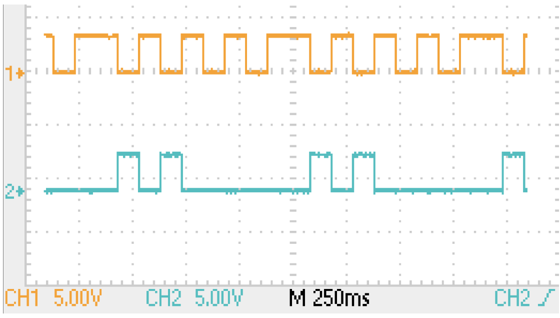


Figure 4.3: Individual pins for the three-level signal. b0=yellow and b1=blue.

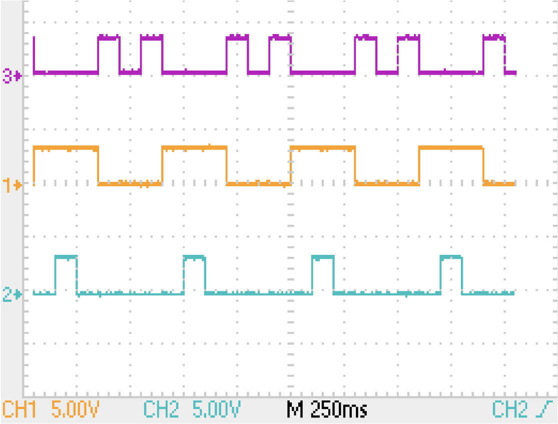


Figure 4.4: Individual pins for the four-level signal. b0=purple, b1=yellow and b2= blue.

In the three-level configuration, two digital output pins, b0 and b1, were used to control the switching grid. Their individual signals are shown in Figure 4.3, where the yellow trace represents b0 and the blue trace represents b1. As seen in Figure 4.4, the four-level configuration required three pins: b0 (purple), b1 (yellow), and b2 (blue). The mapping between bit combinations and output voltage levels is presented in Tables 3.1 and 3.2 for the three-level and four-level configurations, respectively. When compared to these tables, the observed bit sequences were correctly timed and matched the expected patterns.

4.2.3 Observed PWM signals

Figures 4.5-12 present oscilloscope captures of the PWM signals outputted from the switching grid. Each image corresponds to a different pulse width used during testing. These waveforms were recorded to observe how the output signal behaves under varying timing conditions and to verify that the correct voltage levels were produced for each bit pattern. To test the motor winding effectively, the voltage waveform applied to it must exhibit minimal noise and distortion.

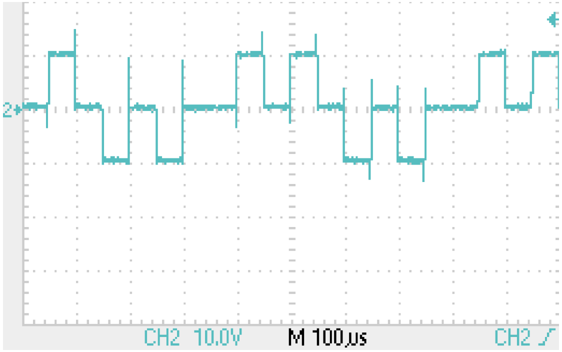


Figure 4.5: 3-level PWM signal. Pulse width = 50 us.

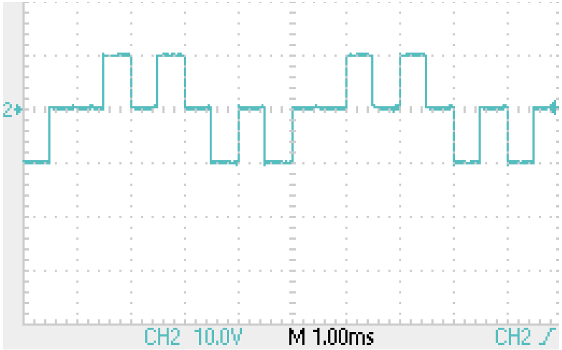


Figure 4.6: 3-level PWM signal. Pulse width = 500 us.

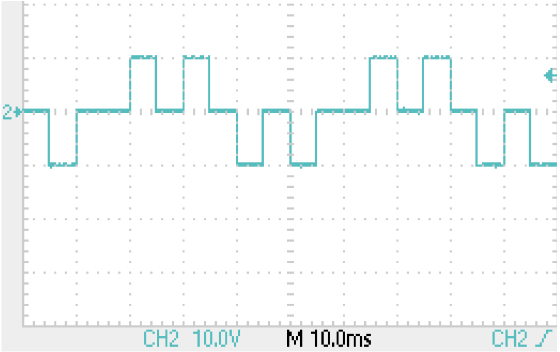


Figure 4.7: 3-level PWM signal. Pulse width = 5 ms.

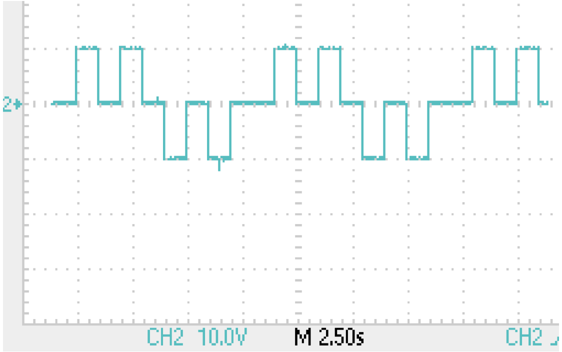


Figure 4.8: 3-level PWM signal. Pulse width = 1 s.

