Integrated Circuits and Applications
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Oscillators and Waveform Generators
Lecture - 25
Square Wave and Triangular Waveform Generators

So, in the last lecture we have discussed various sinusoidal oscillators such as RC phase shift oscillator, Colpitts oscillator, Hartley oscillator, Wein Bridge oscillator, etc. So, these oscillators will generate the sinusoidal waveforms, but operational amplifier can also be used to generate the other type of waveforms such as a square wave, triangular wave, sawtooth wave also. So, the difference between the sinusoidal oscillator and the other waveform generator circuits is that in order to generate the waveforms other than sinusoidal waveforms. So, we have to operate the operational amplifier in saturation region that is the one of the main difference. So, in order to operate in the saturation region so, like in oscillator here also we are going to operate the operational amplifier in positive feedback configuration and we are going to use the principle of the comparator. So, first I will discuss about the square wave generation.

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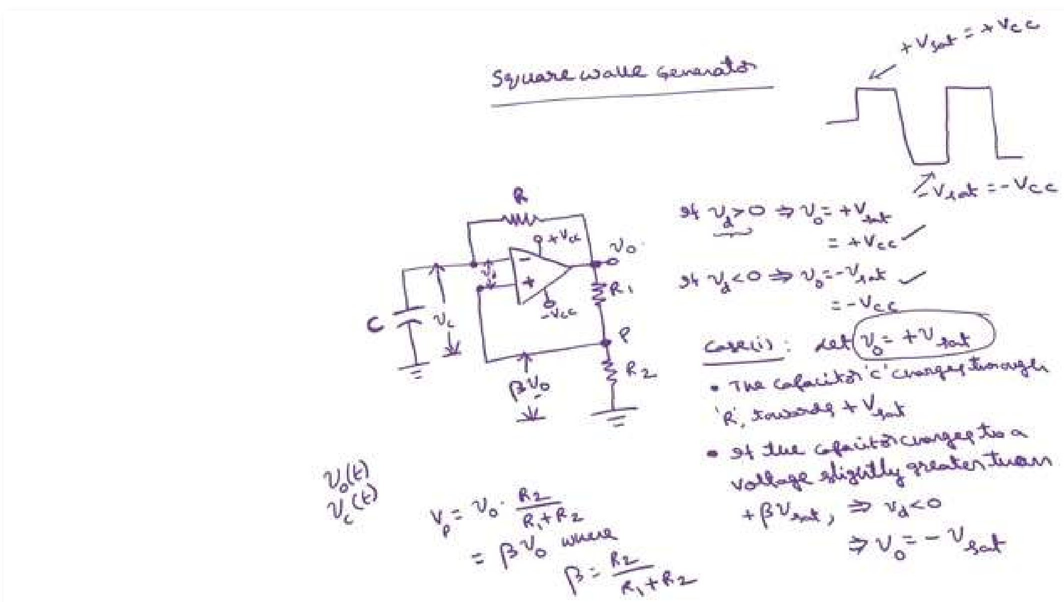

So, because square wave will be having two states so, you have to operate this in saturation region this you can call as positive saturation, this you can call as negative saturation. Normally the saturation voltage is V_{CC} the power supply of the operational amplifier. So, in order to generate this type of waveform so, we will take the operational amplifier and operate in the positive feedback loop. Input we are going to apply to the integrator. This is a basic integrator, there is a feedback path, a voltage divider, this is the output.

So, what is the voltage here at this point? If I call this point as P, v_p will be this is voltage division this is v_o appears across R_1 and R_2 and we are taking the voltage across R_2. So, $v_p = v_o \frac{R_2}{R_1+R_2}$. Let this $\frac{R_2}{R_1+R_2}$ is β so, this is βv_o. So, the voltage here is βv_o where β is $\frac{R_2}{R_1+R_2}$. Let us assume that the voltage across the capacitor is v_C.

Of course, all v_C v_o all function of time only. This $v_o(t)$ and as well as $v_C(t)$ for the sake of simplicity I am not mentioning the time here okay. Now, what is the operation of this circuit? How does this generates the square wave at the output of this circuit? So, if I assume this difference voltage as v_d between these two points, this is different voltage this difference voltage if you call as v_d. Because the operational amplifier operates in the positive feedback mode, if v_d is slightly greater than 0. Difference voltage is positive means output will drive into positive saturation. So, this will be equal to $+V_{CC}$ if you have power supply of $+V_{CC}$ and $-V_{CC}$.

A small value of this difference voltage across this inverting and non-inverting terminals of operational amplifier will drive the output into saturation because of the positive feedback. Even without feedback open loop gain is of the order of 10^5. If you apply the positive feedback the gain will further increases as result of that even a very small difference voltage of v_d which is slightly more than 0, it will drive the operational amplifier into positive saturation. On the other hand if v_d is slightly less than 0, so the operational amplifier will drive into the negative saturation. So, there will be two states at the output of this operational amplifier.

So, in a square wave also we will be having two states. So, we can generate the square wave at the output of the operational amplifier. So, the output v_o can be either $+V_{sat}$ or $-V_{sat}$. Let us assume that the case 1, let output v_o is at $+V_{sat}$. Then what happens to this capacitor? This is v_o, this is resistance R, the capacitor C charges through R resistor towards $+V_{sat}$.

