

Advanced Circuit Analysis



with the HP-28S



EduCALC

27953 CABOT RD
LAGUNA NIGUEL, CA 92677



ADVANCED CIRCUIT ANALYSIS

With the HP-28S

by Robert R. Boyd

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To my Wife LINDA and my Daughter JANA
For still loving a husband/father
who wasn't there.

INTRODUCTION

The purpose of this work is to present a unique method of circuit analysis developed by the author several years ago. However, without a computer the method was not of much practical value for circuits above 3rd order. With a calculator such as the HP-28S, there is a vehicle with which the method can be used on more complicated circuits.

Section I presents the method of setting up the circuit matrices by inspection. Merely by labeling the voltage nodes to be analyzed, and the branch impedances connected to the nodes, the node equations can be written using the principle of superposition. It is not necessary to identify loops, cut sets, trees, chords, links, etc., of the topology. One merely has to know how many impedances are connected to the node in question, and which impedance is connected to the driving voltage. This information can be obtained just by inspection of the circuit.

With linear circuits that contain no dependent sources, the symmetric coefficient matrices using loop or node analysis are very easy to set up. This mnemonic method is presented in just about every undergraduate text on network analysis. However, when dependent sources are introduced, the symmetry disappears along with the mnemonic method. With the technique presented here, the symmetry of the coefficient matrix is of no concern.

Other HP calculators/computers can be used with the material in Section I. A good choice would be an HP-71B with the Math Pac. The HP-41CV or HP-41CX with the Advantage module will also work. Of course, any computer that has complex matrix and double precision capabilities can be used as well.

Section II is exclusively for those readers with HP-28S calculators and familiarity with the operation of the calculator is assumed. Most of the circuits given in section I are analyzed with complete descriptions of the main programs. No attempt has been made to minimize the program code. The interested reader will probably see a better way to do it.

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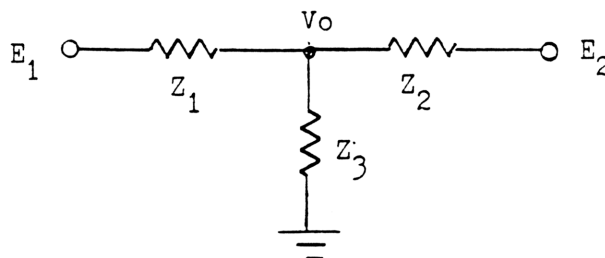
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SECTION I. Setting up The Circuit Matrices.

Notational convention: E => Independent voltage source
V => Dependent voltage source or node voltage
I => Dependent current source or node current
Z => real or complex impedance

Two simple star networks will be analyzed to show a method of solving for the voltage at the center node that is easy to remember. This topology is chosen since any circuit can be formed by combining star networks with 2 or more branches. The method is then generalized to an N-branch star network.

Example 1 Solve for V_o by superposition:
(N = 3)



a. Set $E_2 = 0$, $V_o \rightarrow V_o'$:

$$V_o' = \frac{E_1 Z_2 // Z_3}{Z_1 + Z_2 // Z_3} = \frac{E_1}{1 + \frac{Z_1}{Z_2 // Z_3}}$$

$$\text{Since } Z_2/Z_3 = \frac{1}{\frac{1}{Z_2} + \frac{1}{Z_3}}$$

$$V_o' = \frac{E_1}{1 + Z_1 \left(\frac{1}{Z_2} + \frac{1}{Z_3} \right)}$$

b. Set $E_1 = 0$, $V_o \rightarrow V_o''$:

$$V_o'' = \frac{E_2 Z_1/Z_3}{Z_2 + Z_1/Z_3} = \frac{E_2}{1 + \frac{Z_2}{Z_1/Z_3}}$$

$$V_o'' = \frac{E_2}{1 + Z_2 \left(\frac{1}{Z_1} + \frac{1}{Z_3} \right)}$$

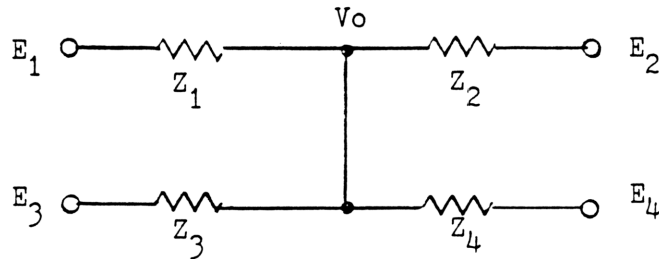
Then by the superposition principle,

$$\begin{aligned} V_o &= V_o' + V_o'' = \frac{E_1}{1 + Z_1 \left(\frac{1}{Z_2} + \frac{1}{Z_3} \right)} + \frac{E_2}{1 + Z_2 \left(\frac{1}{Z_1} + \frac{1}{Z_3} \right)} \\ &= E_1 K_1 + E_2 K_2, \end{aligned}$$

where K_1 and K_2 are dimensionless constants determined by Z_1 , Z_2 , & Z_3 , and are always < 1 .

We try a second example to see if there is a consistent pattern occurring.

