Design Project #2: Voltage Controlled Switches

Electronic Devices and Circuits - 2EI4

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Ideal Switches

Ideal switches are a theoretical concept used in circuit analysis. They have perfect switching behaviour and have 4 key characteristics. First, when the switch is on, there is no voltage drop across the switch in an ideal situation (0 resistance between the input and output) [1]. Secondly, when off, there should be no current flow through the switch [1]. Third, the voltages on each end of the switch can have any value, and the switch will still operate without fail. In other words, V1 and V2 can have an unlimited range [1]. And lastly, when the switch is ON, current can flow in either direction (bidirectional) without bias [2].

Non-Idealities

Qualitative

In reality, "ideal" switches don't exist. Each of the 4 key characteristics of an ideal switch comes with its non-ideality that is reflected within real switches. In an ideal scenario, we have 0 resistance between the input and output while the switch is on. In reality, this "on resistance" is nonzero due to the internal resistances of the components present [1]. In the ideal case, there is no current flow through the switch in the off state [1]. In reality, there is still some current flowing, referred to as "leakage current". As the name suggests, this is an unintended current flow that "leaks" through due to imperfections in the insulating ability of the circuit components, or defects to the physical material of the components [1]. An ideal switch would also be able to operate for an infinite range of input voltage [1]. In reality, switches—and more specifically, the components they are built from have voltage ratings and limits [1]. For example, the MOSFETs used in this project have a maximum voltage rating. Exceeding this limit can cause the switch to exhibit unintended behaviour or simply destroy the components. Lastly, a switch would also ideally be perfectly bidirectional, meaning current can flow equally in either direction when the switch is on [2]. In reality, switches often exhibit directional behaviour due to internal design factors. Real switches based on MOSFETs, contain built-in diodes and other characteristics that cause them to favour current flow in one direction over the other. This will result in the switch behaving as intended in one direction, but not in the opposite.

Quantitative

In reality, the non-idealities of a switch can be expressed quantitatively through measurable electrical properties.

1. On-Resistance: **Ron ≠ 0**
   In an ideal case, a switch should have zero resistance when turned on. However, real switches exhibit a small but finite on-resistance (Ron), which depends on material properties and the internal structure of present components. This resistance leads to a voltage drop across the switch while conducting current, which can be expressed as: $V_{switc} = I \cdot R_{on}$
2. Leakage Current: **Ioff ≠ 0**
   Ideally, when the switch is off, no current should flow. In reality, a small leakage current flows due to imperfect insulation within the switch. This leakage current can be influenced by temperature, material defects, and the quality of the insulating barrier. It can be approximated by: $\boldsymbol{I_{off} = V_{switch}/R_{leak}}$, where R_{leak} represents the resistance of the switch in the off state.
3. Voltage Limit: $\boldsymbol{(V_{min} < V_1, V_2 < V_{max})}$
   While an ideal switch would function over an unlimited voltage range, real-world switches have defined voltage ratings. The voltage across the switch terminals must remain within the allowable range: $\boldsymbol{(V_{min} < V_1, V_2 < V_{max})}$. If these limits are exceeded, unintended behaviour may occur, potentially causing permanent switch failure and damage.
4. Bidirectionality: $\boldsymbol{R_{on}(V_1, V_2)}$
   In an ideal case, the switch should conduct equally well in both directions when turned on. However, real switches can exhibit direction-dependent behaviour, meaning: $\boldsymbol{R_{on}(V_1, V_2) \neq R_{on}(V_2, V_1)}$.

Test Plan

Each of the non-idealities stated must be measured to determine the performance of the switch.

