POWER ELECTRONICS PROJECT

EEE3091F

Prepared By:

Zaheer Dhunny - DHNZAH002

Ronak Mehta - MHTRON001

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Part One – Theoretical Calculations (Pre-Lab)

(a) Assuming an ideal diode and applying KVL to the circuit,

$$V1\sin(\omega t) = Ri(t) + L\frac{di(t)}{dt}$$

The solution can be obtained by expressing the current as the sum of the forced response and the natural response.

$i(t) = i_f(t) + i_n(t)$

The forced response for this circuit is the current that exists after the natural response has been decayed to zero. In this case, the forced response is the steady-state sinusoidal current that would exist in the circuit if the diode was not present. From Phasor analysis,

$$if(t) = \frac{V1}{Z}\sin(\omega t - \theta)\ ,where\ Z = \sqrt{R^2 + (\omega L)^2}\ and\ \theta = \arctan(\frac{\omega L}{R})$$

The natural response is the transient that occurs when the load is energized. It is the solution to the homogeneous differential equation for the circuit without the source or diode:

$$Ri(t) + L\frac{di(t)}{dt} = 0$$

Therefore, $in(t) = Ae^{-\frac{t}{T}}$, where A is a constant and $T = \frac{L}{R}$

$i(t) = i_f(t) + i_n(t)$

$i(t) = \frac{V1}{Z}\sin(\omega t - \theta) + Ae^{-\frac{t}{T}}$

A can be found by using the initial condition. The initial condition of output current is zero.

$i(0) = \frac{V1}{Z}\sin(0 - \theta) + Ae^{-\frac{0}{T}} = 0$

Hence, $A = \frac{-V1}{Z}\sin(-\theta) = \frac{V1}{Z}\sin(\theta)$

$i(t) = \frac{V1}{Z}\sin(\omega t - \theta) + \frac{V1}{Z}\sin(\theta)\, e^{-\frac{t}{T}}$

$i(t) = \frac{V1}{Z}\ [\sin(\omega t - \theta) + \sin(\theta)\, e^{-\frac{t}{T}}]$, i(t) can be written as in terms of angle ωt,

$i(\omega t) = \frac{V1}{Z}\ [\sin(\omega t - \theta) + \sin(\theta)\, e^{-\frac{\omega t}{\omega T}}]$ ……………………………………………………………………(1)

The output current is zero when the diode turns off. The first value of ωt that results in zero current is called the extinction angle β. Substituting ωt = β in (1),

$\sin(\beta - \theta) + \sin(\theta)\, e^{-\frac{\beta}{\omega T}} = 0$ [The extinction angle, β can be found using a numerical method]

$$\mathbf{i(\omega t) = \frac{V1}{Z}\ [\sin(\omega t - \theta) + \sin(\theta)\ e^{-\frac{\omega t}{\omega T}}]\ \text{for } 0 \leq \omega t \leq \beta}$$

$$\mathbf{i(\omega t) = 0 \qquad \text{for } \beta < \omega t \leq 2\pi}$$

$$\boldsymbol{where\ Z = \sqrt{R^2 + (\omega L)^2}\ , \theta = \arctan(\tfrac{\omega L}{R})\ \text{and}\ T = \tfrac{L}{R}}$$

(b) $Z = \sqrt{R^2 + (\omega L)^2} = \sqrt{50^2 + (2\pi(50)(0.2))^2} = 80.30\ \Omega$

$\theta = \arctan(\frac{\omega L}{R}) = \arctan(\frac{2\pi(50)(0.2)}{50}) = 0.8986$ rad

$\omega T = \frac{\omega L}{R} = \frac{2\pi(50)(0.2)}{50} = 1.257$ rad

$V_1 = 25\sqrt{2} = 35.4$ V

Using a numerical method, β is found to be 4.072 rad (233.3° or 12.96 ms)

$$i(\omega t) = 0.4403\ [\sin(\omega t - 0.8986) + 0.3443e^{-\frac{\omega t}{1.257}}]\ \text{for } 0 \leq \omega t \leq 4.072$$

$$i(\omega t) = 0 \qquad \text{for } 4.072 < \omega t \leq 2\pi$$

$I_{dc} = \frac{1}{2\pi}\int_0^{\beta} i(\omega t)d(\omega t) = \frac{1}{2\pi}\int_0^{4.072}(0.4403\ [\sin(\omega t - 0.8986)\ +\ 0.3443e^{-\frac{\omega t}{1.257}}]\ )d(\omega t)$

$I_{dc} =$ **180 mA**

$V_{dc} = I_{dc}R = (180\text{mA})\ (50) = 9\text{V}$ [required for part four]

(c) $I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i^2(\omega t)d(\omega t)} = \sqrt{\frac{1}{2\pi}\int_0^{\beta} i^2(\omega t)d(\omega t)}$

$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{4.072}(0.4403\ [\sin(\omega t - 0.8986)\ +\ 0.3443e^{-\frac{\omega t}{1.257}}]\ )^2 d(\omega t)}$

$I_{rms} =$ **260 mA**

$V_{rms} = \sqrt{\frac{1}{T}\int_0^{T} v^2(t)dt} = \sqrt{\frac{1}{0.02}\int_0^{0.01296}(35.4 sin(314.2t))^2 dt} = 18.9$ V [required for part four]

(d) $P = (I_{rms})^2R = (0.260)^2(50) =$ **3.39 W**

(e) $pf = \frac{P}{S} = \frac{P}{IrmsVrms} = \frac{3.39}{(0.260)(25)} =$ **0.522**