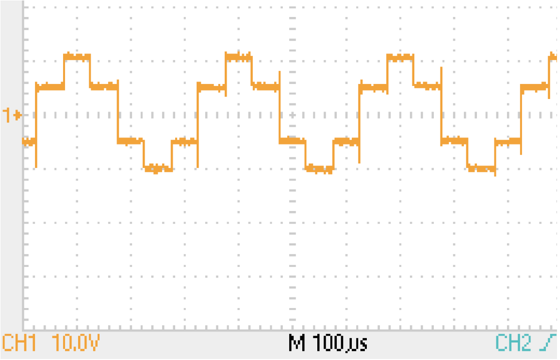


Figure 4.9: 4-level PWM signal. Pulse width = 50 us.

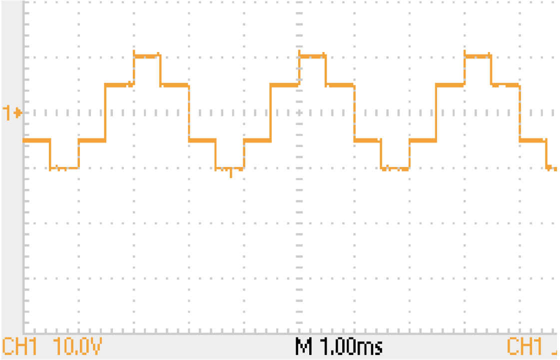


Figure 4.10: 4-level PWM signal. Pulse width = 500 us.

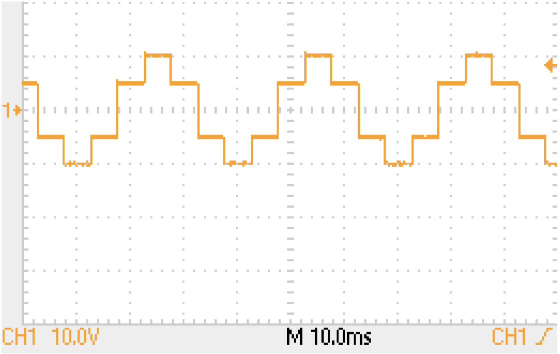


Figure 4.11: 4-level PWM signal. Pulse width = 5 ms.

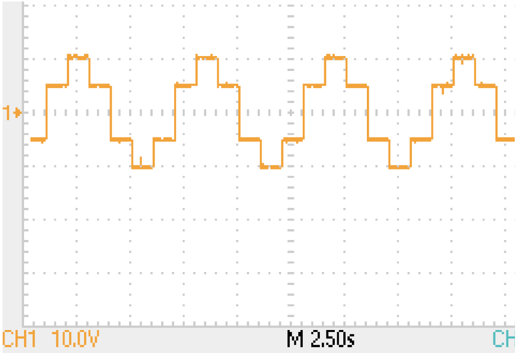


Figure 4.12: 4-level PWM signal. Pulse width = 1 s.

4.2.4 Current response at DUT during motor breakdown emulation

The measured current remained low due to the limited supply voltage used during testing. However, transient spikes generated by the high-voltage switches introduced disturbances into the signal, as highlighted in Figure 4.13.

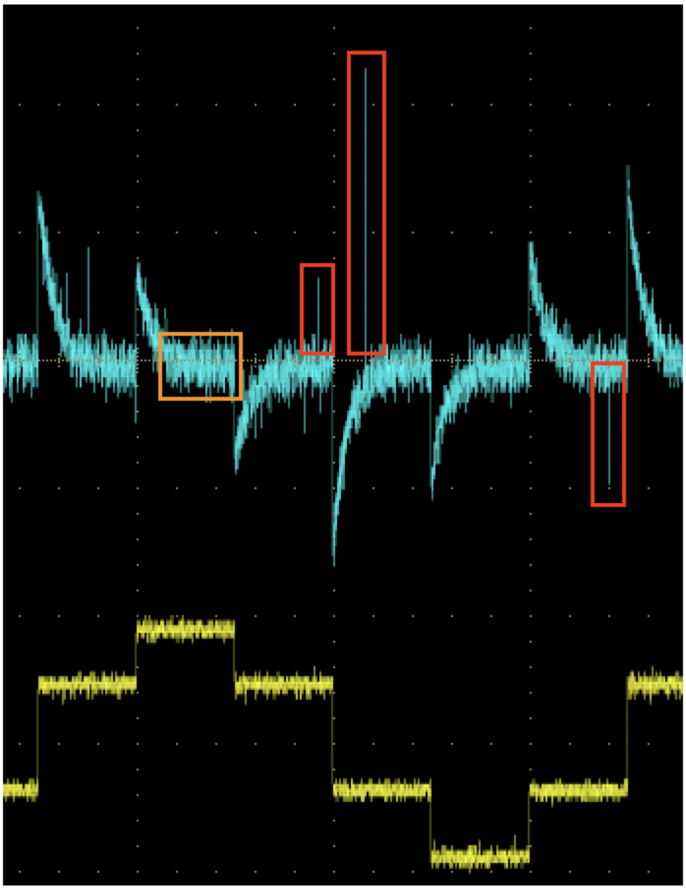


Figure 4.13: Noise during motor breakdown emulation.

In Figures 4.14 and 4.15, the current passing through the DUT is shown in blue, while the voltage waveform is displayed in yellow to highlight the relationship between the two signals. To reduce noise and provide a clearer representation, the oscilloscope was set to sampled averaging mode. This setting smooths out rapid fluctuations in the measurements and works similarly to a low-pass filter, making the main features of the waveforms easier to observe.