Switch 1	
Attribute	**Value**
Vcontrol	0V or 5V
Vsupply	5V
Vin	3V 0V – 10V ramp to test operating range
Measurements/Calculations	
V_{out1}	
I_{off}	
$V_{in} - V_{out}$ (to quantify Ron)	

Switch 2	
Attribute	**Value**
Vcontrol	0V or 5V
Vsupply	5V
Vin	3V 0V – 10V ramp to test operating range
Measurements/Calculations	
V_{out1}	
V_{out2}	
I_{off}	
$V_{in} - V_{out}$ (to quantify Ron)	

Switch 1

Schematic

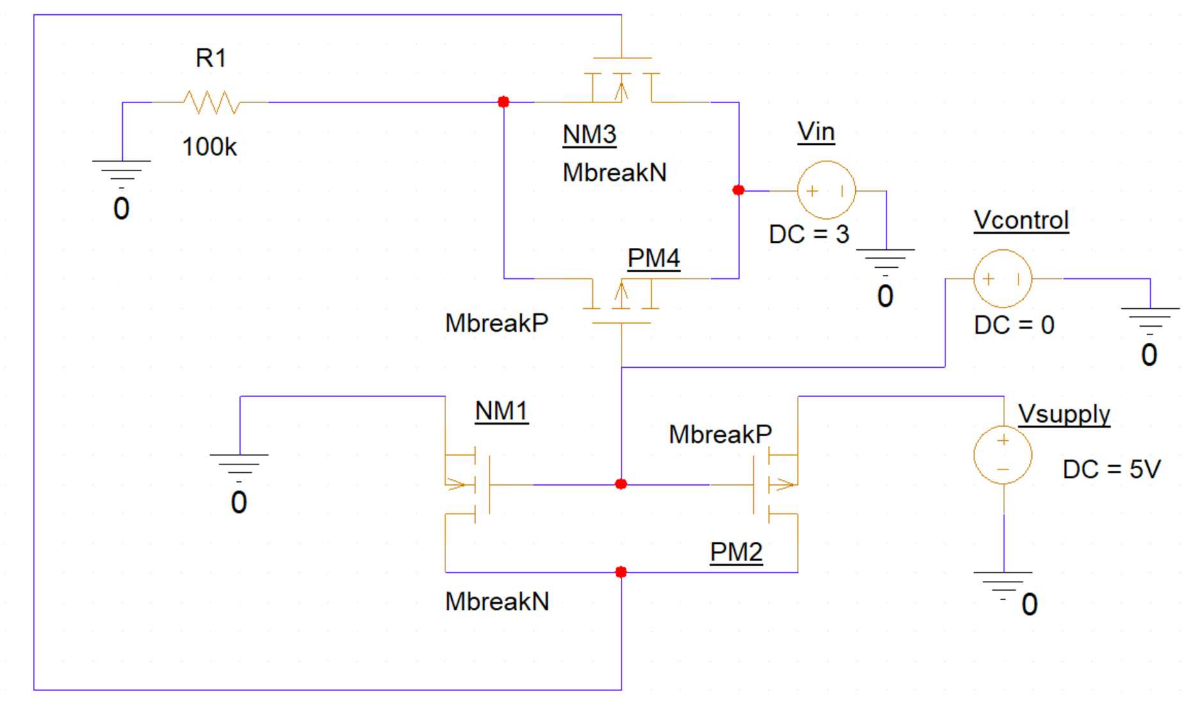

Figure 1: Switch 1 Schematic

Physical Circuit

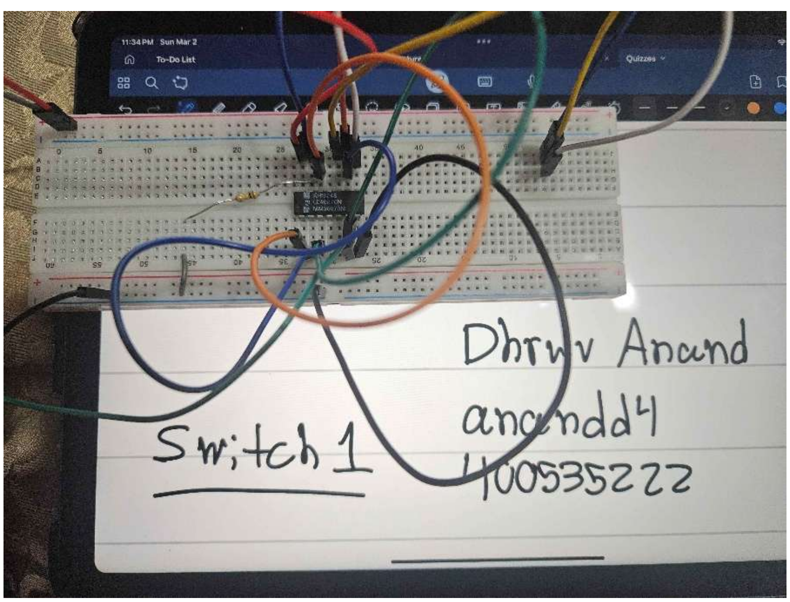

Figure 2: Physical Implementation of Switch Design 1

Measurements

Switch 1 - Measurements/Calculations	
Theoretical Simulation	**Physical Circuit**
$V_{out} = 2.73V$	$V_{out} = 2.71V$
$I_{off} = 6.02\text{pA}$	$I_{off} \approx 0$
$V_{in} - V_{out} = 3V - 2.73V = 0.27V$	$V_{in} - V_{out} = 3V - 2.71V = 0.29V$

