Fundamentals of Electric Theory and Circuits

by

Sridhar Chitta

IK International Publishing House Pvt. Ltd.
4435-36/7, Ansari Road, Daryaganj
New Delhi – 110 002 (India)
Email: info@ikinternational.com Website: www.ikbooks.com
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Software simulation of RC Phase shifting networks

Phase shifts achieved by RC phase shifting networks are best demonstrated by the RC Phase shift oscillator[17]. The schematic in Fig. 1 is of one such a Transistor Phase-Shift Oscillator. In this article, a simulation of the operation of the phase shift network is described using simulation software. To download the software (freely distributed by Texas Instruments, USA) enter "TINA" in the search box of the homepage www.ti.com. Click the first result displayed from the list and follow the instructions to download and install.

Transistor Phase-Shift Oscillator

In every practical oscillator, the loop gain is slightly larger than unity, and the amplitude of oscillations that are first started by tiny noise emfs (signals comprising a wide band of frequencies) in the resistive and amplifier components of the oscillator, is limited by the onset of nonlinearity.

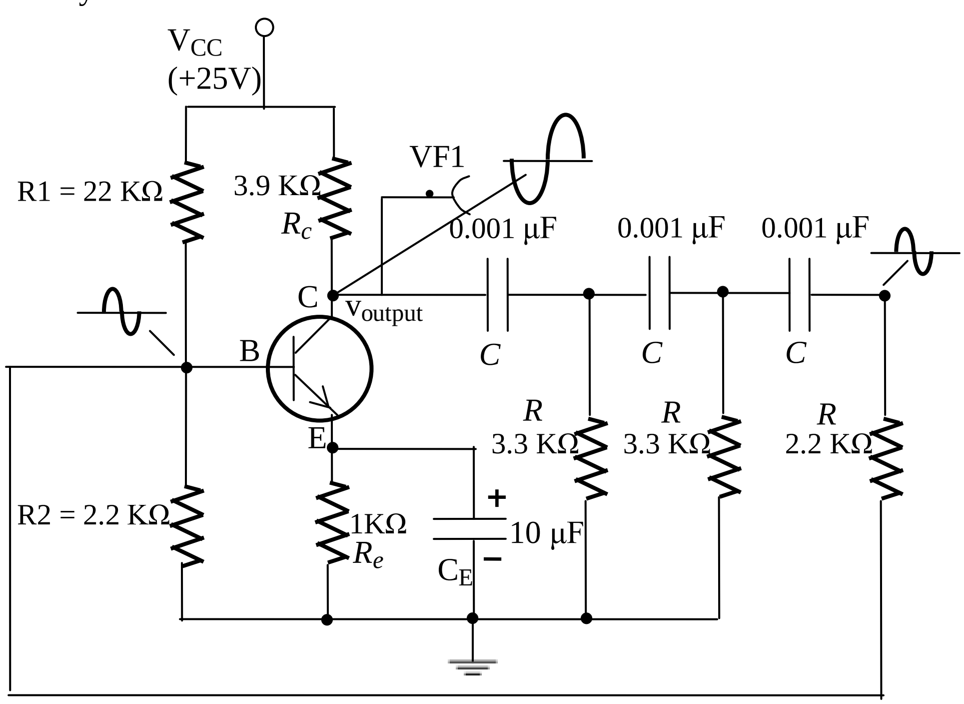


Fig. 1 Transistor Phase-Shift Oscillator

If the loading of the phase-shift network on the amplifier can be neglected, the amplifier shifts by 180º the phase of any voltage (say, tiny noise voltages) which appears on the base of the bipolar transistor amplifier, and the network of resistors and capacitors shifts the phase by an additional amount. If the phase shift introduced by the RC network is precisely 180º, at this frequency the total phase shift from the base around the circuit and back to the base will be exactly zero and the circuit will produce sustained oscillations. Simulation runs using TINA software showed the frequency of oscillation of the circuit in Fig. 1 to be around 12.5 kHz.

Later, we will try and answer how the oscillator produces a single frequency of oscillation.

In Chapter 2 of “Fundamentals of Electric Theory and Circuits”, a description of the circuit processes that cause a sinusoidal signal applied to a CR circuit to shift in phase (lead) is given.
The first simulation described in the procedure below shows this with reference to Fig. 2.
The second simulation shows how with the addition of a second CR stage to the CR circuit, an additional phase shift (lead) is produced.
The third simulation shows how a sinusoidal signal applied to three CR stages produces a large shift in phase (lead).

Simulation 1

1. Open the Tina Schematics Editor page. Click the “Basic” tab and pick and place a resistor, capacitor and a voltage generator in convenient locations following the schematic in Fig. 2. (To rid the cursor of the component after placing it on the editor page, click anywhere on the page else, right click and select “Cancel Mode”).
Then, place the ground symbol from the Basic tab and two Voltage pins (VF1 and VF2) at the input and the output from the Meters tab according to the schematic in Fig. 2.

2. Double-click the resistor and capacitor in succession and set the value of each component in the component dialog box according to the values in the schematic of Fig. **Note:** For megohms, use “M”, for milliohms use “m”, for microfarad use “u” and for nanofarad use “n”. Connect the components using the Wire symbol in the menu bar, according to the schematic in Fig. 2.

3. Next, double click the voltage generator and in the component dialog box, set the signal in the “Signal Editor” to “Sine wave”, amplitude to 2 volts and frequency to 12.5 kHz.

Check the schematic

Perform the Electric Rules Check (ERC) by clicking “Analysis” in the menubar and then clicking “ERC”. This will show up errors and warning messages if the schematic is not proper. Correct the schematic based on the summary displayed by the ERC.