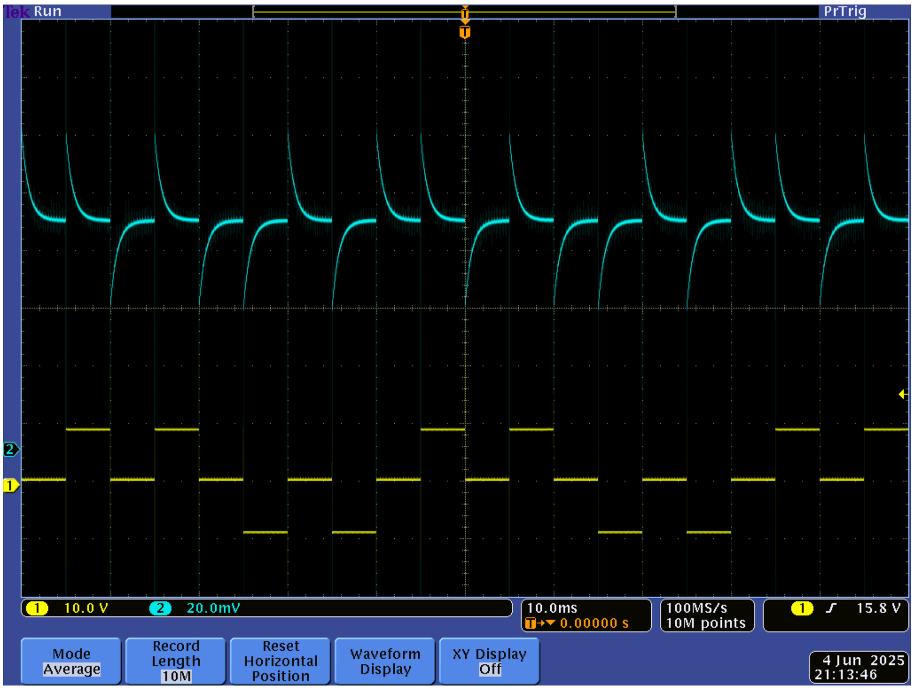


Figure 4.14: DUT current in relation to the three-level voltage waveform.

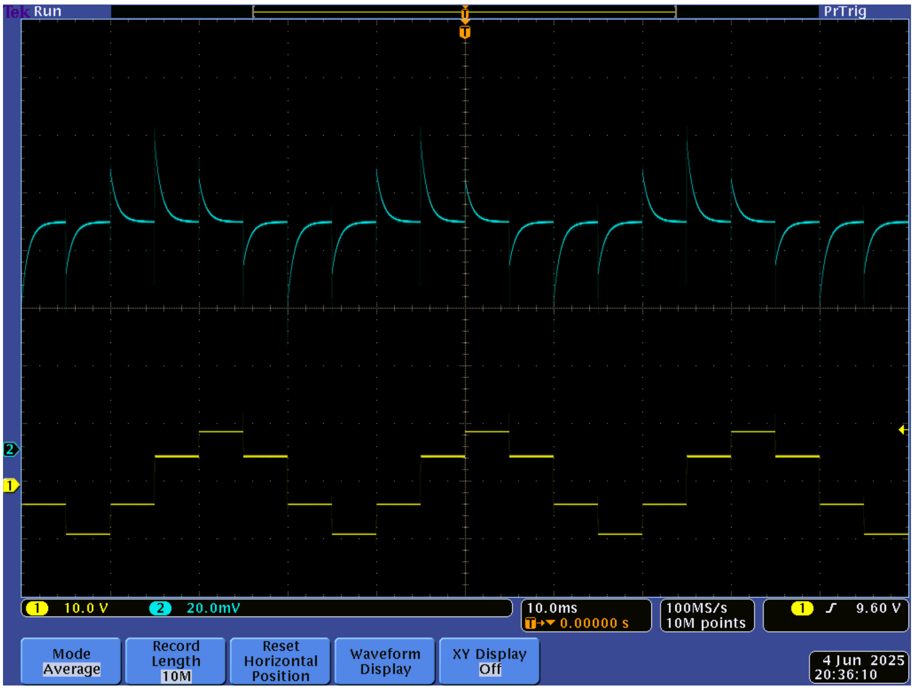


Figure 4.15: DUT current in relation to the four-level voltage waveform.

4.3 Current limit shutdown performance

The core functionality of the current limit detection operated as intended, successfully terminating signal transmission when the predefined threshold was exceeded. However, during testing its reliability was occasionally affected by noise and limitations related to the oscilloscope interface with the LabVIEW program.

5

Conclusion

5.1 Conclusion of the test results

The system successfully generated the intended multi-level voltage waveforms for both test configurations. All observed behaviors were consistent with expectations, given the known limitations of the components used. In particular, longer pulse widths resulted in significantly cleaner and more stable output signals, while shorter pulse widths introduced increased noise and distortion.

5.1.1 Complete voltage waveform generation

First of all, Figures 4.3 and 4.4, which display the individual output signals from the NI card, align with the bit sequences defined in Tables 3.1 and 3.2. This confirms that the LabVIEW program functions correctly in generating the intended signal patterns.

As shown in the figures presented in the results chapter, the 3-level and 4-level configurations exhibited similar behavior. Therefore, they will be discussed together in the following analysis. When referring to a specific signal, such as the 50 μs pulse width, the observations and conclusions apply to both configurations unless otherwise stated.

5.1.1.1 Signal quality at pulse width 50 us

The shortest pulse width tested, 50 μs, resulted in a noisy waveform and proved to be unreliable for motor testing purposes. This behavior is largely due to the physical limitations of the switching components. At shorter pulse widths, the system must transition between voltage levels at a much faster rate, which places increased stress on the gate drivers and high-voltage transistors. Although the gate driver used is capable of switching at frequencies up to 7.1 MHz and is not the limiting factor in this setup, the high-voltage transistors have a specified maximum continuous switching frequency of 10 kHz (corresponding to a period of 100 μs). Operating below this frequency is required for reliable switching. Therefore, the excessive noise observed in the 50 μs waveform can be attributed to the inability of the high-voltage switches to operate at such switching speeds.

