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M.R.M. Rizk

Abstract

This report demonstrates, in a tutorial fashion, the transient analysis of a nonlinear circuit, namely a current switch emitter follower [1]. The response obtained was checked against other responses obtained by a program which uses the state space formulation for the analysis [2] and by SPICE2 [3].

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I. INTRODUCTION

A transient analysis of a CSEF was performed using the companion network approach [4-6]. The report discusses briefly the companion networks which replace the original elements of a nonlinear circuit resulting in a linear resistive circuit which is repeatedly solved to obtain the transient response. The method implies two loops, the first is concerned with the convergence of the nonlinear algebraic equations which are linearized by the companion network, and the second is concerned with the discretization of the time derivatives. To start the analysis a D.C. (steady state) analysis is performed to supply the initial conditions for the transient analysis. The response obtained was verified by SPICE2 [3]. Some of the elements which could not be handled by SPICE2 were modeled by some additional circuits. The listings of the analysis subroutines and the input data to SPICE2 are given in Appendices A and B, respectively.

II. THE COMPANION NETWORK APPROACH

In the transient analysis of nonlinear circuits the equations describing the circuits are algebraic and differential equations. These equations are linearized and discretized according to the integration scheme used for solving these equations. In the companion network approach the linearization and discretization are performed at the branch (element) level. Each element can be represented by a combination of

(1) resistors

(2) independent current sources

(3) voltage - controlled current sources.

Hence the resultant new circuit will be a linear resistive circuit.

Linearization

Consider the diode shown in Fig. 1.a, with the current i_d passing through it and v_d the voltage across its terminals. The current i_d is given by

$$i_d = I_S(e^{\theta v_d}-1) , \tag{1}$$

where

I_S is the saturation current

θ is the inverse of thermal potential.

Linearizing the nonlinear characteristic around a given point i_d^0 (taking the linear part only of the Taylor expansion) the current can be expressed as

$$i_d = i_d^0 + \left.\frac{\partial i_d}{\partial v_d}\right|_{v_d=v_d^0} (v - v^0) . \tag{2}$$

In general, this expression is substituted in the circuit equations which will have to be solved iteratively. So (2) is written as

$$i_d^{m+1} = i_d^m + \left.\frac{\partial i_d}{\partial v_d}\right|_{v_d=v_d^m} (v_d^{m+1} - v_d^m) \tag{3}$$

where m+1 is the present iteration. Equation (3) can be represented or modeled by the companion network shown in Fig. 1.b.

Discretization

The differential equations will contain derivatives w.r.t. time which can be approximated in many different ways according to the integration algorithm used in solving the equations. In the Backward

Euler algorithm, for example, the derivative of a voltage can be approximated by

$$\left.\frac{dv}{dt}\right|_{t=t^{n+1}} = \frac{v^{n+1}-v^{n}}{T} \tag{4}$$

where $T = t^{n+1} - t^{n}$ is the time step of the integration, and n is the time iteration counter. Using this approximation the current passing through a linear capacitor

$$i_C = C\frac{dv}{dt}, \tag{5}$$

would be

$$i_C^{n+1} = C\frac{v_C^{n+1}-v_C^{n}}{T}. \tag{6}$$

This equation can be represented by a companion network as shown in Fig. 2.b. Using higher order, or any different, integration algorithm will result in a different companion network. For example if Gear's integration algorithm (a predictor corrector algorithm [6]) is used the capacitance current is expressed by [4]

$$i_C^{n+1,m+1} = \left(-\frac{C}{a_1 T}\right) v_C^{n+1,m+1} + \left[C\left(\frac{\partial v_C}{\partial t}\right)^{n+1,0} + \frac{C}{a_1 T} v_C^{n+1,0}\right] \tag{7}$$

where a_1 is a constant coefficient, and m is the corrector iteration counter. The linear capacitor will have the companion network shown in Fig. 2.c. For a nonlinear capacitance (Fig. 3.a) the companion network can be as the one shown in Fig. 3.b (Backward Euler).

III. ANALYSIS OF THE CSEF CIRCUIT

With the Companion Network Approach

The CSEF [1] shown in Fig. 4 was analyzed using the companion network approach. The transistor model was the one given in Fig. 5.a. The decoupled equivalent circuit of the lossless transmission line shown in Fig. 5.b was used in the analysis. The circuit parameters, the diode model, the transistor model and the transmission line parameters are given in Tables 1, 2, 3 and 4 respectively.

The circuit initially at equilibrium with input voltage E_1 = -0.776V was analyzed to obtain the initial capacitance voltages. In this case (D.C. or steady state) all the capacitances were removed and the other elements were replaced by their companion networks. The resultant circuit is the one shown in Fig. 6. This linear resistive circuit was analyzed using its nodal equations shown in Fig. 7. This set of equations was solved by the CDC library subroutine GELG [7], where we start with all node voltages $\underset{\sim}{v}^0 = \underset{\sim}{0}$ and find $\underset{\sim}{v}^1$ and so on, iteratively, until convergence is achieved. The values of $\underset{\sim}{v}$ obtained are the initial voltages of the transient analysis.

The circuit shown in Fig. 8 represents the CSEF after replacing the elements and the transistor models by the appropriate companion networks. The nodal admittance matrix of this circuit is given in Fig. 9. At each time step the set of equations is solved (starting with the voltages obtained from the previous time step, iteratively until convergence.

The analysis subroutines for the D.C. and transient cases are given in Appendix A. In the transient analysis a step T of 0.0025 nsec was

used and it took 40 sec to perform the analysis, while having T as 0.025 nsec it took 6 sec only and the results were indistinguishable.

The Analysis Using SPICE2

The general analysis program SPICE2 [3] was used to verify the responses obtained. In order to overcome the problem of handling the nonlinear capacitance in the form of the one given in the transistor model (Fig. 5.a) the current passing through the nonlinear part of the capacitance was represented by the current i_1 of a two dimensional current controlled current source. The currents controlling this source are i_2 and i_3 in two small additional networks as shown in Fig. 10. The coefficients of the polynomial representing i_1 are all zero except the coefficient of the cross terms has the value one. In the circuit where i_2 is passing $P_0 = P_1 I_S$ so as to let i_2 be equal to $P_1 I_S \exp(\theta V_{BE})$. The current i_3 will represent dV_{BE}/dt.

The analysis was also performed by SPICE2 using the built-in models. The parameters of these models were fed in the data to match the model as close as possible to the given model (Fig. 5.a). Responses obtained by the state equations [2], the companion network and by SPICE2 are shown in Fig. 11. Note that the two responses obtained by SPICE2 were almost identical.

The running time of SPICE2, where we modeled the nonlinear capacitance, was 92 sec, while using the built-in models the running time was only 7 sec. This difference is mainly due to the additional elements we have introduced in modeling the nonlinear capacitance which resulted in having 12 additional nodes and node voltages. The data supplied to SPICE2 in the two cases are given in Appendix B.

IV. ACKNOWLEDGEMENT

Thanks are due to Dr. J.W. Bandler for useful discussion, and to Dr. H.L. Abdel-Malek for checking the results with the state-space approach and to Dr. S. Chisholm for useful discussions concerning the use of SPICE2.

V. REFERENCES

[1] C.W. Ho, "Time-domain sensitivity computation for networks containing transmission lines", IEEE Trans. Circuit Theory, vol. CT-18, 1971, pp. 114-122.

[2] H.L. Abdel-Malek, "A unified treatment of yield analysis, worst-case design and yield optimization", Faculty of Engineering, McMaster University, Hamilton, Canada, Report SOC-182, 1977.

[3] L.W. Nagel, "SPICE2: A program to simulate semiconductor circuits", Electronics Research Lab., Univ. of California, Berkeley, Memo. No. ERL-M520.

[4] D.A. Calahan, "Numerical considerations for implementation of a nonlinear transient circuit analysis program", IEEE Trans. Circuit Theory, vol. CT-18, 1971, pp. 66-73.

[5] D.A. Calahan, Computer-Aided Network Design (Revised Edition). New York: McGraw Hill, 1972.

[6] L.O. Chua and P.M. Lin, Computer-Aided Analysis of Electronic Circuits. Englewood Cliffs, NJ: Prentice-Hall, 1975.

[7] Subroutine GELG, System/360 Scientific Subroutine Package, Version III, IBM Programmer's Manual Number 360A-CM-03x, p. 121.