CIRCUIT SCHEMATIC

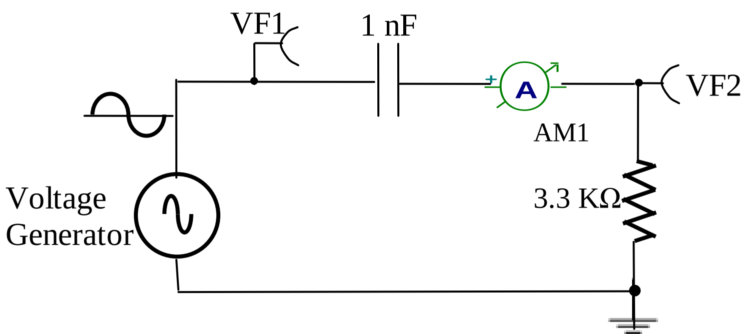


Fig. 2 Phase shift network one CR stage

4. Click “Analysis” in the menu bar and select “AC Analysis”. Then, click on “AC Transfer Characteristic. In the dialog box set the “start” frequency to 10 Hz and the “end” frequency to 1 MHz. Set the “Sweep type” radio button to “Logarithmic” and check the “amplitude & phase” box leaving the other boxes unchecked. Then click OK. The Bode plots of amplitude and phase at the voltage pins vs frequency will be displayed. A screen shot of the Bode plots of amplitude and phase vs. frequency for the single stage CR phase shift network is shown in Fig. Sim1a.

Labeling the Bode plots and making Phase measurements in the Bode plots

To label individual plots in a Bode plot window click the “auto-label” button in the Bode plot display window menu and then click on an individual plot. The plot will be labeled automatically. The exact phase and amplitude values can be measured in the transfer characteristic diagram window by first selecting the phase waveform of interest by clicking on it (it will change to red) and then selecting the “cursor a” from the menu. The cursor cross-hair should then be clicked on the waveform and two mutually perpendicular lines will be displayed. The cursor line can be moved left or right by clicking and holding the left mouse button on the ‘a’ symbol at the top of the plot.

The input voltage generator has a phase of 0 degrees and is a straight line plot at the bottom of the Bode plot window.

Bode Plot Screen shots

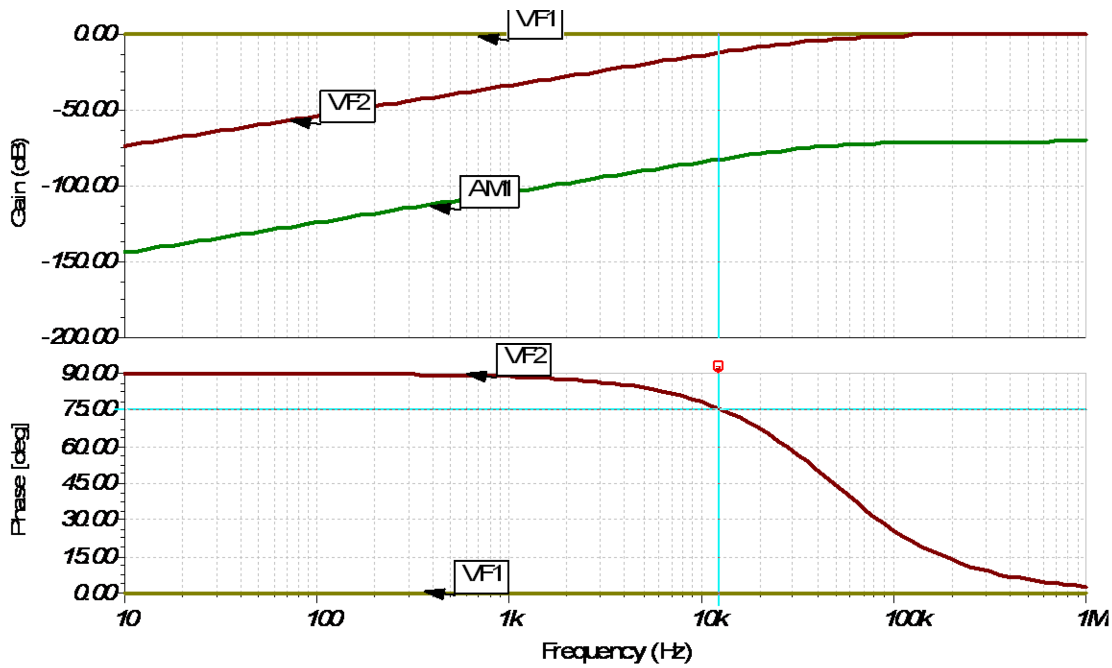
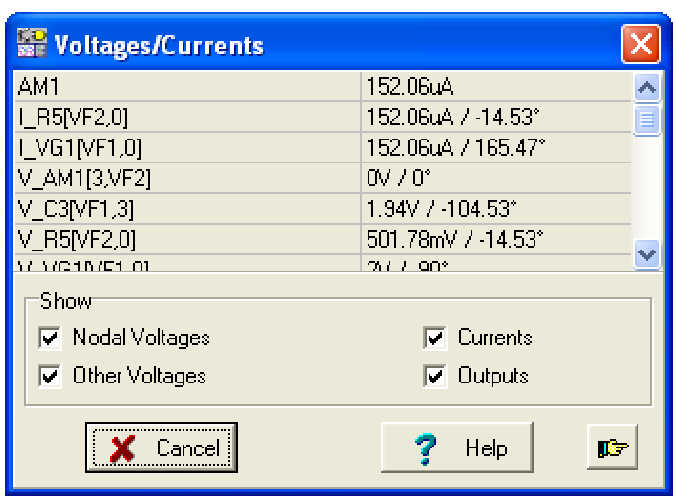


Fig. Sim1a: Bode plots of Amplitude (Gain) and Phase-Single Stage CR network

Note how the phase reduces from 90 degrees(lead) at 10 Hz to about 80.5 degrees(lead) at 8 kHz and nearly 3 degrees at 1 MHz. At 12.5 kHz the phase(lead) is 75.47 degrees. The frequency of the sinusoid produced by the RC phase-shift oscillator of Fig. 1 is about 12.5 kHz. The amplitude of the sinusoid at the output (VF2) is (501.7millivolts) or -12 dB (see note below) at 12.5 kHz. The reference 0 dB of the voltage generator is at 2 volts. The current in the resistor is 152 µA.

The current is measured by inserting an ammeter in the limb where the current is required and clicking "Analysis", and then clicking "AC Analysis". Then click "Table of AC Results" to display various voltages and currents. When reading and interpreting phase values, due note of the voltage generator phase should be read from the table, since in some cases the generator may be adjusted to values other than '0' like say, -90º. A screen shot of the table for the single stage network is shown below.