5.1.1.2 Signal quality at pulse widths 500 us, 50 ms and 1 s

Pulse widths of 500 μs, 5 ms, and 1 s all produced stable and reliable output waveforms. At 500 μs, the signal exhibited a significant reduction in noise compared to the 50 μs case, closely resembling the expected waveform shape shown in Figure 4.1. Although some minor noise remained, the overall signal was consistent and predictable. Increasing the pulse width to 5 ms resulted in an even cleaner waveform with minimal distortion. At this duration, the switching frequency was far below the maximum ratings of the gate drivers and high-voltage switches, reducing electrical stress on the components. The 1 s pulse width showed equally excellent performance, as expected when operating at such low switching speeds. In all three cases, the system delivered accurate signal reproduction suitable for insulation testing. In Table 5.1, a brief summary of the different pulse widths usability can be seen.

Table 5.1: Summary of signal quality at different pulse widths for three- and four-level outputs.

Voltage Levels	Pulse Width	Acceptable for Use?
3-level	50 µs	No
	500 µs	Yes
	5 ms	Yes
	1 s	Yes
4-level	50 µs	No
	500 µs	Yes
	5 ms	Yes
	1 s	Yes

5.1.2 Current measurement evaluation

5.1.2.1 Current characteristics

As seen in the results, the motor winding current appear as spikes. This behavior is attributed to the fact that the current monitor only registers a reading when the voltage changes. The amplitude of these spikes depends on the magnitude of the voltage change. For example, a transition from –5 V to +5 V represents a larger change than a transition from +5 V to +10 V, and consequently results in a more pronounced spike. Additionally, the measured current remained very low throughout the tests. This is expected, as the system was operated with a low supply voltage of 10 V. Applying a higher voltage would naturally produce higher current levels through the winding.

5.1.2.2 Noise transients from the switches and its effect

During the project, persistent noise disturbances from the high-voltage switches were observed. The disturbance manifested as structured voltage transients, reaching amplitudes of up to approximately 2 V. Despite various attempts, these transients could not be eliminated.

When measuring the motor winding current, the noise was clearly seen, since the current was so small. However, when the system is operated with its intended high voltage supply (instead of the ±10V used during validation testing), the noise generated by the internal control circuitry of the switches remain largely unchanged in amplitude. Consequently, as the signal amplitude increases, the noise transients become comparatively small and will therefore not impact the system as much.

5.1.2.3 Challenges in current monitoring and current limit detection

The presence of noise posed challenges in achieving fully reliable current limit detection. To mitigate the impact of noise during testing, an alternative oscilloscope (Tektronix DPO 4034) with improved sample averaging capabilities was employed. However, due to time constraints, this oscilloscope was not interfaced with the LabVIEW program. The original setup, which utilized the Tektronix TDS 2004B oscilloscope, allowed the current limit detection feature to function as intended. Nonetheless, the limited noise suppression capability of the Tektronix TDS 2004B occasionally caused the system to prematurely terminate signal transmission due to false threshold crossings triggered by noise.

When reading the current, the values compared to the current threshold must fall within the oscilloscope's display range. If the signal exceeds this range, the measured values are clipped and no longer accurately reflect the true current. When running a new signal, the oscilloscope requires approximately 5 seconds to auto-set, which means that during those 5 seconds, no value is being read by the program. Therefore, when running a signal, it is recommended to run it once to let the oscilloscope adjust, and then run it again. No further solution to this problem was found.

5.2 Further improvements of the test system

5.2.1 Faster high voltage switches

The primary limitation in the test system lies in the high-voltage switches. While the LabVIEW program, the NI PCI-6541 card, and the gate driver are all capable of operating at significantly higher speeds, the switching speed of the push pull switches constrains the overall system performance. If the existing switches were replaced with faster alternatives capable of handling higher switching frequencies, the system could operate at much shorter pulse widths, thereby enabling a broader range of test conditions

5.2.2 Implementing a fuse or physical switch

Rather than depending exclusively on a software-implemented kill switch to halt testing when the measured current exceeds a predefined threshold, a slot for a fuse or physical switch could be incorporated as an additional protection. Employing both mechanisms introduces redundancy, thereby ensuring that the test sequence is terminated if the DUT becomes damaged.

5.2.3 Develop a custom PCB

Implementing the circuit on a custom-designed printed circuit board (PCB) would improve reliability, reduce the risk of connection issues, and minimize signal noise caused by loose wiring. A PCB layout would also allow for more compact integration of components and easier replication of the system.

5.2.4 Display of individual control signals in the GUI

A useful improvement would be the addition of a feature in the GUI to display the output state of each individual pin on the NI card. This would allow users to monitor and verify the control signals in real time during signal generation.

5.2.5 Design a noise-tolerant current limit detection method

As previously mentioned, the current limit detection is currently sensible to noise. Rather than directly comparing each individual measurement to the threshold, a more robust and noise-tolerant approach can be implemented in the LabVIEW program. For example, computing the average over a set of consecutive values and comparing this averaged result to the threshold would reduce the impact of transient fluctuations and improve the reliability of the detection mechanism.

5.2.6 Environmental and ethical impact

The testing system designed for motor insulation requires energy to operate and this creates some direct environmental costs. The benefits of this testing, however, far outweigh its own energy use. The system provides a reliable and repeatable way to apply stresses to insulation materials and allows researchers to better understand how insulation behaves and degrades over time. This knowledge can lead to the development of improved insulation materials with longer lifetimes and higher efficiency. As a result, the need for frequent replacements is reduced and the overall environmental footprint of motor systems becomes lower. In the long run the insights gained from this testing can bring significant reductions in material waste, energy consumption and manufacturing demand. The environmental savings made possible by such research are much greater than the modest costs of operating the test system itself.