Example 2 Solve for V_o by superposition:
($N = 4$)



$$V_o = \frac{E_1 Z_2 // Z_3 // Z_4}{Z_1 + Z_2 // Z_3 // Z_4} + \frac{E_2 Z_1 // Z_3 // Z_4}{Z_2 + Z_1 // Z_3 // Z_4}$$

$$+ \frac{E_3 Z_1 // Z_2 // Z_4}{Z_3 + Z_1 // Z_2 // Z_4} + \frac{E_4 Z_1 // Z_2 // Z_3}{Z_4 + Z_1 // Z_2 // Z_3}$$

$$V_o = \frac{E_1}{1 + \frac{Z_1}{Z_2 // Z_3 // Z_4}} + \frac{E_2}{1 + \frac{Z_2}{Z_1 // Z_3 // Z_4}}$$

$$+ \frac{E_3}{1 + \frac{Z_3}{Z_1 // Z_2 // Z_4}} + \frac{E_4}{1 + \frac{Z_4}{Z_1 // Z_2 // Z_3}}$$

$$V_o = \frac{E_1}{1 + Z_1 \left(\frac{1}{Z_2} + \frac{1}{Z_3} + \frac{1}{Z_4} \right)} + \frac{E_2}{1 + Z_2 \left(\frac{1}{Z_1} + \frac{1}{Z_3} + \frac{1}{Z_4} \right)}$$

$$+ \frac{E_3}{1 + Z_3 \left(\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_4} \right)} + \frac{E_4}{1 + Z_4 \left(\frac{1}{Z_1} + \frac{1}{Z_2} + \frac{1}{Z_3} \right)}$$

$$(2) \quad V_2 = V_1 K_2, \text{ where } K_2 = \frac{1}{1 + \frac{Z_2}{Z_4}}$$

Equations (1) and (2) can be solved for V_1 and V_2 by elimination or by matrix methods. By elimination:

$V_1 = E_1 K_1 + (V_1 K_2) K_2$, substituting (2) into (1). Then

$$(3) \quad V_1 = \frac{E_1 K_1}{1 - K_2 K_2}$$

Substituting (3) into (2) gives V_2 , or

$$V_2 = V_1 K_2 = \frac{E_1 K_1 K_2}{1 - K_2 K_2}$$

Using matrix methods:

Rearranging (1) and (2) so that the independent terms are on the LH side:

$$E_1 K_1 = V_1 - V_2 K_2$$

$$0 = V_2 - V_1 K_2$$

From this form it is easy to construct the coefficient matrix and independent column vector:

$$\begin{vmatrix} 1 & -K_2 \\ -K_2 & 1 \end{vmatrix} \begin{vmatrix} V_1 \\ V_2 \end{vmatrix} = \begin{vmatrix} E_1 K_1 \\ 0 \end{vmatrix}$$

From now on, matrices will be used exclusively. As the circuits get larger and more complicated, solving for the unknown node voltages using algebra and the elimination method becomes too lengthy and error prone.

$$\frac{1}{1 + A \left(\frac{1}{B} + \frac{1}{C} \right)} = F3(A, B, C),$$

$$\frac{1}{1 + A \left(\frac{1}{B} + \frac{1}{C} + \frac{1}{D} \right)} = F4(A, B, C, D).$$

Note, for example, that $F3(B, C, A) = \frac{1}{1 + B \left(\frac{1}{C} + \frac{1}{A} \right)}$

= $F3(B, A, C)$, i.e., after the first variable, the order is not important since the reciprocals can be summed in any order.

(The F functions are not subscripted since this is the way they will appear in HP-28S programs.)

Getting back to Example 4, we can write out the K factors using this functional notation:

$$K1 = F3(Z1, Z2, Z4), \quad K2 = F3(Z4, Z1, Z2)$$

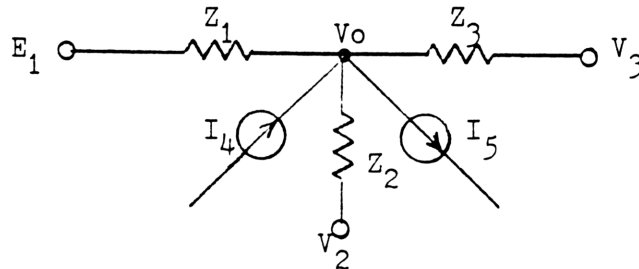
$$K3 = F3(Z2, Z1, Z4), \quad K4 = F3(Z5, Z2, Z3)$$

$$K5 = F3(Z3, Z2, Z5), \quad K6 = F3(Z2, Z3, Z5)$$

Remember that the first Z in F3 is in series with the E or V in question. For example, in $V_i = E_i K_i + \dots$, the first Z in K_i is between V_i and E_i , or Z_i . Be sure to account for all the remaining Z's connected to node V_i ; in this case Z_2 and Z_4 .

One last example before going on to transistor and op-amp circuits:

At this point, we modify our basic star network by adding current sources:



Again, by superposition:

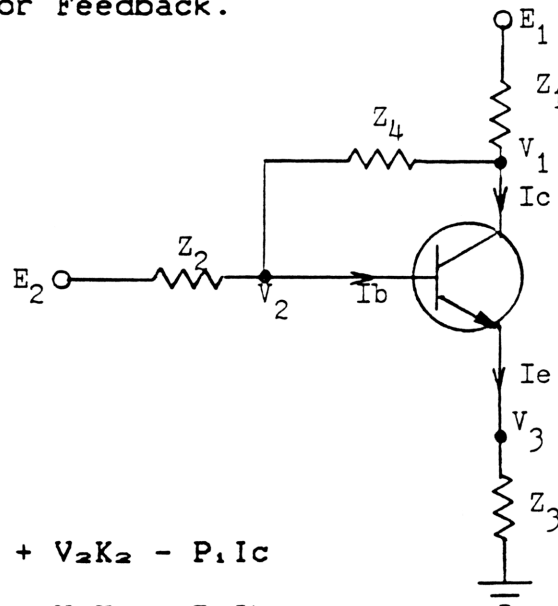
$$V_0 = E_1 K_1 + V_2 K_2 + V_3 K_3 + P_1 I_4 - P_1 I_5,$$

$$\text{where } K_1 = F_3(Z_1, Z_2, Z_3), K_2 = F_3(Z_2, Z_1, Z_3),$$

$$K_3 = F_3(Z_3, Z_1, Z_2), \text{ and } P_1 = Z_1 // Z_2 // Z_3.$$

Note direction of current flow and the sign attached;
toward node => +, away from node => -.

