Objective:

To design and simulate a wattmeter that will output power signal (AC) as well as the average power (DC).

Overview:

Following components will be used in the wattmeter:

- Voltage (De)Amplifier : converts the voltage in usable values
- Current to Voltage converter : converts current into voltage of usable values
- Multiplier : multiplies two signals v_1 and v_2 and outputs a signal kv_1v_2 (k is some constant)
- Low pass filter : To filter the AC signal and get the DC component of power signal which is equal to kP_{avg} where P_{avg} is the average power of signal
- Analog to Digital Converter : to convert the DC signal from low pass filter into digital format

Components Required:

- Operational Amplifiers
- n channel MOSFETs
- Resistors

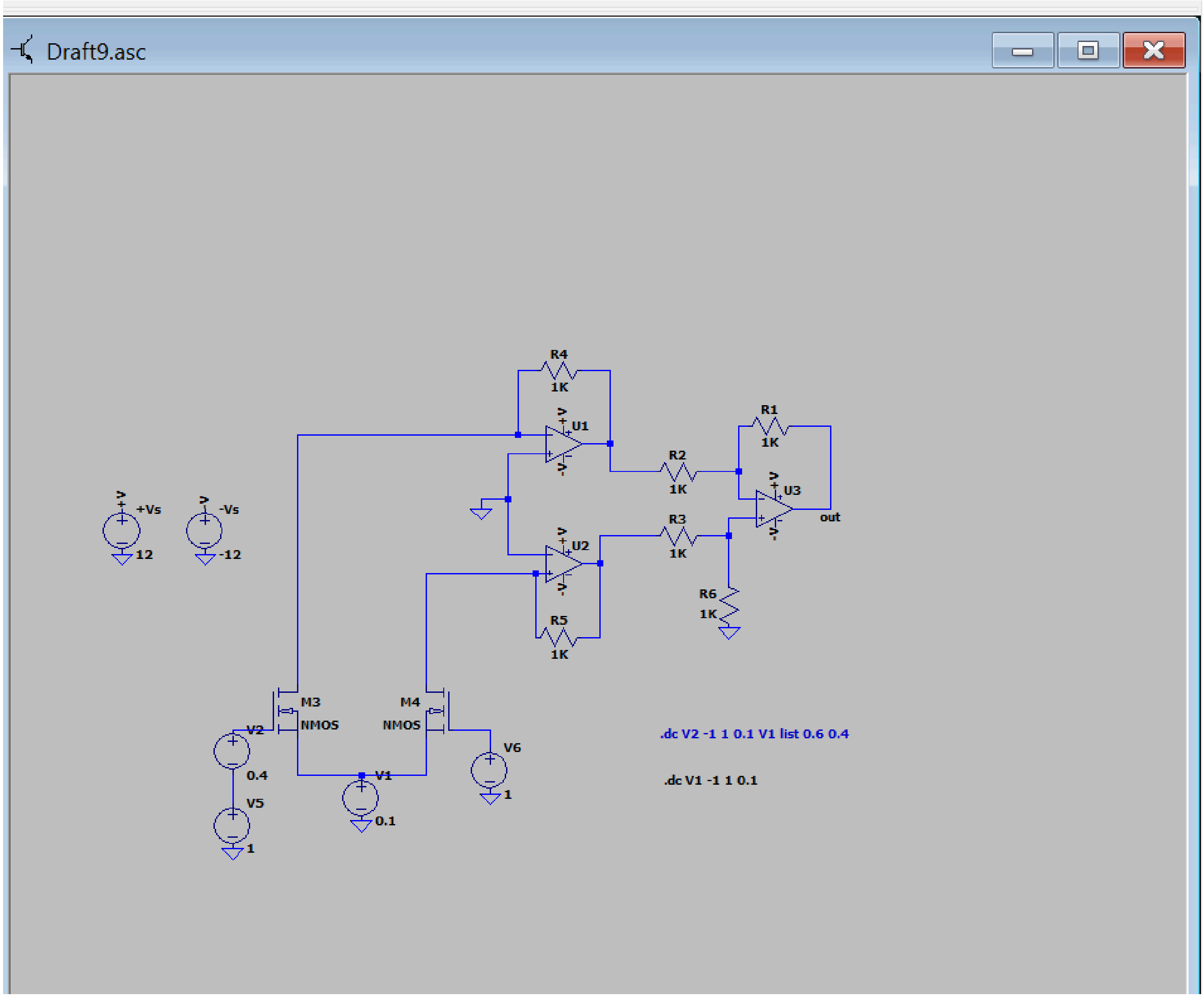
Analysis of Sub-Circuits:

1. Multiplier:

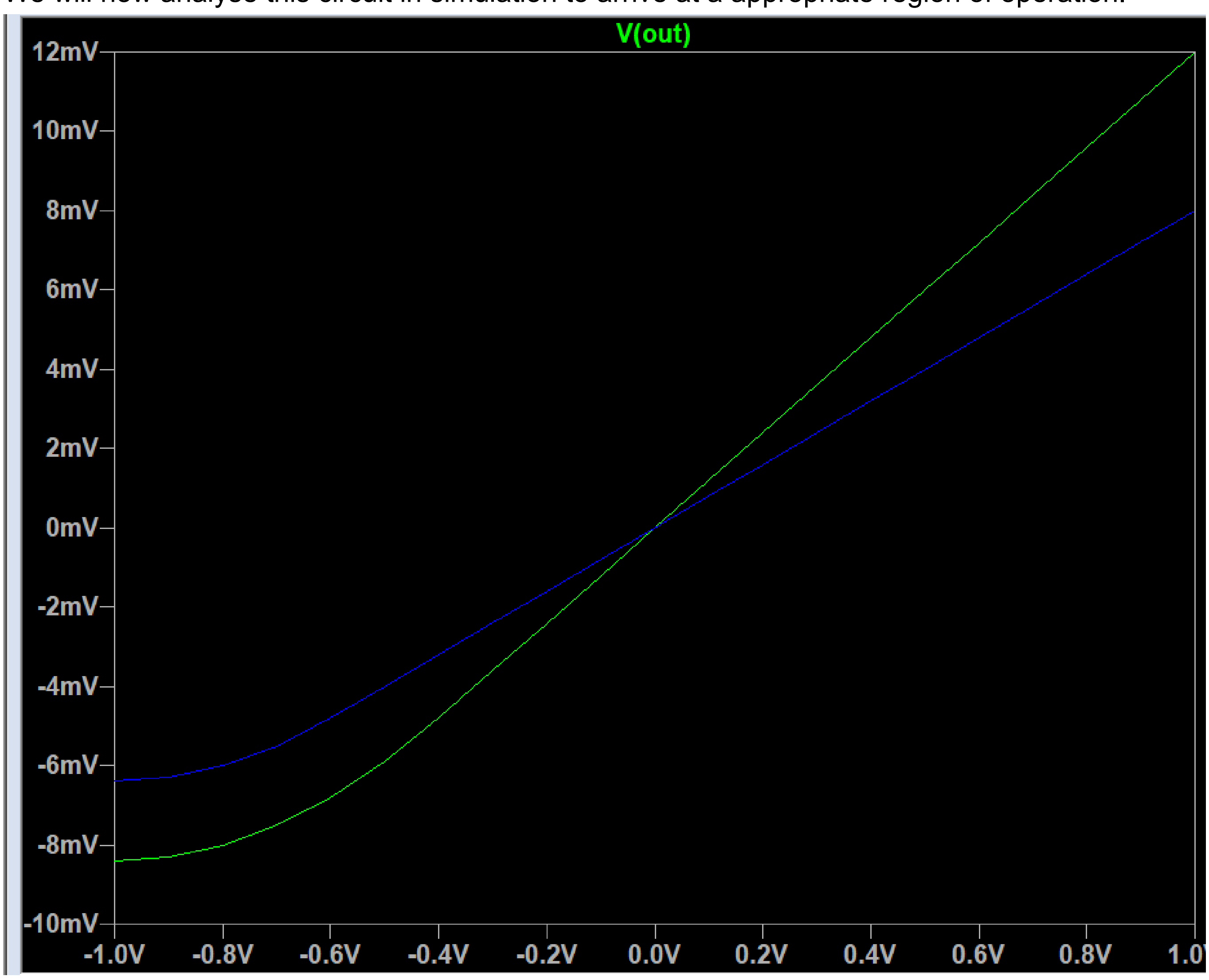
We are using a four quadrant nmos based multiplier from A New Method of Realization of Four-Quadrant Analog Multiplier using Operational Amplifiers and MOSFETs

This circuit, as explained in the paper uses MOSFET and differential amplifier to get an output
kv_1v_2
given two inputs of v_1 and v_2

We will be using the following circuit for mutiplier in LTSpice,



We will now analyse this circuit in simulation to arrive at a appropriate region of operation.