As the frequency of excitation is increased, the capacitor reactance reduces and this causes the phase that was almost 90 degrees at 10Hz to reduce, resulting in the output voltage closely following the applied sinusoidal input in phase.

The output voltage is very small at 10 Hz (-73 dB) due to the large fringe field developed by the capacitor (this can be viewed by checking the “amplitude” box in the “AC Transfer Characteristic” dialog box) and the output voltage increases as the frequency is increased. This is to be expected since at the larger frequencies the reactance of the capacitor is small (small fringe field development) permitting most of the voltage of the generator to be “bypassed” through to the load resistor.

Note: If the output voltage of the network is 0.5 volts with an input of 2 volts, then the signal has reduced in strength to $1/4^{th}$ of its input value. This is expressed in decibels(dB): $20\log\frac{0.5}{2} = -12.04$ dB. If the output voltage is 0.000414 volts, the signal is reduced in strength to 0.000207^{th} of its input value (2 volts). And, with reference to the input voltage of 2 volts (considered 0 dB), this corresponds to $20\log\frac{0.000414}{2} = -73.6$ dB (decibels).

Effect of changing the values of the resistor

5. Double-click the resistor and change its value to 500 ohms. Run the simulation following the step 4 and observe that the phase between the output voltage and input has advanced to 87 degrees at 12.5 kHz. The reduced resistance value makes the fringe field effect stronger and the quality of the network is more capacitive. More charges accumulate on the plates of the capacitor in fixed intervals of time in comparison to the number of charges that can accumulate when the resistance value was 3.3KΩ and these produce stronger fringe fields to oppose the driving input electric field of the generator. The current in the resistor is now 156.9.μA..

6. Double-click the resistor and change its value to 1MΩ. Run the simulation following the step 4 and observe that the phase between the output voltage and input has retarded to 0.7 degrees (near zero degree lead) at a frequency of 12.5 kHz. The large resistance value makes the fringe field weaker and the quality of the network is more resistive. Fewer charges accumulate in the fixed intervals of time in comparison to the amount of charges that can accumulate when the resistance was 3.3KΩ. The weak fringe fields that are produced due to small amounts of charge, cannot significantly oppose the driving input electric field of the generator. The amplitude of the output is quite close to that of the input voltage too.

The current in the resistor is a mere 2 μA.

To view the phase shift of the single stage CR network on the virtual oscilloscope using TINA simulation software

Select “Oscilloscope” from the T&M Menu. After selecting AC coupling, click Run and then Auto in the bottom of the virtual oscilloscope dialog window. Observe the steady-state sinusoidal waveform of VF1. To synchronize screen waveform set Trigger mode to Normal and to view both VF1 and VF2, click the “export curves” button (middle button) in the “Data” section of the Oscilloscope window.

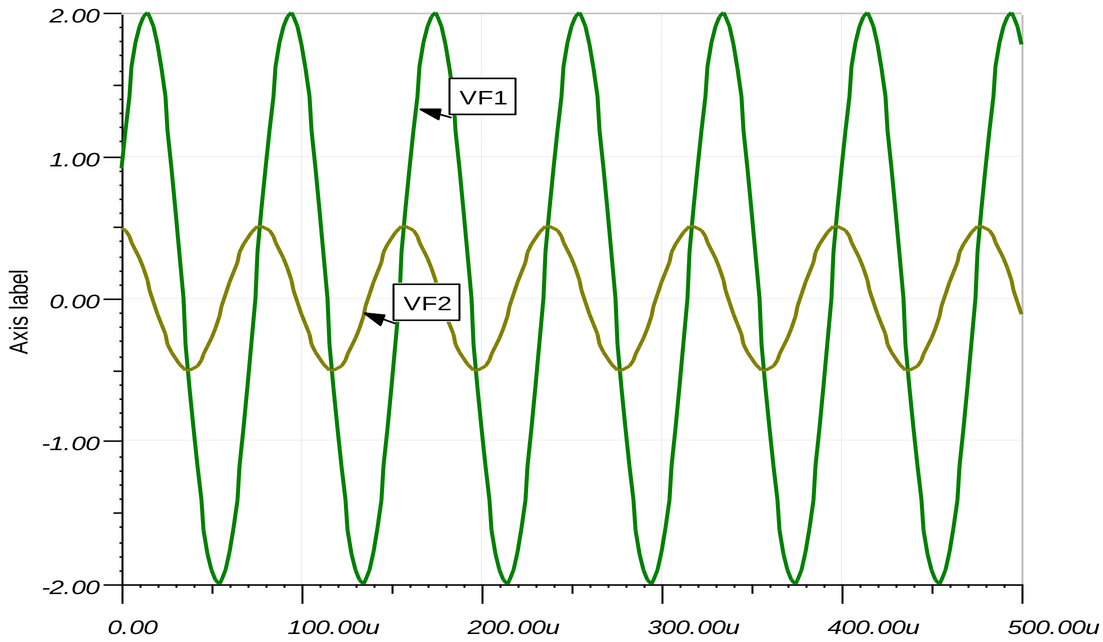


Fig. Sim1b: Oscilloscope waveforms VF1 and VF2 -Single Stage CR network

Simulation 2

7. Open the Tina Schematics Editor page. Click the "Basic" tab and pick and place two resistors, two capacitors and a voltage generator in convenient locations following the schematic in Fig. 3. (To rid the cursor of the component after placing it on the editor page, click anywhere on the page else, right click and select "Cancel Mode").

Then, place the ground symbol from the Basic tab and three Voltage pins (VF1, VF2, and VF3) at the input, the output of the first CR stage and the output of the second CR stage from the Meters tab according to the schematic in Fig. 3.

8. Double-click the resistors and capacitors in succession and set the value of each component in the component dialog box according to the schematic in Fig. 3. **Note:** For megohms, use "M", for milliohms use "m", for microfarad use "u" and for nanofarad use "n". Connect the components using the Wire symbol in the menu bar, according to the schematic in Fig. 3.

9. Next, double click the voltage generator and in the component dialog box, set the signal in the "Signal Editor" to "Sine wave", amplitude to 2 volts and frequency to 12.5 kHz.

