Electrofilter Measurement with Rogowski Coil

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Content

1 Introduction

1.1 Task

Measure the current and voltage for different waste incineration (plastic, non-plastic, medical) with an electro filter voltage of 40 kV.

Master Thesis task

2   Current Transducer Approach

2.1   In terms of alternating current measurement (AC):

In Dommar store, there is a current transducer capable of measuring an alternating current between 0 and 5 A (shown in the figure). It transforms the current into an electric voltage between 0 and 10 V used in the control done through the computer. The figure also shows other characteristics of the current transducer.

Figure 1: current transducer.

However, standard current transducers available in the market are capable of measuring an up to 5A alternating current. In our case, the alternating current can have a current value up to 10A. A proposed solution is to use a transformer 10/5 (an input of 10A is reduced to 5A). In Dommar the available transformer is of 30/5. In this case the precision is lowered.

This Monday the store manager will contact and will let me know about the possibility of getting the 10/5 transformer from Beirut.

Price of the transducer: 50$.

Price of the transformer: unknown. 6$ (transformer 20/5).

2.2   In terms of installation and connection:

As seen on the electrical panel board, the current transducer should be placed between the two circuit breakers available on the electrical panel board to be protected against

temperate. The alternating current coming from the network is connected to the transducer in order to measure it.
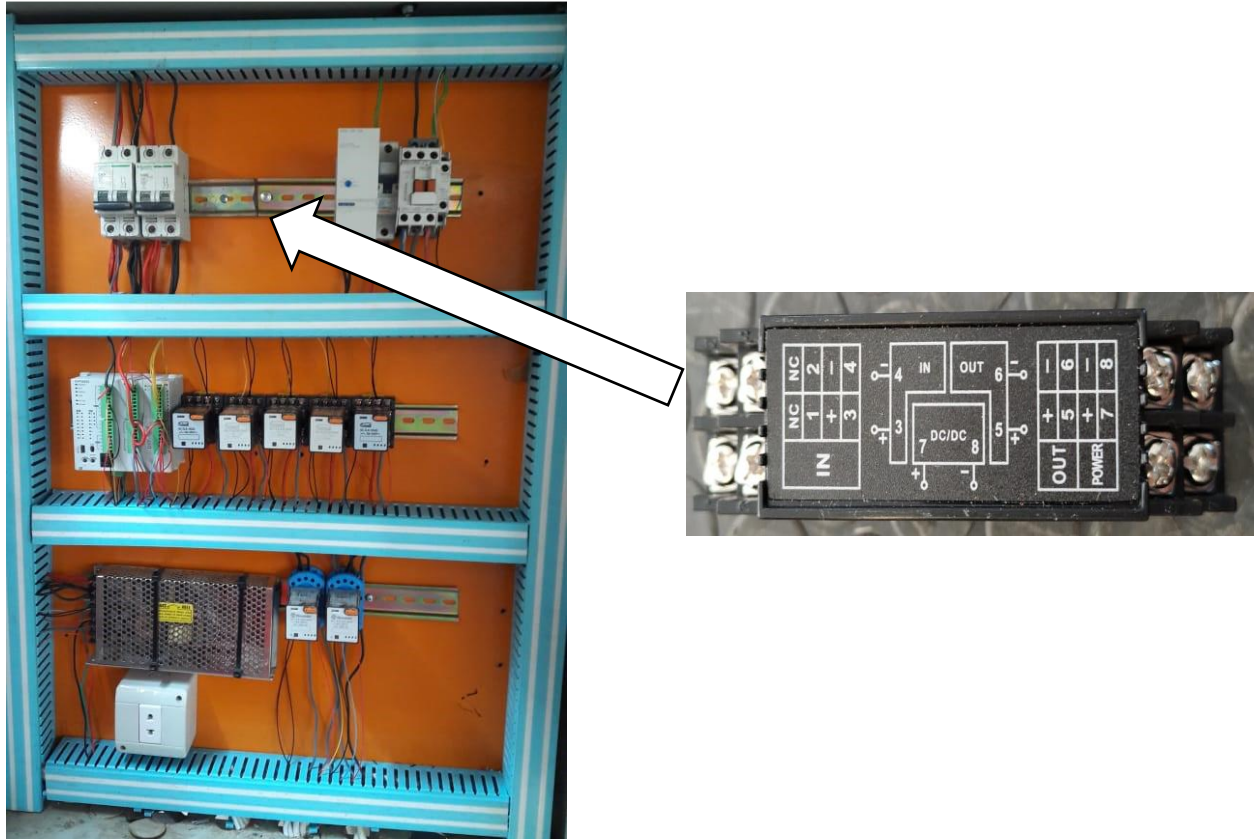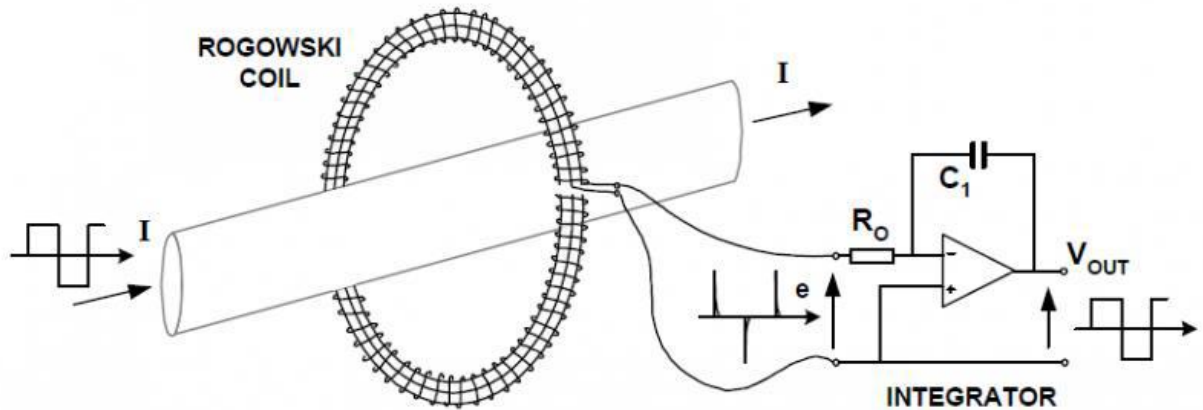

Figure 2: transducer installation.

2.2.1 Questions:

1) Where should we place the transformer?

2) Where is the network's wire? Is it the one going in from below the current breaker? Or the one going out form above?

3   Rogowski Coil Approach

3.1   In terms of alternating current measurement (AC), there are <u>Rogowski Coil</u>:

3.2   What is a Rogowski Coil?

The Rogowski coil is defined as an electrical device that is used to measure alternating current (AC). It is also used to measure the high-speed transient, pulsed current or sinusoidal current. The name Rogowski coil was named after the German physicist Walter Rogowski [1].

A Rogowski coil is an evenly wounded coil with N number of turn and constant cross-section area A. There is no metal core in a Rogowski coil [1].

The end terminal of the coil is returned through the central axis of the coil to another end. Therefore, both terminals are at the same end of the coil [1].

This entire assembly wrapped around the current-carrying conductor whose current we need to measure [1].

3.3   How does a Rogowski Coil Work?

Rogowski coils work on the principle of faraday's law. It is similar to AC current transformers (CTs). In current transformers, the voltage induced in a secondary coil is proportional to the current flow through the conductor [1].

The difference between Rogowski coils and AC current transformers is in the core. In Rogowski coils, an air core is used and in the current transformer, a steel core is used [1].

When current passes through the conductor, it will create a magnetic field. Due to an intersection with a magnetic field, a voltage is induced between the terminals of the Rogowski coil [1].

The magnitude of voltage is proportional to the current passes through the conductor. Rogowski coils are close pathed. Generally, the output of Rogowski coils is connected with the integrator circuit. So, the coil voltage is then integrated to provide an output voltage that is proportional to the input current signal [1].

3.4 Rogowski Coil Current Sensor

Rogowski coil current sensors are preferred due to no magnetic saturation, no overheating, or no hysteresis loss. As such there are very low magnetic losses in Rogowski coils. And it has very low insertion impedance [1].

It is able to sense the current flowing through the conductor. Hence Rogowski coils can also function as current sensors [1].

Rogowski coils are an air-cored toroidal winding wrapped on a conductor. For large currents, the output does not saturate due to the non-magnetic core [1].

It can be designed for a wide range of current measurements as well as protection applications. Rogowski coil sensor converts the input current to an output voltage. And it can sense the current flowing the conductor by integrating the output voltage [1].

There are two types of Rogowski coils; Rigid and Flexible [1].

3.5 Rogowski Coil Design

Consider the conductive element 'dr' at distance 'x' from the origin. The current-carrying conductor is placed at the center of the coil. The figure below shows the arrangement of a typical Rogowski coil [1].
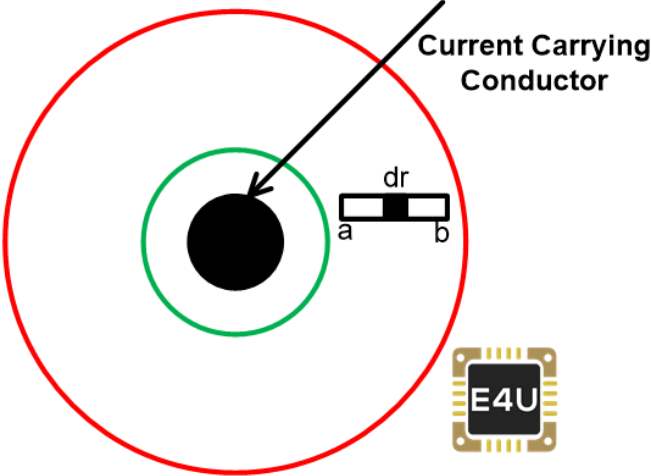
As per biot-savart law, the magnetic strength at distance x is given by;

$$dH = \frac{I_{Primary}}{2\pi x}$$

The magnetic flux density a t point 'dr' is

$$dB = \mu \times dH$$

Where μ is the permeability of free space

From the above equations, the magnetic flux density due to a current flowing through the conductor is

$$dB = \mu \times \frac{I_{Primary}}{2\pi x}$$

The magnetic flux is given as

$$\phi = \int_a^b dB \times dA$$

Where dA is rectangular cross-section area for element 'dr' and that is given as

$$dA = dr \times h$$

$$\phi = \int_a^b \mu \times \frac{I_{Primary}}{2\pi x} \times dr \times h$$

$$\phi = \mu \times \frac{I_{Primary}}{2\pi} \times h \times \int_a^b \frac{1}{x} dr$$

Therefore, total flux is

$$\phi = \mu \times \frac{I_{Primary}}{2\pi} \times h \times \ln\frac{b}{a}$$

$$\frac{d\phi}{dt} = \frac{\mu \times h}{2\pi} \times \ln\frac{b}{a} \times \frac{dI_{Primary}}{dt}$$

As per Lenz's law, the voltage induced due to N turns is

$$V = N \times \frac{d\phi}{dt}$$

$$V = N \times \frac{\mu \times h}{2\pi} \times \ln\frac{b}{a} \times \frac{dI_{Primary}}{dt}$$

So, <u>mutual inductance</u> (M) for the Rogowski coil is

$$M = N \times \frac{\mu \times h}{2\pi} \times \ln\frac{b}{a} \times$$

Now, assume that sinusoidal current flowing through the conductor with an amplitude 'I$_m$' and frequency 'f'.
So, the voltage induced in the Rogowski coil is given by

$$V = M \times \frac{dI_m \sin(2\pi ft)}{dt}$$

$$V = M \times 2\pi f \times I_m \times \cos(2\pi ft)$$

At time t=0, the magnitude of voltage is maximum. So, the peak voltage is given as;

$$V_{Peak} = M \times 2\pi f \times I_m$$

<u>RMS value</u> of the voltage;

RMS value of an AC current represent the equal amount of power in DC current

$$V_{rms} = \frac{V_{peak}}{\sqrt{2}}$$

So, $$V_{RMS} = M \times 4.44f \times I_{RMS}$$
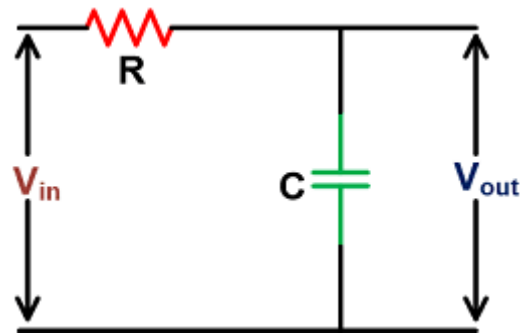
Hence, the induced voltage is proportional to RMS current flowing through the conductor and frequency of the current.