Testing and Theoretical Explanation vs Quantitative Results

When testing the circuit both physically and in Pspice, each non-ideality can be observed.

The first non-ideality is that there will be some resistance between the input and output of the switch. This can be confirmed by measuring the voltage drop between the input and output. The simulation yielded a 2.73V output at the 100k Ω load resistor. Since the input was 3V, we can see a 0.27V drop across the switch, confirming the non-ideality Ron ≠ 0.

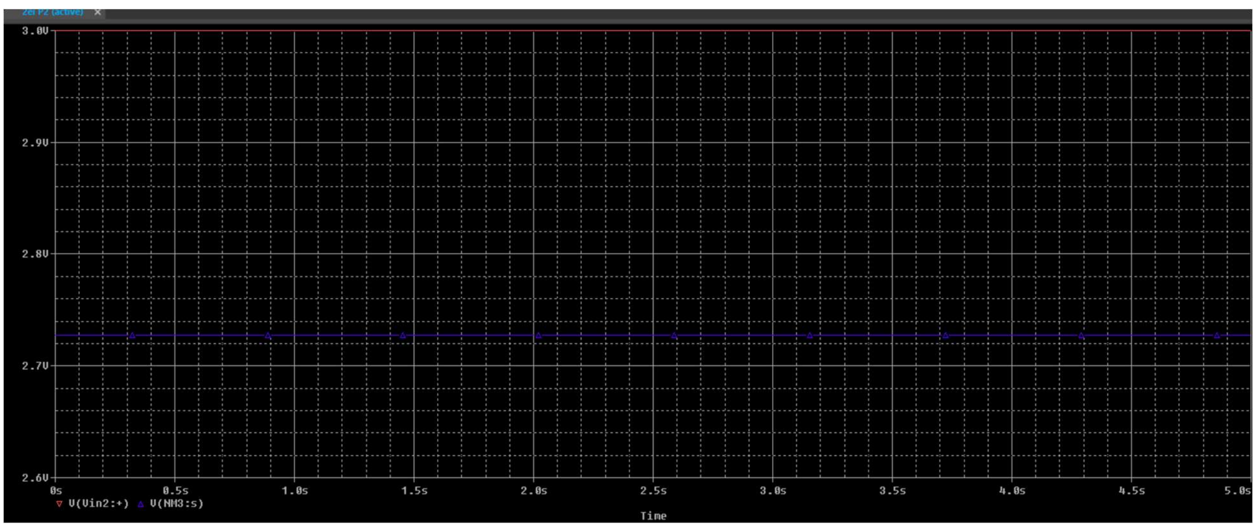

Figure 3: Output Voltage (purple) and Input Voltage (red)

Using the AD3 on the physical build of the switch, the output voltage was found to be 2.71V, which aligns with the 2.73V output of the theoretical simulation. The slight increase in voltage drop can be a result of internal resistances of the AD3.