CIRCUIT SCHEMATIC

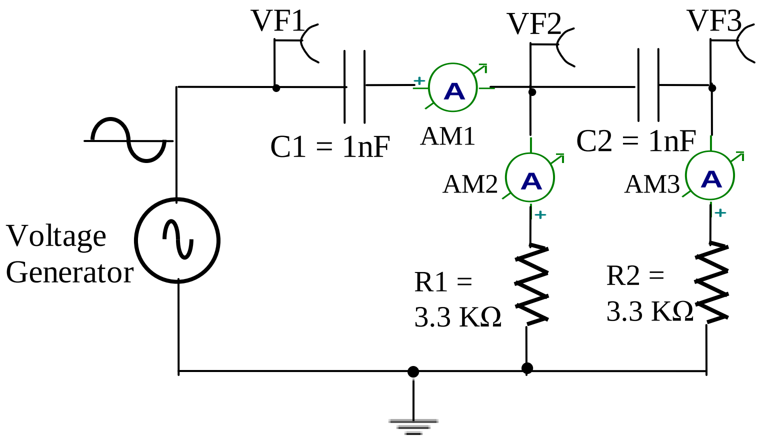


Fig. 3 Phase shifting network with two CR stages

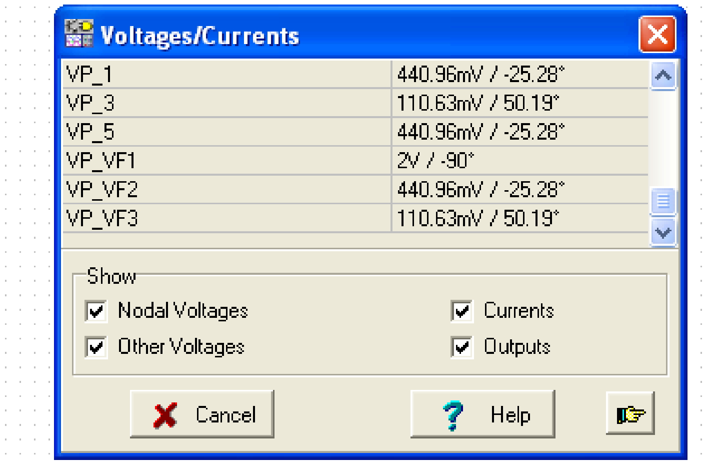
Check the schematic

Perform the Electric Rules Check (ERC) by clicking "Analysis" in the menubar and then clicking "ERC". This will show up errors and warning messages if the schematic is not proper. Correct the schematic based on the summary displayed by the ERC.

10. Click "Analysis" in the menu bar and select "AC Analysis". Then, click on "AC Transfer Characteristic. In the dialog box set the "start" frequency to 10 Hz and the "end" frequency to 1 MHz. Set the "Sweep type" radio button to "Logarithmic" and check the "phase" box. Then click OK. The Bode plots of amplitude and phase at the voltage pins vs frequency will be displayed.

Output of first CR stage

The current in the first stage capacitor is 145.69 µA. The current in the first stage resistor is 133.62 µA while the second stage draws 33.52 µA. Also, note the further reduction in magnitude of output voltage of the first stage due to the loading effect. It is -13.1 dB (amplitude is 441 mV) at 12.5 kHz, representing a reduction of about 1.1 dB from the single CR stage value. *The current is measured by inserting an ammeter in the limb where the current is required and clicking "Analysis", and then clicking "AC Analysis". Then click "Table of AC Results" to display various voltages and currents. When reading and interpreting phase values, due note of the voltage generator phase should be read from the table, since in some cases the generator may be adjusted to values other than '0' like say, -90º. A screen shot of the table for the two stage network is shown below.*



Note how the phase reduces from 90 degrees(lead) at 10 Hz to about 65.42 degrees(lead) at 12.5 kHz. At 1 MHz the lead angle is slightly raised to about 6 degrees(lead). Note that the phase(lead) amount has reduced from the values when the CR stage was not loaded (for the single stage, the lead angle is 75.47 degrees at 12.5 kHz) by the second CR stage. A screen shot of the Bode plots of amplitude and phase vs. frequency for the two stage CR phase shift network is shown in Fig. Sim2a.

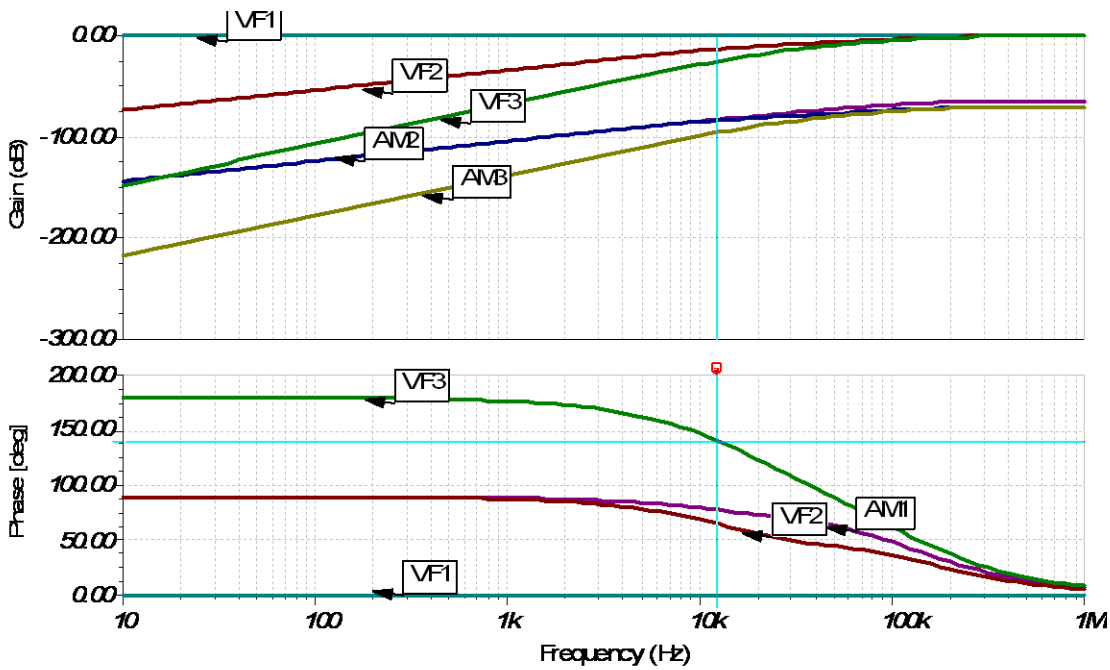


Fig. Sim2a: Bode plots of Amplitude (Gain) and Phase-Two Stage CR network

To view the phase shift of the two stage CR network on the virtual oscilloscope using TINA simulation software

Follow the procedure described in Step 6.