3.6 Rogowski Coil Integrator

According to components used in integrator, there are two types of integrator [1];

- Passive Integrator
- Active Integrator

 i.   Passive integrator

The value of R and C can be estimated by the below equations.

$$\tan(\phi) = \frac{X_c}{R}$$

$$X_c = \frac{1}{2\pi f C}$$

$$\tan(\phi) = \frac{1}{2\pi f C R}$$

$$RC = \frac{1}{2\pi f \tan(\phi)}$$

Where,
Φ = Target phase error
X_C = Capacitive Impedance
R = Resistance
f = Input Frequency

    ii.   Active Integrator
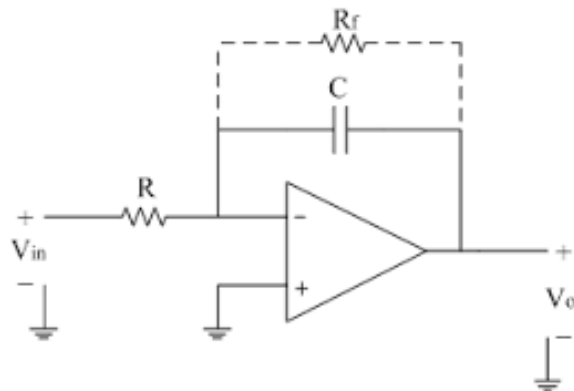
Here, the RC element is in a feedback path of an Amplifier. The gain of the amplifier can be adjusted by using the below equation.

$$Gain = \frac{VOUT_{MAX} - VOUT_{MIN}}{VIN_{MAX} - VIN_{MIN}}$$

$$Gain = -\frac{R_F || X_C}{R_1}$$

1- Questions:

a) which type of integrator should be used ?

b) what is the system that must be installed to make a 0-10 volts control ?

3.7 Rogowski Coil
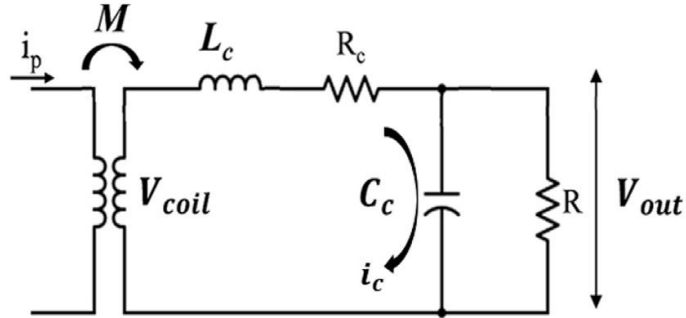
Fig.1: Lumped-element model of Rogowski coil.

$$V_{Coil} = -n\mu_0 A \frac{dI}{dt} = \mp M \frac{dI}{dt} \; [2]$$

3.8 Construction of Rogowski coil

Fig.2 Shows the schematic of the Rogowski sensor in the circular cross-section, which N, x0, a and b are the structural parameters of Rogowski coil [2].

Fig.2: Circular cross-section Rogowski coil.

the optimal values of the structural parameters of the sensor, shown in table (1), were calculated. The sensor with the parameters of Table 1 was constructed [2].

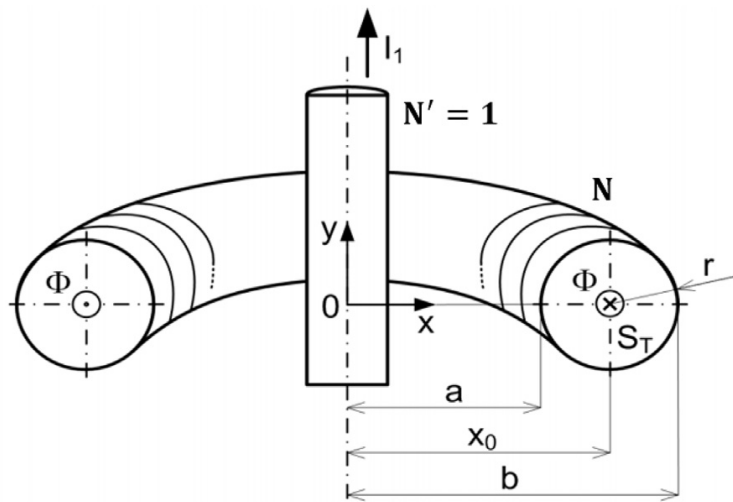| Measured current		I_p	Main radius x_0 (cm)	13.17	
Wire turns		3366	Wire diameter d(mm)/AWG	0.202	32
Core material		Teflon	Self-inductance L_c (mH)	1.702	
Internal radius a(cm)		12.6	Distributed capacitance C_c (nF)	368.2	
External radius b(cm)		13.74	Ohmic resistance R_c (Ω)	72.42	
Internal former radius $(b-a)/2$ without wire diameter (cm)		0.55	Terminal resistance R(Ω)	50	
			Calibration Coefficient kA/V	0.2	

Tab.1: Structural Parameters of Rogowski coil for Alvand tokamak.

This sensor contains 3366 wire turns which is wrapped on a teflon non-magnetic core [2].

The Rogowski sensor produces an output voltage signal Vout equivalent to equation (13). Due to the factor N, the sensor output voltage has a high gain; therefore, the output signal will be easily distinguished from the noises of other parts of the system [2].

$$V_{out} = \mu A \frac{N}{l} \frac{dI}{dt}$$

The winding was returned in the opposite direction to that of the pitchadvancement turn along the central axis of the coil, in order to avoid the effect of a magnetic flux. In this case, both terminals are set at the same end of the coil. Therefore, interference of the unwanted magnetic fields is prevented [2].

3.9 Design experiment of Rogowski Coil in laboratory

I used a rubber tube, then I wraped the turn of the coil around this tube .

Fig.3: Rubber tube.

Fig.4: Rubber tube with coils

Fig.5: Rogowski Coil without integrator.

3.10 Design and construction of active integrator

The DC-control active-type integratorwas constructed. As shown in Fig.6 the time constant of this integrator was selected ten times more than the time duration of the signal [2]. By connecting the output of Rogowski coil to the inverting input terminal of operational amplifiers, the input and output differ in phase and the role of this integrator is shown in equation [2]:

$$G(s) = -R_{ftot} / R_{in}(1 + R_{ftot}C_c s)$$

Operational amplifier OP07CP has ultralow drift and high accuracy to form in-phase amplifier circuit [2]. The negative feedback resistance, Rftot , is equivalent to the resistance of R1, R2 and R3. This resistor, parallel to the Cf capacitor, provides a path to discharging the capacitor while the circuit is not operating and prevents its saturation [2]. The transfer function of the active integrator can be given by equation [2]:

$$G(s) = \frac{-[(R_1+R_2) + (R_1R_3+R_2R_3 + R_1R_2)]}{R_{in}(1 + [(R_1+R_2) + (R_1R_3+R_2R_3 + R_1R_2)]C_f s)}$$

The reconstructed signal of the measured current is amplified after the integration. The gain of this integrator is 10. Roffset is defined is Rin=R1 can eliminate the bias currents of operational amplifiers and the output offset voltage. Cb1 and Cb2 capacitors were added to remove noise on the input bias voltage [2].
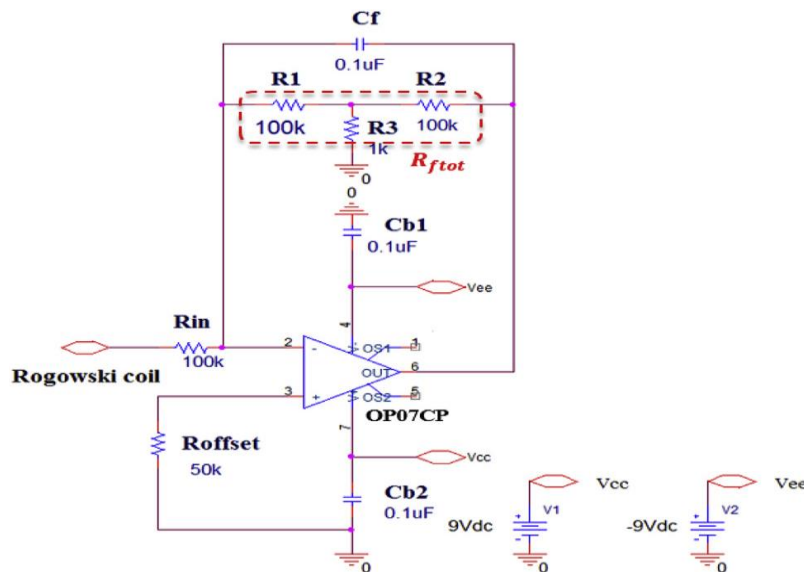

Fig.6: The constructed active integrator with DC gain control.

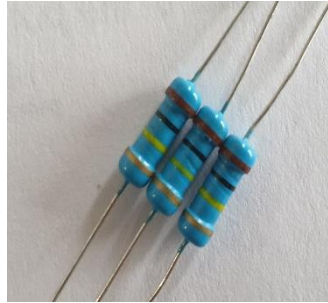## 3.11 Electronic tools used to create an active integrator

There are:

Operational amplifier OP07CP,
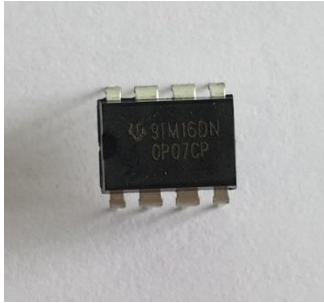
R1, R2,and Rin

