DELHI TECHNOLOGICAL UNIVERSITY

LINEAR INTEGRATED CIRCUITS

PROJECT REPORT

PROJECT TITLE:
EXPONENTIAL VOLTAGE CONTROLLED OSCILLATOR

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ABSTRACT

Voltage Controlled Oscillator

A **voltage-controlled oscillator** (**VCO**) is an electronic oscillator whose oscillation frequency is controlled by a voltage input. The applied input voltage determines the instantaneous oscillation frequency. Consequently, a VCO can be used for frequency modulation (FM) or phase modulation (PM) by applying a modulating signal to the control input. A VCO is also an integral part of a phase-locked loop.

A **voltage-to-frequency converter** (**VFC**) is a special type of VCO designed to be very linear in frequency control over a wide range of input control voltages

Types:

VCOs can be generally categorized into two groups based on the type of waveform produced.

- *Linear* or *harmonic oscillators* generate a sinusoidal waveform. Harmonic oscillators in electronics usually consist of a resonator with an amplifier that replaces the resonator losses (to prevent the amplitude from decaying) and isolates the resonator from the output (so the load does not affect the resonator). Some examples of harmonic oscillators are LC oscillators and crystal oscillators.
- *Relaxation oscillators* can generate a sawtooth or triangular waveform. They are commonly used in integrated circuits (ICs). They can provide a wide range of operational frequencies with a minimal number of external components.

This project tries to exploit one of the applications of VCO namely Exponential VCO or 1V/Octave VCO.

1V/Octave Voltage Controlled Oscillator or Exponential VCO

The basic idea behind an exponential VCO comes from a keyboard.

- This circuit is also known as 1V/Octave synthesizer.
- This means that for every 1V increase in input output frequncy will go above by 1 octave(ie by a factor of 2)
- If you take a piano and play the middle A note (A4), it makes a specific tone which has a frequency of 440Hz. If you now play the A note to the right of this one (12 notes up, A5) the note sounds the same except higher pitch and has a frequency of 880Hz. (The lower note is a harmonic of the upper note which is why they sound OK when played together). Now, if you play the next A note to

the right (A6), the note sounds higher pitched than the previous A note; it has a frequency of 1760Hz.

Any two same notes that are separated by 12 keys is called an octave. For any two keys that are an octave apart, the upper key will have a frequency twice that of the first. The reason for this is because by nature human hearing is logarithmic. This means that for something to sound twice as loud, its amplitude (or frequency in the pitch realm) needs to go up by a factor of two.

Any two same notes that are separated by 12 keys is called an octave. For any two keys that are an octave apart, the upper key will have a frequency twice that of the first. The reason for this is because by nature human hearing is logarithmic. This means that for something to sound twice as loud, its amplitude (or frequency in the pitch realm) needs to go up by a factor of two.

If, for example, we increase the frequency of a waveform from 1Hz to 2Hz, that would be considered an octave apart according to the human ear. But increasing a waveform frequency from 440Hz to 441Hz does not result in an octave change. In fact, the human ear would not be able to distinguish between these two frequencies because the human ear is good at relative changes as opposed to absolute changes.

So with all that complicated theory out of the way, we need to find a method to take in a linear voltage source (1V Octave Keyboard) and convert it into a voltage source that produces exponential voltages. To do this we will use a component that has inherent exponential qualities, the bipolar junction transistor or BJT.

So the basic idea of this project is to use a linear to exponential Voltage converter followed by a VCO.

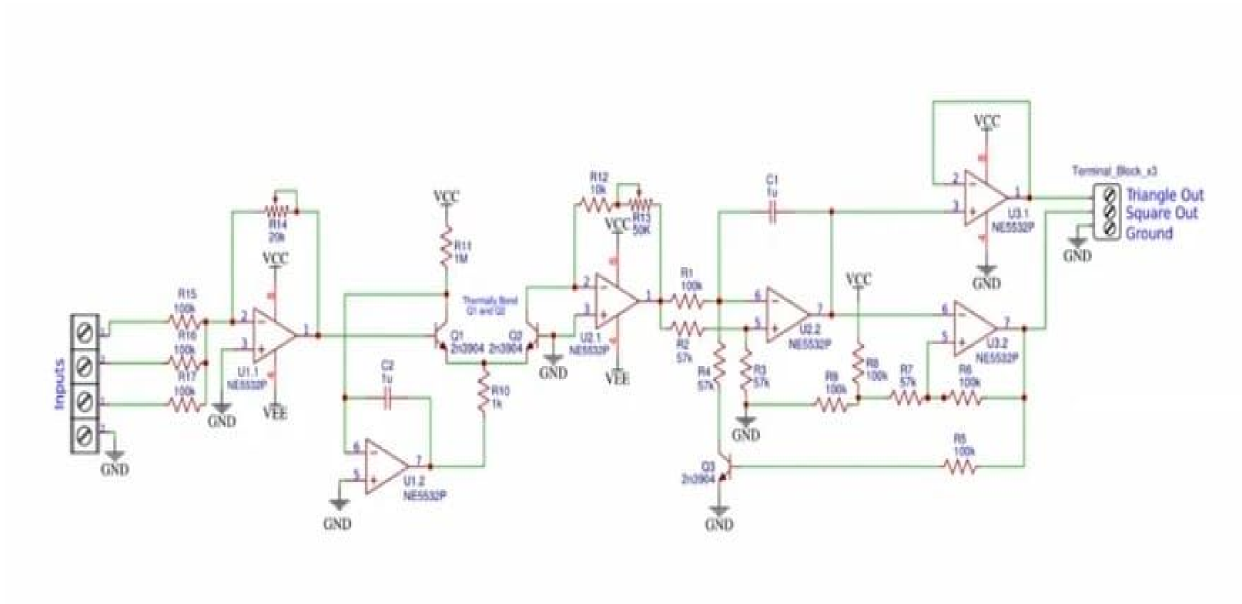
We need a circuit to take in a linear voltage from the keyboard/controllers and produce an exponential voltage which doubles in value for every octave.

The component that will be used for its exponential properties is the BJT. Most will be familiar with the equation that relates the base current to the collector current but this relationship is linear.