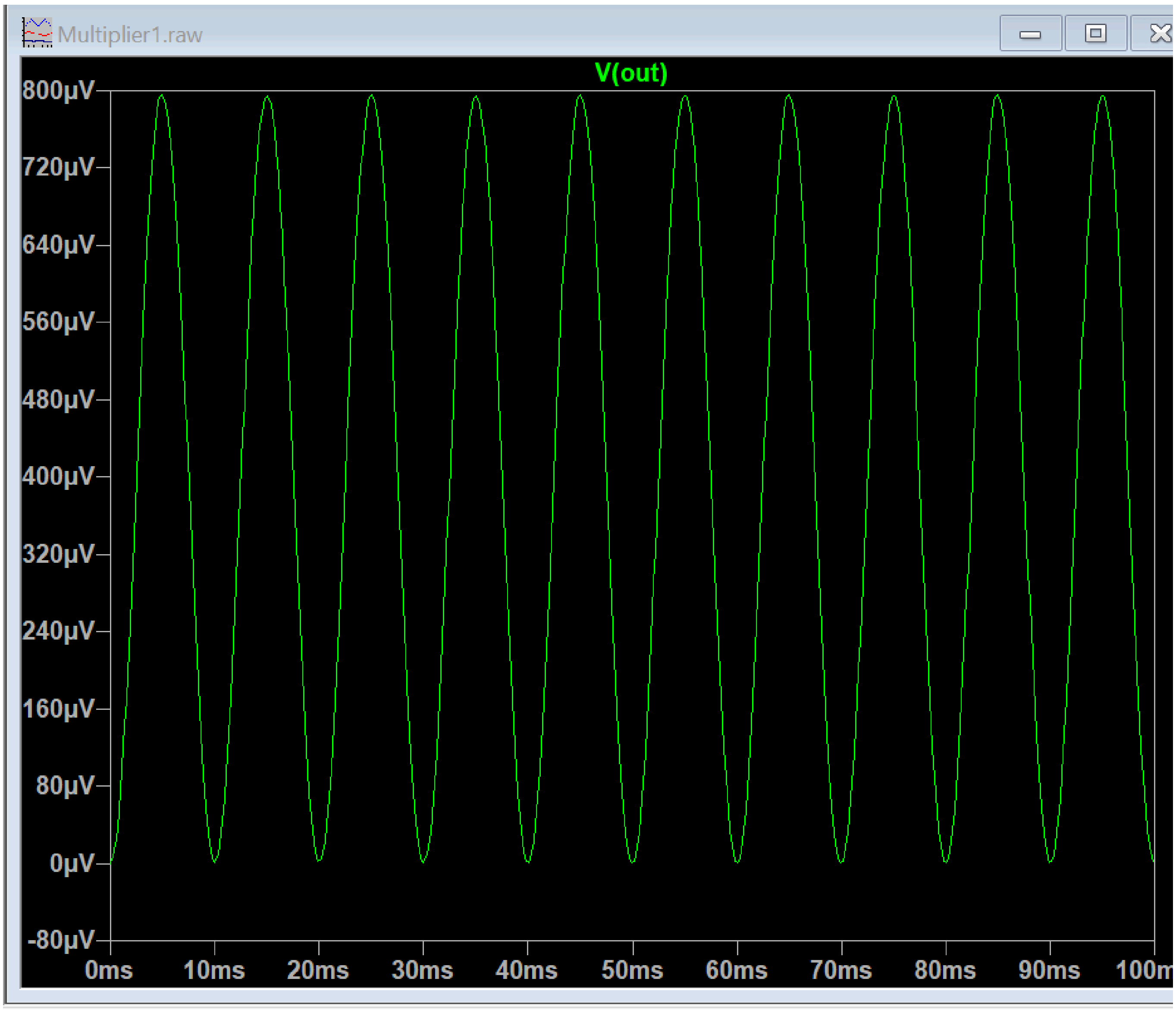


Doing a DC sweep of V2 from -1V to 1V while keeping V2 = 0.4V(blue) and 0.6V(green) we get the above graph, which confirms that this multiplier is working as intended.

However as we can see from the graph there is a distortion when V2 is lower than -0.6V.
On further testing there is another distortion when both V1 and V2 are greater than 0.6V

So to be in non distorted linear region of operation we will ensure that V1 and V2 are both in the region (-0.6V,0.6V). But since -0.6V and 0.6V are very close to distortion a better limitation would be to keep V1 and V2 between (-0.4,0.4).

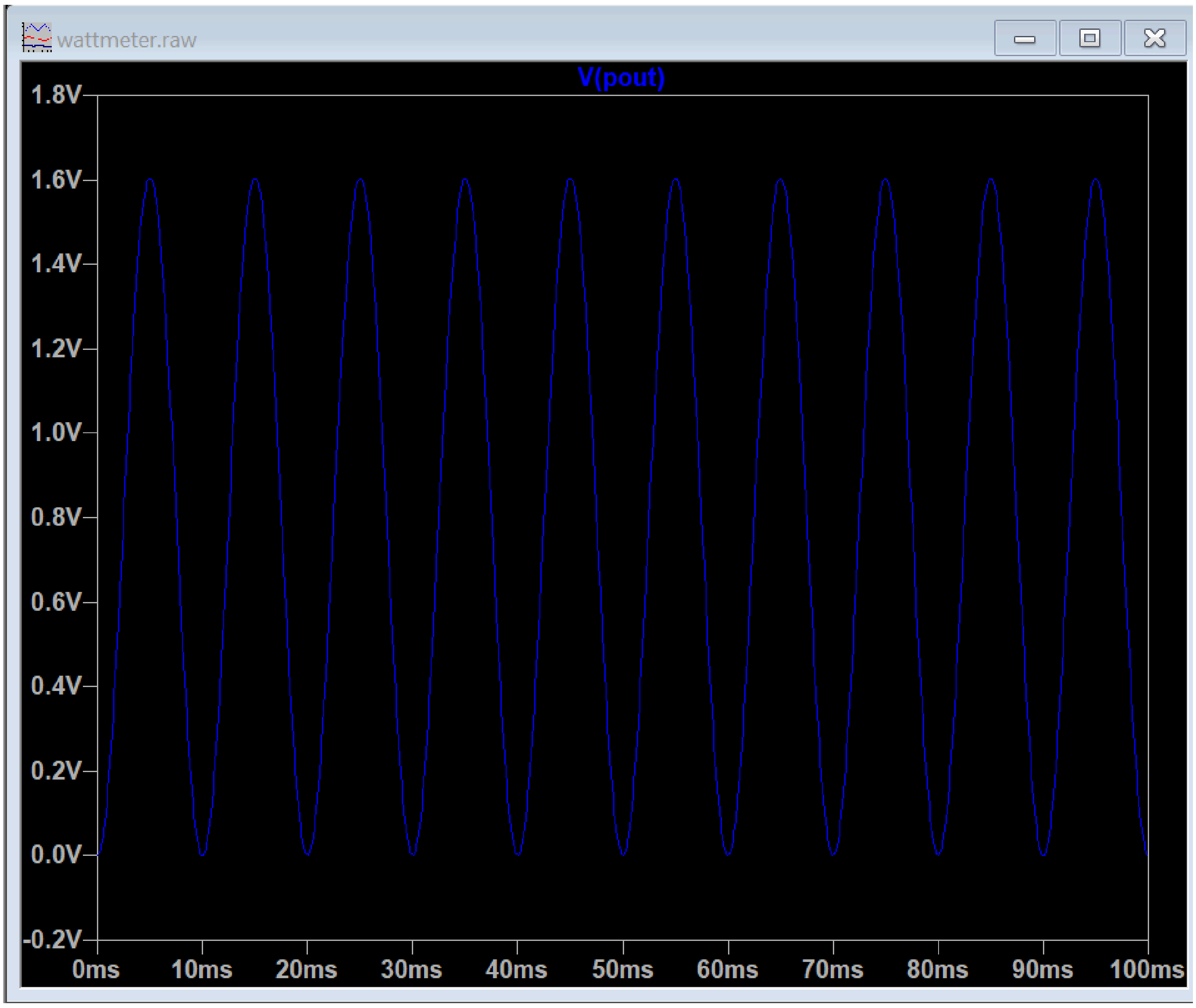
Giving a sin waves of 50Hz and 200mv in both V1 and V2 and running a transient analysis of 100ms,



As we can see this in indeed the graph of a sin^2 wave of frequency 50Hz and Amplitude going from 0V to 800μV.

