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ELECTRICAL AND COMPUTER ENGINEERING
Room D36, Head Hall

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ECE 2701 Experiment 4:

Rectifier Circuits

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Presented to

Dr. Howard Li

Date due: November 29^{th}, 2019

Table of Contents

Abstract

Experiment 4: Rectifier circuits was meant to compare various waveforms of AC (alternating current)-to-DC (direct current) conversion using linear diodes in a rectifier circuit. The diode's main purpose is to provide a linear flow of current: regardless of the source voltage polarity. The primary rectifier circuits seen in class were the subjects of interest, but a diode-bridge full-wave rectifier circuit was also introduced in hopes to examine the advantages of a full wave rectifier circuit when compared to a simple half-wave rectifier.

To accomplish this objective, the team was given a diode bridge, a 1N914 linear diode as well as resistors and a capacitor. These devices were used for the converting circuits mentioned above. Once these circuits were complete, an input voltage source produced by a function generator was attached. Then, its graphical readout as well as the output voltage was displayed by an oscilloscope connected on the other end of the circuit. These output voltages produced in-lab were all variations of rectifier circuits, and each readout was printed out for further analysis.

Furthermore, the reasoning behind visually analysing each circuit was, ultimately, to deduce which circuit provided the best artificial DC voltage. In the end, it was found that a half-wave rectifier circuit with a smoothing capacitor (if given a high enough resistance/capacitance) could be comparable to a DC voltage even if we consider its AC *ripple* effect. A full-wave rectifier output voltage waveform comes in close second, but, due to its harmonic rise/fall in total voltage every half-period, it was not deemed as efficient as the prior circuit mentioned in this paragraph.

The experiment was deemed a success for what it was set out to do, but there could still be improvements made by the team to avoid experimental error. The most prominent one would potentially be the negligence of the diode voltage drop when analysing the circuit. However small, there is still a noticeable difference in V_{in} and V_{out} due to the loss of ~0.7V. Other than this, varying resistance values as well as capacitance, or faulty readings made by the instruments could have also played a part in experimental error.

Introduction

AC electric circuits, in some instances, have an undesired flaw: sinusoidal current flows in the reverse (i.e., negative) direction every half period and flows in the forward (i.e., positive) direction during the other half. This proves to be problematic for loads which require a constant direct current void of fluctuations in current polarity. Research was conducted in order to control the flow of current in an AC circuit, and the solution was as follows: converting the alternating current waveform into an approximate direct current using *diodes*.

Diodes are devices comprised of semiconducting material that only allows certain current to flow through. According to I. L. Veach, diodes are comprised of a cathodic polarity and an anodic polarity (as demonstrated in Figure 1). When the anodic side is positive with respect to the cathode, the diode is considered *forward biased* and current, i_D flows through at the expense of a slight voltage drop (generally ~0.7 V) (2009, p.1).

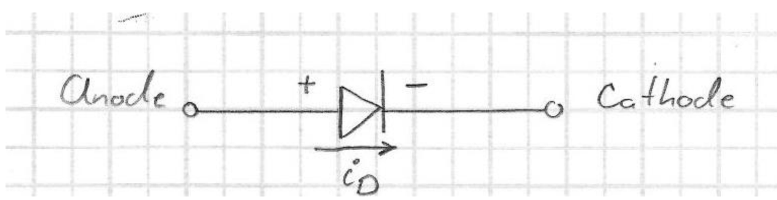
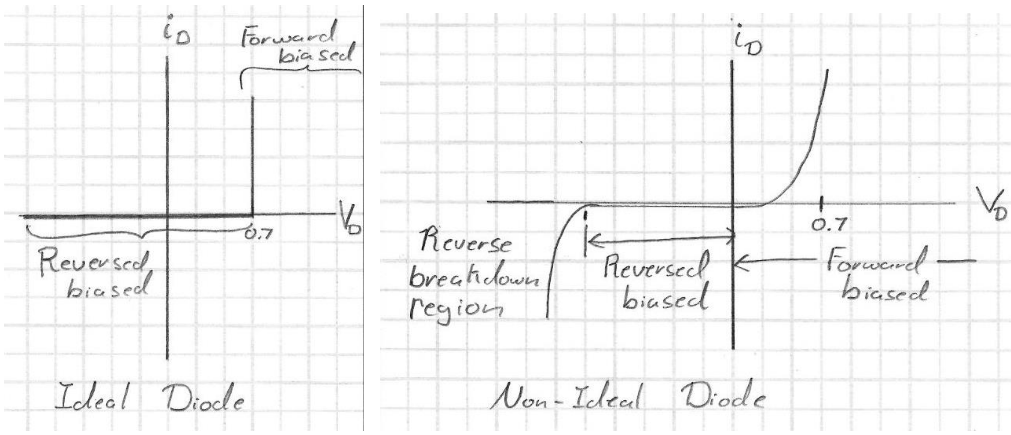


Figure 1. Diode symbol representation while in forward biased polarity.

Conversely, when the polarity is reversed, the diode is *reversed biased*, which means the current flowing through it will be negligibly small, even at high voltages (Veach, 2009, p.1). As an aside, it is worthy to note that a reversed current *can* flow through a reversed biased diode when the a relatively high negative voltage is applied (i.e., known as *reverse breakdown*). However, for the purpose of this experiment, this behaviour will not be investigated further.

Additionally, diodes can be classified as *ideal* or *non-ideal*. As expressed earlier, the approximate voltage drop across a diode is around 0.7 V. In the case of an ideal diode, the drop is exactly 0.7 V and can be represented as a step-response (Figure 2a). In most cases, however, the voltage drop is not exact and must be approximated using *load-line analysis*. This analysis is unrelated to the experiment, but Figure 2b demonstrates the graphical form of a non-ideal diode current response as well as the different regions with respect to varying voltages.



(a) **(b)**

Figure 2. (a) Ideal diode and **(b)** non-ideal diode V-I characteristic diagrams.

In terms of *Experiment 4: Rectifier circuits*, the purpose was to investigate the behaviour of a diode circuit subjected to various conditions. More specifically, a half-wave rectifier, a half-wave rectifier with smoothing capacitor and a full-wave rectifier circuit were systematically observed using an oscilloscope accompanied by a function generator. The results were then used to determine the DC similarity of each circuit's respective output voltage.