So, this output was V_{sat}. So, this capacitor will charges through this resistor towards this $+V_{sat}$. But whenever it charges to a value which is βv_o that is the voltage at positive terminal what happens? If the capacitor charges to a voltage slightly greater than $+\beta$, so v_o is of course V_{sat}. What happens? Now this voltage is slightly more than the voltage here. So, negative terminal voltage is more than positive terminal voltage. So, v_d will be negative implies output v_o will drive into negative saturation. Initially, we started with positive saturation output, now we will get negative saturation.

What happens to the capacitor now? Now capacitor discharges through resistor R towards $-V_{sat}$ because now the output voltage will be $-V_{sat}$. But it will not discharge up to $-V_{sat}$ whenever it discharges to a value which is slightly more than $-\beta V_{sat}$. So, this will be now $-\beta V_{sat}$.

Now this voltage will be a value which is slightly more than βV_{sat} means positive voltage is greater than the negative voltage as a result of that output again will drive into the positive saturation that is v_o is equal to $+V_{sat}$. So, we started with the positive saturation then after some time the output becomes negative saturation again positive saturation the cycle repeats. At output v_o. This is the principle of this square wave generator circuit. We can explain the same principle with the help of the waveforms. This is time axis, let this is the output, this is output of course $v_o(t)$, this is a function of t.

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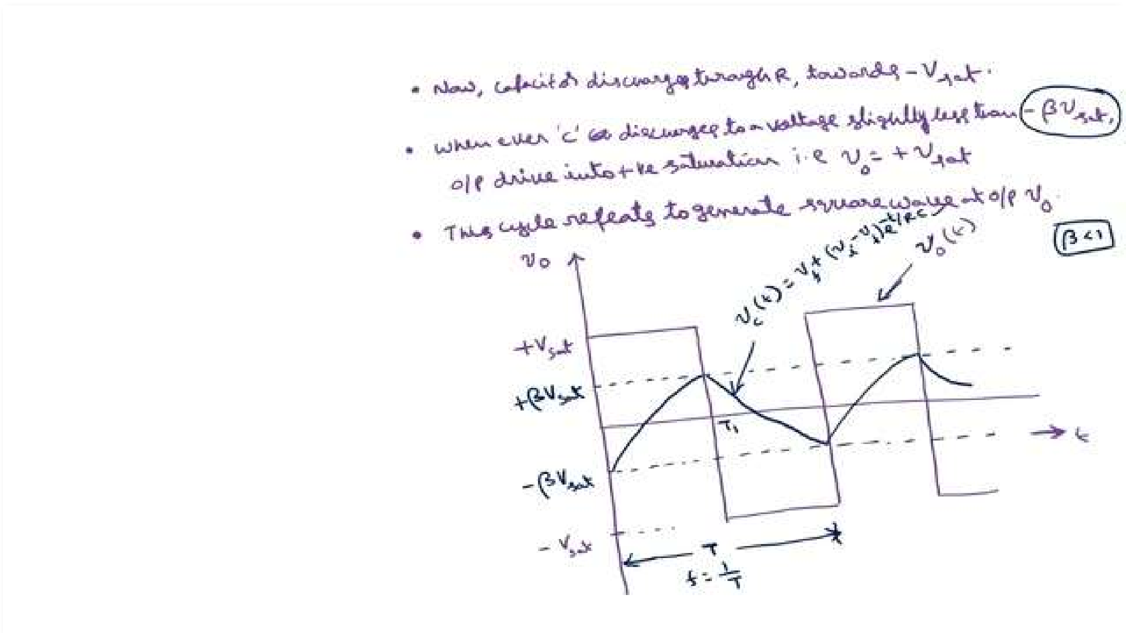

So, what are the two values for this output $+V_{sat}$ and $-V_{sat}$. Now what is the waveform for the voltage across the capacitor? So, you have seen that the voltage across the capacitor varies from this $-\beta V_{sat}$ and in previous case $+\beta V_{sat}$. β is less than 1, choose β less than 1. So, βV_{sat} will be somewhere here. This is $+\beta V_{sat}$ and this is $-\beta V_{sat}$.

So, the voltage across the capacitor varies between these two values. This final voltage across the circuit, final voltage at the output of the circuit is this waveform which is square wave whereas, the voltage across the capacitor varies between $+\beta V_{sat}$ and $-\beta V_{sat}$ according to exponential relation. So, this is the type of variation we will get at $v_C(t)$. Let us call this period as T_1. Now, what is the expression for the frequency of oscillations? This is one complete time period of square wave f is equal to $\frac{1}{T}$.

So, what is the frequency of oscillations of this square wave that is generated at the output of the given circuit? So, in order to derive this we will take the expression for the voltage across the capacitor. This is given by v_f final value plus v_i initial value minus v_f final value times $e^{-t/RC}$. This is one of the famous relation for the voltage across the capacitor which you might have studied in your circuit theory. So, based on this equation I am going to derive the expression for the frequency of oscillations of this square wave generator.

