MADCAT: A STUDENT-DESIGNED SIMULATOR FOR USE IN INTRODUCTORY CIRCUIT-ANALYSIS COURSES

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INTRODUCTION

Computer simulation of electric circuits has become indispensable to both the teaching and practice of electrical engineering. The sophistication and functional capabilities of tools for electric circuit analysis have increased markedly in recent years. This sophistication nevertheless has drawbacks:

- schematic-capture capabilities obscure the details of circuit topology (e.g., nodes, branches);
- details of how the software performs its analyses are hidden from the user;
- extensive availability of macromodels does not contribute to students' understanding the modeling of electronic networks.

A relatively simple circuit simulator program addressing these concerns was desirable for introductory circuit analysis courses. The goals of the simulator project were outlined as follows:

- the simulator would emphasize circuit topology;
- the simulator would be useful for dc and ac analysis;
- the algorithms of the simulator would be relatively "transparent," making it useful as a teaching tool;
- the simulator would support basic elements of electric circuits but would not contain macromodels of electronic devices;
- the simulator would be intuitive to use and would use simple graphical user interfaces wherever possible.

The simulator was begun as a senior project by Kau Teng Lim in the spring of 2000. Matlab provides powerful numerical functionalities as well as extensive graphing capabilities; Matlab also supports graphical user interfaces and structured programming paradigms. Matlab was thus the clear platform of choice for the simulator and helped give the project its name ("MADCAT" means "MAtlab Derived Circuit-Analysis Tool").

MADCAT is intended as a teaching tool for introductory courses in analysis of electric circuits. MADCAT is meant to illustrate how topological concepts and circuit laws may be combined to perform automated analysis of electric circuits. It has been used in this capacity in 2001 and 2002 in EENG 3304, the introductory course in electric circuit analysis at the University of Texas at Tyler.

MADCAT is available as a compressed archive from the College of Engineering and Computer Science of the University of Texas at Tyler at http://cecs.uttyl.edu/ dbeams/ madct/madcat_2000.htm. A user's guide is also available from the same location.

CAPABILITIES OF MADCAT

MADCAT supports bias-point dc analysis, swept dc analysis, and swept-frequency ac analysis. All node voltages and branch currents are computed. Circuits to be analyzed with MADCAT are described in a text-based syntax similar to that used by earlier versions of Spice and PSpice.

MADCAT supports a wide variety of circuit elements commonly encountered in introductory circuit courses: independent voltage and current sources, dependent voltage and current sources, resistors, capacitors, inductors, and mutual inductors.

The user interacts with MADCAT through a series of graphical user interfaces. Results of swept-dc and ac analyses are displayed as Matlab figures; results of bias-point dc analysis are displayed in text format on the Matlab command window.

MADCAT CIRCUIT FILE STRUCTURES

MADCAT circuit files are ASCII text files with one circuit element described per line. The end of the circuit file is denoted by a line ".end." Text beyond that point will be ignored.

Creation of a circuit file requires four basic steps:
1. drawing the circuit schematic and assigning circuit element names;
2. numbering all circuit nodes;
3. assigning numbers and assumed directions to all branch currents;
4. entering data into a circuit file.

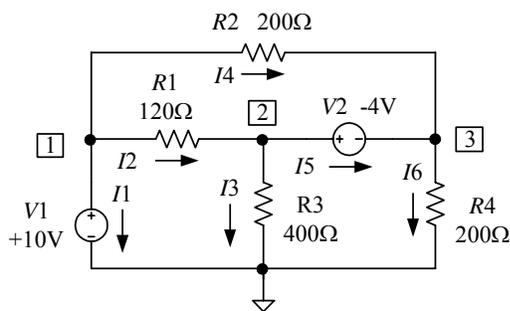Fig. 1 below illustrates the process for a simple circuit consisting of voltage sources and resistances.

Fig. 1. Example of a simple dc circuit. Numbers in square boxes are assigned node numbers. Branch currents and assumed directions are indicated by arrows.

Node numbers and branch current numbers in the example of Fig. 1 are sequential (1,2,…), but this is not necessary. The ground node is always node 0. There is always one circuit element per branch even when two or more circuit elements are in series. The type of circuit element is denoted by the beginning letter of the element name. The complete list of circuit elements supported by MADCAT is given in Table 1.

Table 1. Circuit element types supported by MADCAT.

Element name	Type of element
C<name>	Capacitor
E<name>	Voltage-controlled voltage source (VCVS)
F<name>	Current-controlled current source (CCCS)
G<name>	Voltage-controlled current source (VCCS)
H<name>	Current-controlled voltage source (CCVS)
I<name>	Independent current source
L<name>	Inductor
M<name>	Mutual inductance
R<name>	Resistor
V<name>	Independent voltage source

The general syntax for a line of the description of a circuit element is as follows:

Element	FROM node	TO node	Branch Current	Value

"Element" is the name of a circuit component (e.g., V1, R4). "FROM node" is the number of the node from which current enters the circuit element; "TO node" is the number of the node toward which current flows when it leaves the element. "Branch Current" is the number assigned to the current in the element. "Value" is the component value of the branch element in appropriate units (V, A, Ω, S, F, H). For example, the description of resistor R1 would read:

Element	FROM node	TO node	Branch Current	Value
R1	1	2	2	120

The voltage sources V1 and V2 would be entered as follows:

Element	FROM node	TO node	Branch Current	Value
V1	1	0	1	10
V2	2	3	5	–4

Element values in MADCAT listings may combine numerical values with multipliers denoted by specified characters. Table 2 summarizes these characters and their associated multipliers. Multiplier characters are case-insensitive except for "M" (designating "mega-") and "m" (designating "milli-"). Multiplier characters must follow the numerical value without intervening spaces. For example, the element value of a 1.5MΩ resistor may be equivalently specified as "1.5M," "1500K," "1500k," or "1500000." Characters appended to an element value but not listed in Table 2 are ignored. Thus "120OHMS" and "120Z" are equivalent to "120."