Part Two – Simulations in LTspice

Question 1

(a) **Source voltage, Vs**

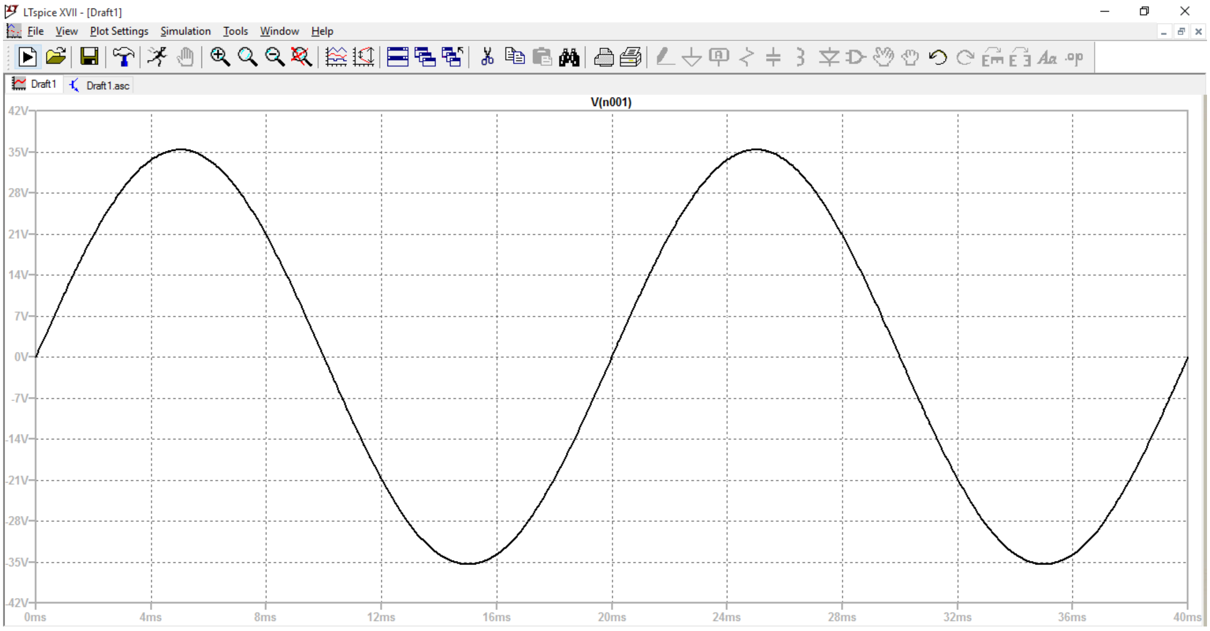


Figure 1: Waveform of source voltage

(b) **Voltage across the diode, V_d**

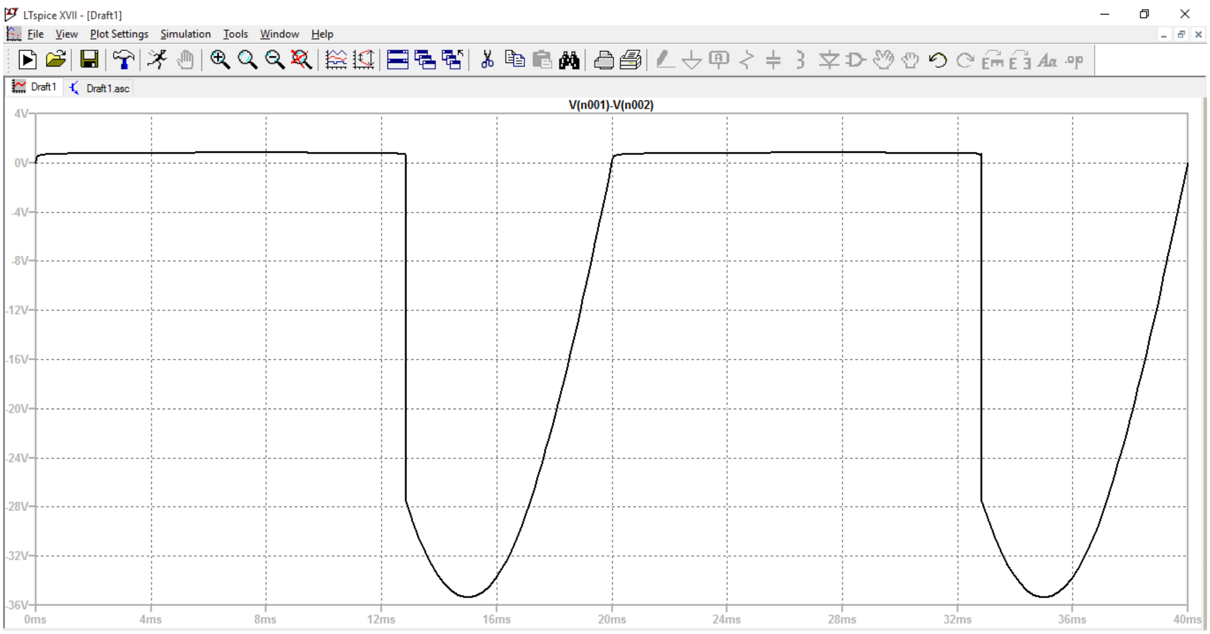


Figure 2: Waveform of voltage across diode

(c) **Output voltage, V_o**

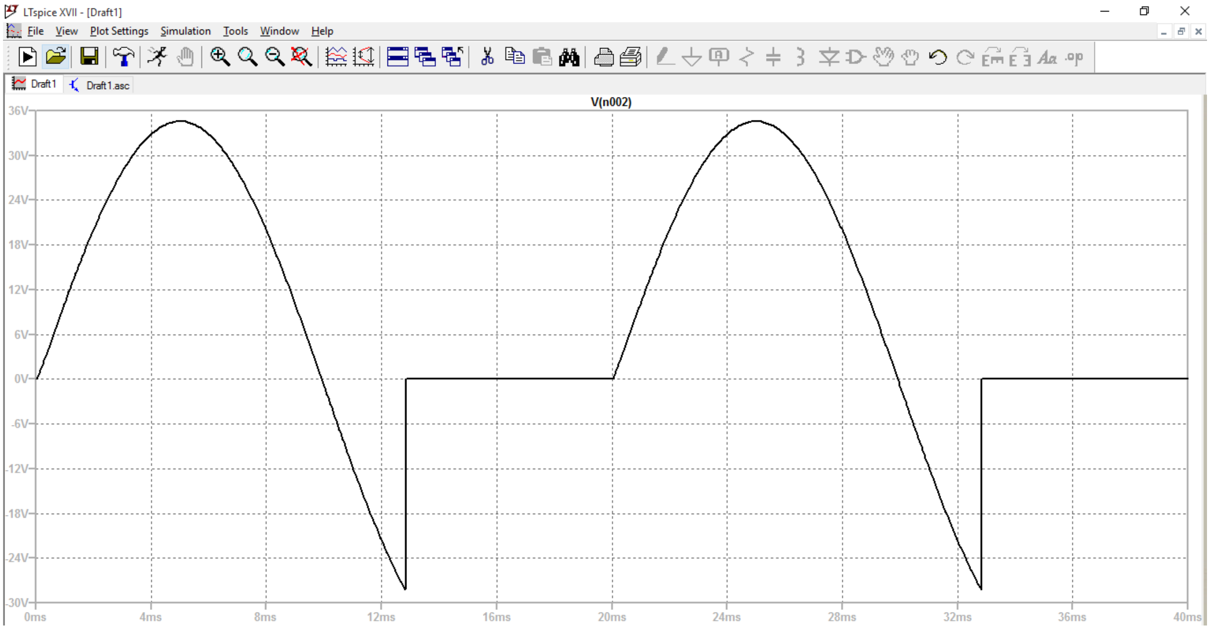


Figure 3: Waveform of output voltage

(d) **Load current, I_o**

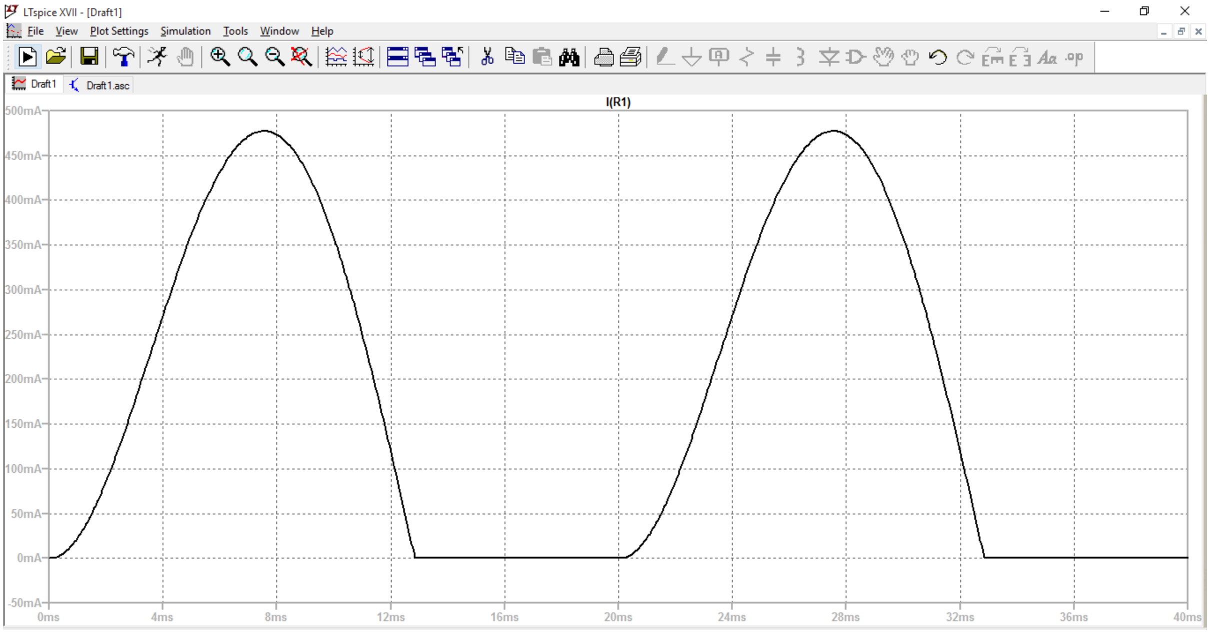


Figure 4: Waveform of load current

Question 2

(a) $\beta = 12.88 \text{ ms} * 2\pi (50)$

$\beta = 4.05 \text{ rad } (231.8°)$

(b) $I_{dc} = 173 \text{ mA}$

(c) $I_{rms} = 252 \text{ mA}$

It can be seen that the extinction angle, the average load current and the rms load current are smaller but still close to the theoretical vales obtained in part one. This is due to the assumption that the diode is ideal in part one.

Question 3

When the source voltage becomes negative, the diode is now reverse biased. As a result, the load current starts to decrease and the voltage across the inductor goes negative from $V_L = L\frac{di(t)}{dt}$. The direction of current must be maintained, and the only way that this can happen is if the non-ground end of the inductor goes to a negative voltage. The diode continues to conduct until the current becomes zero.