In real world operations, diodes are universally used in practically all applications of new-age electrical components. A simple example would be transistors, which use the arbitrary control of alternating current to amplify an output current. In fact, cellular devices also use transistors to control the power usage of electrical components. As such, it is easy to see the usefulness of diodes in all aspects of electricity. Further information on this device as well as the group's experimental results will be elaborated through the following sections of the report.

Experiment

In this section, the group will supply a list of equipment used throughout the experiment, a detailed overview of background theory and the lab procedure. Then, all experimental data obtained in-lab will be explained and analysed accordingly.

3.1) Apparatus

The team used the following equipment during Experiment 4:

- 1N914 Diode or equivalent
- One diode bridge
- Two 10 kΩ resistors
- A 1 μF capacitor
- A function generator
- An oscilloscope
- Red and black conducting wire

3.2) Description of Theory and Procedure

As was discussed above, diodes control the direction of alternating current which aims to act as a "DC converter" of sorts. To elaborate on this, consider circuit with an ideal diode in series with a resistive load (seen in Figure 3).

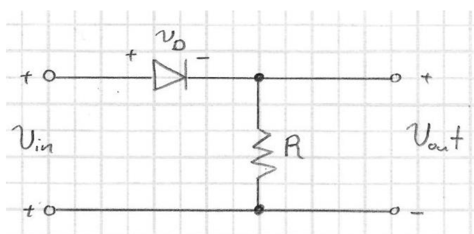


Figure 3. Simple half-wave rectifier circuit.

As one would guess, when the AC voltage source, V_{in}, is positive, current flows through the diode (forward biased) and provides current to the load (directly proportional to the sinusoidal voltage source). When V_{in} is negative, the diode is reversed biased which, in turn, prevents current from flowing through it (Hambley, 2018, p.476). This type of diode circuit is known as a *half-wave rectifier*. Additionally, the relation between its voltage with respect to time multiplied by angular frequency (ωt) can be seen in Figure 4.

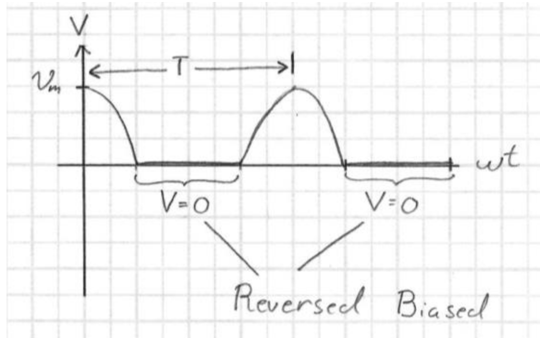


Figure 4. Half-wave rectifier output voltage (V) characteristics over time (ωt).

The main drawback from a half wave rectifier lies in its output voltage. As demonstrated above, every half period has no output voltage and cannot provide power to the load. This, in turn, prevents the circuit to be reliable in general DC power applications. To counter this issue, a *smoothing capacitor* with a sufficiently large magnitude can be placed in parallel with the load (demonstrated in Figure 5).

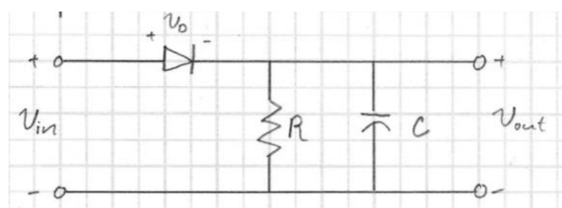


Figure 5. Half-wave rectifier circuit with smoothing capacitor.

When compared to a simple half-wave rectifier, the major difference between them can be seen in Figure 6. According to Hambley, once the forward biased voltage reaches its peak, the fully charged capacitor will slowly discharge (exactly like an RC circuit). The capacitor's stored voltage will then steadily supply current to the load: even if the diode is reversed biased and no current can flow through it (2018, p.477). Thus, the capacitor acts as an alternate voltage supply when the diode prevents the independent voltage source to provide any current to the load.

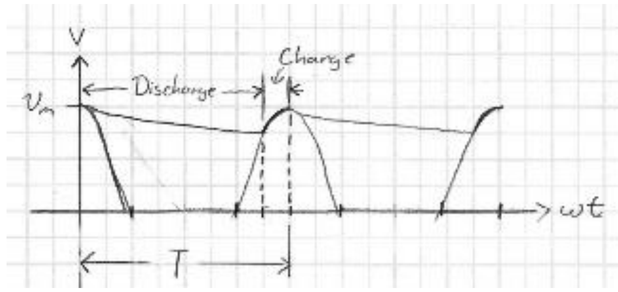


Figure 6. Half-wave rectifier with smoothing capacitor output voltage (V) characteristics over time (ωt).

Furthermore, the figure above depicts two distinct stages of the output voltage: the charging phase and the discharging phase. In the former case, the capacitor's stored voltage is comparatively lower when the input voltage source is forward biased. In such cases, the output voltage is directly proportional to the input voltage (since the voltage drop across the diode is negligible) and Eq.1 is used to find the load voltage at a given time:

$$V_{out} = V_m \cos(\omega t)\,,\ \frac{3\pi}{2} + \alpha \leq \omega t \leq 2\pi \tag{1}$$

Where:

- α = the phase angle of the sinusoidal AC voltage source
- The boundaries are linked to a portion of the overall period of the waveform
- V_m = the peak voltage of the waveform (V)

In the latter case, the diode is reversed biased and the capacitor discharges a voltage compared to a decreasing exponential curve given by Eq.2 below:

$$V_{out} = V_m \exp\left(\frac{-t}{RC}\right),\ \ 0 \leq \omega t \leq \frac{3\pi}{2} + \alpha \tag{2}$$

Where:

- R = load resistance (Ω)
- C = capacitance (μF)
- RC $=\tau$ = time constant

Because of these cycling phases, there will always be a slight voltage drop between the initial and final discharging cycle: a phenomenon known as *ripple*. While this cannot be clearly seen in Figure 6, the team's experimental results correlate well with this phenomenon and will be further discussed herein.

