Semiconductor Devices and Circuits

Chapter-IV : Oscillators

III B.Sc Physics
V Semester

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Chapter 4

Oscillators

4.1 Introduction

An oscillator is an electronic circuit capable of generating periodic waveforms of desired frequency. These waveforms may be *harmonic waveforms* such as sinusoidal waves or *relaxation waveforms* such as saw-tooth waves, square waves or triangular waves. Therefore oscillators can be generally classified as (i) *sinusoidal oscillators* and (ii) *relaxation oscillators*. As periodic waveforms are required in all communication, measurement, display and signal processing applications, oscillators form an essential and integral part of any electronic system.

4.2 Oscillatory Circuit or Tank Circuit or L-C circuit or Resonator Circuit

The heart of any electronic oscillator is a tank circuit constructed by connecting an inductor **L** and a capacitor **C** in parallel to each other. This **L-C** combination, also called as the oscillatory circuit, generates periodic waveforms having a frequency determined by the values of **L** and **C**.

4.2.1 Principle

The capacitor and the inductor are both energy storing elements, with the capacitor storing energy in the form of electric field and the inductor storing energy in the form of magnetic field. When a capacitor charges up, its electric field energy increases. On the other hand if it discharges, its electric field energy decreases. Similarly, when the magnetic flux associated with the motion of electrons across the inductor increases, the magnetic field energy of the inductor increases, while it decreases otherwise. Thus by alternatively charging and discharging a capacitor or increasing and decreasing the magnetic flux associated with the inductor, we get periodic variations in the intensities of the currents or voltages across the circuit, which we call as oscillations.

4.2.2 Working

The working of a tank circuit leading to the generation of oscillations can be analysed in four stages as shown in Figs. 4.1(i-iv).

Stage - I:

Let us consider the inductor and capacitor are connected in parallel through a switch **S**. Further let us assume that the capacitor is charged fully from a D.C source with its lower plate say **A** having an excess of −ve charge and the upper plate **B** having an excess of +ve charge. In this fully charge state, the electric field across the capacitor is a maximum.

As the switch **S** is open no charges flow across the inductor and hence no magnetic flux is generated across it. Consequently the magnetic field energy across the inductor is zero.

Stage - II:

When the switch **S** is closed, −ve charges start to flow from **A** to **B** through the inductor **L** giving rise to an electric current in the direction shown in Fig. 1(b). This causes the capacitor **C** to discharge, which leads to a decrease in its electric field. However the flow of the charges will set up magnetic flux across the inductor, thereby setting up a magnetic field and an electro-motive force *emf* across it. This *emf* will try to oppose the motion of charges, $\left[e = -\frac{d\phi}{dt}\right]$. This is shown in Fig. 4.1(b).

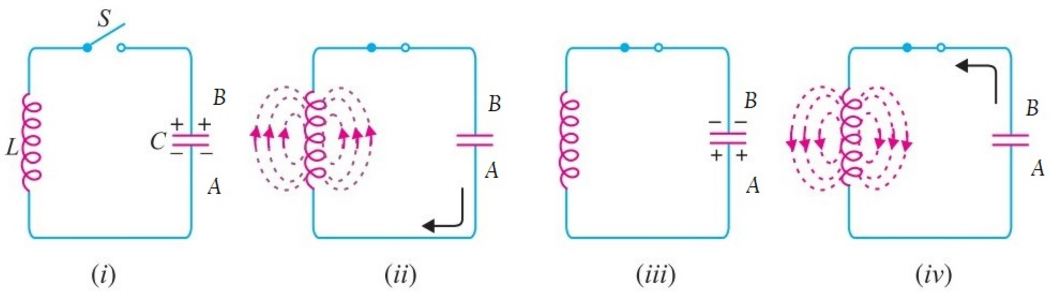

FIGURE 4.1: Four phases showing the building up of energy and their decay in the inductance and capacitance of an LC circuit leading to the generation of oscillations.

Stage - III:

When the charges across plates **A** and **B** become balanced or neutralized, the electric field across the capacitor becomes zero. However the *emf* across the inductor at this point becomes a maximum. It now causes the motion of $-$ve charges from plates **B** to **A** of the capacitor building up an electric field across it, but now in an opposite direction as shown in Fig. 1(c). At the end of this process, as the *emf* opposes the motion of the charges, the magnetic flux generated across the inductor decreases and hence the magenetic energy built up across it becomes zero eventually.