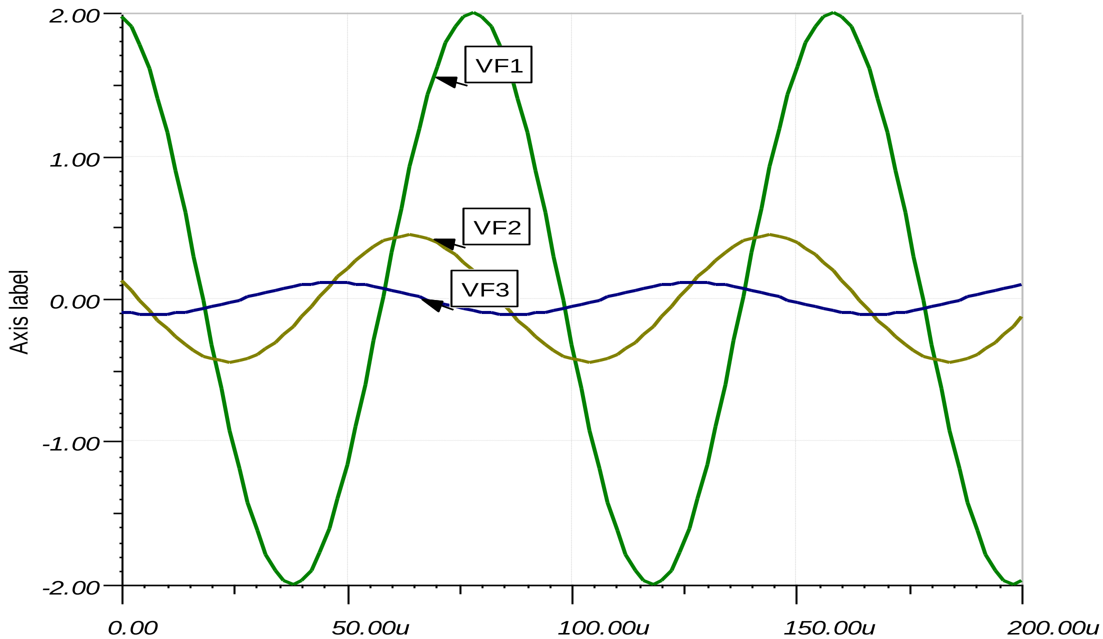


Fig. Sim2b: Oscilloscope waveforms VF1, VF2 and VF3 -Two Stage CR network

Loading effect of the second CR stage on the first CR stage

To intuitively understand the reason for the reduction in phase values, it will be instructive to see what happens when the capacitor is replaced by a short-circuit in the second stage. The magnitude at the output of the first stage reduces sharply and is -17.83 dB at 12.5 kHz.

This is expected, because the capacitor current will rise sharply. It is 155.78 µA in the capacitor and splits equally as 77.89 µA in the resistor R1 and 77.89 µA in the resistor R2. The phase angle rises to about 82.6 degrees (lead) from 65.42 degrees (lead) at 12.5 kHz, indicative of a more capacitive quality of the stage. Remember that the more the capacitor current, the more the accumulation of charge on the capacitor plates in given intervals of time and therefore, the fringe field development is stronger leading to a more capacitive behavior of the stage.

Note: If the CR circuit resistance is "zero" or "near zero", the circuit will be purely capacitive or of strong capacitive quality. Then, the current will be very large at any given frequency and tends to *lead* the voltage by 90 degrees or close to 90 degrees.

Now, reintroduce the capacitor in the second stage. The output voltage of the first stage becomes the source of voltage to the second stage. The plates of the second stage capacitor C2 accumulate charge causing its fringe field to oppose the driving field of the output voltage of the first stage. The second stage network current is reduced and it draws 33.52 µA, a reduction of nearly 44 µA.

The magnitude of the second stage is -25.2 dB. The current in the resistor R1 accordingly is up from 77.89 µA to 133.62 µA. Therefore, the magnitude of the first stage output voltage is up by about 4.7 dB and is at -13.1 dB at 12.5 kHz from its value of -17.83 dB (at 12.5 kHz) obtained without the second stage capacitor.

The phase of the first stage output (VF2) is down to 64.7 degrees(lead) from about 82.6 degrees(lead) since the first stage capacitor current is down from 155.78 µA to 145.69 µA indicative of a behavior of a capacitive-resistive branch. The currents in the two stages do not total up to the capacitor current because the phase angles have not been factored in.

The difference in phase between the first and second stages

The phase difference between the two stages measured by subtracting the phase of the output voltage of the first stage from the phase of the output voltage of the second stage is 139.97 degrees(lead) – 64.7 degrees(lead) = 75.27 degrees(lead).

The magnitude is down by -25.2dB (ampl. = 110.6 mV: generator input ampl = 2V). It should be noted that at the frequency of oscillation of the RC phase shift oscillator of Fig. 1, 12.5 kHz, the phase of the first stage is 64.7 degrees(lead) and the phase difference between the second and first stage is 75.27 degrees(lead).

Simulation 3

11. Open the Tina Schematics Editor page. Click the Basic tab and pick and place resistors, capacitor, a voltage generator and a battery in convenient locations following the schematic of Fig. 4.