The last circuit worth mentioning for this report is a *full-wave rectifier* circuit. As its name states, this circuit is fashioned in a way that always provides current through a load without the need of a smoothing capacitor. As explained by Hambley, this can be accomplished using a *diode bridge* (seen in Figure 7).

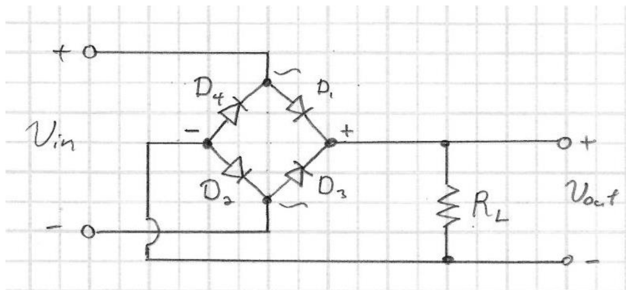


Figure 7. Full-wave rectifier circuit using a diode bridge.

When the AC voltage is positive, current flows through diodes D_1 and D_2. When the voltage is negative, the prior used diodes are reversed biased and the current flows through diodes D_3 and D_4. It is also worthy to note that in both cases, the current flows through the positive polarity of the load (Hambley, 2018, p.479). Furthermore, it is evident that voltage supplied through a diode bridge full-wave rectifier supplies twice as much power when compared to the original half-wave rectifier circuit (Figure 3). Figure 8 illustrates this corresponding increase in voltage that is gained through the diode bridge's constant direct current.

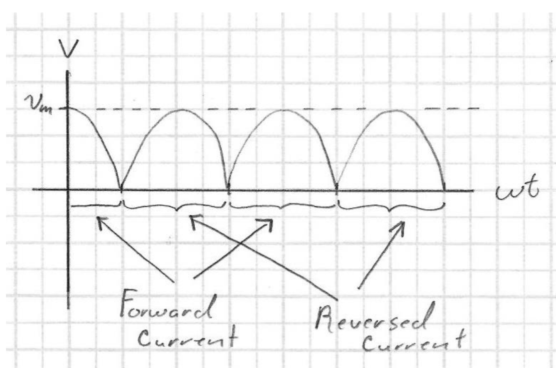


Figure 8. Diode bridge full-wave rectifier output voltage (V) characteristics over time (ωt).

Since the reversed input current now supplies voltage to the load, the output voltage gains an additional half-wave each period, resulting in an increase in overall voltage gain (G = $\left|\frac{V_{out}}{V_{in}}\right|$).

Now, in terms of the experiment itself, the team was tasked with investigating the physical behaviour of each rectifier circuit mentioned above by following a series of steps that will be explained in the following paragraphs of the report.

First, the team was given a diode bridge and a simple diode (as listed in the apparatus). After recording the type number of each diode, it was asked to set up a half-wave rectifier circuit just like Figure 3. A 10 kΩ resistor was used as the load, and, using the function generator, the input voltage was set to a 12 V_{pp} (peak-to-peak) 400 Hz sine wave. After analyzing the shape of the input voltage, V_{in}, with respect to the output voltage, V_{out}, on an oscilloscope, the readings were printed out and used for further examination.

Next, the team installed a 1 μF capacitor in parallel with the resistor to replicate a half-wave rectifier circuit with a smoothing capacitor (constructed the same way as Figure 5). Again, the voltage input/output waveforms were printed out from the oscilloscope and the corresponding behaviour was to be discussed in the report and compared with the half-wave rectifier circuit from the previous part.

Additionally, once the readings from the circuit were properly studied, the behaviour of the output voltage was re-examined after an additional 10 kΩ resistor was placed in parallel with the load and capacitor. The resulting waveform was then printed out the same way as the other two circuits. This was meant for the team to compare both readouts and to explain the reason behind the change in output voltage caused by the decrease in resistance.

Finally, a diode bridge full-wave rectifier circuit was constructed adhering to the same layout as Figure 7. Using the math function on the oscilloscope, a new readout was created, and its result was to be printed out. However, due to technical malfunctions, the team took a photograph of the readout instead. Once this was completed, the team was asked to discuss the shape of the output voltage and to compare it with the initial half-wave rectifier circuit constructed at the very beginning of the experiment.

Upon successfully completing the experiment, it was found that all output voltage waveforms agreed with the theory explained above. It was also found that a half wave rectifier with smoothing capacitor circuit does, in fact, provide a good basis of a DC converter if the capacitance and/or resistance is high enough. Plus, a decrease in resistance will increase the ripple caused by the RC discharge of a half-wave rectifier circuit as well. The full-wave rectifier also proved to work according to theory; as it provided constant ac output voltage during both reversed (negative) and forward (positive) voltage through the circuit.

3.3) Calculations Graphs, Results and Analysis

This section of the report will showcase all data obtained throughout the procedure of the experiment and will answer all pertinent questions asked in the lab manual in hopes to clearly explain the respective output voltage shapes of each rectifier circuit.

Before beginning the analysis, the diode types that were used in the experiment were recorded as follows:

- Rectifier Bridge – W02G – 1.5A, 200V
- Diode – DO-35 – 200mA, 100V

Now, following the order of procedure, Figure 9 is a graphical representation of the behaviour of the half-wave rectifier circuit observed after constructing the initial circuit.

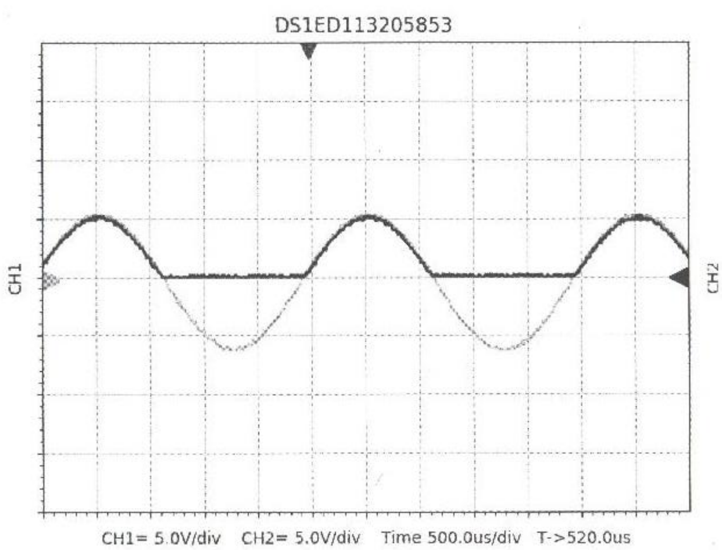


Figure 9. Half-wave rectifier circuit oscilloscope input/output overlay.

