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Nizhny Novgorod, July 20-26, 2008.
NWP-1: Nonlinear Dynamics of Electronic Systems - NDES'2008, pp. 47-48

THE COLPITTS OSCILLATOR FAMILY

E. Lindberg[1], **K. Murali**[2] and **A. Tamasevicius**[3]

[1]Elektro DTU, 348 Technical University of Denmark, DK2800 Kongens Lyngby, Denmark
E-mail: el@elektro.dtu.dk
[2]Department of Physics, Anna University, Chennai-600 025, India
[3]Plasma Phenomena and Chaos Laboratory, Semiconductor Physics Institute,
A. Gostauto 11, Vilnius, LT-01108, Lithuania

Abstract

A tutorial study of the Colpitts oscillator family defined as all oscillators based on a nonlinear amplifier and a three-terminal linear resonance circuit with one coil and two capacitors. The original patents are investigated. The eigenvalues of the linearized Jacobian for oscillators based on single transistors or operational amplifiers are studied.

Introduction

An electronic oscillator is a nonlinear circuit with at least two memory components (charge, flux or hysteresis based). When excited with a dc source an oscillator responds with a steady state signal which may be chaotic of nature in case of more than two memory components. The Colpitts oscillator is one of the most used oscillators especially for high frequencies. The aim of this tutorial is to study Colpitts oscillators defined as any oscillator made from a nonlinear amplifier and a three-terminal linear resonance circuit with one coil and two capacitors called the **Colpitts resonator**.

Electronic oscillators may be classified in families according to the kind and number of memory elements used e.g. the common multi-vibrator family with one capacitor or one coil in connection with a nonlinear amplifier [1], the Wien Bridge family where one RC-series and one RC-parallel circuit occur [2], the negative resistance family where one simple LC resonance circuit occur [3], the Colpitts family where a resonance circuit with two capacitors and one coil occur or the Hartley family where a resonance circuit with two coils and one capacitor occur.

Many years ago when the words "oscillator" and "electronics" were not invented in connection with electrical circuits and systems an "*Oscillation Generator*" was invented by Edwin Henry Colpitts (1872-1949) possibly sometime in the period 1915-1918. Colpitts oscillator topology based on two capacitors and one coil is the electrical dual of Hartleys oscillator topology based on two coils and one capacitor. Colpitts patents are investigated. This tutorial is divided into three sections. First general comments on amplifiers and oscillators, then transistor based Colpitts oscillators and finally Colpitts oscillators based on operational amplifiers are investigated.

Amplifiers and Oscillators

There are four types of **amplifiers** or controlled sources - Voltage Controlled Voltage Source VCVS, Voltage Controlled Current Source VCCS, Current Controlled Voltage Source CCVS and Current Controlled Current Source CCCS. Amplifiers are characterized by a stable time invariant dc bias point which may be used as signal reference. For small signals we have a linear relation between output and input. For large signals we may observe distortion of the signals.

A general amplifier circuit with four impedances is investigated. Two impedances are used for positive- and two impedances are used for negative- feed-back. If we introduce memory elements - capacitors, coils, hysteresis - in the four impedances various types of oscillators may be obtained. With three resistors and one capacitor or one coil four different common multi-vibrator topologies may be obtained [1].

Normally you distinguish between sinusoidal and relaxation **oscillators** but this is not a proper division because the same topology may give rise to both kinds of oscillations at different frequencies [1]. Oscillators are circuits which for constant input signal (dc battery) produce an oscillating output signal (a steady state time varying signal). Oscillators do not have a stable time invariant dc bias point which can be used as signal reference but some times an average bias point is introduced. There are three basic types of oscillators. The **first** type has an unstable initial dc bias point. This type is self-starting when the power supply is connected. The eigenvalues of the linearized Jacobian of the differential equations - the poles - are moving between the right half (RHP) and the left half (LHP) of the complex frequency plane so that a balance is obtained between the energy obtained from the power supply when the poles are in RHP and the energy lost when the poles are in LHP. The **second** type has a stable initial dc bias point. This type needs some extra initial energy in order to start up. The poles are in LHP all the time and some special impulse mechanism is needed to provide energy from the power supply in the steady state. The **third** type is a combination of the two types. It is unstable in the initial dc bias point and the poles are moving around in LHP only in the steady state [4,5].

The frequency of the oscillator is primarily determined by the imaginary part of the complex pole pair (eigenvalue) of the linear resonance circuit involved. The amplitude of the oscillator is primarily determined by the real part of the complex pole pair. If the oscillator is a second order circuit with two linear memory components and a nonlinear amplifier it is impossible to obtain an almost constant frequency corresponding to balancing on the razors edge with the complex pole on the imaginary axis. If the oscillator is a third order circuit with three linear memory components then you may have an extra real pole in connection with the complex pole pair to operate with corresponding to the balancing pole of the tight-rope walker.

Colpitts Oscillators based on Transistors

It is difficult to obtain a complete systematic description of all the possible topologies of the Colpitts oscillator family because it is a third order system. The Colpitts resonator is normally introduced as a triangle circuit but a star circuit with a coil and two capacitors may also be used [6]. Colpitts oscillators based on a single transistor as amplifier in common emitter-, base- or collector-mode are compared.

Experiments with PSpice simulations are presented. A 100kHz Colpitts resonator is designed. Losses are introduced as a resistor in series with the coil because it is impossible in practice to neglect the coil losses. The two capacitors are of different size because it is difficult in practice to obtain exact same value.

The 3 terminals of the transistor may be combined with the 3 terminals of the Colpitts resonator in many ways e.g. by rotating the components of the resonator. A total of 18 topologies have been investigated. It was found that 6 of these gave rise to steady state oscillations. PSpice models for transistors 2N2222 and 2N3904 were used. If a simple Ebers-Moll transport-model with no feed-back for the transistor is introduced only one nonlinearity occur (diode) and the trajectories of the poles in the complex frequency plane may easily be found. A complex pole pair is moving between RHP and LHP and a real pole is moving on the negative real axis. The imaginary part of the complex pole pair is almost constant giving rise to very little phase noise.

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As stated above there are four types of controlled sources - VCVS, VCCS, CCVS and CCCS - but here only Colpitts oscillators based on a perfect piecewise linear voltage controlled voltage source VCVS - operational amplifier - are investigated. A total of 18 topologies have been investigated. It was found that 7 of these gave rise to steady state oscillations. PSpice models for operational amplifiers uA741 (LF) and TL082 (HF) were used. In six of the topologies the Colpitts resonator was coupled between the two input terminals of the op amp and the reference terminal.

Conclusion

The Colpitts oscillator family is investigated. New oscillator topologies with memory components in both positive and negative feed-back path of a perfect operational amplifier are presented. The complex frequency plane trajectories of the eigenvalues of the linearized Jacobian of the differential equations modeling topologies with only one nonlinearity are studied in order to obtain knowledge about the mechanism behind the oscillations [5]. A real pole is moving in the left half plane and a complex pole pair is moving between the right and the left half plane so that energy balance is obtained.

References

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International Symposium

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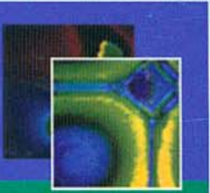

Nizhny Novgorod, Russia
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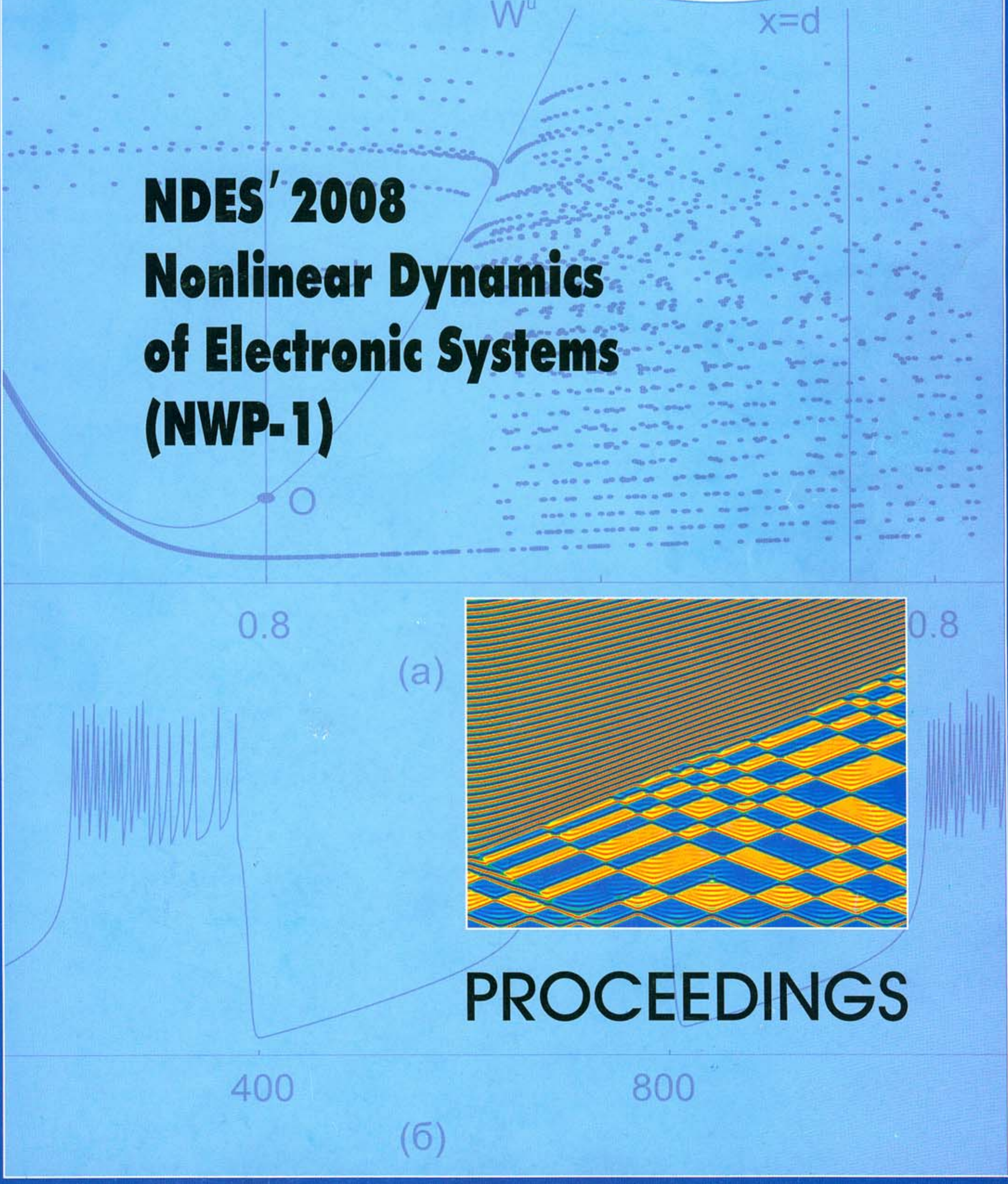

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(NWP-1)

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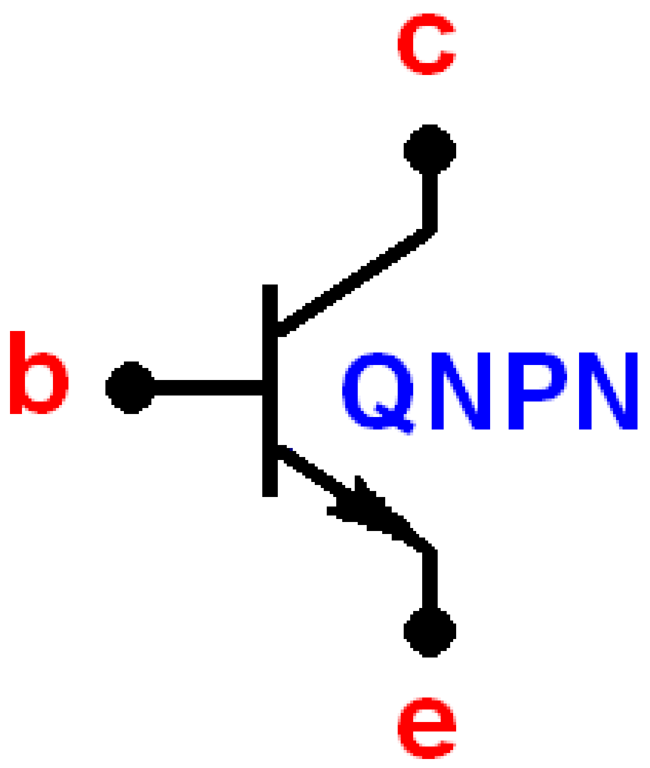
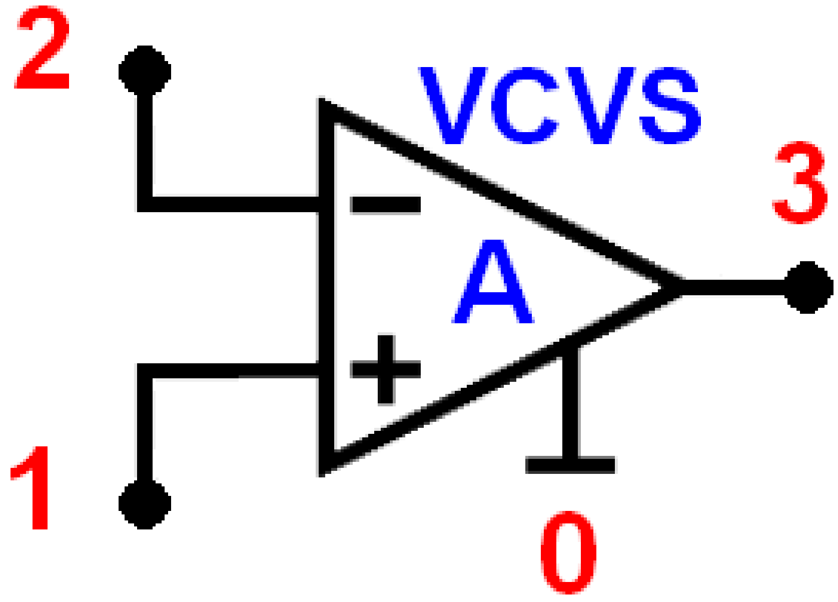
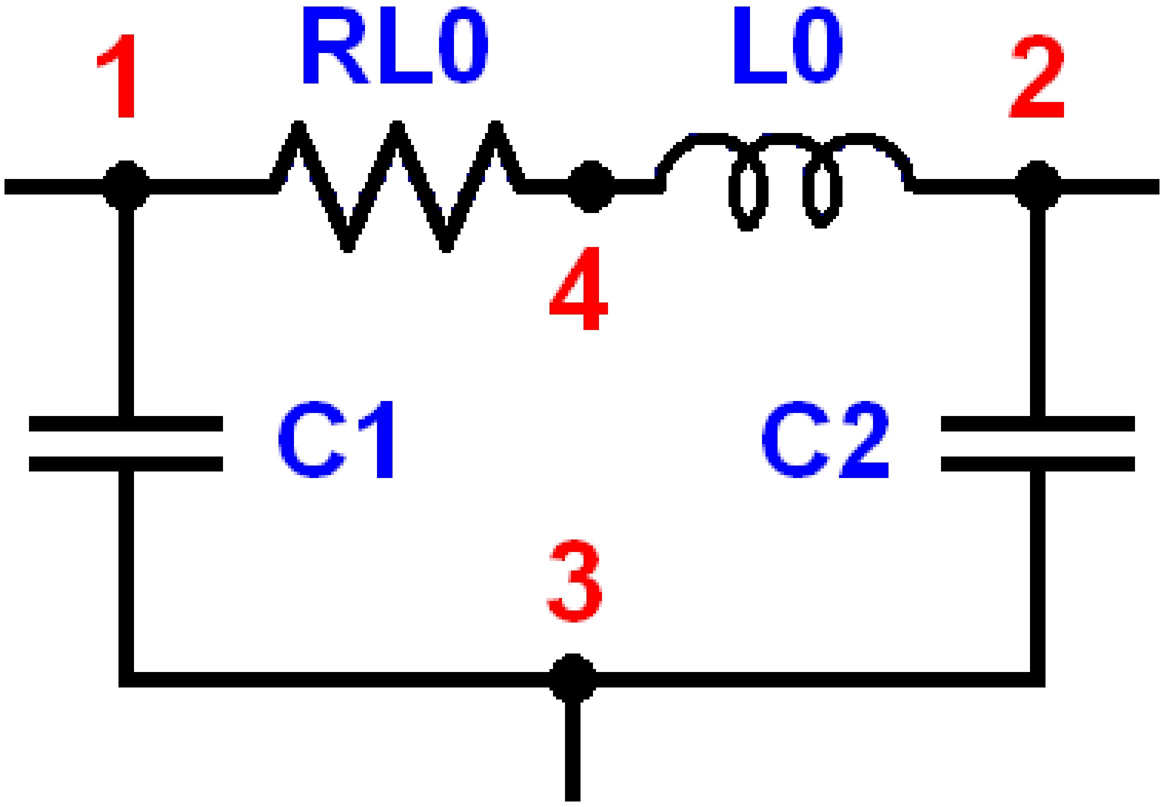
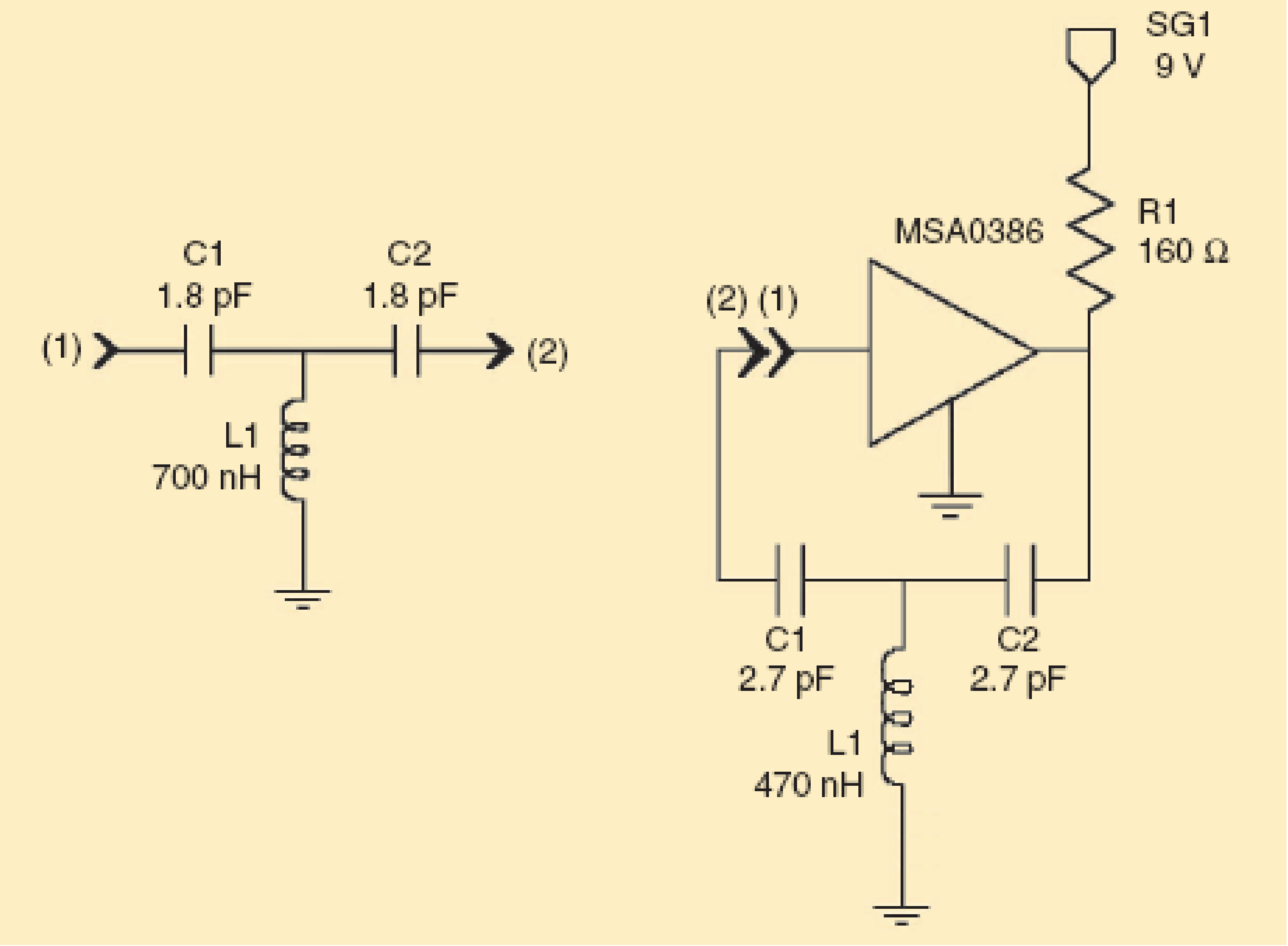






Colpitts Resonator

3'rd order



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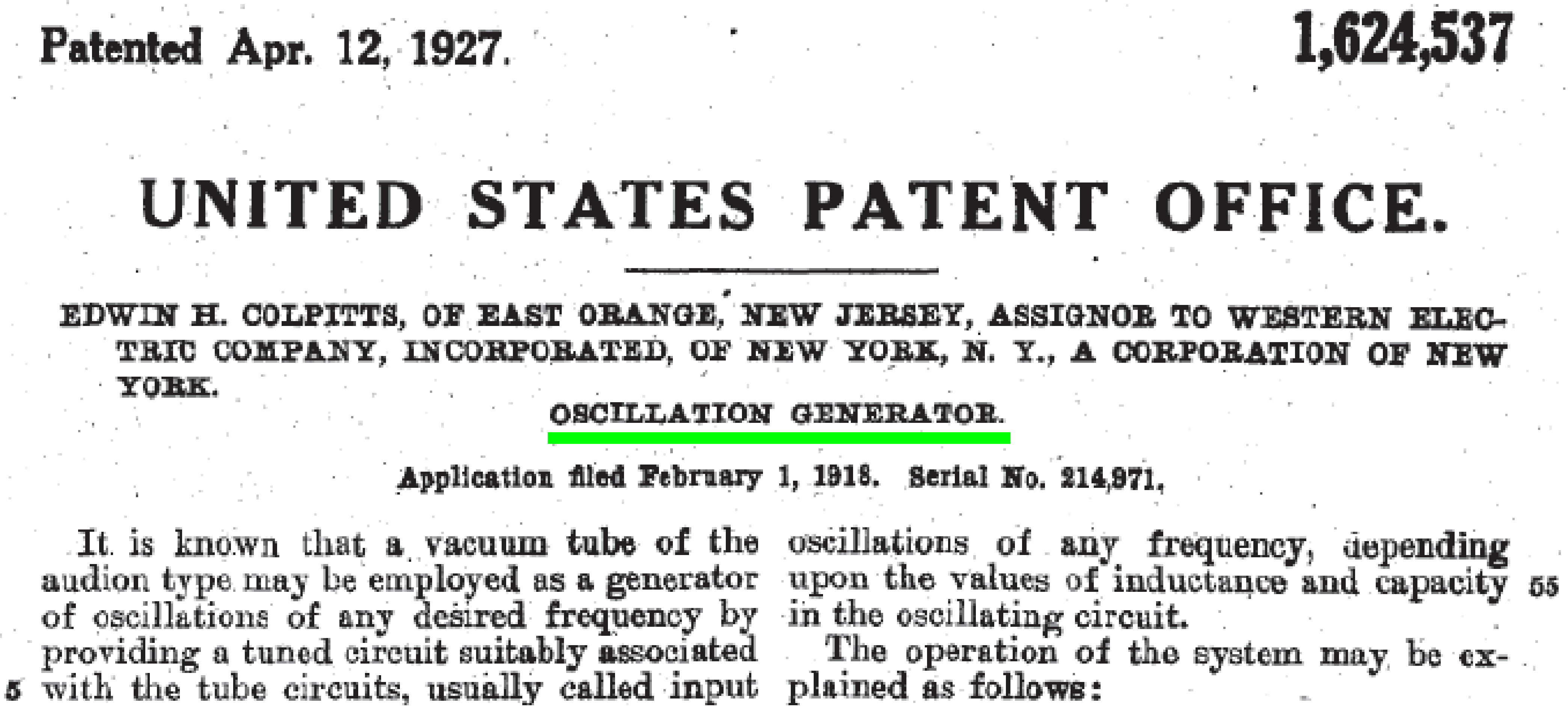
The Colpitts Oscillator Family



Patented Apr. 12, 1927. **1,624,537**

UNITED STATES PATENT OFFICE.