So, voltage across the capacitor $v_C(t)$ is given by $v_f + \left(v_i - v_f\right)e^{-t/RC}$. Here what is v_f final value? v_i initial value? This will be your starting value. So, v_i initial value is $-\beta V_{sat}$ and the final value it has to go up to $+V_{sat}$, but after reaching this $+\beta V_{sat}$ the output changes, but the final desired value is this $+V_{sat}$. So, here initial value is $-\beta V_{sat}$ and the final value is $+V_{sat}$.

If you substitute these values here $-\beta V_{sat} - v_f$ means V_{sat} this is plus, $e^{-t/RC}$. $-(\beta + 1)V_{sat}e^{-t/RC}$. So, one condition here is at t is equal to T_1 this t is equal to T_1 what is the value of this output v_o? this is v_C, v_o value is $+V_{sat}$.

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Frequency of oscillations

$$v_c(t) = v_f + (v_i - v_f)e^{-t/RC}$$

$$\boxed{-\ln(a) = \ln\left(\tfrac{1}{a}\right)}$$

Here, $v_i = -\beta V_{sat}$ and $V_f = +V_{sat}$

$$\therefore v_c(t) = V_{sat} + (-\beta V_{sat} - V_{sat})e^{-t/RC}$$

$$= V_{sat} - (\beta+1)V_{sat}e^{-t/RC}$$

At $t = T_1$; $v_c(t) = +\beta V_{sat}$

$$+\beta \cancel{V_{sat}} = \cancel{V_{sat}} - (\beta+1)\cancel{V_{sat}}e^{-T_1/RC}$$

$$\Rightarrow \beta = 1 - (\beta+1)e^{-T_1/RC} \Rightarrow (\beta+1)e^{-T_1/RC} = 1-\beta$$

$$\Rightarrow e^{-T_1/RC} = \left(\frac{1-\beta}{1+\beta}\right) \Rightarrow -\frac{T_1}{RC} = \ln\left(\frac{1-\beta}{1+\beta}\right)$$

$$\Rightarrow T_1 = -RC\ln\left(\frac{1-\beta}{1+\beta}\right) \Rightarrow T_1 = RC\ln\left(\frac{1+\beta}{1-\beta}\right)$$

So, at t is equal to T_1 what is the value of $v_C(t)$? is βV_{sat} that condition I am going to substitute at t is equal to T_1 what is $v_C(t)$ is equal to $+\beta V_{sat}$. If I substitute this here we will get $+\beta V_{sat} = V_{sat} - (\beta + 1)V_{sat}e^{-T_1/RC}$. So, what will be expression for T_1 which is the half period. So, this V_{sat} this V_{sat} this V_{sat} get cancelled.

So, implies you will get $\beta = 1 - (\beta + 1)e^{-T_1/RC}$ implies if I take this term to the other side and this β terms here this will be $(\beta + 1)e^{-T_1/RC}$ is equal to $1 - \beta$ implies what is $e^{-T_1/RC}$? is equal to $\frac{1-\beta}{1+\beta}$ or $\frac{-T_1}{RC}$ is equal to $\ln(\frac{1-\beta}{1+\beta})$ implies T_1 is equal to $-RCln(\frac{1-\beta}{1+\beta})$.

And if you want to remove this minus sign we have to take this $1 + \beta$ in the numerator, $1 - \beta$ in the denominator because $-\ln(a) = \ln(\frac{1}{a})$. Implies what is T_1? $RCln(\frac{1+\beta}{1-\beta})$.. This is half period and this is symmetric.

So, this total period T is equal to $2T_1$ total time period $2T_1$ is equal to $2RCln(\frac{1+\beta}{1-\beta})$ or what is the frequency of oscillations? f is equal to $\frac{1}{T} = \frac{1}{2RCln(\frac{1+\beta}{1-\beta})}$. This is the frequency with which the square wave at the output of the operational amplifier will be generated. So, basically this frequency depends upon the R, C, β. β is again R_1 and R_2.

So, these four components is going to decide the frequency of oscillations, but what will be the output waveform v_o here? v_o will be between $+V_{sat}$ and $-V_{sat}$ this is $+V_{sat}$ and $-V_{sat}$ these are the values for this v_o.

