ENG-6001B

Electricity Generation and Distribution

002 – Lab Report 2
“Generators, Diodes, Rectifiers, Buck Converters”

by

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1. Introduction

This assignment covers some of the processes used for generating electricity and distributing it. This exercise explores the behaviour of diodes, the design, construction and behaviour of an alternating current generator, a rectifier circuit and a buck converter circuit. The generator constructed produces an alternating current from rotating a crank, through induction and Faraday's law. Standard diodes are electronic components that allow current to flow one direction through the diode, but inhibits it flowing the other way. There are other types of diodes however, and their behaviour will be tested and monitored. This can be used in various ways including rectifying circuits and buck conversion circuits. Rectifiers are circuits designed to convert alternating current (AC) into direct current (DC), for applications such as converting mains electricity into DC electricity for home electronics. A simple one will be built, with different parameters to design for. Buck and boost converters are used to step down or step up DC to DC current. A buck converter will be built, and it's behaviour examined. This exercise essentially goes through generating electricity, then converting and transforming it.

2. Task-by-Task Description of the Assignment

2.1 Generators

2.1.1.

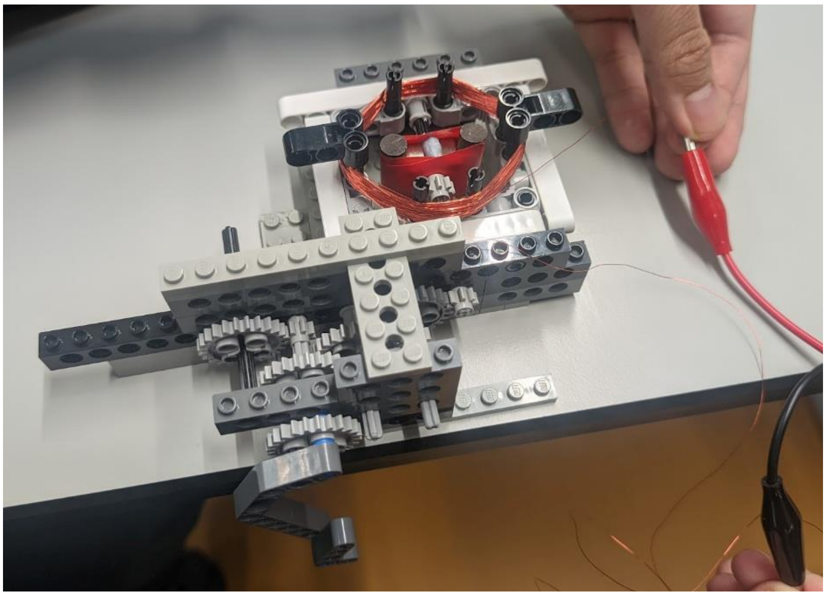


Figure 1 The built generator, featuring 100 turns of coil.

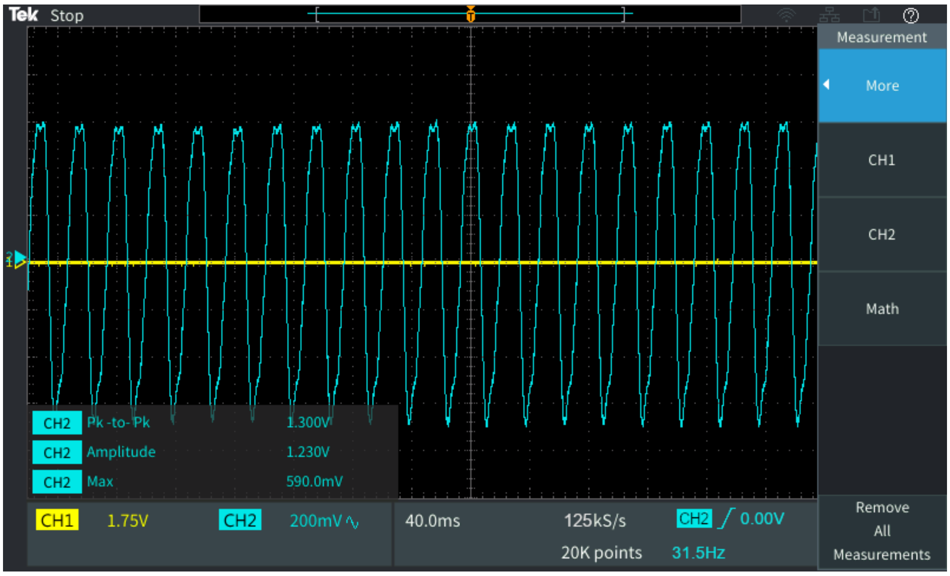


Figure 2 The output of the generator when cranking it at a constant rate.