In the theoretical simulation, the current flowing through the switch in its off state, known as the leakage current, was found to be $I_{off} = 6.02\text{pA}$. This confirms the non-ideality that the current at the output in the off state is non-zero. On the physical circuit, it was found that $I_{off} \approx 0A$. From knowledge of ideal versus real switches, we can assume that, this measurement was not truly 0, but a very small amount of current that the AD3 cannot measure (such as the value obtained in picoamps in the simulation).

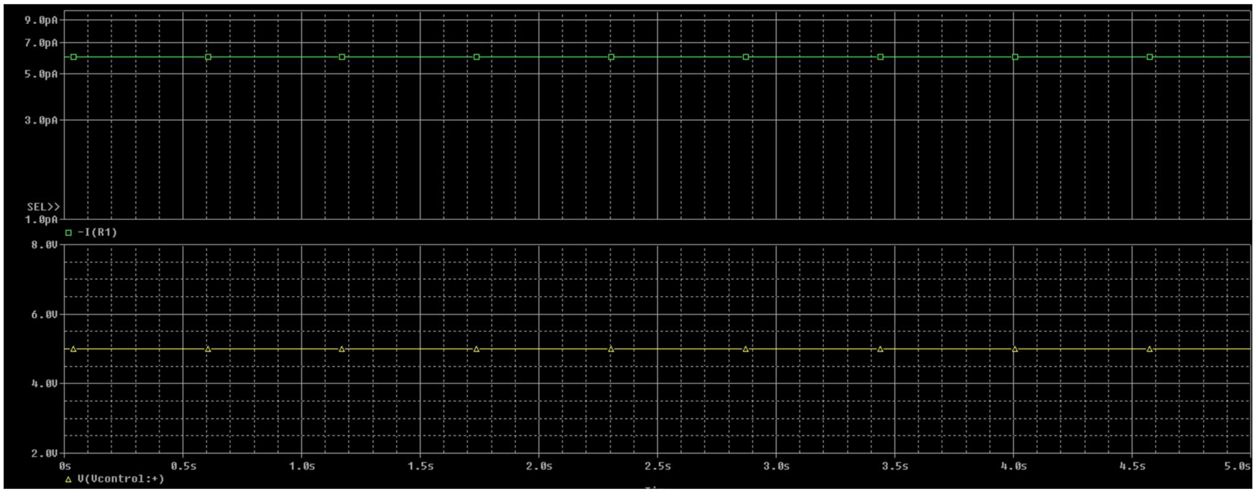

Figure 4: Control Voltage (yellow) and Ioff (green)

Introducing a ramping function from 0 to 10V to the input voltage source in the simulation, it is clear that there is unintended behaviour when the input voltage is under approximately 2V. This can be attributed to the threshold voltage of MOSFETs, which is 1.75V for the available IC. The voltage from the gate to the source must be greater than 1.75V to turn on the MOSFET. Due to this, input voltages under 1.75V will cause unintended behaviour of the switch. Using the AD3 and a 1V input, it was found that the output was close to 0V. It should also be noted that the switch will have an upper limit to its voltage rating, which is equal to the max voltage rating of the MOSFETs or any other components featured in the design.

Lastly, bidirectionality was tested by swapping the load resistor and input voltage source. It can be seen that when the control is set to 5V which turns the switch off, there is still a 2.5V output at the load. This confirms that the switch is non-bidirectional. This was not tested on the physical circuit to protect the components from permanent damage.

