ELECENG 2EI4

Design Project 2 - Voltage Controlled Switch

Instructor: Dr.Haddara
Suchir Ladda - laddas - 400517569
Date: 3/2/2025

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Ideal Switches

An ideal switch is a concept of a device that provides electrical conduction with no loss of energy in the ON position and acts as a perfect insulator in the OFF position. While in the ON position, the switch can be imagined to have infinite conduction in such a way that it can dissipate energy without any loss, allowing both input and output voltages to be equal. This results in total energy and power loss, meaning the switch consumes no power. However, in real life applications, actual switches do have some level of resistance but it is quite negligible resulting in very small voltage drops and considerably less loss of energy.

While in the OFF position, the device serves as a perfect insulator and hence can be imagined to have infinite resistance, which eradicates the flow of any form of current through it, thus providing total separation between its terminals. In comparison to an ideal switch, which does not allow any form of leakage current, practical switches do show indications of having low leakage due to errors in the construction material. Although engineers attempt to correct these faults, eradicating them altogether is impossible.

Another key property of an ideal switch is its ability to handle any voltage across its terminals without failure. Whether dealing with millivolts or thousands of volts, the switch remains operational without breakdown. In reality, physical switches have voltage limits, beyond which insulation breakdown, arcing, or material damage can occur, making careful voltage rating considerations necessary in circuit design.

Additionally, an ideal switch allows current to flow equally well in both directions. This bidirectional nature makes it particularly useful in AC circuits or applications where current direction may change frequently. In contrast, many real-world switches, especially semiconductor-based ones, may have a preferred conduction direction or exhibit varying resistances depending on the flow of current.

Non-Idealities

There are many differences between real and ideal switches. One of the key non-idealities is leakage current (Ioff) when the switch is OFF. Ideally, an open switch should have infinite resistance, preventing any current flow. However, due to material imperfections, stray capacitance, or semiconductor effects, a small leakage current still flows. While typically in the nanoampere range, this can become problematic in low-power applications, causing unintended power consumption or signal integrity issues. Engineers aim to minimize leakage to improve switch isolation.

When the switch is ON, it's ON resistance (Ron) is another major non-ideality. Unlike an ideal switch, which would have zero resistance, real switches always exhibit some small resistance, leading to a voltage drop across the switch. This drop is given by $V_{switch} = I \times R_{on}$, meaning the output voltage is slightly lower than the input. Additionally, power dissipation occurs as $P = I^2 \times R_{on}$, which generates heat and reduces efficiency. Lowering

Ron is crucial in power electronics and signal applications to minimize losses and maximize performance.

Real switches are also constrained by a limited voltage range, meaning they can only operate safely between a minimum (Vmin) and a maximum (Vmax) voltage. If the applied voltage exceeds Vmax, the switch may experience insulation breakdown, arcing, or complete failure. Conversely, if the voltage is below Vmin, the switch may not activate properly, particularly in semiconductor-based switches that require a minimum gate voltage to turn on. Unlike an ideal switch, which would function across all voltage levels, real switches must operate within defined voltage limits.

Lastly, the bidirectionality of a real switch is often imperfect. Ideally, the ON resistance (Ron) should remain constant regardless of whether current flows in one direction (V1 > V2) or the other (V1 < V2). However, in many real switches, particularly semiconductor devices like MOSFETs and BJTs, resistance can vary based on voltage polarity and direction. Some switches are optimized for a single direction, making them less suitable for AC or bidirectional applications. A truly bidirectional switch would maintain a consistent resistance regardless of current direction.

Test Plan

To accurately quantify the non-idealities of a real switch, we will conduct experiments for each key deviation from ideal behavior. The test setup will involve a controlled power supply, measurement instruments such as oscilloscopes and multimeters, and various input signals to evaluate the switch's performance under different conditions.