The first task was to design and construct a simple AC generator with Lego. A magnet (the rotor) was to be spun while surrounded by coils of wire (the stator). The generator featured 100 turns (N=100) of wire, and the rotor was span manually by hand with a crank connected via a gear train, seen in Figure 1. The induced current was then measured on an oscilloscope. Rotating the crank at a constant rate or revolutions per minute (RPM) gave an induced a current at roughly 1.3 volts peak to peak, at a frequency of 31.5Hz as seen in Figure 2. The faster the RPM, the higher the induced voltage. This follows Faraday's law, as the induced electro-magnetic force (EMF) ε is directly proportional to the time rate of change of magnetic flux through the circuit, the formula $\varepsilon = -N\frac{d\phi}{dt}$. The magnetic flux ϕ comprises of B, a fixed magnetic field, and A, the area of the coil. The number of coils, N, multiplies the induced emf. As the magnet or rotor is spinning rather than sliding within the coils however, the magnetic flux is dependent on the angle at which the magnet is in relation to the coils. If for example, the magnet is perfectly perpendicular to the coils, the magnetic flux is at its potential maximum, while if it were in parallel it would be at its minimum. The rotation therefore has alternating and constantly changing magnetic flux, inducing AC current. Due to this the formula changes to $\varepsilon = -N\frac{d(BA\cos\theta)}{dt}$, where B is a fixed magnetic field, A is the area of the coil, and θ is the angle the magnet is at in relation to the coil.

2.1.2.

The rotor's magnetic field, B, is an unknown. As we have all other variables known in the formula $\varepsilon = -N\frac{d(BA\cos\theta)}{dt}$ (N= 100, ε and A can be measured), we can calculate and deduce the value of B when cranking the generator at a fixed rate (change in magnetic flux over change in time is constant). To ensure accuracy of the reading, this can be done over a series of different rates or RPMs where the results are then averaged.

2.2 Diode characteristics

2.2.1.

The next task involved constructing a simple circuit to test and see the characteristics of different types of diodes, in both forward and reverse biases. Forward bias means voltage flows from the anode to the cathode, and vice versa. A diode was connected to a load resistor and DC voltage supply along with an ammeter and voltmeter, as shown in Figure 3.

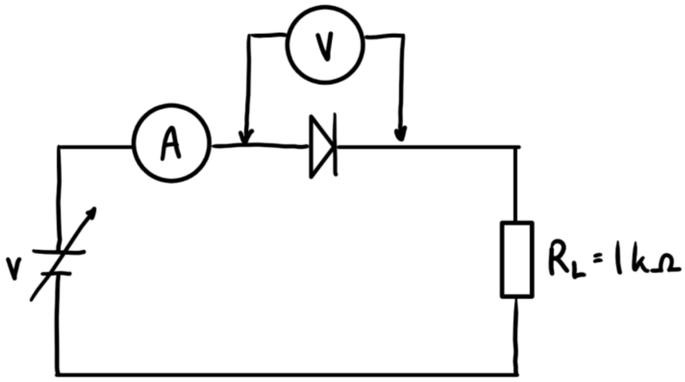


Figure 3 The circuit used for testing different diodes.

The first diode tested was a standard silicone diode (1N4004). The diode was tested in forward and reverse biases.

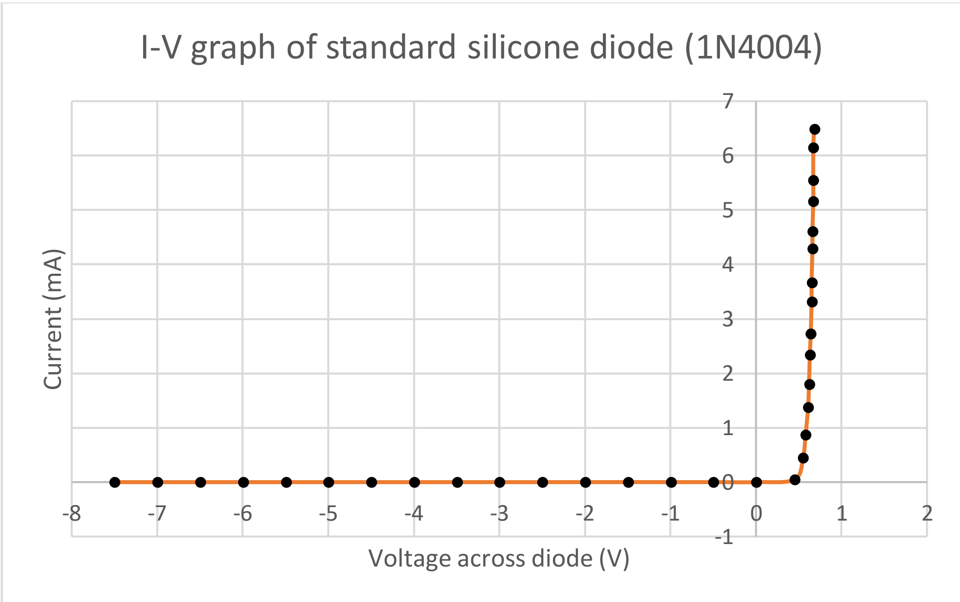


Figure 4 An I-V graph of the standard diode. All current is blocked up to 0.7 volts.