It is important to note that the lightly shaded sine wave underlay represents the input voltage waveform function and the darker curve is the output signal voltage of the circuit. As expected, the shape of the output voltage resembles that of Figure 4. This makes sense, since the negative current of the circuit is reversed biased for a half-period. Thus, the oscilloscope should read an approximate zero output voltage across the diode at this time.

As elaborated in the previous section, this is not a good DC approximation, seeing as it lacks an output voltage every half-period. This means the voltage source does not provide power to the load during after every half-cycle.

Next, after adding the 1 μF smoothing capacitor to the initial circuit (as seen in Figure 5), another readout was obtained (Figure 10). This readout proves the validity of a half-wave rectifier circuit with smoothing capacitor as it clearly depicts the sinusoidal voltage charging the capacitor to its peak voltage of 6V. The decaying curve is the capacitor discharging its voltage as the diode is reversed biased and no current can flow through it. Also, note that the sine function is the input voltage and the darker shaded curve is the output voltage.

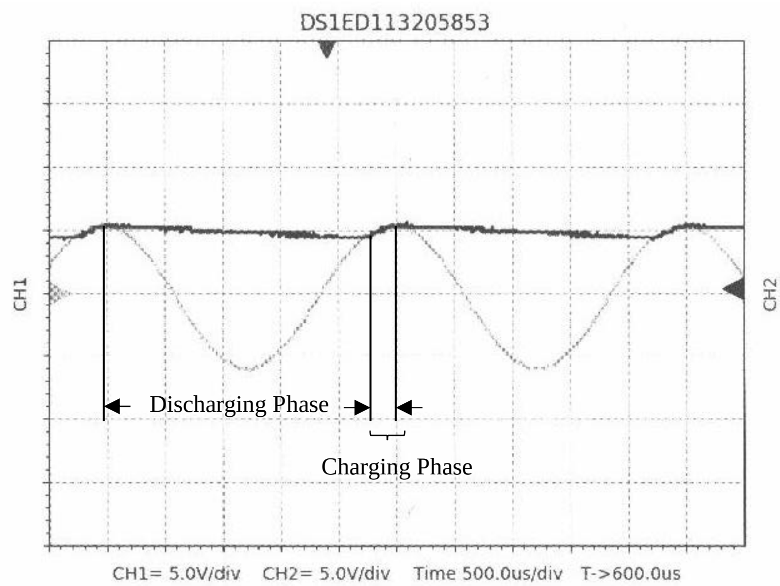


Figure 10. Half-wave rectifier with smoothing capacitor (10 kΩ resistance) input/output overlay.

Compared to the prior graph, this is a much better approximation of a DC voltage. The capacitance is high enough as to create a relatively small ripple of ~1V after every discharging phase of the circuit.

After the previous graph was analysed, a 10 kΩ was added in parallel to the load resistance of 10 kΩ as well as the capacitor. By calculating the resulting resistance by using Eq.3 below, it was found that the resistance decreased to 5V:

$$R_t = \frac{R_1 \times R_2}{R_1 + R_2} = \frac{(10\ k\Omega)(10\ k\Omega)}{(10\ k\Omega)+(10\ k\Omega)} = 5\mathrm{V} \tag{3}$$

Where:

- R_t = Resultant resistance
- R_1 = Load resistance (10 kΩ)
- R_2 = Added resistance (10 kΩ)

Since the overall resistance is decreased, the time constant ($\tau = \mathrm{RC}$) will decrease as well. This will, in theory, cause the decaying exponential slope to increase: raising the AC ripple effect caused by the discharging phase in the process. This theoretical behaviour is supported by the team's experimental results from the second part of the half-wave rectifier smoothing capacitor circuit (Figure 11).

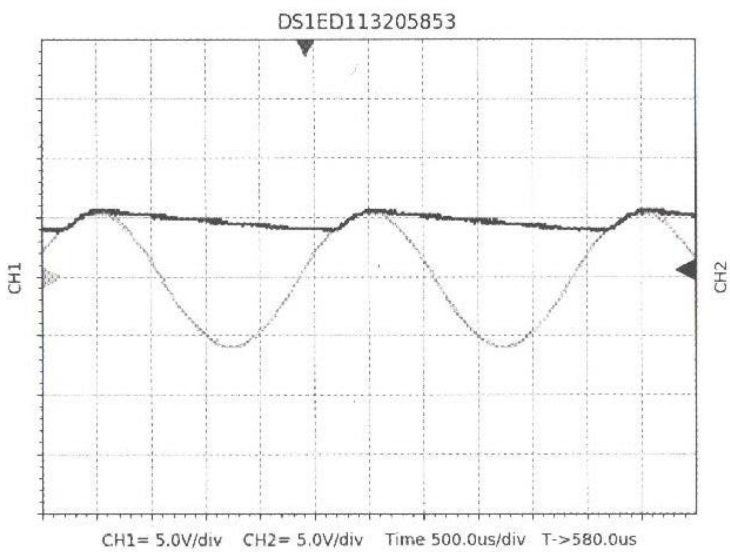


Figure 11. Half-wave rectifier circuit with smoothing capacitor (5 kΩ resistance) input/output voltage overlay.

Figure 11 is almost identical to figure 10, save for a relative difference in the voltage ripple caused by the decrease in the time constant. Thus, this leads the team to the following conclusion: as the time constant for the exponential discharging phase of a half-wave rectifier circuit decreases, the voltage drop before the next charging phase will increase.

The final step of Experiment 4 involved the construction of a full-wave rectifier circuit similar to Figure 7. By using the diode bridge provided at the beginning of lab, a new output voltage waveform can be observed. In this case, the input voltage should provide twice as much power to the load compared to the half-wave rectifier circuit since current flows through it (refer to Figure 8). Therefore, its shape should be a series of positive wave crests subsequent to each other. And, through experimental results (Figure 12), it was found that this behaviour is valid.