Question 4

(a) **Source voltage, Vs**

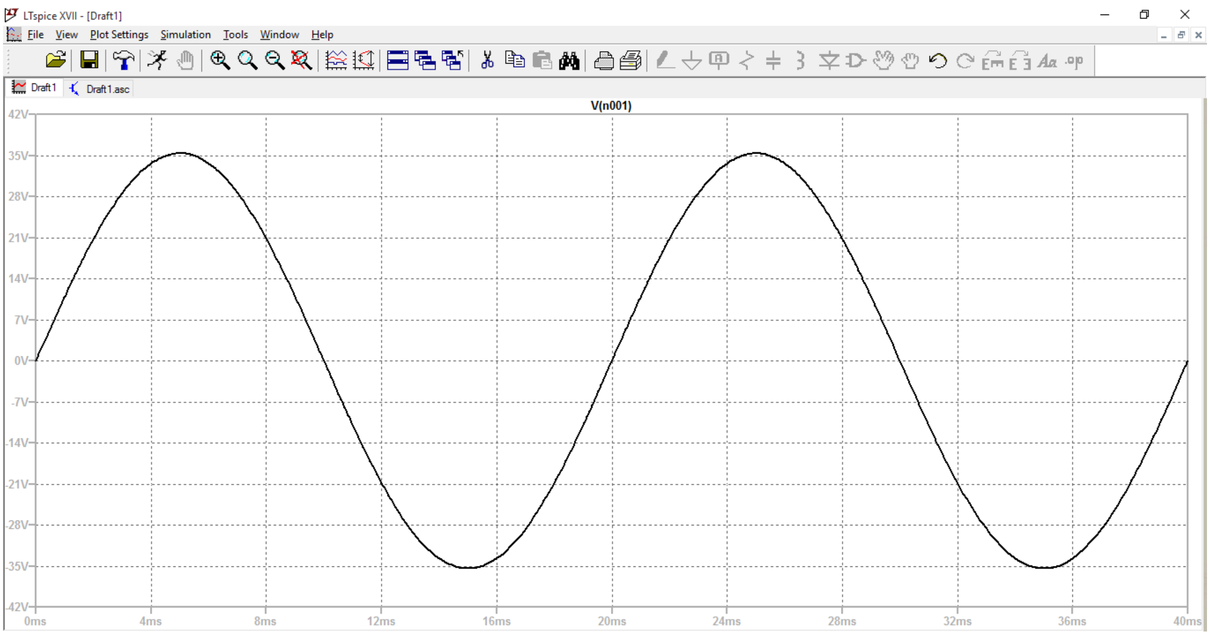


Figure 5: Waveform of source voltage

(b) **Voltage across the diode, V_d**

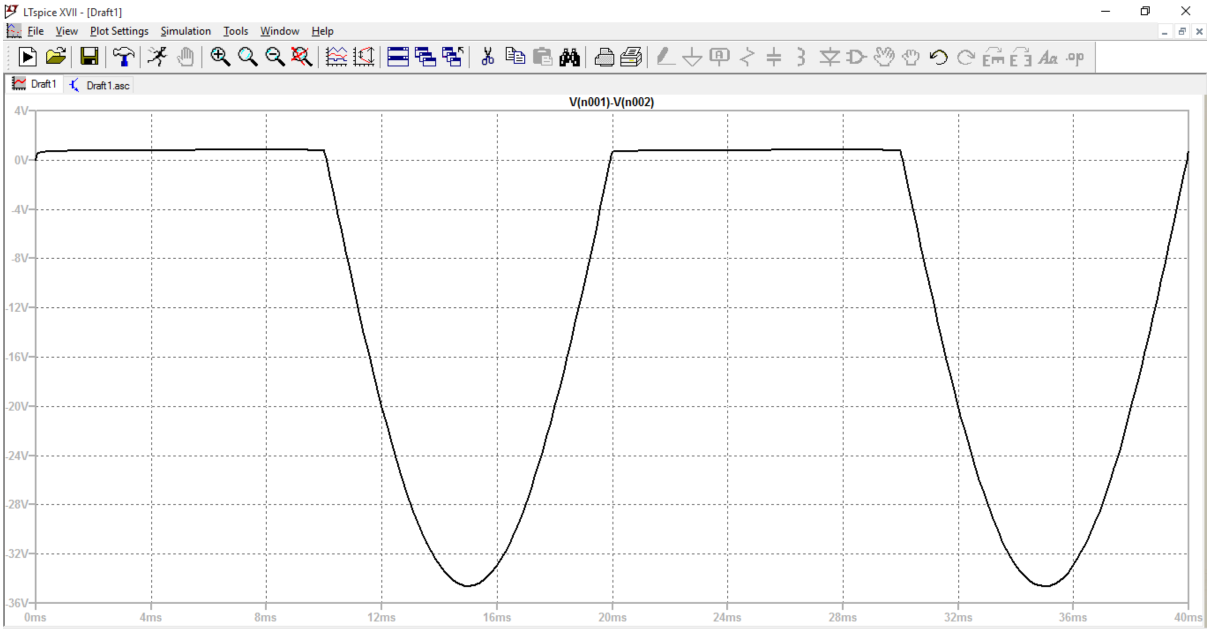


Figure 6: Waveform of voltage across diode

(c) **Output voltage, V_o**

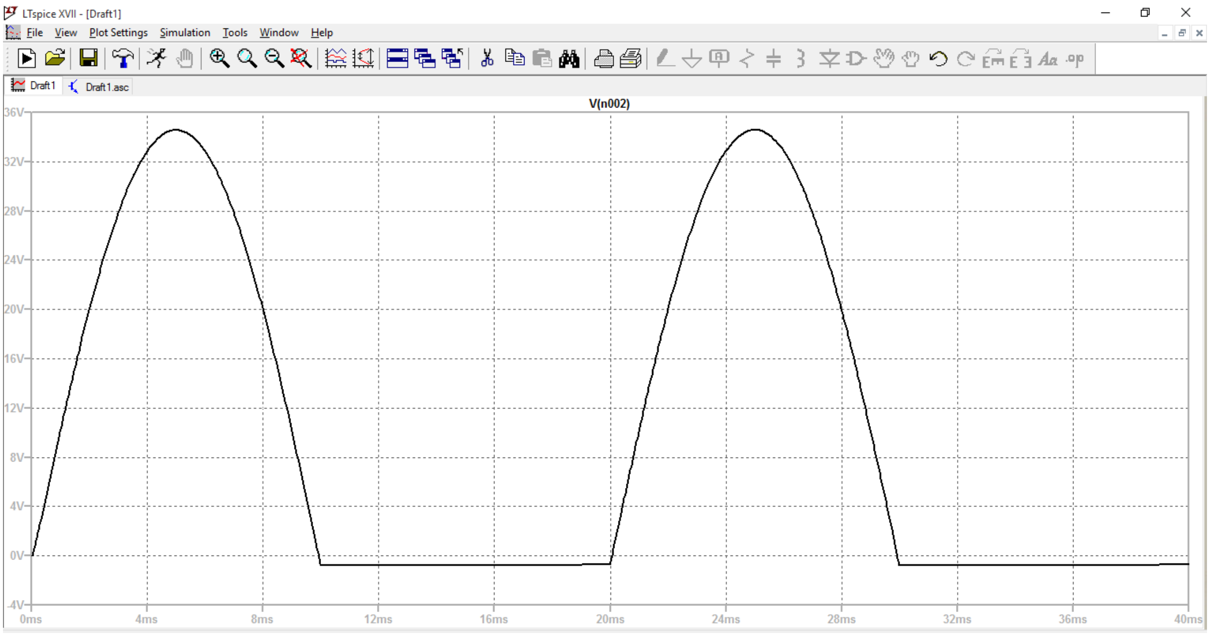


Figure 7: Waveform of output voltage

(d) **Load current, I_o**

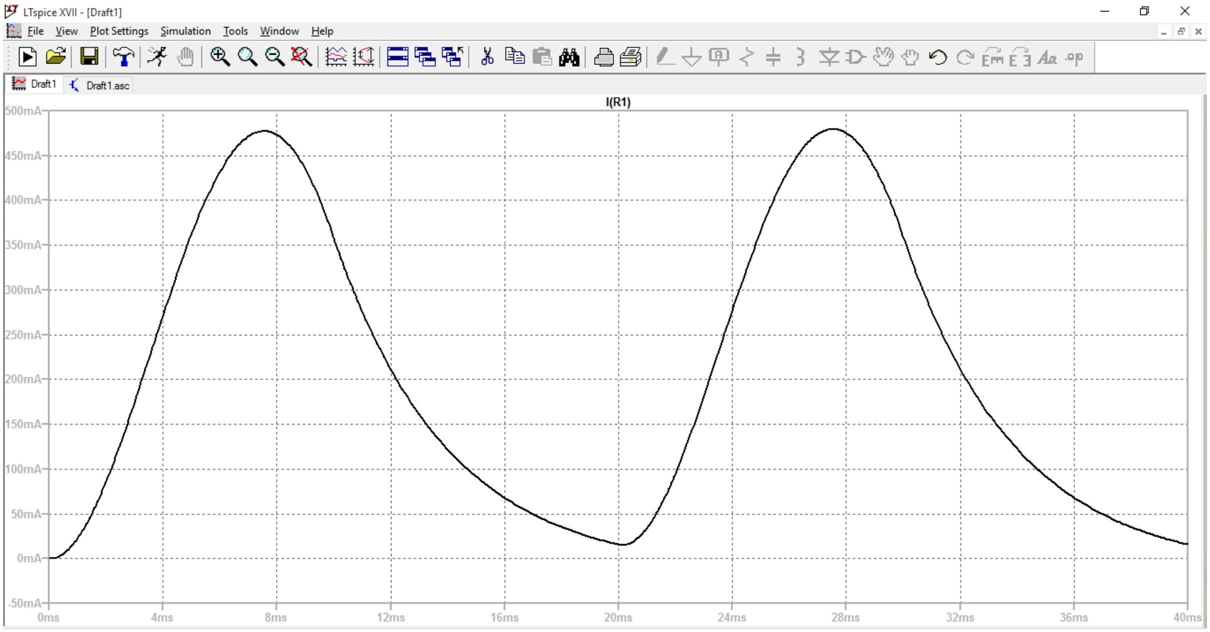


Figure 8: Waveform of load current

The supply voltage stays the same as expected.

When the source voltage is positive, the series diode conducts and the voltage across the diode is around 0.7 V as before but as the source voltage goes negative, the series diode stops conducting and the freewheeling diode starts conducting and the voltage across the series diode is -34.7V due to forward biased voltage drop of the freewheeling diode.