But an Amplitude of 800μV is too small, we can change this by changing the gain of the differential Amplifier used in the Multiplier circuit and also use another amplifier.

Finally, we get a power signal of max 1.6V by amplification



2. Low Pass Filter:

A low pass filter can be used to calculate DC component of the power signal which is equal to its average value.

$$P = V * I$$

$$P = sin(x) * sin(x)$$

assuming frequency to be equal and phase difference zero

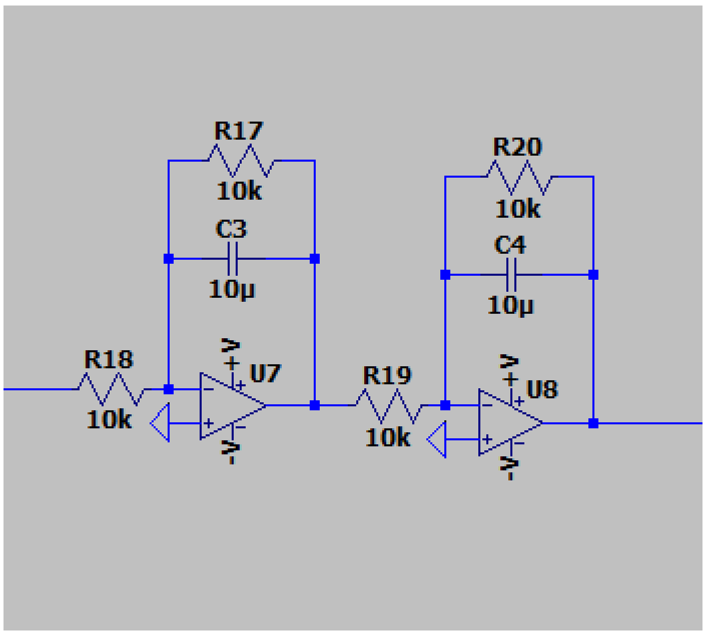
$$P = sin^2(x)$$

$$P = 1 - cos(2x)$$

$$P_{avg} = 1$$

But '1' is just the DC component of our signal.
So, P_{avg} can be calculated with just low pass filter by removing the AC component of the signal.

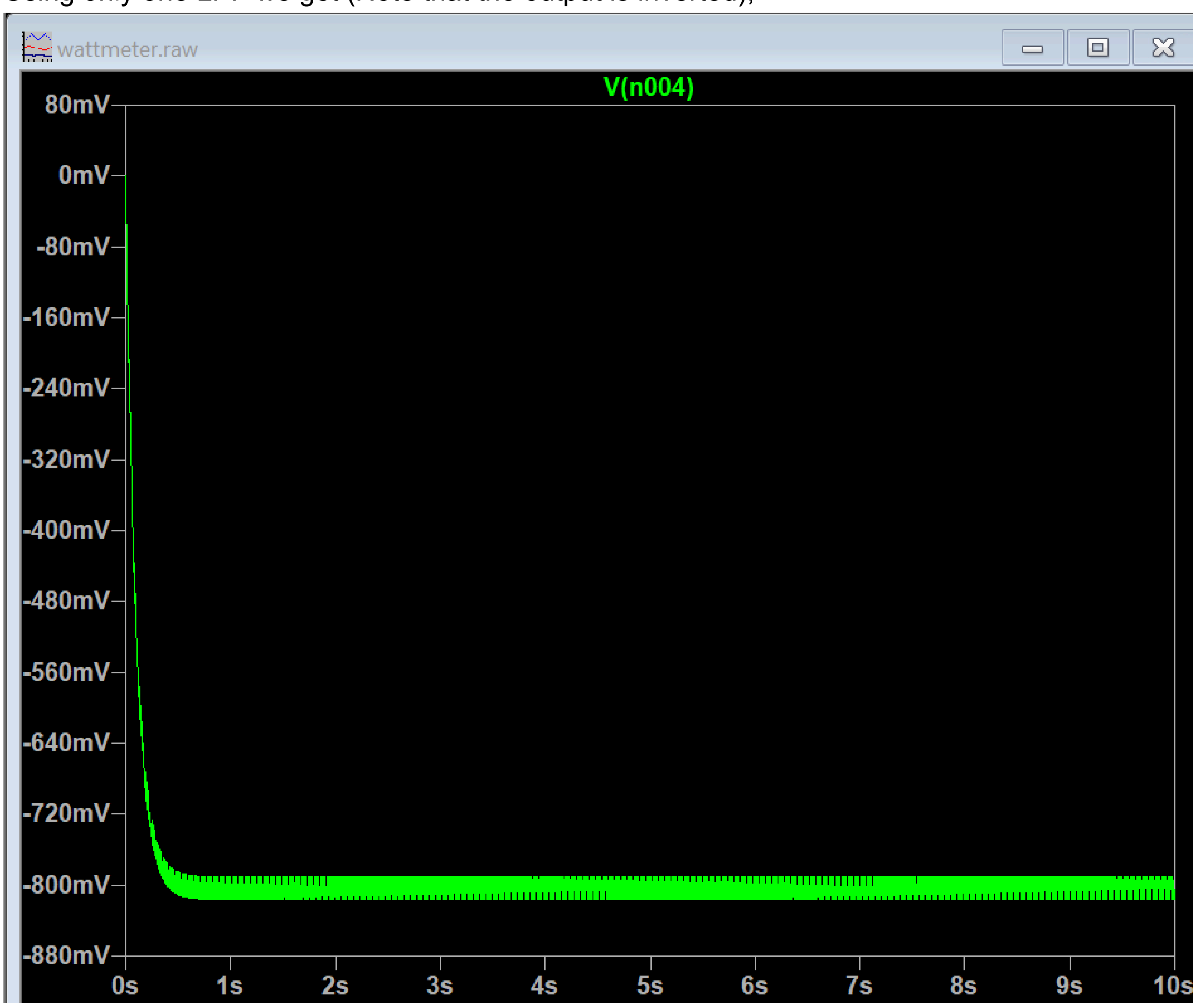
We will be using combination of two Active Low Pass filter to get out DC output.