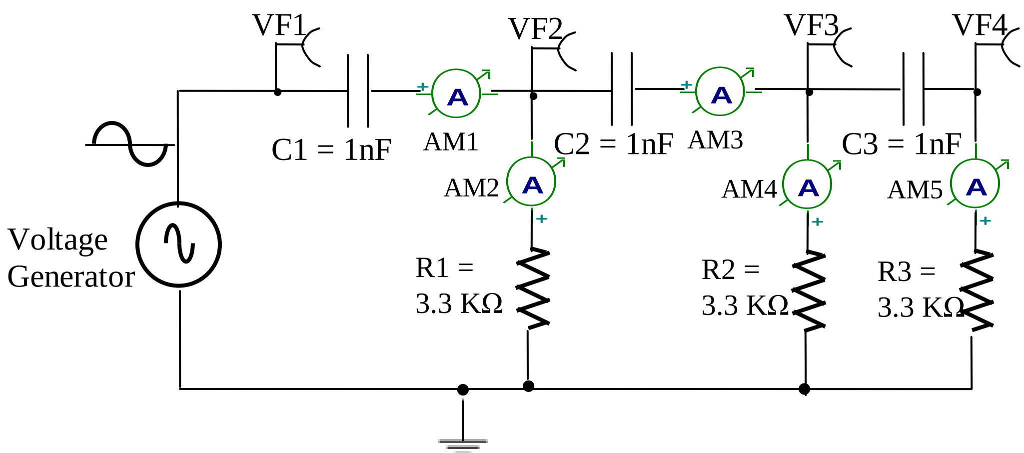


Fig. 4 Phase shifting network with three CR stages

12. Following steps 2 and 3 and after checking the schematic, double-click the capacitors and resistors and set their values indicated in the schematic of Fig. 4. Next, double click the voltage generator and in the component dialog box, set the signal in the "Signal Editor" to "Sine wave", amplitude to 2 volts and frequency to 12.5 k Hz.

Note: For megohms, use "M", for milliohms use "m", for microfarad use "u" and for nanofarad use "n". Connect the components using the Wire symbol in the menu bar, according to the schematic in Fig. 4.

13. Next, double click the voltage generator and in the component dialog box, set the signal in the "Signal Editor" to "Sine wave", amplitude to 2 volts and frequency to 8 kHz.

Check the schematic

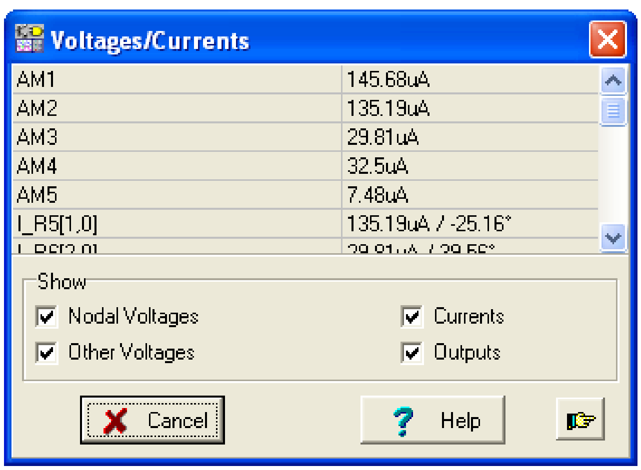
Perform the Electric Rules Check (ERC) by clicking “Analysis” in the menubar and then clicking “ERC”. This will show up errors and warning messages if the schematic is not proper. Correct the schematic based on the summary displayed by the ERC.

14. Click “Analysis” in the menu bar and select “AC Analysis”. Then, click on “AC Transfer Characteristic. In the dialog box set the “start” frequency to 10 Hz and the “end” frequency to 1 MHz. Set the “Sweep type” radio button to “Logarithmic” and check the “phase” box. Then click OK. The Bode plots of amplitude and phase at the voltage pins vs frequency will be displayed.

Output of first and second CR stages (Fig. 4)

The current in the first stage capacitor is 145.68 µA. The current in the first stage resistor is 135.19 µA up from 133.62 µA while the current in the second stage is 29.81 µA down from 33.52 µA.

The current is measured by inserting an ammeter in the limb where the current is required and clicking “Analysis”, and then clicking “AC Analysis”. Then click “Table of AC Results” to display various voltages and currents. When reading and interpreting phase values, due note of the voltage generator phase should be read from the table, since in some cases the generator may be adjusted to values other than ‘0’ like say, -90º. A screen shot of the table for the three stage network is shown below.



A screen shot of the Bode plots of amplitude and phase vs. frequency for the three stage CR phase shift network is shown in Fig. Sim3a.