Example 6 Collector Feedback.



Step 1.

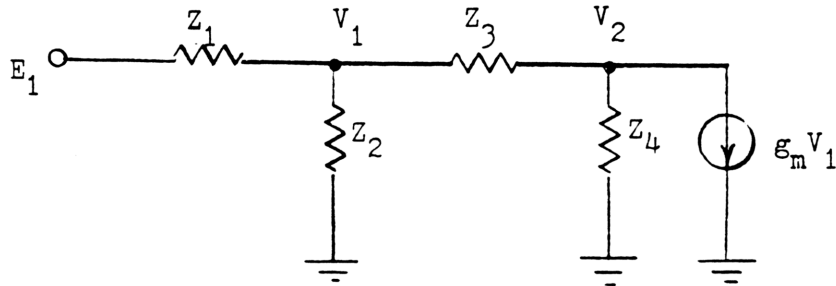
$$V_1 = E_1 K_1 + V_2 K_2 - P_1 I_c$$

$$V_2 = E_2 K_3 + V_1 K_4 - P_2 I_b$$

$$V_3 = Z_3 I_e$$

$$V_2 - V_3 = V_{be} \quad (= 0.6V)$$

Example 7 Common Emitter Hybrid Pi Transistor Model



Note that $(g_m V_1)$ is a voltage-controlled-current-source, or VCCS.

Step 1.

$$V_1 = E_1 K_1 + V_2 K_2$$

$$V_2 = V_1 K_3 - g_m V_1 P_1 = V_1 (K_3 - g_m P_1)$$

Step 2.

$$E_1 K_1 = V_1 - V_2 K_2$$

$$0 = V_2 - V_1 (K_3 - g_m P_1)$$

Step 3.

$$\begin{vmatrix} 1 & -K_2 \\ (g_m P_1 - K_3) & 1 \end{vmatrix} \begin{vmatrix} V_1 \\ V_2 \end{vmatrix} = \begin{vmatrix} E_1 K_1 \\ 0 \end{vmatrix}$$

Step 4.

$$K_1 = F_3(Z_1, Z_2, Z_3), \quad K_2 = F_3(Z_3, Z_1, Z_2)$$

$$K_3 = F_2(Z_3, Z_4), \quad P_1 = Z_3 // Z_4$$

Again, steps 1 thru 4 are no different:

Step 1.

$$V_1 = E_1 K_1 + V_2 K_2$$

$$\begin{aligned} V_2 &= V_1 K_3 + V_2 K_4 = V_1 K_3 - A V_1 K_4 \\ &= V_1 (K_3 - A K_4) \end{aligned}$$

Step 2.

$$E_1 K_1 = V_1 - V_2 K_2$$

$$0 = V_2 - V_1 (K_3 - A K_4)$$

Step 3.

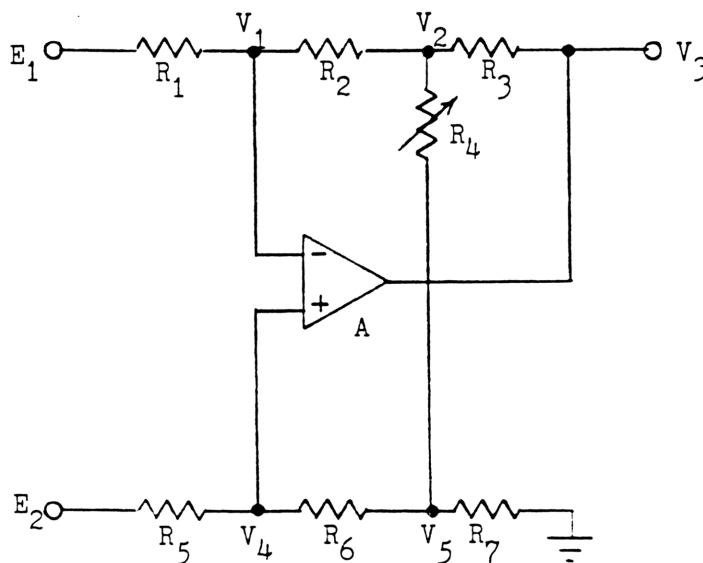
$$\begin{vmatrix} 1 & -K_2 \\ (A K_4 - K_3) & 1 \end{vmatrix} \begin{vmatrix} V_1 \\ V_2 \end{vmatrix} = \begin{vmatrix} E_1 K_1 \\ 0 \end{vmatrix}$$