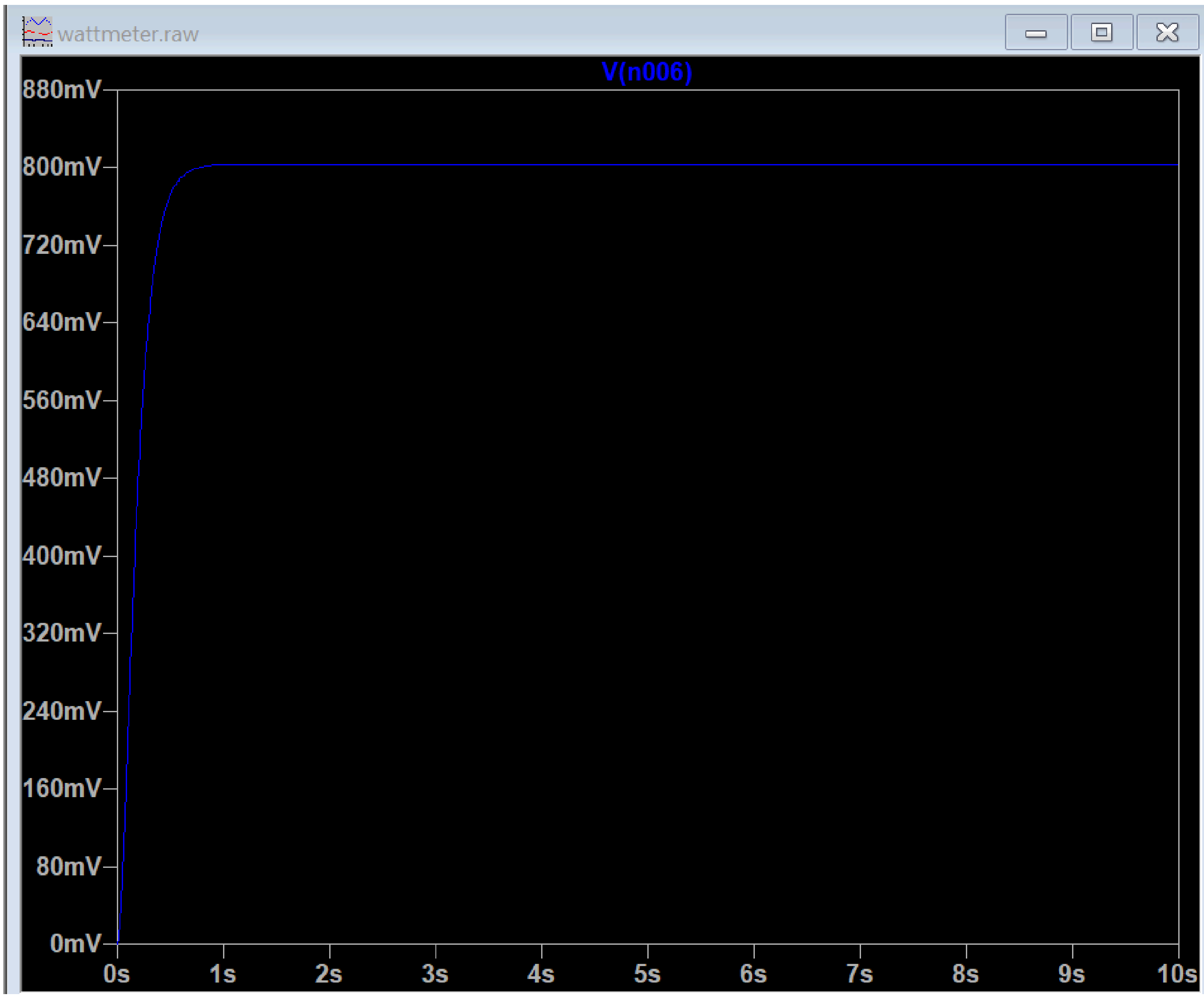
The cutoff frequency of this filter is given by $f_{cutoff} = \frac{1}{2\pi RC}$

Calculating we get $f_{cutoff} \approx 1.59Hz$
Which will be good enough for all our uses.