R3
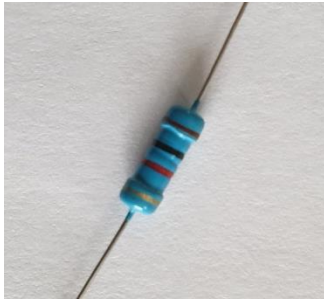
Roffset

Cb1, Cb2, Cf

Battery 9v DC

Battery connecting tape

3.12 Using EagleCAD to create a schematic and to do switch to board

Schematic file	**SCH** louay.sch
Board file	**BRD** louay.brd
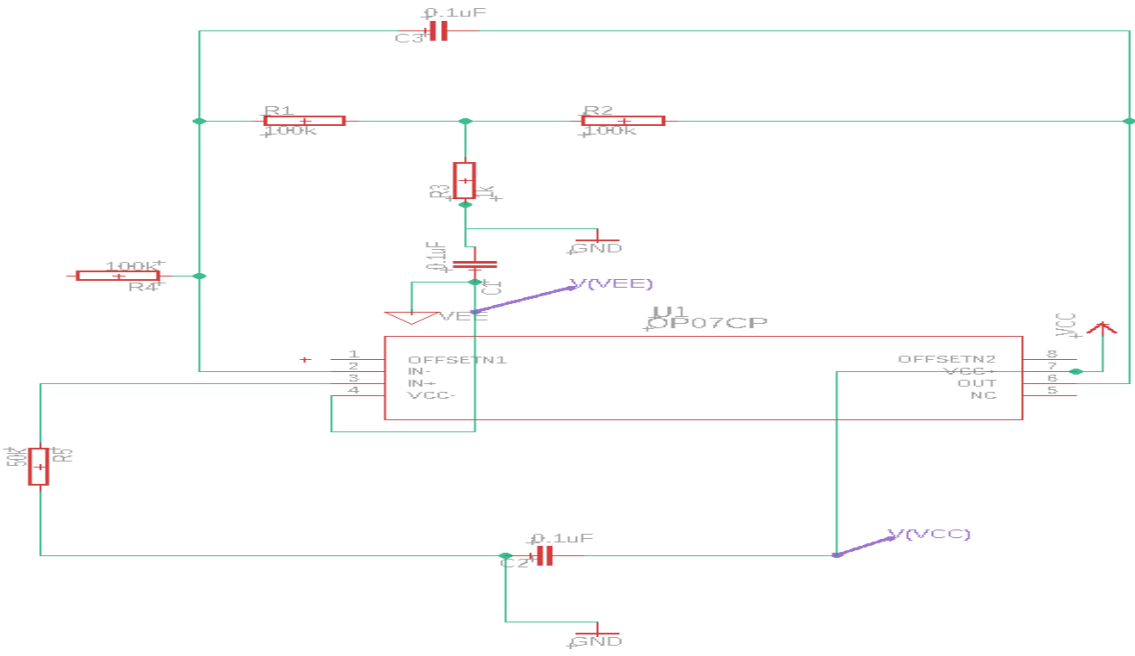
Fig.7: Schematic
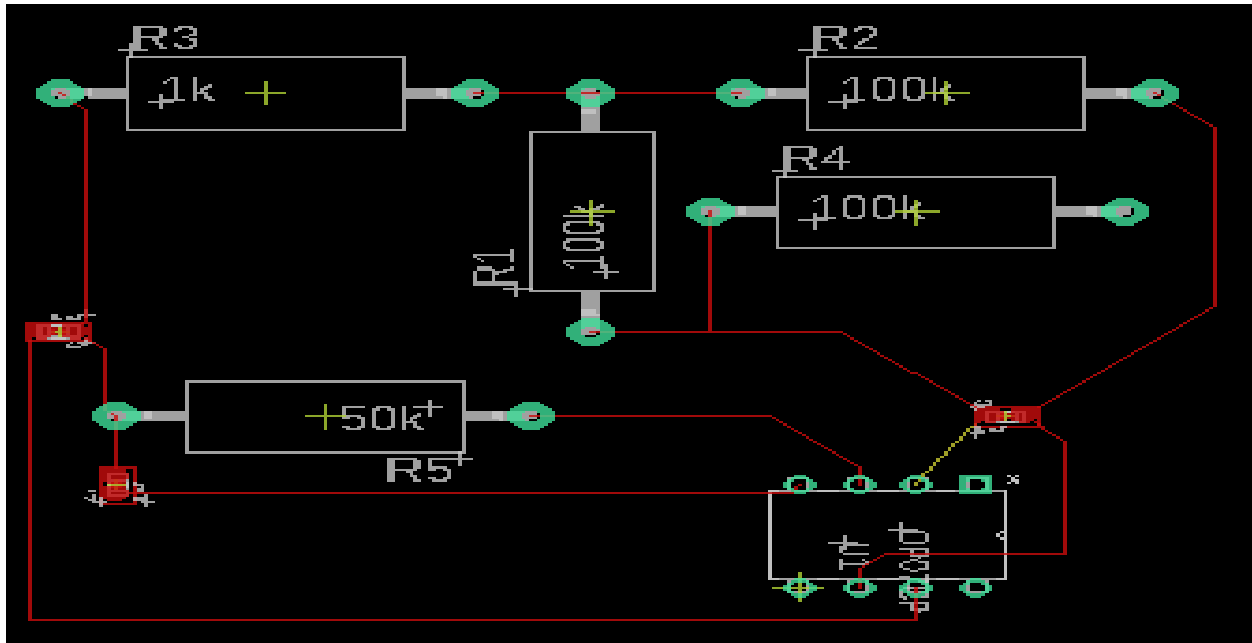
Fig.8: Board

3.13 Construction of an active integrator connected to the coil in laboratory

Using the drawn circuit, we build the active integrator which is connected to the coil. This is how we build the Rogowski Coil.
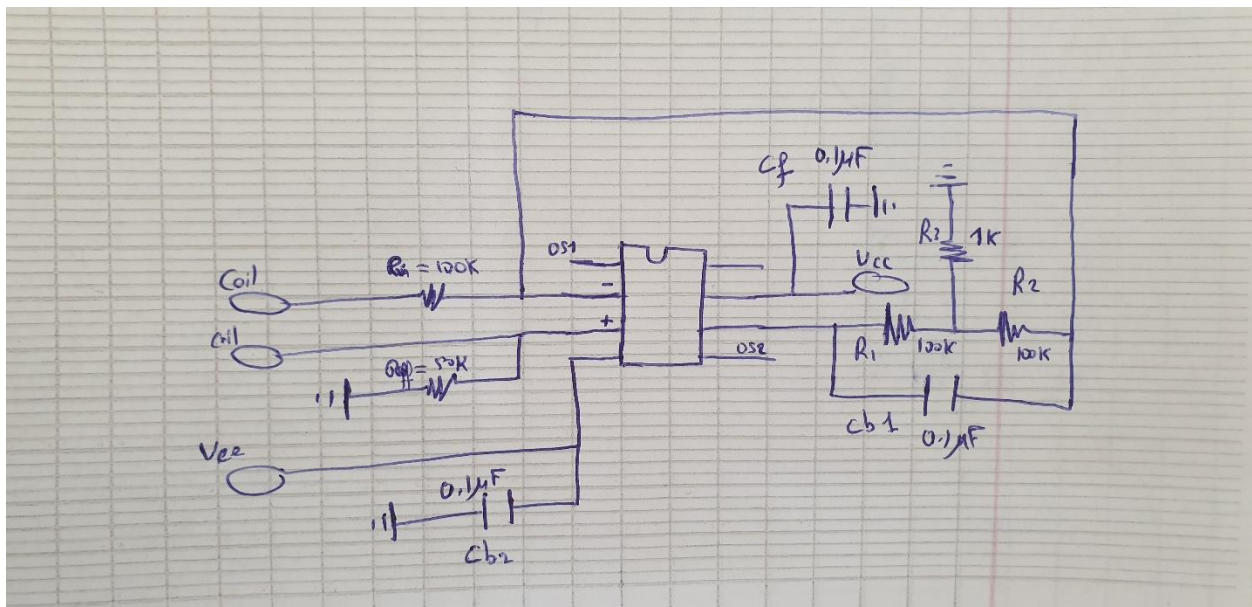
Fig.9: Electric circuit
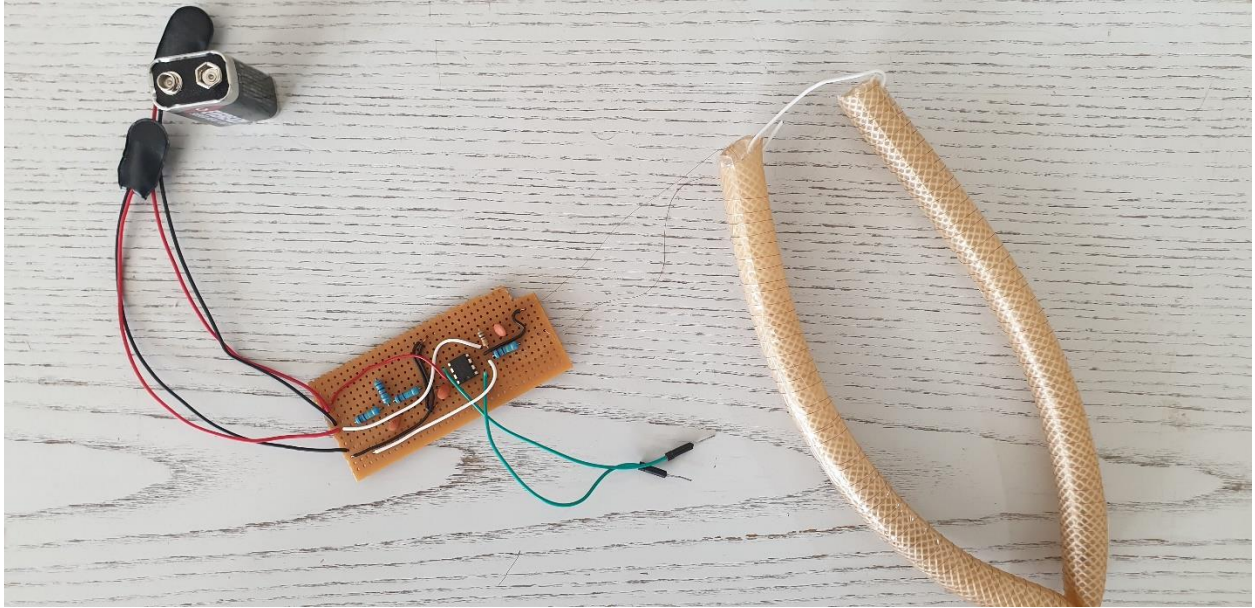
Fig.10: Rogowski Coil

NOTE: We need another battery 9v DC.

3.14 The formulas that should be used after construction a rogowski coil:

The voltage produced by a Rogowski coil is [3]

$$v(t) = \frac{-AN\mu_0}{l} \frac{dI(t)}{dt}$$

Where,

- $A = \pi r^2$, is the area of one of the small loops,
- N, is the number of turns,
- $l = 2\pi R$, is the length of the winding (the circumference of the ring),
- $\frac{dI(t)}{dt}$, is the rate of change of the current threading the loop,
- $\mu_0 = 4\pi \cdot 10^{-7}$, V·s/(A·m) is the magnetic constant,
- R, is the major radius of the toroid,
- r, is its minor radius.
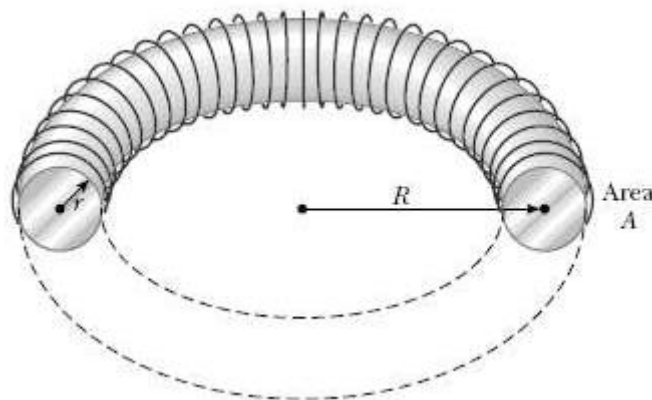
Fig.11: Major radius and minor radius of the toroid.

This formula assumes the turns are evenly spaced and that these turns are small relative to the radius of the coil itself [3].

The output of the Rogowski coil is proportional to the derivative of the wire current. The output is often integrated so the output is proportional to the wire's current [3]:

$$V_{out} = \int v \, dt = \frac{-AN\mu_0}{l} I(t) + C_{integration}$$

In practice, an instrument will use a lossy integrator with a time constant much less than the lowest frequency of interest. The lossy integrator will reduce the effects of offset voltages and set the constant of integration to zero [3].

At high frequencies, the Rogowski coil's inductance will decrease its output [3].