As seen by the graph in Figure 4, the diode essentially only allows current to flow through it in one direction – voltage must be higher at the anode of the diode than the cathode (forward bias). From all reverse bias voltages up to up to 0.7V essentially no current passes through the current. This “knee” value is based off of the material of semiconductor the diode is made from. Silicone diodes respond at 0.7V, while Germanium diodes respond earlier at 0.3V. Regular diodes also exhibit “breakdown”, where if the voltage in reverse bias is high enough current increases rapidly and the diode is destroyed. Reverse voltage this high however was not achieved or tested for safety and the diode’s sake.

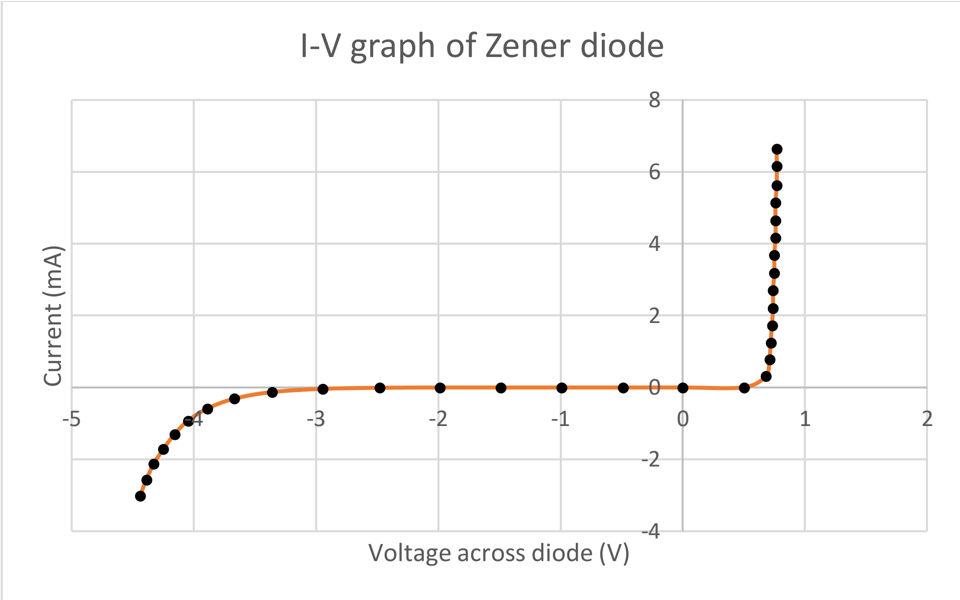


Figure 5 An I-V graph of a Zener diode. It is similar from the standard diode except has a predictable breakdown leak of current if the reverse voltage is low enough.

Testing a Zener diode achieves different results. Forward bias gives the same results, where essentially no current is allowed to flow up until 0.7 volts, but reverse bias voltage demonstrates a characteristic of Zener diodes standard diodes do not feature. When they near breakdown voltages, they allow or "leak" a small amount of current to pass predictably. This can be seen in Figure 5, and this trait prevents the diode from damage, and is a defined and predictable value unlike standard diodes. This feature can be used to regulate voltage for example, by connecting a Zener diode in reverse bias, as if the voltage exceeds the breakdown value current will flow and can be used as a shunt in a circuit.

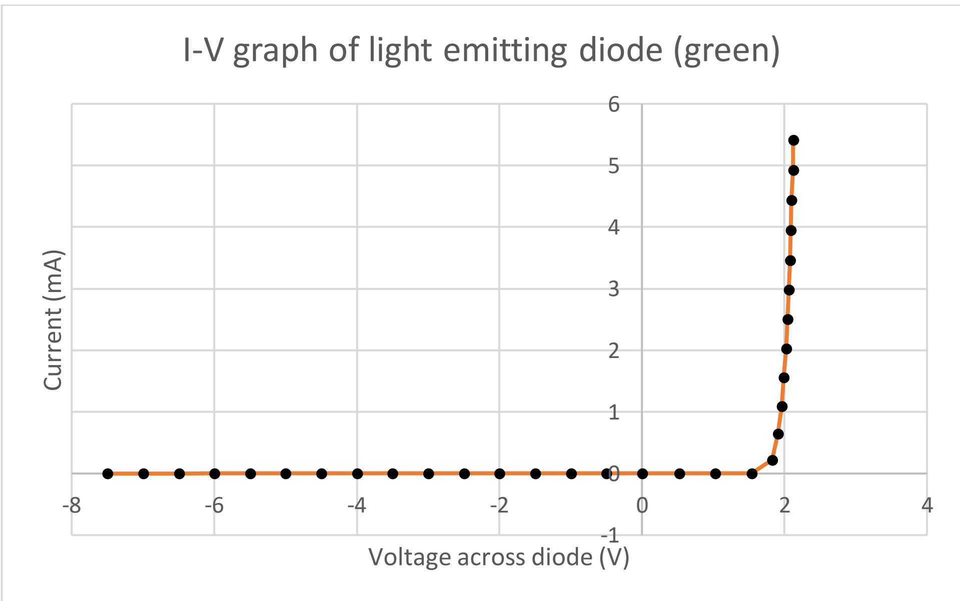


Figure 6 An I-V graph of a green light emitting diode. It is similar to the standard diode except the voltage where current is allowed to flow is higher.