EDWIN H. COLPITTS, OF EAST ORANGE, NEW JERSEY, ASSIGNOR TO WESTERN ELECTRIC COMPANY, INCORPORATED, OF NEW YORK, N. Y., A CORPORATION OF NEW YORK.

OSCILLATION GENERATOR.

Application filed February 1, 1918. Serial No. 214,971.

It is known that a vacuum tube of the audion type may be employed as a generator of oscillations of any desired frequency by providing a tuned circuit suitably associated with the tube circuits, usually called input oscillations of any frequency, depending upon the values of inductance and capacity in the oscillating circuit.

The operation of the system may be explained as follows:

TUBE.

OSCILLATION GENERATOR.

Application filed February 1, 1918. Serial No. 214,971.

It is known that a vacuum tube of the audion type may be employed as a generator of oscillations of any desired frequency by providing a tuned circuit suitably associated with the tube circuits, usually called input and output circuits. In previous generators the coupling between the input and output circuits has been electro-magnetic. In accordance with this invention, the couplings between the input circuit and the oscillation circuit and between the output circuit and the oscillation circuit are made electrostatic. Some of the advantages of this arrangement are herein enumerated. One advantage of this form of generator is that the generation of oscillations of a frequency not determined by the period of the tuned circuit is prevented. Another advantage is that it enables the generator to be connected to an antenna in a transmitting system without causing any part of the generator to be short-circuited. This and other novel advantages will be most readily understood by reference to the following detailed description taken in connection with the accompanying drawings, in which Fig. 1 represents one form of the generator of this invention; Fig. 2 is a modification of Fig. 1; and Fig. 3 illustrates how the generator may be associated with a transmitting antenna.

Referring to Fig. 1, 6 is an evacuated vessel of the audion type containing a filament 7, an anode 8, and a grid or im-

oscillations of any frequency, depending upon the values of inductance and capacity in the oscillating circuit.

The operation of the system may be explained as follows:

Assume that a slight disturbance is impressed upon the grid 9. Corresponding changes but of greater amplitude will then occur in the output circuit current from the source of voltage 11. Due to the mutual capacity reactance 13 between the output circuit and the oscillating circuit, these current changes in the output circuit will set up oscillations in the oscillating circuit of a period determined by the amount of inductance and capacity in the circuit. The current in the oscillating circuit will create an alternating current voltage drop across the terminals of the condenser 16, and since this condenser is common to both the input circuit and the oscillating circuit, the alternating voltage will be impressed between the grid 9 and the filament 7. This voltage will then cause corresponding current variations in the output circuit as explained above, so that the cycle of operations will be repeated and the tube will be caused to generate oscillations of constant amplitude and of a frequency determined by the tuning of the oscillating circuit. These oscillations may be impressed in any suitable manner, as by a transformer 22, upon a work circuit 23, whereby the oscillations may be em-

The Colpitts Oscillator Family

The drawings of Colpitts's

US patent (filed 1918, issued 1927),

1,624,537

and his

Canadian patent (filed 1919, issued 1920)

203986

are identical

April 12, 1927.

E. H. COLPITTS

OSCILLATION GENERATOR

Filed Feb. 1, 1918

1,624,537 **us**

203986 **ca**

Fig. 1.

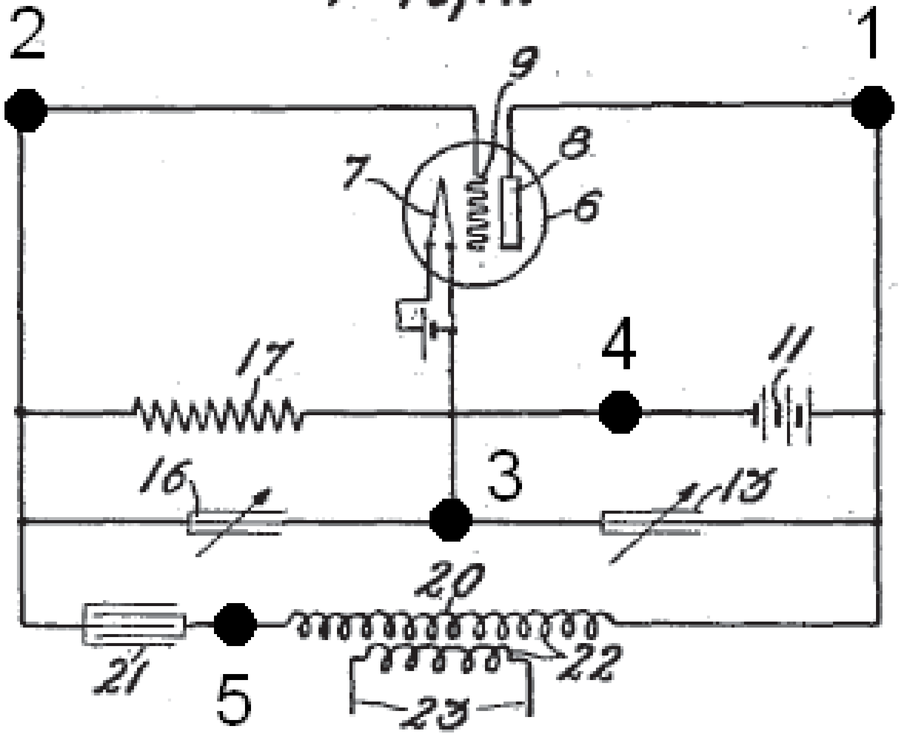
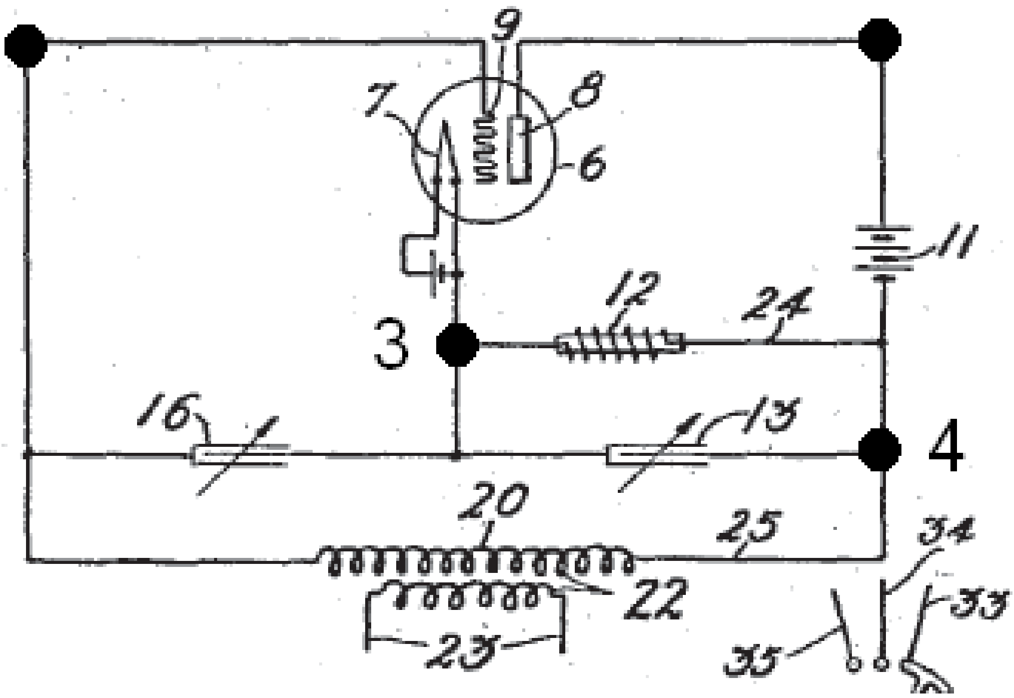
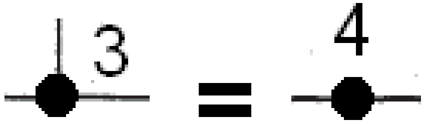


Fig. 2.





Oscillation Generator

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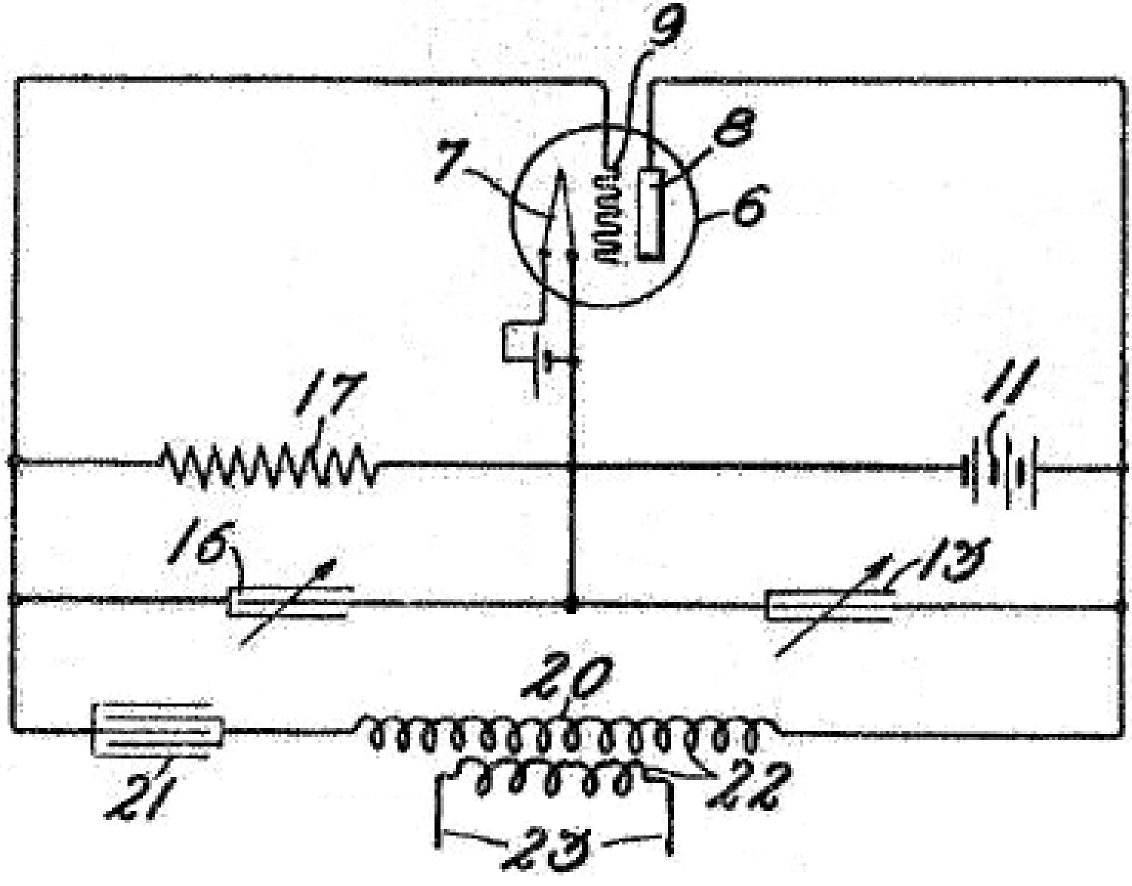
Fig. 1.



Colpitts's Canadian Patent filed 1919 issued 1920

The Colpitts Oscillator Family

Colpitt's oscillator topology
based on two capacitors and one coil
is the electrical dual of
Hartley's oscillator topology
based on two coils and one capacitor.

Hartley's patent was
filed 1915 and issued 1920.

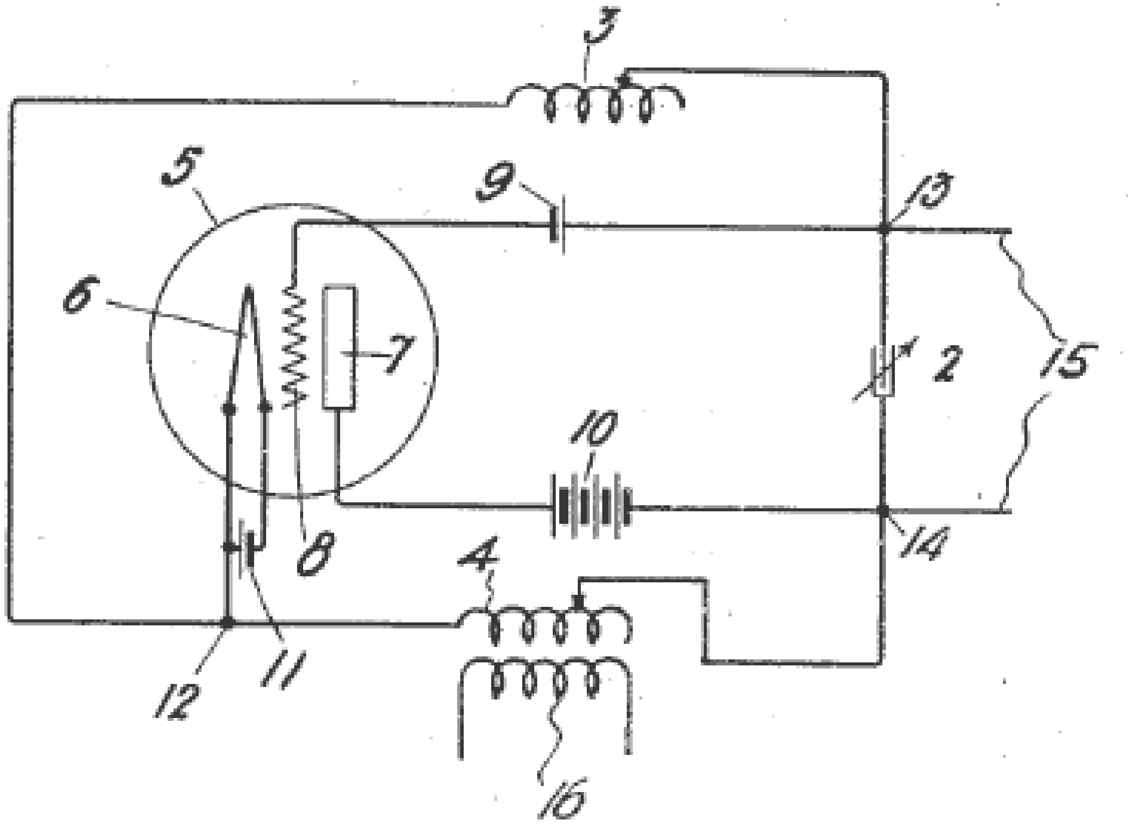
The Colpitts Oscillator Family

R. V. L. HARTLEY.

OSCILLATION GENERATOR.

APPLICATION FILED JUNE 1, 1915.

1,356,763. Patented Oct. 26, 1920.



The Colpitts Oscillator Family

It is interesting to observe that the
topology with
"a stopping condenser of large capacity (21)"
in series with the coil (20)
"to prevent the flow of direct current"
- now known as the
Clapp oscillator
- is included.

April 12, 1927.

1,624,537 **us**

203986 **ca**

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Filed Feb. 1, 1918

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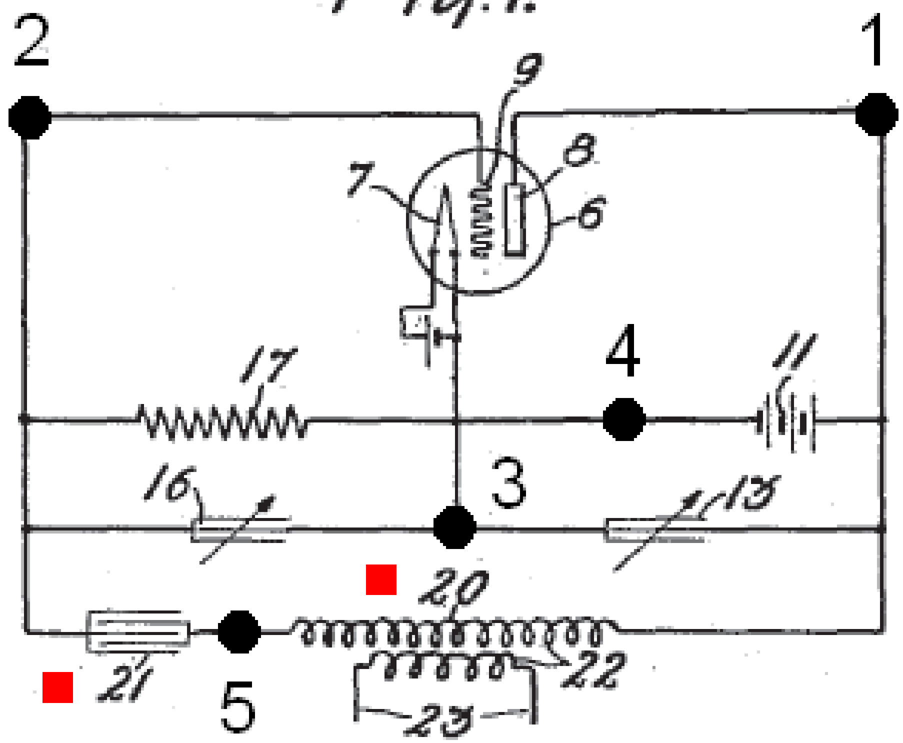

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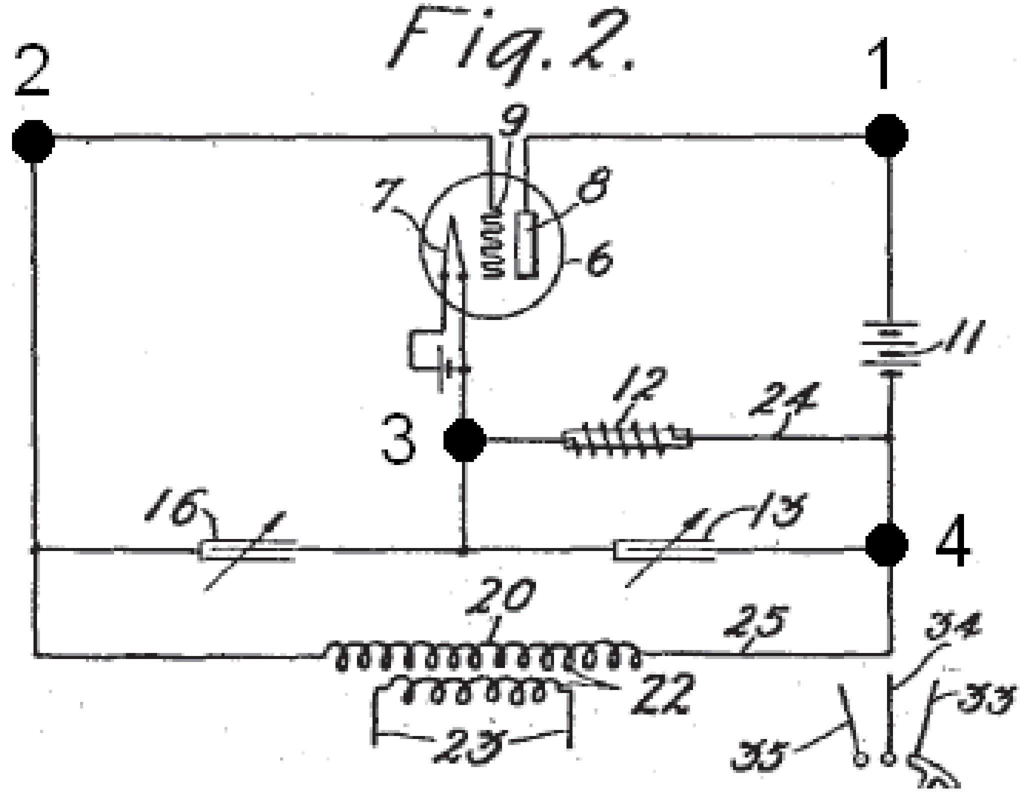
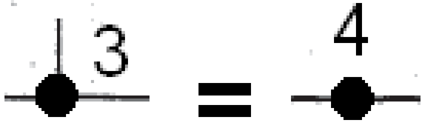
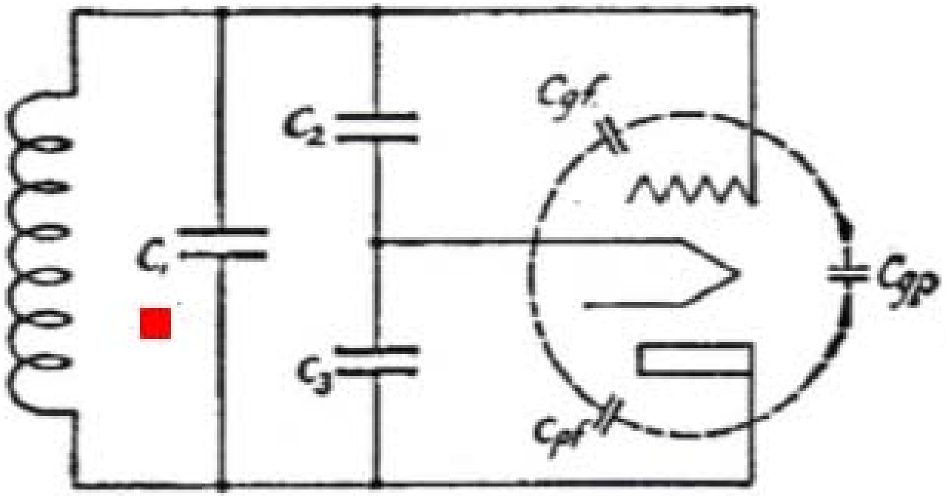


Clapp !





g	grid
f	filament = cathode
p	plate = anode

FIG. 1. THE ADVANTAGES OF A COLPITTS CIRCUIT EXPLAINED

Each tube capacity is shunted by a condenser which must be large for best results. In the set here described C2 and C3 each have a fixed capacity of 400 μμfd and C1 has a maximum capacity of 250 μμfd. Thus the capacity across the coil may be as large as 650 μμfd. It is never made less than 420 μμfd. This should be compared with ordinary amateur practice.

Dudley, Beverly, "A low-power master-oscillator transmitter",
Q.S.T. American Radio Relay League,
Vol.12 Issue.2, pp 10-14, 1928

Frozen Eigenvalues Approach

the circuit is linearized at a certain moment and the placements in the complex frequency plane of the eigenvalues of the Jacobian are found

pole trajectories in LHP and RHP

Colpitts 3'rd order i.e.