The inductance of a toroid is [3]:

$$L = \mu_0 N^2 (R - \sqrt{R^2 - r^2})$$

2} The values of the Structural parameters used in the construction of a rogowski coil:

Parameters	Values
R1	100 kΩ
R2	100 kΩ
R3	1 kΩ
Rin	100 kΩ
Roffset	50 kΩ
C1 (Cb1)	0.1 µF
C2 (Cb2)	0.1 µF
C3 (Cf)	0.1 µF
Operational amplifier	OP07CP
Battery 1	9 Volts DC
Battery 2	9 Volts DC
N (Number of turns)	94 Turns
R (Major radius)	8 cm
r (Minor radius)	1 cm

Tab.2: Structural Parameters of Rogowski.

3.15 Fix some errors in the installed electrical circuit in the lab

- Common ground   - Pin 5 is NC   - Output is on pin 6   - Pin 8 and the ground are the OS

3.15.1 Update on EagleCAD

New Schematic file	SCH louay.sch
New Board file	BRD louay.brd

Fig.12: New schematic

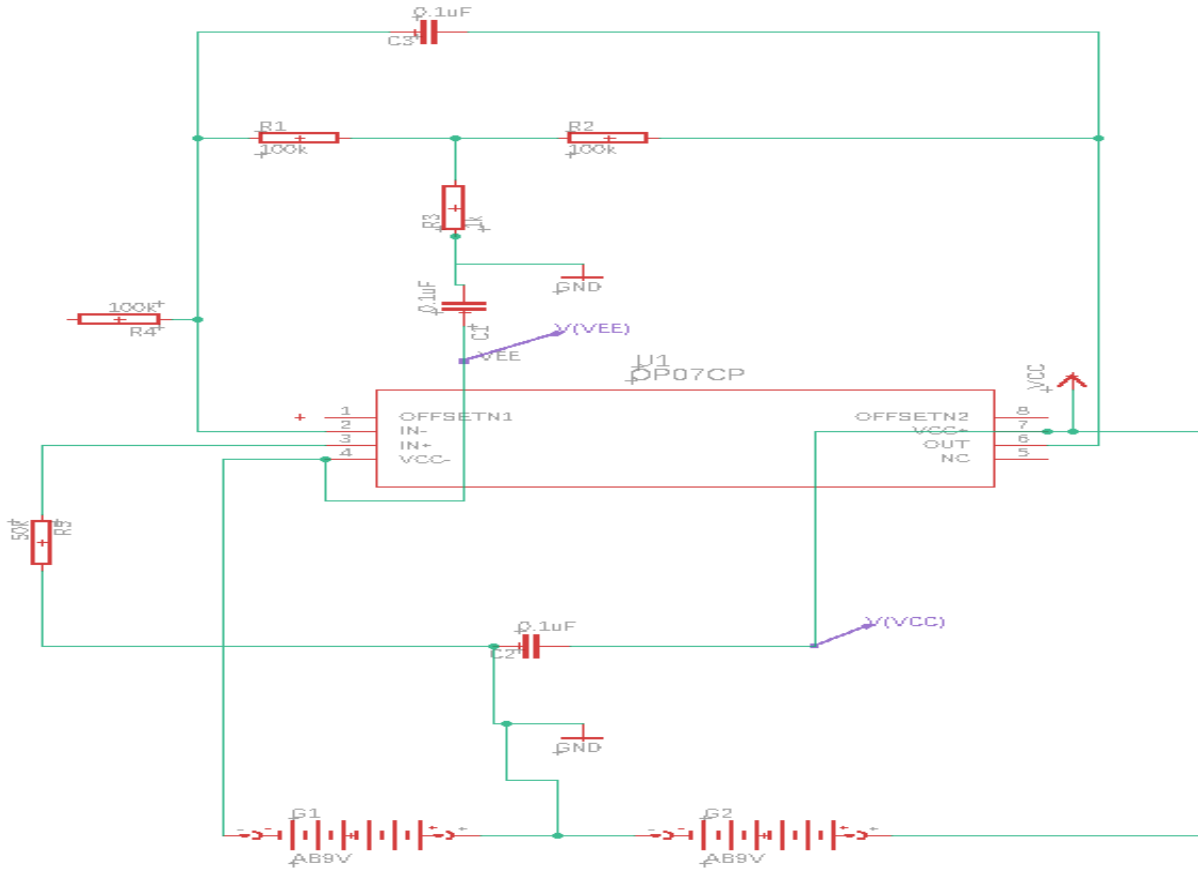
Fig.13: New Board

3.15.2 Update on the electrical circuit in lab
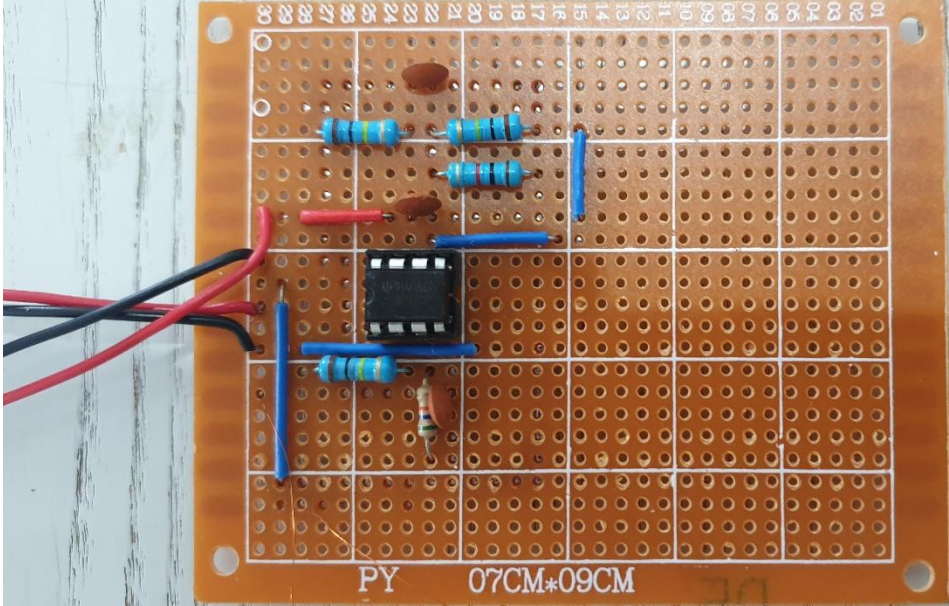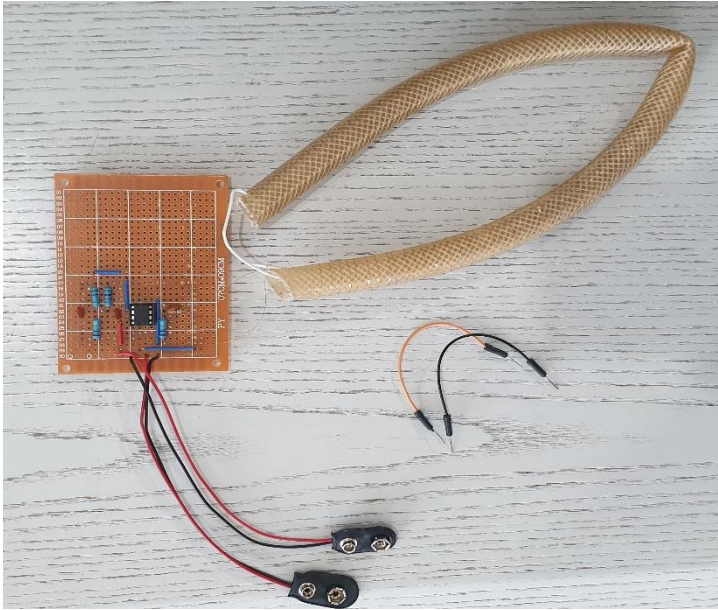

Fig.14: New Electrical circuit

Fig.15: Rogowski Coil

3.16 Comparison between op07cp and op77f

The operational amplifier OP07CP is the same as OP07C, the OP77 is the next generation of the OP07.

Parameter	Symbol	Conditions	OP77E Min	OP77E Typ	OP77E Max	OP77F Min	OP77F Typ	OP77F Max	Unit
INPUT OFFSET VOLTAGE	VOS			10	25		20	60	µV
LONG-TERM STABILITY[1]	V_{OS}/Time			0.3			0.4		µV/Mo
INPUT OFFSET CURRENT	I_{OS}			0.3	1.5		0.3	2.8	nA
INPUT BIAS CURRENT	I_B		–0.2	1.2	2.0	–0.2	1.2	2.8	nA
INPUT NOISE VOLTAGE[2]	e_{np-p}	0.1 Hz to 10 Hz		0.35	0.6		0.38	0.65	$µV_{p-p}$
INPUT NOISE VOLTAGE DENSITY	e_n	$f_O = 10$ Hz; $f_O = 100$ Hz[2]; $f_O = 1000$ Hz		10.3; 10.0; 9.6	18.0; 13.0; 11.0		10.5; 10.2; 9.8	20.0; 13.5; 11.5	nV/$\sqrt{Hz}$
INPUT NOISE CURRENT[2]	i_{np-p}	0.1 Hz to 10 Hz		14	30		15	35	pA_{p-p}
INPUT NOISE CURRENT DENSITY	i_n	$f_O = 10$ Hz; $f_O = 100$ Hz[2]; $f_O = 1000$ Hz		0.32; 0.14; 0.12	0.80; 0.23; 0.17		0.35; 0.15; 0.13	0.90; 0.27; 0.18	pA$\sqrt{Hz}$
INPUT RESISTANCE Differential Mode[3] Common Mode	R_{IN} R_{INCM}		26	45 200		18.5	45 200		MΩ GΩ
INPUT RESISTANCE Common Mode	R_{INCM}			200			200		GΩ
INPUT VOLTAGE RANGE	IVR		±13	±14		±13	±14		V
COMMON-MODE REJECTION RATIO	CMRR	$V_{CM} = ±13$ V		0.1	1.0		0.1	1.6	µV/V
POWER SUPPLY REJECTION RATIO	PSRR	$V_S = 3$ V to 18 V		0.7	3.0		0.7	3.0	µV/V
LARGE-SIGNAL VOLTAGE GAIN	A_{VO}	$R_L \geq 2$ kΩ	5000	12000		2000	6000		V/mV
OUTPUT VOLTAGE SWING	V_O	$R_L \geq 10$ kΩ; $R_L \geq 2$ kΩ; $R_L \geq 1$ kΩ	±13.5; ±12.5; ±12.0	±14.0; ±13.0; ±12.5		±13.5; ±12.5; ±12.0	±14.0; ±13.0; ±12.5		V
SLEW RATE[2]	SR	$R_L \geq 2$ kΩ	0.1	0.3		0.1	0.3		V/µs
CLOSED-LOOP BANDWIDTH[2]	BW	A_{VCL} 1	0.4	0.6		0.4	0.6		MHz
OPEN-LOOP OUTPUT RESISTANCE	R_O			60			60		Ω
POWER CONSUMPTION	Pd	$V_S = ±15$ V, No Load; $V_S = ±3$ V, No Load		50; 3.5	60; 4.5		50; 3.5	60; 4.5	mW
OFFSET ADJUSTMENT RANGE		Rp = 20 kn		±3			±3		mV