The light emitting diode (LED) behaves similarly to the standard diode, with the exception that the voltage it starts allowing current to flow is based off of the colour or wavelength of light the diode emits, seen in Figure 6. Different colours require different semiconductor materials, which respond to different minimum voltages. This LED responds to roughly 1.9 volts.

2.3 Rectifiers

2.3.1.

The next exercise was to build and study half wave rectifiers. Rectifier circuits convert alternating into direct current. This can be used for applications such as converting transmission currents that are typically alternating into direct current for applications such as powering computers. A half wave rectifier only converts the positive flow of alternating current into direct current. One with no smoothing was constructed, shown in Figure 7.

a.

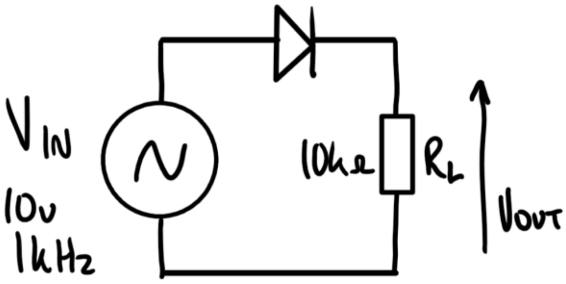


Figure 7 The first unsmoothed half wave rectifier circuit built.

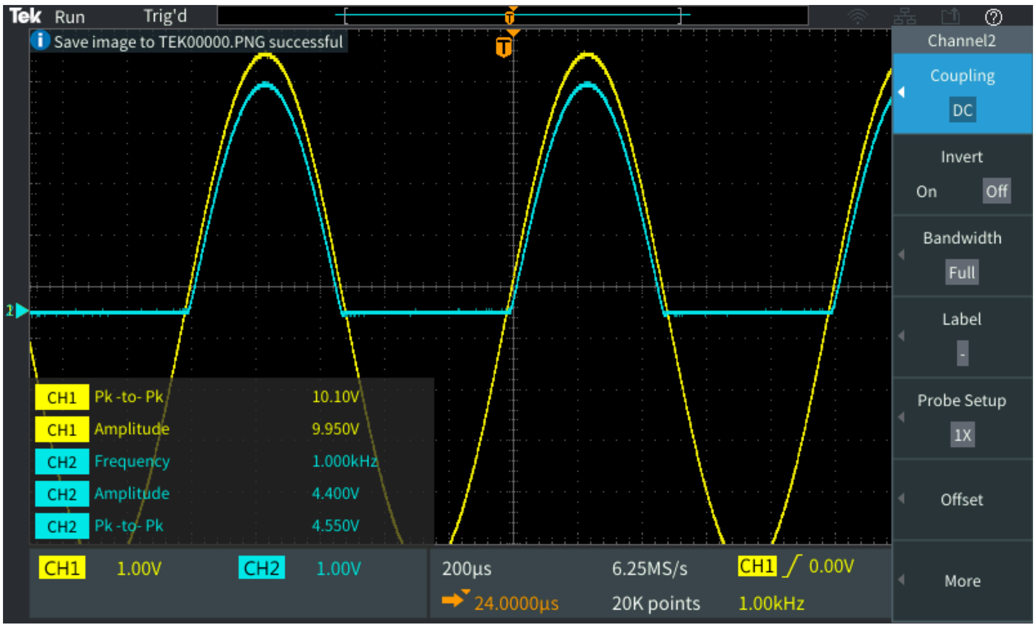


Figure 8 The output of the unsmoothed half wave rectifier. Voltage is halved as well as featuring a small further voltage drop. Negative voltage is removed.

The first circuit constructed was a half wave rectifier with no smoothing. It was to take in a 10V 1KHz input and have its output connected to a 10KΩ resistor. Looking at the input (channel 1) and output (channel 2) of the rectifier, voltage is roughly halved, as the negative part of the AC voltage is simply removed by the diode blocking reverse voltage and therefore lost. Additional losses V_D of roughly 0.5V are present also. As this circuit simply removes any negative part of the input current, its output is not optimal and is considered low quality for direct current.

b.

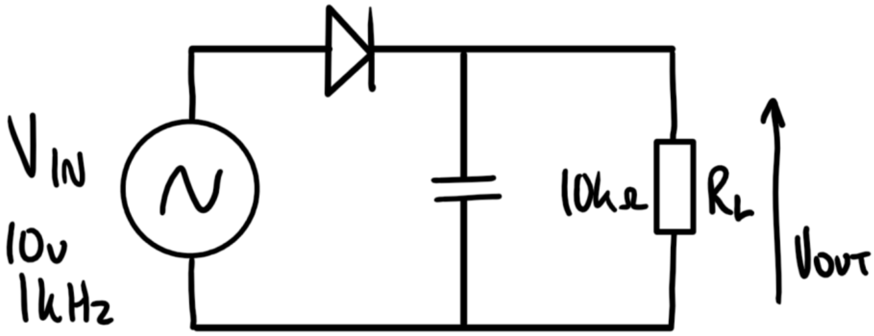


Figure 9 The period rectifier circuit with an added smoothing capacitor.