Using only one LPF we get (Note that the output is inverted),

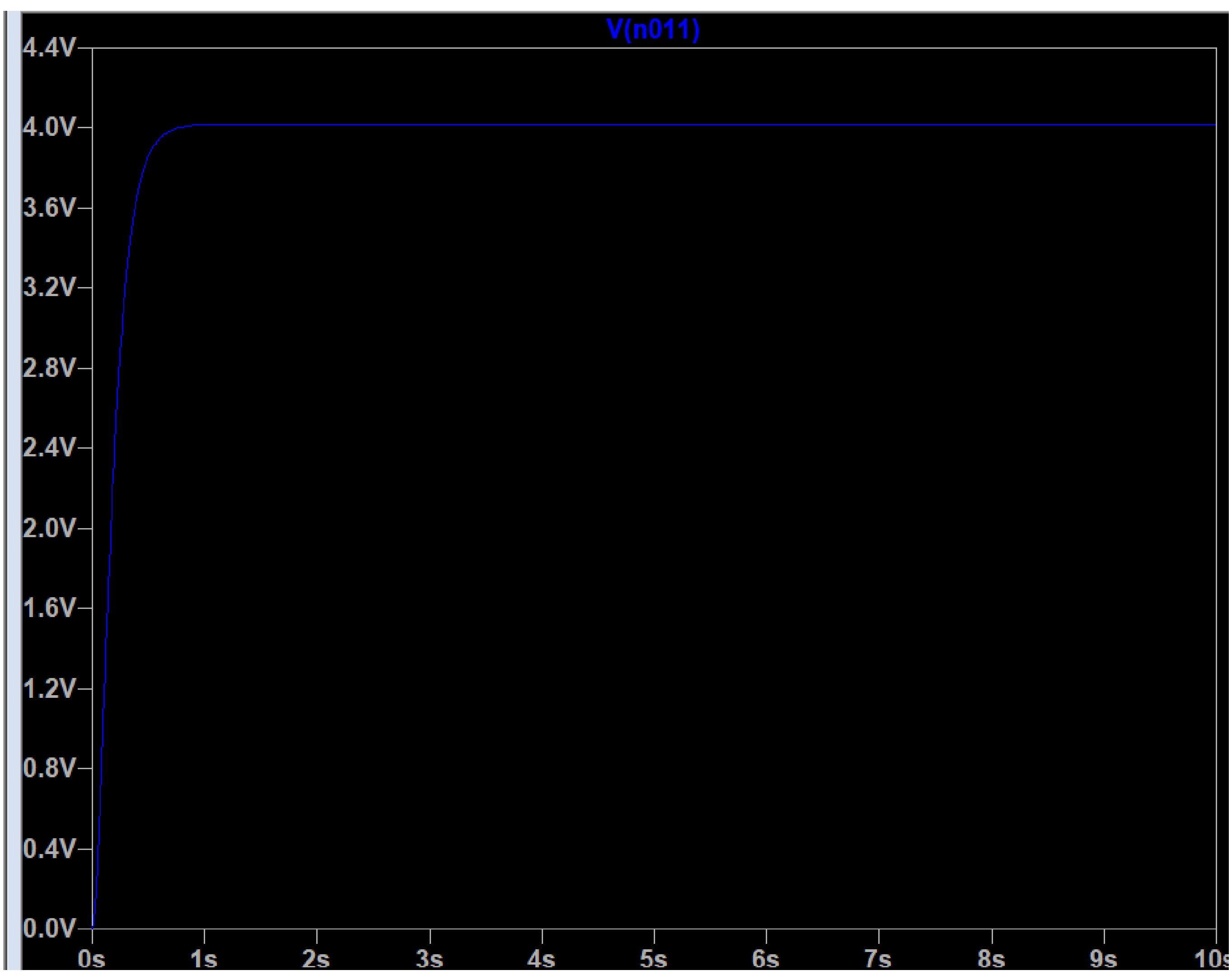


Using another LPF on this output,

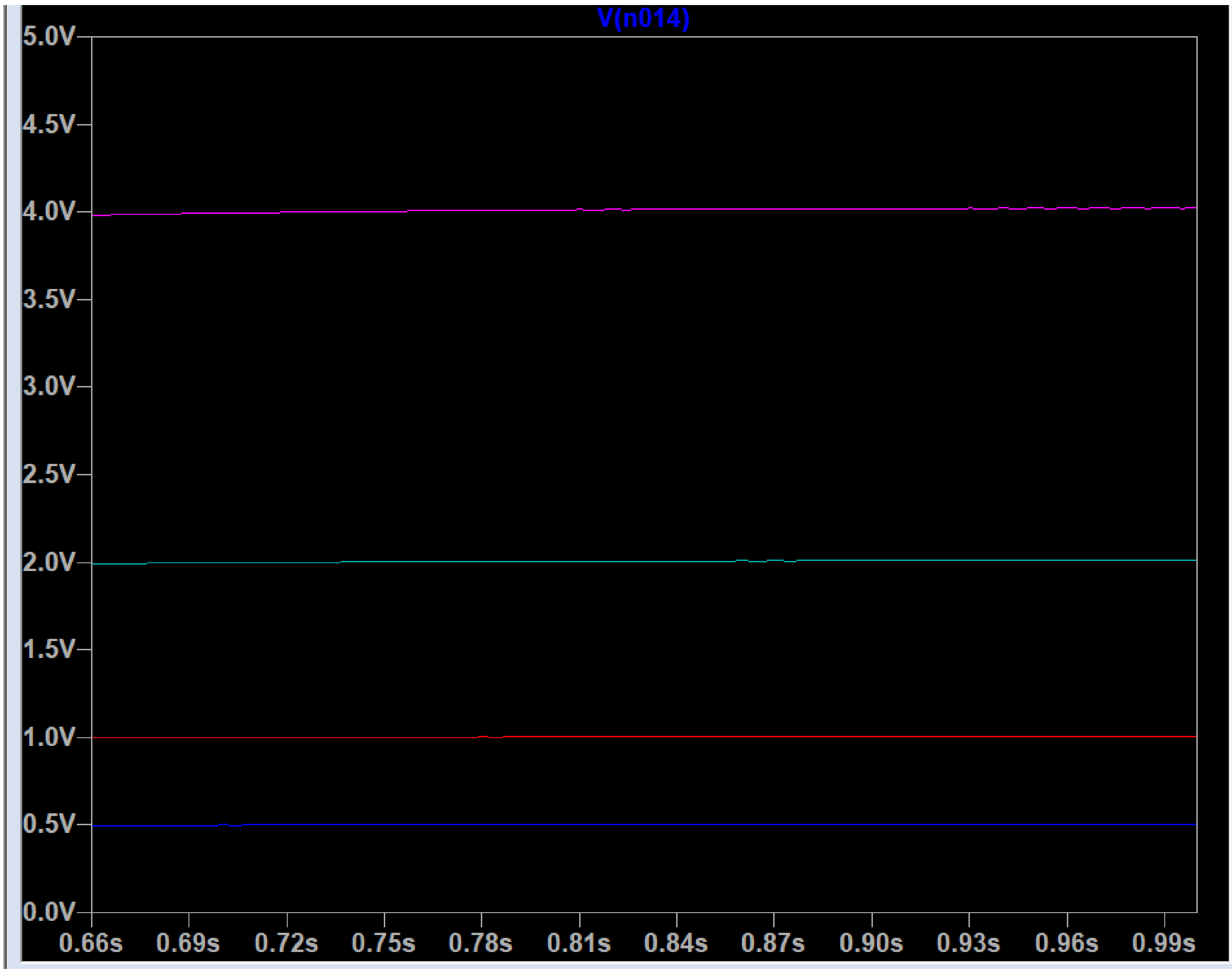


The output converges on a DC value at about 500-600 ms, this will be the response time of the wattmeter.

A maximum signal of 800mV DC is difficult to work with so we will amplify this signal 5 times to a maximum of 4V.



Keeping V2 = 400mv and giving and stepping V1 at 50mv 100mv 200mv and 400mv we get



Which confirms that the LPF is working as intended and gives output as kv_1v_2

3. Current and Voltage:

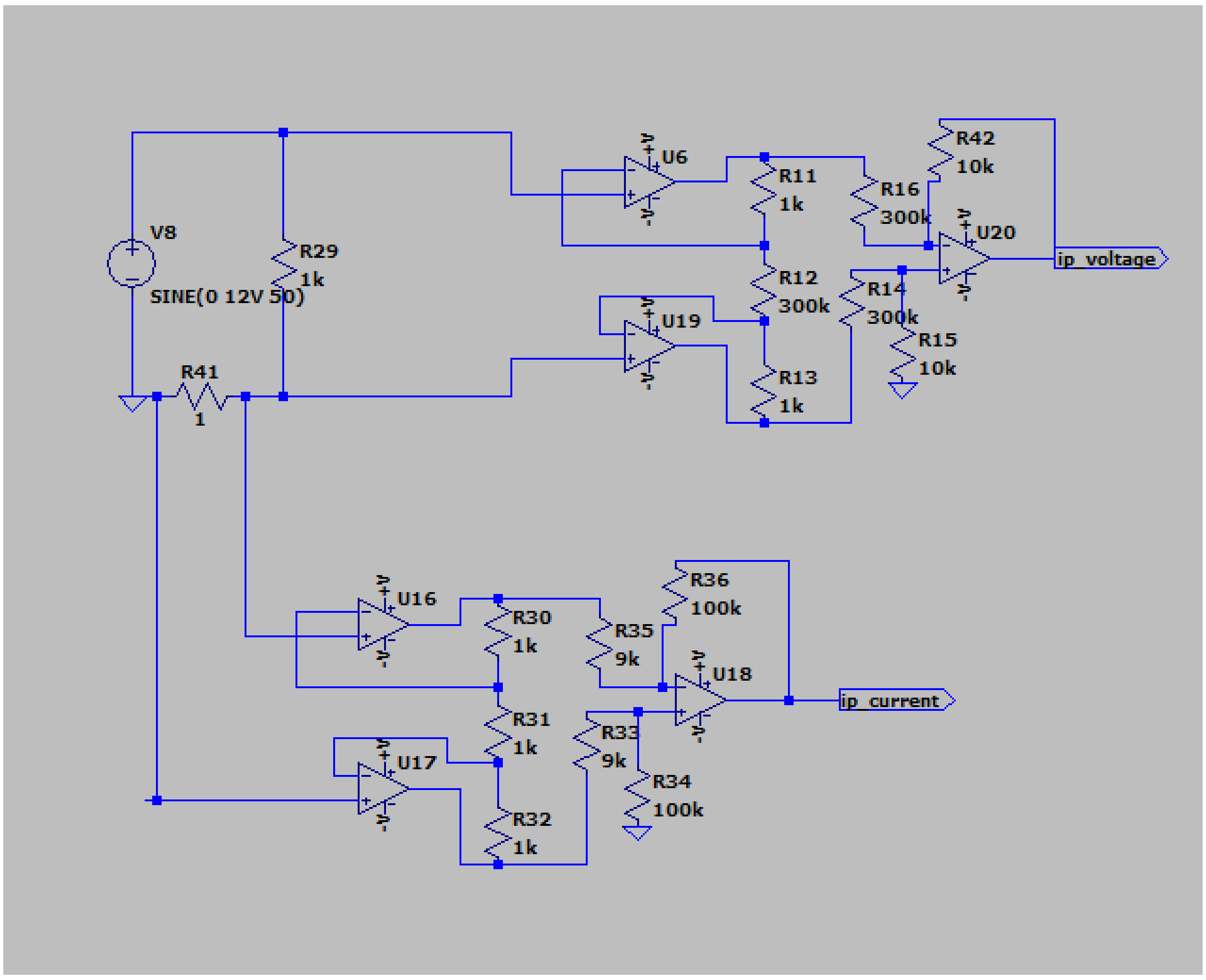
We will be using instrumentation amplifier for converting voltage and current into usable format.

Current: Current can be measured by connecting a small resistance in series with the circuit and measuring the voltage across is. We will be using a 1 Ohm resistance for measuring current.

Maximum current encountered for our purposes will be 12mA($12V/1k\Omega$,) so we will get a voltage drop of 12mV across the resistor, which we will amplify to 400mV to use multiplier to its full capacity.

Maximum current wattmeter can support can be easily changed by changing the gain of the instrumentation amplifier.

Voltage: Maximum voltage that this wattmeter supports will be 12V, which we will (de)amplify to 400mV.



Calculations

Now we can calculate the scaling factors for our power and average power signals,

For AC power signal, peak value is 1.6V when we give an voltage input of 12V peak and current input of 12mA peak (12V/1$k\Omega$), calculating peak power should be 144mW.

$$1.6V = k_{ac} \times 144mW$$

$$k_{ac} = \frac{1}{90} \times 10^3 \;\; V/W$$

For DC power signal, peak value is 8V for average power of 72mW(144mW/2).

$$4V = k_{dc} * 72mW$$

$$k_{dc} = \frac{1}{18} \times 10^3 \;\; V/W$$

4. Analog to Digital Converter

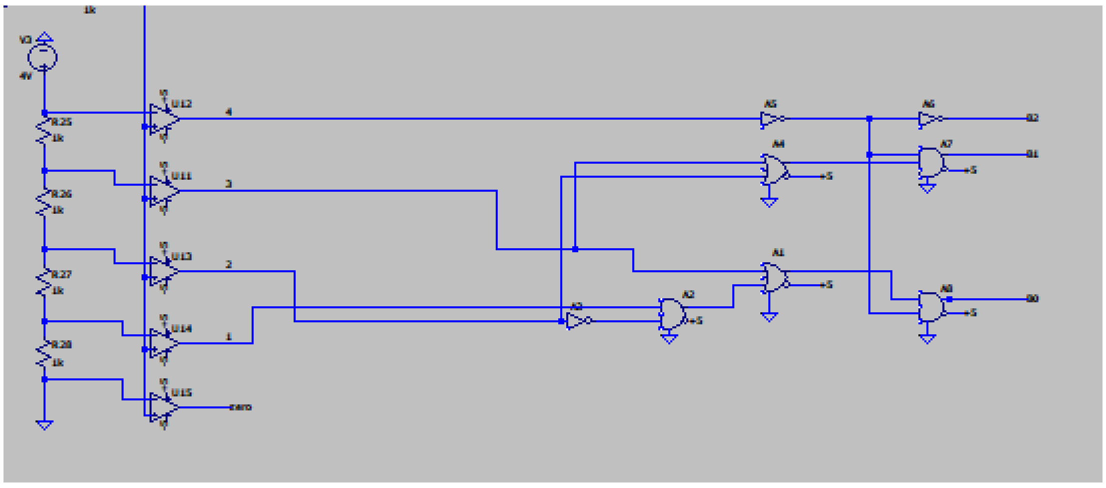
Our main objective was to get average power in DC which is now completed. The DC output can be used for several purposes one of which could be conversion to Digital to display the values to user on digital display, using the value in an microcontroller to do further processing.