Fig.16: Electrical specifications of OP77F

PARAMETER		TEST CONDITIONS		T$_A$ [2]	OP07C			OP07D			UNIT
					MIN	TYP	MAX	MIN	TYP	MAX	
V$_{IO}$	Input offset voltage	V$_O$ = 0 V	R$_S$ = 50 Ω	25°C		60				150	µV
				0°C to 70°C		85				250	
α$_{VIO}$	Temperature coefficient of input offset voltage	V$_O$ = 0 V	R$_S$ = 50 Ω	0°C to 70°C		0.5				2.5	µV/°C
	Long-term drift of input offset voltage	See				0.4					µV/mo
	Offset adjustment range	R$_S$ = 20 kΩ,	See Figure 2	25°C		±4					mV
I$_{IO}$	Input offset current			25°C		0.8				6	nA
				0°C to 70°C		1.6				8	
α$_{IIO}$	Temperature coefficient of input offset current			0°C to 70°C		12				50	pA/°C
I$_{IB}$	Input bias current			25°C		±1.8				±12	nA
				0°C to 70°C		±2.2				±14	
α$_{IIB}$	Temperature coefficient of input bias current			0°C to 70°C		18				50	pA/°C
V$_{ICR}$	Common-mode input voltage range			25°C	±13	±14		±13	±14		V
				0°C to 70°C	±13	±13.5		±13	±13.5		
V$_{OM}$	Peak output voltage	R$_L$ ≥ 10 kΩ			±12	±13		±12	±13		V
		R$_L$ ≥ 2 kΩ		25°C	±11.5	±12.8		±11.5	±12.8		
		R$_L$ ≥ 1 kΩ				±12			±12		
		R$_L$ ≥ 2 kΩ		0°C to 70°C	±11	±12.6		±11	±12.6		

PARAMETER		TEST CONDITIONS [1]	OP07C	OP07D	UNIT
			TYP	TYP	
V$_n$	Input offset voltage	f = 10 Hz	10.5	10.5	nV/√Hz
		f = 100 Hz	10.2	10.3	
		f = 1 kHz	9.8	9.8	
V$_{N(PP)}$	Peak-to-peak equivalent input noise voltage	f = 0.1 Hz to 10 Hz	0.38	0.38	µV
I$_n$	Equivalent input noise current	f = 10 Hz	0.35	0.35	nV/√Hz
		f = 100 Hz	0.15	0.15	
		f = 1 kHz	0.13	0.13	
I$_{N(PP)}$	Peak-to-peak equivalent input noise current	f = 0.1 Hz to 10 Hz	15	15	pA
SR	Slew rate	R$_L$ ≥ 2 kΩ	0.3	0.3	V/µs

Fig.17: Electrical specifications of OP07C

By comparing the outputs of the two operational amplifiers, we demonstrate that we can use the OP77F instead of OP07CP in the simulation because the output of the two operational amplifiers are very close and also because the spice model of OP07CP is not available on internet.

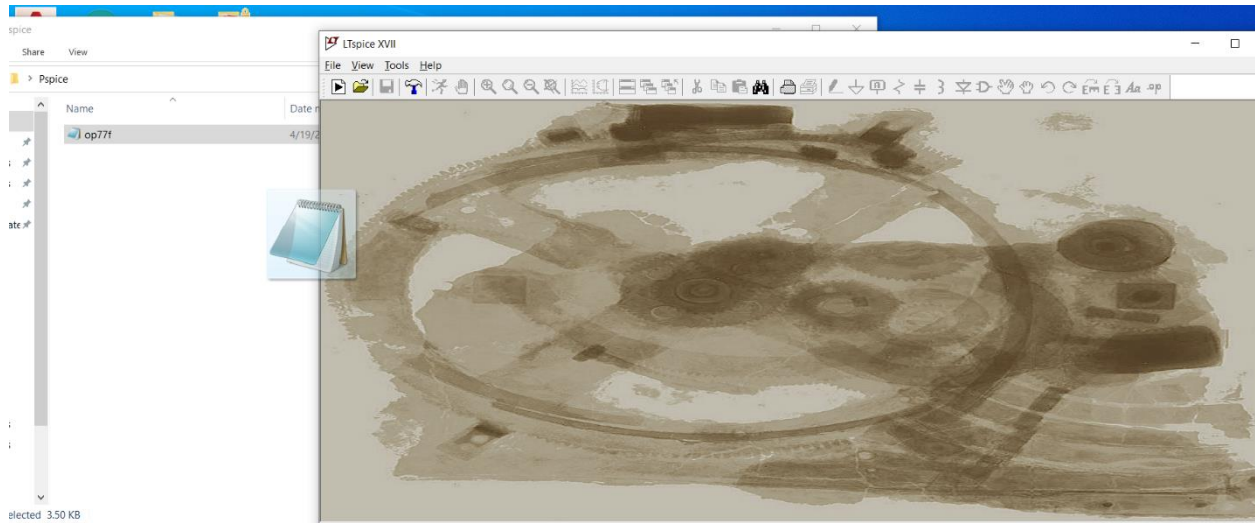## 3.17 How to insert and use the OP77F code downloaded from the Internet into the LTspice:

op77f.cir

Fig.18: Step one


```
* OP77F SPICE Macro-model
* Description: Amplifier
* Generic Desc: 6/30V, BIP, OP, Low Vos, Precision, 1X
* Developed by: JCB / PMI
* Revision History: 08/10/2012 - Updated to new header style
* 2.0 (12/1990) - Re-ordered subcircuit call out nodes to put the output node last.
*              - Changed Ios from 2.8E-9 to 1.4E-9
*        - Added F1 and F2 to fix short circuit current limit.
* Copyright 1990, 2012 by Analog Devices, Inc.
*
* Refer to http://www.analog.com/Analog_Root/static/techSupport/designTools/spiceModels/license/spice_general.htm
* indicates your acceptance with the terms and provisions in the License Statement.
*
* BEGIN Notes:
*
* Not Modeled:
*
* Parameters modeled include:
* This version of the OP-77 model simulates the worst case
* parameters of the 'F' grade.  The worst case parameters
* used correspond to those in the data book.
*
* END Notes
*
* Node assignments
*            non-inverting input
*            | inverting input
*            | | positive supply
```
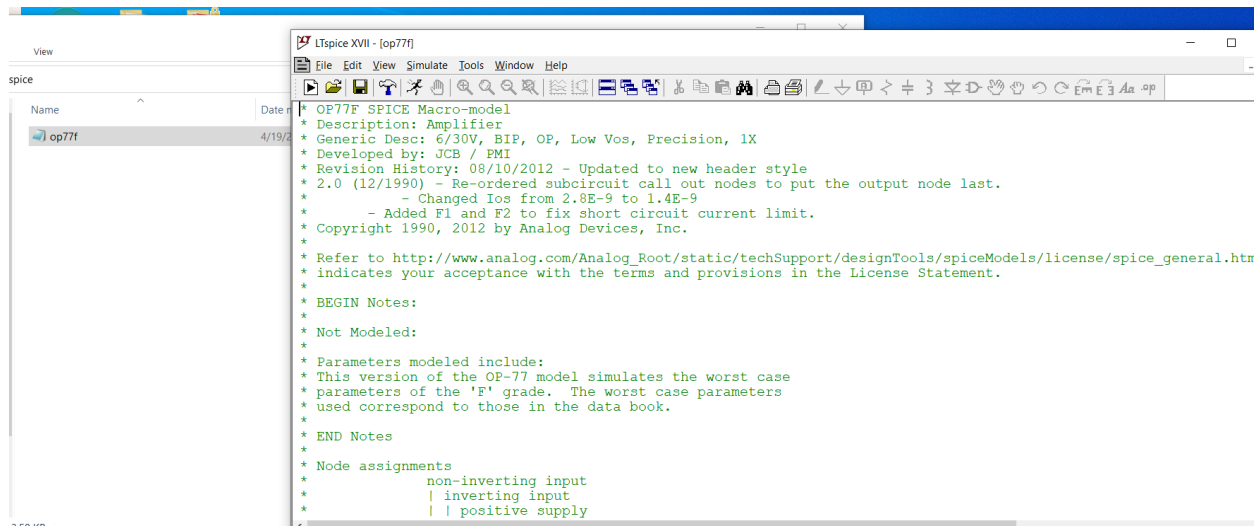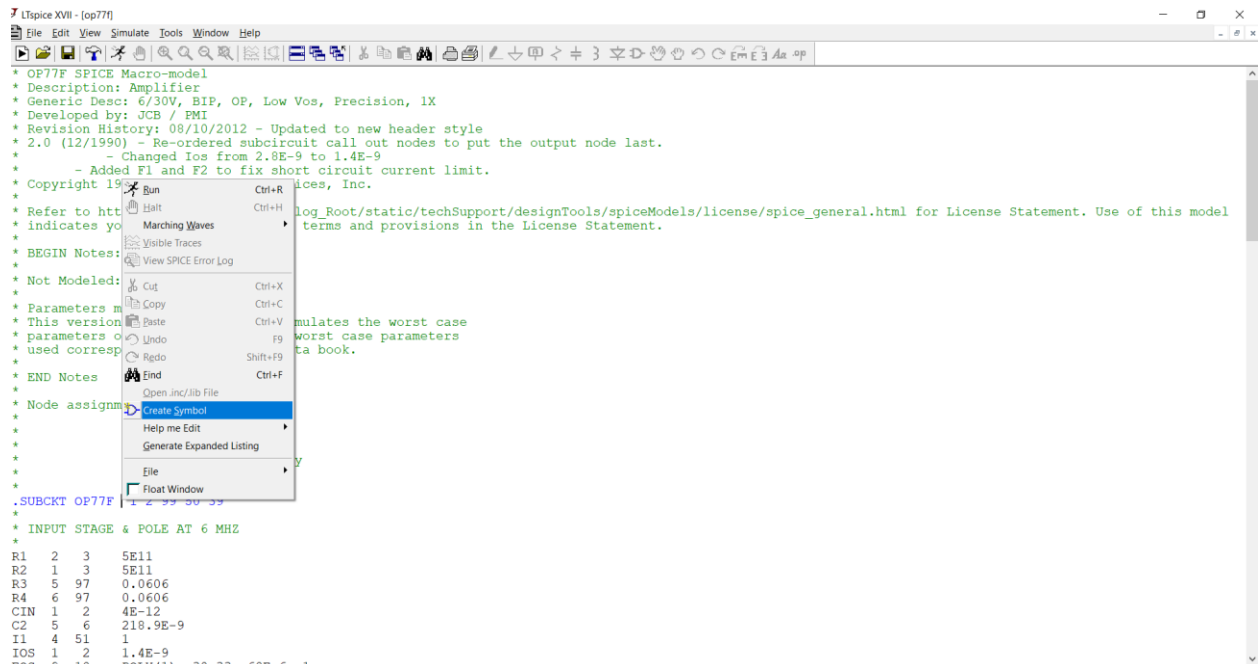
Fig.19: Step two
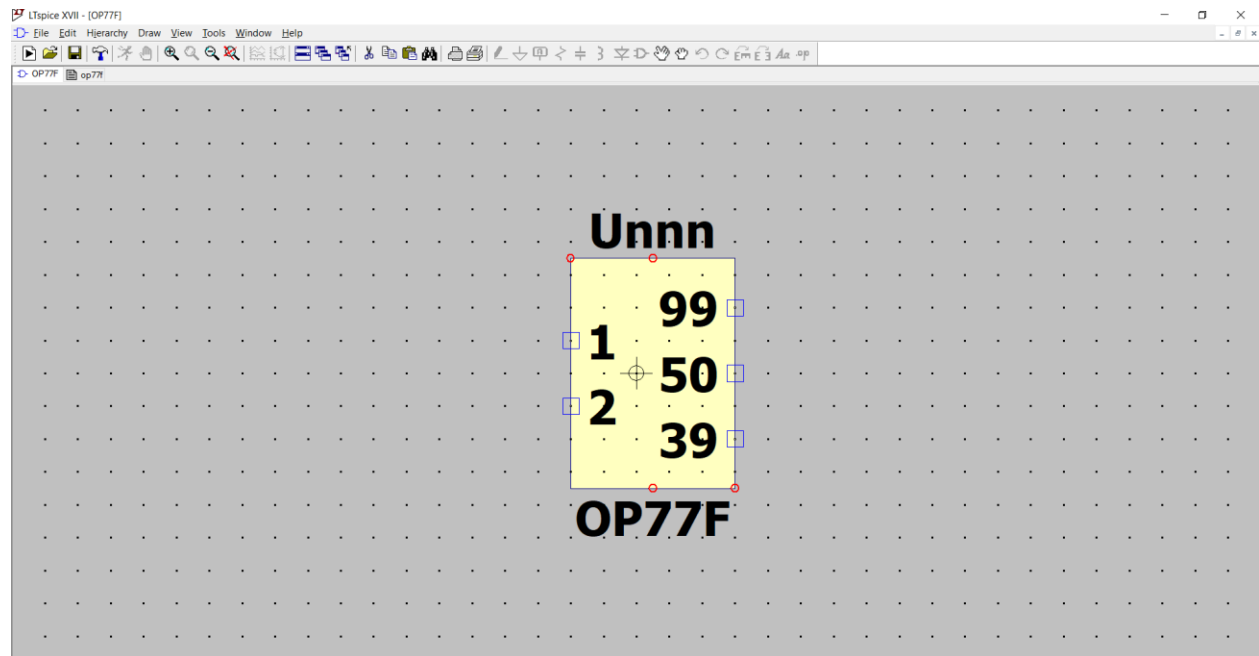
26