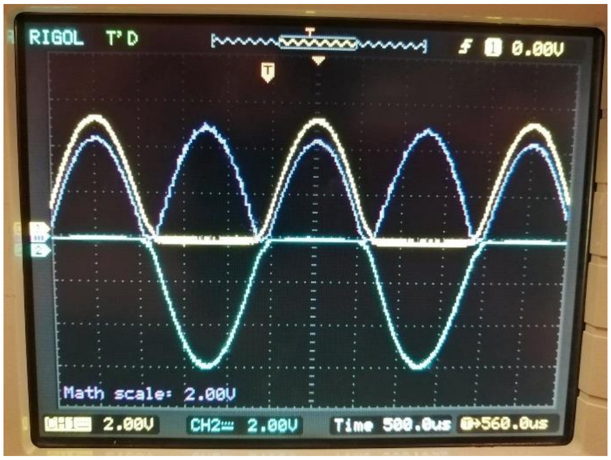


Figure 12. Full-wave rectifier voltage input (green), voltage output (yellow) and returned math function true output voltage (purple).

After converting the voltage input/output overlay into a math function on the oscilloscope (purple sine function), it can be deduced by the above graph that the voltage is, in fact, a full wave rectifier circuit. Since the diode bridge provides a constant current through the load (regardless of positive/negative voltage), it makes sense that the output voltage adopts the purple function waveform.

The slight decrease in voltage compared to the output function (yellow) could be attributed to the diode voltage drop, or it could be due to human error which will be discussed in the next section.

Now, if we do a side-by-side comparison of the initial half-wave rectifier printout and the diode bridge full-wave rectifier circuit, we can see a clear distinction between the two (illustrated in Figure 13). As is mentioned in the prior sections of the report, the half-wave rectifier only partially provides a power output, whereas the full-wave rectifier is constantly providing power to the load (since power is provided throughout the entire period waveform). Thus, when compared to the initial half-wave rectifier circuit, the diode bridge full-wave rectifier has a good DC voltage representation.

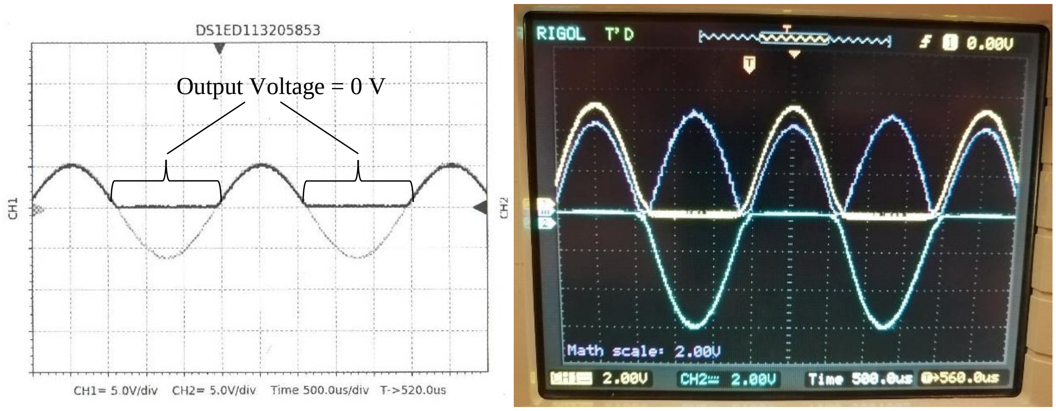


Figure 13. Side-by-side comparison of a half-wave rectifier circuit and a full wave rectifier circuit (depicted by the purple waveform function).

As an aside, it is deemed that a half-wave rectifier circuit with a smoothing capacitor provides a better DC voltage compared to a full wave rectifier circuit, seeing as its shape is much more linear in nature. This can be especially true if the time constant is relatively high enough.

Discussion

The examination of elementary diode circuits allowed us to further understand the behavior of half wave and full wave rectifiers used in this experiment. As was discussed above, various comparisons were conducted by studying graphs displayed by the oscilloscope from half-wave and full wave rectifier circuits with resistors, capacitor and/or diodes. The graphs provided an observation through given parameters (i.e. V_{in}, V_{out}, and V_{PP}). After conducting the experiment, various behaviors were found experimentally; most of which were theoretically expected such as the addition of a resistor in figure 11.

While the experimental data output remained within reasonable parameters, it still raises the question of why the reading may have been higher or lower than the expected theoretical readings of the graphs. This could be due to many variables, but, for the purpose of this report, the following paragraphs elaborate on the most common errors that the team could think of.

Potential human errors encountered in the lab which could have altered our readings range from misreading the output voltage waveform on the oscilloscope to improperly setting up the circuits.

Experimental errors consisted of some being unavoidable. Environmental factors such as a change in temperature would evidently alter the readings on the oscilloscope (e.g., varying resistance, capacitance or even the diodes). Faulty calibration of the devices used in the lab such as oscilloscope and function generator may have resulted in a variation of the readings as well. As the name states, unavoidable errors cannot be altered directly, but being aware of these variables could equally reduce the margin of error while also creating a better understanding of the phenomena.

Conclusion

Experiment 4 provided a clear insight in the understanding of half-wave and full-wave rectifiers by understanding the behavior of elementary diodes. It was determined that the addition of a capacitor to the circuit created a smoother current/voltage waveform and a better representation of DC voltage. Thus, it is expected that adding more capacitance to a circuit will result in a reduced AC waveform curve. Thus, obtaining a perfectly linear voltage output with minimal ripple would be a true DC voltage output.

However, it is very important to reiterate the human and random errors that were encountered during the experiment that may have altered the actual results. Firstly, obtaining a graphical reading, the change in temperature may have affected the true value, even if only slightly. Additionally, the true value of the resistors and capacitor could have slight deviations as well resulting in inaccurate readings. It is also important to note that an improper calibration of the oscilloscope and function generator may have provided improper values even if only slightly. Thus, resulting in improper graphical reading cause a difference between theoretical and experimental readings no matter how off the values may be.

In conclusion, as with any experiment, the results could have been more accurate if it was performed multiple times. Given more time, the team could have meticulously gone through every circuit to assure a strong and reliable connection through each conductor as well. Through it all, however, the team successfully completed what they were set out to do: Examine the behavior of elementary diode circuits.