3 real poles or

1 real pole and 1 complex pole pair

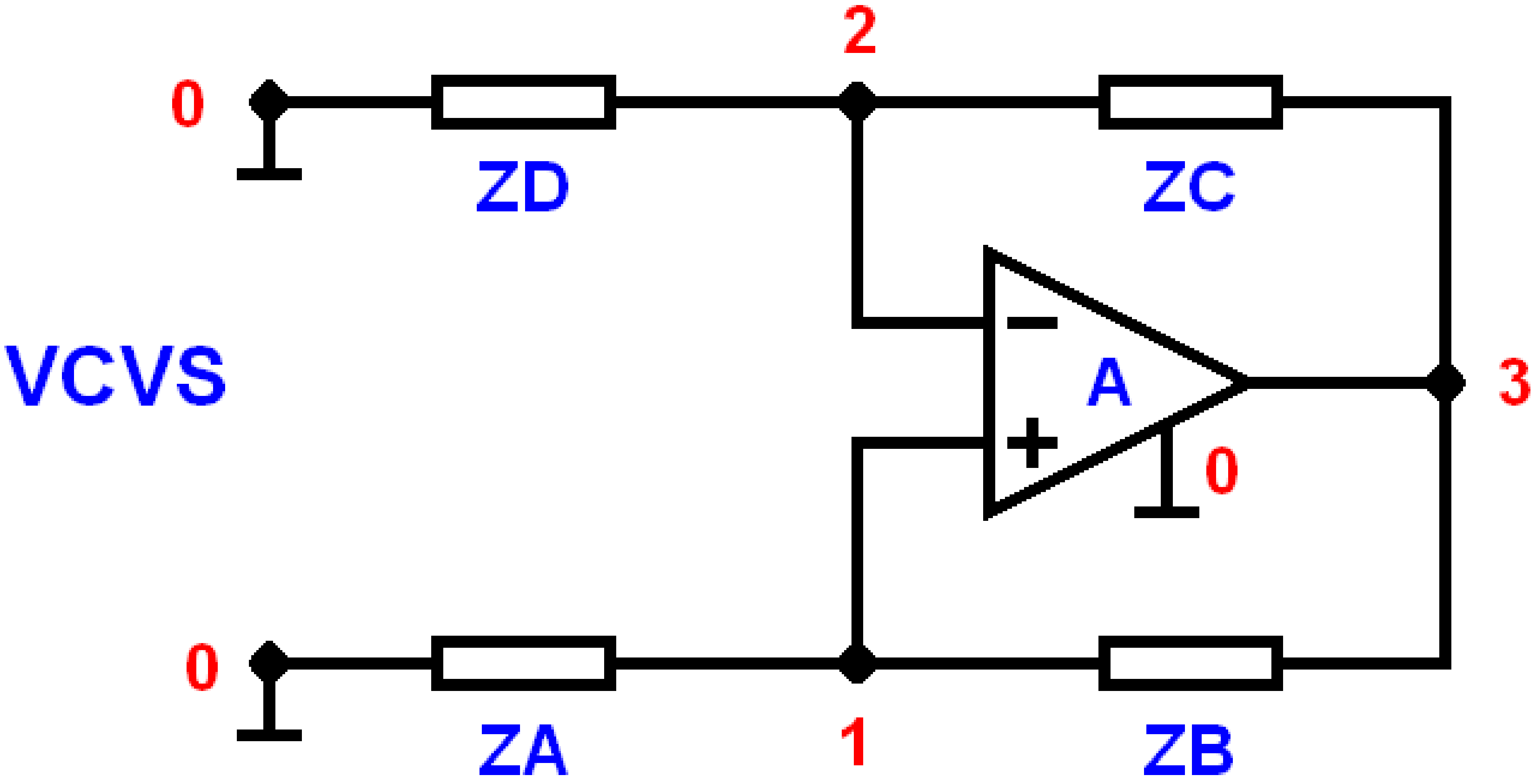
There are four types of
amplifiers or controlled sources

VCVS	VCCS	CCVS	CCCS
"mu"	"gm"	"rm"	"beta"

Stable time invariant dc bias point
signal reference

Small signals: linear transfer

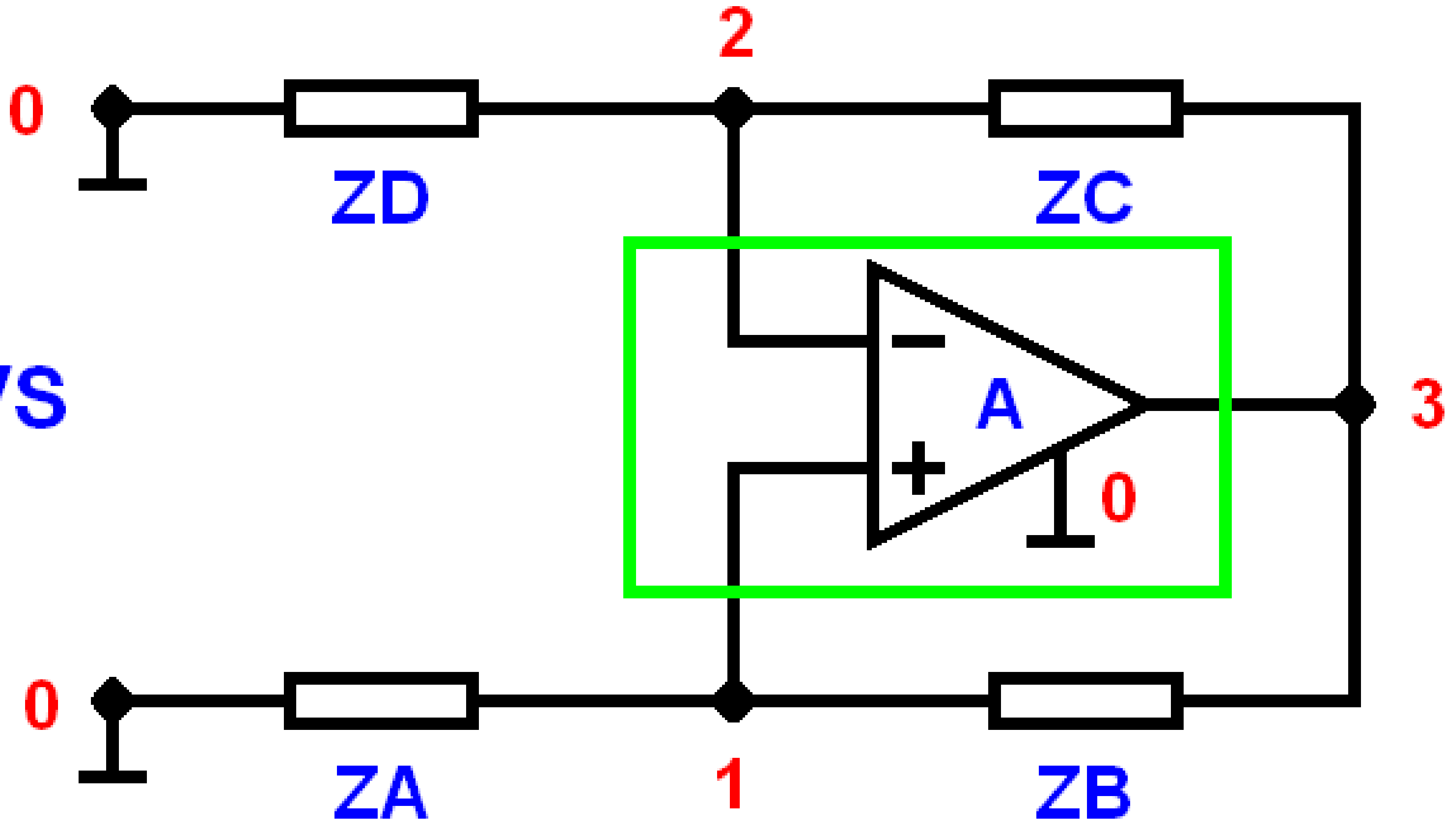
Large signals: nonlinear transfer
distortion



Amplifier with

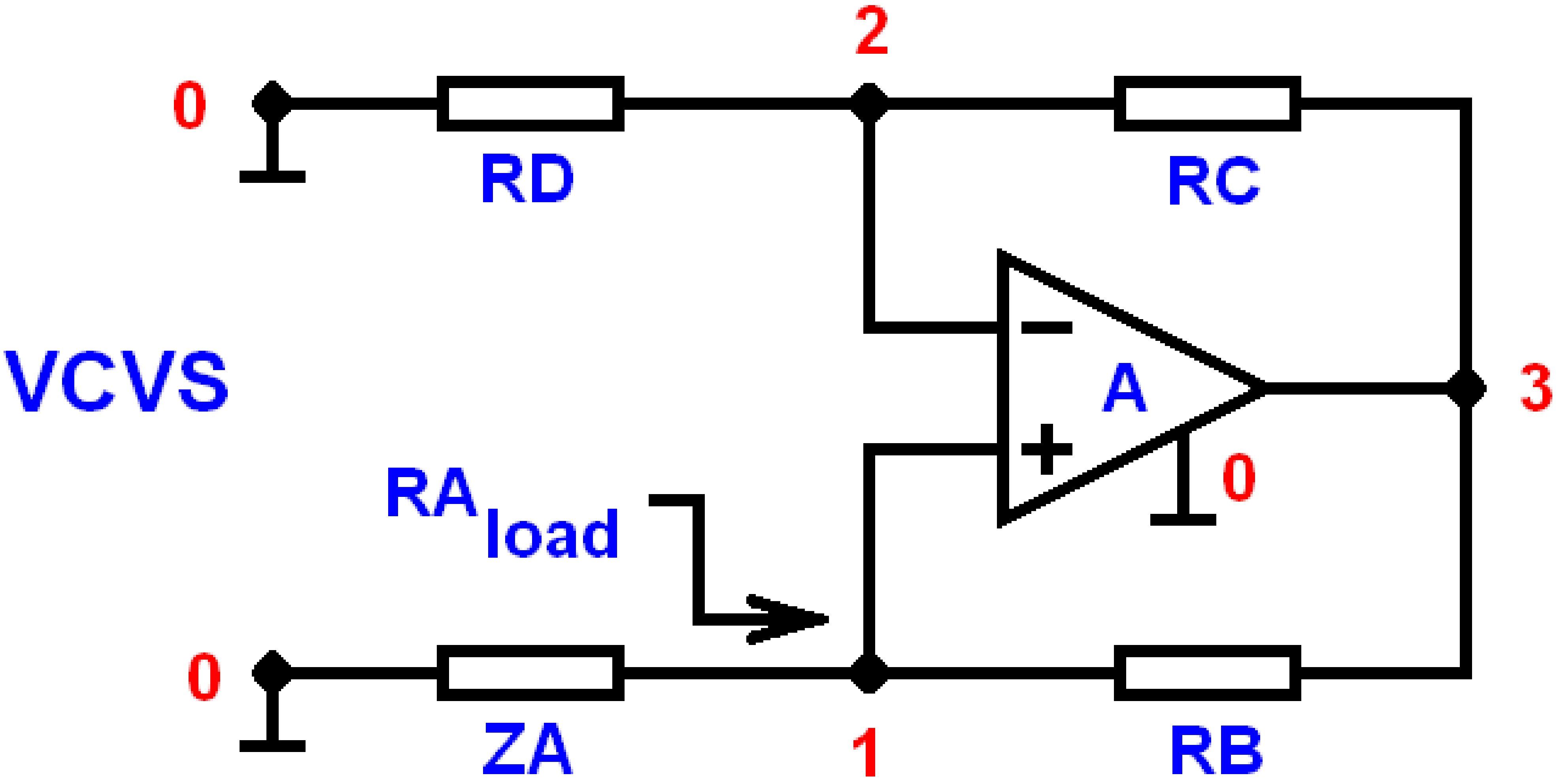
positive and negative feed-back

VCVS



Perfect amplifier:

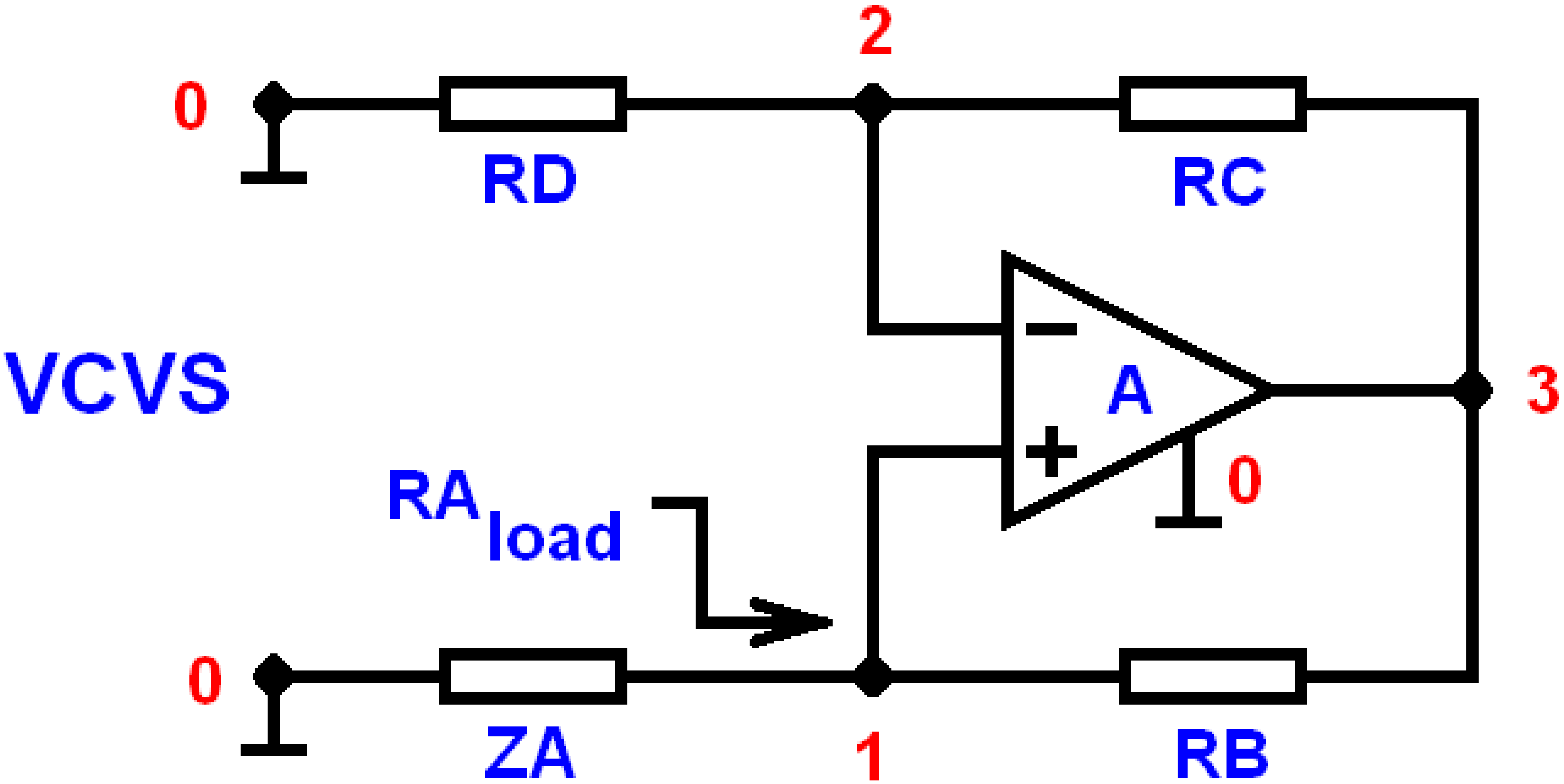
$Z_{in} = \infty$ $Z_{out} = 0$ $V_3 = A * (V_1 - V_2)$



$$A = \infty \qquad RA_{load} = -\frac{RB * RD}{RC}$$

$$A = 0 \qquad RA_{load} = +\ RB$$

Negative Resistance



$$RA_{load} = 0 \quad \text{for} \quad A = -\left(1 + \frac{RC}{RD}\right)$$

$$RA_{load} = \infty \quad \text{for} \quad A = +\left(1 + \frac{RD}{RC}\right)$$

Oscillators are nonlinear circuits.

The Barkhausen criteria will only give you a starting point as a "linear oscillator" with a complex pole pair on the imaginary axis

not sufficient for steady state oscillations

In most cases you are lucky and your circuit will oscillate for some reason

Oscillators are nonlinear circuits.

The Barkhausen Stability Criterion is simple, intuitive, and wrong ;-).

http://web.mit.edu/klund/www/weblatex/node4.html#SECTION00041000000000000000

Kent H Lundberg

2002-11-14

Barkhausen criteria

Vimal Singh,
"A note on determination of oscillation startup condition",
Analog Integr. Circ. Sig. Process (Springer 2006),
vol.48, pp.251–255

Abstract: There prevails a widespread notion that, given a closed-loop system, oscillation will commence and build up therein if the magnitude of loop gain is greater than unity at the frequency at which the angle of loop gain is zero degree. Three novel examples in which this notion fails are presented.

Barkhausen criteria

Vimal Singh,
"Failure of Barkhausen oscillation building up criterion: Further evidence",
Analog Integr. Circ. Sig. Process (Springer 2007),
vol.50, pp.127–132

Abstract: It has been suggested in many textbooks that, given a closed-loop system, oscillation will commence and build up therein if the magnitude of loop gain is greater than unity at the frequency at which the angle of loop gain is zero degree. A novel ideal op-amp based counterexample to this suggestion is presented. The Letter serves to substantiate the findings in a recent Letter. A discussion relating to the finite gain of op-amp is included.

Oscillators are nonlinear circuits.

relaxation versus sinusoidal ;-(

A certain topology may act as a

relaxation oscillator

at low/high frequencies

and as a

sinusoidal oscillator

at high/low frequencies

Oscillators are nonlinear circuits.

Three basic types of oscillators

1 Unstable initial dc bias point

Eigenvalues of the linearized Jacobian
moving between RHP and LHP

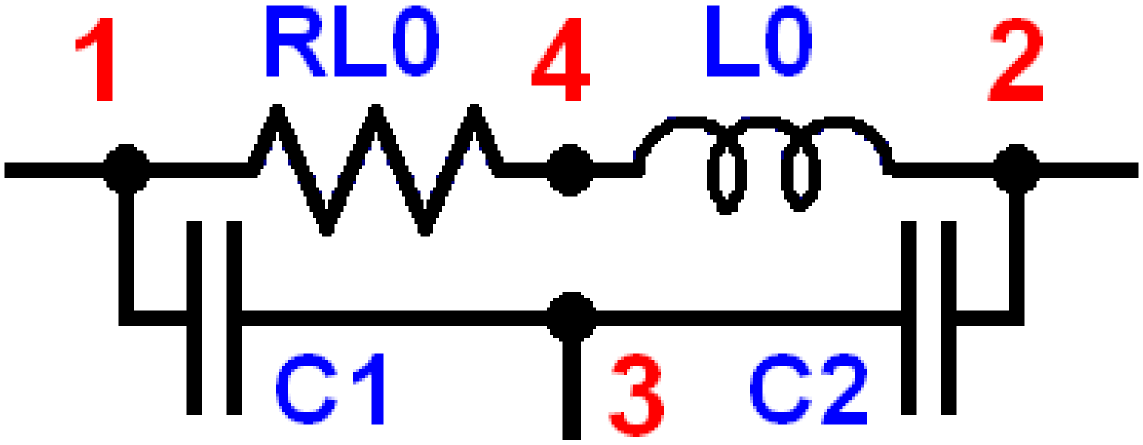
2 Stable initial dc bias point

Needs some extra initial energy
The poles are in LHP all the time ???
Special impulse mechanism is needed

3 Combination of 1 and 2

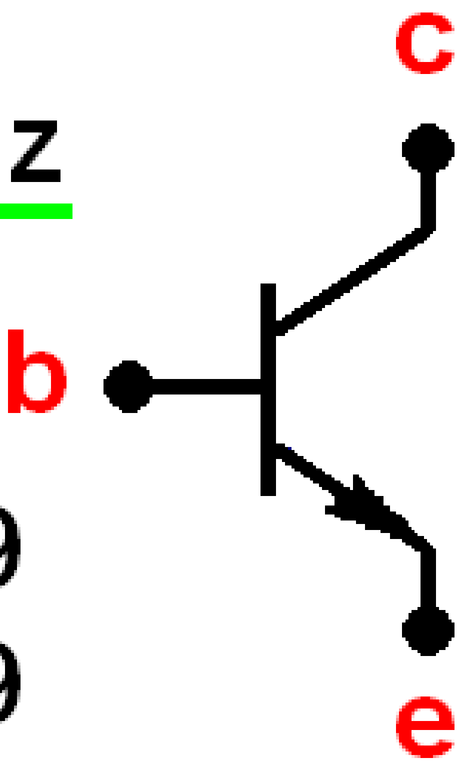
Poles are moving around in LHP only

COLPITTS RESONATOR

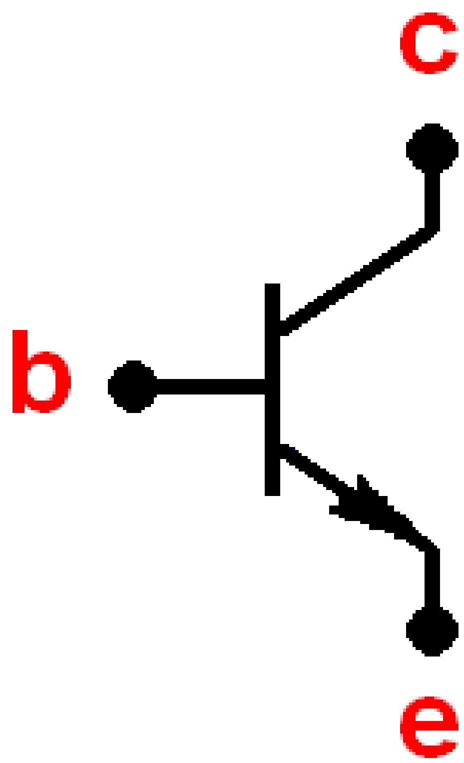


```
.subckt  colpitts  1  2  3
* colpitts resonator
  RL0    1  4         50
  L0       4  2        1e-3
  C1       1  3      4.8127562223e-09
  C2       2  3      5.347506914e-09
.ends
```

100kHz



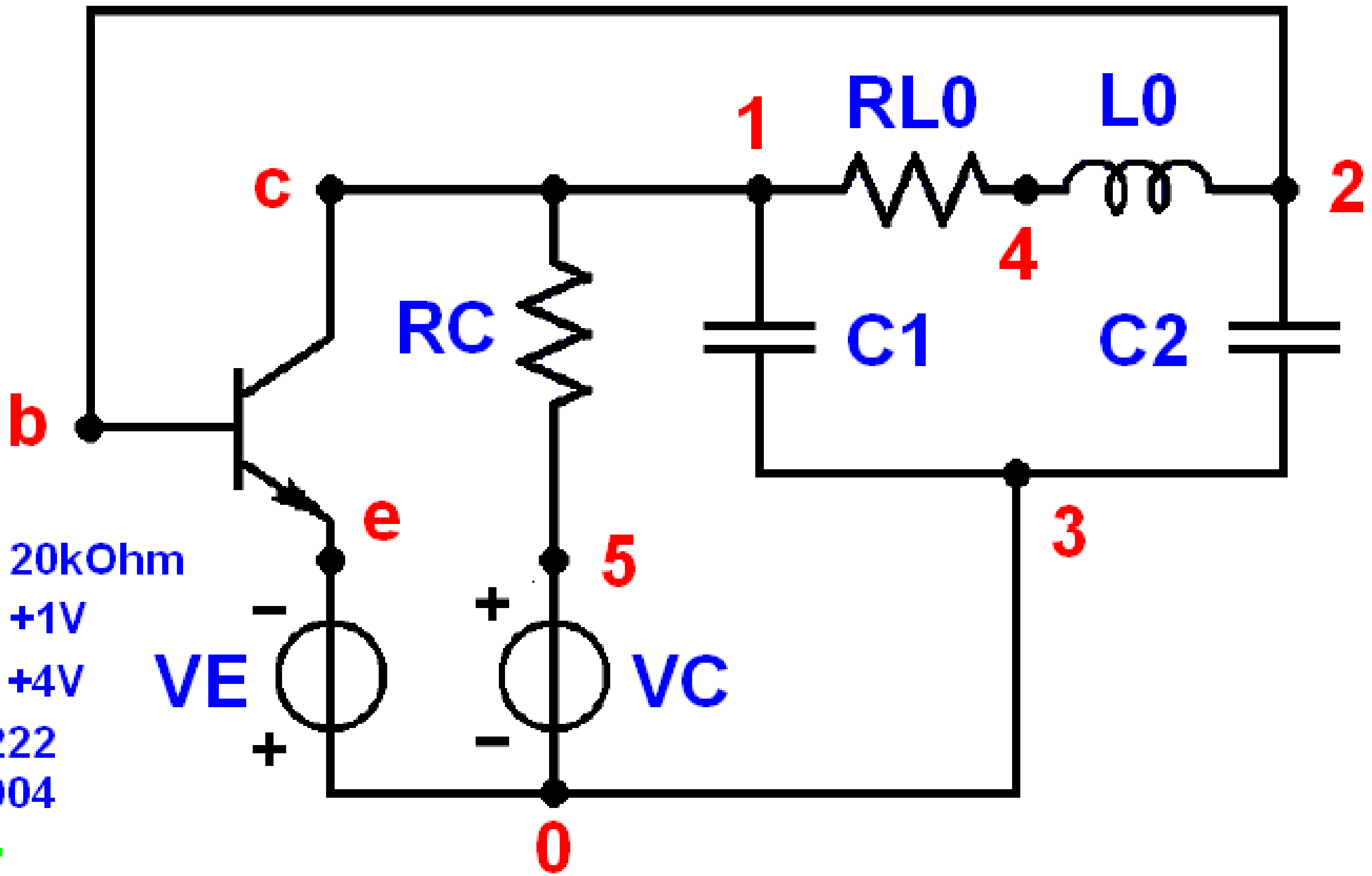
Case:	CE			CB			CC		
QNPN	e	c	b	b	e	c	c	b	e
	1	2	3	1	2	3	1	2	3
	2	3	1	2	3	1	2	3	1
	3	1	2	3	1	2	3	1	2
	1	3	2	1	3	2	1	3	2
	3	2	1	3	2	1	3	2	1
	2	1	3	2	1	3	2	1	3