Step 4

$$K_1 = F_2(Z_1, Z_2), K_2 = F_2(Z_2, Z_1)$$

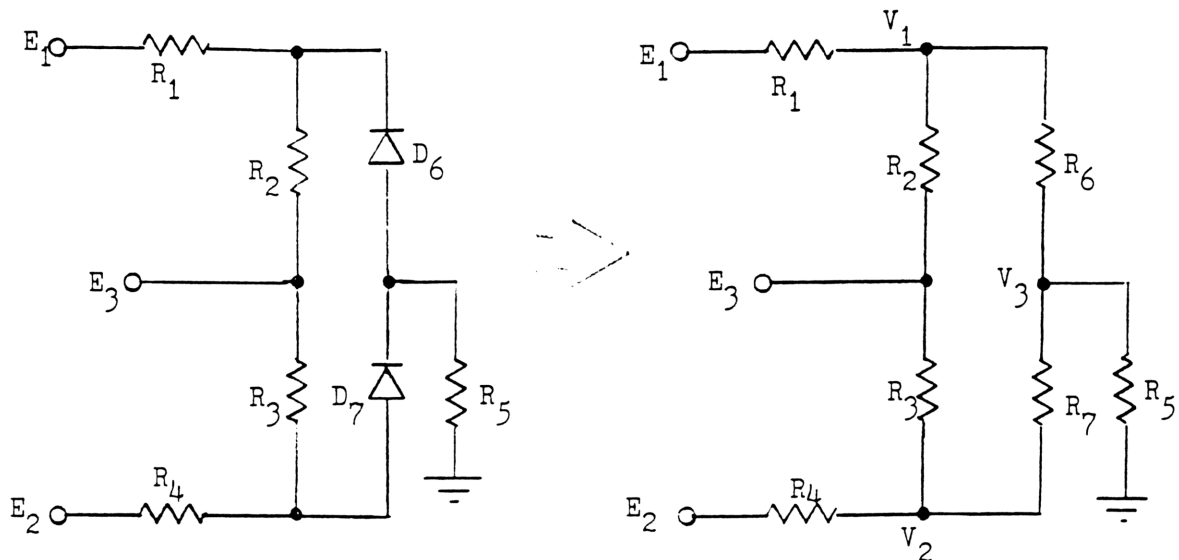
$$K_3 = F_3(Z_2, Z_3, Z_4), K_4 = F_3(Z_4, Z_2, Z_3)$$

Example 9 Adjustable gain differential amplifier.



Example 10 Non-linear Circuits.

Some non-linear diode circuits can be solved by converting the diodes to resistors (in series with a 0.6V source if need be). The method is to monitor the voltages across the resistor (diode) for polarity. If the "diode" becomes reverse biased, then change its value to 10 Megohms. If it becomes forward biased, change its value to, say, 10 ohms.



Step 1 (For the circuit on the right)

$$V_1 = E_1 K_1 + E_3 K_2 + V_3 K_3$$

$$V_2 = E_2 K_4 + E_3 K_5 + V_3 K_6$$

$$V_3 = V_1 K_7 + V_2 K_8$$

Step 1.

$$V_1 = E_1 K_1 + V_2 K_2 + V_4 K_3$$

$$V_2 = V_1 K_4 + V_3 K_5$$

$$V_3 = V_2 K_6 + V_4 K_7$$

$$V_4 = V_1 K_8 + V_3 K_9 + V_4 K_{10}$$

$$V_5 = V_4 K_{11}$$

$$V_4 = A(V_3 - V_5)$$

Step 2.

$$E_1 K_1 = V_1 - V_2 K_2 - V_4 K_3$$

$$0 = V_2 - V_1 K_4 - V_3 K_5$$

$$0 = V_3 - V_2 K_6 - V_4 K_7$$

$$0 = V_4 - V_1 K_8 - V_3 K_9 - V_4 K_{10}$$

$$0 = V_5 - V_4 K_{11}$$

$$0 = V_4 - AV_3 + AV_5$$

Step 3.

$$\begin{vmatrix} 1 & -K_2 & 0 & -K_3 & 0 & 0 \\ -K_4 & 1 & -K_5 & 0 & 0 & 0 \\ 0 & -K_6 & 1 & -K_7 & 0 & 0 \\ -K_8 & 0 & -K_9 & 1 & 0 & -K_{10} \\ 0 & 0 & 0 & 0 & 1 & -K_{11} \\ 0 & 0 & -A & 0 & A & 1 \end{vmatrix} \begin{vmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_4 \end{vmatrix} = \begin{vmatrix} E_1 K_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{vmatrix}$$

Step 1.

$$V_1 = E_1 - I_{e2}Z_1$$

$$V_2 = E_1K_1 + V_3K_2 + Ib_2P_1$$

$$V_3 = V_2 - Ic_1Z_3$$

$$V_4 = E_3 - Ib_1Z_4$$

$$V_5 = E_2K_3 + V_4K_4 + I_{e1}P_2$$

$$V_6 = E_2K_5 + V_5K_6 + Ic_2P_3$$

$$V_{be1} = V_4 - V_5$$

$$V_{be2} = V_1 - V_2$$

Step 2.

$$E_1 = V_1 + (1 + B_2)Ib_2Z_1$$

$$E_1K_1 = V_2 - V_3K_2 - Ib_2P_1$$

$$0 = V_3 - V_2 + B_1Ib_1Z_3$$

$$E_3 = V_4 + Ib_1Z_4$$

$$E_2K_3 = V_5 - V_4K_4 - (1 + B_1)Ib_1P_2$$

$$E_2K_5 = V_6 - V_5K_6 - B_2Ib_2P_3$$

$$V_{be1} = V_4 - V_5$$

$$V_{be2} = V_1 - V_2$$

By now the astute reader has probably seen the similarity of the F3 and F4 K factor functions with the parallel impedance function. There are two alternate formulations of these functions that may result in shorter HP-28S programs.