Summary of Each Team Member's Role

Dominic Geneau poured a lot of time into the experimental procedure and the drafting of this report. Accompanied by Abdul Wasey, he constructed each rectifier circuit during the experiment and analysed their oscilloscope readout accordingly. He then wrote the introduction, experiment and abstract for the lab report (all hand drawn figures were of his making as well). Additionally, Dominic proof-read the entire document to provide an adequate professional document that is worthy of presentation.

Abdul Wasey gave him time into the experimental procedure and forming of the report. Accompanied by Dominic Geneau, he constructed the rectifier circuit during the experiment and analyzed the readings from the oscilloscope accordingly. He then wrote the discussion and conclusion for the report. Additionally, he re-read the report to ensure the entire document was adequately professional and worthy of presentation.

References

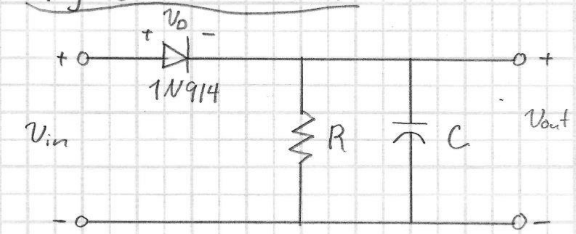
Hambley, A. R. (2018) *Electrical engineering: Principles and applications* (7th ed.). Hoboken, NJ: Pearson Education Inc.

Veach, I. L. (2009) *EE2701 experiment 4: Rectifier circuits* [PDF Document]. Retrieved from UNB D2L online website: https://lms.unb.ca/d2l/le/content/160443/viewContent/1616305/View

Appendix A – Pre-Lab Calculations & Raw Data

UNIVERSITY OF NEW BRUNSWICK	FACULTY OF ENGINEERING	Page
Course No. ECE 2701	Assignment No. LAB 4 Date Nov - 22nd - 2019	of
Problem No. Pre - Lab	By Dominic Geneau (3675144)	

Figure 4-3 Circuit



Given

$R = 10\ k\Omega$

$C = 1\ \mu F$

$V_m = 6V$

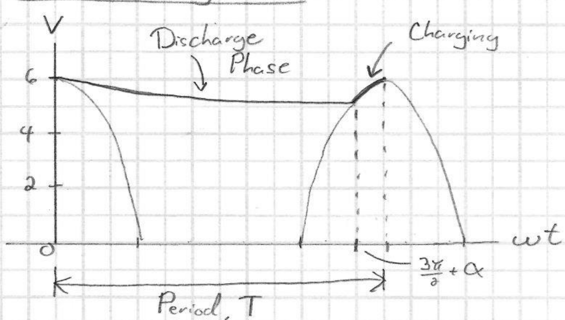
$\omega = 2\pi f = 2\pi(400Hz)$

$= 800\pi\ \frac{rad}{s}$

$V_{in} = 6\cos(800\pi t)$

$v_D \simeq 0.7V$

V-ωt Diagram



Note: This is a good DC voltage approximation (voltage drop is slight compared to half-rectifier circuit without capacitor).

Charging Phase

→ When charging, capacitor's voltage is lower than V_m and is "charged" by the source voltage. Thus, V_{out} can be approximated by KVL / Parallel voltage analysis

$$V_{in} = V_{out} + V_D \Rightarrow V_{out} = 6\cos(800\pi t) - \underbrace{0.7}_{\text{negligeable}}$$

$$\boxed{V_{out}(t) = 6\cos(800\pi t)\,V} ;\ \frac{3\pi}{2} + \alpha \leq \omega t \leq 2\pi$$

Discharging Phase

→ Diode is reversed biased and full capacitor "discharges" by the decreasing exponential solved in-class.

$$V_{out} = V_m \exp\left(\frac{-t}{RC}\right) = 6\exp\left(\frac{-t}{(10k\Omega)(1\mu F)}\right)$$

$$\boxed{V_{out}(t) = 6\exp\left(\frac{-t}{0.01s}\right)V} ;\ 0 \leq \omega t \leq \frac{3\pi}{2} + \alpha$$

Name: Dominic Geneau ID number: 3675144 Date: Nov 22nd, 2019

Resolve Pre-lab

EE2701 Experiment 4
Summary of Results

1. List the diode types you were provided.

Rectifier Bridge - WO2G - 1.5A, 200V

Diode - DO-35 - 200mA, 100V

2. Attach a copy of the oscilloscope display printout obtained for the half-wave rectifier circuit of Figure 4-3. Explain briefly why the output waveform has the form it does.

diode only accepts forward biased current, Hence, a reversed current will not provide any voltage/current through diode.

Is this a very good DC voltage? Explain.

No, since we lose half a period waveform and the remaining voltage function is a sign wave

3. Attach a copy of the oscilloscope printout obtained for the output of the half-wave rectifier with a 1 μF capacitor added in parallel with R_L.

Explain the changes in the form of v_{out} caused by adding the capacitor.

capacitor ~~equalizes~~ discharges and "smoothens" voltage drop when ~~capacitor is~~ diode is reversed biased

Is this a very good DC voltage? Explain.

Yes, capacitor discharges when diode is reversed biased and when

4. Attach a copy of the oscilloscope printout obtained for the output of the half-wave rectifier with annother $10k\Omega$ resistor in parallel to R_L and the 1μF capacitor.

Explain the changes in the form of v_{out} caused by adding the extra resistor in parallel withe capacitor and R_L.

the decreasing exponential curve discharge is ~~steeper~~ steaper because of a decrease in resistance ($10k\Omega \rightarrow 5k\Omega$)

5. Attach a printout of the oscilloscope display obtained for the output voltage of the full-wave rectifier

What is the difference between the observed form of v_{out} for this circuit and that observed for the basic half-waye rectifier of step 2 of the procedure?