Switch 1 Test Plan

The first test will measure the ON-state resistance (Ron) and voltage drop, which determine how much resistance the switch introduces when conducting. To do this, we will set Vcontrol to 0V to turn the switch ON, apply Vsupply at 5V, and set V1 to 5V while connecting V2 to a load. By measuring the voltages at V1 and V2 while the switch is conducting, along with the current flowing through the switch, we can calculate Ron using the formula Ron = (V1 - V2) / I. Additionally, power dissipation due to the switch resistance can be determined using $P = I^2 \times Ron$. If Ron is too high, it can lead to unwanted voltage drops and excessive power dissipation, making the switch inefficient in high-current applications.

Another important test will evaluate the voltage operating range (Vmin and Vmax), which determines the range of voltages the switch can handle before it stops functioning as expected. In this test, Vsupply will be gradually increased from 0V to 10V while keeping Vcontrol = 0V to observe the switch's behavior at both low and high voltages. We will monitor the voltage at V2 and identify at what point the switch no longer operates correctly. This will allow us to determine Vmin, the minimum voltage required for the switch to function, and Vmax, the maximum voltage beyond which failure occurs due to insulation breakdown or excessive leakage current.

Finally, we will test bidirectional conductance by checking whether the switch behaves the same regardless of current direction. To do this, we will set Vcontrol to 0V to turn the switch ON, apply Vsupply at 5V, and measure the ON resistance when V1 > V2. We will then reverse the voltage polarity so that V2 > V1 and measure the resistance again. If Ron varies significantly between these two cases, it indicates that the switch is not truly bidirectional and may introduce inconsistencies in AC or bidirectional circuits.

Switch 2 Test Plan

When the switch is turned ON, it introduces a small but measurable resistance that affects performance. To measure this, Vcontrol will be set to 0V to close the switch. A voltage of 5V will be applied to V1, and we will alternate between connecting VA and VB to observe the switching behavior. By measuring the voltage difference between V1 and VA (or VB) while recording the current flow, the ON resistance can be calculated as Ron = (V1 - VA) / I. If Ron is too high, it will cause excessive voltage drop and power dissipation, which is undesirable in high-current applications.

The switch should operate correctly over a defined voltage range. To test this, Vsupply will be ramped from 0V to 10V, while Vcontrol remains at 0V. The voltages at V1, VA, and VB will be monitored to determine if the switch continues to function correctly throughout the range. If the switch starts behaving unpredictably outside a certain voltage range, we can define Vmin and Vmax, indicating the limits within which the switch performs as expected.

This test determines whether the switch behaves identically regardless of the direction of current flow. With Vcontrol set to 0V, a voltage will be applied first at V1 and then at VA while keeping VB at ground. The resistance will be measured in both configurations to ensure that the switch provides consistent conduction in both directions. If significant variations are observed, it suggests that the switch is not fully bidirectional and may introduce performance inconsistencies in AC applications.

By conducting these tests, we can quantify the non-idealities of Switch Type 2 and determine whether it meets the necessary performance criteria.