b. $T' = \frac{1}{f} = \frac{1}{1000}$ $\quad V_{max} = 4.55v \quad V_{min} = 4.55 \times 0.95 = 4.3225v$

$$RC = \frac{-T'}{\log\left(\frac{V_{min}}{V_{max}}\right)} \Rightarrow 10000 \times C = \frac{-\frac{1}{1000}}{\log(0.95)} \Rightarrow 10000 \times C = 0.04489056748 \Rightarrow C = 4.489 \times 10^{-6} F$$

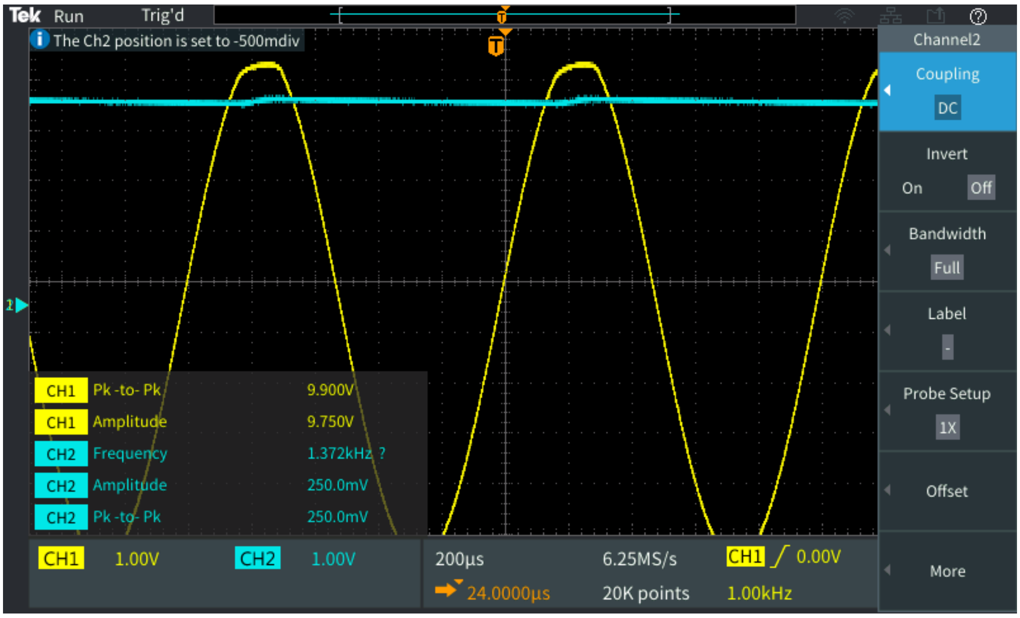


Figure 10 The output of the smoothed rectifier. A small ripple of roughly 5% can be seen. Clipping on the input voltage can also be seen.

To alleviate this, a smoothing capacitor was added to the circuit, shown in Figure 9. This works by having the capacitor charge during the rising portion of the alternating voltage input, and discharge where the voltage drops. A ripple voltage of 5% was required. This means the difference between the maximum and minimum output voltage was to be a maximum of 5%. To calculate the correct capacitor value to achieve this, the formula $RC = \frac{-T'}{log\left(\frac{v_{min}}{v_{max}}\right)}$, where R is the value of the resistor (10KΩ), C is the value of the capacitor, and $-T'$ is the time span where the capacitor discharges. As this is a half wave rectifier, the value would be the inverse of the input frequency. The ripple voltage requirement of 5% means we can replace $\frac{v_{min}}{v_{max}}$ with 95% or 0.95. Using these values, the value of the required capacitor equates to 4.489uF. For the circuit a 4.4uF capacitor was used. Looking at Figure 10 output is as expected – minus the losses V_D, the output is flat aside from a small ripple of 250mV, less than 5%. It is to be noted that the input voltage has had its peaks flattened slightly or is clipping.

This could be from the diode not being ideal, allowing some current through backwards, or it could be from the capacitor charging.

2.3.2.

The next task is to increase load on the rectifier, while maintaining the same ripple. This was done by reducing the resistor value, and requires increasing the capacitor value used to compensate. This is because more charge is required to smooth the higher load.

a.

$$RC = \frac{-T'}{\log\left(\frac{V_{min}}{V_{max}}\right)} \Rightarrow 1000 \times C = \frac{-\frac{1}{1000}}{\log(0.95)} \Rightarrow 1000 \times C = 0.04489056748 \Rightarrow C = 4.489 \times 10^{-5} F$$