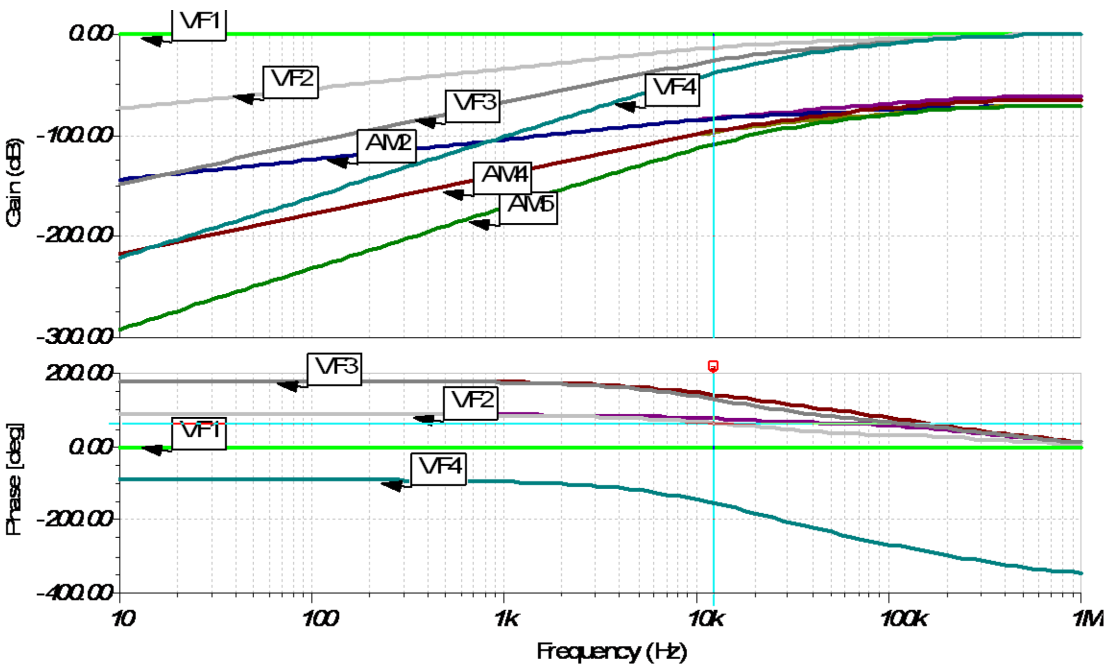


Fig. Sim3a: Bode plots of Amplitude (Gain) and Phase-Three Stage CR network

The magnitude of the first stage output (VF2) is now -13.1 dB at 12.5 kHz, not registering any change to its value before the addition of the third stage.
The phase angle of the first stage output (VF2) is 64.8 degrees(lead) and is slightly up from its value without the addition of the third stage which was 65.42 degrees(lead).
The magnitude of the second stage output (VF3) at 12.5 kHz is -26.2 dB (ampl = 98.3 millivolts), down from its value of -25.2 dB before the addition of the third stage. Again, this is to be expected because of the fringe field effects of the capacitor in the third stage. The current in the second stage resistor is 29.81 μA. The phase difference between the second and the first stages is now 64.72 degrees(lead) and is down sharply from the value of 75.27 degrees(lead) that was present without the addition of the third stage. An indication of this is provided from the current in the second stage capacitor C2 which is 32.5 μA and is down from the value of 33.52 μA registered before the addition of the third stage.

Output of second and third CR stages (Fig. 4)

The current in the third stage capacitor is 7.48 μA. The magnitude of the third stage CR network voltage (VF4) is -38.2 dB, which shows that the signal is largely attenuated, as a result of the combined effect of the three capacitors gradually decreasing the magnitude of the input voltage at the output of each stage by the reactance effect. The third stage voltage angle leads the second stage output voltage by 75.47 degrees.

To view the phase shift of the three stage CR network on the virtual oscilloscope using TINA simulation software
Follow the procedure described in Step 6.
A screen shot of the waveforms at VF1, VF2, VF3 and VF4 is shown in Fig. Sim3b.

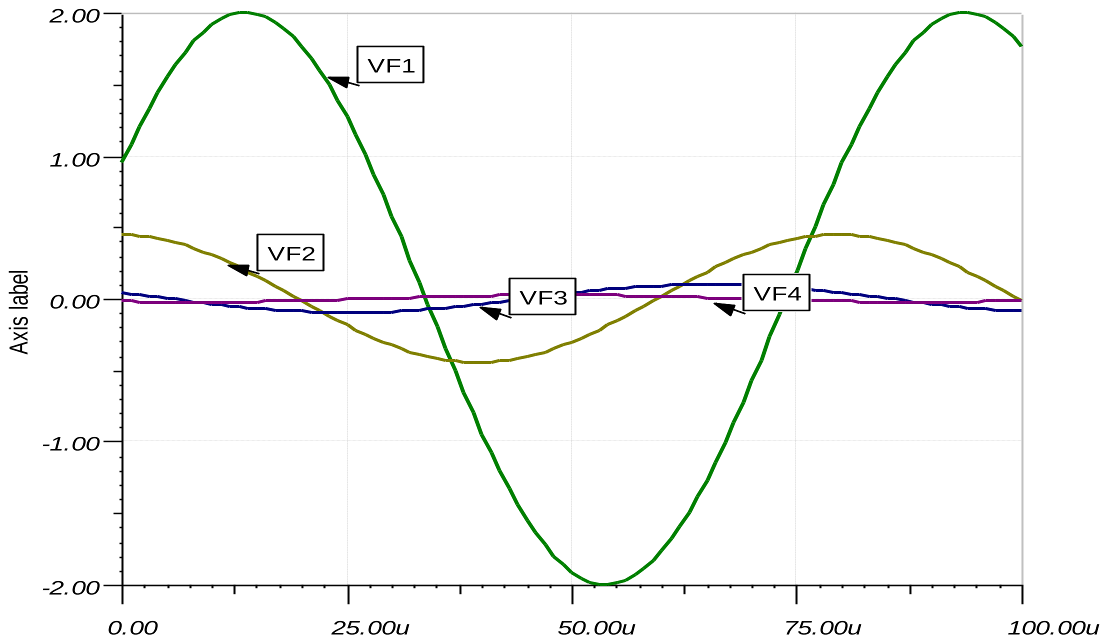


Fig. Sim3b: Oscilloscope waveforms VF1, VF2, VF3 and VF4 -Three Stage CR network

Summarizing, the phase lead in degrees with the input frequency at 12.5 kHz, between the first stage and the voltage generator, the second and first stage, and the third and second stage is 64.8 degrees(lead), 64.72 degrees(lead) and 75.47 degrees(lead) respectively. Each CR stage attenuates the signal quite significantly as can be seen from the sharp dip in dB values of the second and third stages of -26.2 dB and -38.2 dB respectively. The effect on the first stage output with the addition of subsequent stages is not quite so significant (-12 to -13 dB).

The total phase shift between the third stage and the voltage generator is about 205 degrees.

It should not be surprising that the value is different from 180 degrees, which we hoped to achieve by selecting identical CR network stages, and that each would contribute 60 degrees. While at first glance at Fig. 4, it may have seemed that the phase shifts contributed by each stage of the three stage RC network will be identical, the approach ignores loading effects of individual stages. What is observed, is that the loading effects combine in a manner such that the phase shifts reduce from their unloaded values as more and more stages are added.

Consider the output voltage phase variation in the first stage. With a single stage, the phase lead was 75.47 degrees. With the addition of one more stage, the first stage phase changed to 65.42 degrees(lead). And with the addition of the third stage, the first stage phase reduced to 64.8 degrees(lead).

We could have argued (rather naively) that increasing the number of stages should have resulted in more current in the network due to increased loading and this should have increased the lead angle rather than decreasing it. The counterargument lies in the result of the experiment of replacing the capacitor with a short as demonstrated in "Loading effect of the second CR stage on the first CR stage" of Simulation 2**.** In that experiment, with the capacitor of the second stage replaced by a short circuit, the classic loading effect resulted in an *increase* in the phase angle(lead) of the output voltage, giving the network (now resembling a single stage CR network), a more capacitive quality.