Switch type 1

Circuit Schematic

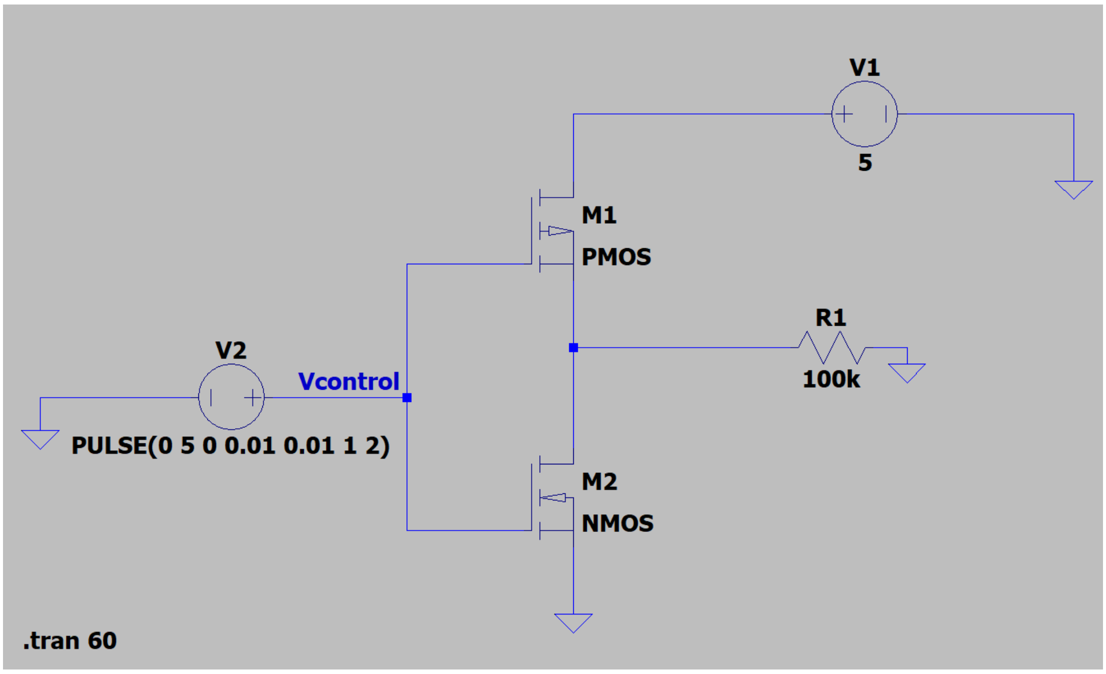

Figure 1: Circuit Schematic of Switch 1

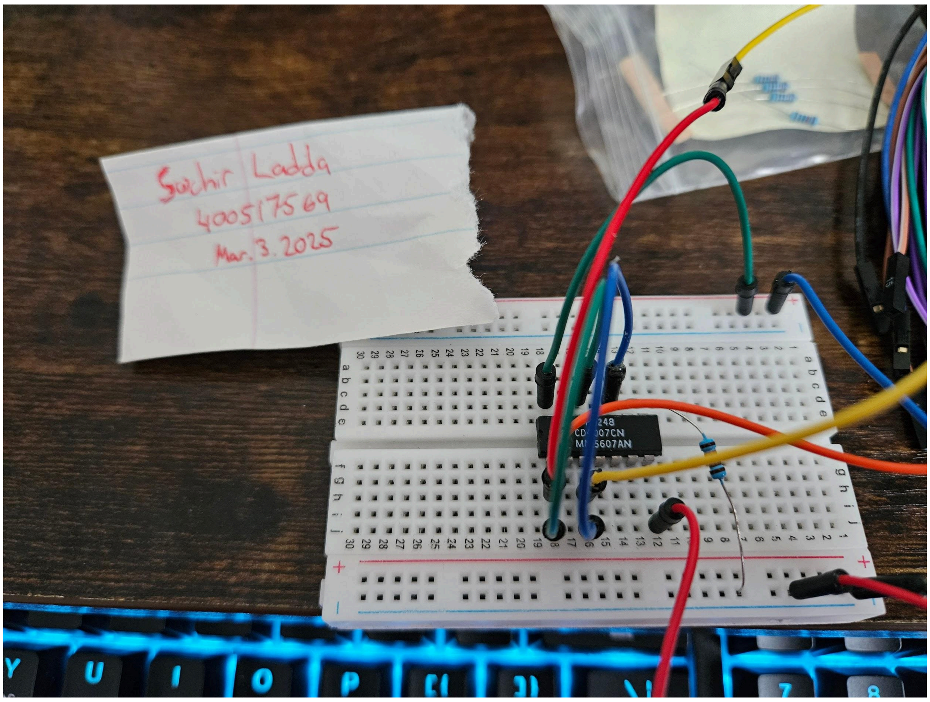

Figure 2: Physical Circuit Implementation of Switch 1

Measurements

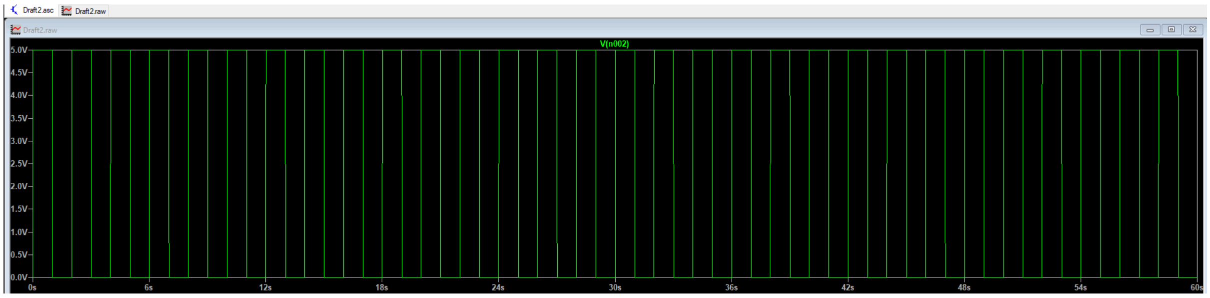

Figure 3: Square wave pulse from 0-5V being sent in

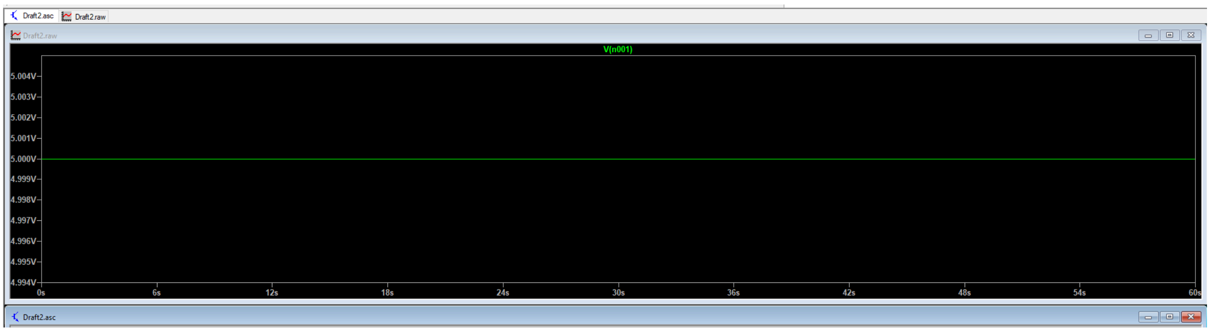

Figure 4: 5V DC input

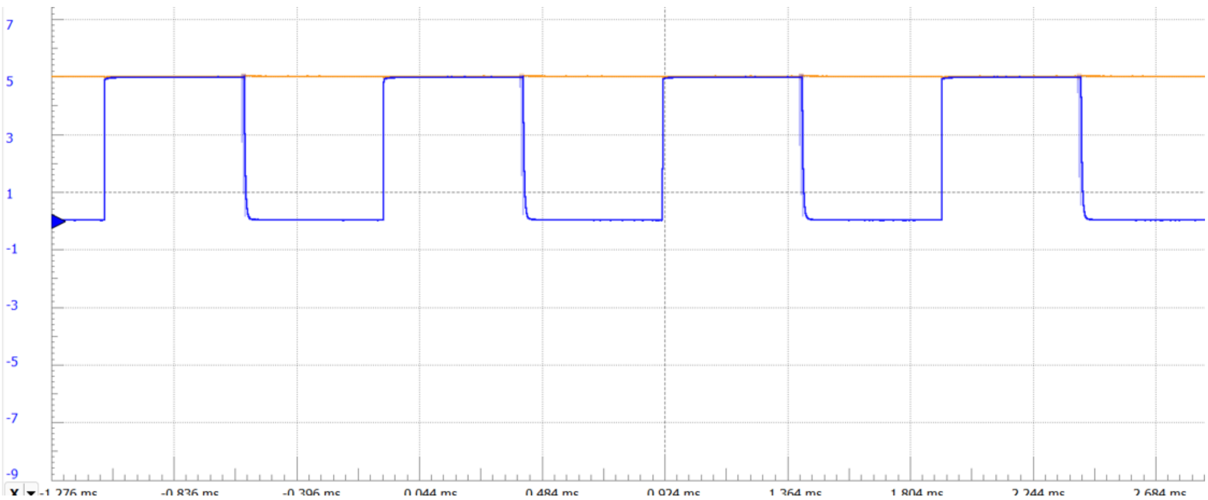

Figure 5: AD3 output

Theoretical Explanation

The switch design is bidirectional, incorporating both n-type and p-type MOSFETs. Bidirectionality is a key characteristic of an ideal switch, making it an essential factor in this design. The final output screenshot illustrates the switch's behavior, where the control