A naive ADC can be built to demonstrate how this would look like.

We can get an average power signal of 0V to 4V

For two bit ADC, B0 = 1 + 3 and B1 = 3 + 2

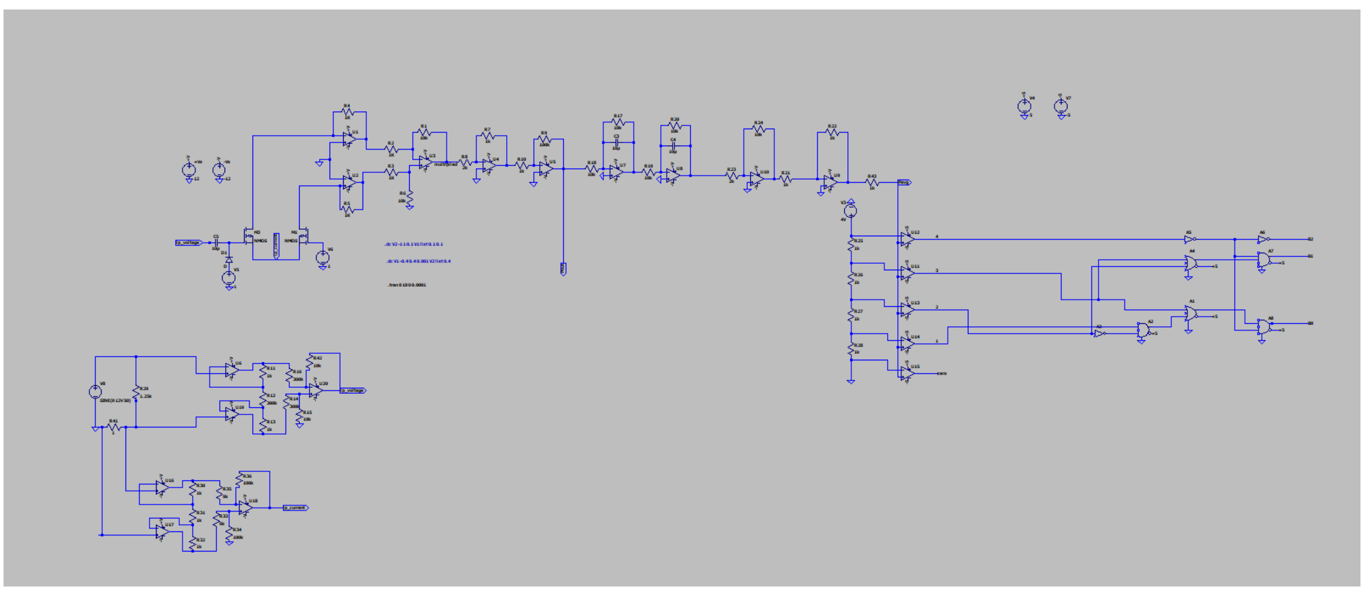
Now we can use this signal in ADC to convert it in digital format.



connecting these outputs in an priority encoder we will get the output in binary.
The binary values will then need to me scaled by k_{dc} which we calculated earlier to get true value of power.

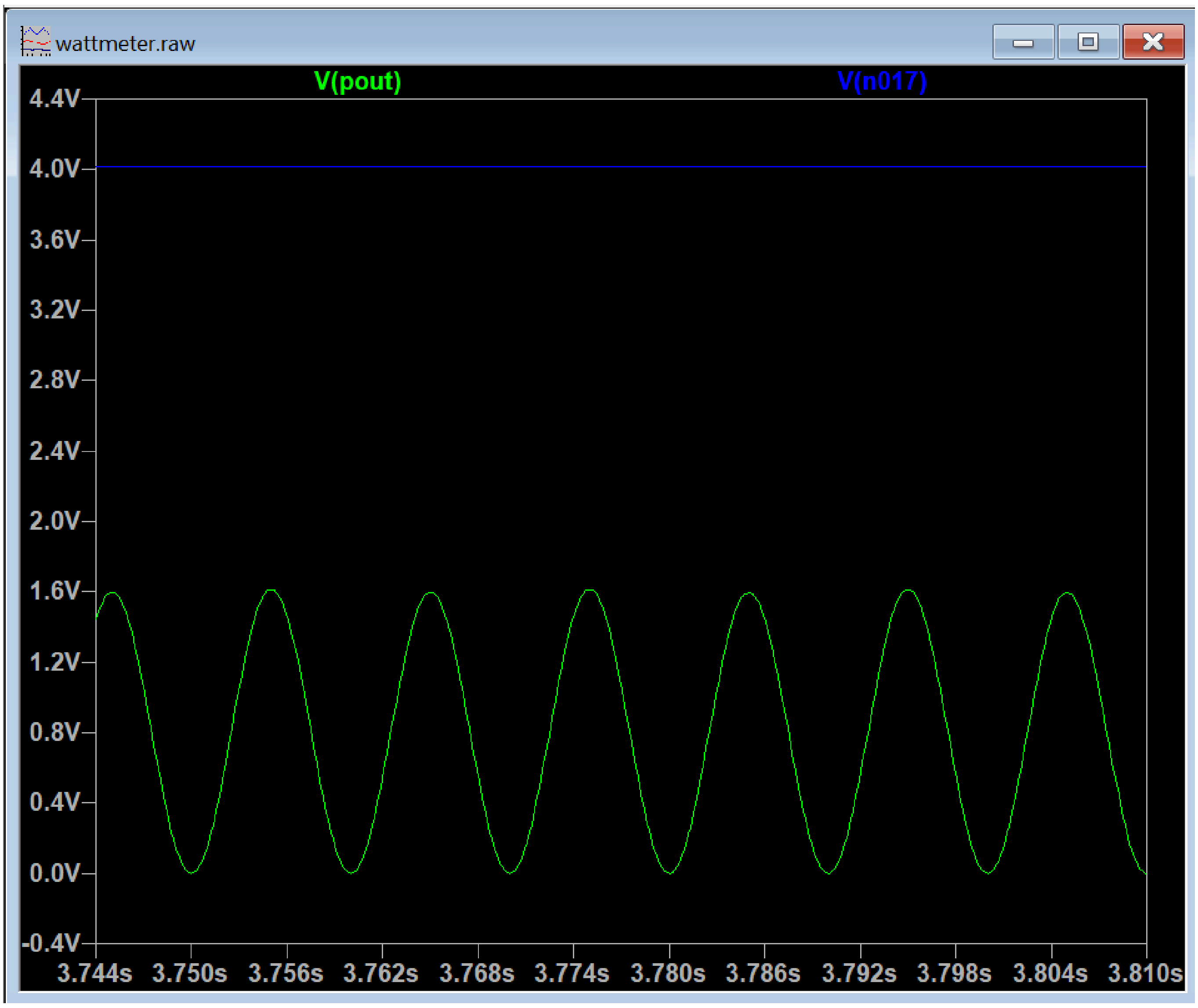
However to get a decent precision with ADC we will need to make at least 16bit encoder which is difficult to do in LTSpice as it is mostly specialized for analog, which is why from now for further analysis we will use the DC output power.