TABLE 1

CIRCUIT PARAMETER VALUES

R_1	281.33 Ω
R_2	75.00 Ω
R_3	78.24 Ω
R_4	45.53 Ω
E_2	4.03 V
E_3	1.13 V
E_4	1.66 V
C_0	1.25 pF

TABLE 2

DIODE MODEL PARAMETERS

I_{SD}	diode saturation current	0.6×10^{-9} A
C_{JD}	depletion layer capacitance	0.12 pF
TT_D	transit time	0.01 ns
θ	inverse of thermal potential	38.668 V^{-1}

$$I_D = I_{SD}(\exp(\theta V_D) - 1)$$

$$C_D = C_{JD} + TT_D \frac{dI_D}{dV_D}$$

TABLE 3

TRANSISTOR MODEL PARAMETERS

I_S	saturation current	0.6×10^{-9} A
α	common base current gain	0.99
R_B	base resistance	50.0 Ω
C_C	collector junction capacitance	0.5 pF
C_{JE}	emitter junction depletion layer capacitance	0.12 pF
TT	base transit time	0.01 ns
θ	inverse of thermal potential	$38.668\ V^{-1}$

$$I_E = I_S\ (\exp(\theta V_{BE})-1)$$

$$I_C = \alpha\ I_E$$

$$C_E = C_{JE} + TT\ \frac{dI_E}{dV_{BE}}$$

R_B and C_C are assumed zero for transistor T_3

TABLE 4

TRANSMISSION LINE PARAMETERS

Z_0	characteristic impedance	92.004 Ω
τ	delay time	0.25 ns

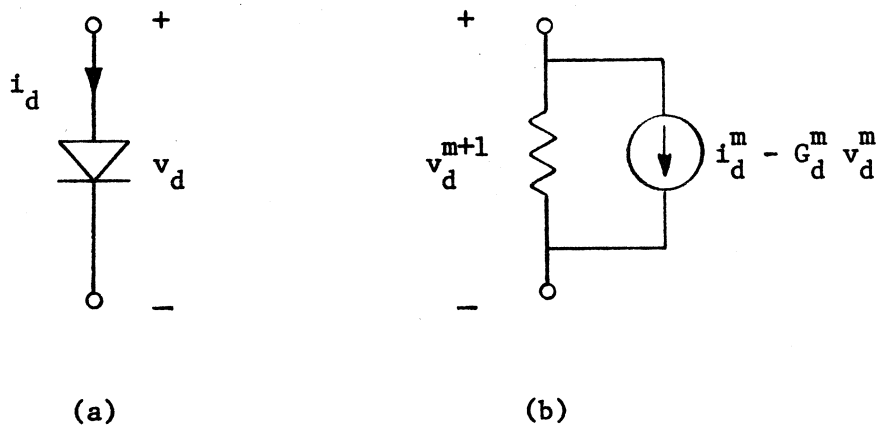


Fig. 1. a) A diode, b) its companion network.

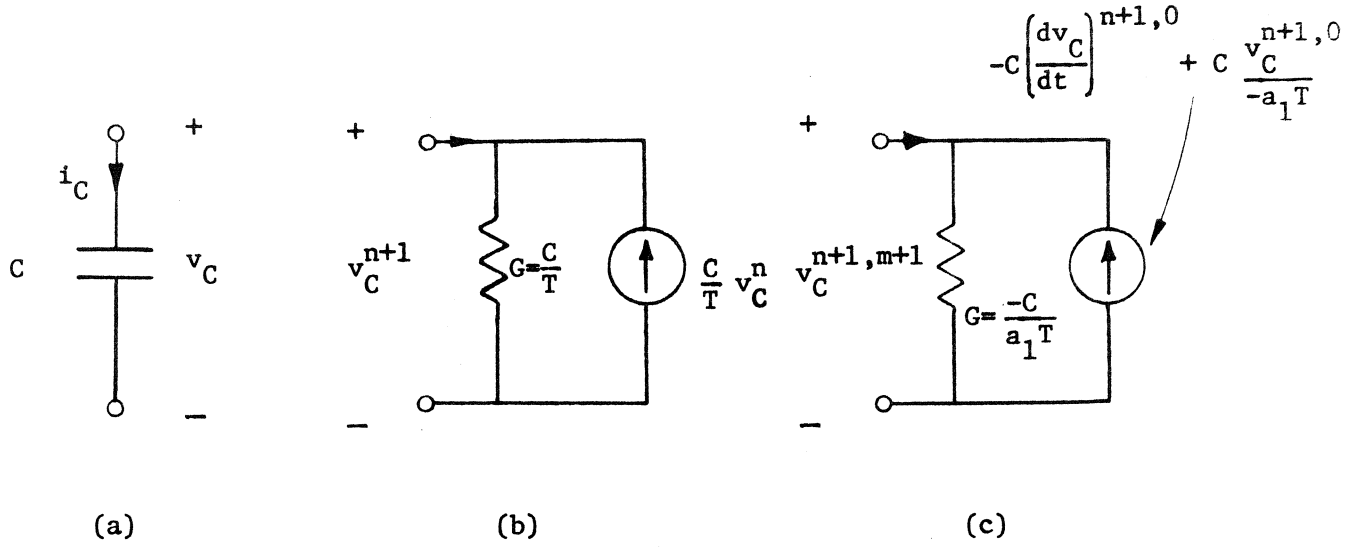


Fig. 2. a) A linear capacitor, b) its companion network using backward-Euler formula, c) its companion network using Gear's formula.

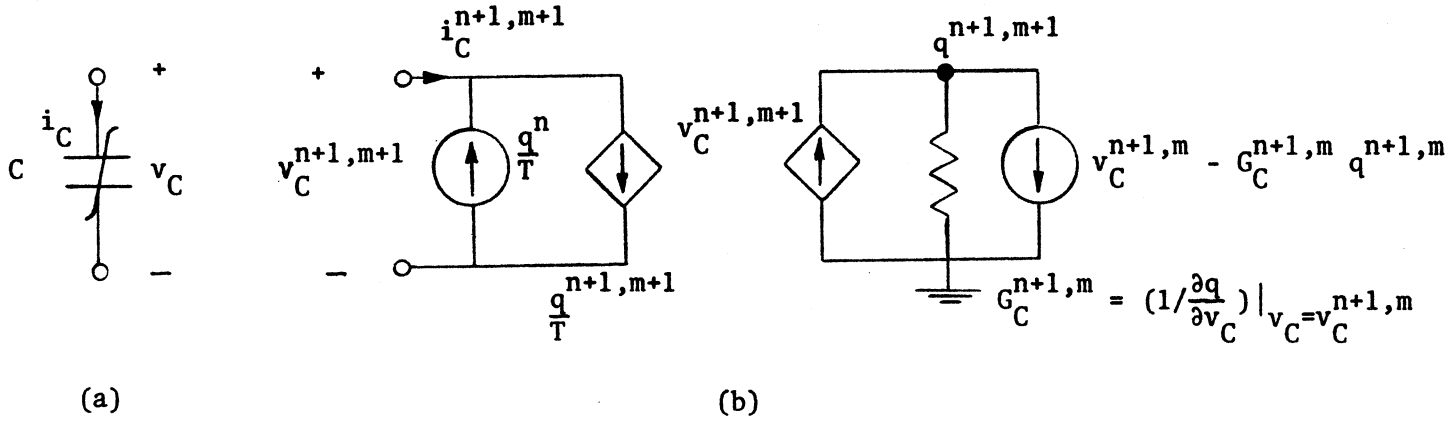


Fig. 3. a) A nonlinear capacitance, b) its companion network (note $q^{n+1,m+1}$ represents the node voltage).