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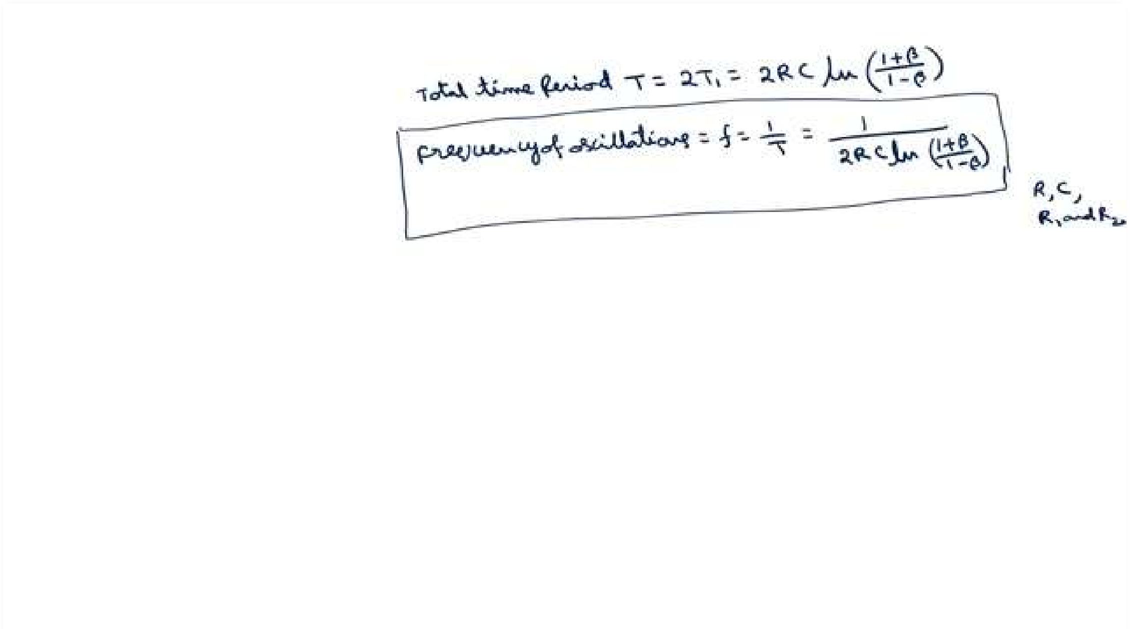

Suppose if I want the output voltage levels other than V_{sat} $+V_{sat}$ and $-V_{sat}$ what you have to do? For that we can connect diodes at the output of this circuit. If I connect two diodes here zener diodes, then this output voltage is this is without zener diodes. With zener diodes what will be the output?

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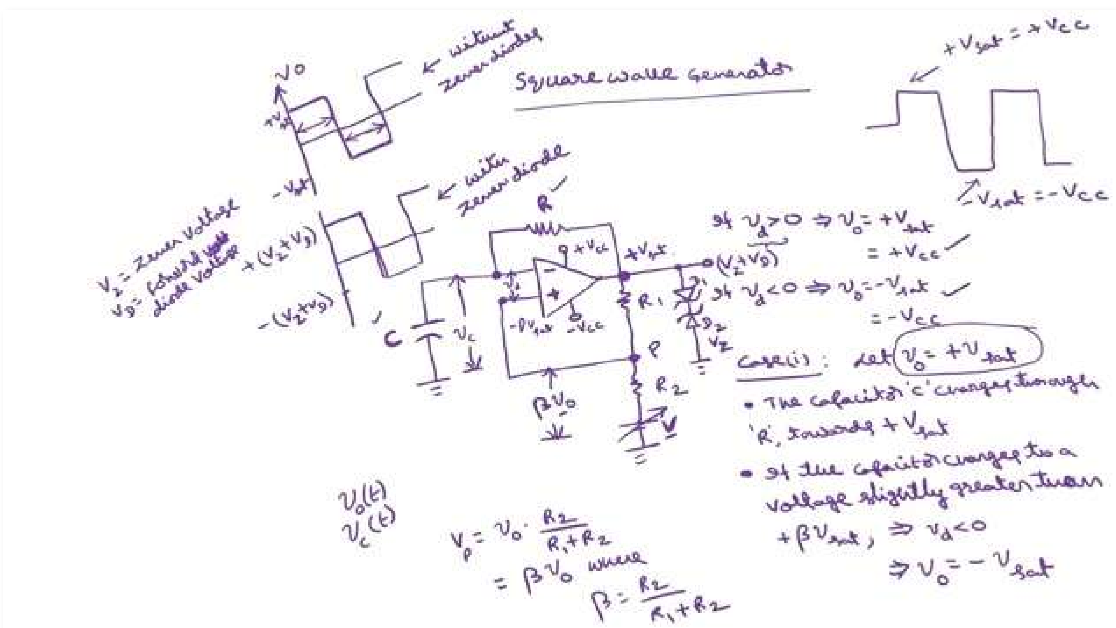

If this voltage is $+V_{sat}$ what happens to this diode D_1? D_1 is on, D_2 is off. If I assume that v_z is the zener voltage across the each diode I am taking two symmetrical diode and v_d is the voltage drop forward voltage drop across the zener diode. Then what will be the output voltage? We know that if I reverse bias the zener diode it will generate the v_z and this is forward biased.

So, this will generate when forward voltage drop of v_d okay. So, total voltage here will be when this is $+V_{sat}$ the voltage here will be $v_z + v_d$. Similarly, if this is $-V_{sat}$ then you will get $-v_z + v_d$. So, as a result of that you will get a waveform whose values varies between this plus of $v_z + v_d$, where v_z is zener voltage and v_d is the forward diode voltage and this will be $-(v_z + v_d)$. So, other than this $+V_{sat}$, $-V_{sat}$ also can be generated the output, but this is with zener diodes.

But in any case both the signals are square waves only that is on time is equal to off time this is on period this is off period both are same. If you want a symmetrical square wave what you have to do is so, instead of connecting this to the ground you connect to some variable voltage. If I vary this I can generate a symmetrical wave on time off time will be different. So, this is how you can generate at this output square wave or rectangular wave by varying this v if v is equal to 0 square wave if I vary the v you can generate the rectangular wave.