Therefore, without the capacitor in the second stage, the argument holds. But, because of the capacitors in the CR networks of the second and subsequent stages, the factor responsible for the reduction in phase angle(lead), is the attenuation that they introduce (like a sort of back emf) due to the fringe field development by charges accumulating on the plates of the capacitors. Note the drop in current in the first stage capacitor, as the number of stages in the phase shifter was increased. For one stage, the current is 152 μA. With the second stage, the first stage capacitor current is 145.69 μA. With the addition of the third stage, the first stage capacitor current is 145.68 μA.

The RC Phase Shift Oscillator (Fig. 1)

Note that the circuit of the RC Phase Shift Oscillator shown in Fig. 1 incorporates a 2.2 KΩ resistor in the third stage of the phase-shifting network. This is so, because the biasing network comprising resistors R1|| R2 and the input impedance of the transistor provide an additional resistance in series with the resistor of the third CR stage to make up 3.3 K Ω.

How does the oscillator produce a single frequency of oscillation ?

At some frequency, (the oscillator will *adjust itself* and pick the one frequency from the band that the tiny noise emfs that the resistors and transistors introduced at switch ON) the phase shift introduced by the RC network will be precisely 180º. And, at this frequency the total phase shift from the base around the circuit and back to the base will be exactly zero.

The expression (Ref.[17]) for frequency is $f = \frac{1}{2\pi RC}\frac{1}{\sqrt{6+4(R_c/R)}}$ for the RC phase-shift oscillator shown in Fig. 1 and a detailed proof of this is available here http://www.inictel-uni.edu.pe/sites/default/files/archivos/2014/publicaciones/12/rc_phase_shift_oscillators.pdf.

Simulation runs using TINA software showed the frequency of oscillation of the RC Phase Shift Oscillator shown in Fig. 1 to be around 12.5 kHz.

15. Open the Tina Schematics Editor page. Click the Semiconductors tab and pick and place an "NPN" transistor on the centre of the page. Double click the transistor and set the Part No. to BC107.

16. Next, Click the Basic tab and pick and place resistors, capacitors and the battery in convenient locations following the schematic of Fig. 1. (To rid the cursor of the component after placing it on the editor page, click anywhere on the page else, right click and select "Cancel Mode").

Then, place the ground symbol from the Basic tab and a Voltage pin at the output from the Meters tab.

17. Double-click the resistors, capacitors and transistors in succession and set the parameter value of each component in the component dialog box. For transistors ensure that the right part no. is selected. **Note:** For megohms, use “M”, for milliohms use “m”, for microfarad use “u” and for nanofarad use “n”. Connect the components using the Wire symbol in the menu bar, according to the schematic in Fig. 1.

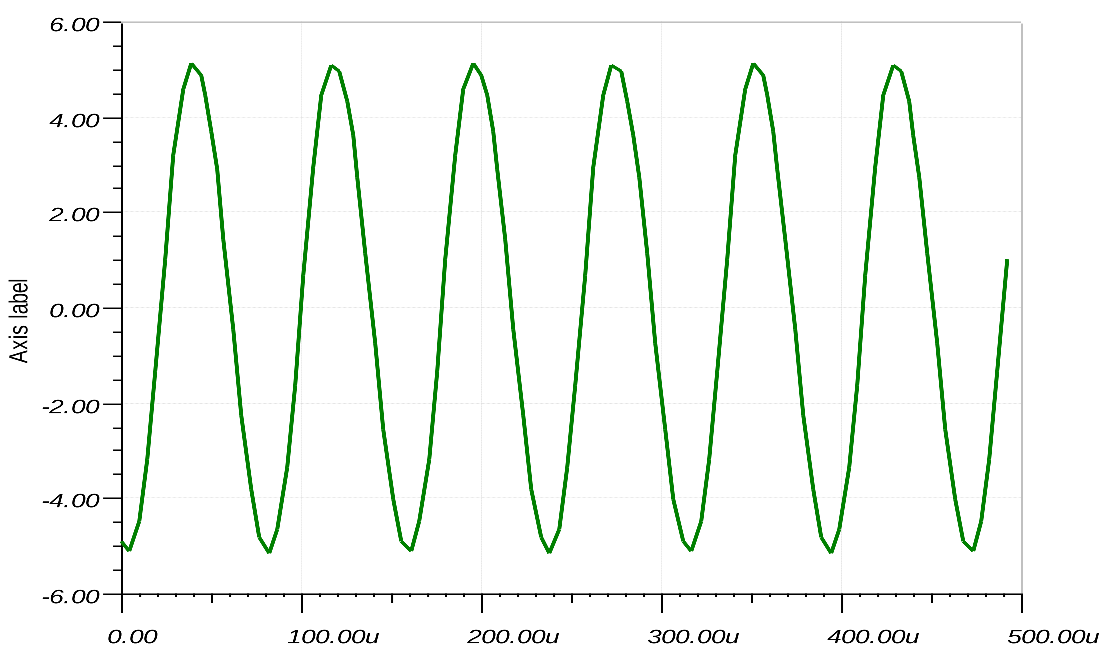
18. Double-click the power supply symbol and set to 25V DC.

Check the node voltages

The Electric Rules Check (ERC) can be performed by clicking Analysis in the menubar and then clicking ERC. This will show up errors and warning messages if the schematic is not proper. Correct the schematic based on the summary displayed by the ERC.

To view the Oscillator output on the virtual oscilloscope

Select “Oscilloscope” from the T&M Menu. After selecting AC coupling, and setting the Vertical Volts/div to 2 volts, click Run and then Auto in the bottom of the virtual oscilloscope dialog window. To synchronize the screen waveform set Trigger mode to Normal. Next, click the “export curves” button (middle button) in the “Data” section of the Oscilloscope window.



A note on realizing identical phase shifts: If identical phase shifts are desired between each of the CR network then each of these networks should be isolated from the other by incorporating voltage followers or common-collector amplifiers between the stages thereby minimising loading effects.