The equation that relates the base-emitter voltage to the collector current is exponential:

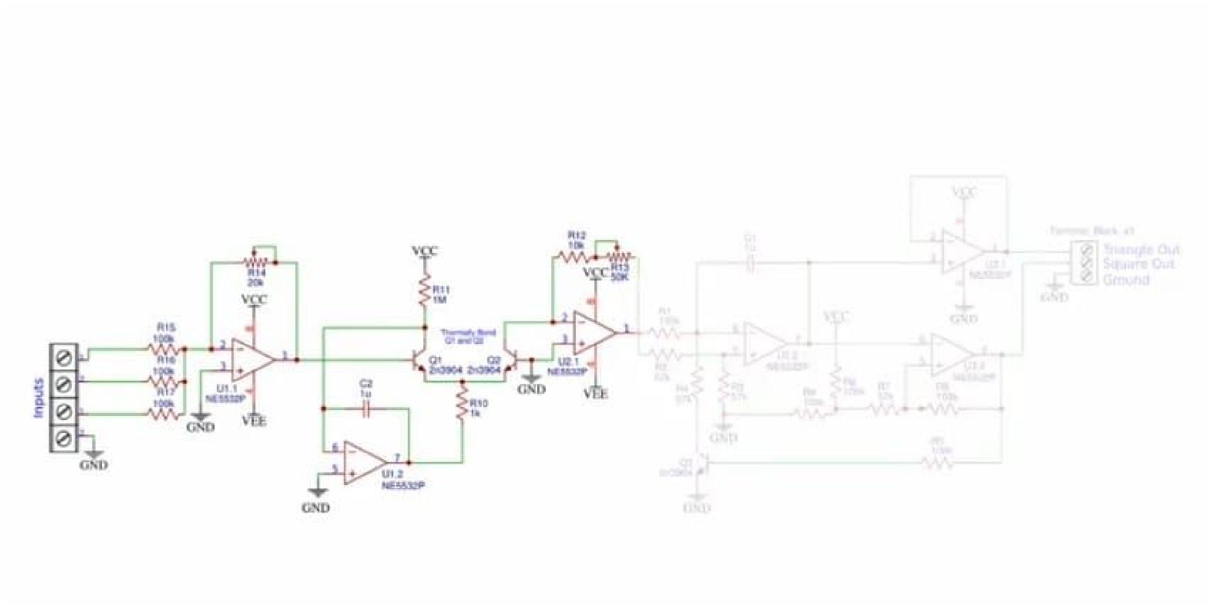
$I_c = I_s \exp(V_{be}/V_t)$

CIRCUIT DIAGRAM and EXPLANATION:

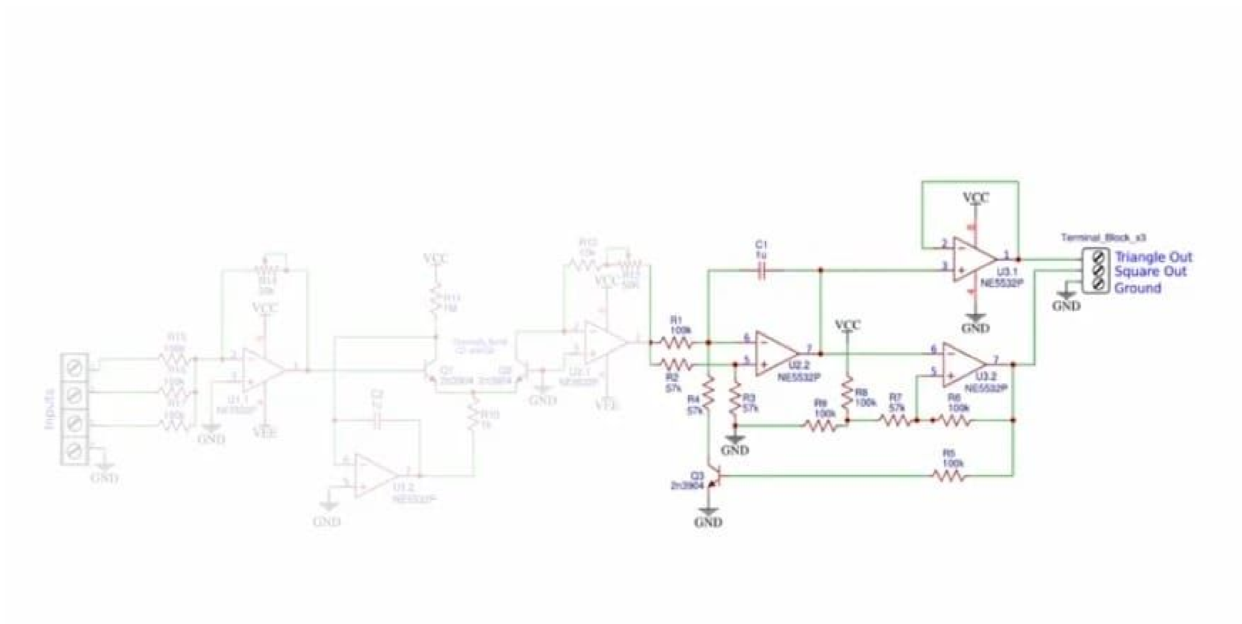


The main circuit is divided into 2 parts:
a)The exponentiator
b)The Voltage Controlled Oscillator