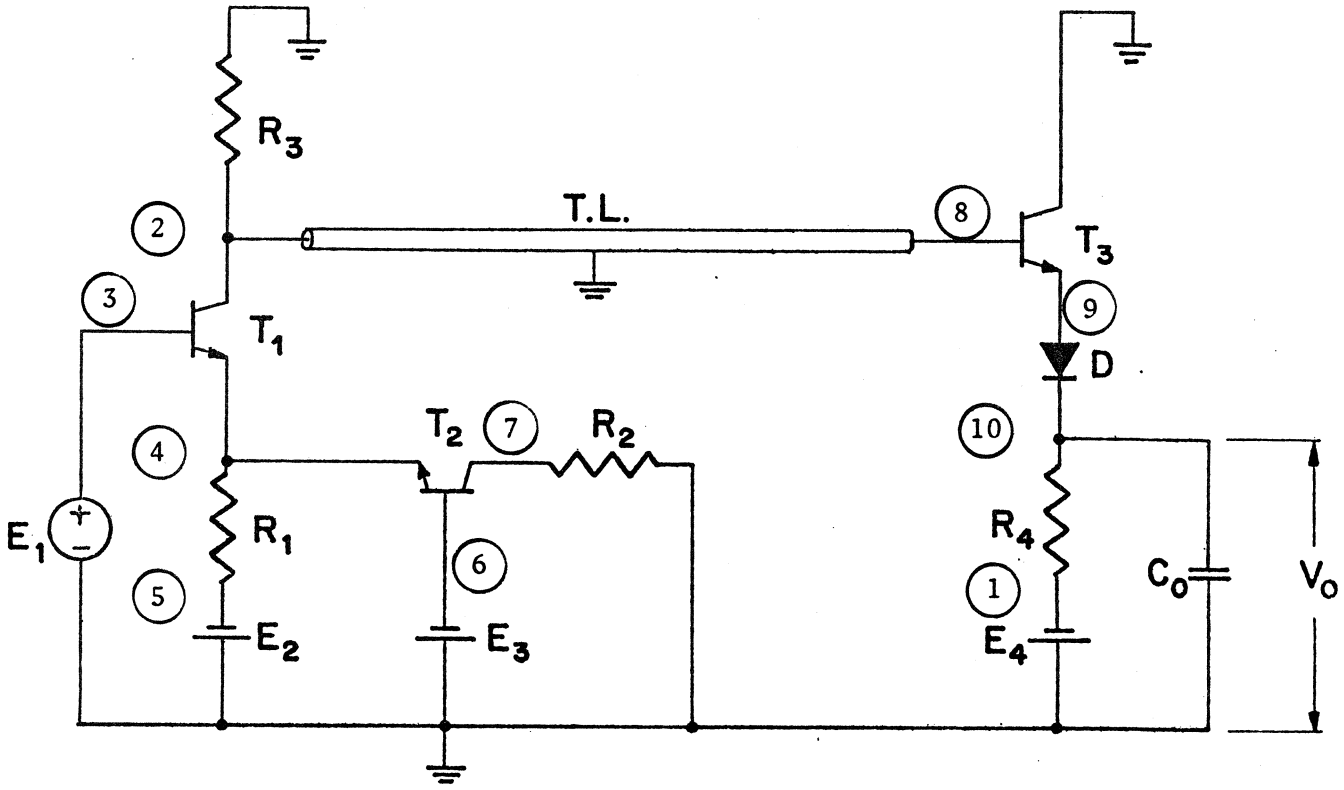


Fig. 4. The CSEF circuit [1].

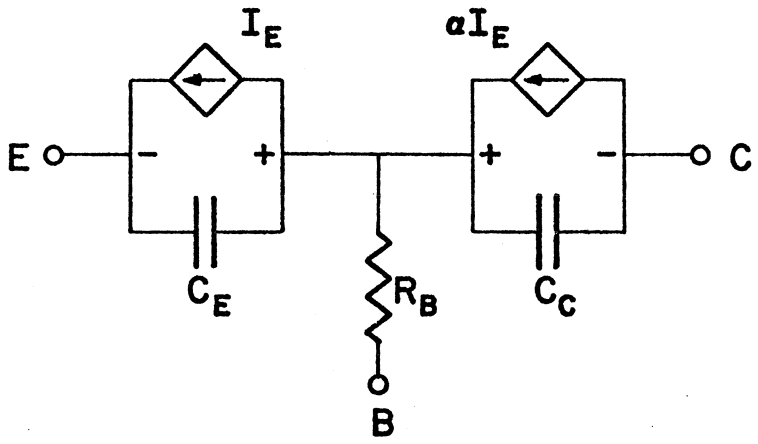
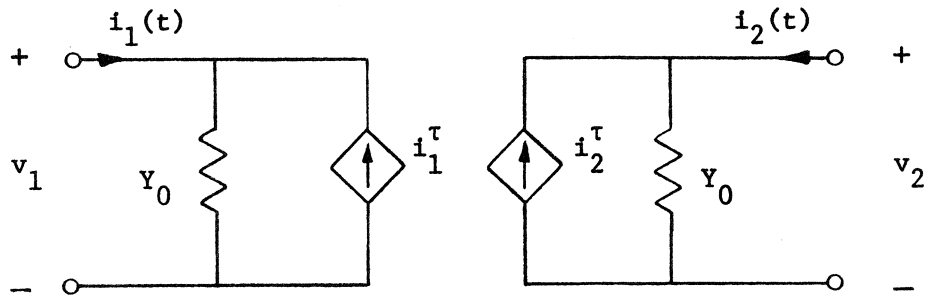


Fig. 5.a. The transistor model.



$$i_1^\tau = Y_0\, v_1(t-\tau) + i_1(t-\tau)$$

$$i_2^\tau = Y_0\, v_2(t-\tau) + i_2(t-\tau)$$

Fig. 5.b. The equivalent circuit of the transmission-line used in the nodal admittance analysis.

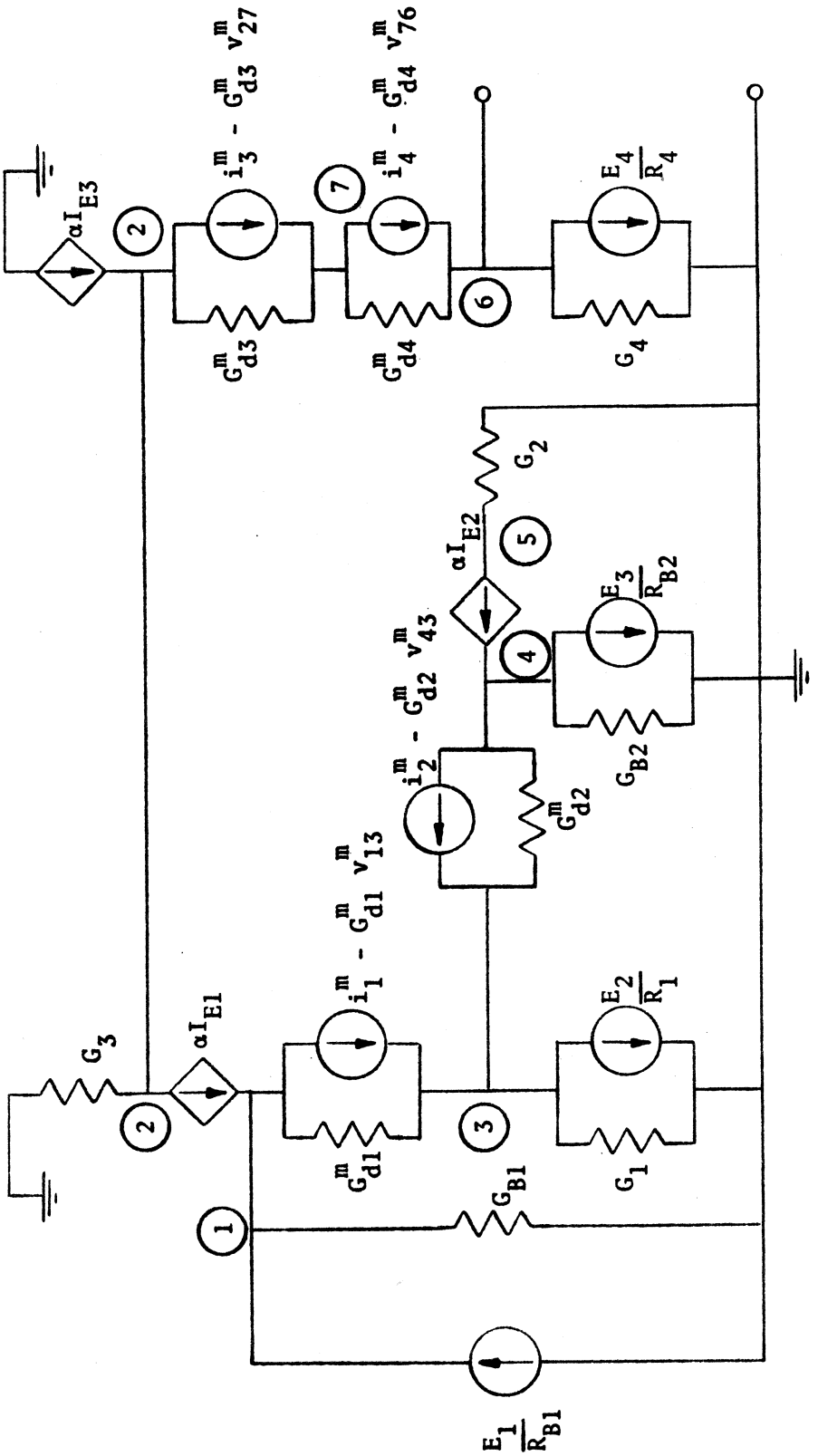


Fig. 6. The CSEF with the transistor and diode model elements (with capacitors removed) replaced by their companion networks for the D.C. analysis.