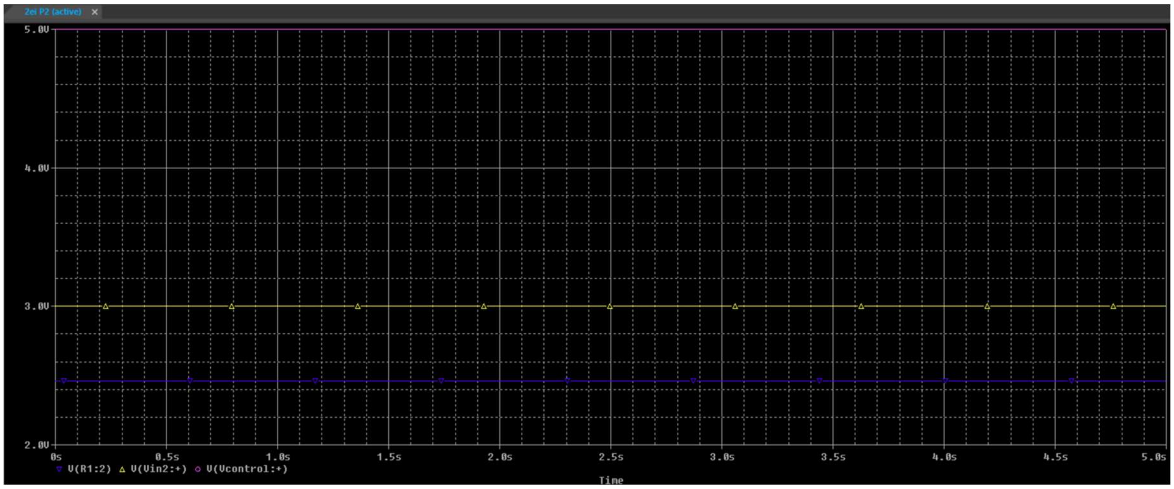

Figure 5: Control Voltage (pink), Input Voltage (yellow), and Output Voltage (purple)

Design Trade-offs

This design features 4 MOSFETS, 3 voltage sources, and one 100kΩ resistor. Using many MOSFETs, this design is complex and costly. Unfortunately, it is difficult to create a design using fewer MOSFETs while still having the Vsupply, Vout, and Vin isolated from each other. Designs for a voltage-controlled switch exist using 1 or 2 MOSFETS, but these designs require tying Vsupply with Vin, meaning Vin has a fixed value for which the circuit operates. This is outside the requirements of this project. Overall this complex and more costly design was required to meet the performance. Additionally, since there is a finite range of input voltage under which the switch operates as intended, applications utilizing very high or low voltages would be unable to implement this switch in their device.