CCCS

18 patterns

6 ss osc



RC = 20kOhm

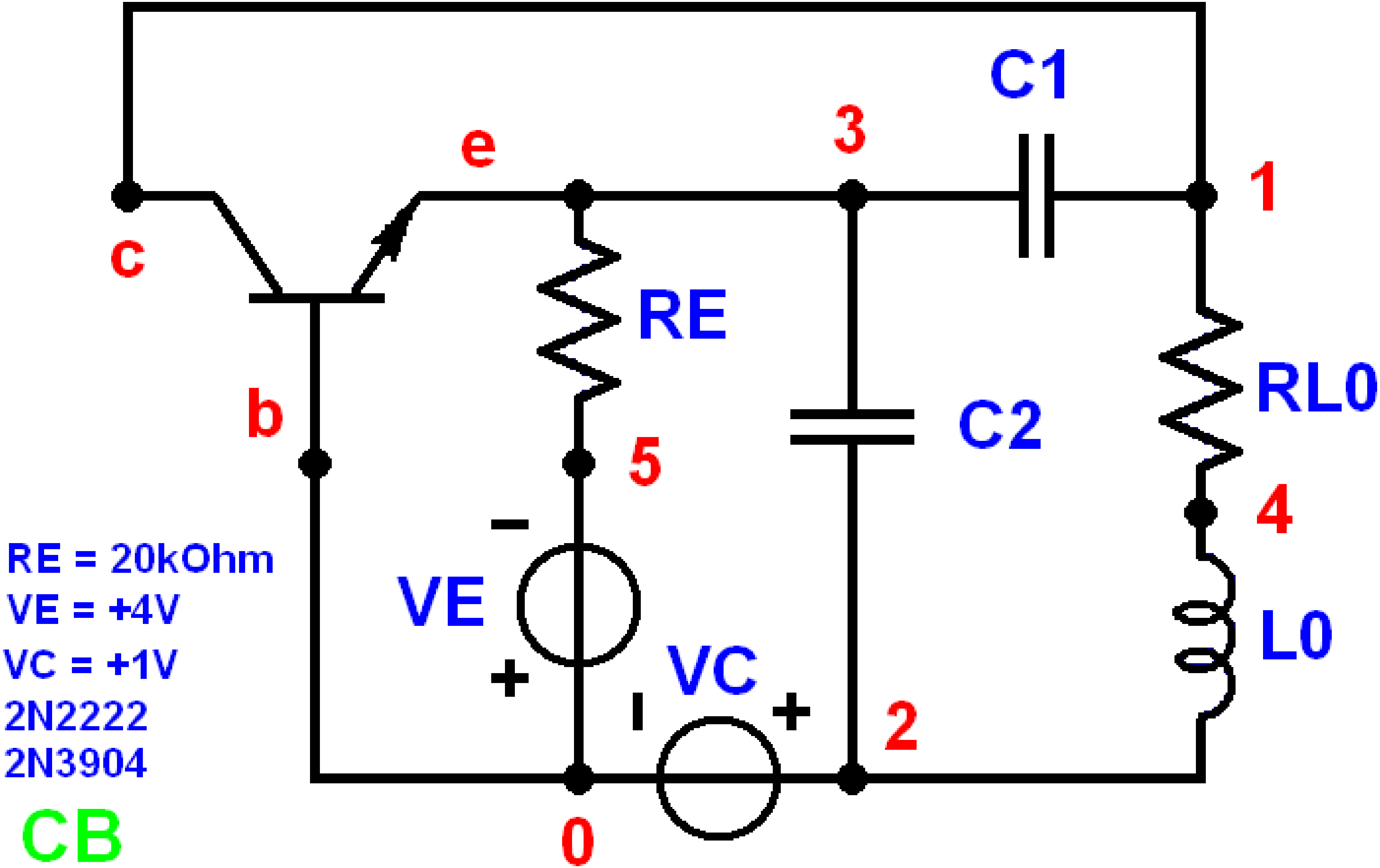
VE = +1V

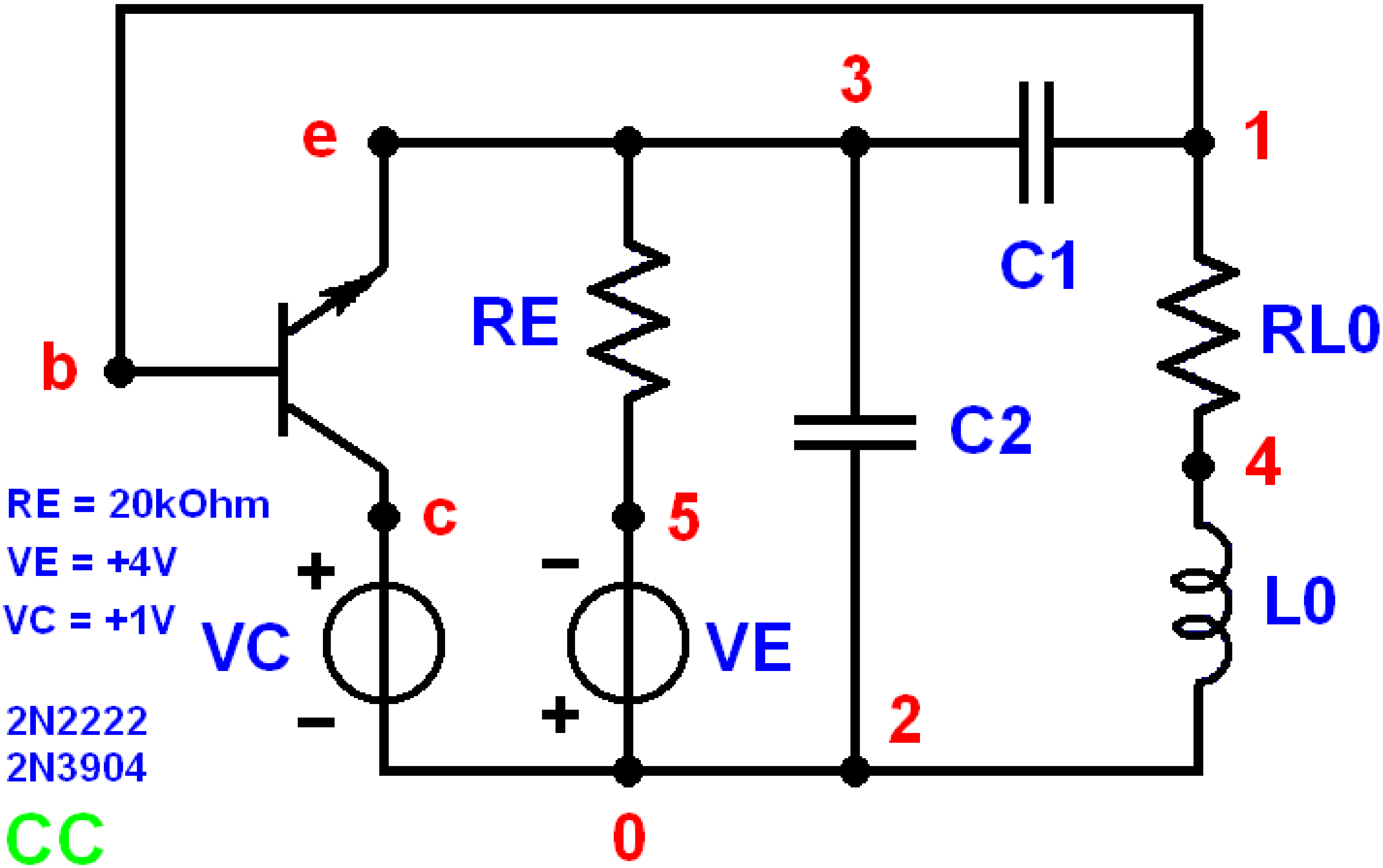
VC = +4V

2N2222

2N3904

CE


C1
e
3
1
c
RE
RL0
b
C2
5
4
RE = 20kOhm
VE = +4V
VC = +1V
2N2222
2N3904
VE
L0
VC
2
CB
0

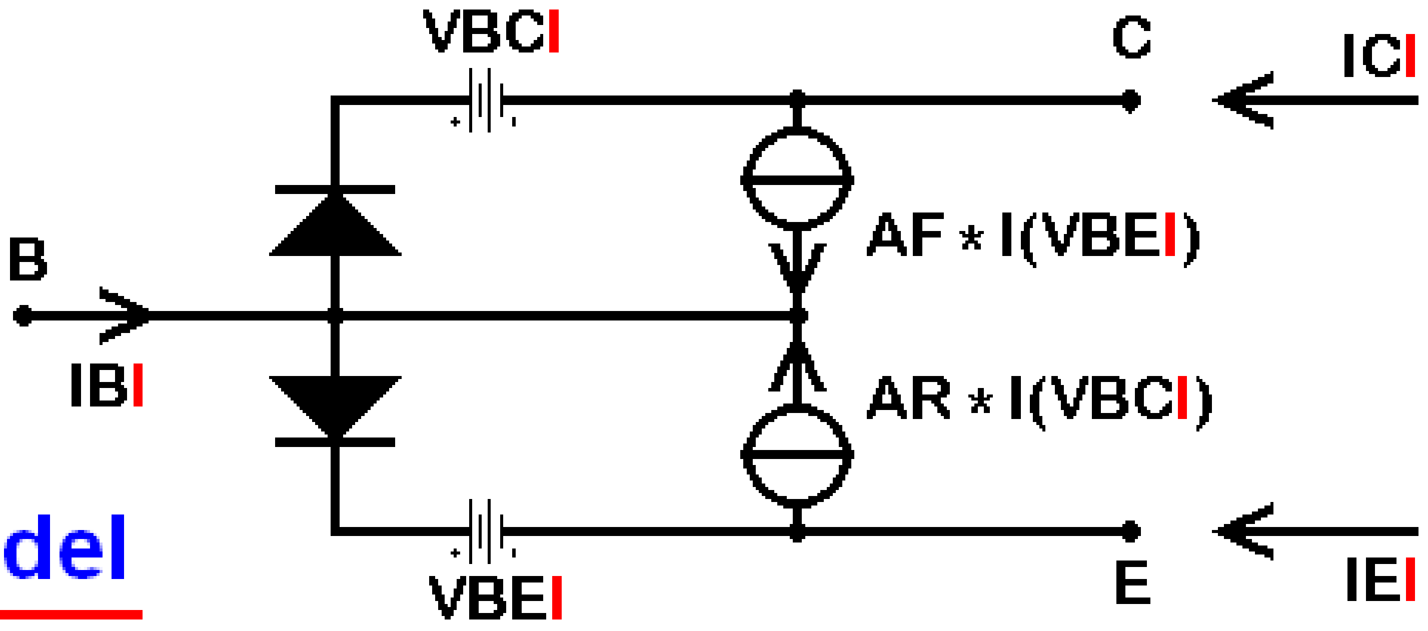


RE = 20kOhm
VE = +4V
VC = +1V

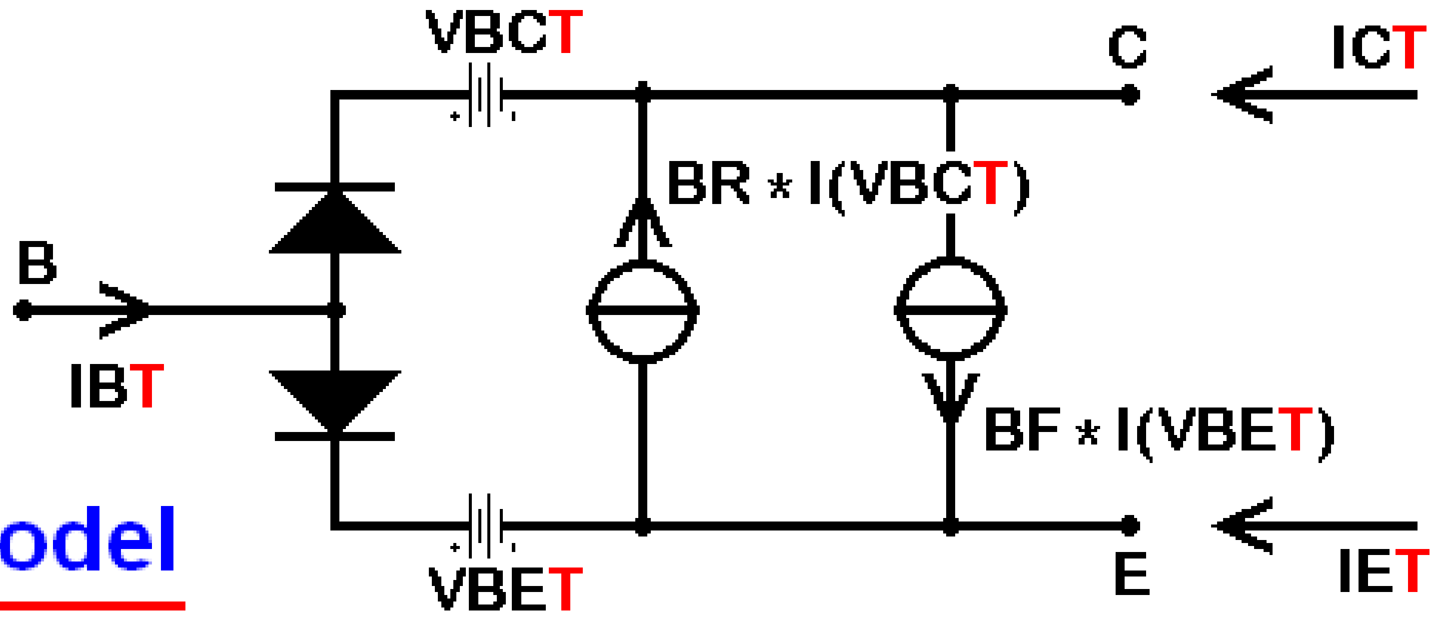
2N2222
2N3904

CC

Ebers-Moll Injection Model



Ebers-Moll Transport Model



Ebers-Moll Injection Model

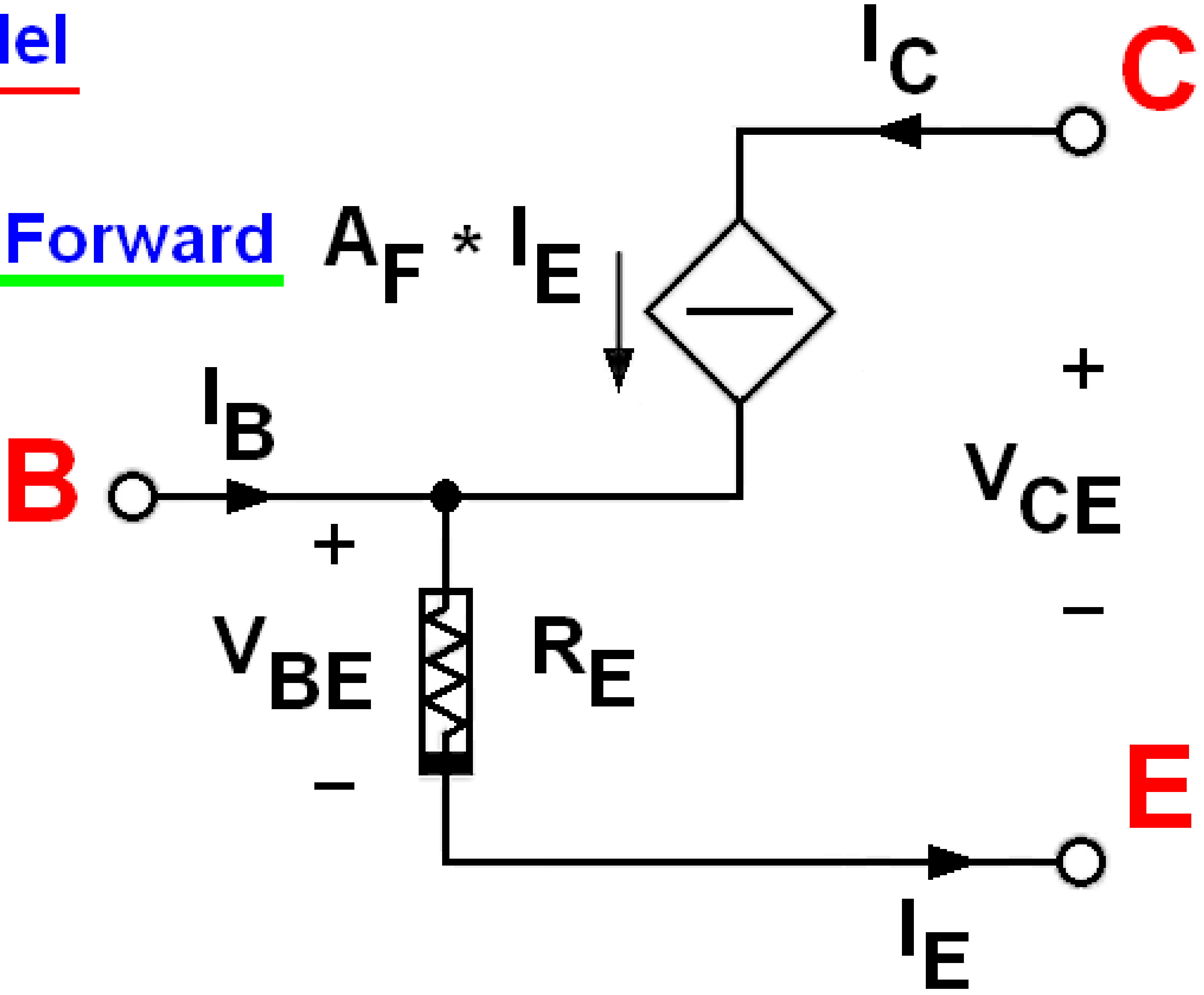
AF = 0.9976

BF = 415.67

$$A_F = \frac{B_F}{B_F + 1}$$

$$B_F = \frac{A_F}{1 - A_F}$$

Forward



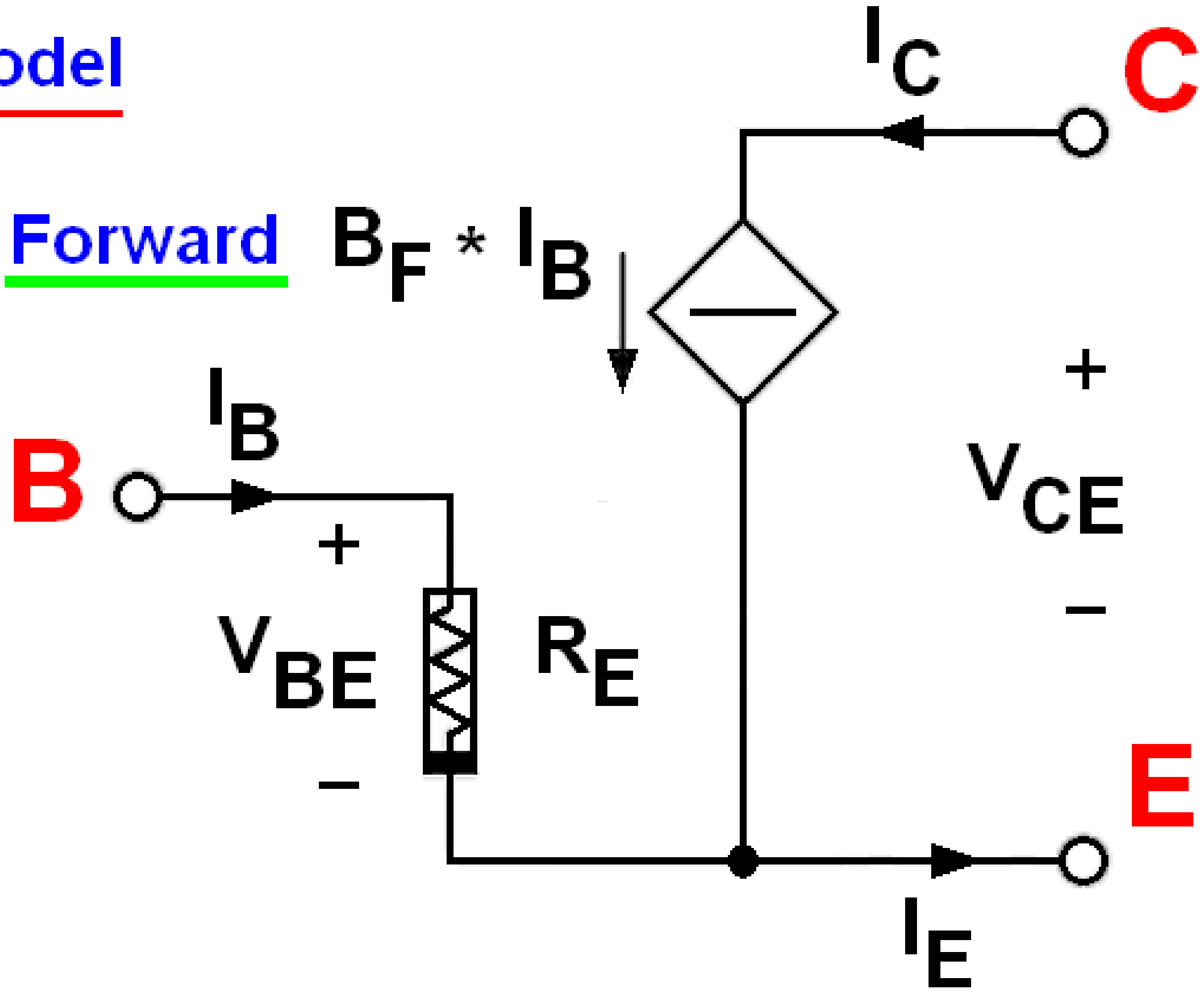
Ebers-Moll Transport Model

BF = 415.67

AF = 0.9976

$$B_F = \frac{A_F}{1 - A_F}$$

$$A_F = \frac{B_F}{B_F + 1}$$



Frozen eigenvalue approach

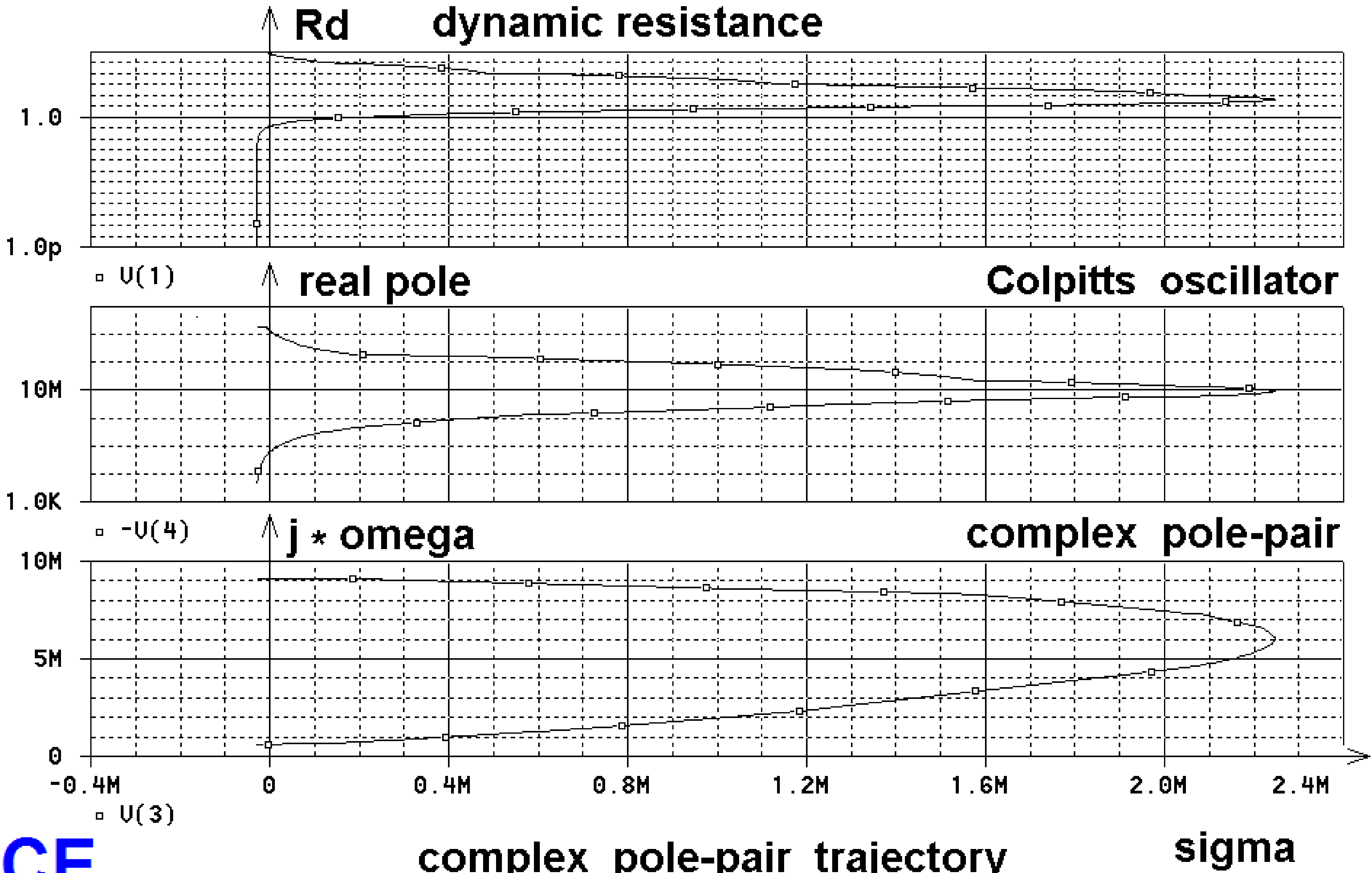
Eigenvalues of linearized Jacobian of differential equations