Stage - IV:

As the electric field energy across the capacitor is now a maximum, it starts to discharge, causing the electric field across it to decrease. This will however increase the magnetic field across the inductor. The only difference in this case when compared to stage -I is that the direction of the current flow as well as the direction of the magnetic flux will be opposite as shown in Fig. 1(d).

This four stage process is continued alternatively in time giving rise to periodic variations in the intensities of currents and voltages in the circuit thereby setting up oscillations in it.

4.2.3 Frequency of Oscillations

The frequency of oscillations is given by

$$f = \frac{1}{2\pi\sqrt{LC}} \quad \text{Hz}, \tag{4.1}$$

where L is the inductance of the coil and C is the capacitance of the capacitor. Eqn. 4.1 tells that as the frequency depends inversely on L and C, if either L or C or both are increased, the frequency f will decrease and vice-versa.

4.2.4 Dissipation in Tank Circuit

In a tank circuit, the electrical energy of the capacitor is converted into the magnetic energy of the inductor coil and vice-versa. During this process a fraction of the energy of oscillations is dissipated or lost because of

1. heating of the inductor coil ane

2. radiation in the form of electromagnetic waves to free space.

These losses are called as $\left(I^2R\right)$ losses. Due to this dissipation, the amplitude of the waveforms decrease with each successive cycle of operation, giving rise to *damped oscillations*. Eventually the oscillations die down as shown in Fig. 4.2(i).

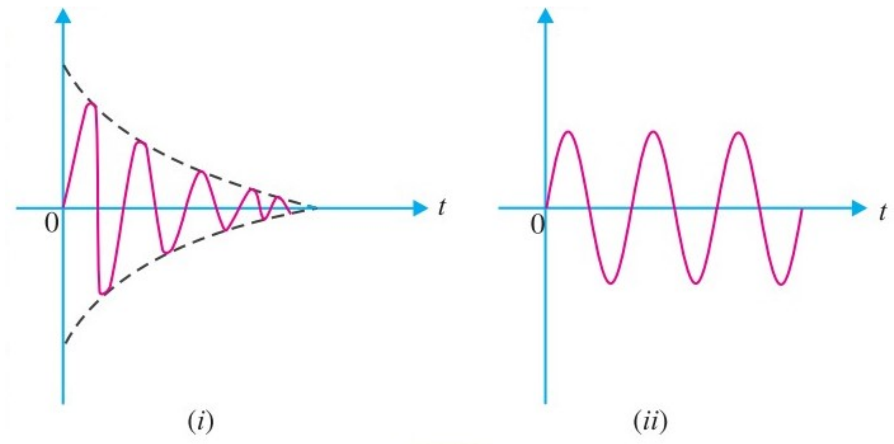

FIGURE 4.2: (i) Damped oscillations and (ii) sustained or undamped oscillations in an LC circuit.

In order to obtain *undamped* or *sustained oscillations* we require

1. a correct amount of energy equal to the $\left(I^2R\right)$ losses suffered by the circuit to be provided during each cycle of operation.
2. the applied energy should have the same frequency as those of the oscillations produced and
3. the phase and the external energy should also be the same as the phase of the oscillations produced in the circuit.

The *sustained oscillations* so produced when these conditons are met are shown in Fig. 4.2(ii).

4.3 Transistor Oscillators

The block diagram of a transistor oscillator is shown in Fig. 4.3. It consists of three parts, namely

1. the tank circuit
2. an amplifier

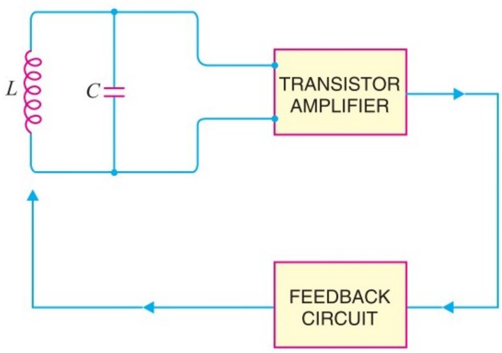

FIGURE 4.3: Three parts of a transistor oscillator circuit, namely the LC circuit, an amplifier circuit and the feedback network.