For example, if

$$K1 = F4(Z1, Z2, Z3, Z4), K2 = F4(Z2, Z1, Z3, Z4), \\ K3 = F4(Z3, Z1, Z2, Z4), K4 = F4(Z4, Z1, Z2, Z3),$$

a shorter way of computing K1 through K4 is

$$K1 = F4(Z1, Z2, Z3, Z4), K2 = (K1 * Z1) / Z2, \\ K3 = (K1 * Z1) / Z3, K4 = (K1 * Z1) / Z4.$$

Note that the denominator of K_i is Z_i , $i = 2, 3, 4$.

Still another way of calculating K1 through K4 is

$$P1 = Z1 // Z2 // Z3 // Z4, \text{ then}$$

$$K1 = P1 / Z1, K2 = P1 / Z2, K3 = P1 / Z3, \text{ and } K4 = P1 / Z4.$$

The form here is $K_i = P1 / Z_i$

Also note that $K1 + K2 + K3 + K4 = 1$.

These methods should be used after becoming familiar with the HP-28S programming structures in section II. For the sake of consistency, the programs in section II will be given using the original method.

'F4'

<< -> a b c d '1/(1+a*(1/b+1/c+1/d))' >>

'PZ2' (Two parallel impedances, e.g., $P1 = Z_1 // Z_2$)

<< INV SWAP INV + INV >>

'PZ3' (Three parallel impedances)

<< PZ2 PZ2 >>

'PZ4' (Four parallel impedances)

<< PZ3 PZ2 >>

We will first solve example 3 (ladder network) using the DC analysis program DCAP given below. For this analysis Z_1 thru Z_4 will become R_1 thru R_4 .

Following this example, the AC analysis program ACAP will be demonstrated using capacitors for two of the branches.

The following short program DCAP should now be written in the CKTAS directory:

'DCAP'

<< KRV SKF MAT CKTAS >>

The four commands are explained as follows:

KRV (K and R Variables) is a subdirectory under the CKTAS parent directory. This subdirectory should be created before running 'DCAP'. Using a subdirectory to store the K factors and component values keeps alot of clutter out of the parent directory CKTAS.

SKF (Store K Factors) is a subprogram that is unique to each circuit. It is used to obtain the component values in the KRV subdirectory and create the K factors. The K factors are then stored under their names, i.e, $K_1 \rightarrow 'K1'$, etc.

The values of $R_1 = 1K$, $R_2 = 2K$, $R_3 = 3K$, and $R_4 = 4K$, should now be stored under their names in the KRV subdirectory. Also store 10 in the variable 'E1'.

The AC analysis program ACAP is a little more involved. However it will not change from circuit to circuit.

'ACAP'

<< 'BF' STO	[BF=beginning frequency]
INV 'PD' STO	[PD=points/decade]
BF + 'ND' STO	[ND=total no. of decades]
ND BF - PD / 1 + 1 ->LIST	
0 0 R->C CON 'VOUT' STO	[VOUT=storage for output]
'VOUT' 1 1 ->LIST	[Put indexed 'VOUT' on stack]
BF ND FOR f f 'F' STO	[Store log frequency]
DCAP	[See DCAP program]
R->P C->R	[Put magnitude & phase angle on stack]
IF 2 FS? THEN SWAP DROP	[Get phase angle if flag 2 set]
ELSE DROP LOG 20 * END	[Else get dB magnitude]
F SWAP R->C PUTI	[Put (F,dB) or (F,angle) in VOUT storage]
PD STEP	[Next frequency]
CLEAR VOUT ARRY-> DROP >>	[Clear and put VOUT on stack]

Note: The CKTAS directory should contain the following objects, not necessarily in the order given: DCAP KRV SKF MAT ACAP P24 P23 P22 F4 F3 F2 SRL PRL HZ PRC SRC C L. The KRV subdirectory should have only components and K factor values plus the directory change program 'UP'.

When finished, the top number on the stack (level 31) should be (2.000,-0.118) in FIX 3 format. The level 1 number should be (5.000,-71.935). To plot this run, clear the stack and enter 0 space -75 BPLT. The corner frequency breakpoint should be very evident at about $\log F = 2.8$ or $F = 631$ Hz. The second breakpoint will occur at $F=13090$ Hz or $\log F = 4.117$.

The slope at $\log F = 5$ is the dB value at $\log F = 4.9$ minus the dB value at $\log F = 5$ divided by the frequency increment of $1/ND$ or

$$\text{slope} = (-71.935 - (-67.939))10 = -39.96 \text{ dB/decade}$$

or approximately -40 dB/decade, which we would expect for a two pole low pass filter.

Pressing ATTN will clear the plot and you should see the name 'VOUT' at level 1. Pressing EVAL, ARRY->, DROP, will return the data points to the stack.

For new component values, neither SKF nor MAT has to be changed. For new component types such as Z1 ---> C1, Z2 ---> R2, Z3 ---> C3, and Z4 ---> R4, (a high pass filter), only SKF has to be changed. Of course, for a new circuit topology, e.g. twin-T, both SKF and MAT will have to be changed.

Example 4, the lattice network is omitted.

Example 5. Twin-T Network

Step 1. Before entering values for the twin-T network, the ladder network values must be purged from the KRV subdirectory: KRV, MEMORY, NEXT, CLUSR, ENTER, USER. You should see an empty (KRV) directory.