voltage (Vcontrol) alternates between 0V and 5V. When Vcontrol is 5V, the switch is in the OFF state and should exhibit the property that I1=I2=0. Conversely, when Vcontrol is 0V, the switch enters the ON state, ensuring that V1=V2.

To verify these theoretical predictions, we analyzed the final output. When Vcontrol is 0V, V2 measures 5V, confirming that V1=V2 as expected. Additionally, a 100kΩ resistor was added to the output of the switch. However, when Vcontrol is set to 5V, V2 drops to 0V, regardless of V1 being 5V, demonstrating the expected OFF-state behavior.

These observations can also be confirmed mathematically. In the ON state, the resistance is calculated as:

$$R_{ON} = \frac{5V - 5V}{50\mu A} = 0\Omega$$

Similarly, in the OFF state, the resistance is given by:

$$R_{OFF} = \frac{0V - 5V}{15nA} = \infty\Omega$$

Design Tradeoffs

The major tradeoff in this design was balancing the need to demonstrate all required aspects while working within the limitations of available components. The simplest design considered used only a single MOSFET, but it was not bidirectionally conductive and was therefore not selected as the final design. On the other hand, more complex circuits involved three or four MOSFETs and additional components like inverters, which were not permitted in the circuit's construction. To strike a balance between complexity and simplicity while accurately representing the key characteristics of an ideal switch, the chosen design was selected.