Similarly, without this zener diodes output swing will be $2V_{sat}$ and with this zener diodes the output swing will be $2(v_z + v_d)$ means it varies from $-V_{sat}$ to $+V_{sat}$ without zener diodes with zener diodes it varies from $-(v_z + v_d)$ to $+(v_z + v_d)$. This is all about the square wave generation.

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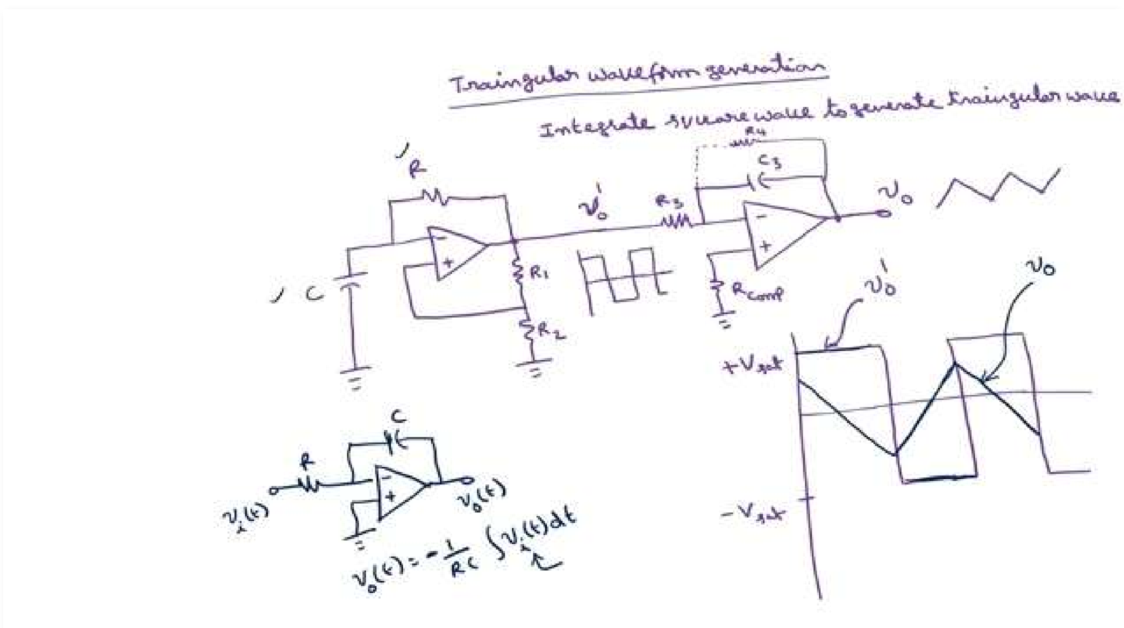

So, the next type of waveform is triangular wave. The very basic principle of this triangular wave generation is you take a square wave and you integrate. If you integrate the square wave you will get the triangular wave. So, we know the integrated circuit we know the square wave generator circuits you just cascade these two circuits we will get a triangular waveform generation circuit. So, this square wave generation circuit which we have discussed just now is this. Let us call this output as v_o'. So, v_o' is square wave which we have already discussed now.

Now, this connect to the integrator. The final output we call as v_o. v_o will be a rectangular waveform. This you call as R_3 C_3 this is R_{comp} compensation which will be easy to nullify the offset voltage and currents which we have discussed in the earlier lecture. And for a practical integrator we require another resistor here which you have discussed in the earlier lecture and let us call this as R_4 this is practical integrator. So, basically the input output waveforms of this integrator will be this is the square wave generated after the first stage $+V_{sat}$ $-V_{sat}$ and this waveform is v_o' this v_o'. And what is v_o? During the positive portion this will be negative going ramp.

There are two values which varies this is the triangular waveform this is your v_o. So, we know that for a simple integrator which we have discussed in the earlier lectures without compensation and without the shunting resistor if I take a simple integrator $v_i(t)$, $v_o(t)$. So, you have derived the expression for $v_o(t)$ as $-\frac{1}{RC}\int v_i(t)dt$. So, here in this region this is $+V_{sat}$ input is $+V_{sat}$ because of this minus sign you will get negative going ramp and during this portion negative V_{sat} is there. So, output of this integrator will be positive going ramp. So, this is how we can generate the triangular wave at the output of the integrator. There is alternative circuit also where we can avoid the use of this R and C also.