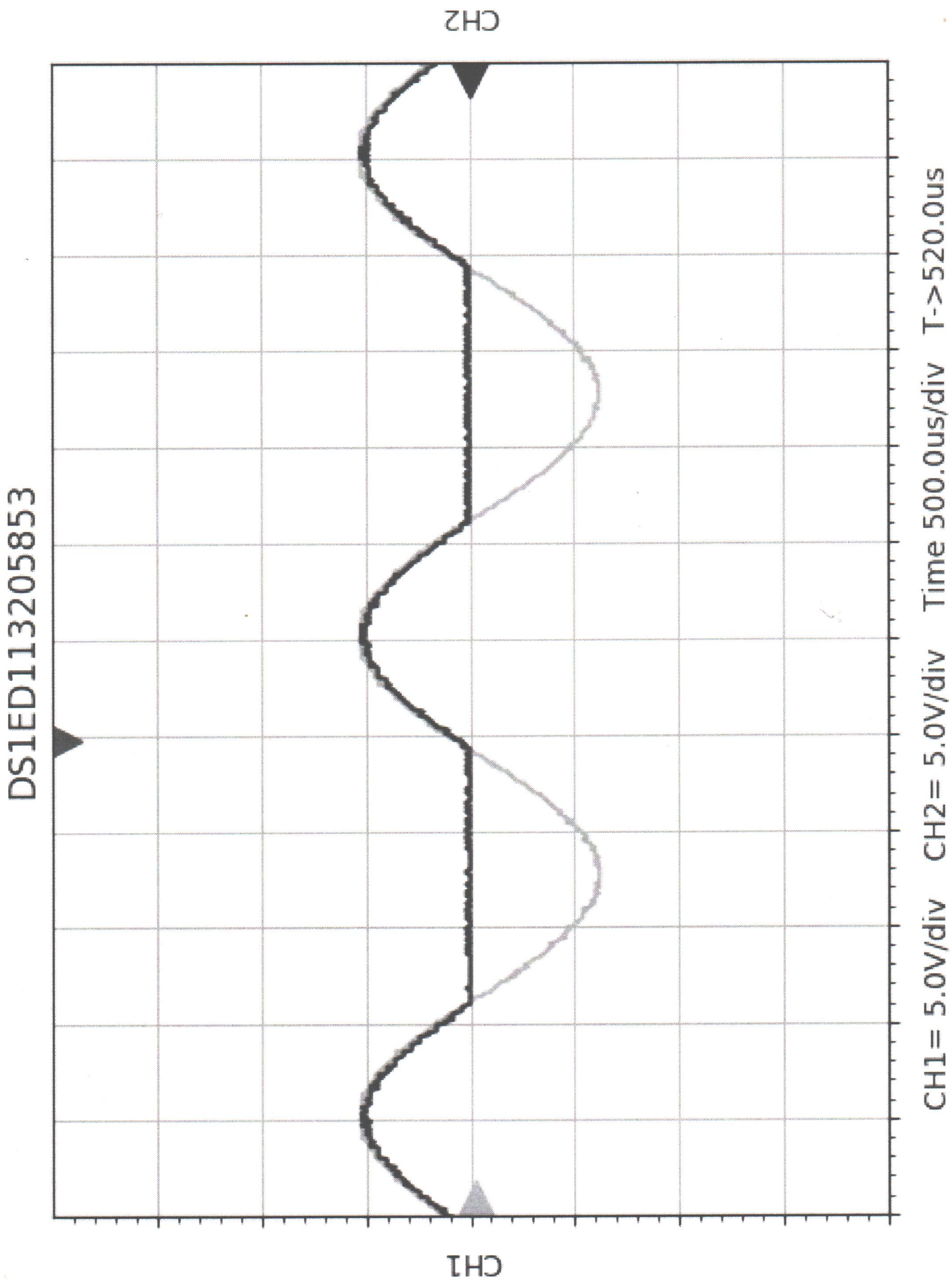
Step 2 Only provides voltage (V_{out}) over a halfperiod (ΩΩ)

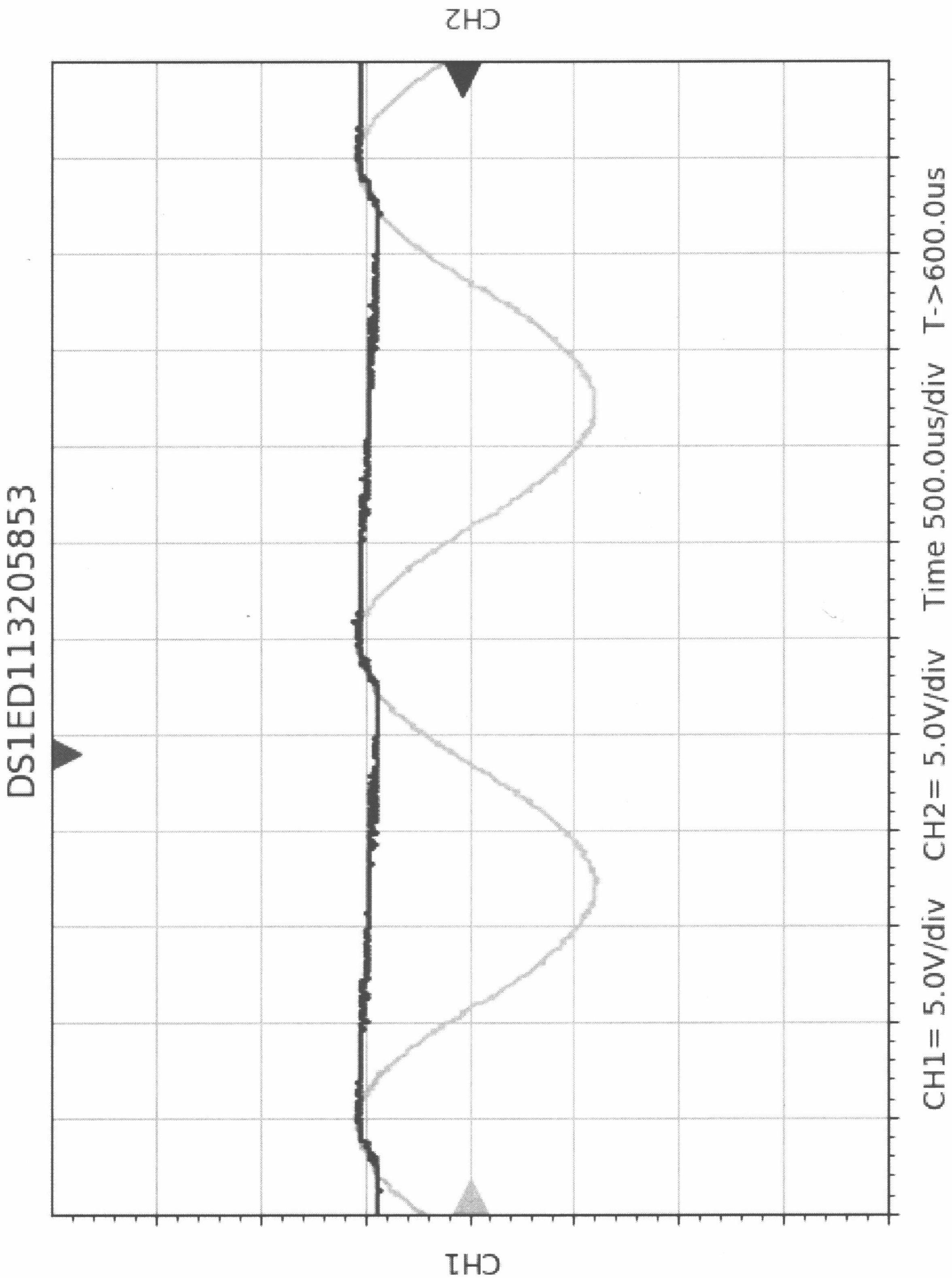
Step 5 provides voltage (V_{out}) over entire period (ΩΩΩ)