Moreover, developing and using a test system for motor insulation carries important ethical considerations. The system provides researchers with reliable data that can lead to safer and more durable motor designs. This supports ethical responsibility toward end users by helping ensure that motors operate reliably and with reduced risk of failure. At the same time, extending the lifetime of insulation materials reduces waste and the demand for raw resources, which aligns with the ethical duty to minimize environmental harm.

5.3 Final remarks

All project goals outlined at the beginning were largely achieved. A LabVIEW-based software solution was developed, providing features such as signal generation, load/save functionality, and real-time current monitoring. The program was fully integrated with the selected NI PCI-6541 card, which proved to be an appropriate choice for generating precise digital output signals. The current limit detection feature functioned as intended in principle. However, due to high levels of noise, it was occasionally falsely triggered. This issue is expected to diminish when operating the system at higher voltages, where the signal-to-noise ratio will be significantly improved.

A power amplification stage was designed and implemented using gate drivers, allowing the NI card to reliably control the high-voltage switching grid. One of the central objectives of the project was generating controlled, multi-level output waveforms and it was successfully met. The system produced both three-level and four-level signals based on predefined bit combinations and voltage mappings. Validating the chosen approach of using bit-mapping to control the switches. These signals maintained their shape and voltage accuracy across a range of pulse widths, demonstrating the stability and reliability of the hardware and control logic.

Overall, the system performs as intended and is well-suited for insulation testing applications where configurable, high-voltage pulse generation is required.

Bibliography

[1] Hammarström, T. J. Å. (2018) Partial discharge characteristics within motor insulation exposed to multi-level PWM waveforms. In *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 25, no. 2, pp. 559–567. doi:10.1109/TDEI.2017.006994.

[2] National Instruments, "What is LabVIEW? Graphical Programming for Test & Measurement," *www.ni.com*, 2024. `https://www.ni.com/en/shop/labview.html`

[3] National Instruments, "PCI-6541 Specifications" *https://www.ni.com*, 2025. `https://www.ni.com/docs/en-US/bundle/pci-6541-specs/page/specs.html`

[4] Producer/Consumer Architecture in LabVIEW," *www.ni.com*, 2025. `https://www.ni.com/en/support/documentation/supplemental/21/producer-consumer-architecture-in-labview0.html`

[5] L. Balogh, "Fundamentals of MOSFET and IGBT Gate Driver Circuits Application Report Fundamentals of MOSFET and IGBT Gate Driver Circuits," 2017. `https://www.ti.com/lit/ml/slua618a/slua618a.pdf`

[6] Behlke, "Fast High Voltage Transistor Switches". `https://www.behlke.com/pdf/151-03-gsm.pdf`

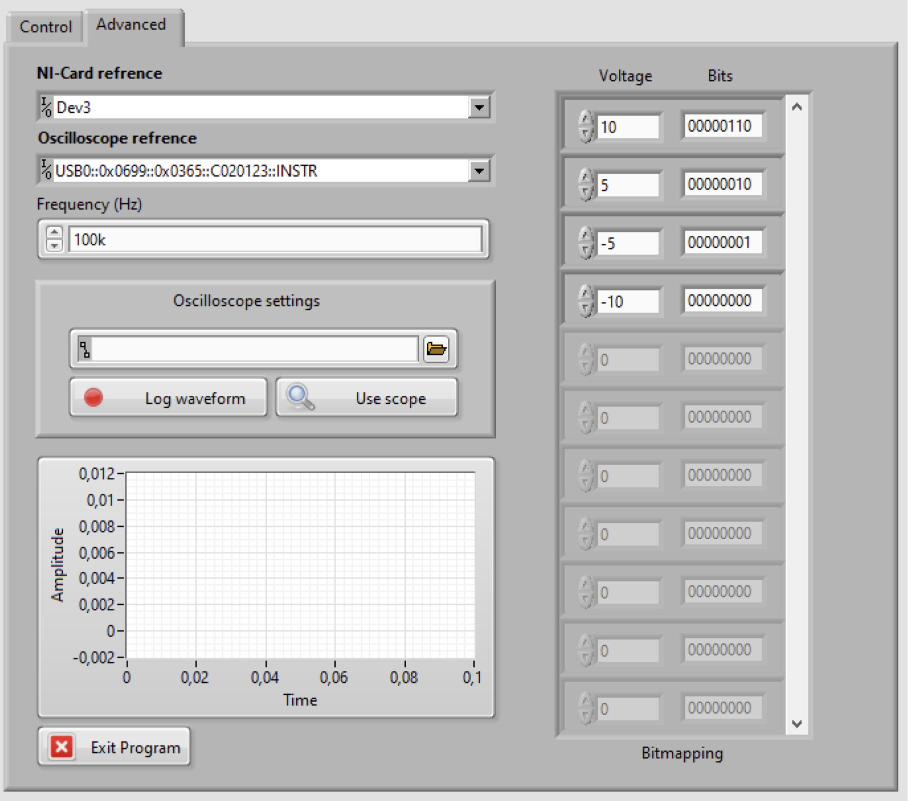
[7] Microchip Technology, "TC4426M/TC4427M/TC4428M", RS Components. `https://docs.rs-online.com/f840/0900766b813863f4.pdf`

[8] Pearson Electronics, "Pearson current monitor model 8585C". `https://pearsonelectronics.com/pdf/8585C.pdf`

[9] Md Abdus Salam and Quazi Mehbubar Rahman, *Fundamentals of Electrical Circuit Analysis*. Singapore Springer Singapore, 2018, pp. 203-204.