3. a feedback network.

Tank Circuit

This is the heart of the oscillator. It consists of an inductor L and a capacitor C connected in parallel to each other. It generates waveforms of frequency determined by the relation $f = \frac{1}{2\pi\sqrt{LC}}$.

Transistor Amplifier

This circuit takes the oscillations of the tank circuit and gives an amplified form of these as the output. For this purpose it requires a DC power source. It converts the DC power into AC power.

Feedback Network

This circuit determines the fraction of the output energy of the transistor amplifier that should be taken and given as the input to the tank circuit as positive feedback so as to overcome the $\left(I^2R\right)$ losses in energy during each cycle of oscillation.

4.4 Barkhausen Criteria for Sustained Oscillations

For a transistor oscillator to produce sustained oscillations, we require that

1. The feedback should be positive. This means that the nett phase shift around the loop should be 0^o or 360^o. This requires the phase of the feedback voltage and the electrical oscillations in the circuit to be the same, that is

$$\phi = 0^o \tag{4.2}$$

2. The feedback factor or the loop gain of the feedback network should be unity, that is

$$|\beta A| = 1 \tag{4.3}$$

where β is the feedback ratio and A is the open loop gain of the amplifier.

Clubbing these two conditions we get a complete relationship as

$$\beta A = 1 + j\phi, \tag{4.4}$$

where $j = \sqrt{-1}$ is the imaginary unit.

4.4.1 Mathematical Implication of the Barkhausen Criteria

The gain of a positive feedback amplifier, called as the closed loop gain is given as

$$A' = \frac{1}{(1 - \beta A)}, \tag{4.5}$$

where A is the open loop gain, that is gain without feedback, β is the feedback ratio or feedback fraction and A' is the closed loop gain.

If $\beta A = 1$, then Eqn. 4.5 implies that $A' \to \infty$, that is the gain with feedback becomes infinity. Practically it is not possible to realize an amplifier having an infinite gain. What it means physically is that, the amplifier will generate an oscillatory output even when no input signal is applied to it. This means that the amplifier will now get converted to an oscillator.

4.5 Colpitts Oscillator

A Colpitt's oscillator is an electronic circuit capable of generating sinusoidal oscillations of desired frequency. It contains

- a transistor in Common Emitter configuration and
- a tank circuit or an LC circuit containing a split capacitor, say C_1 and C_2 and an inductor L.

The circuit of a Colpitt's oscillator is shown in Fig. 4.4.

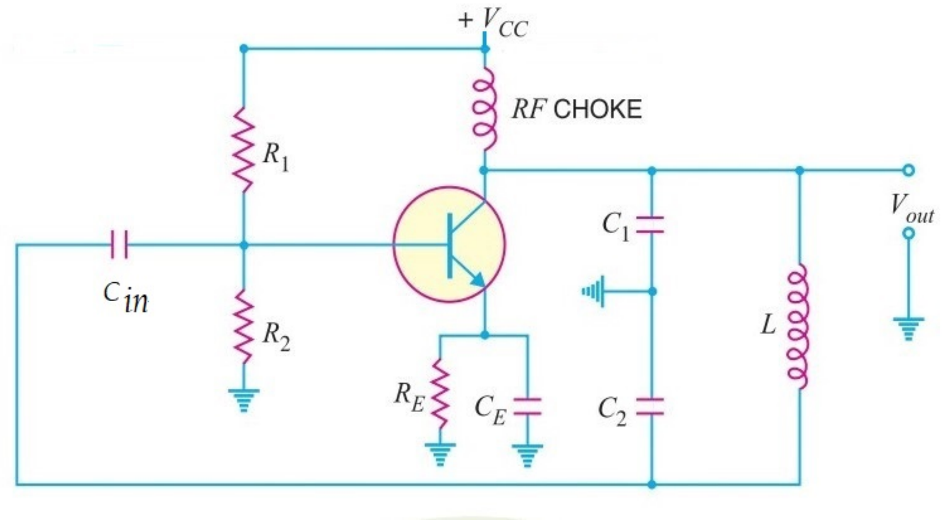

FIGURE 4.4: The circuit diagram of a transistor Colpitt's oscillator.