When the source voltage is positive, the output voltage is the same as before but as the source voltage goes negative, the output voltage still goes to negative but only to around -0.7V (forward biased voltage drop of freewheeling diode) this time and it stays at around -0.7 V until the next cycle. (For an ideal diode the output voltage is always positive).

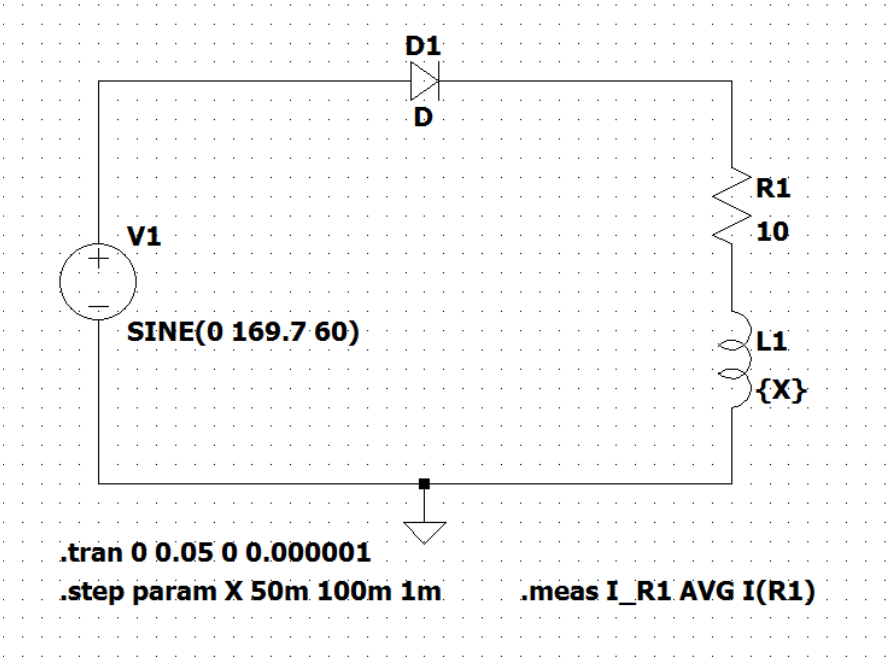
The load current is now continuous for the whole cycle compared to the load current before the addition of the freewheeling diode. It can be said that the load current has been made DC.

Question 5

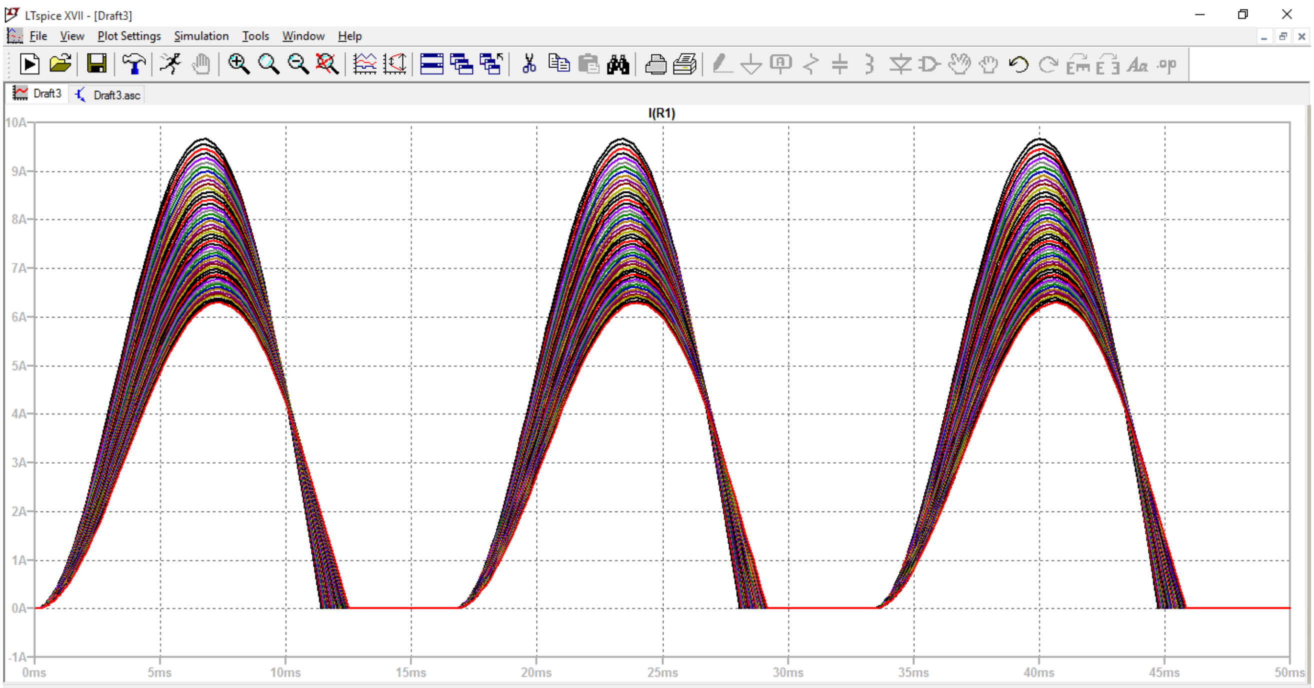
By adding a freewheeling diode across the RL load and making the load time constant ($T = \frac{L}{R}$) large enough, the load current in the circuit can be made continuous.

Part Three – Rectifier Design using LTspice

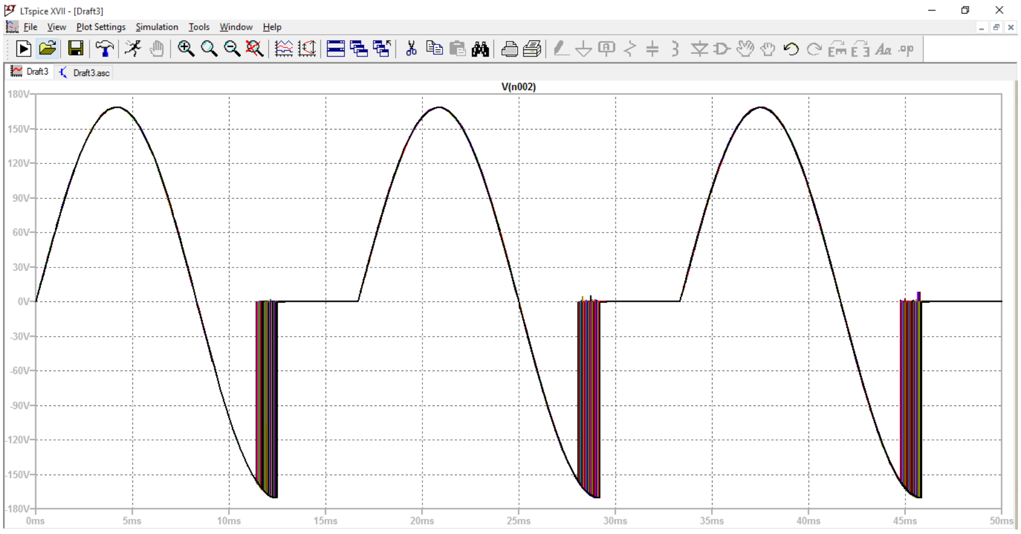
The half-wave rectifier is designed as shown below. Parametric sweep (.STEP command) is used in order to look for the inductance value which make the average current 3 A. After several trials, the correct inductance is found to be between 50mH and 100mH. Another parametric sweep ranging from 50mH and 100mH, stepping 1mH each time, is done. A way to get more comprehensible results is to use .measure directive to find the average load current for each stepped inductance value. These measurements are found in the "SPICE Error Log" and a graph of average load current against inductance is plotted.