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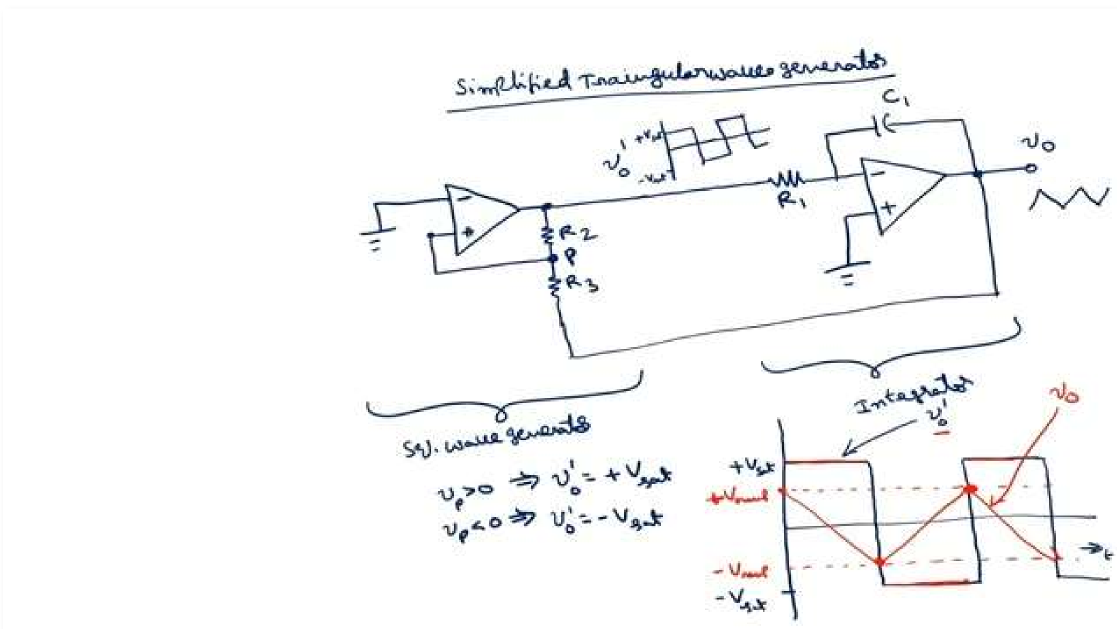

The alternative circuit for the triangular wave generator is we will just take a simple comparator we just ground this negative terminal and positive terminal will be connected to resistor divider. This is a simple comparator let us call this output as v_o' then apply this to the integrator. I am not showing the feedback resistor for the practical op-amp and the R compensation also for the sake of simplicity. I am going to connect this point to the final output. This part will generate square wave this is integrator. The waveform is square wave. Here we will get a triangular wave. Let us call this as R C or R_1 C_1. So, this is R_2 R_3 let us call this point as point P.

Now, we can analyze this circuit. So, if this v_P is slightly greater than 0 negative voltage is 0 the voltage at inverting terminal is 0 and voltage at positive terminal which is non-inverting terminal if I call as v_P if v_P is slightly greater than 0 then what will be v_o', $+V_{sat}$ because this is having positive feedback. So, more gain. So, output will be $+V_{sat}$. If v_P is slightly less than 0 this value is less than this value. So, negative value is more than positive value.

So, output will be negative saturation. So, as a result of that here a square wave will be generated. And what is the condition for this change in the output from $+V_{sat}$ to $-V_{sat}$ and $-V_{sat}$to $+V_{sat}$. So, there will be some voltage at this P which is going to affect the transition of this output from $+V_{sat}$ to $-V_{sat}$. We are going to find out that voltage.

So, for that if I take these waveforms. So, this is the waveform after the comparator this is $+V_{sat}$ and this is $-V_{sat}$. Then what will be the voltage across the final output v_o. So, this is positive saturation means at the output of this integrator we will get negative going ramp. So, this final voltage v_o varies between the two voltage levels which we will call as $+V_{ramp}$ $-V_{ramp}$. I am going to derive the expression for this $+V_{ramp}$ and $-V_{ramp}$.

So, this type of waveform will be generated at final v_o. So, what is the expression for $+V_{ramp}$ and $-V_{ramp}$ where the output will changes from $+V_{sat}$ to $-V_{sat}$. Here there is a point here where there is a transition from $+V_{sat}$ to the $-V_{sat}$ of this v_o'. Similarly, at this point from $-V_{sat}$ to $+V_{sat}$ okay. So, for that we are going to perform some analysis.

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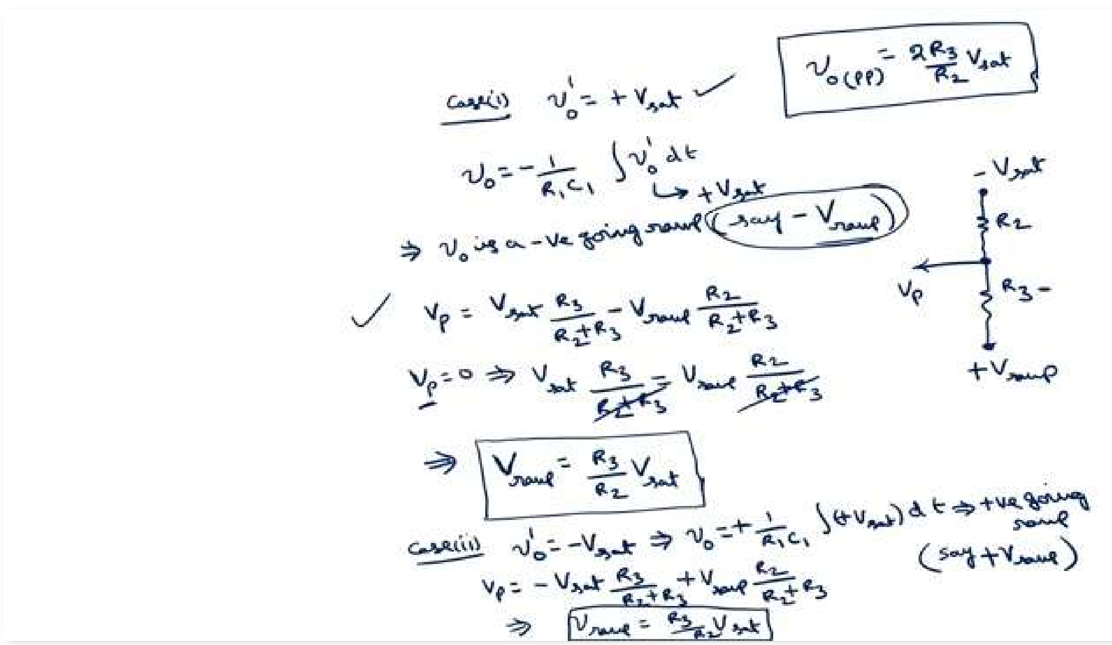