Fig.20: Step three

Fig.21: Step four

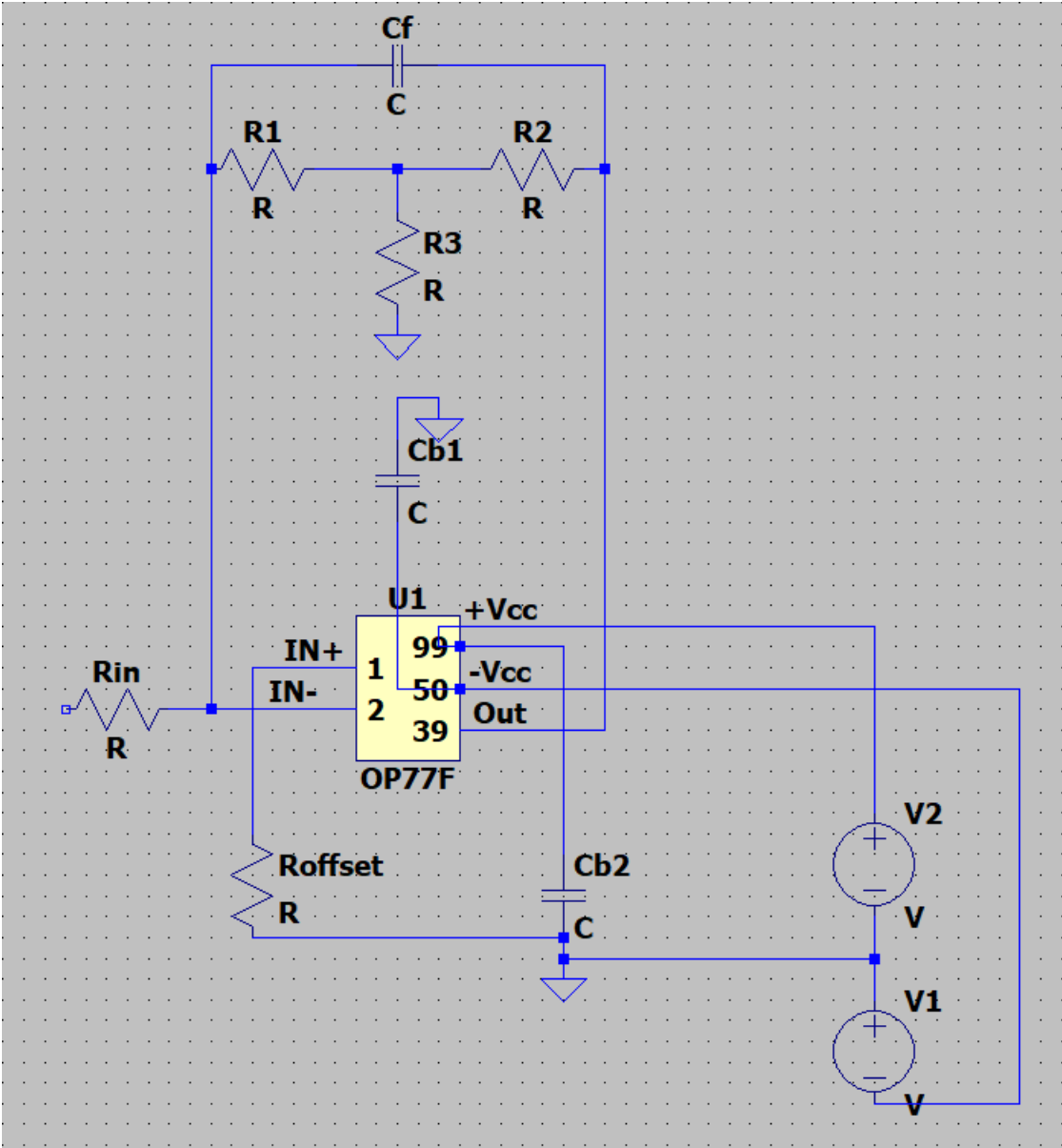## 3.18 The electronic circuit schematique in LTspice
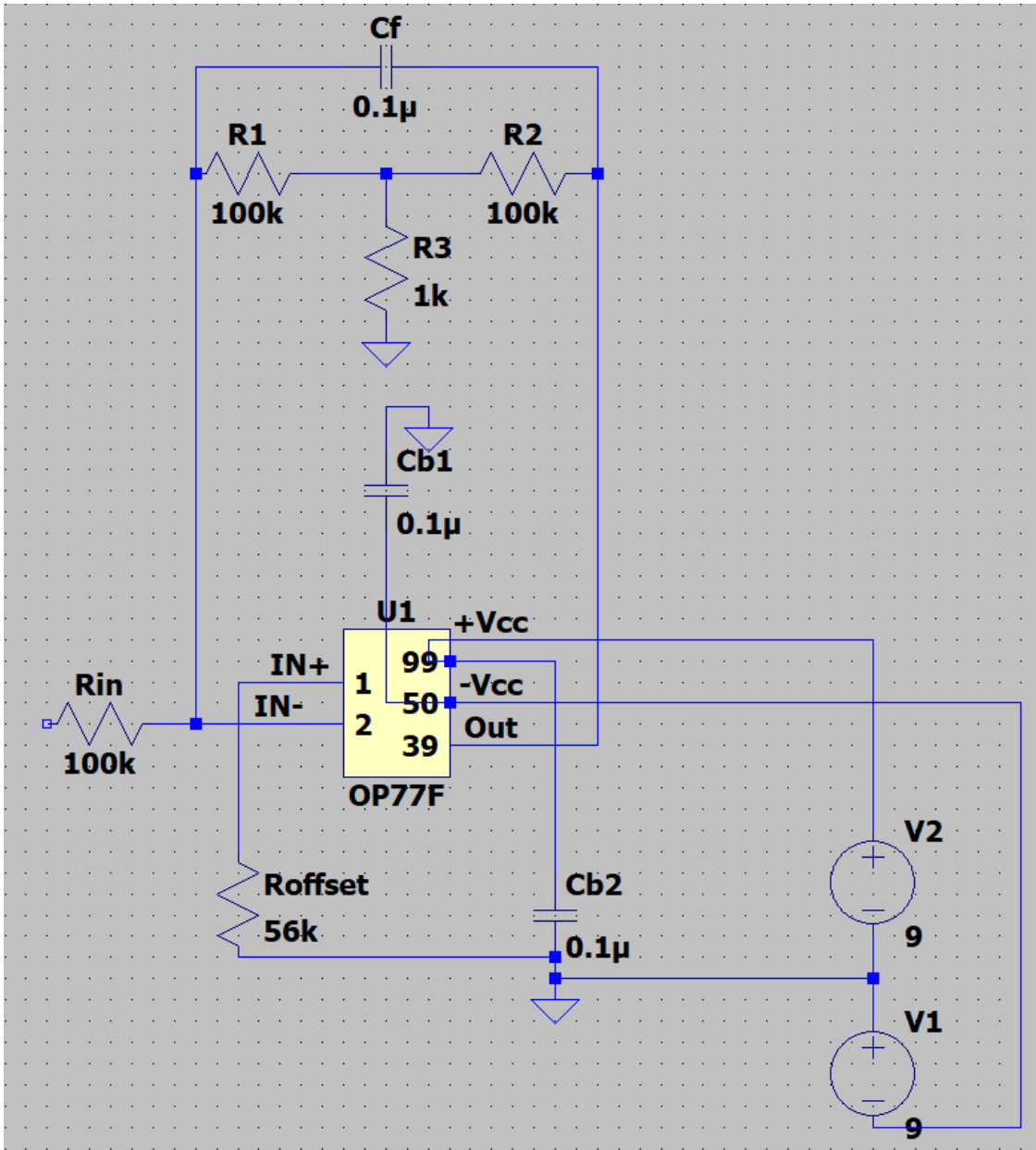