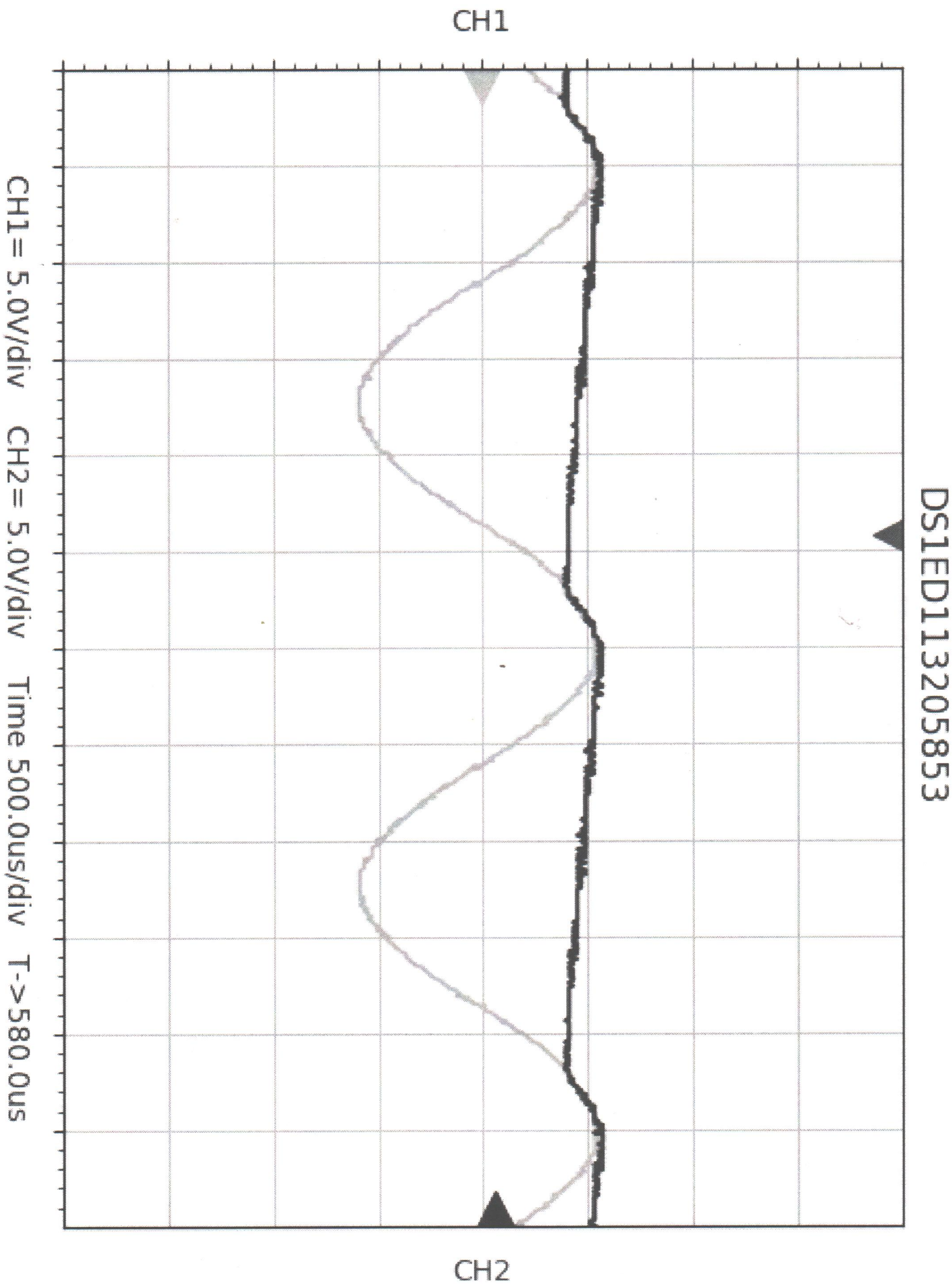
Is this a very good DC voltage? Specifically, is it a better DC voltage than the output of the basic half-wave rectifier of step 2 of the procedure? Explain.

Yes, because current is always flowing through the circuit (diode bridge). and provides voltage when Voltage is reversed.

Appendix B – Oscilloscope Rectifier Circuit Printouts


DS1ED1132205853
CH2
CH1
CH1= 5.0V/div CH2= 5.0V/div Time 500.0us/div T->520.0us


DS1ED113205853
CH1= 5.0V/div
CH2= 5.0V/div
Time 500.0us/div
T->600.0us
CH1
CH2


CH1
CH1= 5.0V/div CH2= 5.0V/div Time 500.0us/div T->580.0us
DS1ED113205853
CH2

RIGOL T'D
0.00V
Math scale: 2.00V
CH1 2.00V
CH2 2.00V
Time 500.0us
560.0us