Switch 2

Schematic

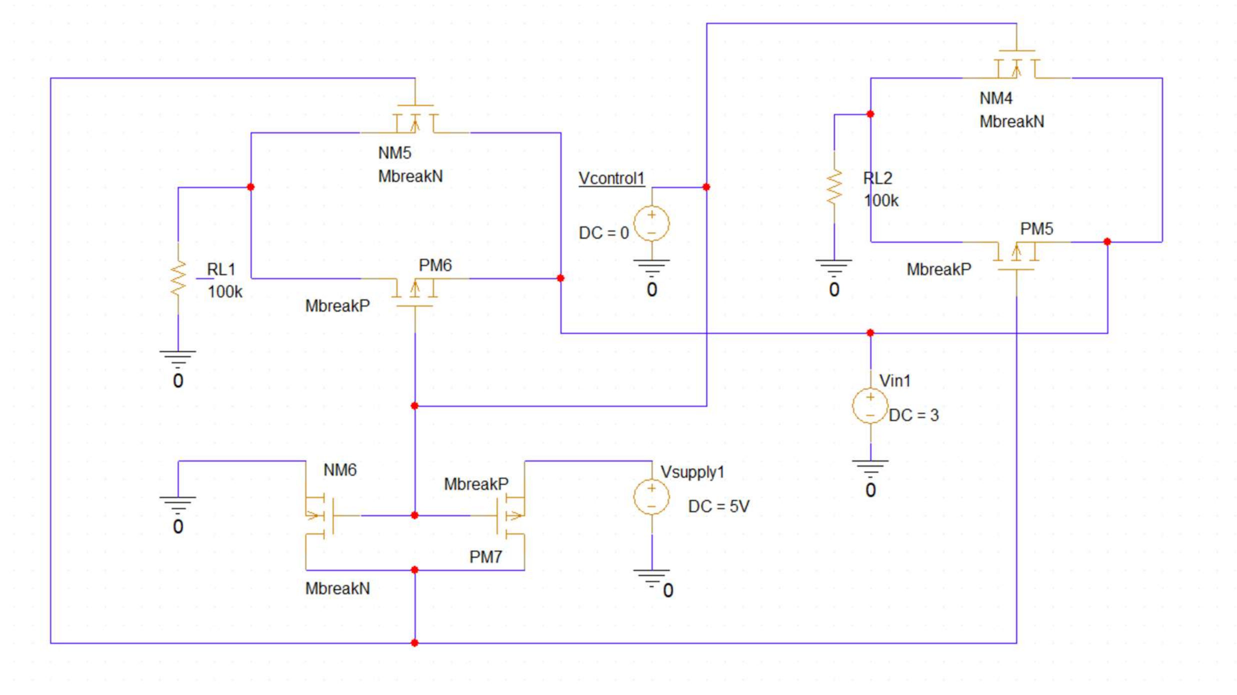

Figure 6: Switch 2 Schematic

Physical Circuit

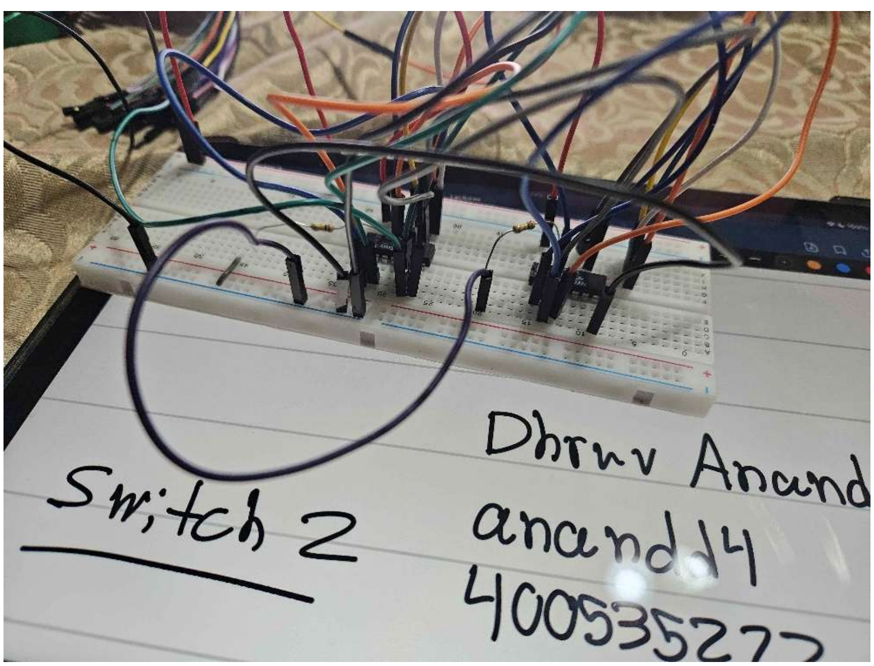

Figure 7: Physical Implementation of Switch Design 2

Measurements

Switch 2 - Measurements/Calculations	
Theoretical Simulation	**Physical Circuit**
$V_{out1} = 2.73V$	$V_{out1} = 2.71V$
$V_{out2} = 2.73V$	$V_{out2} = 2.73V$
$I_{off1} = 6.02\text{pA}$	$I_{off1} \approx 0A$
$I_{off2} = 6.02\text{pA}$	$I_{off2} \approx 0A$
$V_{in1} - V_{out1} = 3V - 2.73V = 0.27V$	$V_{in1} - V_{out1} = 3V - 2.70V = 0.30V$
$V_{in2} - V_{out2} = 3V - 2.73V = 0.27V$	$V_{in2} - V_{out2} = 3V - 2.71V = 0.29V$