Fig.22: Schematic without values

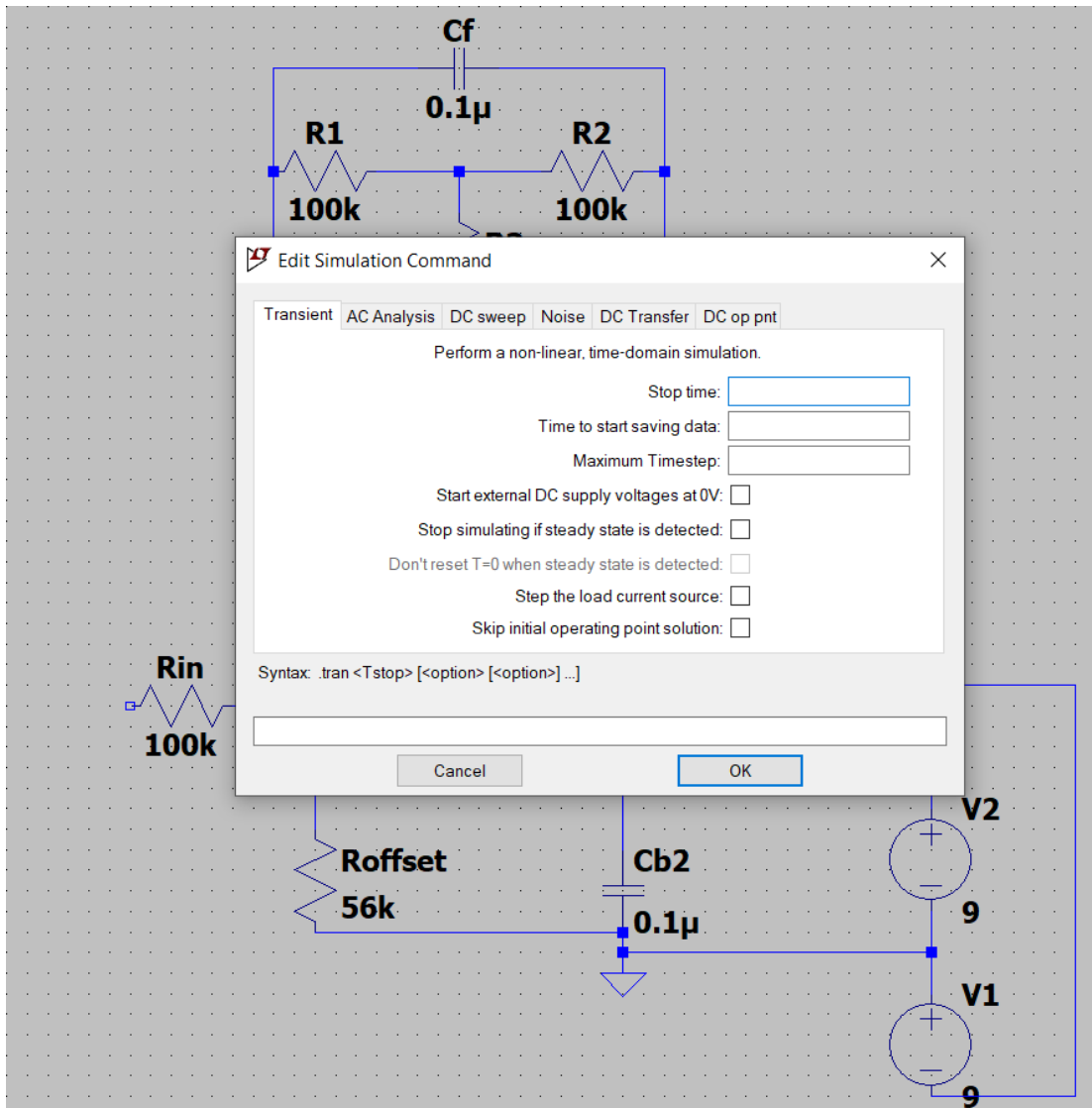Fig.23: Schematic with values

Fig.24: The six options of simulation

We use two options of simulation: (Transient) and (DC in ont)
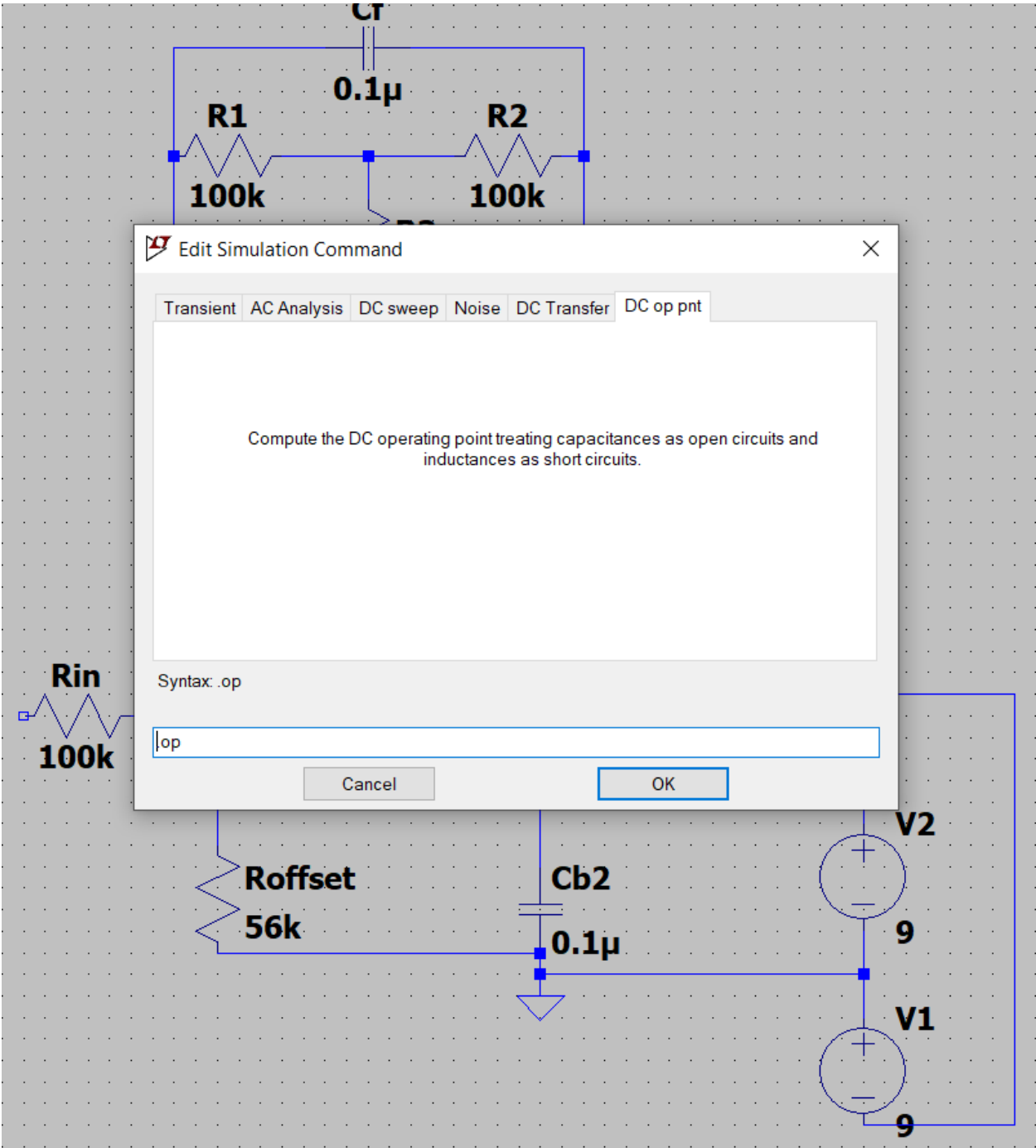
3.19 Simulation (DC on pnt)

Fig.25: First simulation

```
⚓ * C:\Users\Loay\Desktop\LTSPICE INTEGRATOR.asc                                    ✕

        --- Operating Point ---

V(in-):           -0.000174724   voltage
V(in+):           -0.000234725   voltage
V(+vcc):           9             voltage
V(-vcc):          -9             voltage
V(out):           -0.00345361    voltage
V(n001):          -3.55719e-005  voltage
V(nc_01):         -0.000174724   voltage
I(Cb2):            9e-019        device_current
I(Cb1):            9e-019        device_current
I(Cf):            -3.27889e-022  device_current
I(Roffset):       -4.19152e-009  device_current
I(Rin):           -2.71051e-025  device_current
I(R3):            -3.55719e-008  device_current
I(R2):            -3.41804e-008  device_current
I(R1):             1.39152e-009  device_current
I(V2):            -0.00149       device_current
I(V1):            -0.00149003    device_current
Ix(u1:1):          4.19152e-009  subckt_current
Ix(u1:2):          1.39152e-009  subckt_current
Ix(u1:99):         0.00149       subckt_current
Ix(u1:50):        -0.00149003    subckt_current
Ix(u1:39):         3.41804e-008  subckt_current
```
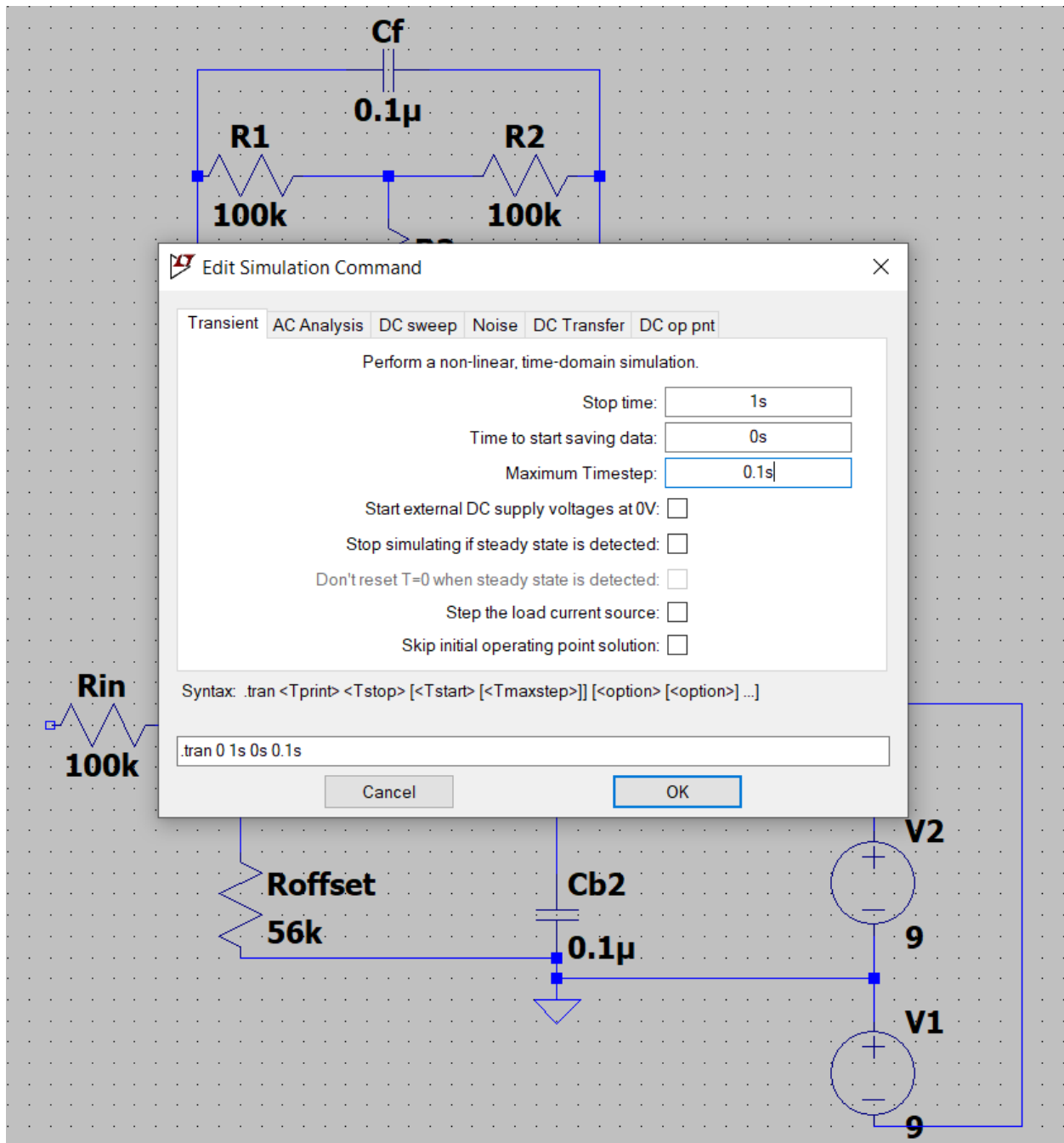
Fig.26: Results of first simulation