A

Appendix 1: Software configuration guide



NI-Card refrence
Dev3
Oscilloscope refrence
USB0::0x0699::0x0365::C020123::INSTR
Frequency (Hz)
100k

Voltage	Bits
10	00000110
5	00000010
-5	00000001
-10	00000000
0	00000000
0	00000000
0	00000000
0	00000000
0	00000000
0	00000000
0	00000000

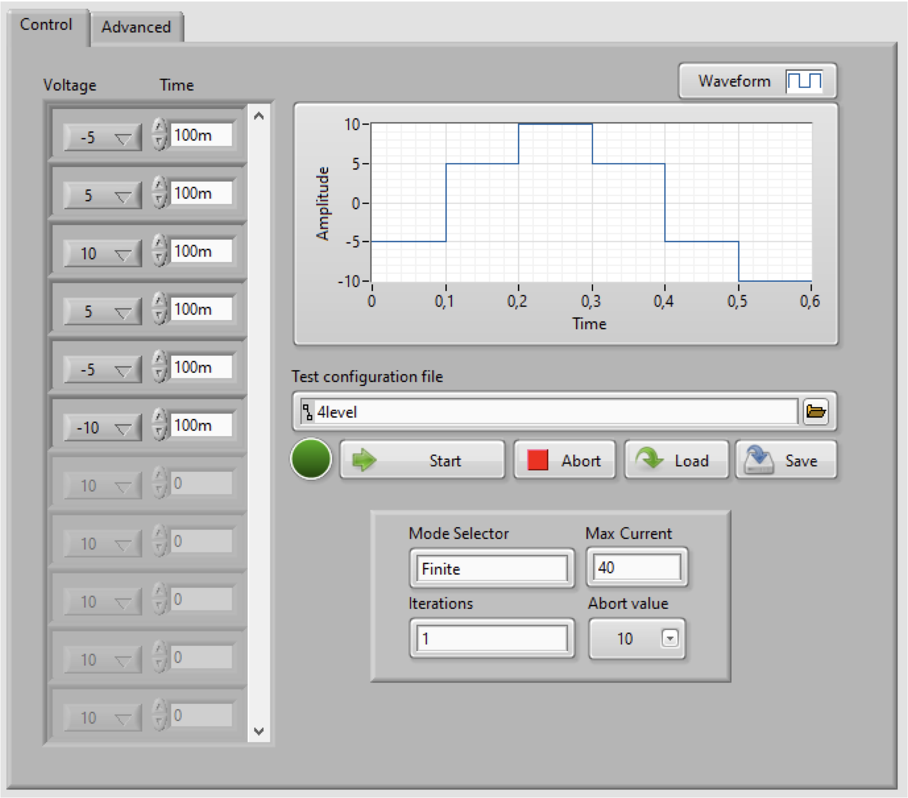
Figure A.1: Advanced tab example.

1. Configure the Advanced Tab

Before creating and transmitting signals, set up the system parameters in the **Advanced Tab**:

- **Select Hardware:**
  - Choose the correct NI-card from the available options.
  - Select the connected oscilloscope from the list.
- **Voltage-to-Bit Pattern Mapping:**
  - Define how digital bits correspond to voltage output levels:

        - Enter the appropriate binary number (bit pattern) next to each voltage level.
        - For example, entering `00000110` next to +10 V maps the bit pattern `00000110` to a 10 V output from the switching grid.
    - These mappings determine the available voltage levels you can select when creating signals in the Control Tab.
- **Frequency Selection:**
    - Select an appropriate frequency for signal generation based on your desired pulse duration.



Voltage	Time
-5	100m
5	100m
10	100m
5	100m
-5	100m
-10	100m
10	0
10	0
10	0
10	0
10	0

Test configuration file: 4level

Mode Selector: Finite

Max Current: 40

Iterations: 1

Abort value: 10

Figure A.2: Control tab example.

2. Configure the Control Tab

After setting up the Advanced tab, proceed to define the signal:

- **Voltage-Time Array:**
    - Define the output signal by selecting voltage levels and specifying their durations.
    - The waveform graph provides a visual preview of your defined signal.
- **Signal Mode Selection:**
    - Use the **Mode Selector** to choose how the signal behaves:
        - **Finite Mode:** Enter the number of iterations the signal should run.

        - **Repeat Mode:** The signal repeats indefinitely. (Iteration count is irrelevant in this mode.)
- **Set Current Threshold:**
    - Under **Max Current**, specify the threshold current:
        - The transmission aborts automatically if the measured current exceeds this threshold.
- **Define Abort Voltage Level:**
    - Set the desired **Abort Value**, which is the voltage level the system outputs if an abort occurs.
- **Save and Load Signals:**
    - To **save** a configured signal:
        - Enter a filename and click **Save**.
    - To **load** a previously saved configuration:
        - Enter the filename and click **Load**.
- **Start Transmission:**
    - Press **Start** to initiate signal transmission.
    - A green indicator lamp illuminates during transmission.