$$
\begin{bmatrix}
G_{B1}+(1-\alpha)G_{d1}^{m} & & (\alpha-1)G_{d1}^{m} & & & & \\
\alpha G_{d1}^{m} & G_3+(1-\alpha)G_{d3}^{m} & -\alpha G_{d1}^{m} & & & & (\alpha-1)G_{d3}^{m} \\
-G_{d1}^{m} & & G_1+G_{d1}^{m}+G_{d2}^{m} & -G_{d2}^{m} & & & \\
 & & (\alpha-1)G_{d2}^{m} & G_{B2}+(1-\alpha)G_{d2}^{m} & & & \\
 & & -\alpha G_{d2}^{m} & \alpha G_{d2}^{m} & G_2 & & \\
 & & & & & G_4+G_{d4}^{m} & -G_{d4}^{m} \\
 & -G_{d3}^{m} & & & & -G_{d4}^{m} & G_{d4}^{m}+G_{d3}^{m}
\end{bmatrix}
\begin{bmatrix} v_1^{m+1} \\ v_2^{m+1} \\ v_3^{m+1} \\ v_4^{m+1} \\ v_5^{m+1} \\ v_6^{m+1} \\ v_7^{m+1} \end{bmatrix}
=
\begin{bmatrix}
\frac{E_1}{R_{B1}}+(\alpha-1)(i_1^m-G_{d1}^m\, v_{13}^m) \\
-\alpha(i_1^m-G_{d1}^m\, v_{13}^m)+(\alpha-1)(i_3^m-G_{d3}^m\, v_{27}^m) \\
-\frac{E_2}{R_1}+(i_1^m-G_{d1}^m\, v_{13}^m)+(i_2^m-G_{d2}^m\, v_{43}^m) \\
-\frac{E_3}{R_{B2}}+(\alpha-1)(i_2^m-G_{d2}^m\, v_{43}^m) \\
-\alpha(i_2^m-G_{d2}^m\, v_{43}^m) \\
-\frac{E_4}{R_4}+(i_4^m-G_{d4}^m\, v_{76}^m) \\
-(i_4^m-G_{d4}^m\, v_{76}^m)+(i_3^m-G_{d3}^m\, v_{27}^m)
\end{bmatrix}
$$

Fig. 7. Nodal equations of the circuit shown in Fig. 6.

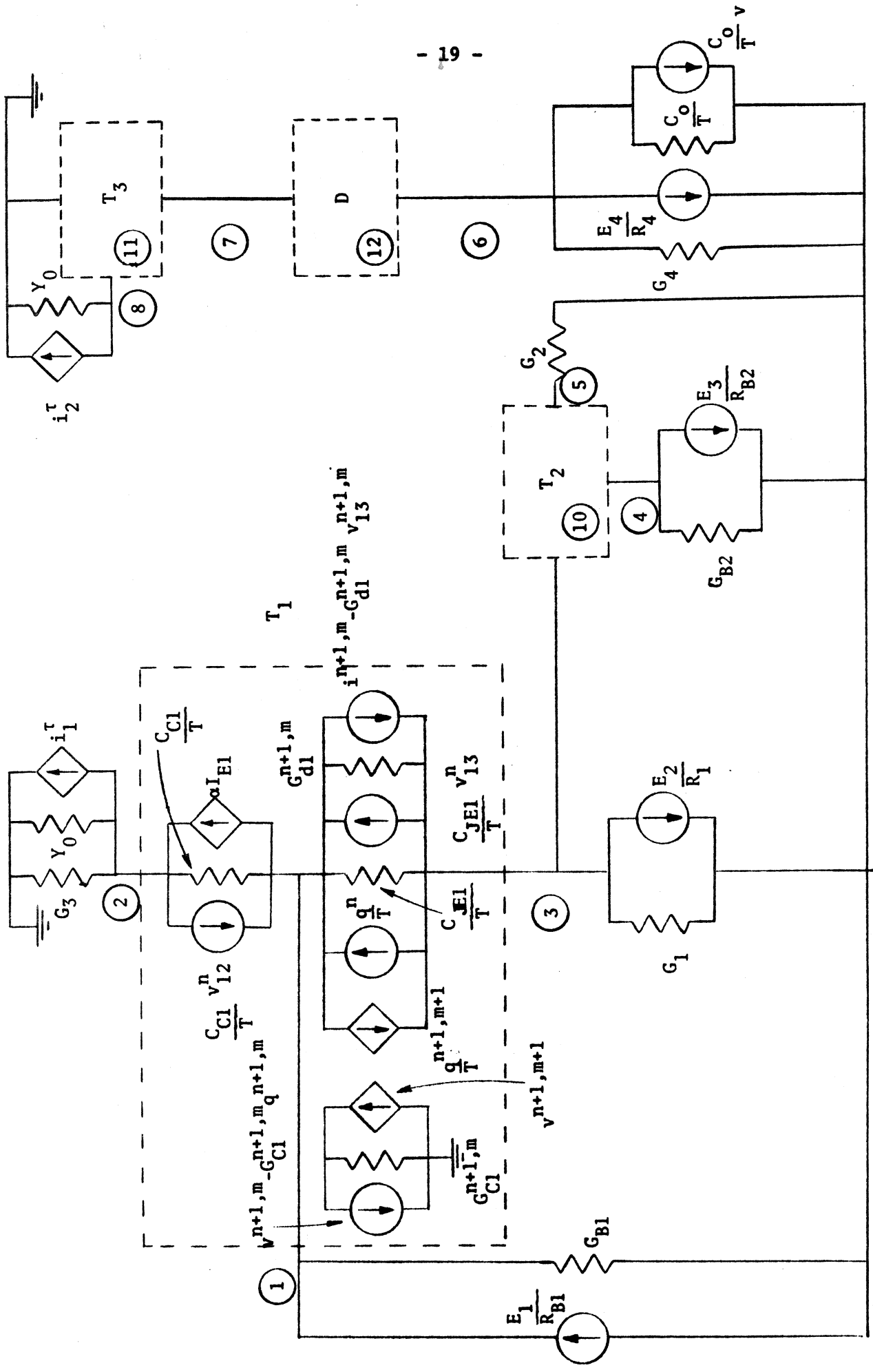


Fig. 8. The CSEF equivalent circuit. T_2 is exactly like T_1, T_3 is T_1 with C_C removed and D is T_1 without the collector junction.

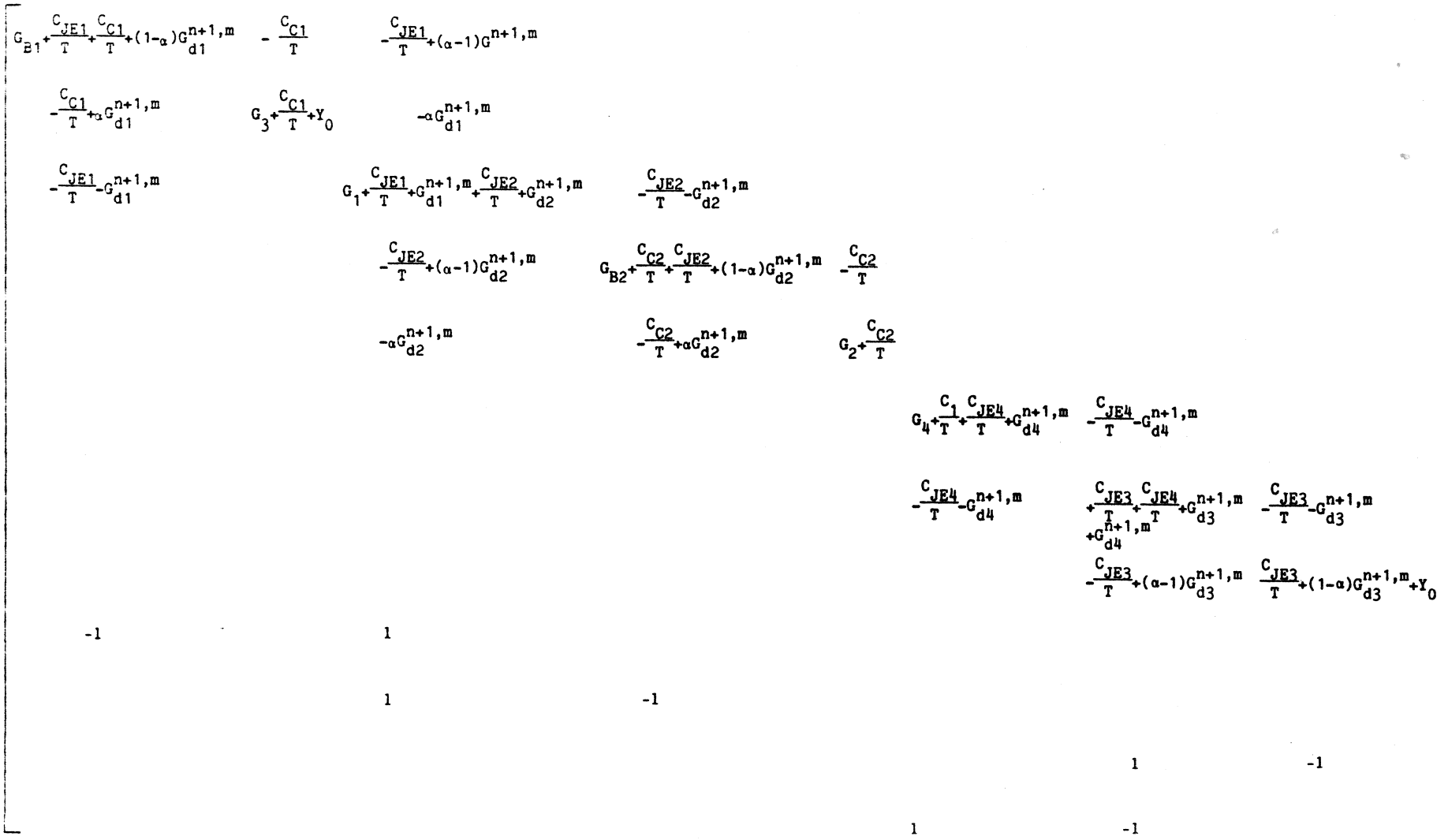


Fig. 9. L.H.S. part of the nodal equations of the circuit shown in Fig. 8.