Testing and Theoretical Explanation vs Quantitative Results

When testing the circuit both physically and in Pspice, each non-ideality can be observed.

The first non-ideality is that there will be some resistance between the input and output of the switch. This can be confirmed by measuring the voltage drop between the input and output. Testing the input vs output 1, the simulation once again yielded a 2.73V output at the first 100kΩ load resistor. Since the input was 3V, we can see a 0.27V drop across the switch, confirming the non-ideality Ron ≠ 0.

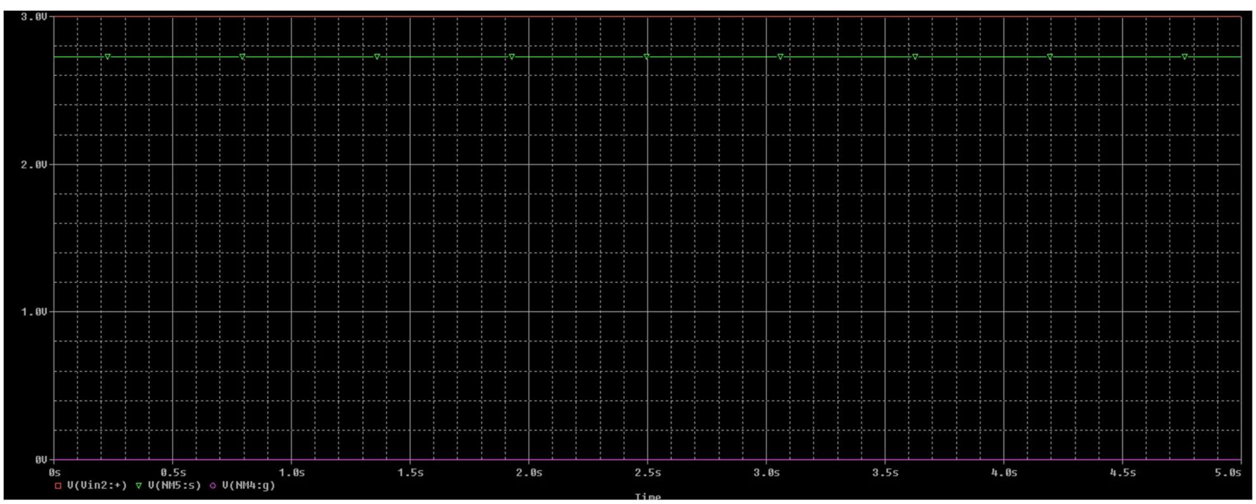

Figure 8: Input Voltage (red), Output 2 (green), Output 1 (pink)

Switching the control to 5V, the output of the switch will now be at the second 100kΩ load resistor. The simulation yielded the same output of 2.73V at output 2.

Using the AD3 on the physical build of the switch, the output voltage was found to be 2.7V at each load resistor, which aligns with the 2.73V output of the theoretical simulation. The slight increase in voltage drop can be a result of internal resistances of the AD3.

In the theoretical simulation, just as in switch one, the current flowing through the switch towards the output that is in its off state was found to be $I_{off} = 6.02\text{pA}$. This confirms the non-ideality that the current at the output in the off state is non-zero. On the physical circuit, it was found that $I_{off} \approx 0A$. Just as in switch one, the current is likely non-zero, but the AD3 is unable to read currents of that magnitude.