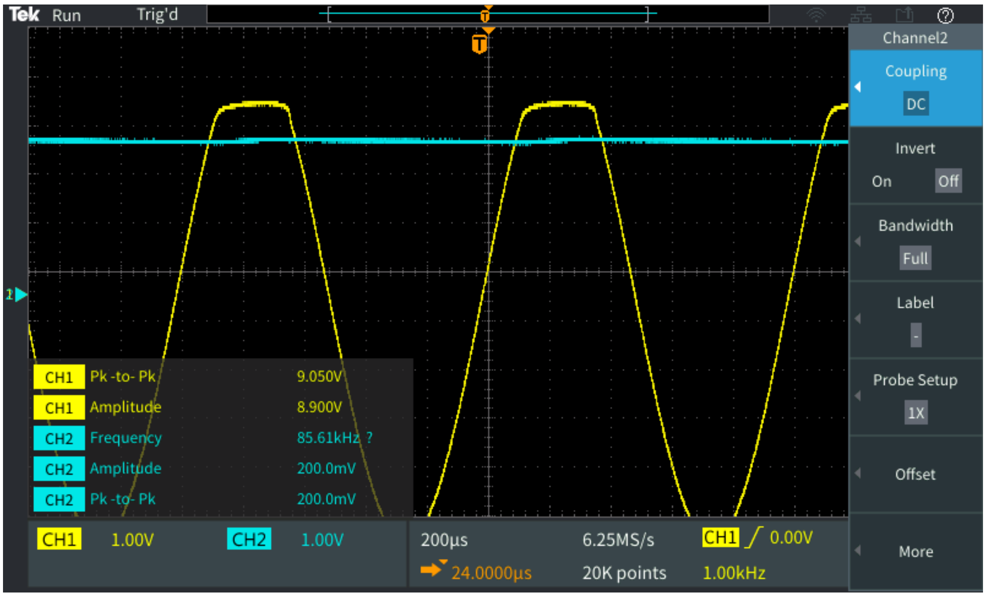


Figure 11 The modified rectifier built for higher loads. The ripple is still present, but the clipping the input voltage features is increased.

The first change was to substitute the 10kΩ resistor with a 1KΩ resistor. This would change the required capacitor value to 44.890uF (a 41.7nF capacitor was used in the circuit). Testing this confirms the rectifier continues to function correctly, as similar results are gained from the initial smoothed rectifier seen in Figure 11. It is to be noted that the clipping on the input voltage has become more extreme.

b.

$$RC = \frac{-T'}{\log\left(\frac{V_{min}}{V_{max}}\right)} \Rightarrow 100 \times C = \frac{-\frac{1}{1000}}{\log(0.95)} \Rightarrow 100 \times C = 0.04489056748 \Rightarrow C = 4.489 \times 10^{-4} F$$

The next change was to substitute the load resistor with a 100Ω resistor. This again requires a stronger capacitor still, with a value of 44.891mF. This was not tested as this value is quite large and potentially unsafe for the electronics laboratory. Multiple smaller capacitors could be used in parallel to substitute this however.

2.3.3.

Finally, the last test was to test different and lower input frequencies, changing capacitor values to maintain the 5% ripple. To do this, $-T'$ would be changed. As it is the period of the input wave, $-T'$ will increase.

a.

$$RC=\frac{-T'}{\log\left(\frac{V_{min}}{V_{max}}\right)} \Rightarrow 10000\times C=\frac{-\frac{1}{500}}{\log(0.95)} \Rightarrow 10000\times C=0.08978113496 \Rightarrow 8.978113496\times10^{-6}F$$

The first frequency change was down to 500HZ. This made $-T'$ become 1/500, changing the capacitor value to 8.978uF.

b.

$$RC=\frac{-T'}{\log\left(\frac{V_{min}}{V_{max}}\right)} \Rightarrow 10000\times C=\frac{-\frac{1}{50}}{\log(0.95)} \Rightarrow 10000\times C=0.8978113496 \Rightarrow 8.978113496\times10^{-5}F$$

The second frequency was 50Hz. This made $-T'$ become 1/50, changing the capacitor value to 89.781uF.

2.4 Buck converter

The final circuits to be built and studied are buck converters. Boost and Buck converters are a method of stepping up or down DC to DC voltage. A buck converter steps down the input DC voltage, and essentially works similarly to pulse width modulation (PWM). Essentially the circuit uses a transistor or switch to rapidly open and close the input current. The output then becomes the ratio between how long the circuit is open for to how long it is closed for. For example, if the circuit was closed for 20% of the time and open 80% of the time, the output DC voltage would roughly be 20% the input voltage. This can be expressed as $v_{out} = Dv_{in}$, where D is the percentage of time the circuit is spent closed. The period where the transistor or switch is closed is duty cycle period DT, and the period where it is open is $(1-D)T$.

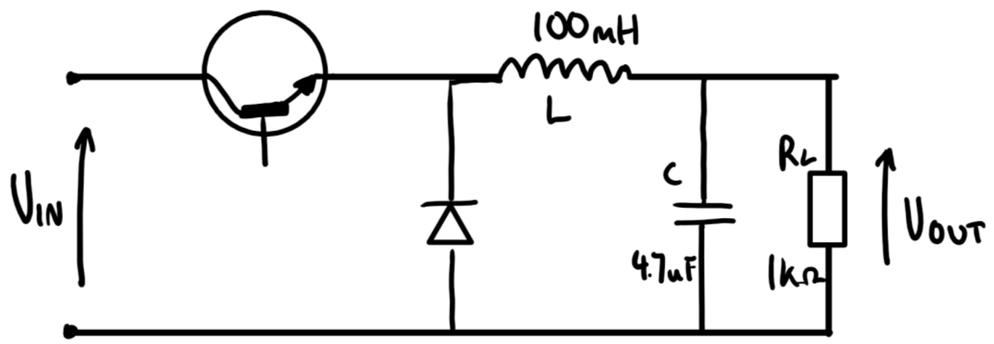


Figure 12 The buck converter that was built. The transistor and input voltage was replaced with a square wave generator.