The circuit uses a voltage divider bias using resistances ($R_1 - R_2$) for biasing the base of the transistor. A radio frequency choke or inductance coil (*RF CHOKE*) provides a DC return path, while preventing AC signals from entering the source $+V_{CC}$. The resistance R_E, called as the emitter bypass resistance provides for the thermal stabilization, while the emitter bypass capacitor C_E provides for an AC path to the ground. The capacitor C couples the feedback to the input of the oscillator.

The tank circuit contains two ganged capacitors C_1 and C_2, having a centre tapped connection. This causes the the capacitor C_1 to be included in the output part of the circuit and the capacitor C_2 to be included in the input part of the circuit. The output is fed to the ($C_1 - C_2$) combination from the collector of the amplifier. A portion of this output , namely the voltage across the capacitor C_2 is fed to the input, that is to the base of the transistor. When the Barkhausen contitions are met, the sustained oscillations are set up in the LC circuit. The frequency of the oscillations is given by

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{4.6}$$

where

$$C = \frac{C_1 \times C_2}{C_2 + C_1} \tag{4.7}$$

The transistor produces an inversion in phase by 180^o or π radians. The centre tapping across the capacitors C_1 and C_2 causes another inversion in phase by 180^o or π radians. Hence the total phase of the signal fedback to the amplifier is 360^o or 2π radians with respect to the input.

We know the condition for sustained oscillations is that the open loop gain of the amplifier is given by $A > \frac{1}{\beta}$. But the feedback fraction is given by $\beta = \frac{C_1}{C_2}$. Therefore

$A > \dfrac{1}{C_1/C_2}$ or the condition for sustained oscillations becomes $A > \left(\dfrac{C_2}{C_1}\right)$.

The above inequality tells that the minimum value for the transistor amplifier gain should be greater than the ratio of the voltages across the capacitances C_1 and C_2.

The output is taken by means of inductive coupling from the inductance L of the tank circuit.

Proof

We know that the feedback fraction of the oscillator is the ratio of the output voltage to the input voltage, that is

$$\beta = \frac{V_{C2}}{V_{C1}}$$

But voltage is the product of the current and the ac resistance, therefore

$$\beta = \frac{IX_{C2}}{IX_{C1}},$$

But the ac resistance of the capacitor C_1 is

$$\begin{aligned} |X_{C1}| &= \left|\frac{1}{j\omega_{C1}}\right| \\ &= \frac{1}{\omega_{C1}}, \end{aligned}$$

Similarly the ac resistance of the capacitor C_2 is

$$\begin{aligned} |X_{C2}| &= \left|\frac{1}{j\omega_{C2}}\right| \\ &= \frac{1}{\omega_{C2}} \end{aligned}$$

Therefore substituting these, the feedback fraction becomes,

$$\beta = \left(\frac{C_1}{C_2}\right).$$

Hence the proof.

4.6 Hartley's Oscillator

A Hartley's oscillator is an electronic oscillator circuit wherein

- the tank circuit contains a split inductor, say L_1 and L_2 and
- the feedback is by the autotransformer action.

The circuit of a Hartley's oscillator is shown in Fig. 4.5. Similar to the Colpitt's oscillator, it consists of a transistor in Common Emitter configuration.

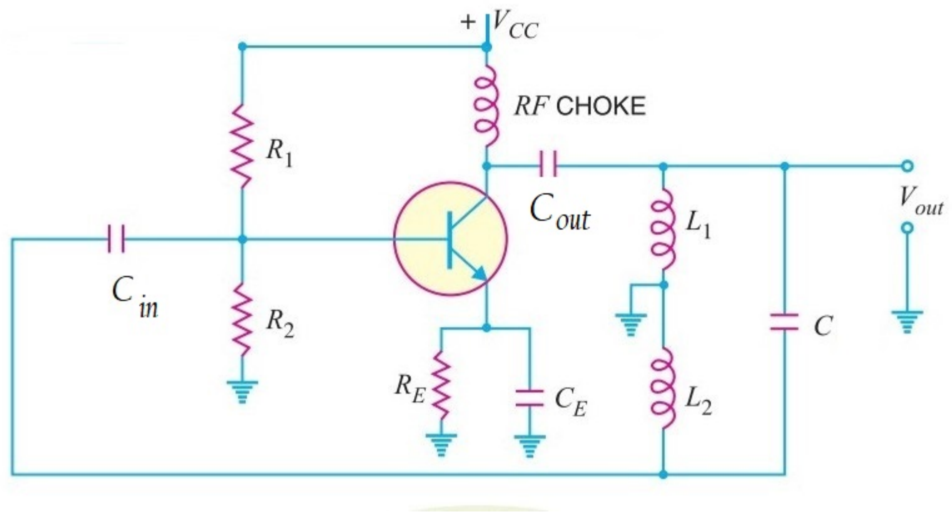

FIGURE 4.5: The circuit diagram of a transistor Hartley's oscillator.