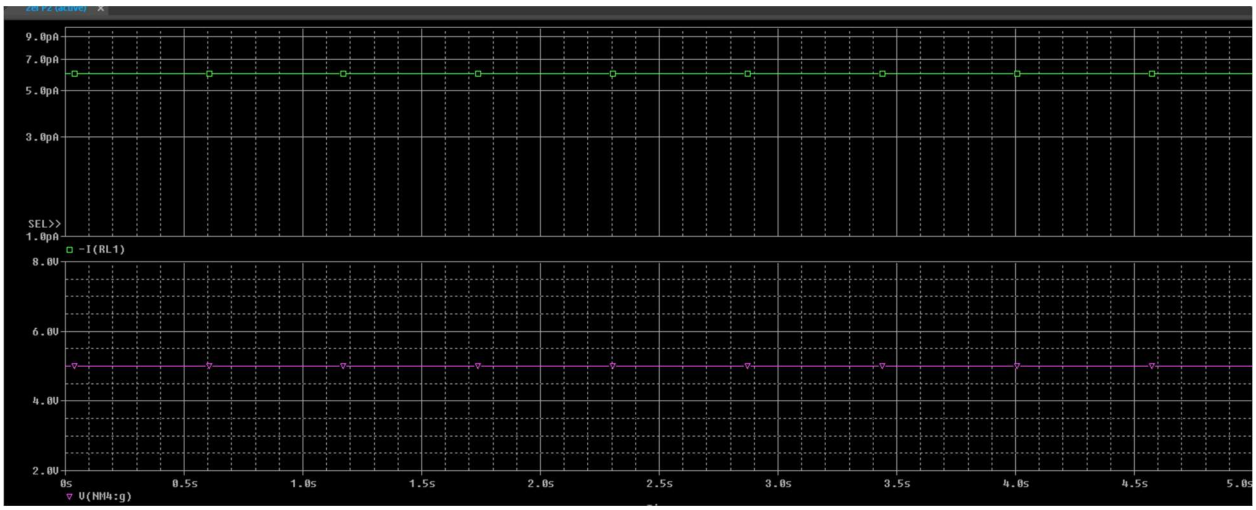

Figure 9: Control Voltage (pink) and Current at Output 1 (green)

Just as in switch 1, introducing a ramping function from 0 to 10V to the input voltage source in the simulation, it is clear that there is unintended behaviour when the input voltage is under approximately 2V. Once again, this can be attributed to the threshold voltage of MOSFETs. Using the AD3 and a 1V input, it was found that the output was close to 0V. Similarly, it should also be noted that the switch will have an upper limit to its voltage rating equal to the max voltage rating of the MOSFETs or any other components featured in the design.

Lastly, bidirectionality was tested by swapping the load resistor and input voltage source. It can be seen that when the control is set to 5V there is significant voltage at both outputs, not just 1 or the other. This confirms that the switch is non-bidirectional. This was not tested on the physical circuit to protect the components from permanent damage.

Design Trade-offs

This design features 6 MOSFETS, 3 voltage sources, and two 100kΩ resistors. Using many MOSFETs, this design is even more complex and costly. This complex and more costly design was required to meet the performance, specifically to ensure changing the control changes where the output goes, rather than a simple on/off. Just as previously, since there is a finite range of input voltage under which the switch operates as intended, applications utilizing very high or low voltages would be unable to implement this switch in their device.

References

[1] O. Ahmed, “Lecture 2,” Odayahmeduot WordPress, Nov. 2015. [Online]. Available: https://odayahmeduot.wordpress.com/wp-content/uploads/2015/11/lecture-02.pdf. [Accessed: Feb. 15, 2025].

[2] The MathWorks, Inc., “Ideal Switch,” MathWorks. [Online]. Available: https://www.mathworks.com/help/sps/powersys/ref/idealswitch.html. [Accessed: Feb. 15, 2025].