A)The Exponentiator



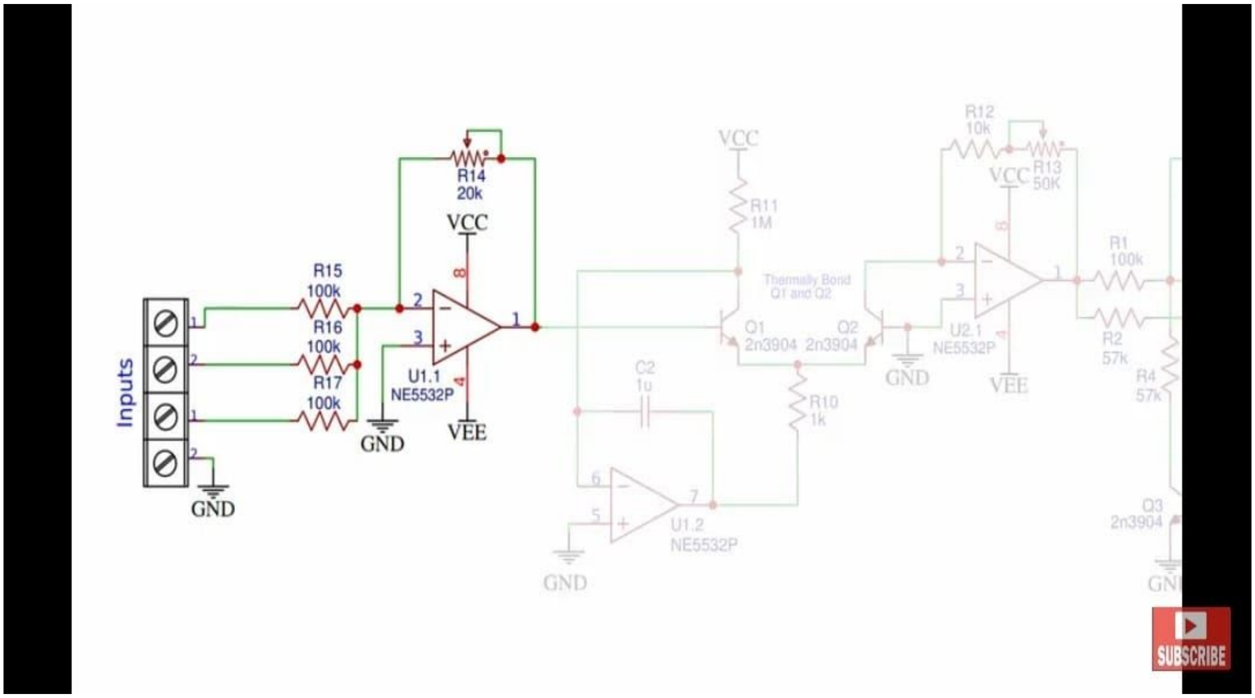
B)The Voltage Controlled Oscillator



1.Parts of the Exponentiator

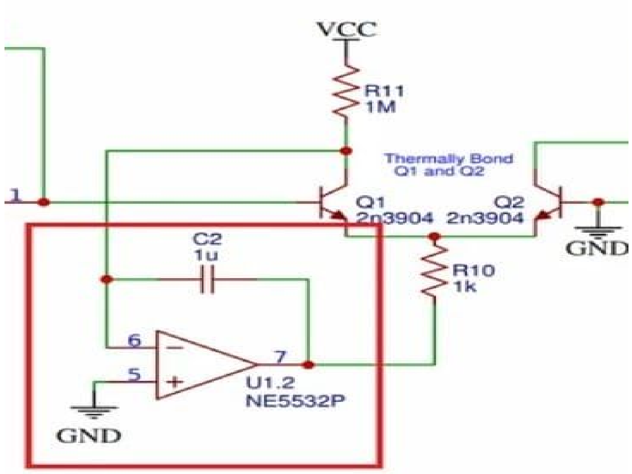
A)The summer:

The summer would take all the inputs from the keyboard and sum their values.So the summer has a number of components like the keys ,the tones etc.

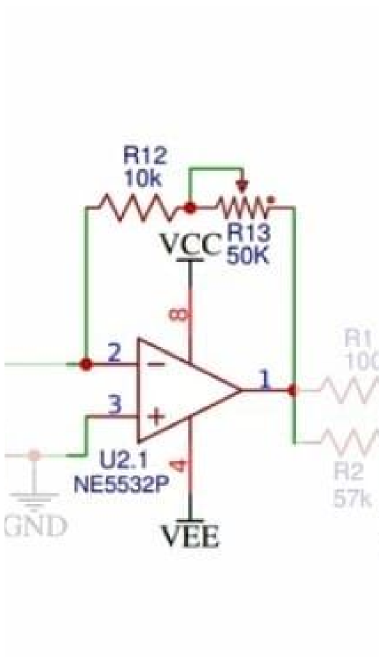


b)The integrator

This integrator’s job is to maintain the current across the transistor.Any change in the current in the transistor base may make corresponding change in the base emittter current in Q2.These changes will cause an exponential change in the collector current current of the transistor.



c)The transimpedance amplifier
We need a voltage output and not a current output so we use a transimpedance amplifier to convert current to a proportional voltage.



d)The differential pair

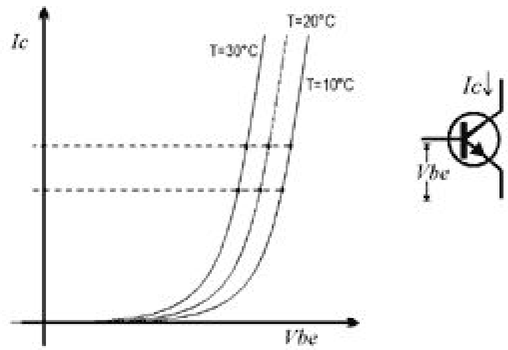
This is used to exponentiate the current in the circuit.

The component that will be used for its exponential properties is the BJT. Most will be familiar with the equation that relates the base current to the collector current but this relationship is linear.

The equation that relates the base-emitter voltage to the collector current is exponential:

$$I_C = I_S(e^{(\frac{qV_{be}}{kT})} - 1)$$

In order to broaden the knowledge about this frequently employed circuit, I provide this discussion here. To understand this document I will provide you with the needed knowledge about transistors. A little maths is involved however, mainly log and exp laws. I don't give all the derivations, if you're not into maths, then take the results for god given ;-)



$$I_c = I_s \cdot [\, exp\ (\frac{q \cdot Vbe}{k \cdot T}) - 1\,]$$

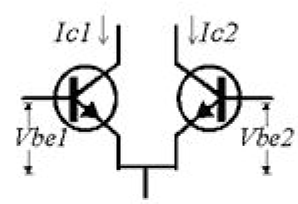
In Figure 1 you see the dependancy between Vbe and Ic, for a single transistor, as well as its mathematic form, the Ebers Moll equation. From the equation (and even more from the graph) you can see that Ic relates exponentially to Vbe. This is already what we want, but there is one problem hidden in the equation. Is (the collector leakage current) is largely dependant upon temperature. Infact it doubles for a 10 degrees temperature increment. There is a second temperature dependancy in the argument of the exp function, which we'll discuss later. k is the Boltzmann constant, and q the charge of an electron.

One can use this relationship between Ic and Vbe directly if one keeps the transistor at constant temperature. This could be done if the circuit is kept at some stable elevated temperature. In uncritical applications, like VCAs, one occasionally sees a single transistor as exponential current source.

$$I_c = I_s \cdot [\, exp\ (\frac{q \cdot Vbe}{k \cdot T}) - 1\,]$$

$$\xrightarrow{Ic>>Is} \quad I_c = I_s \cdot exp\ (\frac{q \cdot Vbe}{k \cdot T})$$

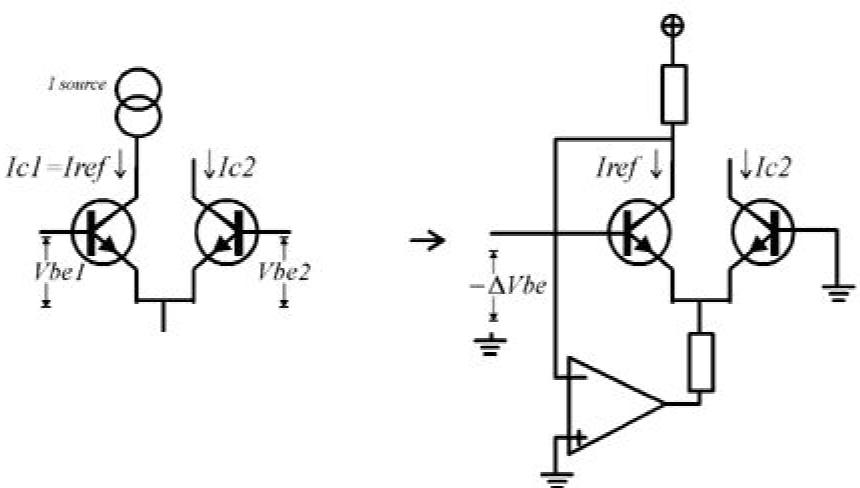
$$\xrightarrow{Is1=Is2} \quad \Delta Vbe = \frac{k \cdot T}{q}\, ln\, (\frac{I_{c2}}{I_{c1}})$$