Only one non-linearity: Base-Emitter Diode

Dynamic resistance Rd

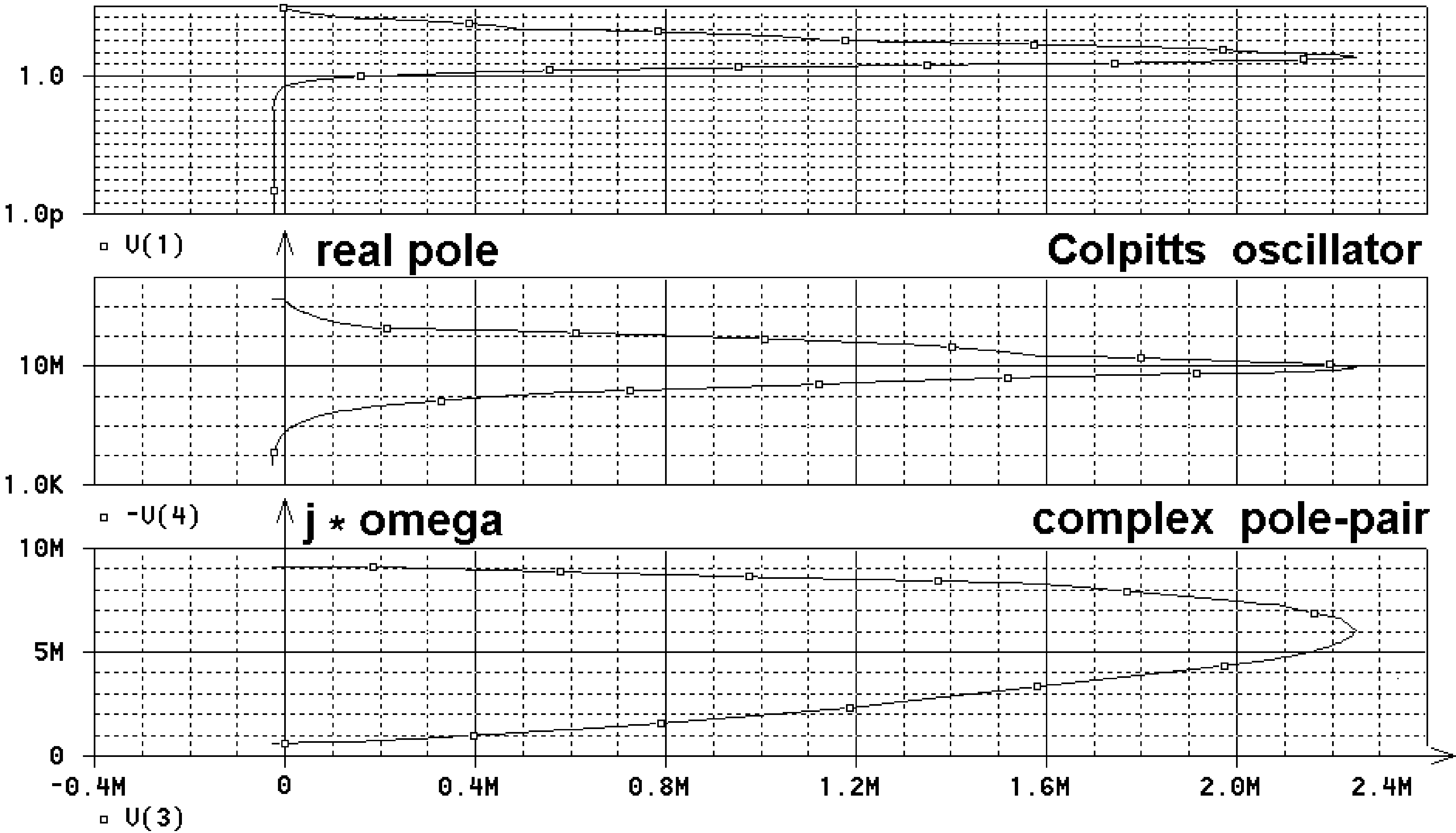
ANP3

Trajectories of poles in the complex frequency plane



CE

complex pole-pair trajectory



Colpitts oscillator

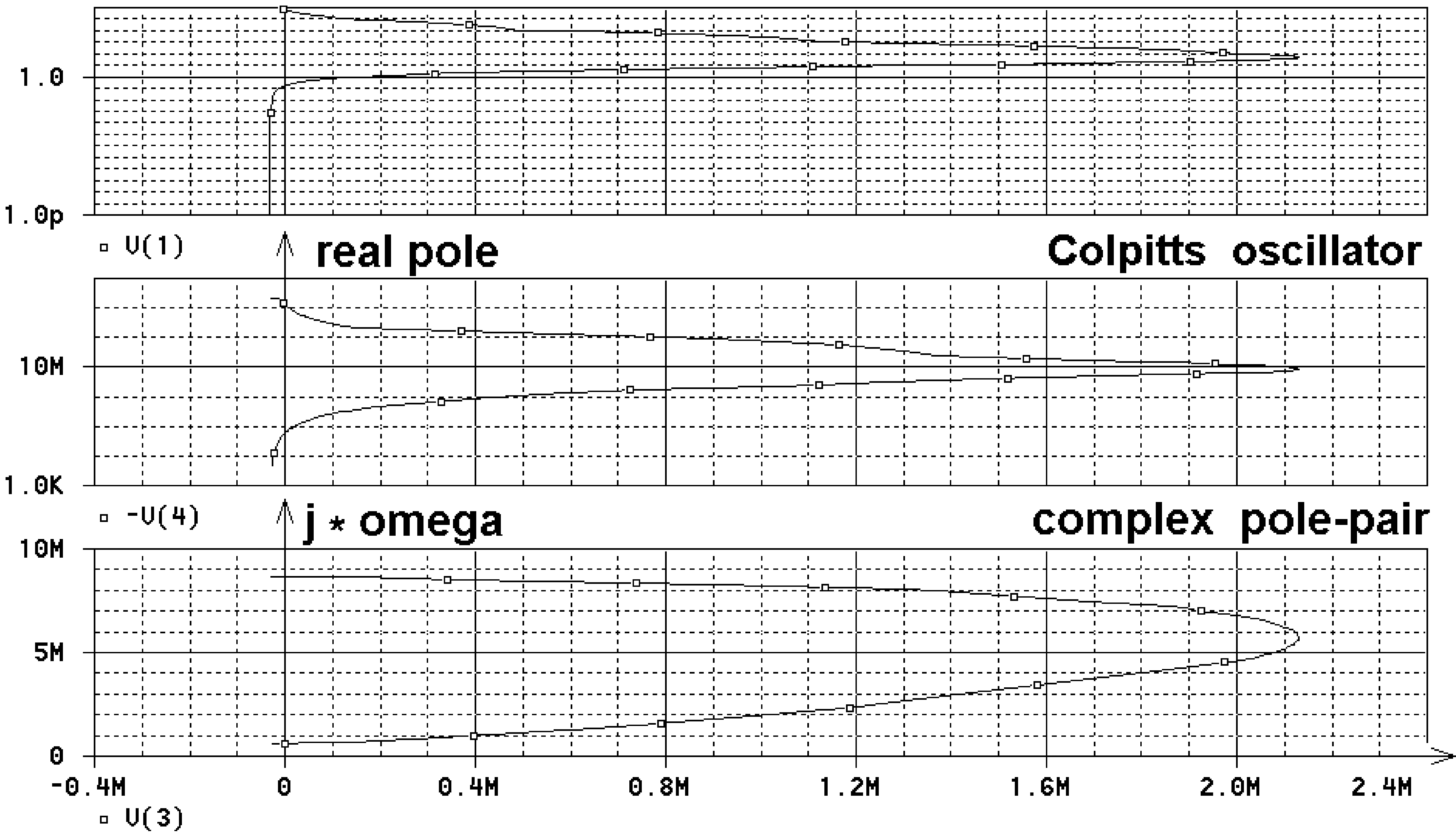
complex pole-pair

CB

complex pole-pair trajectory

sigma

Colpitts oscillator



real pole

complex pole-pair

j * omega

sigma

CC

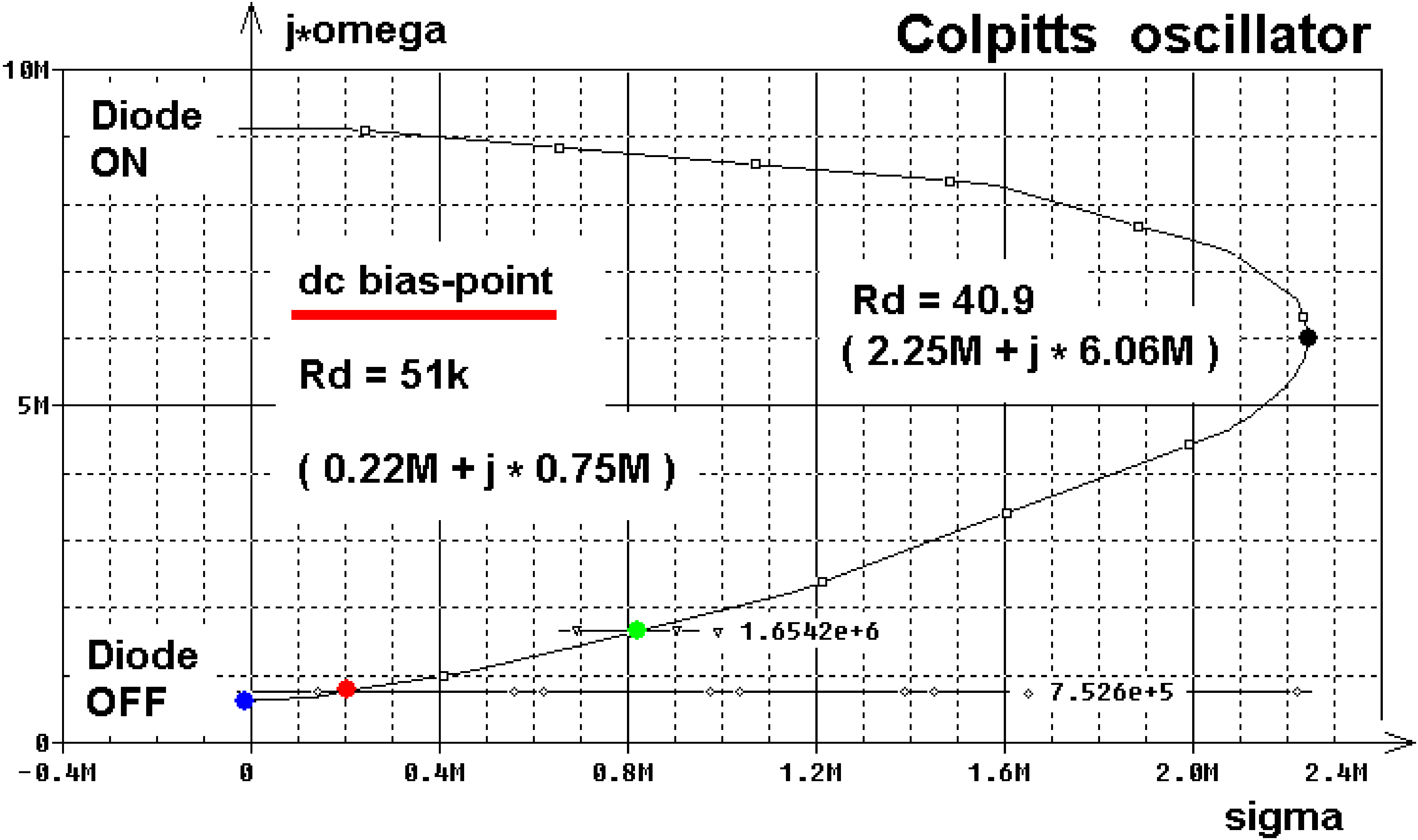
complex pole-pair trajectory

CE Colpitts Oscillator

	Rd	sigma	j*omega	real-p
OFF	1e+12	−0.03M	0.63M	−4.92k
dc bias	51k	+0.22M	0.75M	−0.50M
ON	2.5k	+0.84M	1.65M	−1.81M

Frozen eigenvalues as function of dynamic resistance Rd of base-emitter diode

Colpitts oscillator



Diode ON

dc bias-point

Rd = 51k

(0.22M + j * 0.75M)

Rd = 40.9

(2.25M + j * 6.06M)

Diode OFF

CE

complex pole-pair trajectory

NDES'97: Non-linear Dynamics Applications

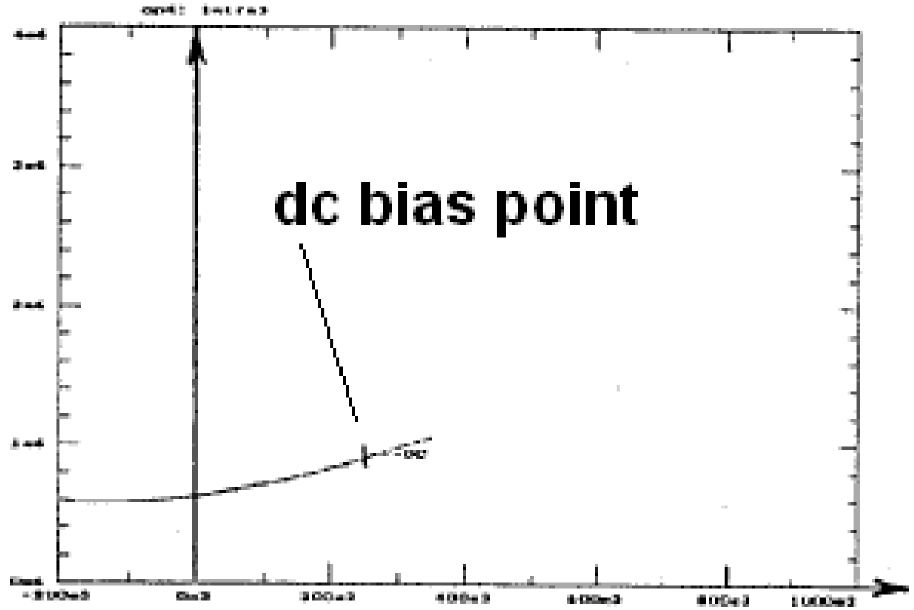


Figure 7: x-axis: real part, y-axis: positive imaginary part of complex pole pair.
First order limit cycle case.

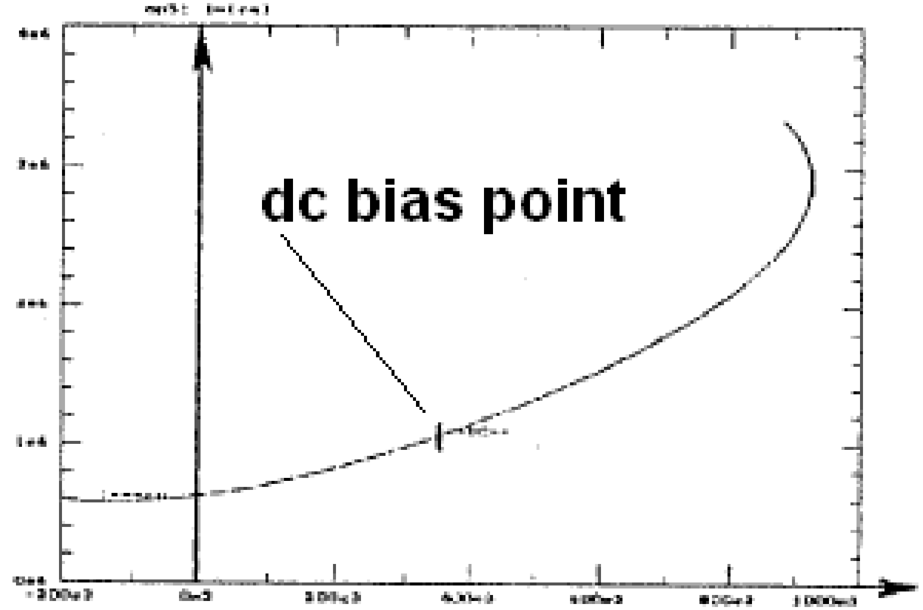


Figure 8: x-axis: real part, y-axis: positive imaginary part of complex pole pair.
Chaotic "limit cycle" case.

Erik Lindberg,
"Colpitts, Eigenvalues and Chaos"
Proceedings 5'th International Specialist Workshop,
Nonlinear Dynamics of Electronic Systems,
NDES'97, June 26-27 1997 Moscow Russia, pp 262-267.

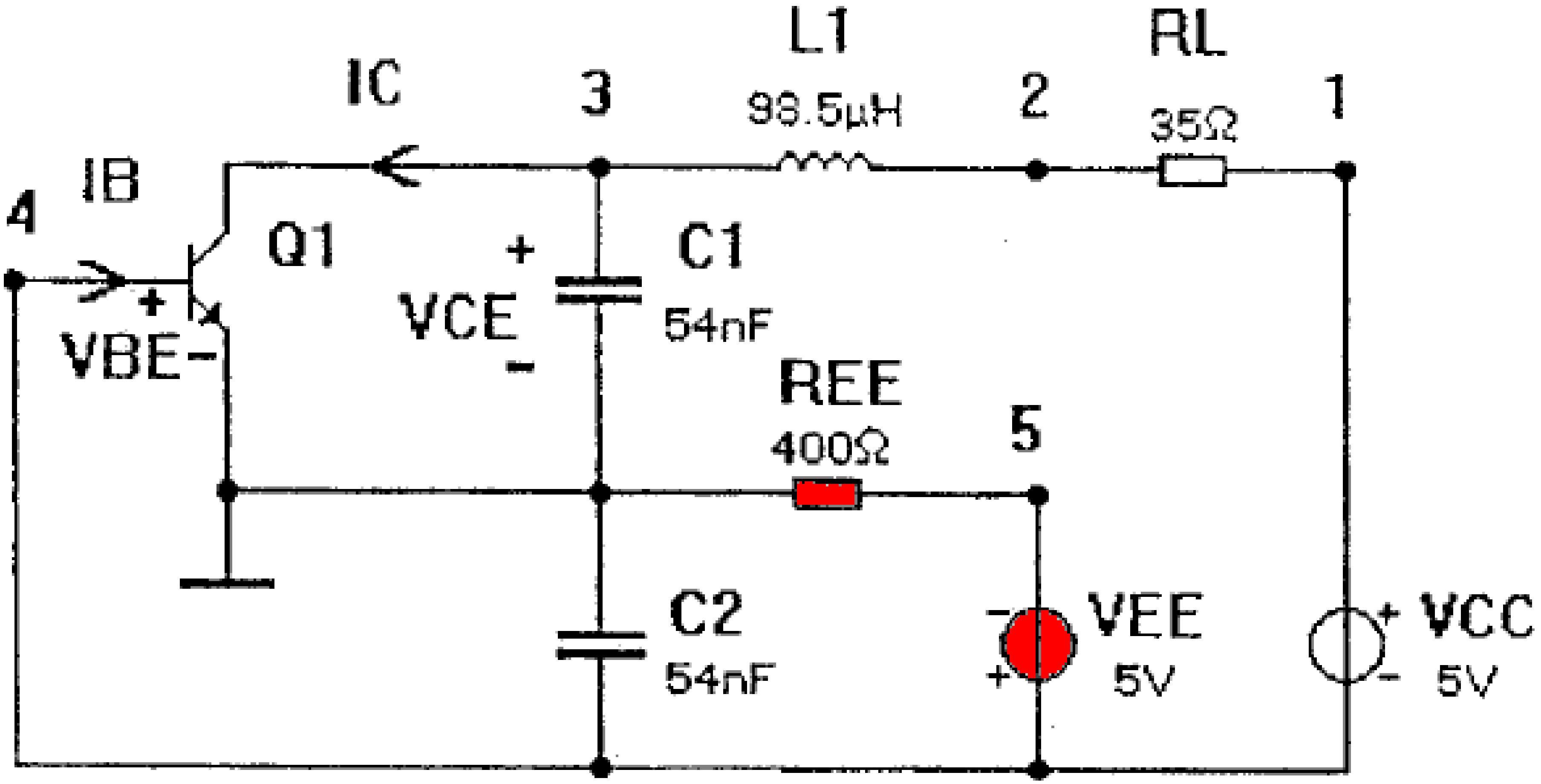
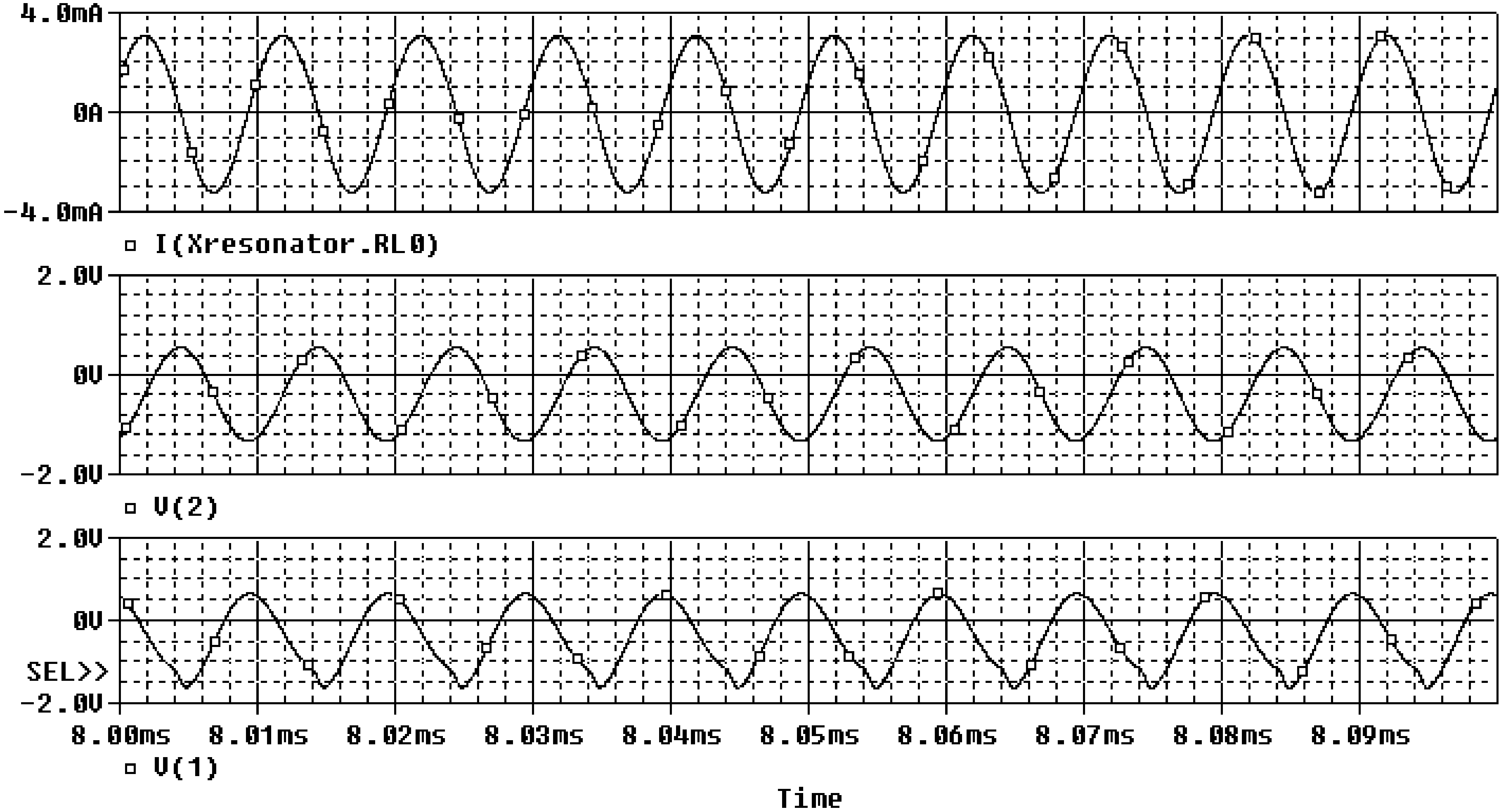


Figure 1: Colpitts oscillator.