1. Simulation (Transient)
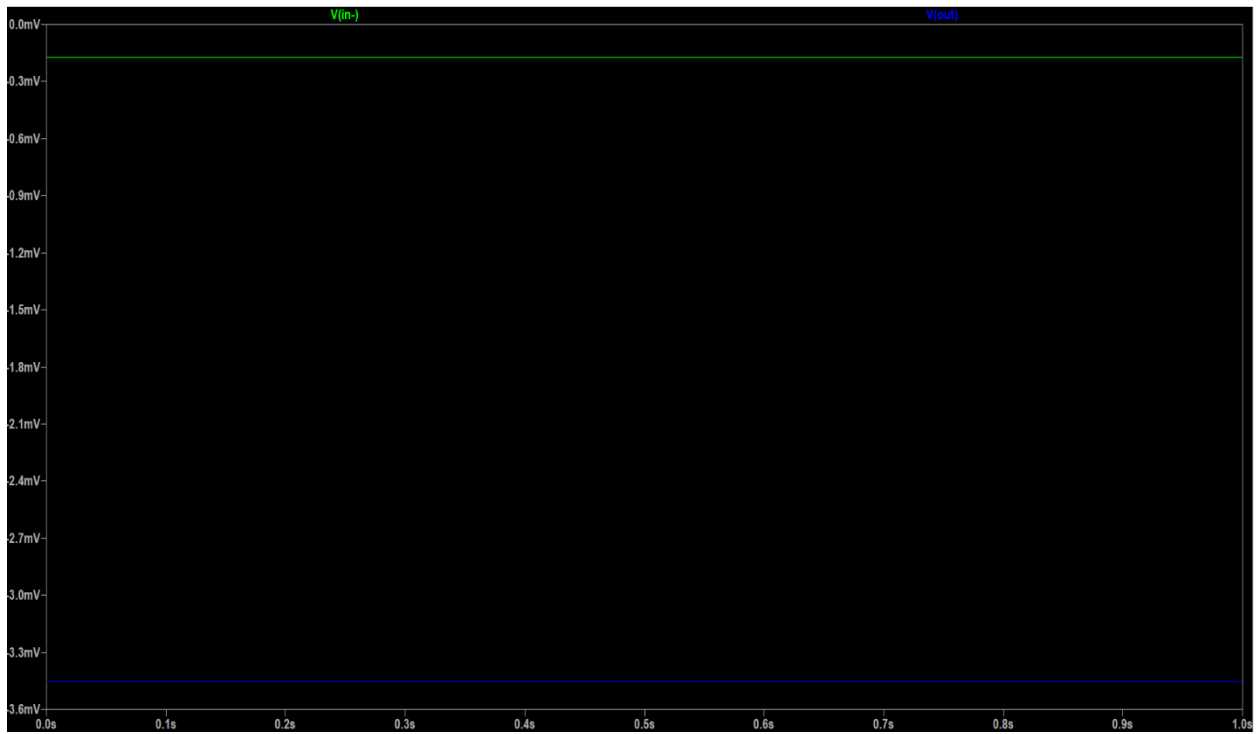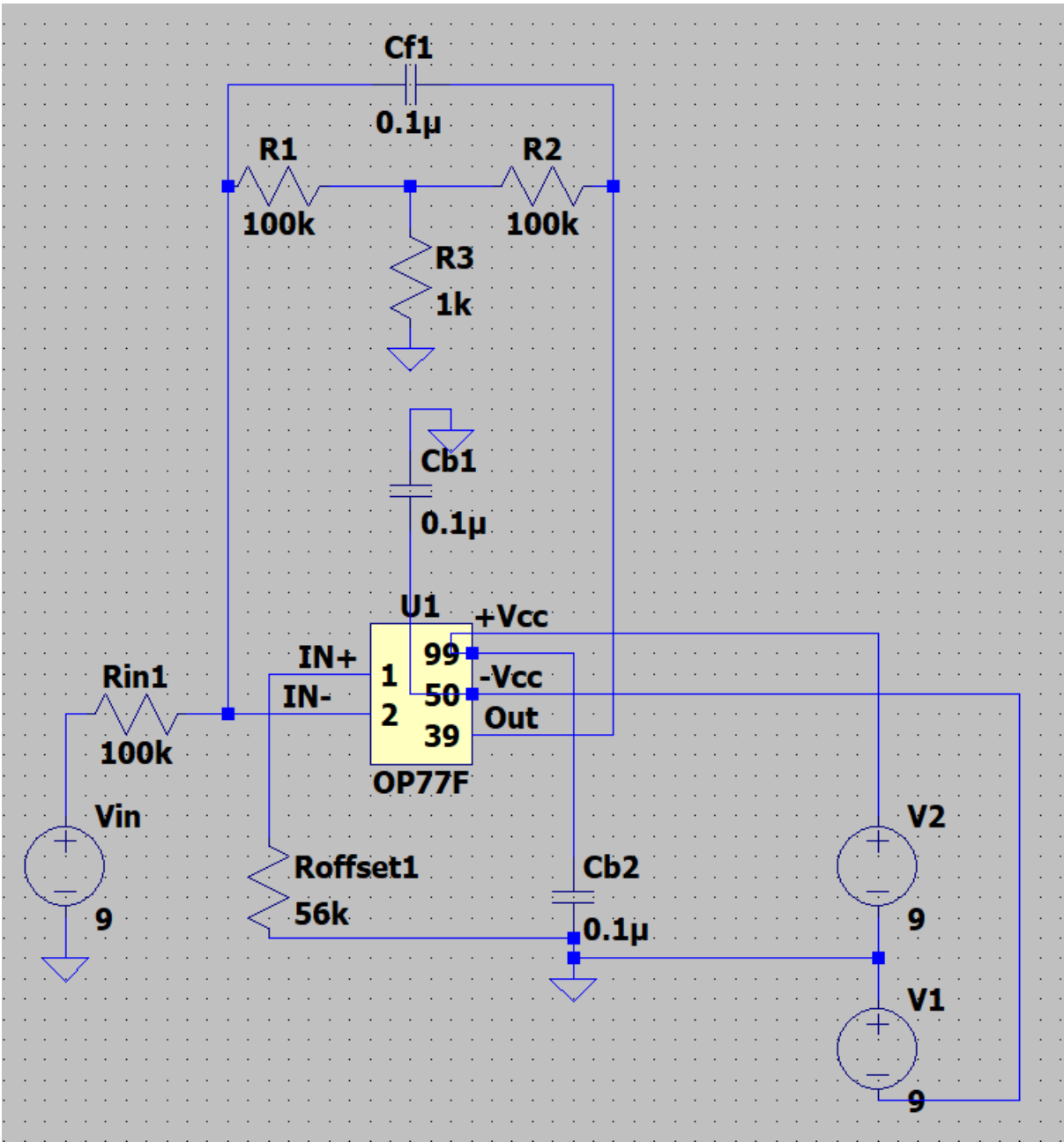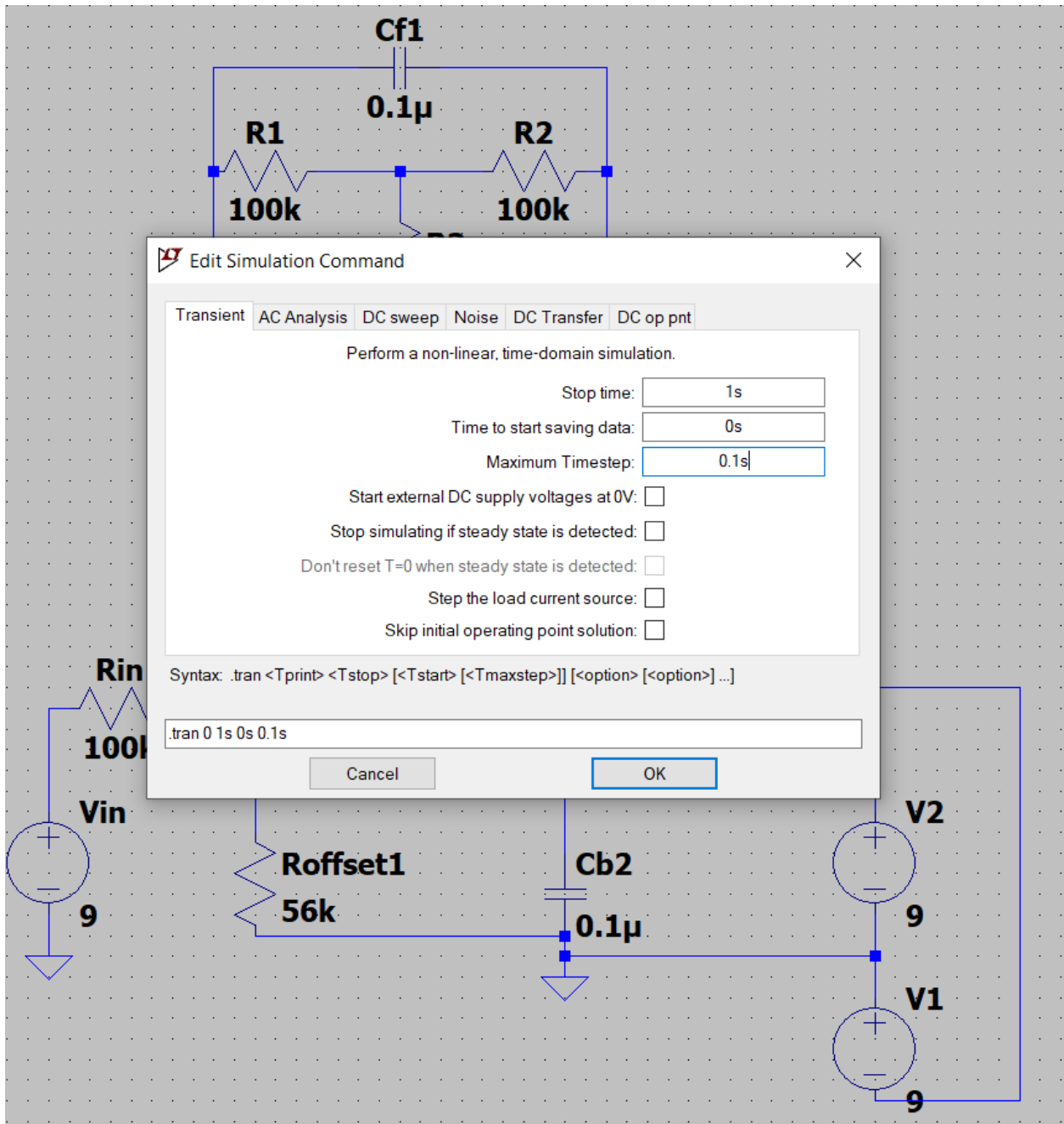

Fig.27: Second simulation

Fig.28: Results of second simulation

3.20 Add an input voltage to the schematic

Cf1
0.1μ

R1
100k

R2
100k

Edit Simulation Command ✕

Transient | AC Analysis | DC sweep | Noise | DC Transfer | DC op pnt

Perform a non-linear, time-domain simulation.

Stop time:	1s
Time to start saving data:	0s
Maximum Timestep:	0.1s

Start external DC supply voltages at 0V: ☐
Stop simulating if steady state is detected: ☐
Don't reset T=0 when steady state is detected: ☐
Step the load current source: ☐
Skip initial operating point solution: ☐

Syntax: .tran <Tprint> <Tstop> [<Tstart> [<Tmaxstep>]] [<option> [<option>] ...]

.tran 0 1s 0s 0.1s

Cancel | OK

Rin
100k

Vin
9

Roffset1
56k

Cb2
0.1μ

V2
9

V1
9

4   Remaining tasks

1. First task: The Rogowski coil should be tested first by doing several measurements in the laboratory, and then plotting the voltage as a function of current. From this diagram, we can find out the equation that relates both voltage and current.
2. Second task: A numerical comparison should be made between the voltage values that we obtain through the equation we mentioned earlier and the theoretical equation in the article (the equation written on page 18).
3. Third task: When making sure that the comparison was close, then we must design and construct a small plastic house in order to put the Rogowski coil inside it, and of course there must be an exit for two electrical lines.
   If the comparison is too far, another type of coil and another type of core should be used.
4. fourth task: In the fourth stage, the Rogowski coil must be given to a person specialized in the PLC to doing the power control system.
5. Final task: In the last stage, the Rogowski coil must be tested at the station. Of course, we must measure the current in the area located before the large voltage (40 KV), that is, directly before entering into the Electro filte . In other words, at the region where the voltage is found at its normal value (220 volts).
   After that, there is a physical equation through which we can identify the value of the current in the Electro filter, which is:
   $$V1/V2 = I2/I1$$
   With,
   V1= 220 v ,
   V2= 40 Kv ,
   I1= Done in final task ,
   I2= ??

   After we get the value of the current I2, we can evaluate the work and efficiency of this Electro Filter, and this is what we want to reach in this work.

5   Literature

[1] https://www.electrical4u.com/rogowski-coil/

[2] https://www.sciencedirect.com/science/article/abs/pii/S1738573319301755

[3] https://en.wikipedia.org/wiki/Rogowski_coil