2.4.1.

To verify this, the buck converter seen in Figure 12 was built where the transistor or switch was replaced with a square wave generator running at 100KHz. A load resistor of 1KΩ was used, with a smoothing capacitor of value 4.7uF, and an inductor of value 100mH. The duty cycle was then varied in regular intervals from 0% to 100%, and the output DC voltage across the load resistor measured.

Figure 13 The input and output of the buck converter at 99%, 1% and 50% duty cycle. Output follows input voltage multiplied with duty cycle, minus a small voltage drop.

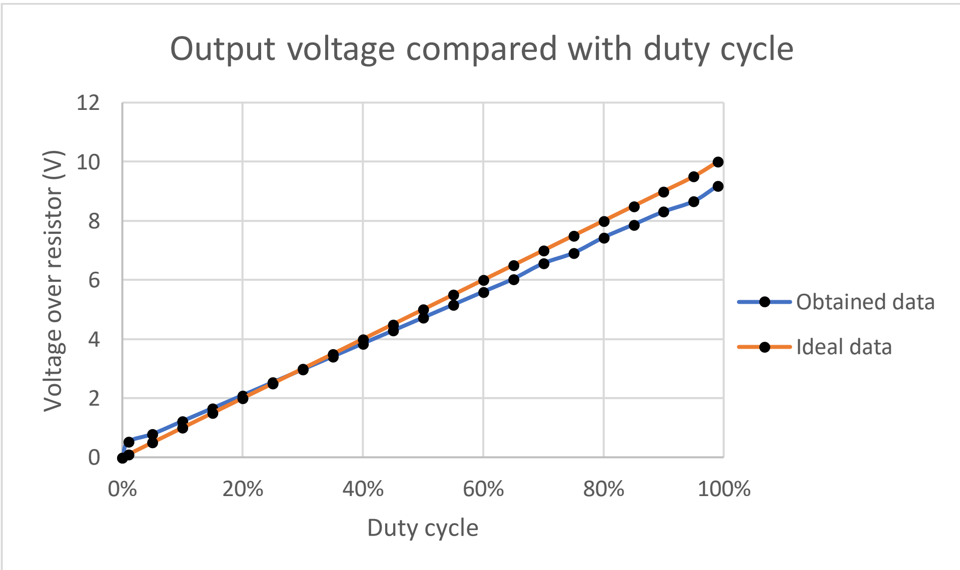


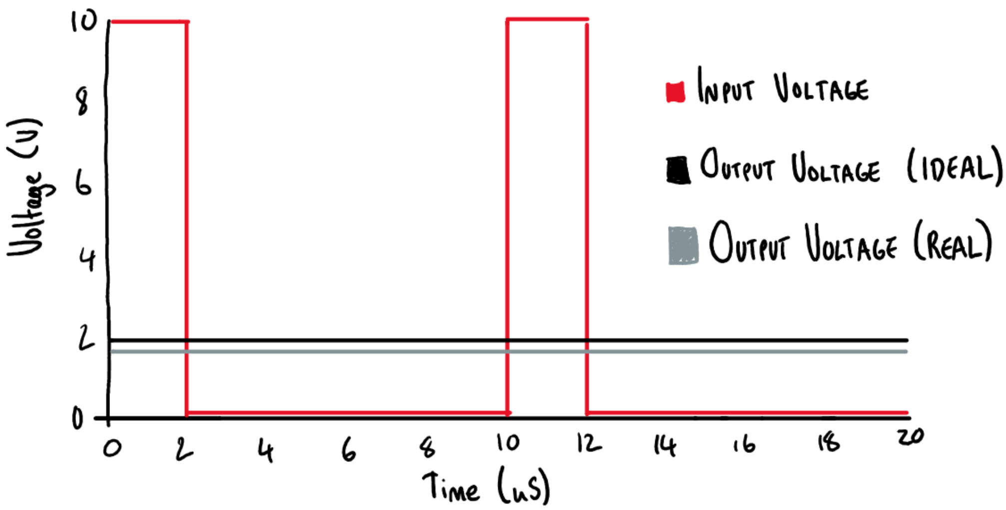
Figure 14 A graph of the output voltage in relation with duty cycle. It trends mostly ideally, with a slight offset in output voltage.

As per the results graph in Figure 14, the output voltage is directly proportional to the input voltage multiplied with the duty cycle – 50% duty cycle outputs roughly 50% of the input voltage. The circuit does exhibit some lost voltage the higher the duty cycle is. An example is at 99% duty, instead of outputting 9.9V, it outputs 9.187V. This could be from variance between ideal and actual values, as well as potential internal resistances of components.