Here the resistances ($R_1 - R_2$) form a voltage divider bias, for biasing the base of the transistor. A radio frequency choke or inductance coil (*RF CHOKE*) provides a DC return path, while preventing AC signals from entering the source $+V_{CC}$. The emitter bypass resistance R_E provides thermal stabilization, that means that even if the temperature varies, the output at the collector terminal of the transistor remains steady. The emitter bypass capacitor C_E provides for an AC path for the signals to flow to the ground. The capacitor C couples the feedback to the input of the oscillator.

The tank circuit contains a capacitor C connected in parallel to a centre tapped split inductance L_1 and L_2. The centre tap is connected to the ground. This causes the the inductor L_1 to be connected to the output part (collector-emitter section) of the circuit and the inductor L_2 to be connected to the input part (base-emitter section)of the circuit.

The two halves L_1 and L_2 form an auto-transformer. A portion of the output namely the voltage across L_1 is inductively coupled through L_2 to the base of the transistor amplifier. This is called as *auto-transformer action*.

By the transistor action, an inversion in phase by 180^o or π radians is produced. Further due to the centre tapping across the inductors L_1 and L_2 another inversion in phase by

180^o or π radians is caused. This causes the total phase shift of the signal fedback to the amplifier to be 360^o or 2π radians with respect to the input. Hence positive feedback is accomplished.

The capacitances C_c are called as coupling capacitors They allow only the ac part of the signals to be coupled, while rejecting the dc voltages. This is to safeguard the transistor as well as the load from getting damaged due to the high dc voltage.

When the Barkhausen criteria are satisfied then the sustained oscillations are set up in the tank circuit and the frequency of the oscillations is given by

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{4.8}$$

where

$$L = L_1 + L_2 + 2M, \tag{4.9}$$

where L_1 and L_2 are the self-inductances and M is the mutual inductance arising between the centre tapped inducator coils.

If $2M \ll (L_1 + L_2)$, then the value of the inductor becomes

$$L = L_1 + L_2. \tag{4.10}$$

Note: We know the condition for sustained oscillations is that the open loop gain of the amplifier and the feedback fraction are related as $A > \dfrac{1}{\beta}$. But the feedback fraction is given by $\beta = \dfrac{L_2}{L_1}$. Therefore $A > \dfrac{1}{L_2/L_1}$ or the condition for sustained oscillations becomes $A > \left(\dfrac{L_1}{L_2}\right)$.

The output is taken by means of inductive coupling as shown in the Fig. (4.5).

Proof

We know that the feedback fraction of the oscillator is the ratio of the output voltage to the input voltage, that is

$$\beta = \frac{V_{L_2}}{V_{L_1}}$$

But voltage is the product of the current and the ac resistance, therefore

$$\beta = \frac{IX_{L_2}}{IX_{L_1}},$$

But the ac resistance of the inducttor L_1 is

$$\begin{aligned} |X_{L_1}| &= |j\omega_{L_1}| \\ &= \omega_{L_1}, \end{aligned}$$

Similarly the ac resistance of the inductor L_2 is

$$\begin{aligned} |X_{L2}| &= |j\omega_{L_2}| \\ &= \omega_{L_2}, \end{aligned}$$

Therefore substituting these, the feedback fraction becomes,

$$\beta = \left(\frac{L_2}{L_1}\right).$$

Hence the proof.

4.7 LC and RC Oscillators

For sustained oscillations in an oscillator, the Barkhausen condition requires that

1. a phase shift of 180^o to be introduced by the feedback network.
2. closed loop gain A' be greater than unity.