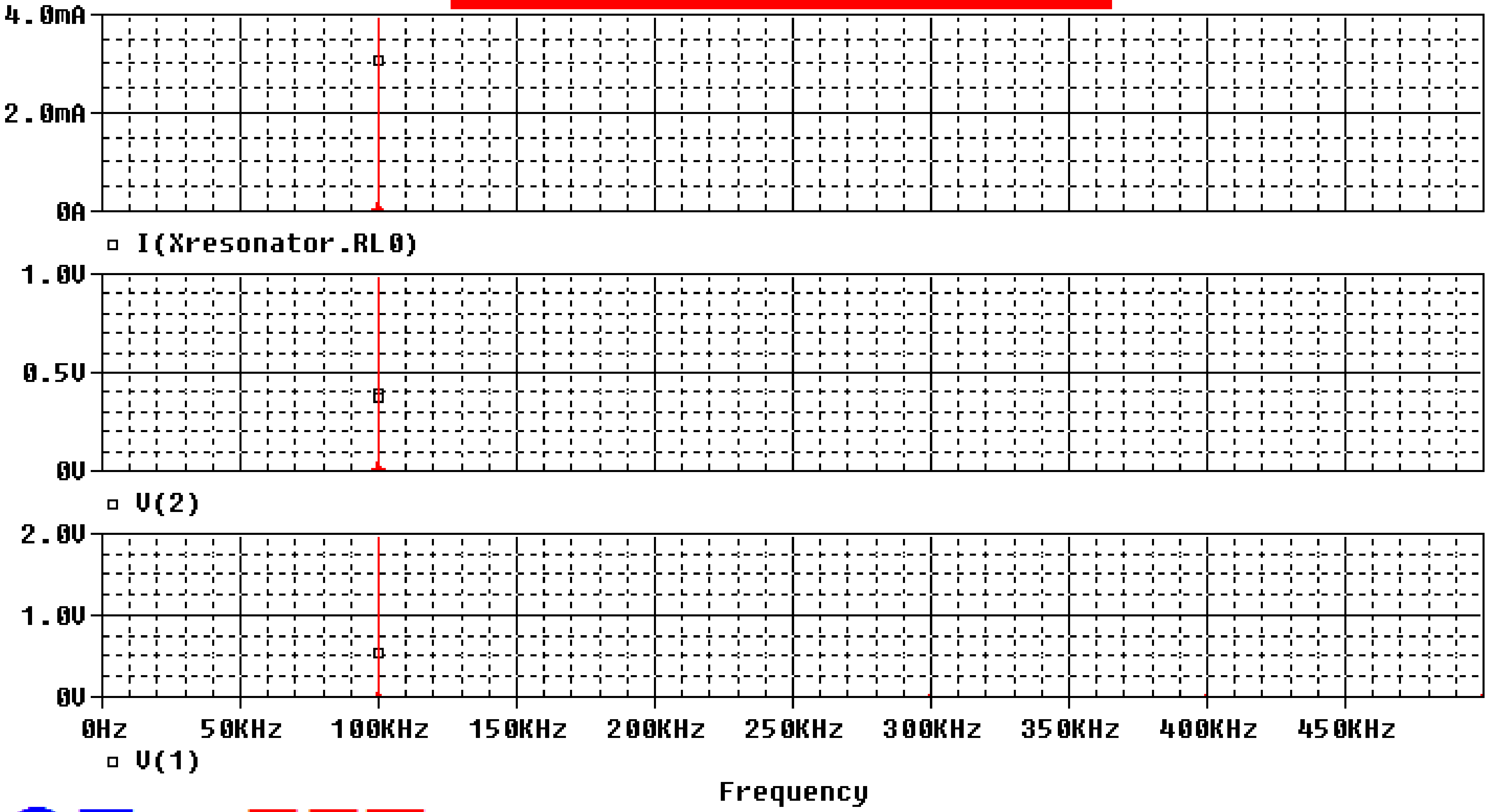
Colpitts Oscillator



CE **FFT**

time: 0.5ms - 10.0ms

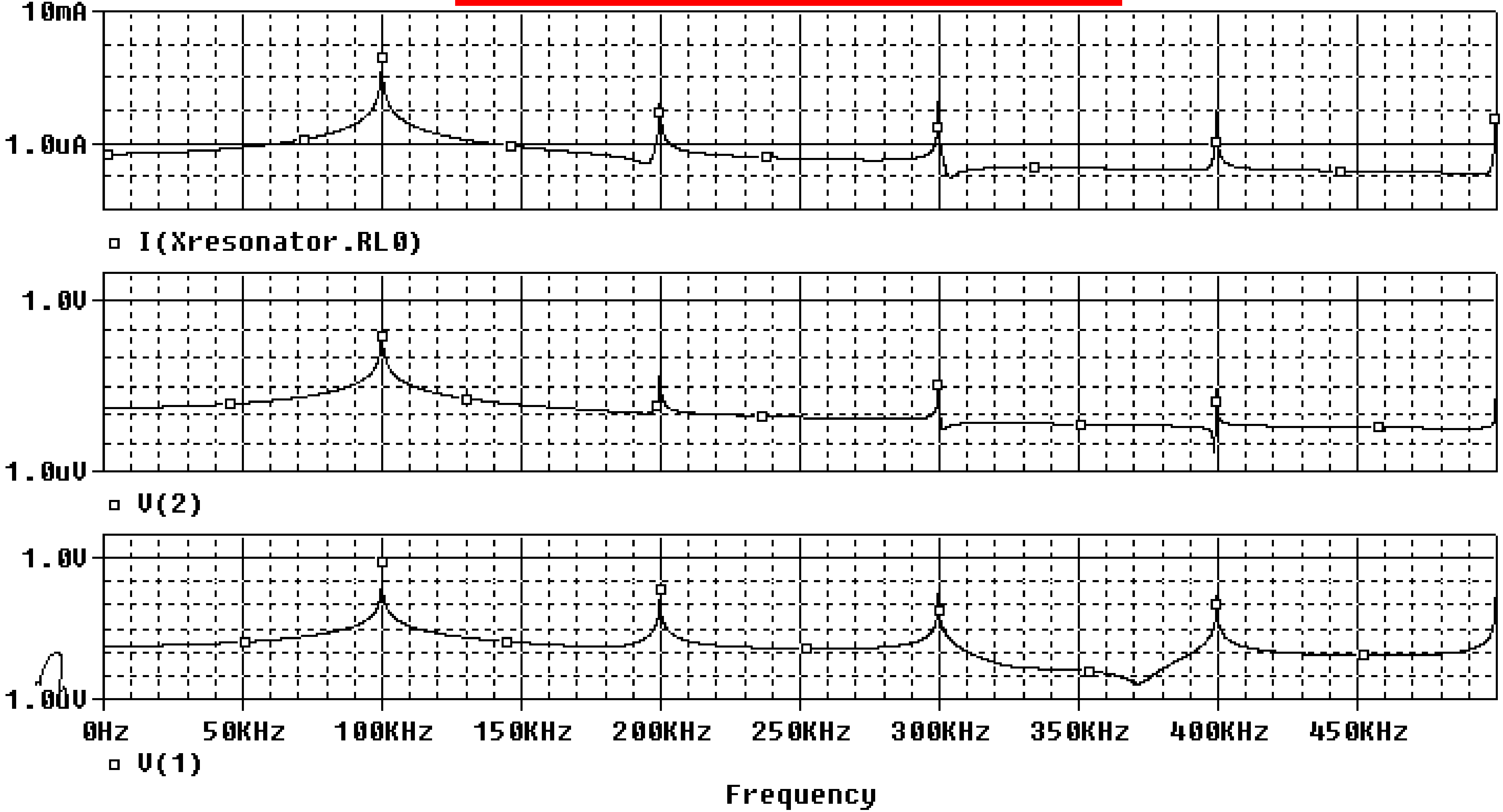
Colpitts Oscillator



CE FFT

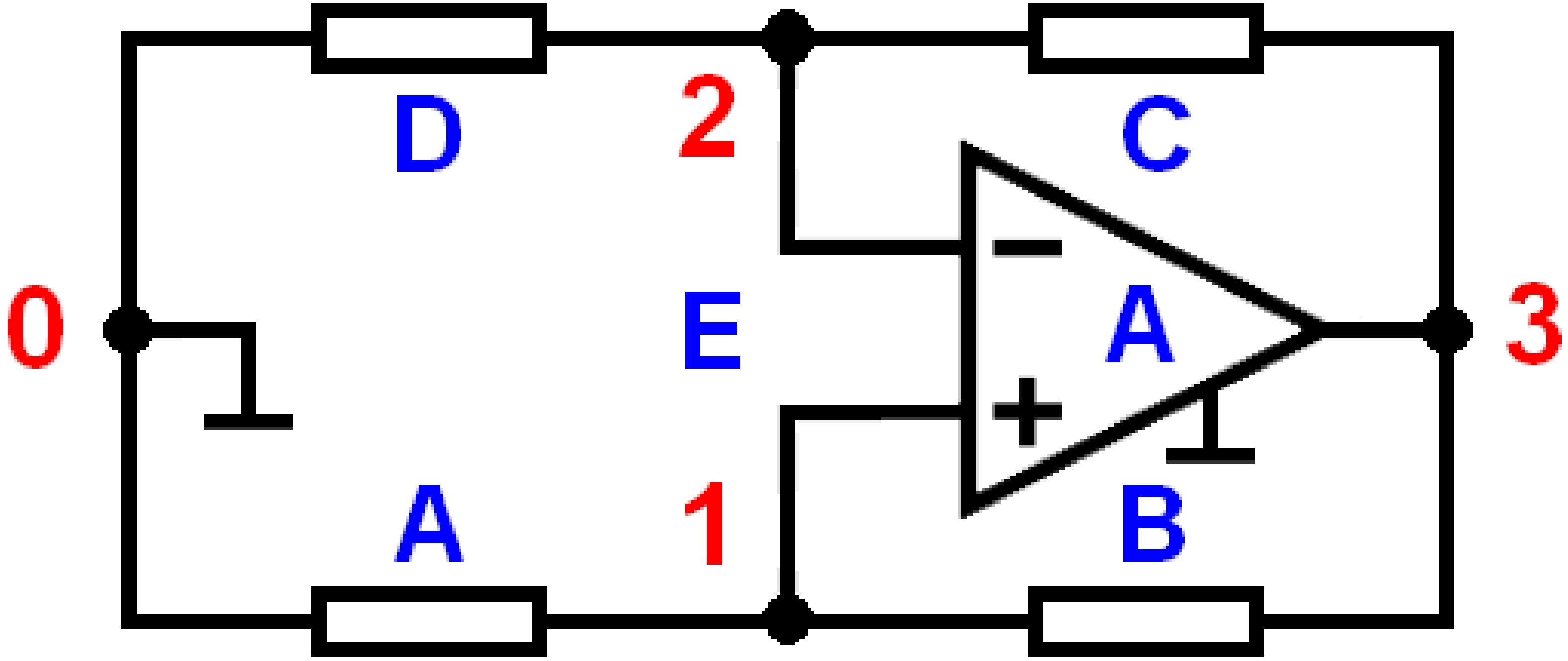
time: 0.5ms - 10.0ms

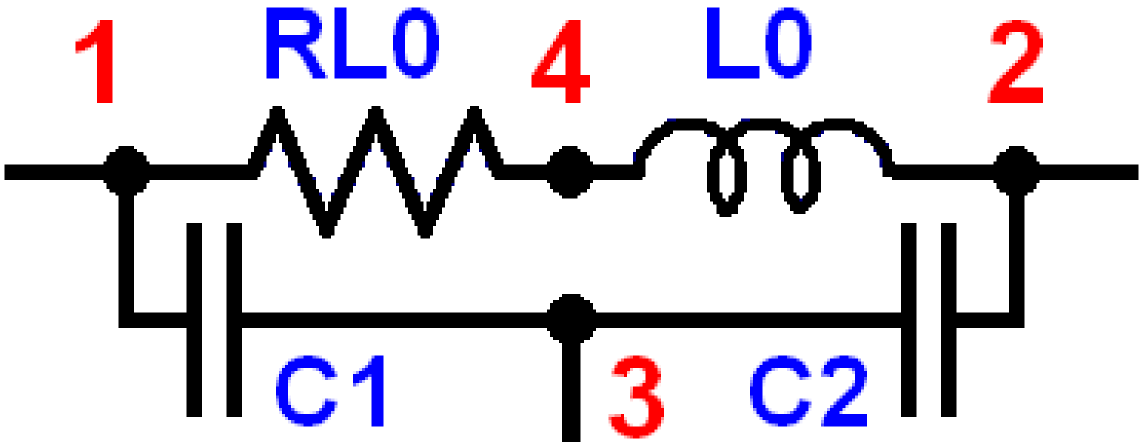
Colpitts Oscillator



CE FFT

time: 0.5ms - 10.0ms


D
2
C
0
E
A
3
A
1
B


1
RL0
4
L0
2
C1
3
C2

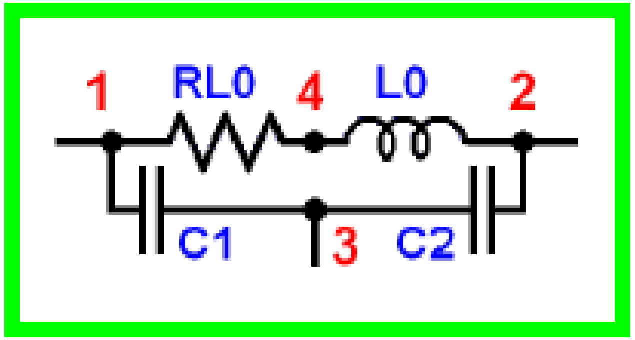
Case:	B	C	E	
AMP	1 3 0	2 3 0	2 1 0	
VCVS	1 2 3	1 2 3	1 2 3	
Case B2	2 3 1	2 3 1	2 3 1	
	3 1 2	3 1 2	3 1 2	
	1 3 2	1 3 2	1 3 2	
	3 2 1	3 2 1	3 2 1	
	2 1 3	2 1 3	2 1 3	Case E6

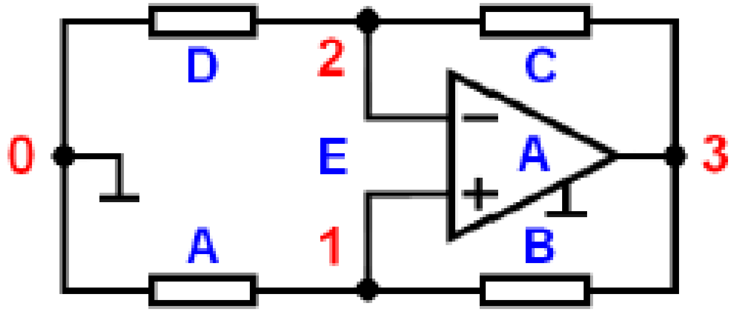
18 patterns

7 ss osc

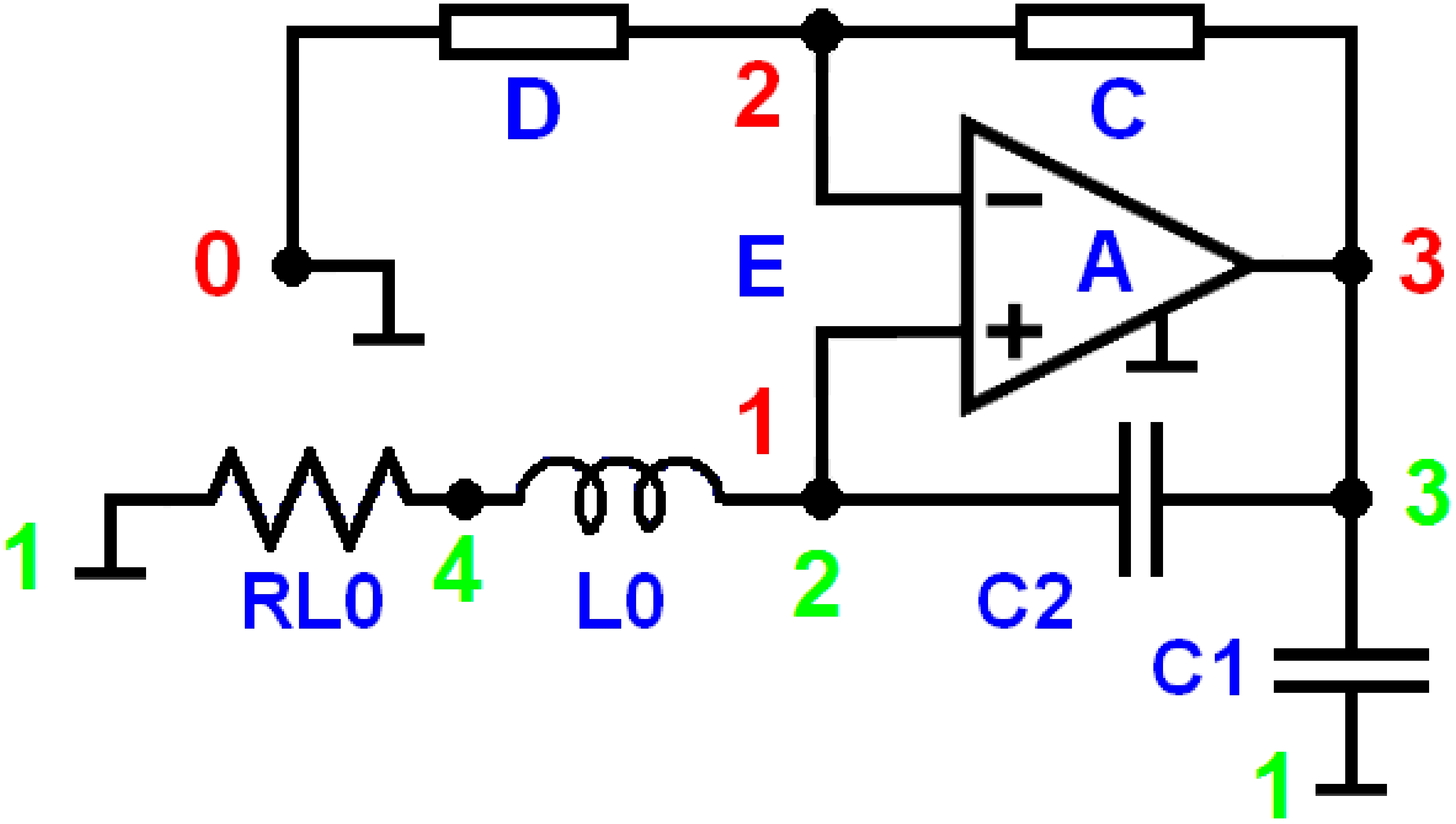
Case B2

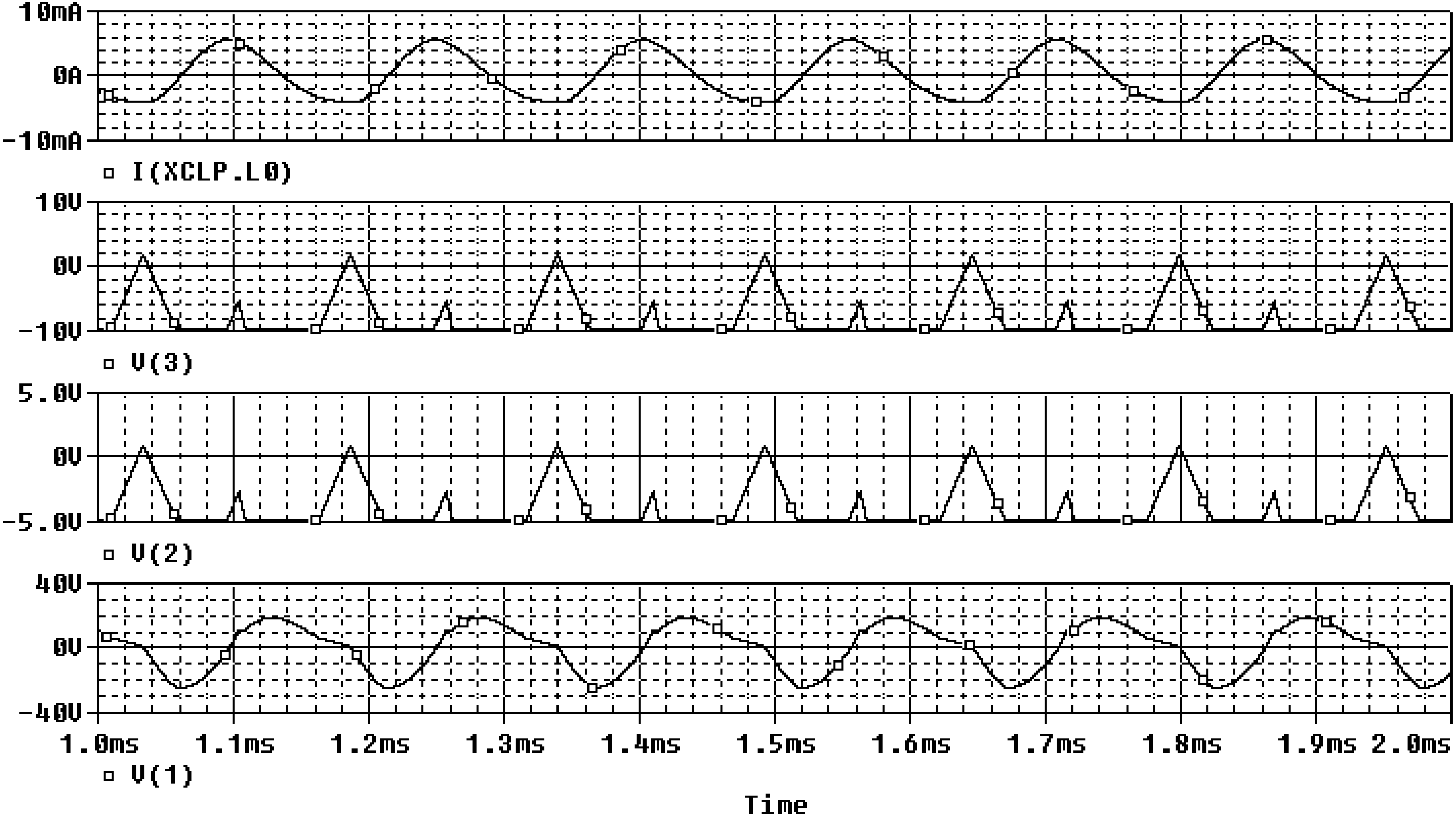
```
* case B   1  2  3
*   XCLP   1  3  0  colpitts   ; no osc
   XCLP   0  1  3  colpitts   ; ss osc
*   XCLP   3  0  1  colpitts   ; no osc
*
*   XCLP   1  0  3  colpitts   ; ss osc
*   XCLP   0  3  1  colpitts   ; no osc
*   XCLP   3  1  0  colpitts   ; damp osc
*
*  RA     1  0     800
*  RB     1  3     800
   RC     2  3     800
   RD     2  0     800
```