Final Circuit:



Uses:

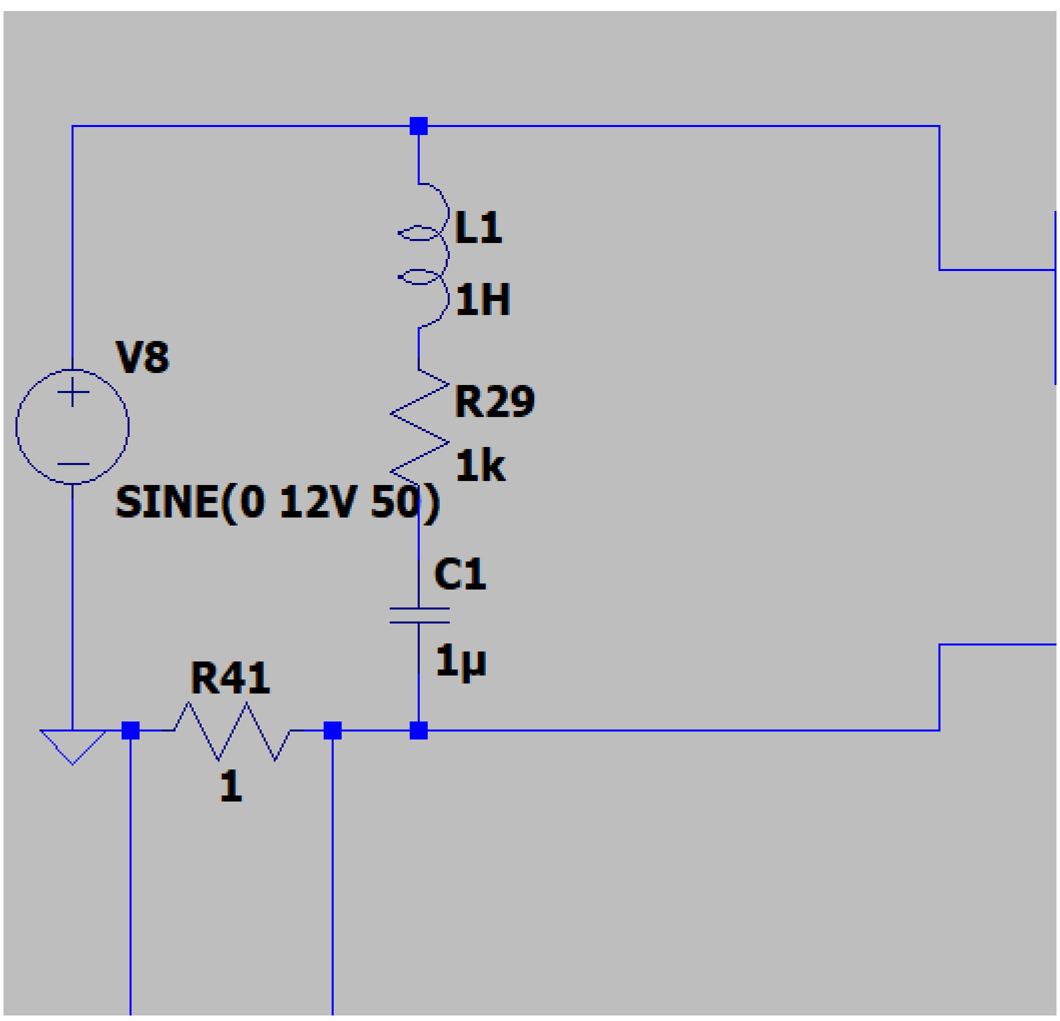
Calculating Power consumed by resistor,

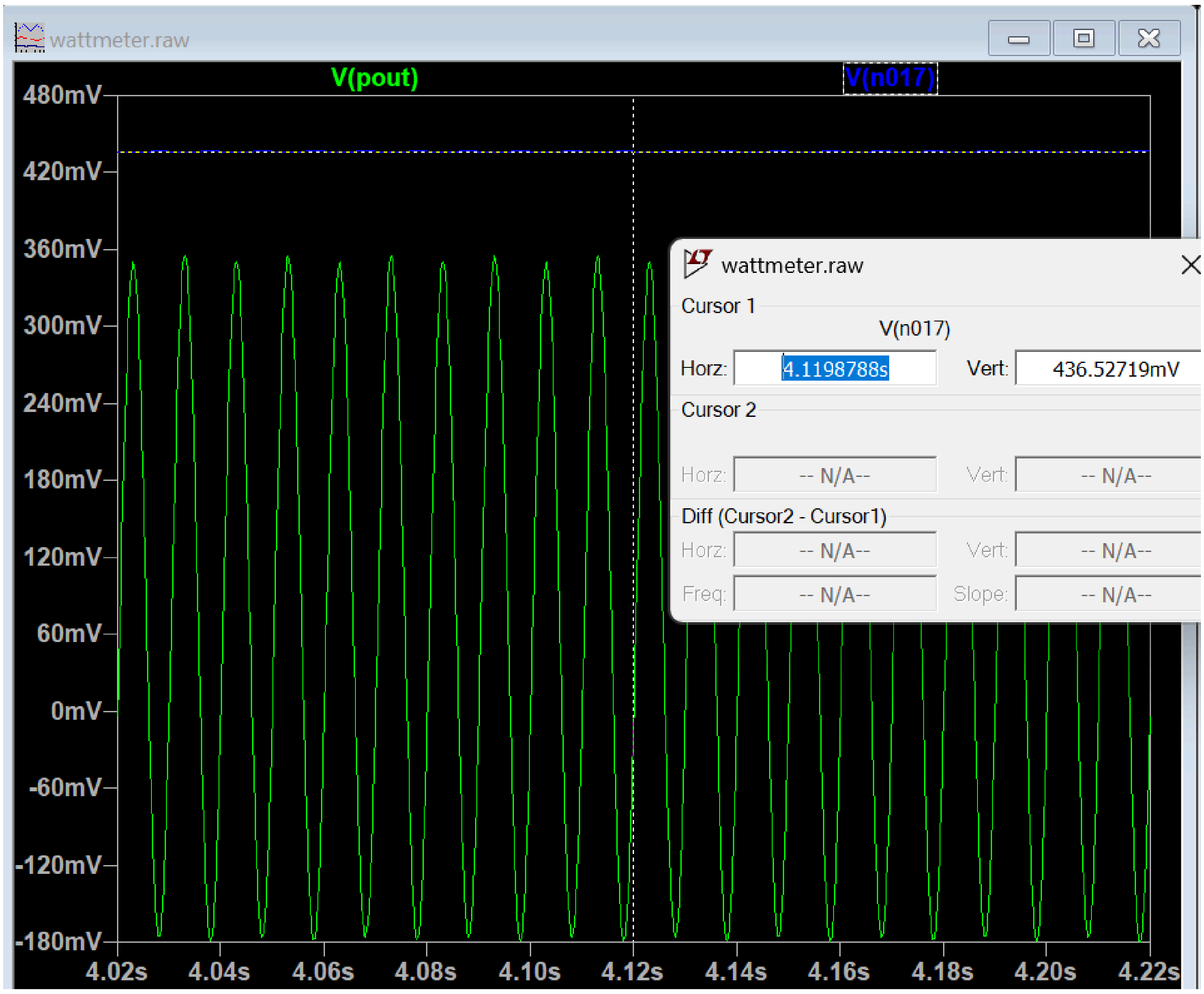


A sin^2 wave completely above x-axis, i.e. no phase difference between current and voltage thus power is always positive.

$$P_{avg} = \frac{4V}{k_{dc}} = 72mW$$

With a series capacitor and inductor,





The power signal can be seen going below x axis because of capacitor and inductor,

$$P_{avg} = \frac{436mV}{k_{dc}} = 7.848mW$$

The average power consumed is also lower than in the case of only resistor.