$$
\begin{bmatrix}
\frac{1}{T} & & & & & & & & & & & \\
 & & & & & & & & & & & \\
-\frac{1}{T} & -\frac{1}{T} & & & & & & & & & & \\
 & \frac{1}{T} & & & & & & & & & & \\
 & & & & & & & & & & & \\
 & & & & -\frac{1}{T} & & & & & & & \\
 & & & -\frac{1}{T} & \frac{1}{T} & & & & & & & \\
 & & & \frac{1}{T} & & & & & & & & \\
G^{n+1,m}_{C_1} & & & & & & & & & & & \\
 & G^{n+1,m}_{C_2} & & & & & & & & & & \\
 & & & G^{n+1,m}_{C_3} & & & & & & & & \\
 & & & & G^{n+1,m}_{C_4} & & & & & & &
\end{bmatrix}
\begin{bmatrix}
v_1^{n+1,m+1} \\ v_2^{n+1,m+1} \\ v_3^{n+1,m+1} \\ v_4^{n+1,m+1} \\ v_5^{n+1,m+1} \\ v_6^{n+1,m+1} \\ v_7^{n+1,m+1} \\ v_8^{n+1,m+1} \\ v_9^{n+1,m+1} \\ v_{10}^{n+1,m+1} \\ v_{11}^{n+1,m+1} \\ v_{12}^{n+1,m+1}
\end{bmatrix}
=
\begin{bmatrix}
\frac{C_{JE1}}{T}(v_1^n - v_3^n) + \frac{q_1^n}{T} + (\alpha-1)(i_1^{n+1,m} - G_{d1}^{n+1,m}\, v_{13}^{n+1,m}) + \frac{C_{C1}}{T} v_{12}^n + \frac{E_1}{R_{B1}} \\
-\frac{C_{C1}}{T} v_{12}^n + i_2^\tau - \alpha(i_1^{n+1,m} - G_{d1}^{n+1,m}\, v_{13}^{n+1,m}) \\
-\frac{E_2}{R} - \frac{q_1^n}{T} + \frac{C_{JE1}}{T} v_{13}^n + (i_1^{n+1,m} - G_{d1}^{n+1,m}\, v_{13}^{n+1,m}) - \frac{C_{JE2}}{T} v_{43}^n + (i_2^{n+1} - G_{d2}^{n+1,m}\, v_{43}^{n+1,m}) - \frac{q_2^n}{T} \\
-\frac{E_3}{R_{B2}} + \frac{C_{JE2}}{T} v_{43}^n + (\alpha-1)(i_2^{n+1,m} - G_{d2}^{n+1,m}\, v_{43}^{n+1,m}) + \frac{q_2^n}{T} + \frac{C_{C2}}{T} v_{45}^n \\
-\frac{C_{C2}}{T} v_{45}^n - \alpha(i_2^{n+1,m} - G_{d2}^{n+1,m}\, v_{43}^{n+1,m}) \\
-\frac{E_4}{R_4} - \frac{C_1}{T} v_6^n + (i_4^{n+1,m} - G_{d4}^{n+1,m}\, v_{76}^{n+1,m}) - \frac{q_4^n}{T} - \frac{C_{JE4}}{T} v_{76}^n \\
-(i_4^{n+1,m} - G_{d4}^{n+1,m}\, v_{76}^{n+1,m}) + (i_3^{n+1,m} - G_{d3}^{n+1,m}\, v_{87}^{n+1,m}) - \frac{C_{JE3}}{T} v_{87}^n - \frac{q_3^n}{T} + \frac{q_4^n}{T} + \frac{C_{JE4}}{T} v_{76}^n \\
\frac{q_3^n}{T} + \frac{C_{JE3}}{T} v_{87}^n + (\alpha-1)(i_3^{n+1,m} - G_{d3}^{n+1,m}\, v_{87}^{n+1,m}) + i_1^\tau \\
-v_{13}^{n+1,m} + G_{C_1}^{n+1,m}\, q_1^{n+1,m} \\
-v_{43}^{n+1,m} + G_{C_2}^{n+1,m}\, q_2^{n+1,m} \\
-v_{87}^{n+1,m} + G_{C_3}^{n+1,m}\, q_3^{n+1,m} \\
-v_{76}^{n+1,m} + G_{C_4}^{n+1,m}\, q_4^{n+1,m}
\end{bmatrix}
$$

Fig. 9. (cont.)R.H.S. part of the nodal equations of the circuit shown in Fig. 8.

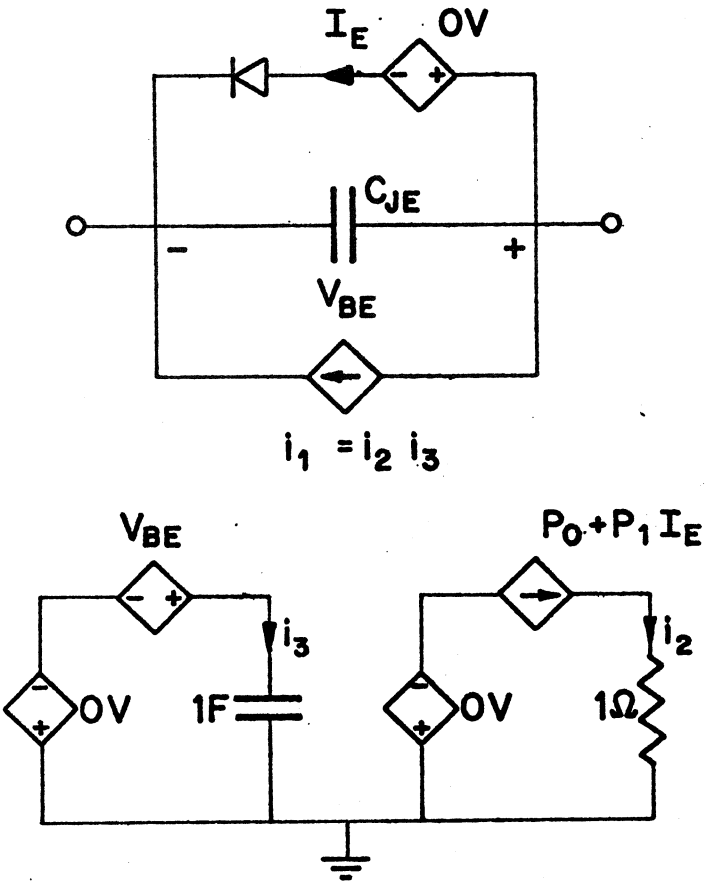


Fig. 10. An equivalent circuit for the transistor emitter junction supplied to SPICE2.