Case 1 v_o' is say at $+V_{sat}$. So, what happens to v_o? $v_o = -\frac{1}{R_1C_1}\int v_o' dt$. This is expression for the integrator because this resistance is R_1 C_1 this voltage is v_o' and final output is v_o. So, the relation between this v_o v_o' R_1 C_1 is $-\frac{1}{R_1C_1}$, $v_o' = v_o$. If with this v_o' is $+V_{sat}$ implies v_o is a negative going ramp that is what I have shown in this diagram.

So, when this is $+V_{sat}$, v_o is negative going ramp with a slope of $\frac{1}{RC}$. Now what should be this V_{ramp} voltage at which again this changes this v_o' changes from $+V_{sat}$ to $-V_{sat}$. What is that point that we have to derive? For that I will assume that this v_o is say $-V_{ramp}$. So, when v_o' is $+V_{sat}$ I will assume that v_o attains a value of V_{ramp} then what will be the situation? So, this is $+V_{sat}$ that time I am assuming that this is $-V_{ramp}$. So, for this voltage divider circuit what will be this? This will be $+V_{sat}$ this point and this point is at $-V_{ramp}$.

So, what is the expression for the voltage at P? I will take this circuit separately. So, this point is $+V_{sat}$ this point is $-V_{ramp}$ and I want this voltage. So, the circuitry will be this is R_2 R_3 this is $-V_{ramp}$ this is $+V_{sat}$ R_2 R_3 I want voltage this is v_P. So, this is basically a principle of superposition we can apply principle of superposition to find out v_P.

So, in order to find v_P first you ground this V_{ramp}. If you ground this V_{ramp} what will be the output voltage V_{sat} times I am taking voltage across R_3 means $\frac{R_3}{R_2+R_3}$. Now, the contribution due to this V_{sat} will be now this is $-V_{ramp}$ now you ground this and you are taking voltage across R_2 and ground. So, this is $-V_{ramp}\frac{R_2}{R_2+R_3}$. Let us first assume that v_P is equal to 0 implies at what value of V_{ramp} we will get v_P is equal to 0. $V_{sat}\frac{R_3}{R_2+R_3} = V_{ramp}\frac{R_2}{R_2+R_3}$.

So, these two will get cancelled. So, implies what is V_{ramp}? $\frac{R_3}{R_2}V_{sat}$. This is the voltage at which v_P becomes 0. If this capacitor discharges to a value which is slightly more than this V_{ramp} what happens? This voltage will be less than this voltage as a result of that this $+V_{sat}$ becomes now $-V_{sat}$ that is where this point slightly just above this V_{ramp}. So, there is a transition from $+V_{sat}$ to $-V_{sat}$.

Now, second case is v_o' becomes now $-V_{sat}$. So, whenever this output v_o discharges to a value which is slightly more than this V_{ramp}. So, at that time v_o' becomes $-V_{sat}$. Now, what is v_o? $-\frac{1}{R_1C_1}\int(-V_{sat})dt$. So, this minus minus becomes plus as a result of that this is positive going ramp. We can see that here this is positive going ramp when output is $-V_{sat}$.

And what is the expression for this V_{ramp} again? In a similar manner now what will be the situation here to generate this v_P now implies vo will goes to $+V_{ramp}$ going ramp and we are calling this output as $-V_{ramp}$ now you call as say $+V_{ramp}$. Now what will be this output now this will be $+V_{ramp}$ that time here this will be $-V_{sat}$. So, again what will be this v_P? similar to this expression. Now in place of $+V_{sat}$ we have $-V_{sat}$ in place of $-V_{ramp}$ we have $+V_{ramp}$.

You just change the signs of V_{sat} and V_{ramp}. So, v_P will be $-V_{sat}\frac{R_3}{R_2+R_3} + V_{ramp}\frac{R_2}{R_2+R_3}$. So, implies what is V_{ramp}? We will get the same expression $\frac{R_3}{R_2}V_{sat}$. So, the expression for this V_{ramp} this is positive V_{ramp} and this is $-V_{ramp}$, but the magnitude of this voltage is same $\frac{R_3}{R_2}V_{sat}$. So, there is a transition okay. Now what is peak output voltage v_o peak to peak? This is V_{ramp} this is $-V_{ramp}$.