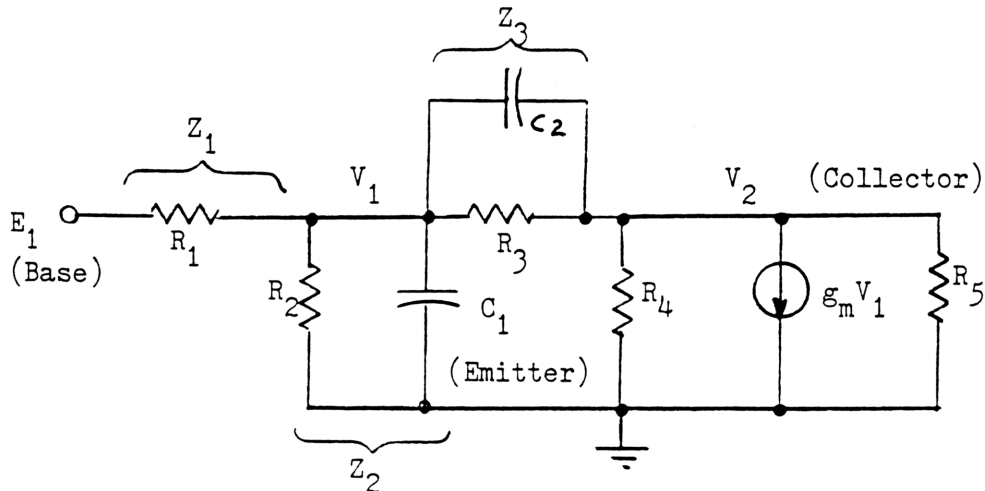
Step 2. Key in and store the following values:

```
C1 = 0.01uF
R2 = 133K
C3 = 0.01uF
R4 = 267K
C5 = 0.02uF
R6 = 267K
R7 = 10Meg
E1 = 1
```

Also key in << CKTAS >>, 'UP', STO, for the directory change. Press 'UP' when done to change directories.

Example 7 Common Emitter Hybrid Pi Transistor Model

The circuit used for the analysis is shown below:



Note that $Z_1 \rightarrow R_1$; $Z_2 \rightarrow R_2 // C_1$; $Z_3 \rightarrow R_3 // C_2$;
 $Z_4 \rightarrow R_4 // R_5$. (See page 11.)

Step 1. Purge the contents of the KRV directory except 'UP'.

Step 2. Store the following typical component values in the KRV subdirectory: (See reference 1.)

$R_1 = 100$	$R_3 = 4 \text{ Meg}$
$R_2 = 1 \text{ K}$	$R_4 = 80 \text{ K}$
$C_1 = 100 \text{ pF}$	$R_5 = 10 \text{ K (Collector load)}$
$C_2 = 3 \text{ pF}$	$GM = 0.025 \text{ (25 mA/V)}$

Step 2. Modify the SKF and MAT subprograms as follows:

'SKF'

```
<< R2 C1 PRC 'Z2' STO R3 C2 PRC 'Z3' STO
```

```
R4 R5 P22 'Z4' STO R1 Z2 Z3 F3 'K1' STO
```

```
Z3 R1 Z2 F3 'K2' STO Z3 Z4 F2 'K3' STO Z3 Z4 P22
```

```
'P1' STO >>
```

(Note faster method of calling F2 & F3 functions.)

Example 8 Inverting op-amp

Step 1. Purge KRV except for UP.

Step 2. Store the following component values.

```
R1 = 10 K           (Z1)
R2 = 15 K           (Z2)
R3 = 1 K; C1 = 0.015 uF (Z3)
R4 = 15 K           (Z4)
A0 = 10E3           (Aol)
W1 = 2 * pi * 10E6 = 62.832E6 (Op-amp rolloff)
E1 = 1
```

Step 3. Key in SKF and MAT:

'SKF'

<< R3 C1 SRC 'Z3' STO R1 R2 F2 'K1' STO

R2 R1 F2 'K2' STO R2 Z3 R4 F3 'K3' STO

R4 Z3 R2 F3 'K4' STO

1 1 HZ ["1 HZ" gives w]

W1 / R->C A0 SWAP / 'A' STO >> [A = Aol/(1 + jw/w1)]

'MAT'

<< 1 K2 NEG A K4 * K3 - 1 2 2 2 ->LIST

->ARRY E1 K1 * 0 2 1 ->LIST ->ARRY

SWAP / ARRY-> DROP2 A * NEG >> [V3 = -A V1]

Step 4. Analyze the circuit.

Do five decades at 5 points per decade starting at 10 Hz:

5, space, 5, space, 1, ACAP

```
Level 26: (1.000,9.539)    [DC gain of 30K/10K in dBV]
Level 1:  (6.000,28.094)   [Gain increase due to feedback
                           T network.]
```

A0 'A' STO >>

'MAT'

<< 5 IDN 'A1' STO K2 NEG 'A1(1,2)' STO

K3 NEG 'A1(2,1)' STO K4 NEG 'A1(2,3)' STO

K5 NEG 'A1(2,5)' STO A 'A1(3,1)' STO A NEG 'A1(3,4)' STO

K7 NEG 'A1(4,5)' STO K9 NEG 'A1(5,2)' STO

K8 NEG 'A1(5,4)' STO

E1 K1 * 0 0 E2 K6 * 0 5 1 ->LIST ->ARRY

A1 / ARRY-> 3 DROPN

3 ROLLD DROP2 >> [Get V3]

Step 4. Analyze the circuit.

Press DCAP to see: -11.993 V

Change R4 to 3 K; press DCAP to see -6.665.

V3 = -10.002 V when R4 = 1.332 K.

(Example 10 will be covered after example 12.)

Example 11 Fifth Order Active Filter

Step 1. Purge KRV except UP.