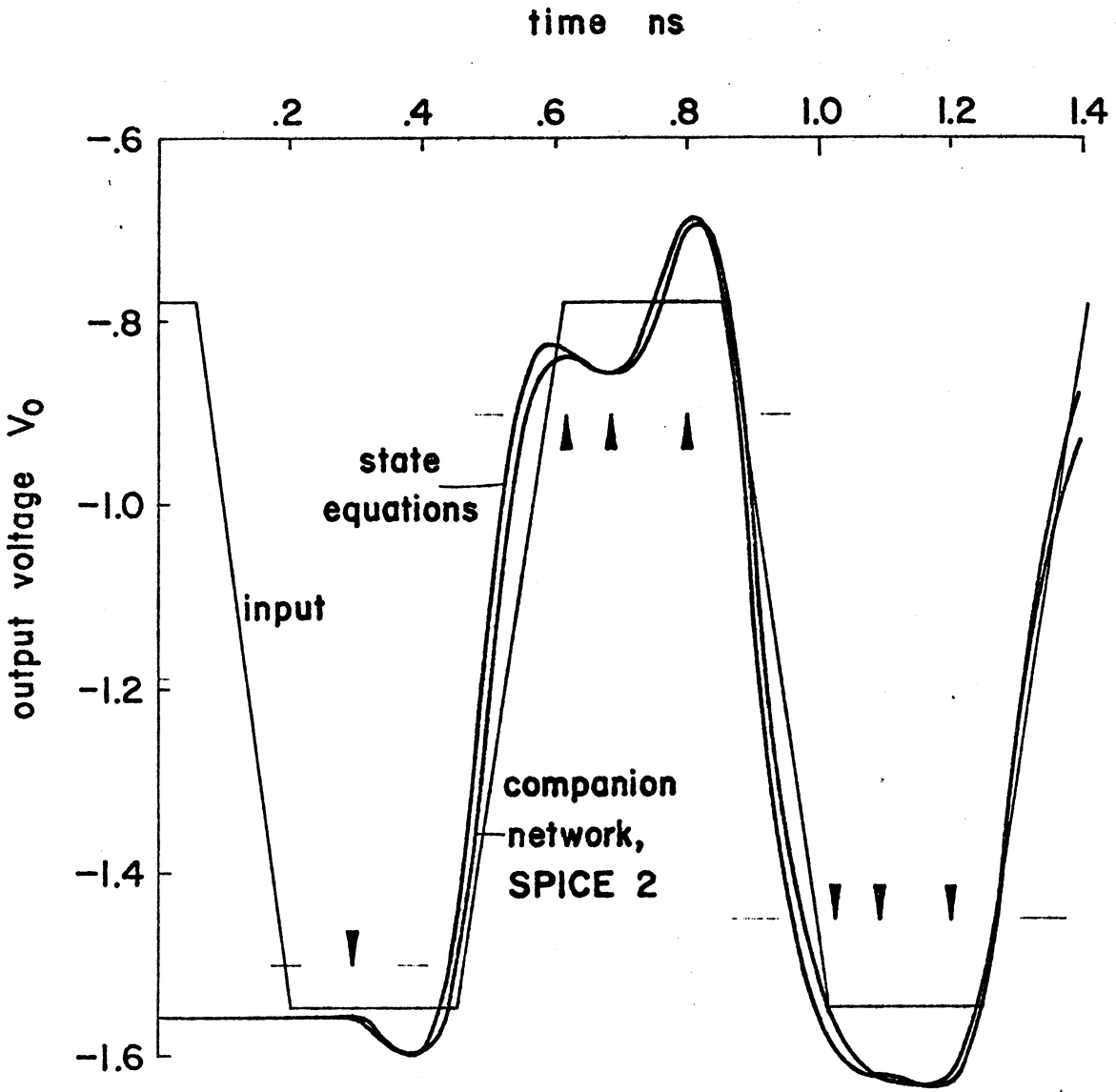


Fig. 11. Response of the CSEF circuit obtained by the companion network approach, SPICE2 and the state equations approach with the parameter values given in Tables 1,2,3 and 4.

Appendix A

Listing of the analysis programs of the CSEF circuit

A1) in the steady-state case (the capacitors removed)