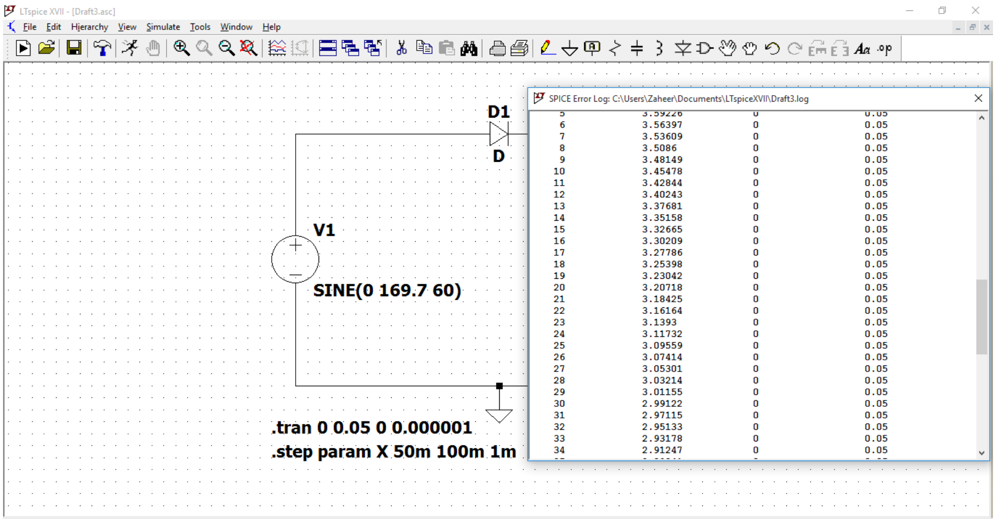
Parametric plot of load current



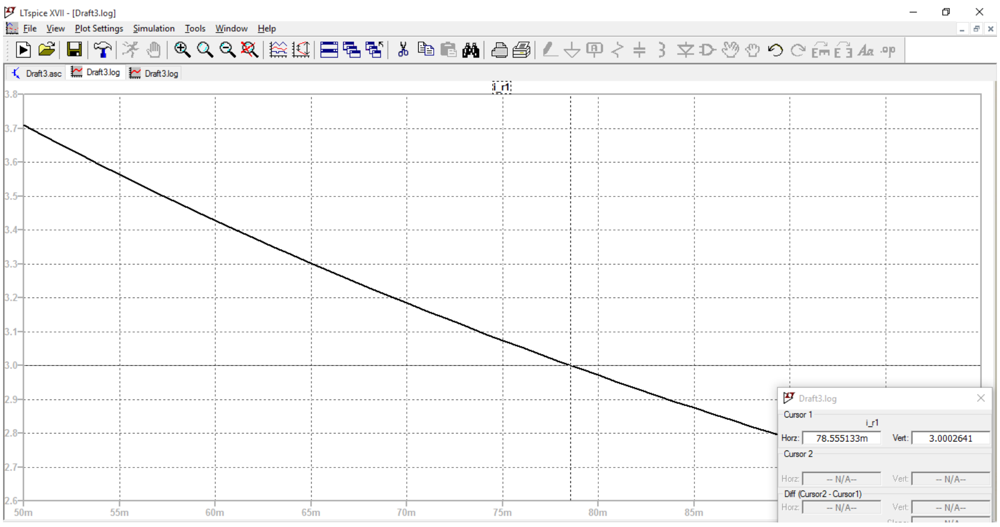
Parametric plot of output voltage



SPICE Error Log showing measured average load current

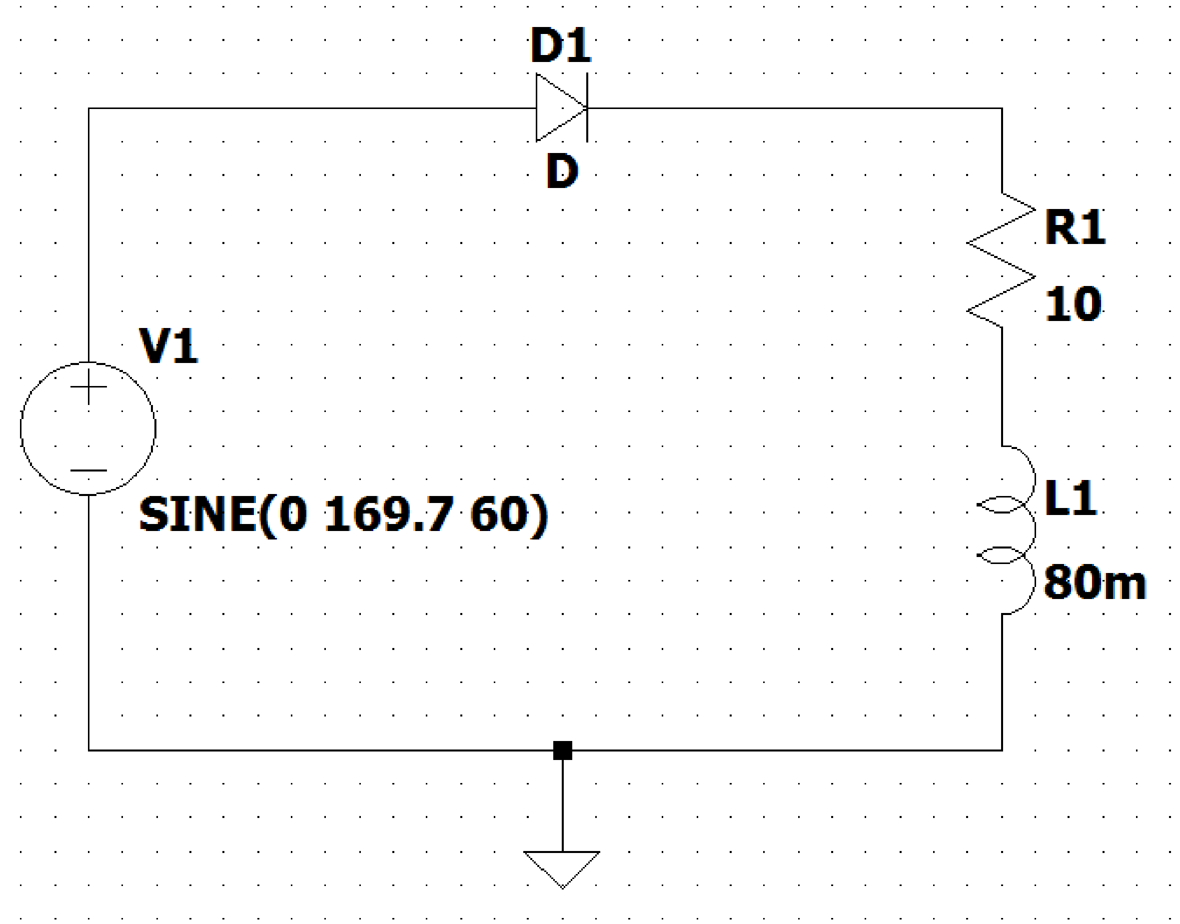


Graph of average load current against inductance



The exact value for the inductance is found to be 78.6 mH. We are going to round it off to 80 mH.

FINAL DESIGN



WAVEFORM OF OUTPUT VOLTAGE OF FINAL DESIGN

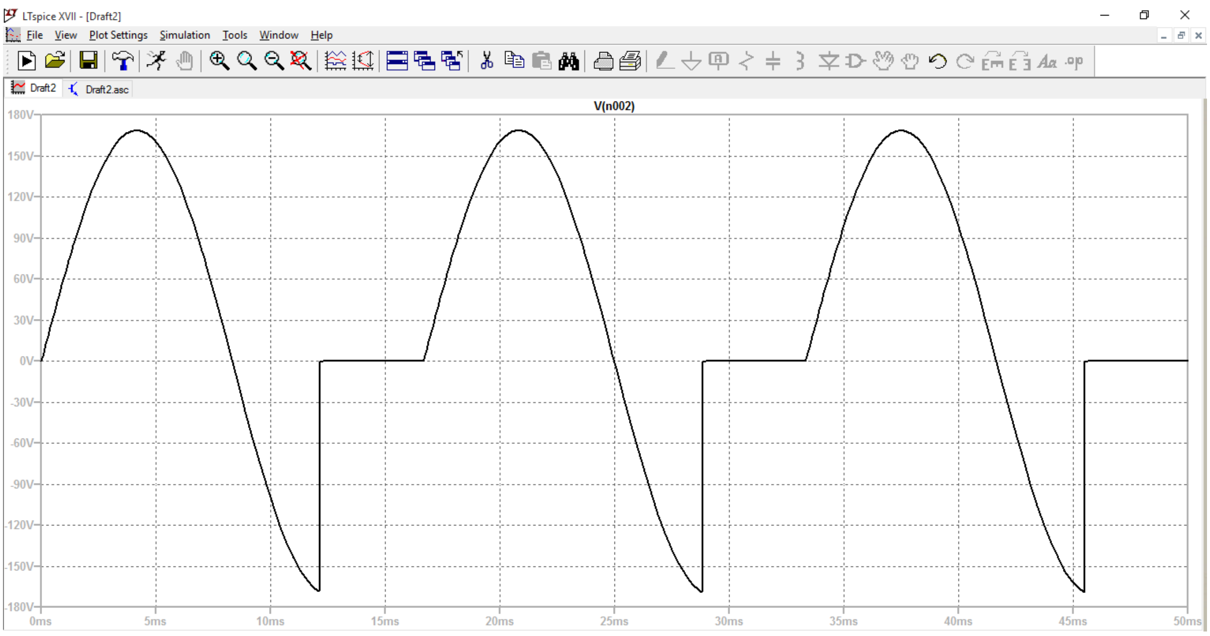


Figure 9: Waveform of output voltage

<u>WAVEFORM OF LOAD CURRENT OF FINAL DESIGN</u>

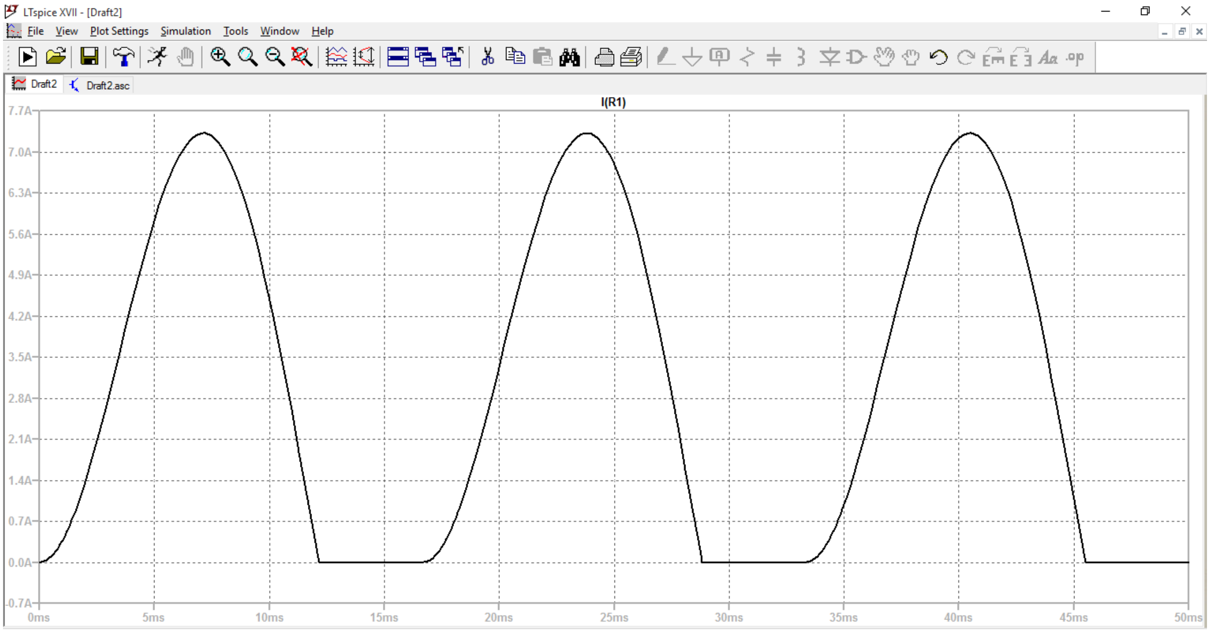


Figure 10: Waveform of load current

Part Four – Experimental Results

(a)

Load Resistor (Ω)	V_{dc} (V) [Experimental]	I_{dc} (mA) [Experimental]	V_{dc} (V) [Theoretical]	I_{dc} (mA) [Theoretical]
20	10.82	544.9	11.2	562.1
50	10.85	217.8	11.2	224.9
90	10.97	118.9	11.2	124.9

From theory we know, $V_{dc} = \frac{Vm}{\pi}$ (2) , $I_{dc} = \frac{Vm}{\pi R}$ (3)

In the derivation to get equations 2 and 3, we assume that the diode is ideal and so the output voltage is equal to the source voltage. But a practical diode has a forward voltage drop across it and this causes smaller average voltages and currents. In addition to this, the rms voltage set up in the lab is not exactly 25 V rms.