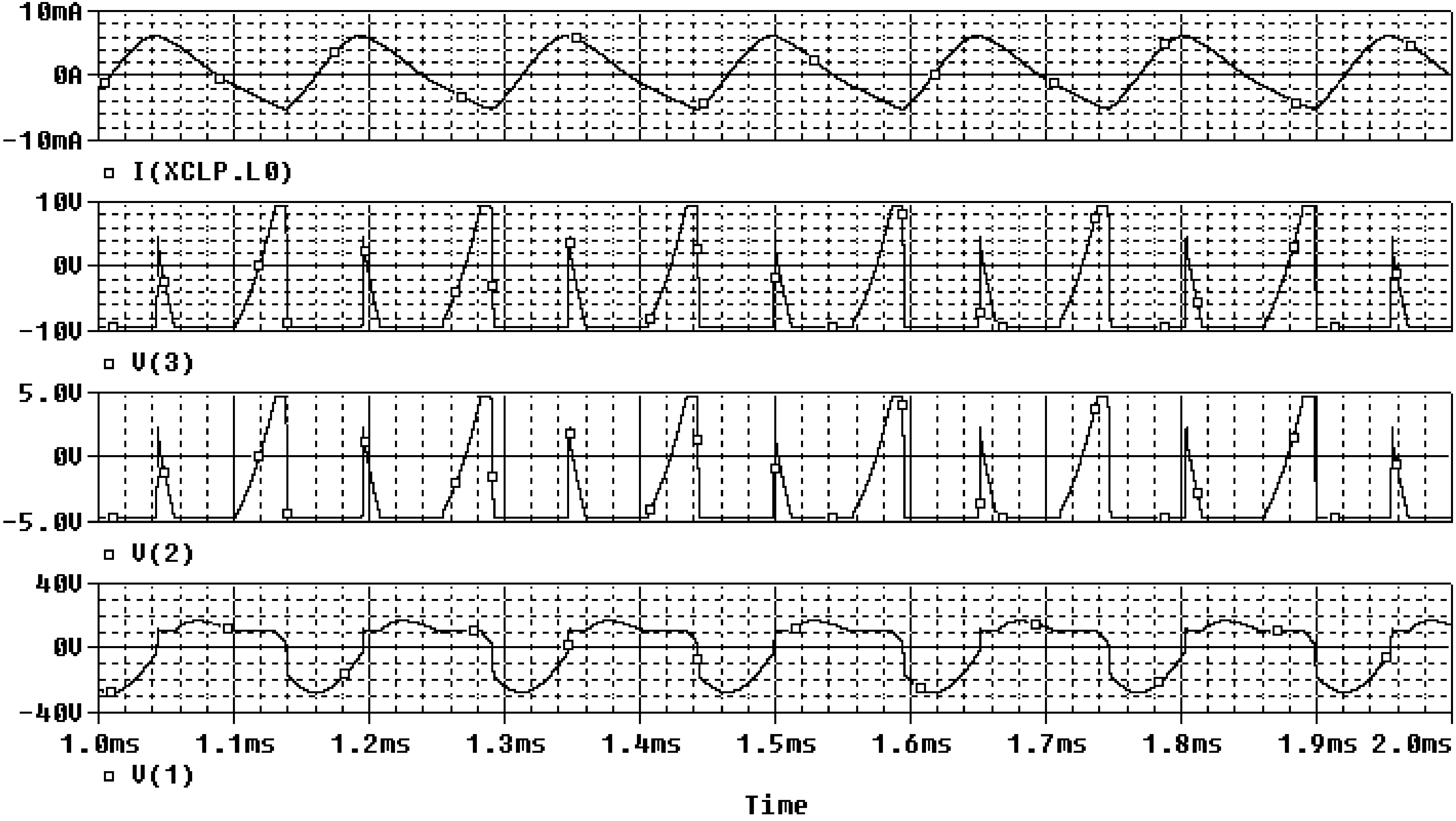
Case B2





XOPAMP: uA741

Case B2

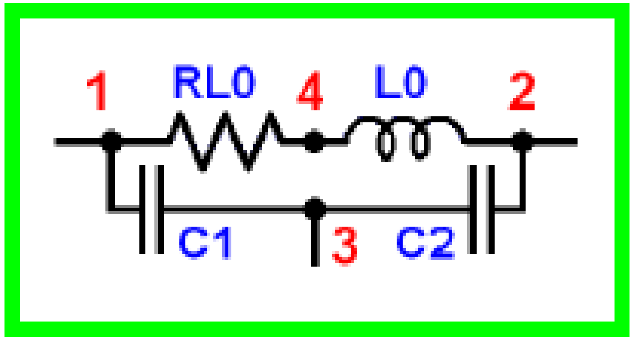


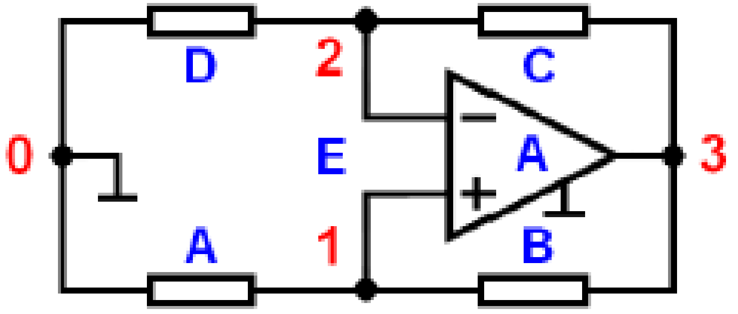
XOPAMP: TL082

Case B2

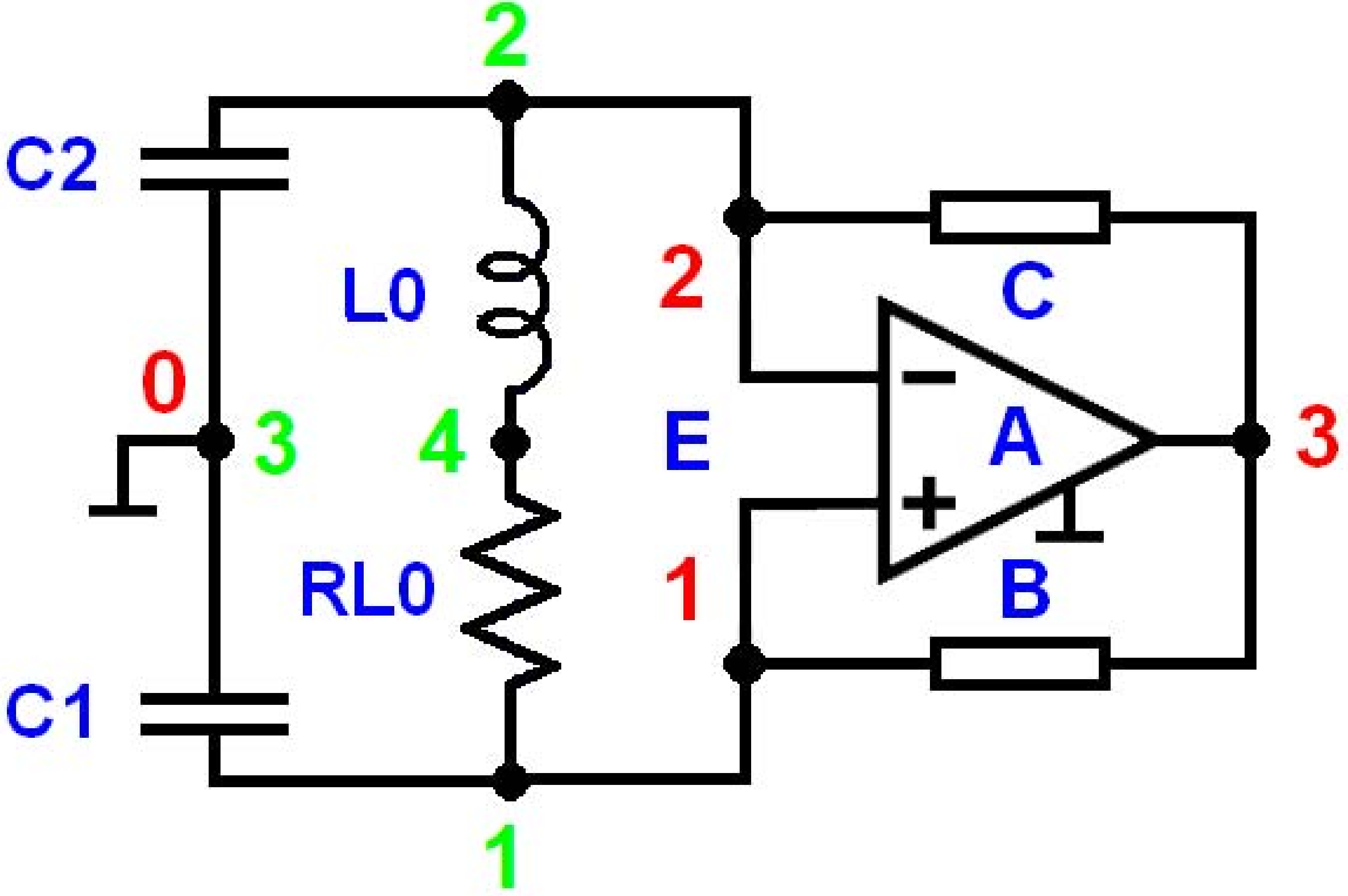
Case E6

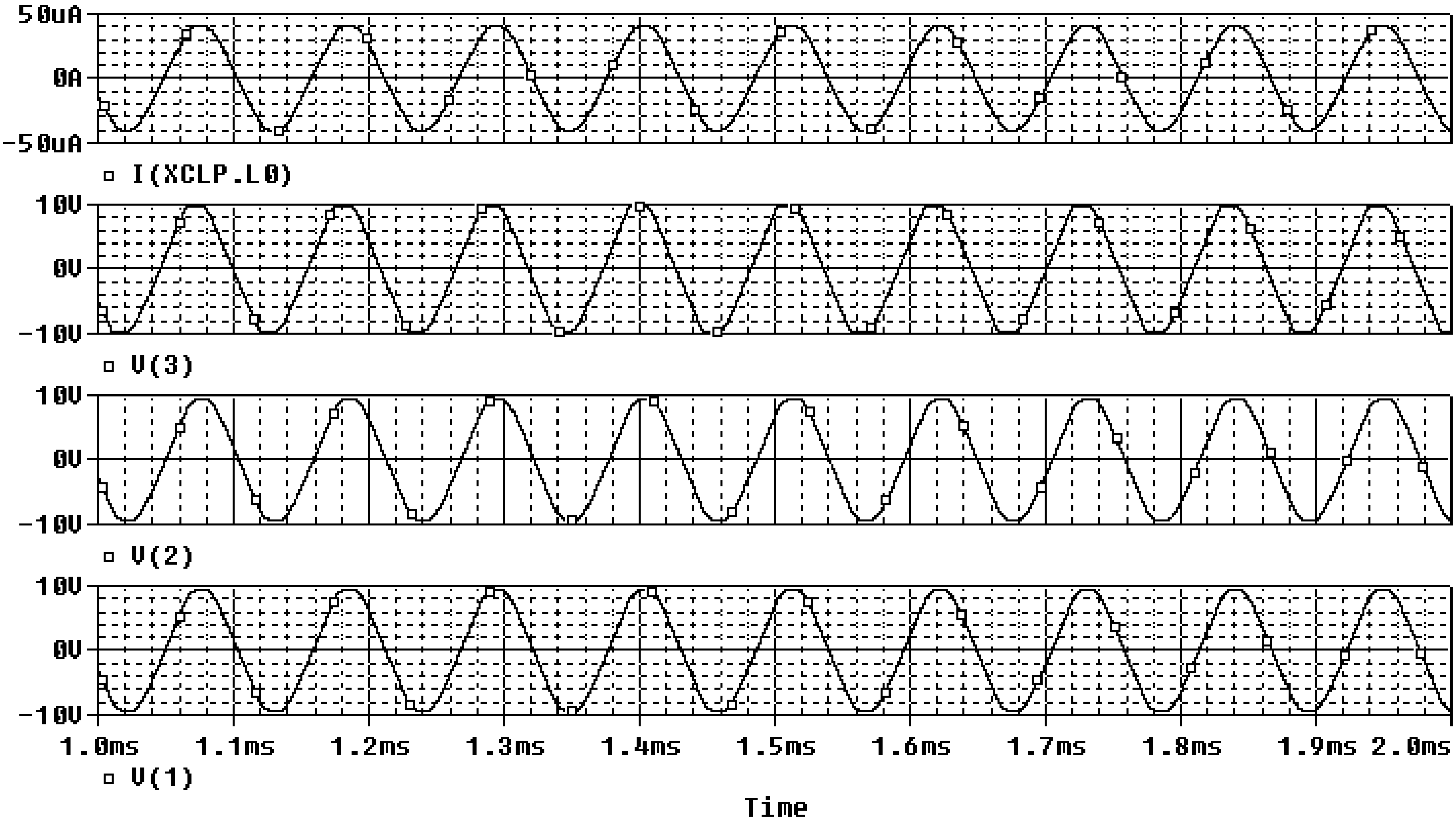
```
* case E   1  2  3
*   XCLP   2  1  0  colpitts   ; conv. problems
*   XCLP   0  2  1  colpitts   ; no osc
*   XCLP   1  0  2  colpitts   ; ss osc
*
*   XCLP   2  0  1  colpitts   ; no osc
*   XCLP   0  1  2  colpitts   ; ss osc
    XCLP   1  2  0  colpitts   ; ss osc
*
*  RA     1  0     800
   RB     1  3     800
   RC     2  3     800
*  RD     2  0     800
```