A2) in the transient case.

```
      PROGRAM TST (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)                10
      DIMENSION G(7,7),V(7),C(7),Y(7,7)                                  20
C                                                                        30
C     DEFINE TRANSISTOR AND DIODE PARAMETERS                             40
C                                                                        50
      CSAT=.6E-9                                                         60
      SAT2=CSAT                                                          70
      AL=38.668                                                          80
      ALCS=2.32008E-8                                                    90
      ALCS2=ALCS                                                        100
      ALPH=.99                                                          110
      A=.01                                                             120
      B=-A                                                              130
C                                                                       140
C     DEFINE NETWORK PARAMETER VALUES                                   150
C                                                                       160
      CB=1./50.                                                         170
      C1=1./281.33                                                      180
      C2=1./75.                                                         190
      C3=1./78.24                                                       200
      C4=1./45.533                                                      210
      CUR1=-.776*CB                                                     220
      CUR2=C1*4.03                                                      230
      CUR3=CB*1.13                                                      240
      CUR4=C4*1.655                                                     250
C                                                                       260
      DO 1 I=1,7                                                        270
      DO 1 J=1,7                                                        280
      G(I,J)=0.                                                         290
1     CONTINUE                                                          300
      DO 2 I=1,7                                                        310
      V(I)=0.                                                           320
2     CONTINUE                                                          330
      V(1)=-.781                                                        340
      V(2)=-.7782                                                       350
      V(3)=-1.211                                                       360
      V(4)=-1.13                                                        370
      V(5)=-1.177E-5                                                    380
      V(6)=-1.57                                                        390
      V(7)=-1.175                                                       400
      M=0                                                               410
20     M=M+1                                                            420
      V13=V(1)-V(3)                                                     430
      V43=V(4)-V(3)                                                     440
      V27=V(2)-V(7)                                                     450
      V76=V(7)-V(6)                                                     460
      E1=EXP(AL*V13)                                                    470
      E2=EXP(AL*V43)                                                    480
      E3=EXP(AL*V27)                                                    490
      E4=EXP(AL*V76)                                                    500
      GD1=ALCS*E1                                                       510
      GD2=ALCS*E2                                                       520
      GD3=ALCS*E3                                                       530
      GD4=ALCS2*E4                                                      540
      G(1,1)=GB+A*GD1                                                   550
      G(1,3)=B*GD1                                                      560
      Z1=ALPH*GD1                                                       570
      G(2,1)=Z1                                                         580
      G(2,2)=G3+A*GD3                                                   590
      G(2,3)=-Z1                                                        600
      G(2,7)=B*GD3                                                      610
C                                                                       620
      G(3,1)=-GD1                                                       630
      G(3,3)=G1+GD1+GD2                                                 640
      G(3,4)=-GD2                                                       650
C                                                                       660
      G(4,3)=B*GD2                                                      670
      G(4,4)=GB+A*GD2                                                   680
      Z3=-ALPH*GD2                                                      690
      G(5,3)=Z3                                                         700
      G(5,4)=-Z3                                                        710
      G(5,5)=G2                                                         720
      G(6,6)=G4+GD4                                                     730
      G(6,7)=-GD4                                                       740
```

```
      G(7,2)=-GD3                                                        750
      G(7,6)=-GD4                                                        760
      G(7,7)=GD4+GD3                                                     770
C                                                                        780
C     LOAD CURRENT VECTOR                                                790
C     DEFINE CURRENT SOURCES WITH SUPERSCRIPT N+1,M                      800
C                                                                        810
      C1=CSAT*(E1-1.)-GD1*V13                                            820
      C2=CSAT*(E2-1.)-GD2*V43                                            830
      C3=CSAT*(E3-1.)-GD3*V27                                            840
      C4=SAT2*(E4-1.)-GD4*V76                                            850
      C(1)=CUR1+B*C1                                                     860
      C(2)=-ALPH*C1+B*C3                                                 870
      C(3)=-CUR2+C1+C2                                                   880
      C(4)=-CUR3+B*C2                                                    890
      C(5)=-ALPH*C2                                                      900
      C(6)=-CUR4+C4                                                      910
      C(7)=-C4+C3                                                        920
C                                                                        930
C                                                                        940
C     STORE THE G MATRIX BEFORE GAUSS ELIMINATION                        950
C                                                                        960
      DO 3 I=1,7                                                         970
      DO 3 J=1,7                                                         980
      Y(I,J)=G(I,J)                                                      990
3     CONTINUE                                                          1000
      CALL GELG(C,G,7,1,1.E-3,IER)                                      1010
      ERR=0.                                                            1020
      DO 4 I=1,7                                                        1030
      W=V(I)-C(I)                                                       1040
      ERR=ERR+W*W                                                       1050
4     V(I)=C(I)                                                         1060
C                                                                       1070
C     TEST CONVERGENCE AND RESTORE THE G MATRIX                         1080
C                                                                       1090
      DO 5 I=1,7                                                        1100
      DO 5 J=1,7                                                        1110
      G(I,J)=Y(I,J)                                                     1120
5     CONTINUE                                                          1130
      WRITE(6,500)  M                                                   1140
500   FORMAT(50X,I5)                                                    1150
      IF(ERR.GT.1.E-16.AND.M.LT.25) GO TO 20                            1160
C                                                                       1170
C     PRINT OUTPUT                                                      1180
      WRITE(6,50) (V(I),I=1,7)                                          1190
50    FORMAT(5X,7E16.8)                                                 1200
      STOP                                                              1210
      END                                                               1220
```

```
      PROGRAM TST ( INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)                    10
      DIMENSION G( 12,12),V( 12),C( 12),Y( 12,12),VV1( 100),VV2( 100),AI1( 100)  20
     $,AI2( 100),E(2)                                                         30
      LOGICAL IND1                                                            40
      DATA EU,EB,SL/0.776,1.552,-5.17333333/                                  50
C                                                                             60
C     NK IS THE NUMBER OF NODES                                               70
C     T IS THE TIME STEP                                                      80
C     KF IS THE TAU OF THE TRANSMISSION LINE/T                                90
C                                                                             100
      NK=12                                                                   110
      KF=100                                                                  120
      MR=0                                                                    130
      K=0                                                                     140
      KK=0                                                                    150
      DO 400 I=1,KF                                                           160
      AI1( I)=0.                                                              170
      AI2( I)=0.                                                              180
      VV1( I)=0.                                                              190
      VV2( I)=0.                                                              200
400   CONTINUE                                                                210
C                                                                             220
      IND1=.TRUE.                                                             230
      TIM=0.                                                                  240
      T=.25E-11                                                               250
      CX1=0.                                                                  260
      CX2=0.                                                                  270
C                                                                             280
C     DEFINE PARAMETERS OF THE TRANSISTORS AND DIODE                          290
C                                                                             300
      CSAT=.6E-9                                                              310
      SAT2=CSAT                                                               320
      AL=38.668                                                               330
      ALCS=2.32008E-8                                                         340
      ALCS2=ALCS                                                              350
      TT=.01E-9                                                               360
      TX1=TT*CSAT                                                             370
      TZ=TX1/T                                                                380
      TX2=TT*SAT2                                                             390
      TZ2=TX2/T                                                               400
      TMAX=1.4E-9                                                             410
C                                                                             420
C     DEFINE THE CONSTANT ELEMENTS VALUES                                     430
C                                                                             440
      ALPH=.99                                                                450
      A=.01                                                                   460
      B=-A                                                                    470
      GB=1./50.                                                               480
      X1=.12E-12/T                                                            490
      X2=.5E-12/T                                                             500
      X3=1.248E-12/T                                                          510
      XP=X1+X1                                                                520
      G1=1./281.33                                                            530
      G2=1./75.                                                               540
      G3=1./78.24                                                             550
      G4=1./45.533                                                            560
      YO=1./92.004                                                            570
      CUR2=G1*4.03                                                            580
      CUR3=GB*1.13                                                            590
      CUR4=G4*1.655                                                           600
C                                                                             610
      DO 1 I=1,NK                                                             620
      DO 1 J=1,NK                                                             630
      G( I,J)=0.                                                              640
1     CONTINUE                                                                650
      X4=GB+X1+X2                                                             660
      X5=G1+X1                                                                670
      X6=X4+X1                                                                680
      X7=G4+X3                                                                690
      X8=X1+YO                                                                700
      X9=1./T                                                                 710
C                                                                             720
C     CONSTANT ELEMENTS IN THE G MATRIX                                       730
C                                                                             740
```

```
      G(1,2)=-X2                                                        750
      G(1,9)=X9                                                         760
      G(2,2)=G3+X2+YO                                                   770
      G(3,9)=-X9                                                        780
      G(3,10)=-X9                                                       790
      G(4,5)=-X2                                                        800
      G(4,10)=X9                                                        810
      G(5,5)=G2+X2                                                      820
      G(6,12)=-X9                                                       830
      G(7,11)=-X9                                                       840
      G(7,12)=X9                                                        850
      G(8,11)=X9                                                        860
      G(9,1)=-1.                                                        870
      G(9,3)=1.                                                         880
      G(10,3)=1.                                                        890
      G(10,4)=-1.                                                       900
      G(11,7)=1.                                                        910
      G(11,8)=-1.                                                       920
      G(12,6)=1.                                                        930
      G(12,7)=-1.                                                       940
C                                                                       950
C     INITIAL CONDITIONS (OBTAINED FROM STEADY STATE ANALYSIS)          960
C                                                                       970
      DO 2 I=1,NK                                                       980
      V(I)=0.                                                           990
2     CONTINUE                                                         1000
      V(1)=-.78100994                                                  1010
      V(2)=-.77778347                                                  1020
      V(3)=-1.2111048                                                  1030
      V(4)=-1.1300                                                     1040
      V(5)=-.9807813E-6                                                1050
      V(6)=-1.557929                                                   1060
      V(7)=-1.1678564                                                  1070
      V(8)=V(2)                                                        1080
      CX1=V(2)*YO                                                      1090
      CX2=CX1                                                          1100
C                                                                      1110
      M=0                                                              1120
10    TIM=TIM+T                                                        1130
      K=K+1                                                            1140
      MR=MR+1                                                          1150
C                                                                      1160
C     SET UP VARIABLES WITH N, AND CONSTANT WITH M                     1170
C                                                                      1180
      VN13=V(1)-V(3)                                                   1190
      VN12=V(1)-V(2)                                                   1200
      VN43=V(4)-V(3)                                                   1210
      VN76=V(7)-V(6)                                                   1220
      VN45=V(4)-V(5)                                                   1230
      VN87=V(8)-V(7)                                                   1240
      VN6=-V(6)                                                        1250
      CUR5=X1*VN13                                                     1260
      CUR6=X2*VN12                                                     1270
      CUR7=X1*VN43                                                     1280
      CUR8=X2*VN45                                                     1290
      CUR9=X3*VN6                                                      1300
      CUR10=X1*VN87                                                    1310
      CUR11=X1*VN76                                                    1320
      Q1N=TZ*(EXP(AL*VN13)-1.)                                         1330
      Q2N=TZ*(EXP(AL*VN43)-1.)                                         1340
      Q3N=TZ*(EXP(AL*VN87)-1.)                                         1350
      Q4N=TZ2*(EXP(AL*VN76)-1.)                                        1360
      IF(IND1) GO TO 7                                                 1370
      J=K-KK                                                           1380
      CX1=YO*VV1(J)+AI1(J)                                             1390
      CX2=YO*VV2(J)+AI2(J)                                             1400
7     CONTINUE                                                         1410
C                                                                      1420
C     DEFINE INPUT VOLTAGE                                             1430
C                                                                      1440
      IF(K.GT.20) GO TO 221                                            1450
      E(1)=EU                                                          1460
      GO TO 229                                                        1470
221   IF(K.GT.80) GO TO 222                                            1480
```

```
      E(1)=EU-SL*(TIM-0.05E-9)/1.E-9                                    1490
      GO TO 229                                                         1500
222   IF(K.GT.180) GO TO 223                                            1510
      E(1)=EB                                                           1520
      GO TO 229                                                         1530
223   IF(K.GT.240) GO TO 224                                            1540
      E(1)=EB+SL*(TIM-0.45E-9)/1.E-9                                    1550
      GO TO 229                                                         1560
224   IF(K.GT.340) GO TO 225                                            1570
      E(1)=EU                                                           1580
      GO TO 229                                                         1590
225   IF(K.GT.400) GO TO 226                                            1600
      E(1)=EU-SL*(TIM-0.85E-9)/1.E-9                                    1610
      GO TO 229                                                         1620
226   IF(K.GT.500) GO TO 227                                            1630
      E(1)=EB                                                           1640
      GO TO 229                                                         1650
227   E(1)=EB+SL*(TIM-1.25E-9)/1.E-9                                    1660
229   CONTINUE                                                          1670
      CUR1=-E(1)*GB                                                     1680
C                                                                       1690
C     SET UP THE REST OF G MATRIX(VARIABLE ENTRIES)                     1700
C     WITH SUPERSCRIPT N+1,M                                            1710
C                                                                       1720
20     M=M+1                                                          1730
      V13=V(1)-V(3)                                                     1740
      V43=V(4)-V(3)                                                     1750
      V76=V(7)-V(6)                                                     1760
      V87=V(8)-V(7)                                                     1770
      E1=EXP(AL*V13)                                                    1780
      E2=EXP(AL*V43)                                                    1790
      E3=EXP(AL*V87)                                                    1800
      E4=EXP(AL*V76)                                                    1810
      GD1=ALCS*E1                                                       1820
      GD2=ALCS*E2                                                       1830
      GD3=ALCS*E3                                                       1840
      GD4=ALCS2*E4                                                      1850
      GC1=1./(TT*GD1)                                                   1860
      GC2=1./(TT*GD2)                                                   1870
      GC3=1./(TT*GD3)                                                   1880
      GC4=1./(TT*GD4)                                                   1890
C                                                                       1900
      G(1,1)=X4+A*GD1                                                   1910
      G(1,3)=-X1+B*GD1                                                  1920
      Z1=ALPH*GD1                                                       1930
      G(2,1)=-X2+Z1                                                     1940
      G(2,3)=-Z1                                                        1950
      G(3,1)=-X1-GD1                                                    1960
      G(3,3)=G1-G(3,1)+X1+GD2                                           1970
      G(3,4)=-X1-GD2                                                    1980
      Z2=A*GD2                                                          1990
      G(4,3)=-X1-Z2                                                     2000
      G(4,4)=X4+Z2                                                      2010
      Z3=-ALPH*GD2                                                      2020
      G(5,3)=Z3                                                         2030
      G(5,4)=-X2-Z3                                                     2040
      G(6,6)=X7+GD4+X1                                                  2050
      G(6,7)=-GD4-X1                                                    2060
      G(7,6)=-GD4-X1                                                    2070
      G(7,7)=XP+GD3+GD4                                                 2080
      G(7,8)=-X1-GD3                                                    2090
      Z4=A*GD3                                                          2100
      G(8,7)=-X1-Z4                                                     2110
      G(8,8)=YO-G(8,7)                                                  2120
      G(9,9)=GC1                                                        2130
      G(10,10)=GC2                                                      2140
      G(11,11)=GC3                                                      2150
      G(12,12)=GC4                                                      2160
C                                                                       2170
C     LOAD CURRENT VECTOR                                               2180
C     DEFINE CURRENT SOURCES WITH SUPERSCRIPT N+1,M                     2190
C                                                                       2200
      C1=CSAT*(E1-1.)-GD1*V13                                           2210
      C2=CSAT*(E2-1.)-GD2*V43                                           2220
```

```
      C3=CSAT*(E3-1.)-GD3*V87                                          2230
      C4=SAT2*(E4-1.)-GD4*V76                                          2240
C                                                                      2250
      C(1)=CUR5+Q1N-A*C1+CUR6+CUR1                                     2260
      C(2)=-CUR6-ALPH*C1+CX2                                           2270
      C(3)=-CUR2-Q1N-CUR5+C1-Q2N-CUR7+C2                               2280
      C(4)=-CUR3+CUR7-A*C2+Q2N+CUR8                                    2290
      C(5)=-CUR8-ALPH*C2                                               2300
      C(6)=-CUR4-CUR9+C4-Q4N-CUR11                                     2310
      C(7)=-C4+C3-CUR10-Q3N+Q4N+CUR11                                  2320
      C(8)=Q3N+CUR10-A*C3+CX1                                          2330
C                                                                      2340
      C(9)=-V13+GC1*TX1*(E1-1.)                                        2350
      C(10)=-V43+GC2*TX1*(E2-1.)                                       2360
      C(11)=-V87+GC3*TX1*(E3-1.)                                       2370
      C(12)=-V76+GC4*TX2*(E4-1.)                                       2380
C                                                                      2390
C     STORE THE G MATRIX BEFORE GAUSS ELIMINATION                      2400
C                                                                      2410
      DO 3 I=1,NK                                                      2420
      DO 3 J=1,NK                                                      2430
      Y(I,J)=G(I,J)                                                    2440
3     CONTINUE                                                         2450
      CALL GELG(C,G,NK,1,1.E-3,IER)                                    2460
      ERR=0.                                                           2470
      DO 4 I=1,NK                                                      2480
      W=V(I)-C(I)                                                      2490
      ERR=ERR+W*W                                                      2500
4     V(I)=C(I)                                                        2510
C                                                                      2520
C     TEST CONVERGENCE AND RESTORE THE G MATRIX                        2530
C                                                                      2540
      DO 5 I=1,NK                                                      2550
      DO 5 J=1,NK                                                      2560
      G(I,J)=Y(I,J)                                                    2570
5     CONTINUE                                                         2580
      IF(ERR.GT.1.E-12.AND.M.LT.15) GO TO 20                           2590
C                                                                      2600
      VV1(MR)=V(2)                                                     2610
      VV2(MR)=V(8)                                                     2620
      AI1(MR)=YO*V(2)-CX2                                              2630
      AI2(MR)=YO*V(8)-CX1                                              2640
C     PRINT OUTPUT                                                     2650
      MK=MOD(K,5)                                                      2660
      IF(MK.NE.0) GO TO 22                                             2670
      WRITE(6,40) TIM,M,V(6)                                           2680
22    IF(K.GE.KF) IND1=.FALSE.                                         2690
      IF(TIM.GE.TMAX)  STOP                                            2700
      M=0                                                              2710
      MM=MOD(K,KF)                                                     2720
      IF(MM.NE.0) GO TO 10                                             2730
      KK=KK+KF                                                         2740
      MR=0                                                             2750
      GO TO 10                                                         2760
C                                                                      2770
40    FORMAT(20X,E16.8,10X,I5,10X,E16.8,/)                             2780
50    FORMAT(5X,11E10.4)                                               2790
101   FORMAT(E16.8)                                                    2800
500   FORMAT(50X,I5)                                                   2810
      END                                                              2820
```