3. Reading and Logging Using the Oscilloscope (Advanced Tab)

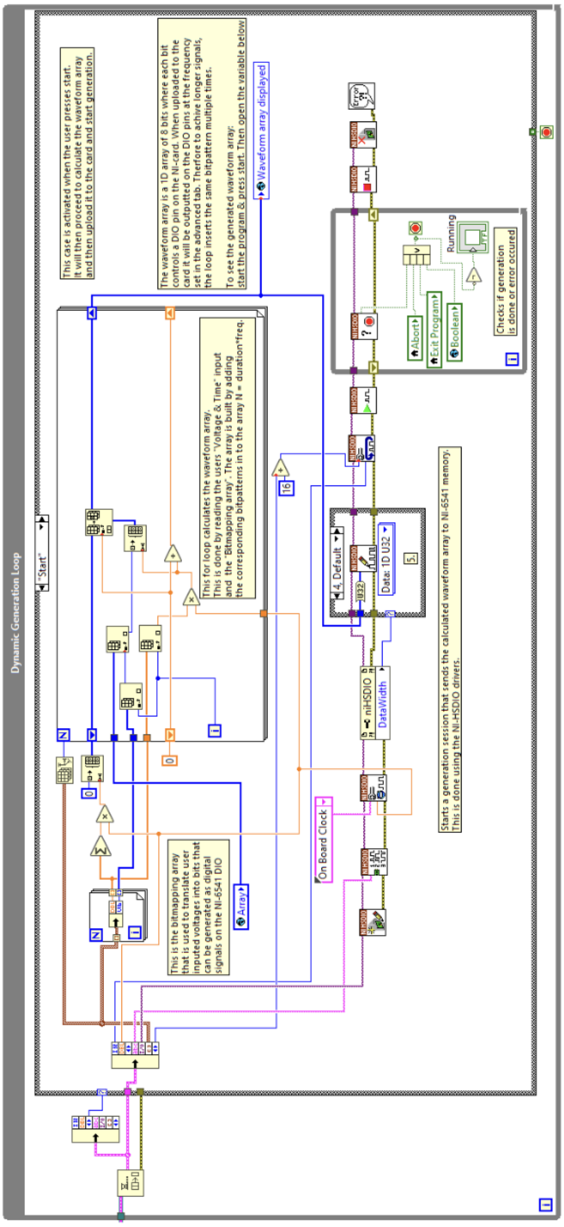
Once the signal has been transmitted:

- **Initiating Oscilloscope Readings:**
    - Enable oscilloscope readings by selecting **Use Scope**.
    - *Note:* When transmitting a new signal, the oscilloscope may need a few seconds to adjust before displaying accurate waveform data. If delays occur, resend the signal. Subsequent readings will appear promptly after the initial adjustment. Additionally, make sure that the probe is set to channel 1 on the oscilloscope.
- **Logging Waveform Data:**
    - To record waveform measurements:
        - Press **Log Waveform**.
        - Specify a filename to store logged data.
    - Even if waveform logging is disabled, the system continuously monitors the current against the defined threshold.

Following this structured approach ensures reliable operation of the test system and accurate signal generation.

B

Appendix 2: LabVIEW code



This case is activated when the user presses start.
It will then proceed to calculate the waveform array
and then upload it to the card and start generation.

The waveform array is a 1D array of 8 bits where each bit
controls a DIO pin on the NI-card. When uploaded to the
card it will be outputted on the DIO pins at the frequency
set in the advanced tab. Therfore to achive longer signals,
the loop inserts the same bitpattern multiple times.

To see the generated waveform array:
start the program & press start. Then open the variable below

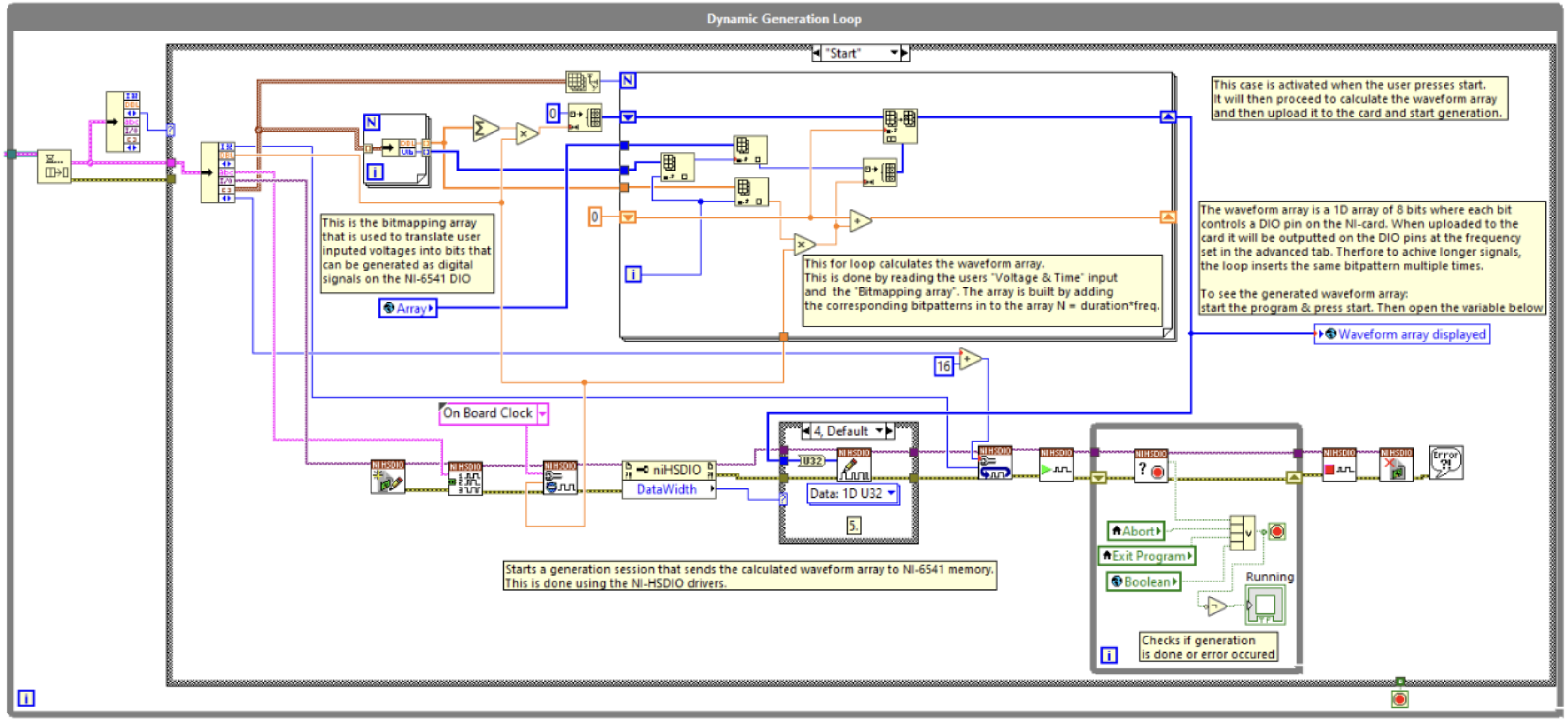
This for loop calculates the waveform array.
This is done by reading the users "Voltage & Time" input
and the "Bitmapping array". The array is built by adding
the corresponding bitpatterns in to the array N = duration*freq.