$Vbe2 - Vbe1 =: \Delta Vbe$

To get rid of the temperature dependancy of Is one can use a second transistor as shown in Figure 2. The trick is that for the *difference* in the two Vbe's Is plays no role. Look at the two points on the leftmost graph in Figure 1. "Read" the collector currents at the two points, and imagine the corresponding difference for Vbe. Now look at the same Ic's on the other graphs and read the corresponding Vbe difference. They are the same. This is the way the first order temperature effect is cancelled. Of course one can put this into a more mathematical form, which I included in Figure 2. It shows that the logarithmic ratio of currents is proportional to the difference in Vbe. Or put the other way round (if one of the two currents is held fixed): Ic relates exponentialy to delta Vbe. Now to meet the requirement that one of the transistors has a fixed current, one uses a current source. In a simpler form a resistor can be used, forcing some current into the collector (This has drawbacks however, the voltage over the resistor will vary with the input. So the current won't be fixed. One sees this in less precise convertors for Q control or the like) One can see that the current at the other collector is proportional (for a fixed Vbe) to this current. When delta Vbe = 0 the current in both transistors is equal. The circuit is a current mirror then. One can also see that one can use this reference current to linearly modulate the current at the output. I.e. linear FM in VCOs.

$$\Delta Vbe = \frac{k \cdot T}{q}\, ln\left(\frac{I_{c2}}{I_{c1}}\right) \xrightarrow{Ic1=Iref} Ic2 = Iref \cdot exp\left(\frac{\Delta Vbe \cdot q}{k \cdot T}\right)$$



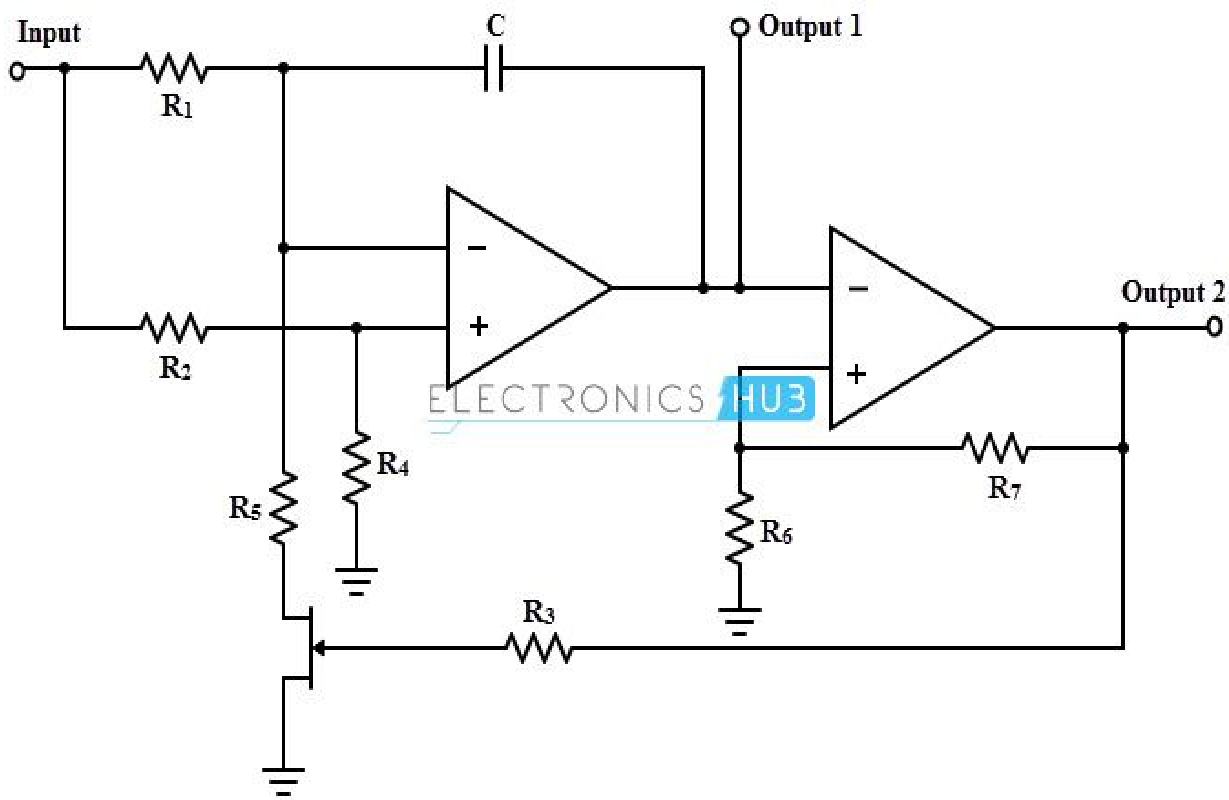
A more elaborate circuit is the one of Figure 3, which is the familiar exponentiator. Here the opamp is used as a current source to hold the current thru one of the transistors fixed. (Ic would vary in the simpler resistor circuit.) Theoretically one can use either bases to put the control voltage in, but usually the left one is used because it makes less demand on the driving impedance which would have to be very low for the other one. As you may notice Vbe goes the other way round than in the circuit above. So in the circuit shown, the output current increases for input voltages going towards the negative supply. Hence an inverting opamp amplifier is usually added (which is handy because you can sum up many signals here). The opamp shown is just a current source. The upper resistor determines the reference current (Iref=Vsupply/R). The lower resistor delimits the maximum current thru the exponentiator. Around 1-4 kOhms is normally used. The maximum output current is approximately the opamps negative saturation voltage divided by the value of the resistor. This is of course only true for currents lower than the maximum output current for the opamp. The equation given for Ic2 shows there is still temperature dependancy. This is a second order effect. The above discussion has eliminated the first order effect, the equation is independant of Is now. We see that the scaling is still temperature dependant, that is the wanted 1V/octave scaling messes up with temperature, thus at drifting temperatures the VCO frequency could change, and the octaves would be squashed or stretched, this is of course undesirable. From the right equation one can see an important fact, if deltaVbe = 0, then the argument of the exp function is zero, and independant of temperature. The exponentiator has the lowest temperature dependancy when operated arround the reference current. This means that one can improve stability, by choosing the reference current appropriately. One should choose the current so that it gives a frequency in the region where the design should be most stable. From the relation C=I*t/V you should be able to figure out what the frequency will be for a particular current.

The whole discussion so far relies on that the transistors are at the same temperature. This is the reason why transistors are used which are on the same chip.

2.The VOLTAGE CONTROLLED OSCILLATOR:

A **Voltage Controlled Oscillator** is an oscillator which produces oscillating signals (waveforms) with variable frequency. The frequency of this waveform is varied by varying the magnitude of the Input voltage. For now you can imagine a Voltage Controlled Oscillator (VCO) to be a black box which takes in Voltage of variable magnitude and produces an output signal of variable frequency, and the frequency of the output signal is directly proportional to the magnitude of the input voltage.

VCO Circuit Diagram:



How It Oscillates

The circuit oscillates in the pattern listed below:

1. Q3 is on and so the integrator's output rises.
2. The integrator's output eventually crosses the Schmitt trigger's upper threshold.
3. The Schmitt trigger's output now switches to 0V.
4. Q3 is now off and so the integrator's output begins to fall.
5. The integrator's output eventually falls below the Schmitt trigger's lower threshold.
6. The Schmitt trigger's output now switches to 5V.
7. Q3 now turns on (so go back to step 1).