2.5 Questions

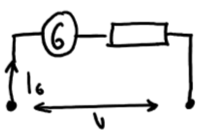
A. $f = \frac{1}{T}$ $T = 10us = 1 \times 10^{-6} s$ $f = 1000000 = 1MHz$

$D = 20\% = 0.2$



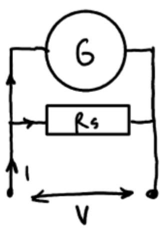
B. a. $I_{max} = 100uA$ $R = 10\Omega$ Max Voltage $= 1mV$ $V = 50v$

$$R_{Shunt} = \frac{V}{I_G} - R_G = \frac{50}{100 \times 10^{-6}} - 10 = 499990\Omega \approx 500k\Omega$$



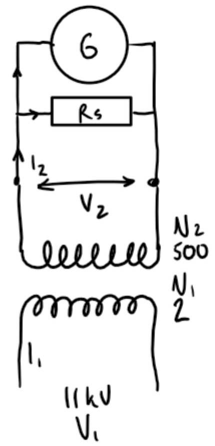
b. $I_{max} = 100uA$ $R = 10\Omega$ Max Voltage $= 1mV$ $I = 2A$

$$R_{Shunt} = \frac{I_G \times R_G}{(I - I_G)} = \frac{100 \times 10^{-6} \times 10}{(2 - 100 \times 10^{-6})} = \frac{10}{19999}\Omega = 5.000250013 \times 10^{-4}\Omega \approx 5 \times 10^{-4}\Omega$$



c. 500A 11kV

$\frac{I_1}{I_2} = \frac{N_2}{N_1}$ $\frac{500}{2} = \frac{N_2}{N_1} = \frac{250}{1}$ $N_2 = 250$ $V_2 = I_2 \times R_A = 2 \times 10 = 20v$



d. There would be incredibly high voltage, both dangerous and component damaging.

$$V_2 = V_1 \frac{N_2}{N_1} = 11000 \times \frac{500}{2} = 2750000v$$

C. a. $\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{11000}{550} = 20$ 20:1

b. $I_1 = \frac{N_2}{N_1} \times I_2 = \frac{10}{20} = 0.5A$

c. $P_2 = 550 \times 10 = 5500 \times \frac{100}{95} = 5789.47368421053W$

D. a. 400 kV EHV, 132 kV HV, 33kV MV, 11kV MV, 400/230 LV

Extra high voltage, High voltage, Medium voltage, Medium voltage, Low voltage

b. $P = IV$

(EHV) $5000000 = I \times 400000$, $I = 12.5A$

(HV) $5000000 = I \times 132000$, $I = 37.8\dot{7}\dot{8}A$

(MV) $5000000 = I \times 33000$, $I = 151.\dot{5}\dot{1}A$

(MV) $5000000 = I \times 11000$, $I = 454.\dot{5}\dot{4}A$

(LV) $5000000 = I \times 400$, $I = 12500A$

(LV) $5000000 = I \times 230$, $I = 21739.1304347826lA$

c.

Trading high current and low voltage for high voltage and low current greatly reduces power loss from power lines through heat, increasing efficiency. This is because power loss through transmission lines is proportional to the current flowing through them. Trading current for voltage allows for the transmission of the same amount of power while reducing current. For example, transmitting at 1000V vs 10000V. 100kW/1000V = 100A, and 100A Squared x R = 10kW of power lost through heat. Meanwhile 100kW/10000V = 10A, and 10A Squared X R = 100W of power lost through heat.

This conversion can be done with transformers at either end of the transmission line, stepping up and then down voltage. For example, a voltage of 230V and 23A can be stepped up to 2300V and 2.3A with a 1:100 turn transformer for transmission, reducing power loss from 23 Squared x R to 2.3 Squared x R. The opposite can then be done at the destination to return to 230V.

3 Discussion and Conclusions

This assignment served to demonstrate a few key processes of electricity generation and distribution, and how the real-world circuits relate to theory. An example of inducing and generating alternating current was performed and analysed, methods converting said current into direct current was performed including exploring the behaviour of components crucial to the process, and stepping the resultant direct current down was also performed. These processes are essentially a simplified version of real-world electricity generation and distribution, bar a few processes such as synchronising generators and transforming AC to AC current. Electricity or alternating current is generated with generators at a power station, transported and distributed over the national grid, then potentially converted to direct current and used in applications such as the home. A few things are of note. There are some differences between ideal and real circuits. For example, many of the components and constructed circuits featured slight voltage drops that would not be present in an ideal design. The input voltage clipping with the rectifier is another example of features that are not present in ideal circuits. This must be accounted for in designs used in the real world. Another consideration for the real world is available components. For example, capacitors of a high enough value were not available for testing higher loads for the rectifier.

Bibliography

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2.2

- Lecture week 9: Voltage rectifiers, Inverters, Buck & Boost converters, slide 8
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2.3

- Lecture week 9: Voltage rectifiers, Inverters, Buck & Boost converters, slides 21-27

2.4

- Lecture week 9: Voltage rectifiers, Inverters, Buck & Boost converters, slides 37-42

2.5

- Why is electricity transmitted at high voltages? - Solved (electricalclassroom.com)
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- Lecture week 10: Transformers, transmission lines, Asynchronous generators, slides 4-9, 17, 26, 30-39