This is the bitmapping array
that is used to translate user
inputed voltages into bits that
can be generated as digital
signals on the NI-6541 DIO

Starts a generation session that sends the calculated waveform array to NI-6541 memory.
This is done using the NI-HSDIO drivers.

Checks if generation
is done or error occured

Figure B.1: Oscilloscope waveform acquisition loop



This case is activated when the user presses start.
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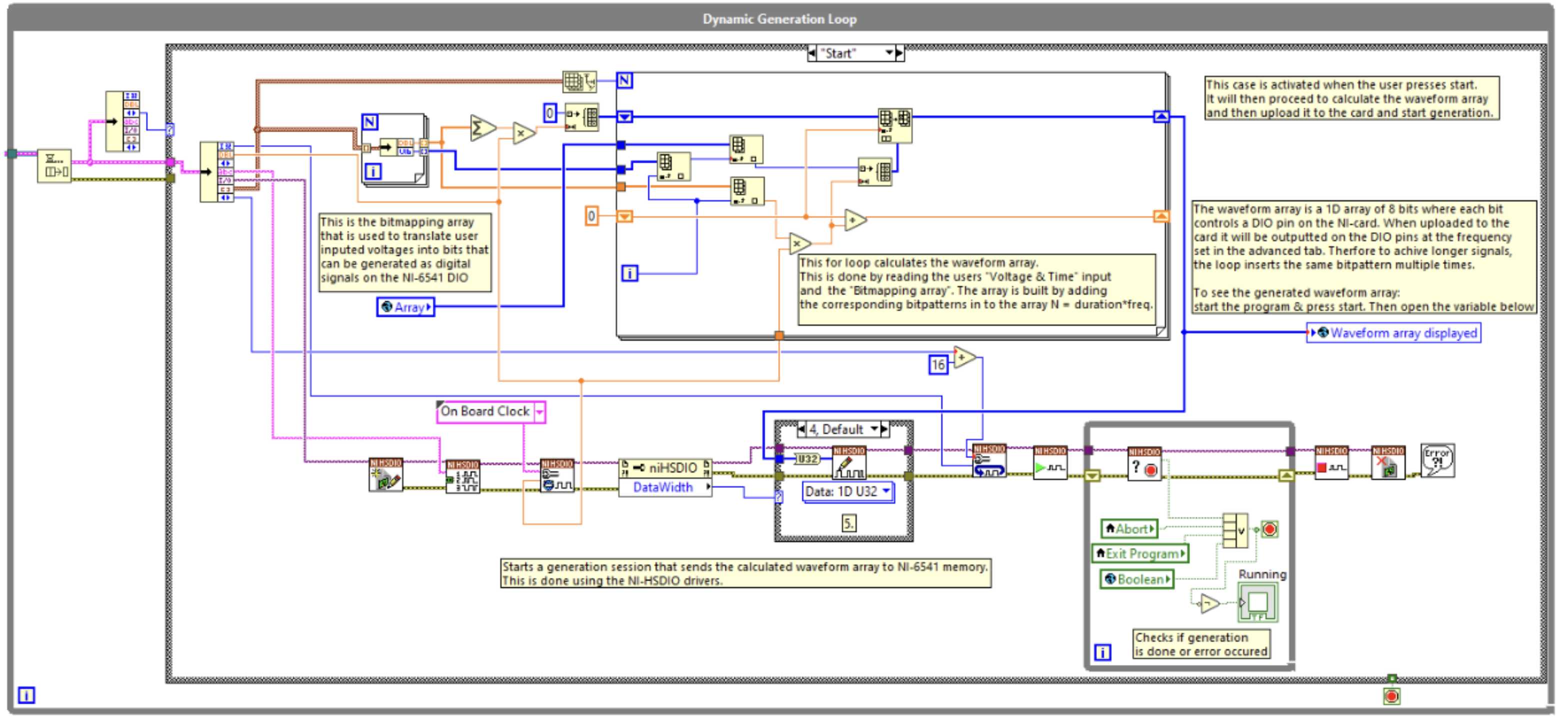
and the "Bitmapping array". The array is built by adding
the corresponding bitpatterns in to the array N = duration*freq.

Starts a generation session that sends the calculated waveform array to NI-6541 memory.
This is done using the NI-HSDIO drivers.

Checks if generation
is done or error occured

Figure B.2: Oscilloscope waveform acquisition loop



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The waveform array is a 1D array of 8 bits where each bit
controls a DIO pin on the NI-card. When uploaded to the
card it will be outputted on the DIO pins at the frequency
set in the advanced tab. Therfore to achive longer signals,
the loop inserts the same bitpattern multiple times.

To see the generated waveform array:
start the program & press start. Then open the variable below

Starts a generation session that sends the calculated waveform array to NI-6541 memory.
This is done using the NI-HSDIO drivers.

Checks if generation
is done or error occured

Figure B.3: Oscilloscope waveform acquisition loop

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