(b)

Inductor (mH)	V_{dc} (V)	I_{dc} (mA)	V_{rms} (V)	I_{rms} (mA)	β(°)	Δt(ms)
200	8.54	173.0	18.2	254.8	226.8	12.6
400	6.73	128.6	19.9	186.1	255.6	14.2
600	5.52	101.7	21.1	144.6	266.4	14.8

Theoretical → V_{dc} = 9 V, I_{dc} = 180 mA, I_{rms} = 260 mA, V_{rms} = 18.9 V

LTspice → V_{dc} = 8.64 V, I_{dc} = 173 mA, I_{rms} = 252 mA, V_{rms} = 18.4 V

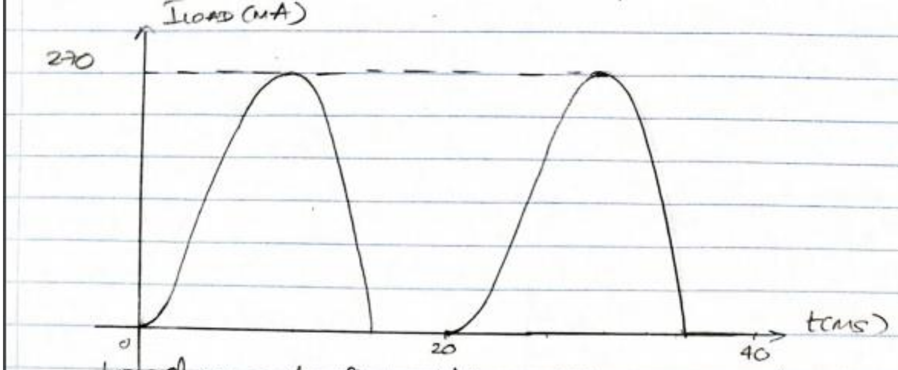
Experimental → V_{dc} = 8.54 V, I_{dc} = 173.0 mA, I_{rms} = 254.8 mA, V_{rms} = 18.2 V

In the derivation to get the average and effective (RMS) values, we assume that the diode is ideal and so the output voltage is equal to the source voltage. But a practical diode has a forward voltage drop across it and this causes smaller average and effective (RMS) voltages and currents compared to the theoretical ones. The values obtained from LTspice are different from the practical ones as the voltage drop across the diode is not the same as a different model is used. Also, the voltage drop across the diode does not stay constant and may vary throughout the experiment. In addition to this, the rms voltage set up in the lab is not exactly 25 V rms.

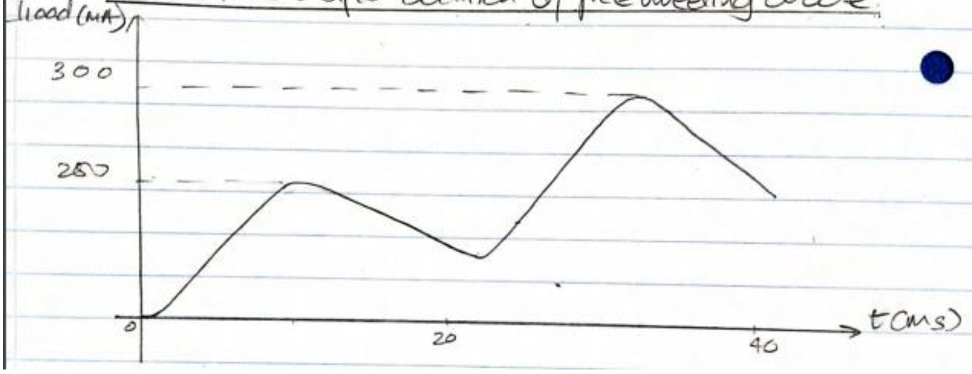
(c) The freewheeling diode prevent negatives voltage appearing across the load for an ideal diode but for a practical diode the output voltage goes to around -0.7V when the source voltage goes negative.

A large inductor with a freewheeling diode provides a mean of establishing a nearly constant load current. The current is now continuous as shown in the figure below. By large inductor, it is meant that $\frac{L}{R}$ >> T.

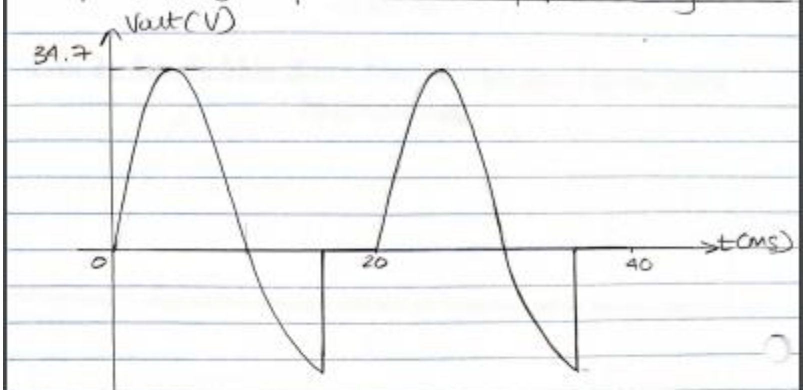
Load current before addition of freewheeling diode



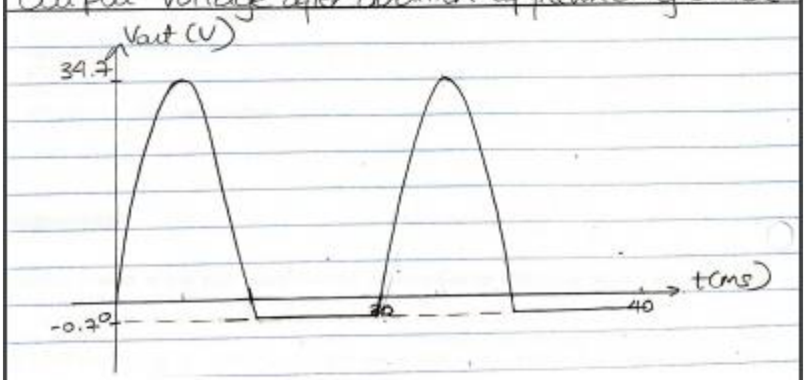
Load current after addition of freewheeling diode



Output voltage before addition of freewheeling diode



Output voltage after addition of freewheeling diode



(d)

Capacitor (μF)	V_{dc} (V)
22	11.16
470	24.91

The function of the output capacitor is to reduce the variation in the output voltage making it more DC. The output voltage ripple is reduced by increasing the filter capacitor C_1. Therefore, to make the output voltage more DC, we increase the capacitance of C_1.