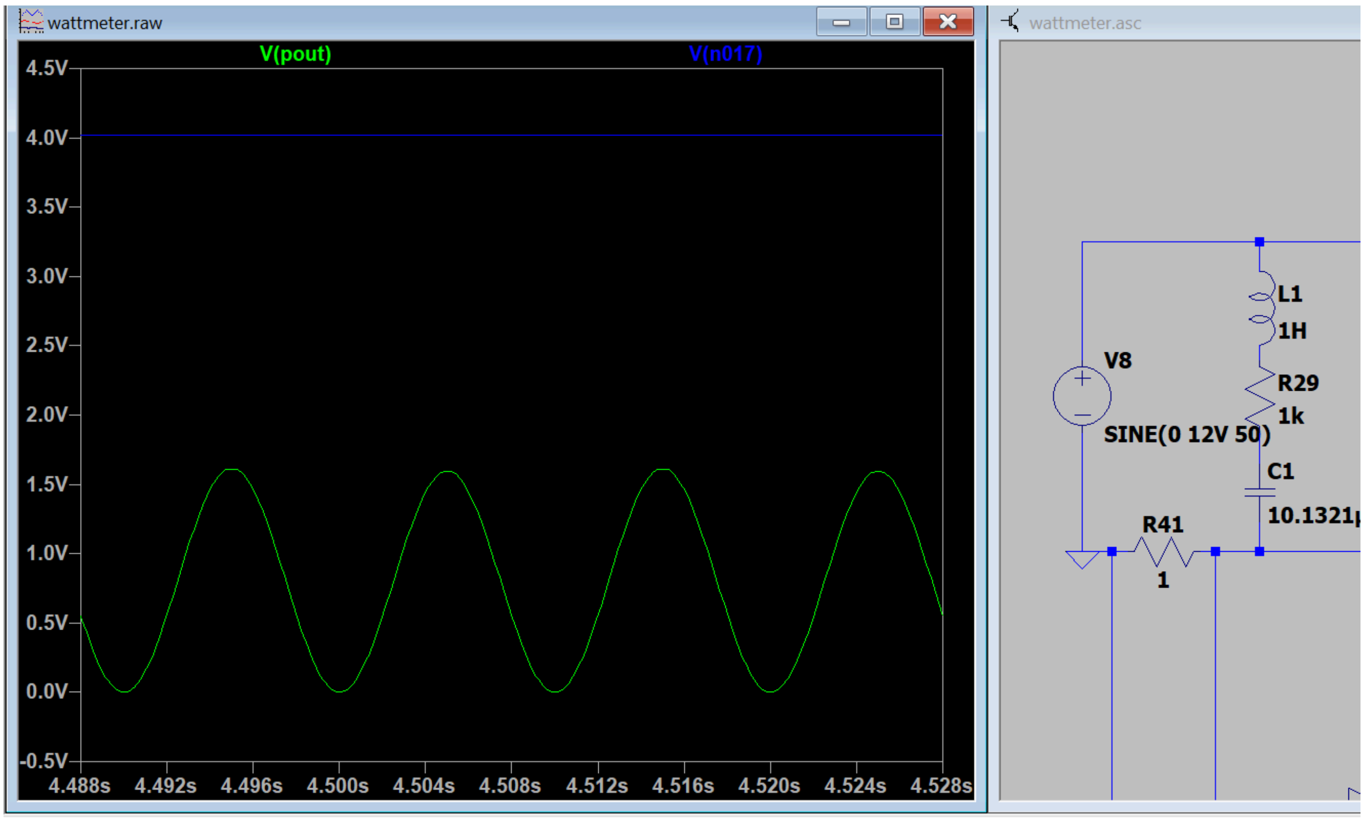
Resonance,

$$\omega = \frac{1}{\sqrt{LC}}$$

$$2\pi f = \frac{1}{\sqrt{LC}}$$

$$LC = \frac{1}{4\pi^2 f^2} \approx 10.1321 \times 10^{-6}$$

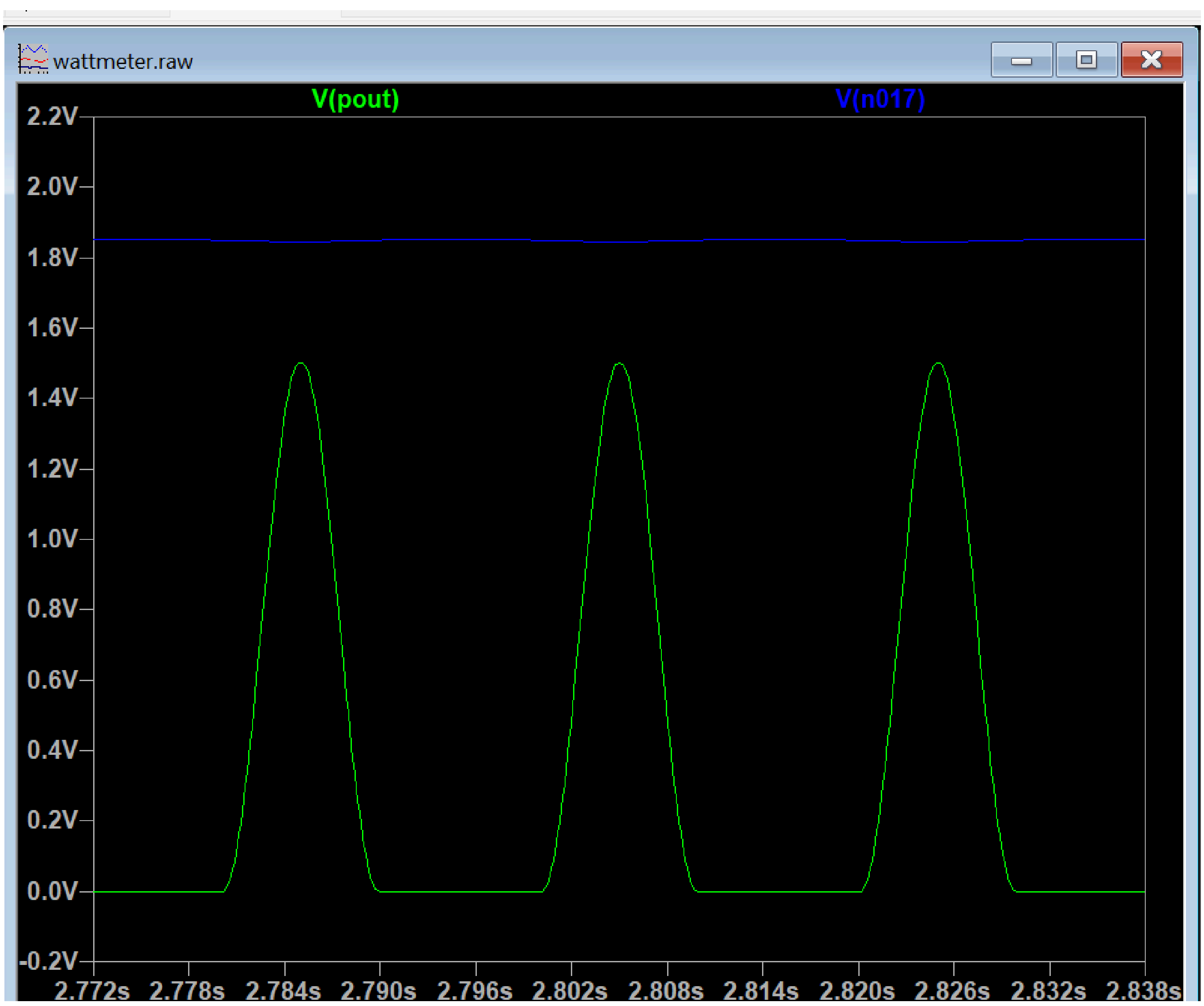
Let L = 1H then C = 10.1321μF to satisfy resonance condition.



$$P_{avg} = \frac{4V}{k_{dc}} = 72mW$$

Power consumed is same as one consumed with only resistance.

Diode,



Since the current only flows in one cycle of voltage signal, only one cycle of power is consumed.

Here, $P_{out} = 1.84V$

$$P_{avg} = \frac{1.84V}{k_{dc}} = 33.12mW$$

The power consumed is not exactly half of only resistor case, this could be because of the voltage drop across the diode.

Conclusion:

As we can see this wattmeter can be used to calculate power consumed of various circuit components like resistors ,capacitors ,inductors ,diodes ,etc. subject to the current and voltage constraints laid out earlier.

Improvements:

- The current rage could be improved by adjusting the gain of instrumentation amplifier, the range we picked was only for convenience of analysis so no modification other than gain should be required to improve current range.
- The ADC can be improved by adding more bits, this will increase the complexity of encoder however finding good encoder is not difficult.