In Colpitts and Hartley oscillators, the phase shift of 180^o is obtained by using centre-tapped capacitor or centre-tapped inductor in the LC circuit. As they use L-C network, they are called as *LC oscillators*.

However a phase shift of 180^o can also be achieved by using a network of resistances and capacitancess. Such oscillators are called *RC Oscillators* or *Phase Shift Oscillators*. Examples of such oscillators are transistor phase shift oscillator, Wein's Bridge oscillator etc.

4.8 Transistor Phase Shift Oscillator

A phase shift oscillator is a generator of sinusoidal waveforms using an R-C feedback network to generate oscillations. The circuit of a phase shift oscillator is shown in Fig. (4.6).

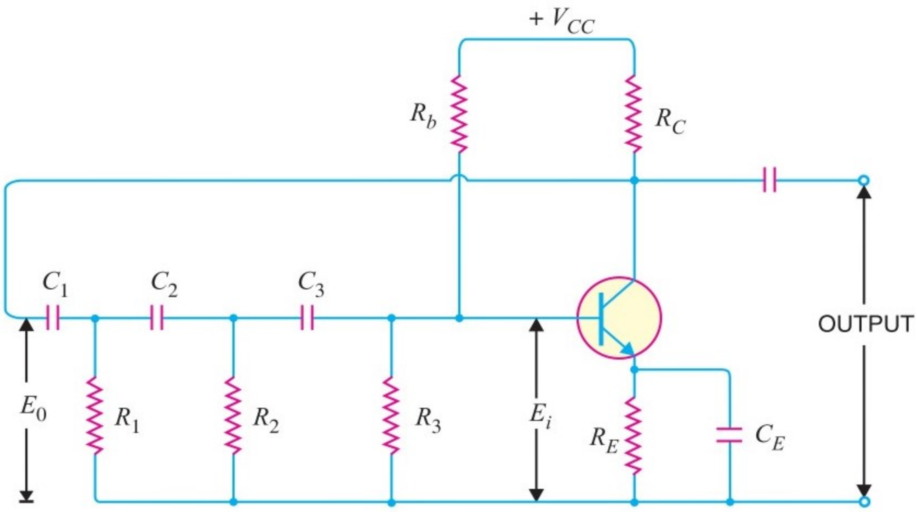

FIGURE 4.6: The circuit diagram of a transistor phase shift oscillator.

The feedback network consists of three RC sections. The values of R and C are so chosen that each RC section produces a phase shift of 60^o, such that the total phase shift of the signal passing through the RC network is 180^o. This is fed to the input of the transistor amplifier. This amplifier itself introduces a phase shift of 180^o for the signal by transistor action. Hence a total phase shift of 360^o is achieved at the collector of the amplifier. This ensures the condition for positive feedback. A portion of the output from the collector is given to the RC feedback network.

The transistor phase shift oscillator uses a voltage divider bias formed by the resistance R_3 of the third RC section and another resistance R_b. The resistance R_C controls the voltage drop across the transistor. It restricts the current across the collector to acceptable levels. The emitter by-pass resistance R_E ensures the thermal stability for th eamplifier while emitter by-pass capacitance C_E ensures zero resistance path for the AC signals. The capacitor at the collector couples the output to the load (any electronic device).

Let us assume that $R_1 = R_2 = R_3 = R$ and $C_1 = C_2 = C_3 = C$. Then the frequency of the oscillations is given by

$$f = \frac{1}{2\pi\sqrt{6}RC}\text{Hz} \tag{4.11}$$

The Eqn. (4.11) tells that by adjusting the values of the resistances and capacitances in the RC network, a phase shift oscillator of desired frequency can be obtained. It is found that the feedback ratio should be given by $\beta \geq \left(\frac{1}{29}\right)$. This means that the open loop gain of the amplifier should be atleast equal to 29, that is $A = 29$.

4.8.1 Advantages and Disadvantages

1. As they do not use inductors, which are bulky they can be used for any application requiring constant frequencies below $10KHz$.

2. As the Barkhausen conditions are satisfied for the frequency decided by the R and C values, it can generate true sine waves.

3. However, as it is difficult to tune capacitors precisely, it cannot be used for applications which require variations in frequencies.

Note: As $A \geq \left(\frac{1}{\beta}\right) \geq 29$, transistors having high gain are to be used to overcome the heat losses in the RC network.