Step 2. Store the following values in the KRV subdirectory:

C1 = 0.03 uF	(Z1)
R2 = 2 K	(Z2)
R3 = 70 K	(Z3)
C4 = 0.02 uF	(Z4)
C5 = 1.895 nF	(Z5)
R6 = 140 K	(Z6)
C7 = 0.01 uF	(Z7)
R8 = 12 K	
C8 = 0.4 nF	(Z8 = R8//C8)
R9 = 2.7 K	(Z9)
R10 = 3.2 K	(Z10)

Step 4.

Due to its size, the ACAP program will take some time.
(About 12 seconds for each frequency point.)

Examine 5 decades, 5 points per decade, starting at
100 Hz:

5, space, 5, space, 2, ACAP

The stack should show:

```
Level 26: (2.000,-51.889)
Level 18: (3.600,1.965)      [Peak value]
Level 1:  (7.000,-40.515)
```

To plot: CLEAR, 5, space, -55, BPLT

The area between $\log F = 2.0$ and $\log F = 3.4$ shows an
elliptical response with a very steep 5th order climb
to the peak value, and a 1st order rolloff.

Example 12 Complementary Feedback Amplifier

Step 1. Purge KRV except for UP.

Step 2. Store the following component values in the KRV
subdirectory.

R1 = 200	E1 = +15 V
R2 = 1K	E2 = -15 V
R3 = 0.1	E3 = +5 V
R4 = 10K	B1 = 100
R5 = 1.5K	B2 = 100
R6 = 300	
R7 = 5.1K	

Step 3.

'SKF'

<< R2 R3 F2 'K1' STO R3 R2 F2 'K2' STO

R5 R7 F2 'K3' STO R7 R5 F2 'K4' STO

R6 R7 F2 'K5' STO R7 R6 F2 'K6' STO

R2 R3 PZ2 'P1' STO R5 R7 PZ2 'P2' STO

R6 R7 PZ2 'P3' STO >>

Example 10 Non-linear Circuit.
(Reference 3.)

Step 1. Purge KRV except for UP.

Step 2. Store the following component values:

R1 = 3 K
R2 = 2 K
R3 = 2 K
R4 = 3 K
R5 = 10 K
R6 = 10 Meg (Initial value)
R7 = 10 Meg " "
E1 = +5 V
E2 = -5 V

Step 3.

'SKF'

<< R1 R2 R6 F3 'K1' STO R2 R1 R6 F3 'K2' STO

R6 R1 R2 F3 'K3' STO R4 R3 R7 F3 'K4' STO

R3 R4 R7 F3 'K5' STO R7 R3 R4 'K6' STO

R6 R7 R5 F3 'K7' STO R7 R6 R5 F3 'K8' STO >>

'MAT'

<< 1 0 K3 NEG 0 1 K6 NEG K7 NEG K8 NEG 1

3 3 2 ->LIST ->ARRY E1 K1 * E3 K2 * +

E2 K4 * E3 K5 * + 0 3 1 ->LIST ->ARRY

SWAP / ARRY-> DROP >> [Leave voltage vector
on stack]

Step 4. In order to see the affect of a varying input voltage and to change the "diode" resistor values if forward or reversed biased, a different main program is required which will be labeled VSWP for "voltage sweep". This main program is similar in structure to ACAP and is given below with comments

Step 4.

Level 1 = (15.000,6.245)

Level 8 = (1.000,0.001)

[Dead-space]

Level 16 = (-15.000,-6.245)

For plot, key in:

CLEAR, 7, space, -7, BPLT.

The dead-space portion of the limiter should be apparent.

For output impedance Z_o :

$$Z_o = Z_e // (Z_7 + Z_4 // (Z_5 + Z_4 // (Z_2 + Z_1 // Z_2)))$$

Or by chained fractions:

$$\text{Let } A_2 = 1/Z_2 + 1/Z_1$$

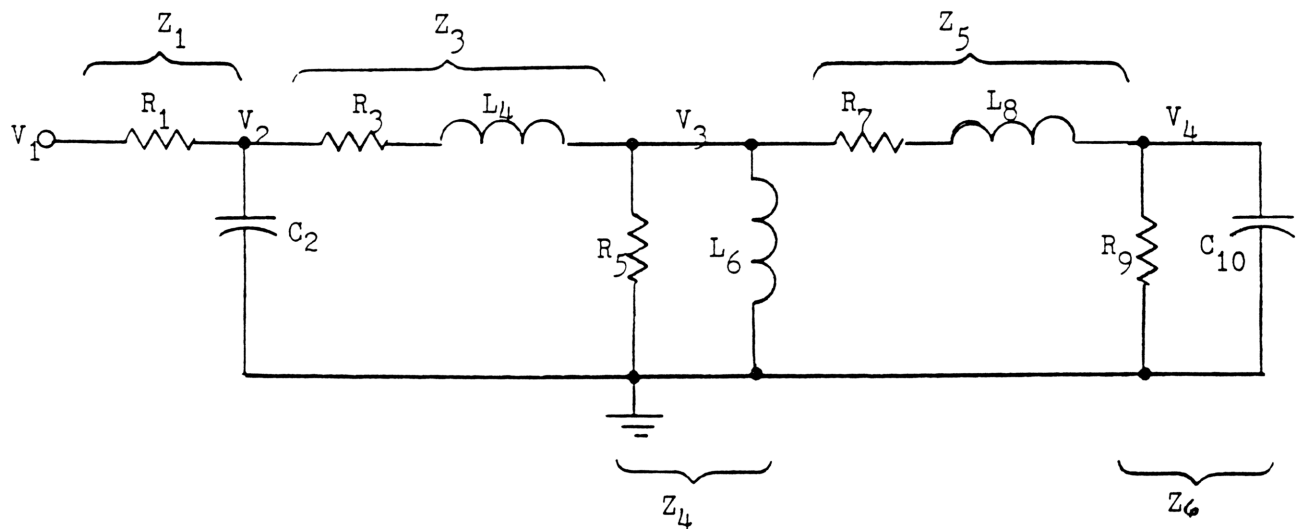
$$A_4 = 1/Z_4 + 1/(Z_2 + 1/A_2)$$

$$A_5 = 1/Z_5 + 1/(Z_4 + 1/A_4)$$

$$A_7 = 1/Z_7 + 1/(Z_5 + 1/A_5)$$

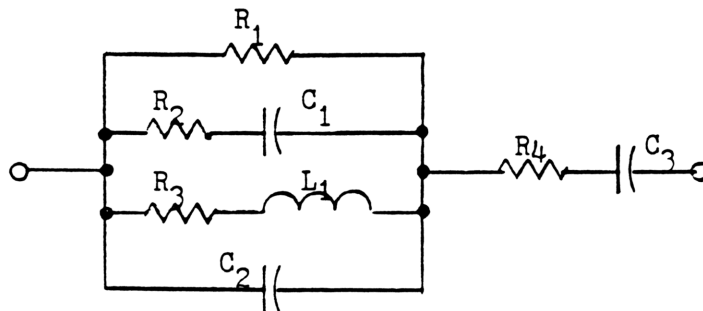
$$Z_o = 1/A_7$$

The ladder network shown below will be analyzed using the above expressions for the output voltage. The circuit is a model of a high frequency transformer. (Ref. 4)
The topology is a 3 L-section ladder network.



II. Building Branch Impedances with the HP-28S

Branch impedances other than the simple series and parallel RC or RL given by the subprograms on page 22 are easy to construct. For example, for the branch impedance Z1 shown below

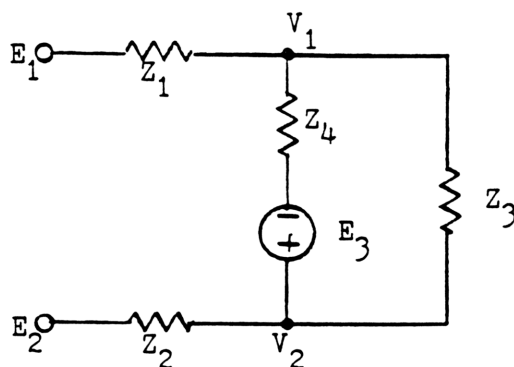


the HP-28S sequence is

```
R1 C2 PRC R2 C1 SRC R3 L1 SRL PZ3 R4 C3 SRC +
'Z1' STO.
```

III. Floating Voltage Sources

Floating voltage sources are sometimes required for diode and transistor models where the value of the voltage source in series with a resistor is about 0.6V. Whatever the purpose, they are analyzed as shown in the example below:



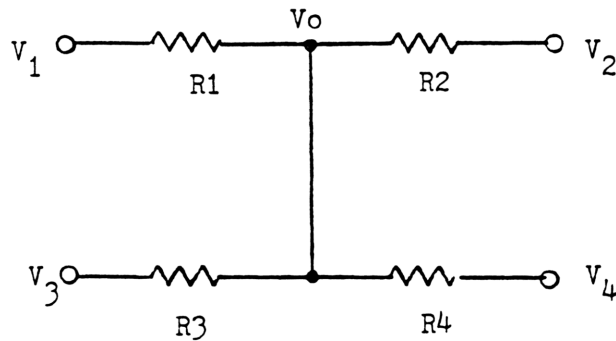
IV. Designing with K Factors

The following is an example of how K factors can be used in circuit design:

Given the N = 4 star network shown below, determine the required resistor values such that

$$\begin{aligned} V_o &= V_1 K_1 + V_2 K_2 + V_3 K_3 + V_4 K_4 \\ &= V_1(0.1) + V_2(0.2) + V_3(0.3) + V_4(0.4) \end{aligned}$$

for any values of V_1 thru V_4 . (Note that $K_1 + K_2 + K_3 + K_4$ must = 1.)



One solution method would be to generate a set of four simultaneous equations from Kirchoff's Current Law or Kirchoff's Voltage Law, for the four unknown resistor values. However, using K factors allows the simultaneous equations to be avoided:

Let $R_1 = 1K$, then

$$R_2 = R_1 K_1 / K_2 = 1000(0.1) / 0.2 = 500 \text{ ohms.}$$

$$R_3 = R_1 K_1 / K_3 = 100 / 0.3 = 333 \text{ ohms.}$$

$$R_4 = R_1 K_1 / K_4 = 100 / 0.4 = 250 \text{ ohms.}$$

References:

1. Pulse, Digital, and Switching Waveforms, Millman & Taub, 1965, p. 7.
2. Operational Amplifiers. Design and Applications, Graeme, Tobey, & Huelsman, 1971, p. 202.
3. Introduction to Operational Amplifier Theory and Applications, Wait, Huelsman, & Korn, 1975, p. 147.
4. Reference Data for Radio Engineers, 5th Ed., ITT/Sams, p. 12-1.
5. Algorithms for RPN Calculators, Ball, 1978, p. 272.
6. Modeling The Bipolar Transistor, Getreu, 1976, Tektronix.