Switch type 2

Circuit Schematic

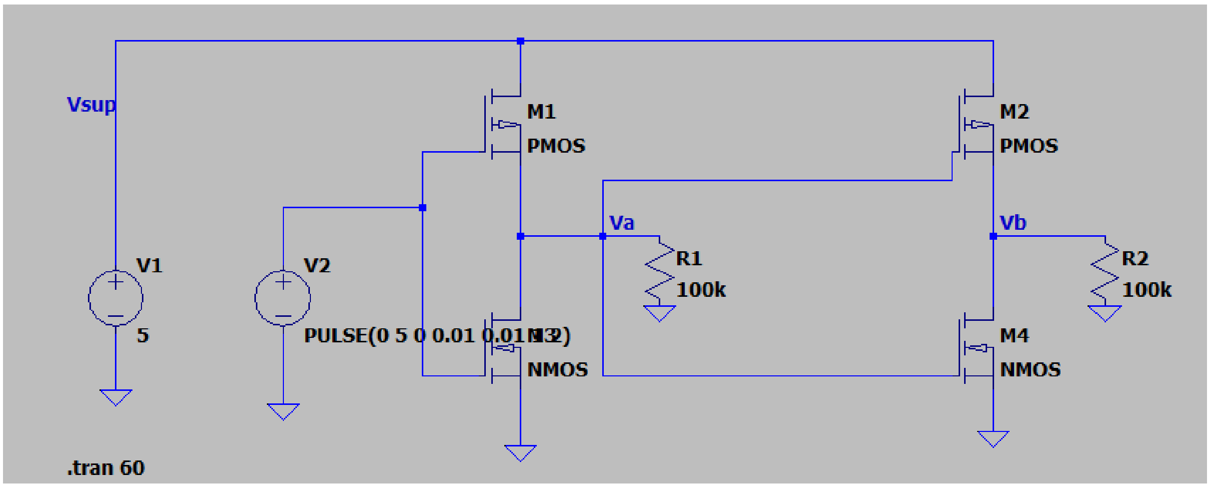

Figure 6: Circuit Schematic of Switch 2

Measurements

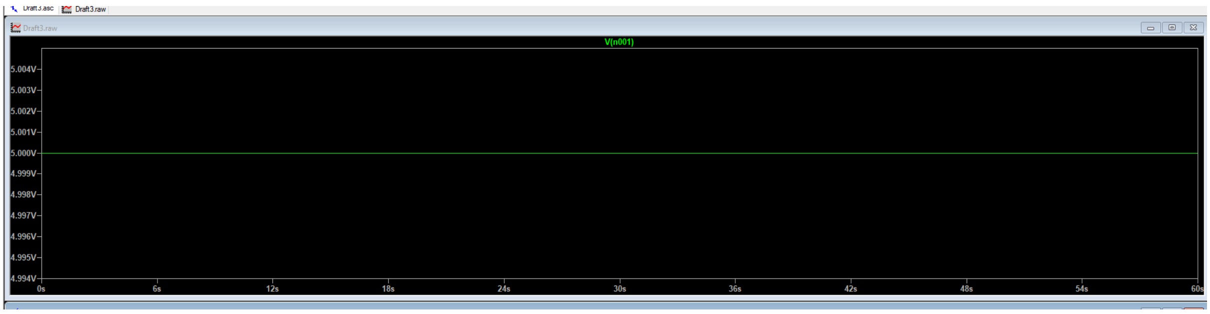

Figure 7: 5V input

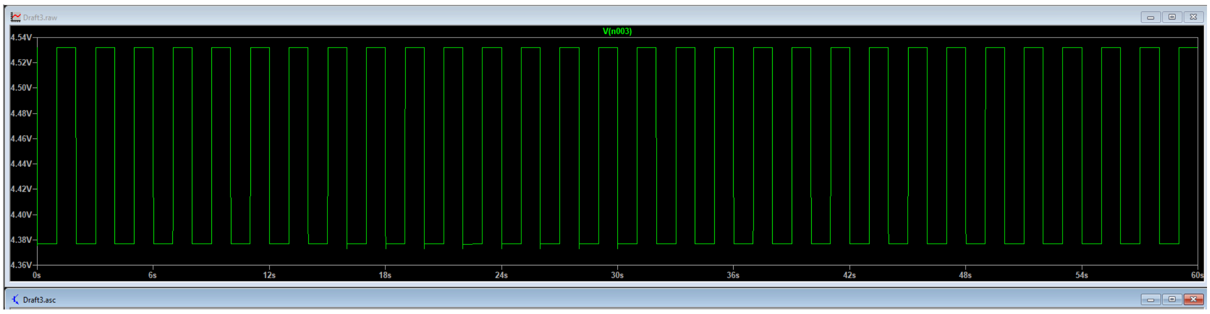

Figure 8: Va output

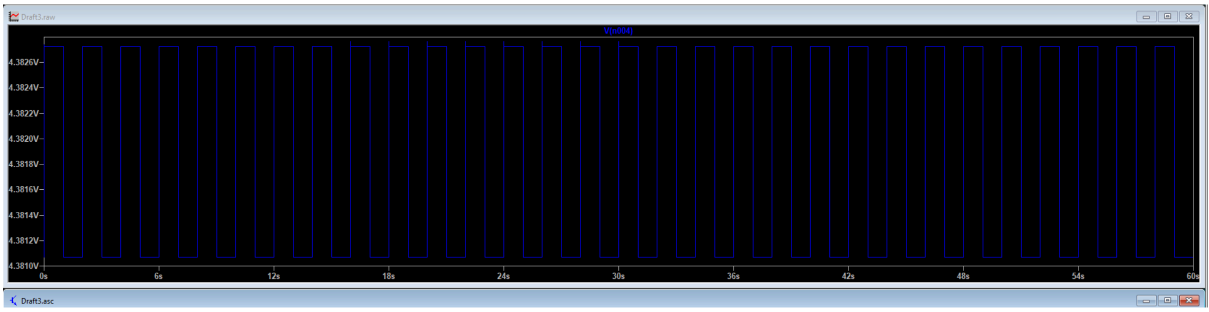

Figure 9: Vb output

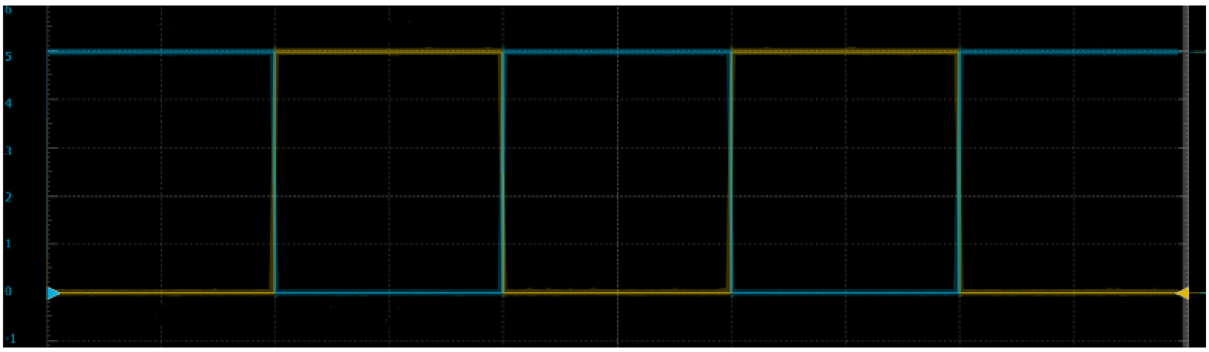

Figure 10: AD3 output

Theoretical Explanation

The above results depict the simulation output for the Switch Type 2 design. To evaluate the switch's functionality, the voltages Va, Vb, and the circuit's current were analyzed to determine the switch's output behavior under different control voltage conditions.

Specifically, when Vcontrol is set to 0V, the circuit's output should be taken from Va, and when Vcontrol is 5V, the output should correspond to Vb.

By examining the provided graphs, we can confirm this expected behavior. When Vcontrol is at 5V, Vb measures 5V, while Va is 0V. Conversely, when Vcontrol is 0V, Va registers 5V, and Vb drops to 0V. These results indicate that the circuit is operating correctly.

Design Tradeoffs

Several trade-offs were considered in the construction of the second switch design, with the primary decision revolving around balancing complexity and practicality. The most significant compromise was opting for a slightly less comprehensive design in favor of simplicity and ease of implementation.

An alternative approach involved a more intricate configuration using both MOSFET ICs provided in the 2EI4. This design closely resembled an ideal switch, offering better performance in terms of bidirectional conduction and minimal resistance. However, due to the increased complexity, both in terms of circuit design and physical implementation, a more streamlined solution was chosen.

References

[1] A. S. Sedra, K. C. Smith, T. C. Carusone, and V. Gaudet, Microelectronic circuits, 8th ed. New York, NY: Oxford University Press, 2019.