Here is a simple explanation of how this circuit works:

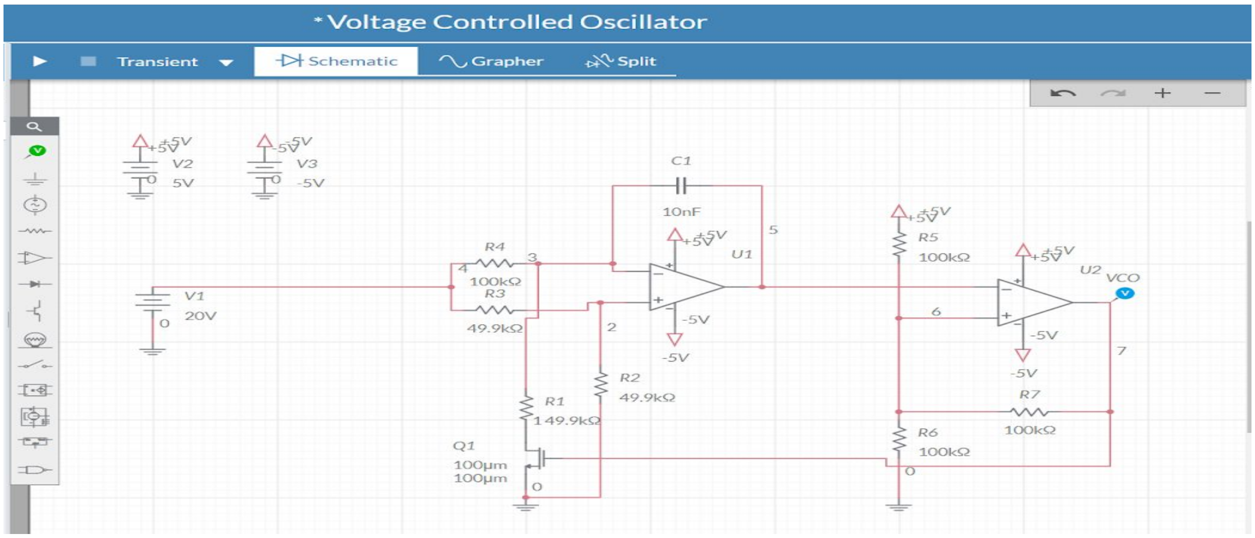
- U1B is used to both sum the individual inputs (KEY, TUNE and LFO) and scale the input voltage such that 1V in produces -18mV on the output (note that it’s an inverting configuration).
- Q1 and Q2 form a differential pair.
- U2B is used to maintain constant current through Q1. Changes in Q1’s base voltage lead to corresponding changes in Q2’s base-to-emitter voltage and, consequently,

exponential changes in Q2's collector current.

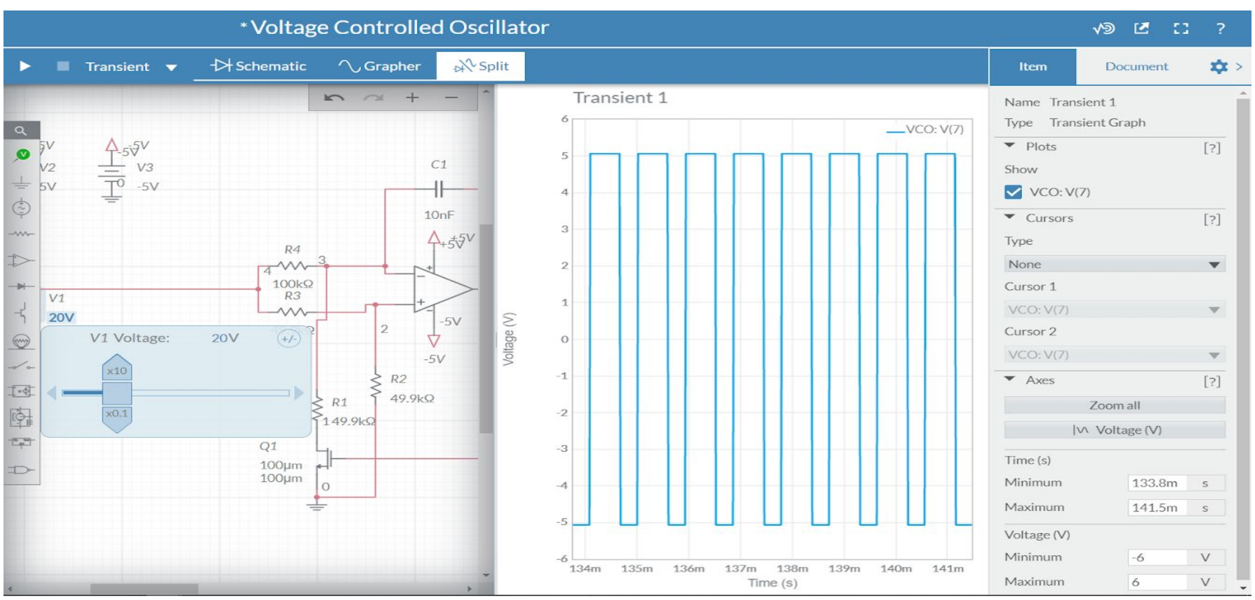
- Q1 and Q2 MUST HAVE VERY SIMILAR HFE!
- U1A is a current-to-voltage converter (R1 and RV1 are chosen so that when the input voltage is 5V, the output voltage is also 5V).

SIMULATION RESULTS:

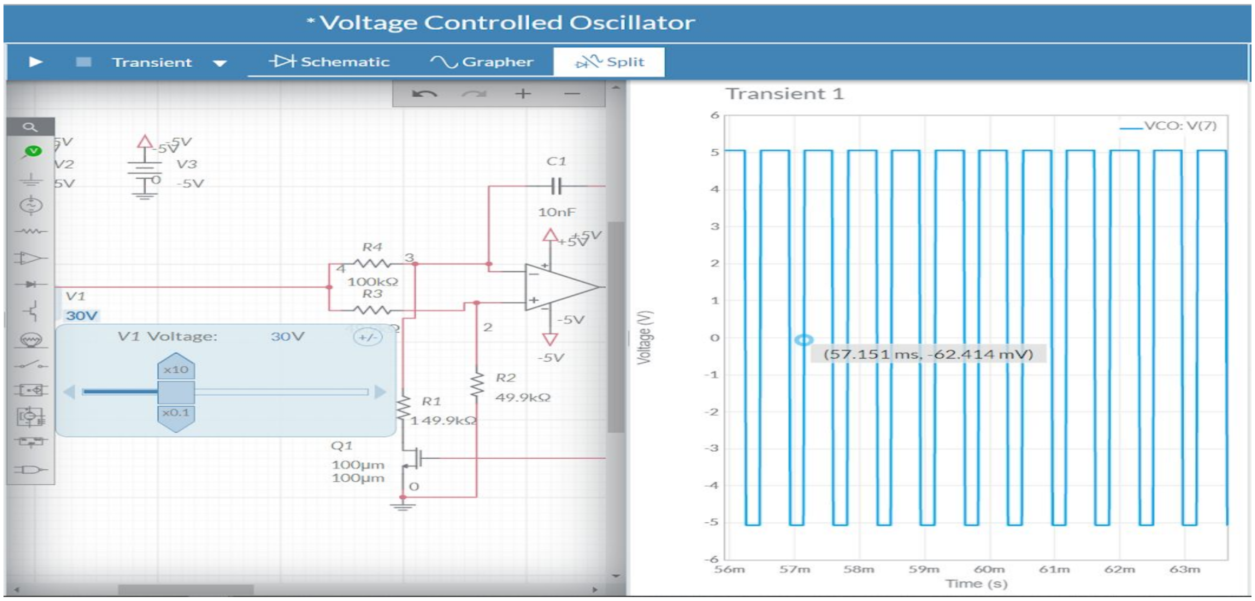
1.VCO SIMULATIONS



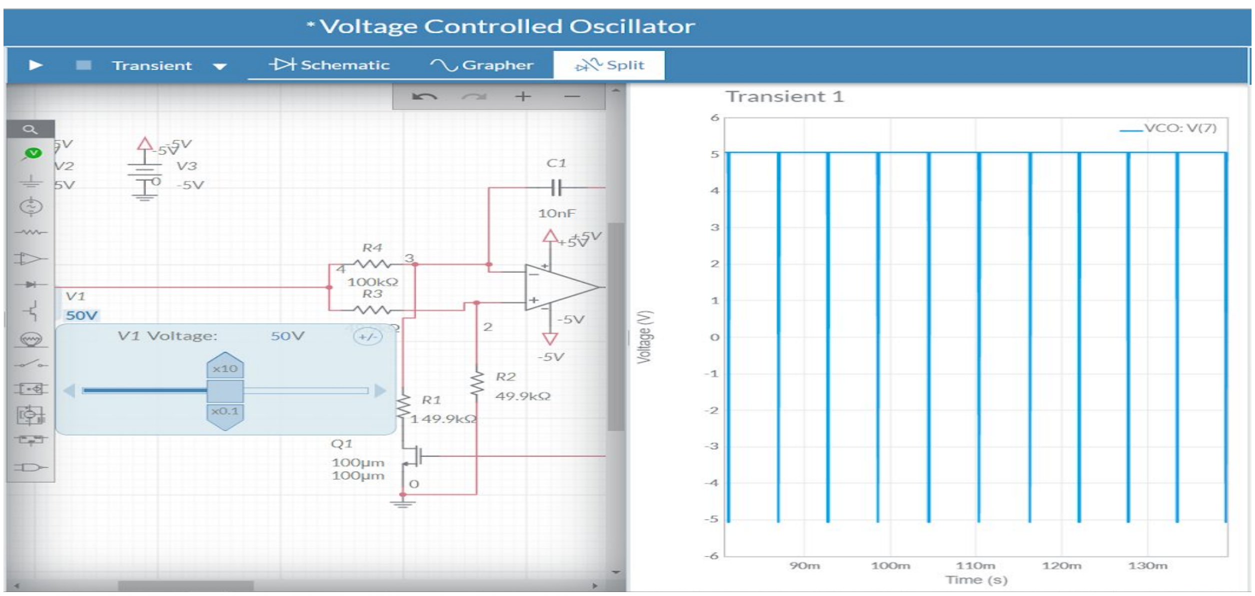
When V=20V



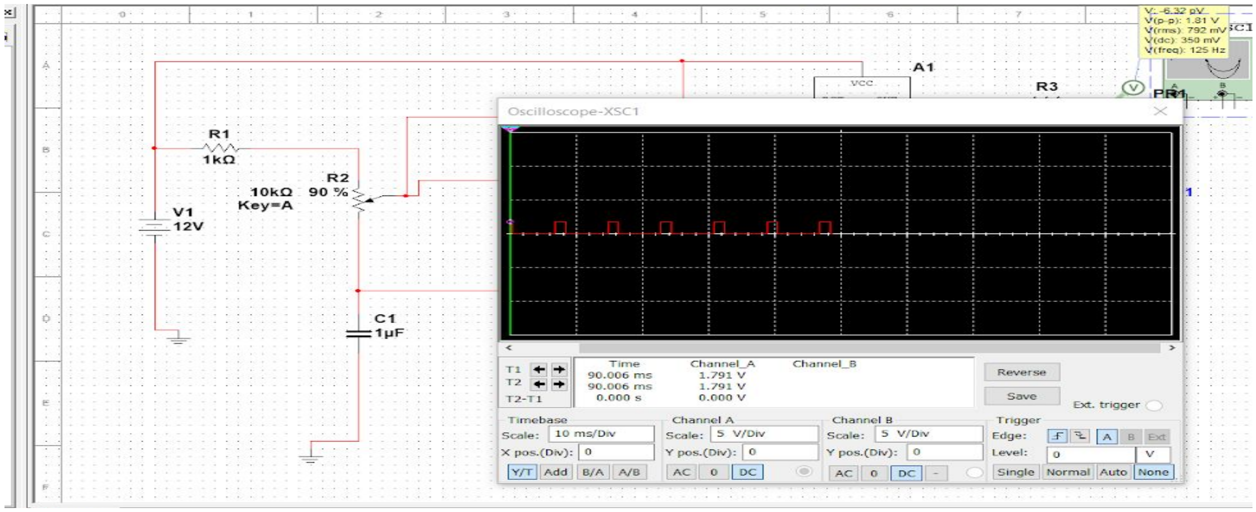
When V=30V

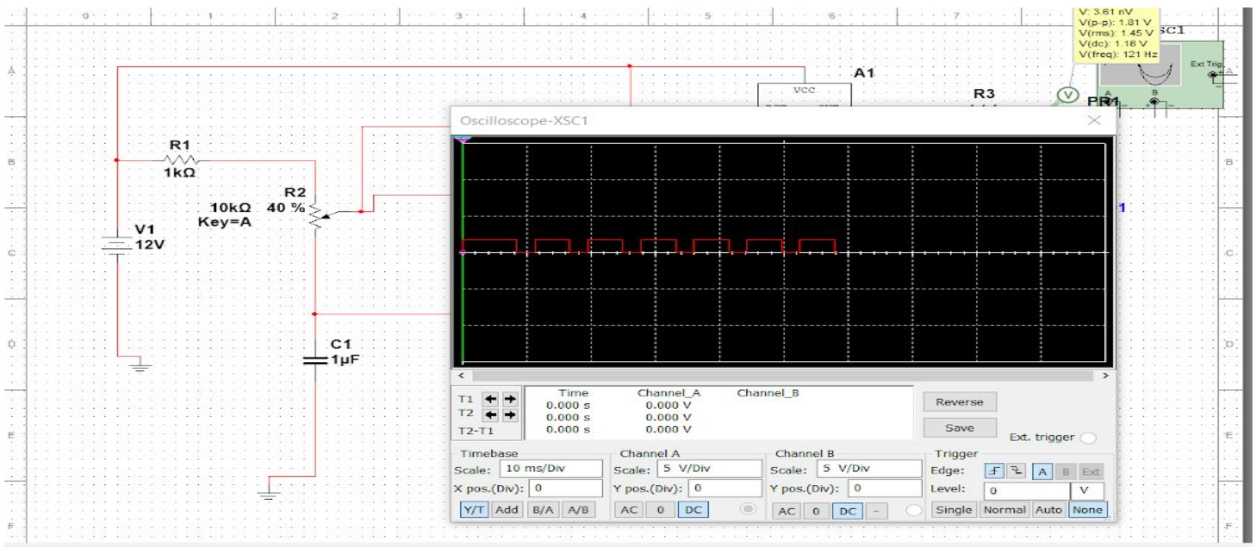


When V=50V



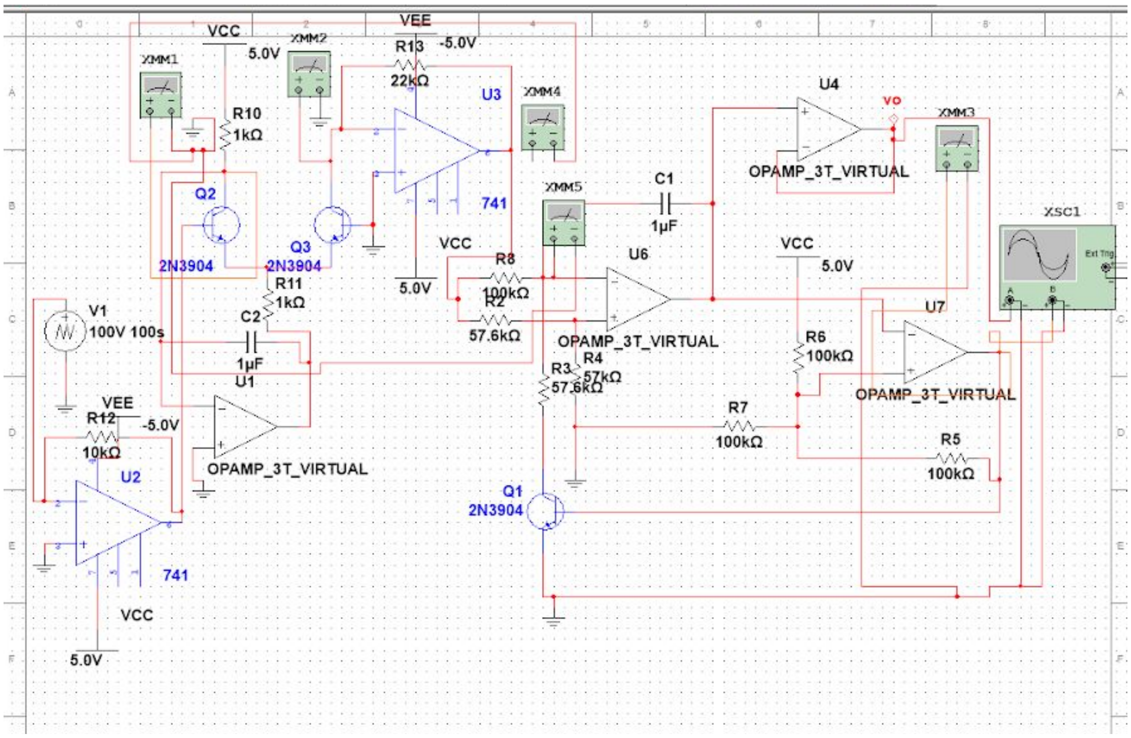
Using 555



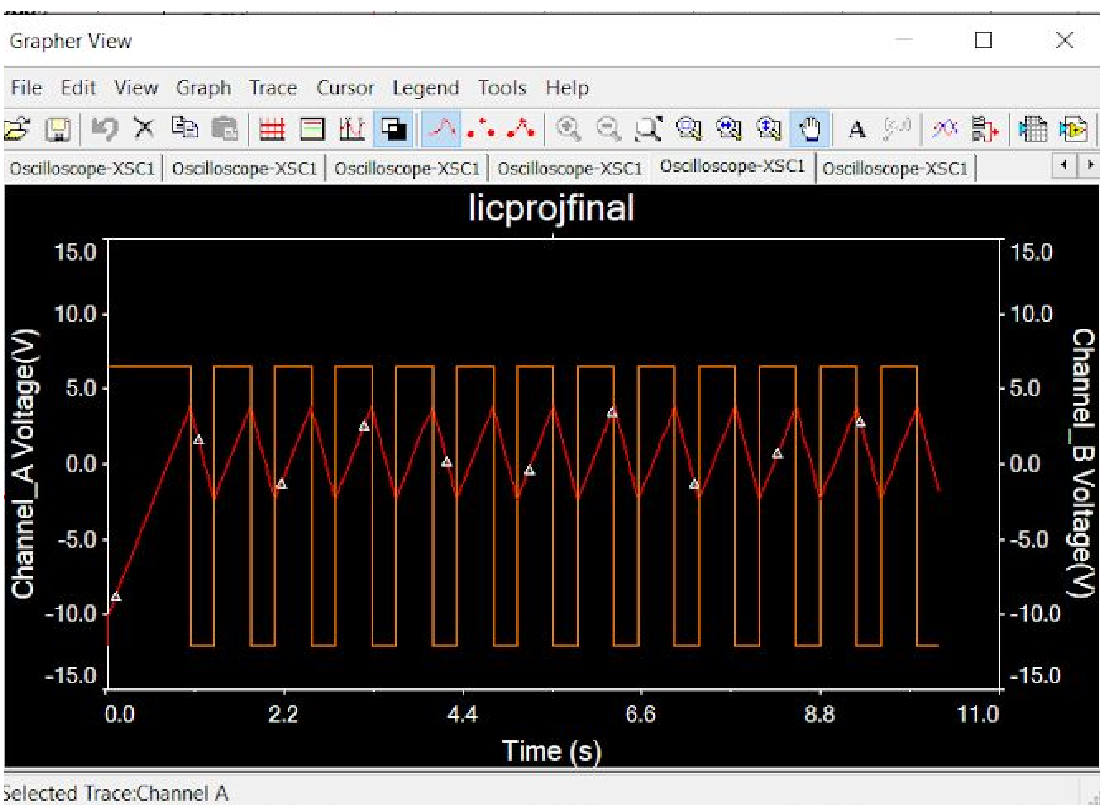


2.EXPONENTIAL VCO SIMULATION

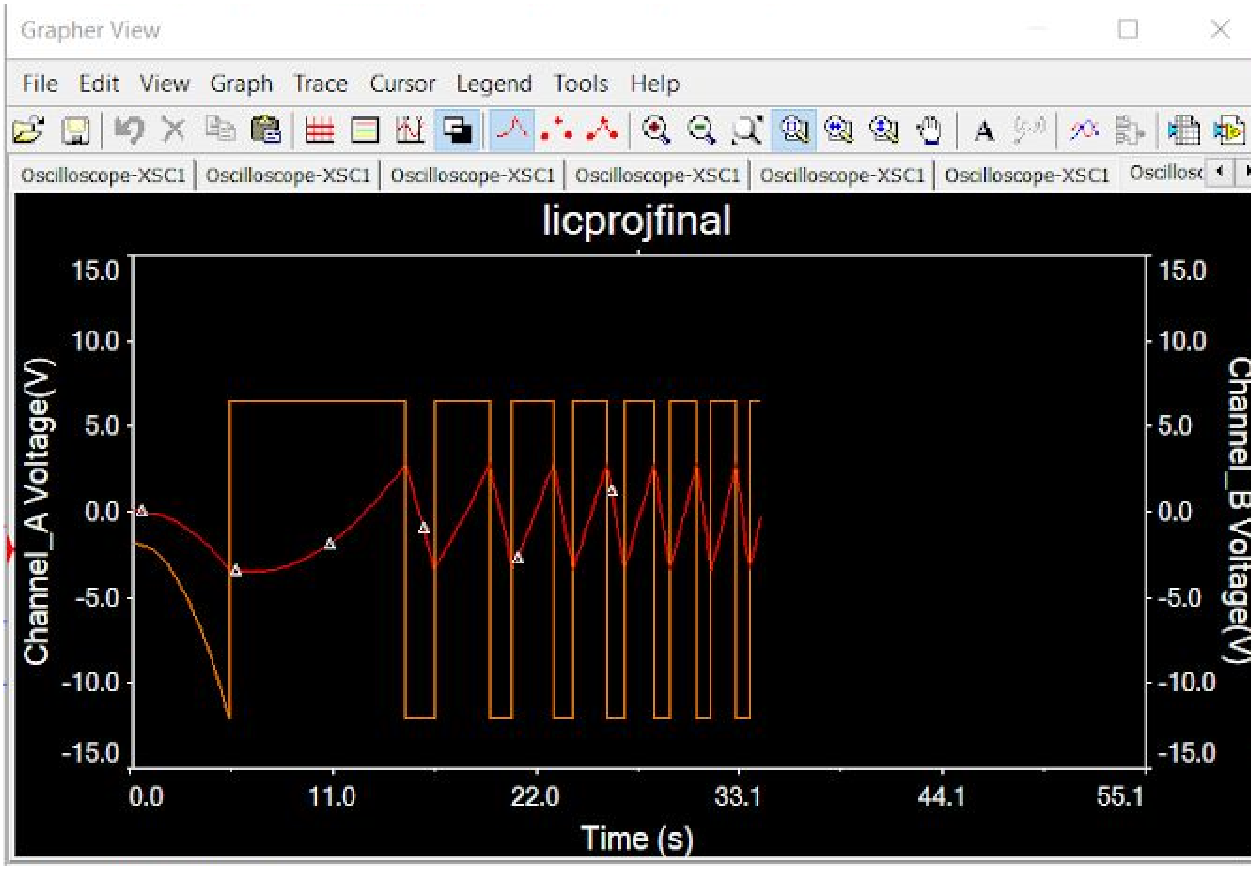
A)Circuit Diagram



B)Simulation Results

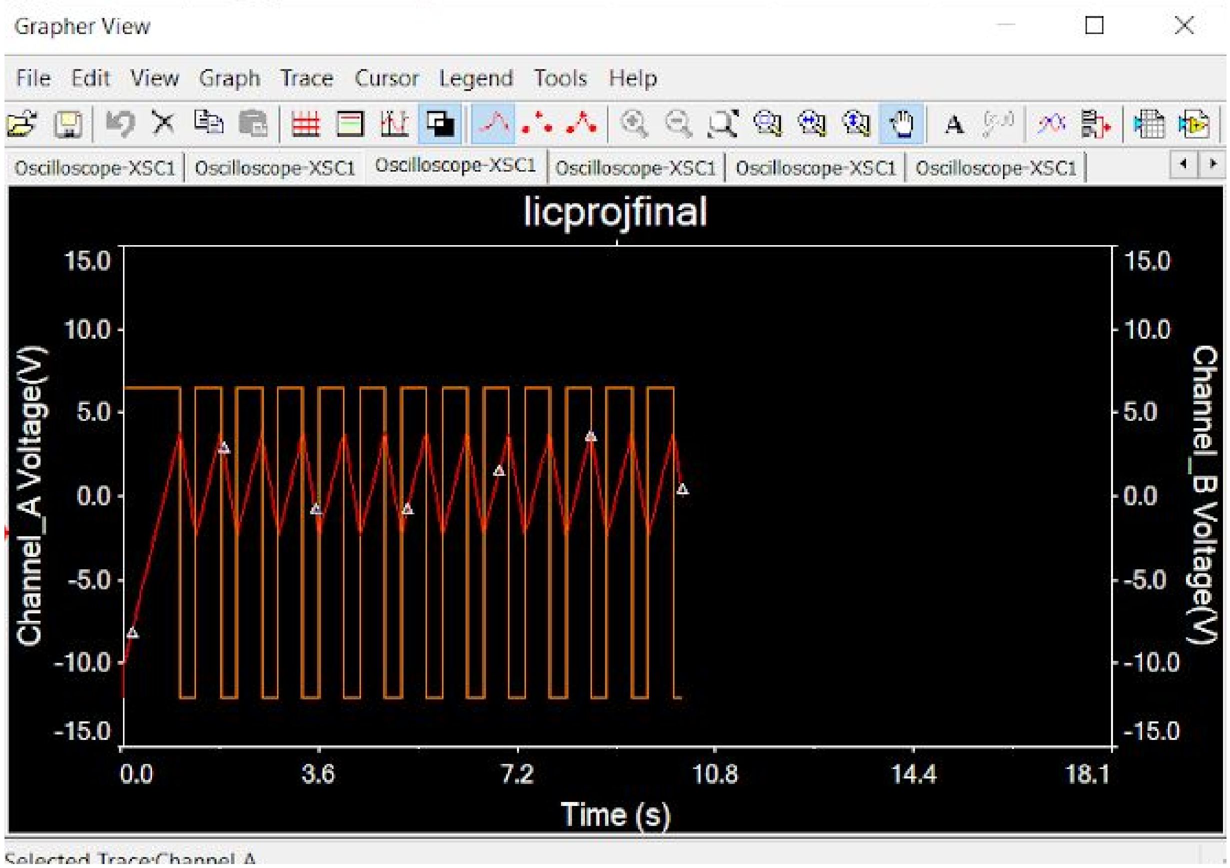


Comparison between simulation of VCO and Exponential VCO



VCO SIMULATION:
The frequency for this simulation result can be approximated to nearly 3/11 Hz=0.27Hz

For exponential VCO for the same value of Voltage the simulation is:



Which shows a frequency of nearly f=5/3.6 =1.388Hz which is definitely higher than that obtained by the linear VCO.

This shows that the exponential VCO gives better frequency ranges than the linear VCO which was required as per our requirements.

CONCLUSION:

This brings us to the conclusion of the discussion over Exponential VCO.Some drawbacks may be noted in the simulation results.These may occur due to lack of hardware simulations .Also the transistors require to be thermally bound which is not possible during simulations.The simulation results may be kept as a standard for recording that the circuit works pretty fine .The circuit also might not show many usual properties as it is only a simulation and there are limitations in the simulation.Also this circuit has been made devoid of the negative voltage generator project which may also be why the simulation might not adhere with other standards.However this does not imply that this circuit is incorrect which is clearly visible from the simulation results.

Exponential VCO are used in audio devices like keyboards.The practical implementation of these circuits are really interesting and an engrossing field of study for people interested in the study of VCOs and audio engineering.

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