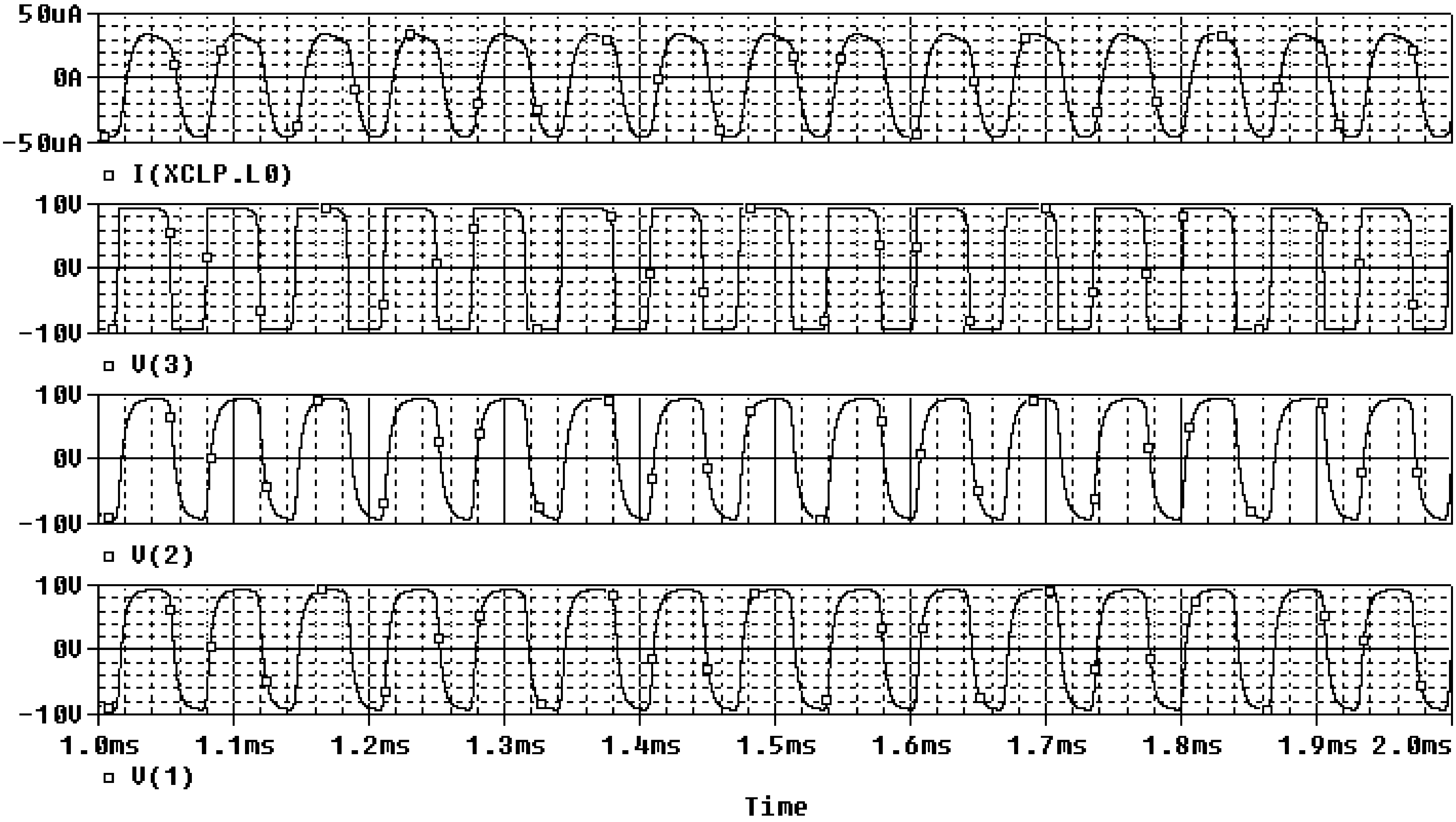
Case E6





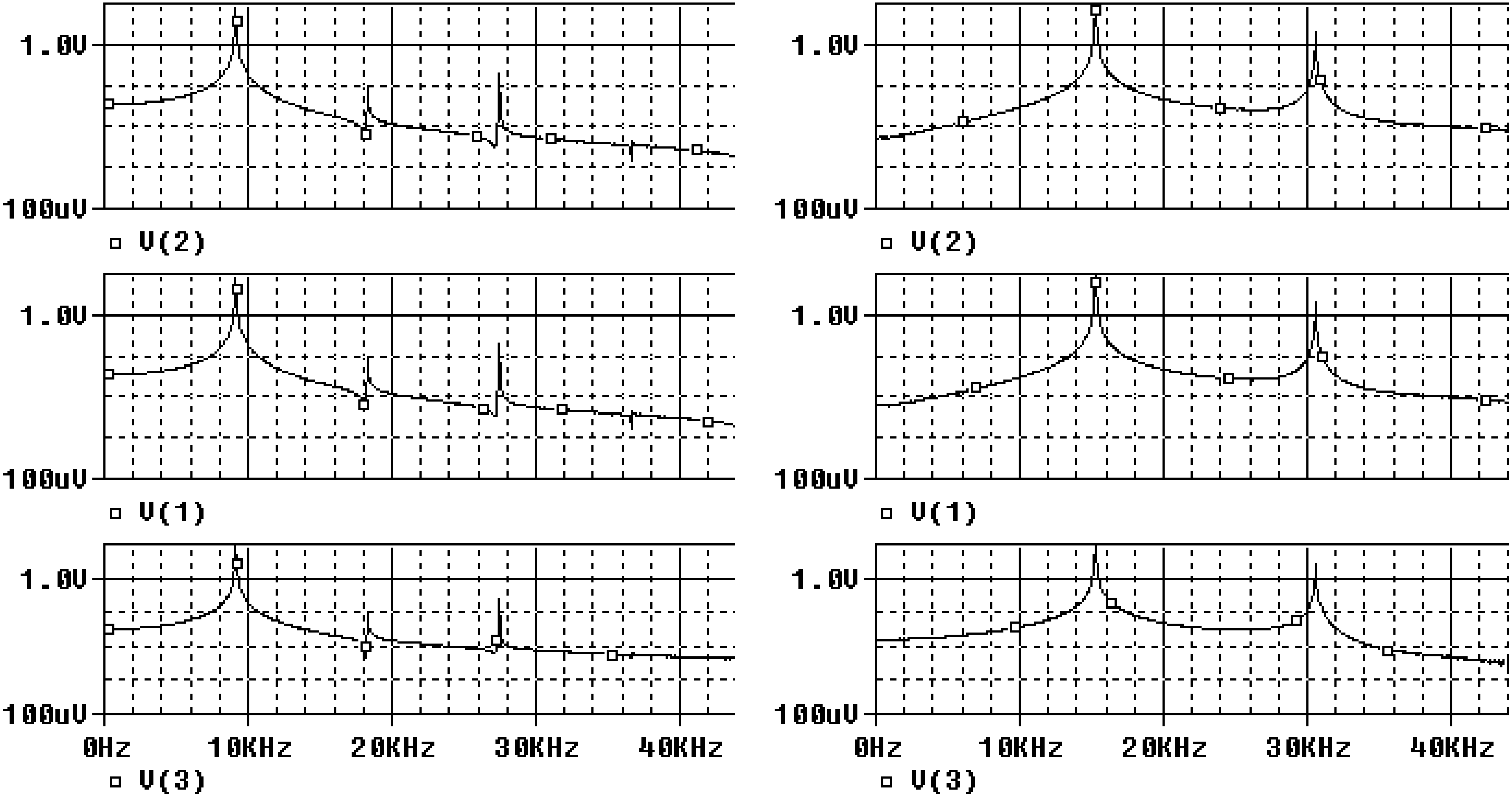
XOPAMP: uA741

Case E6



XOPAMP: TL082

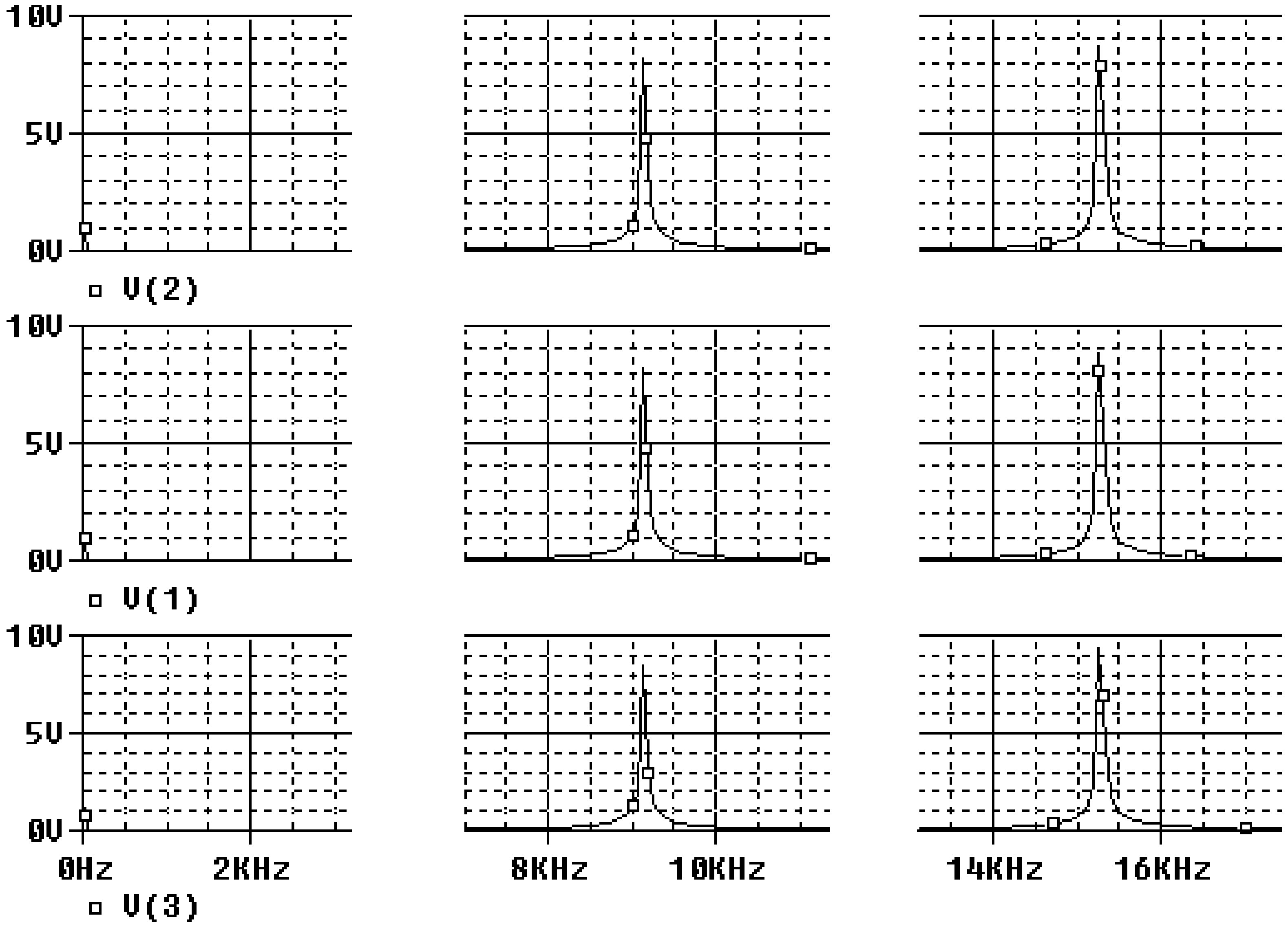
Case E6



ua741

TL082

Case E6

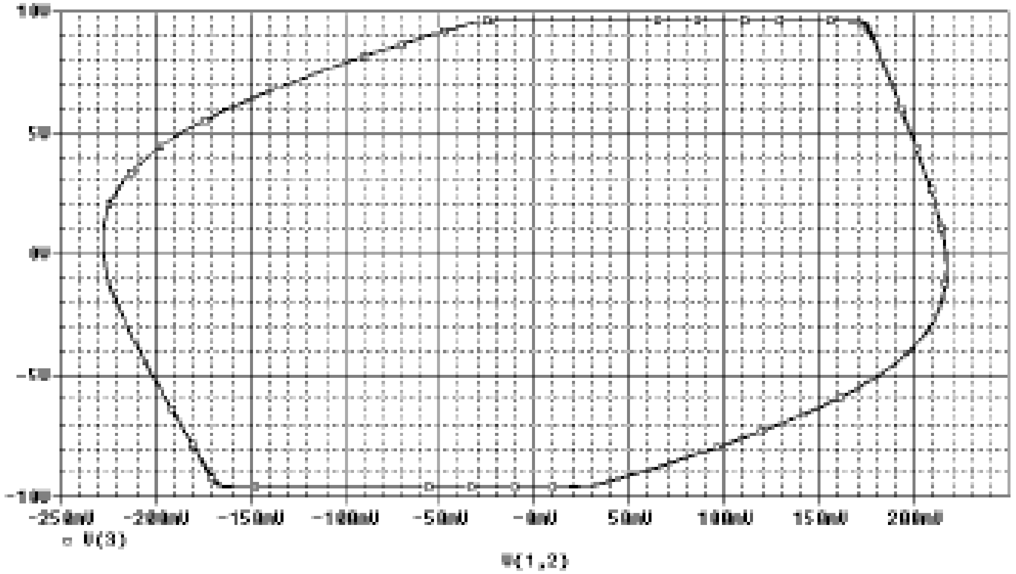


Case E6

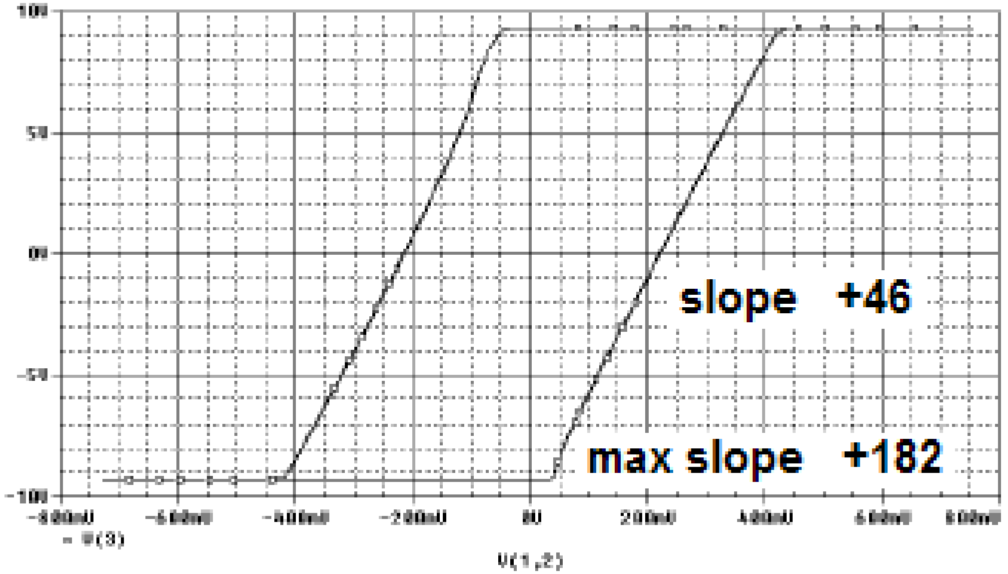
ua741

TL082

Case E6



ua741



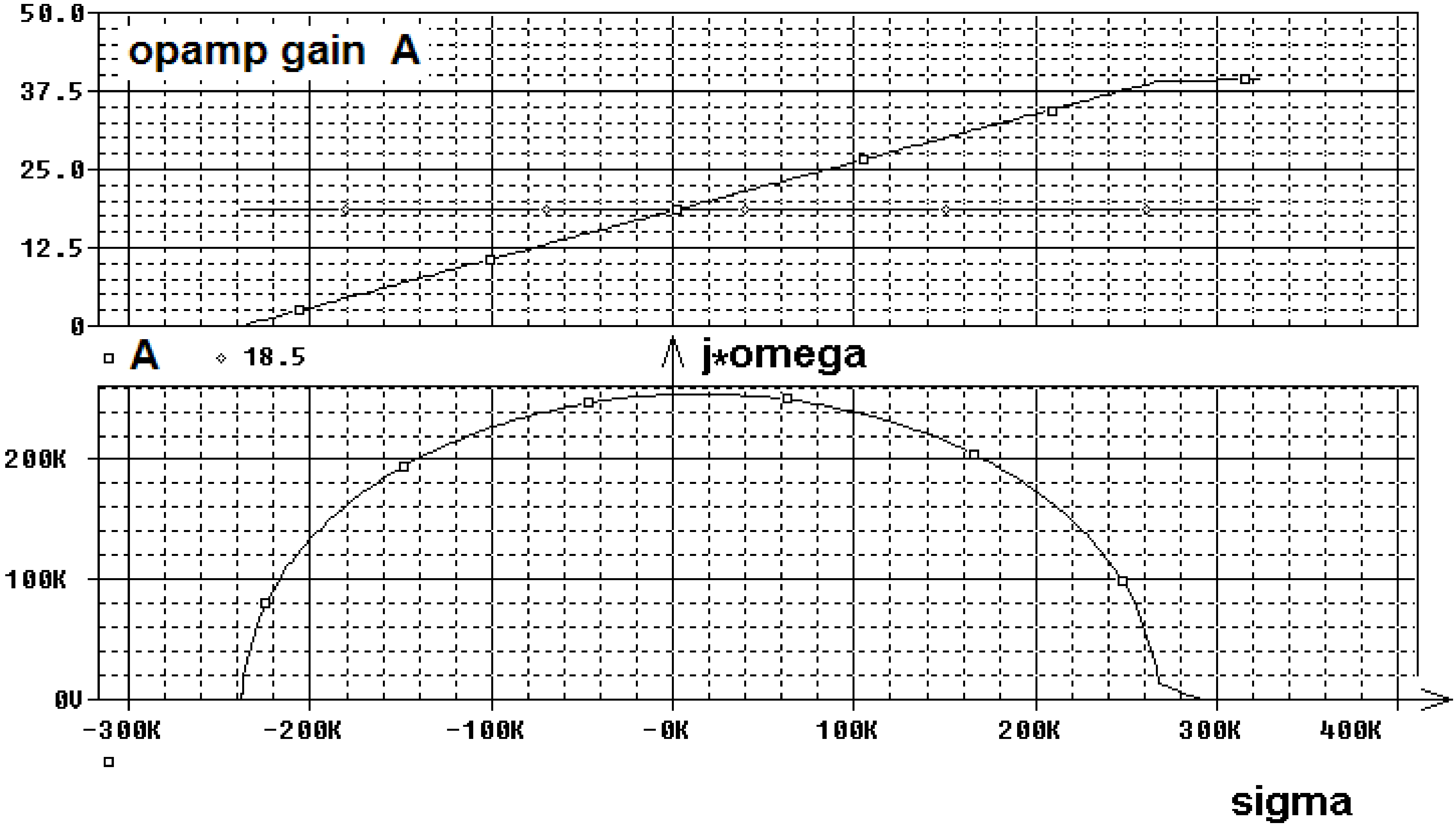
slope +46

max slope +182

TL082

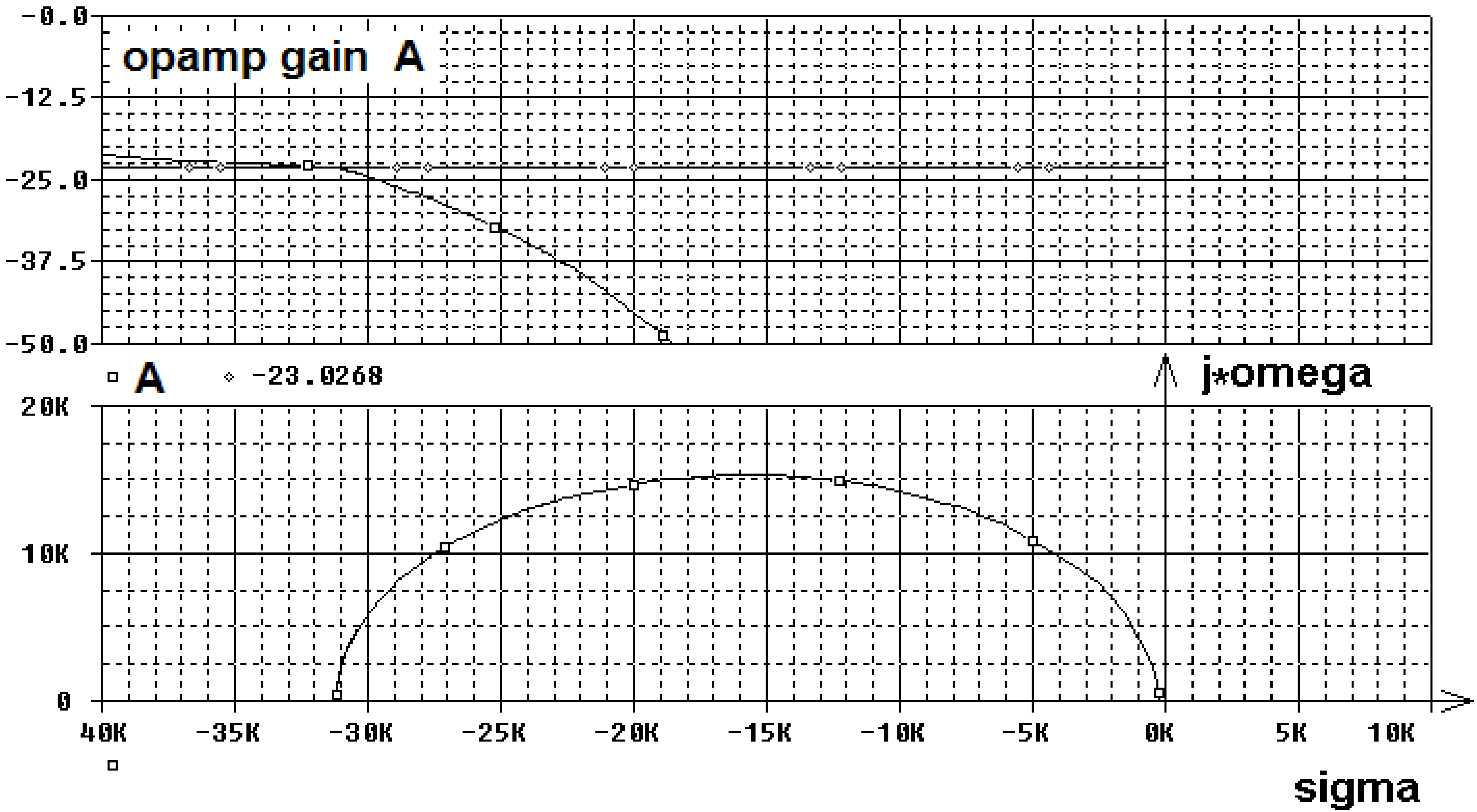
dynamic transfer-characteristics of operational amplifiers

slope: $V3 = A * (V1 + V2)$



Case E6

complex pole-pair trajectory



Case E6

complex pole-pair trajectory

Gain A	Poles		**Case E6**
0	−0.230e+6	−17.7e+3	0.00e-01
+46	0.589e+6	0.126e+6	−13.5e+3
−46	−1.65e+6	−19.7e+3 ± j	14.8e+3
+182	4.22e+6	24.5e+3	−9.67e+3
−182	−5.21e+6	−6.44e+3 ± j	12.3e+3
+1e+9	26.0e+12	−0.500e+3	0.00e-01
−1e+9	−26.0e+12	−0.500e+3	0.00e-01
1.0E+12	−0.500e+3	0.00e-01	0.00e-01

1 Colpitts Oscillator Family

2 Amplifiers and Oscillators

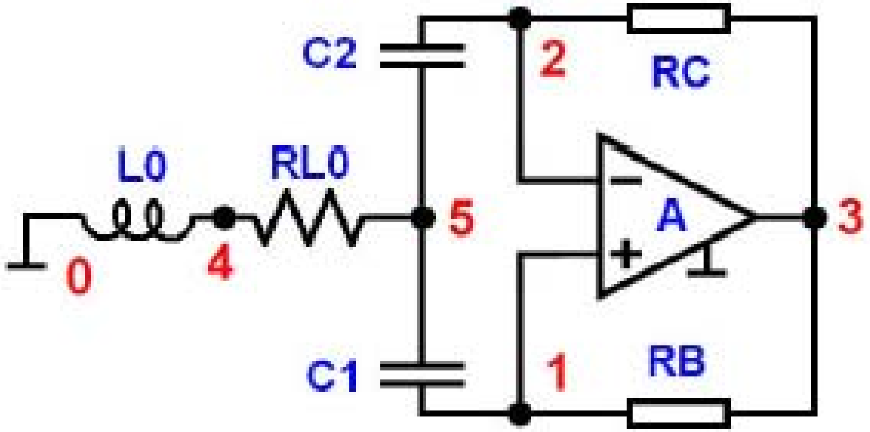
3 Colpitts Oscillators based on Transistors

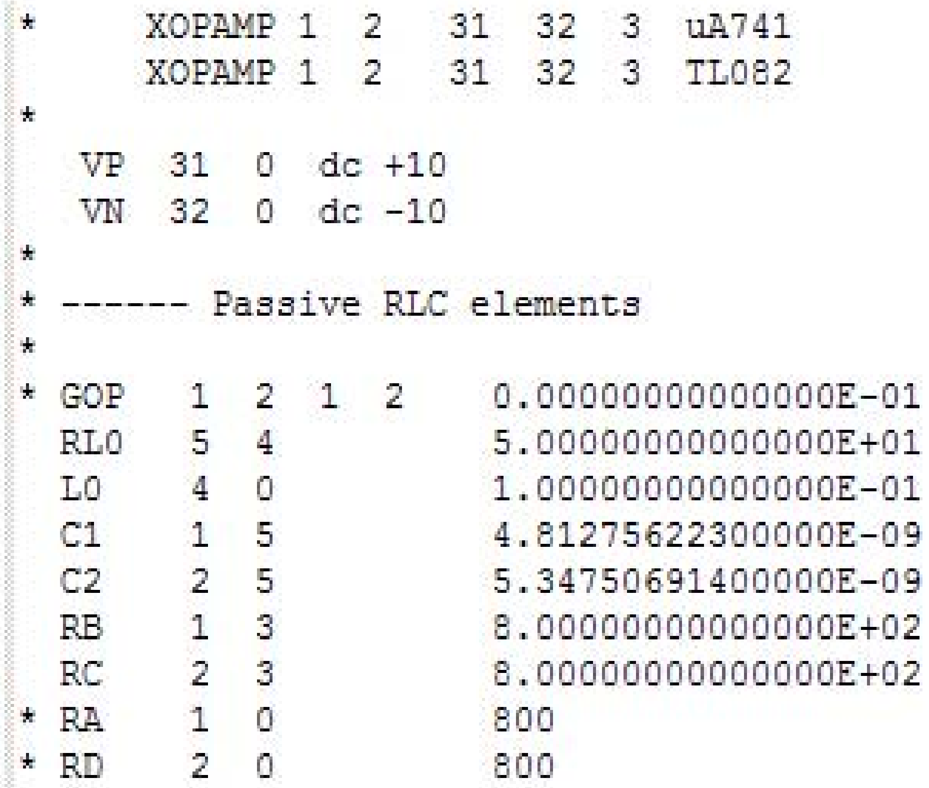
4 Colpitts Oscillators based on Amplifiers

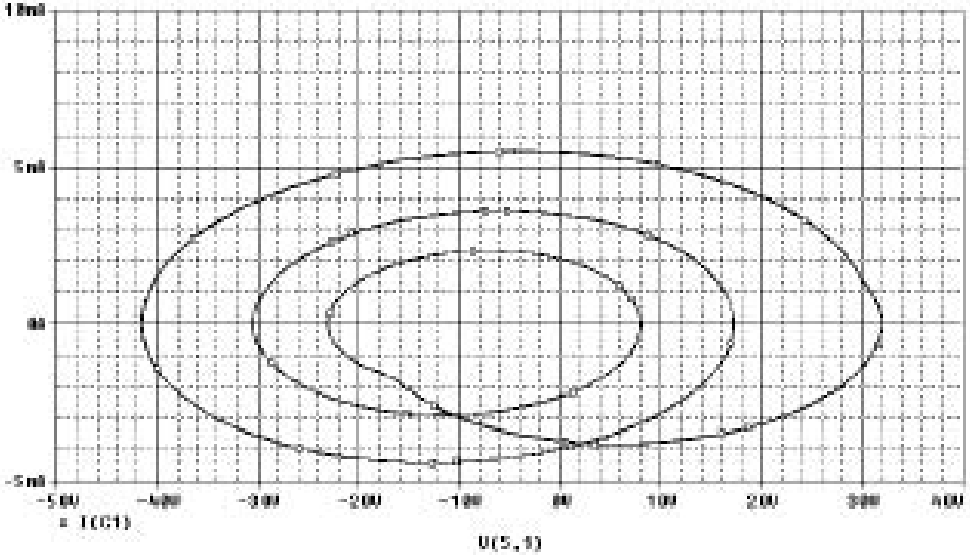
5 Conclusion

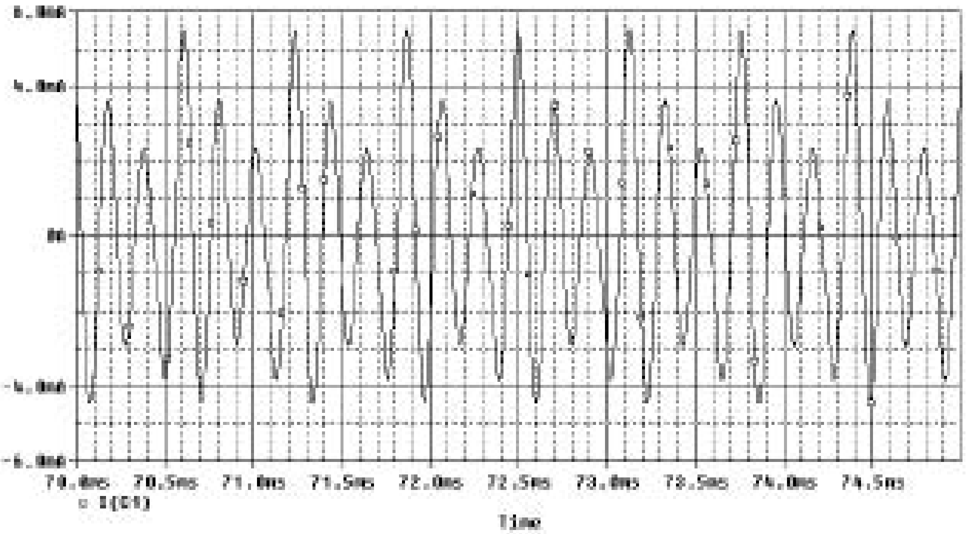
Conclusion

- The Colpitts oscillator family is investigated.
- New oscillator topologies with memory components in both positive and negative feed-back path of a perfect operational amplifier are presented.
- The complex frequency plane trajectories of the eigen-values of the linearized Jacobian of the differential equations modeling topologies with only one nonlinearity are studied in order to obtain knowledge about the mechanism behind the oscillations.
- A real pole is moving in the left half plane and a complex pole pair is moving between the right and the left half plane so that energy balance is obtained.




```
*       XOPAMP 1   2    31   32   3   uA741
        XOPAMP 1   2    31   32   3   TL082
*
   VP  31   0   dc +10
   VN  32   0   dc -10
*
* ------ Passive RLC elements
*
* GOP    1   2   1   2     0.00000000000000E-01
  RL0    5   4             5.00000000000000E+01
  L0     4   0             1.00000000000000E-01
  C1     1   5             4.81275622300000E-09
  C2     2   5             5.34750691400000E-09
  RB     1   3             8.00000000000000E+02
  RC     2   3             8.00000000000000E+02
* RA     1   0             800
* RD     2   0             800
```





Thank you for your attention