Appendix B

Data, supplied to SPICE2, for the CSEF circuit

B1) with the equivalent circuit of the emitter junction

B2) with built-in transistor models.

```
CURRENT SWITCH EMITTER FOLLOWER                                                  10
R1    4   5   281.33                                                           20
R2     7   0   75.                                                            30
R3     2    0   78.24                                                         40
R4    10   1   45.533                                                         50
CO       10   0   1.248E-12                                                   60
T1       2   0   8   0 Z0=92.004   TD=.25NS                                   70
VJ2      0   5    DC 4.03                                                     80
VE3      0    6     DC    1.13                                               90
VE4      0    1    DC   1.655                                                100
VE1      3   0   PWL(0   -.776   .05NS   -.776   .2NS   -1.55   .45NS -1.55   .6NS   110
+-.776   .85NS    -.776   1.NS   -1.55   1.25NS   -1.55   1.4NS   -.776)       120
D1    9   10    DMOD                                                           130
D2       13   4  DMOD                                                         140
D3     14   4   DMOD                                                          150
D4     15   9   DMOD                                                          160
CE1    11   4   0.12P                                                         170
CC1    11   2   0.5P                                                          180
CE2    12   4   0.12P                                                         190
CC2    12   7   0.5P                                                          200
CE3    8   9   0.12P                                                         210
RB1    3   11   50.                                                           220
RB2    12   6   50.                                                           230
RT1    17   0   1.                                                            240
RT2    20   0   1.                                                            250
RT3    23   0   1.                                                            260
CT1    25   0   1.E-8                                                         270
CT2    26   0   1.E-8                                                         280
CT3    27   0   1.E-8                                                         290
VT1    11   13   DC   0.                                                      300
VT2    12   14   DC   0.                                                      310
VT3    8   15   DC   0.                                                       320
VT4    16   17   DC   0.                                                      330
VT5    19   20   DC   0.                                                      340
VT6    22   23   DC   0.                                                      350
VT7    18   25   DC 0.                                                        360
VT8    21   26   DC   0.                                                      370
VT9    24   27   DC   0.                                                      380
E1     18   0   13   4   1                                                    390
E2     21   0   14   4   1                                                    400
E3     24   0   15   9   1                                                    410
F1     2   11   VT1   0.99                                                    420
F2     7   12    VT2    0.99                                                  430
F3     0   8   VT3   0.99                                                     440
F4     0   16   VT1   2.3200E-10    3.8668E-2                                 450
F5     0   19    VT2   2.32008E-10   3.8668E-2                               460
F6     0   22   VT3   2.32008E-10    3.8668E-2                               470
F7     11   4   POLY(2)   VT4   VT7   0 0 0 0 1                              480
F8     12   4   POLY(2)   VT5   VT8   0 0 0 0 1                              490
F9     8   9   POLY(2)   VT6   VT9   0 0 0 0 1                               500
.TRAN    0.0125NS   1.4NS                                                    510
.PRINT TRAN V(10,0)                                                          520
.PLOT   TRAN V(10,0)                                                         530
.MODEL   DMOD D IS=.6E-9                                                     540
.END                                                                         550
```

```
CURRENT SWITCH EMITTER FOLLOWER                                                  10
R1    4   5   281.33                                                           20
R2     7   0   75.                                                            30
R3     2    0   78.24                                                         40
R4    10   1   45.533                                                         50
CQ       10   0   1.248E-12                                                   60
T1      2   0   8   0 Z0=92.004   TD=.25NS                                     70
VE2     0   5    DC 4.03                                                      80
VE3     0    6     DC    1.13                                                90
VE4     0    1    DC   1.655                                                 100
VE1     3   0   PWL(0   -.776   .05NS   -.776   .2NS   -1.55   .45NS -1.55   .6NS   110
+-.776   .85NS    -.776   1.NS   -1.55   1.25NS   -1.55   1.4NS   -.776)      120
D1    9   10    DMOD                                                           130
QT1    2   3   4   QMOD                                                       140
QT2    7   6   4   QMOD                                                       150
QT3    0   8   9   QM1                                                        160
.TRAN    0.0125NS   1.4NS                                                     170
.PRINT TRAN V(10,0)                                                          180
.PLOT   TRAN V(10,0)                                                         190
.MODEL   DMOD D IS=.6E-9                                                     200
.MODEL    QMOD   NPN   BF=99.   IS=.6E-9   RB=50.  TF=.01NS   CJE=0.12PF   CJC=0.   210
+    MC=0.    ME=0.                                                          220
.MODEL    QM1   NPN   BF=99.   IS=.6E-9   TF=.01NS   CJE=0.12PF   ME=0.   MC=0.   230
.END                                                                         240
```

SOC-193

ANALYSIS OF A CURRENT SWITCH EMITTER FOLLOWER USING THE COMPANION NETWORK APPROACH

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Revised:

Key Words: Nonlinear circuit analysis, companion network formulation, integration methods

Abstract: This report demonstrates, in a tutorial fashion, the transient analysis of a nonlinear circuit, namely a current switch emitter follower. The response obtained was checked against other responses obtained by a program which uses the state space formulation for the analysis and by SPICE2.

Description: Contains Fortran listing, user's manual.
The listing contains 336 cards, of which 68 are comment cards.
There are also 79 lines of data for SPICE2.

Related Work: SOC-182, SOC-185, SOC-192, SOC-194.

Price: $15.00.