So, implies what is v_o peak to peak? In one case $-V_{ramp}$ another case $+V_{ramp}$. v_o peak to peak will be now $2\frac{R_3}{R_2}V_{sat}$. This is one of the important result which we are going to use to derive the expression for the frequency of oscillations. So, this is about the analysis of this triangular wave generator.

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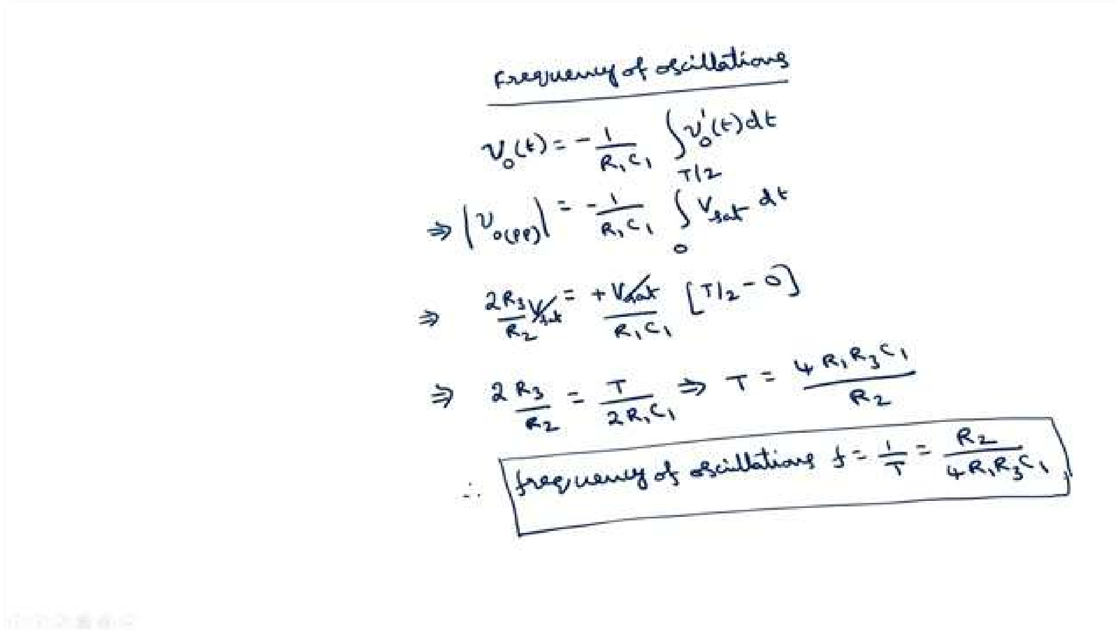

Now what is the frequency of oscillations? So, we know that $v_o(t)$ or $v_o = -\frac{1}{R_1C_1}\int v_o' dt$. So, if I consider the period from 0 to $\frac{T}{2}$ call this as 0 this as $\frac{T}{2}$. So, within this period 0 to $\frac{T}{2}$. So, this output v_o is having a swing of $+V_{ramp}$ to $-V_{ramp}$ that is peak to peak voltage is $2V_{ramp}$. So, now we are taking the limit from 0 to $\frac{T}{2}$ that time v_o will be between $+V_{ramp}$ to $-V_{ramp}$. So, this is equal to $-\frac{1}{R_1C_1}$ I am taking the limit from 0 to $\frac{T}{2}$ during this v_o' will be V_{sat} , $+V_{sat}$. This is $+V_{sat}$ between 0 to $\frac{T}{2}$, but that time what will be this $v_o(t)$? this will be v_o peak to peak. So, this is equal to $-\frac{V_{sat}}{R_1C_1}\left[\frac{T}{2} - 0\right]$. Integral of dt is t.

So, the limits are $\frac{T}{2}$ to 0 and what is v_o of peak to peak which we have just derived? $2\frac{R_3}{R_2}V_{sat}$ implies this V_{sat} V_{sat} get cancelled what is expression for T taking this v_o as magnitude. So, I am just a neglecting this minus sign I am taking only magnitude of this one. So, what will be the expression for T? $2\frac{R_3}{R_2}$ is equal to $\frac{T}{2R_1C_1}$ implies what is T? $\frac{4R_1R_3C_1}{R_2}$. This is the time period. What is the frequency of oscillations? f is equal to $\frac{1}{T}$. This is equal to $\frac{R_2}{4R_1R_3C_1}$, this is the expression for the frequency of oscillations of triangular wave. So, this is the circuit diagram of a triangular wave if I want to have here the sawtooth waveform instead of grounding this if I connect to variable a potentiometer this you ground this you connect to $-V_{EE}$.

So, with this change so, here you can generate instead of triangular wave you can generate the sawtooth waveform. So, remaining analysis everything is same the only thing is you have to add a potentiometer here. So, the same circuit can be used for generating the triangular wave as well as sawtooth waveform. This is all about the waveform generation. So, in the next lecture we will discuss about a specialized IC called as a 555 timer. This also can be used to generate square wave, triangular wave and rectangular waves etcetera. Thank you.