Table 2. Element value multiplier characters recognized by MADCAT.

Character	Multiplier
G, g	10^9
M	10^6
K, k	10^3
m	10^{-3}
U, u	10^{-6}
N, n	10^{-9}
P, p	10^{-12}

A "+" sign preceding an element value is also ignored. Thus the value of V1 in the example above could have been equivalently specified in any of the following forms:

- 10
- 10V
- 10Volts
- +10
- +10V
- 0.01kV
- +10000mV

There is no specified order for entering circuit elements. A complete MADCAT listing for the circuit of Fig. 1 is:

```
V1    1    0    1    +10V
R1    1    2    2    120
R3    2    0    3    400
R2    1    3    4    200
V2    2    3    5    -4V
R4    3    0    6    200
.end
```

The more-complex circuit of Fig. 2 shows MADCAT used to model active devices. The circuit of Fig. 2 is a single-pole low-pass filter with dc voltage gain of –10 and a corner frequency of 1 kHz. The triangular region encloses a linear model of an operational amplifier with a limited gain-bandwidth product. The dc open-loop gain is set by the value of Eamp, a voltage-controlled voltage source (VCVS). The open-loop gain exhibits a single-pole low-pass frequency response with the corner frequency of the open-loop gain set by Rp and Cp. The dc open-loop gain is 100,000, the corner frequency of the open-loop gain is 100Hz and the gain-bandwidth product is 10MHz for the specified values of Eamp, Rp, and Cp. VCVS Eo serves as a unity-gain buffer.

A complete MADCAT listing for the circuit of Fig. 2 follows:

```
VS      1    0    1    1V   0
Rin     1    2    2    3K
Cf      2    8    5    5.305nF
Rp      6    7    4    1K
Cp      7    0    10   1.59uF
Eamp    6    0    11   100000  0   2
Rf      2    8    12   30K
Eo      8    0    13   1       7   0
.end
```

The line representing the independent voltage source VS contains an extra entry representing the phase of the independent source. Phase is ignored in dc analyses and is assumed to be 0 if not specified.

Fig. 2. MADCAT model of an active single-pole low-pass filter.   This network uses a linear model of an operational amplifier with limited gain-bandwidth product. Note that node and branch current numbers are not sequential.

The specification of a VCVS is given in the example below. The value parameter of a VCVS is its voltage gain; the node numbers following the value are the nodes between which the controlling voltage appears.

In this example, the output voltage of VCVS Eamp appears between nodes 6 and 0 is 100,000 times the differential voltage appearing between nodes 0 and 2. The specification format for a VCVS is also used for a voltage-controlled current source (VCCS); the value of a VCCS is its transconductance. The format of current-controlled current sources is similar except that the pair of controlling nodes is replaced by a single controlling branch current. The value of a current-controlled current   source (CCCS) is its current gain; the value of a current-controlled voltage source (CCVS) is its transresistance.

 One further example will illustrate how mutual inductance is represented in MADCAT.

Fig. 3.   A series circuit consisting of an ac current   source   and   two   mutually-coupled inductors.

Mutual inductance is specified by the name of the mutual inductance followed by the names of the two coupled inductors and the value of the mutual inductance.   A MADCAT file representing Fig. 3 is given below.   This example also shows the use of comment lines preceded by "%."

Element name	FROM node	TO node	Branch Current	Value	+ Control-ling node	– Control-ling node
Eamp	6	0	11	100000	0	2

```
%  An example of mutual inductance
%  in MADCAT.  The mutual inductance
%  may be specified before, after, or
%  between the specifications of the
%  coupled inductors.
%
Mab        La     Lb              15mH
%
%  Mab assumes a flux-coupling coefficient
%  of 0.75 between inductors La and Lb.
%
La         2      1      1        40mH
Isrc 0     2      2      1Amp 0
Lb         1      0      3        10mH
 .end
```

Note in Fig. 3 that the dotted ends of inductors are assumed to be connected to the inductors' FROM nodes. The overall inductance of La and Lb in series in Fig. 3 will be 80mH (La + Lb + 2Mab) because of the presumed connection; reversing either inductor (by exchanging its FROM and TO nodes) would give an inductance of 20mH (La + Lb −2Mab).

INSTALLING AND RUNNING MADCAT

MADCAT consists of a number of Matlab script and function files (".m files"). Copying these files installs MADCAT. The MADCAT files may be copied to the default Matlab working directory or to another directory. If the MADCAT files are in another directory, the user will need to either add it to the Matlab search path or change the Matlab working directory to that directory before launching MADCAT.

MADCAT is launched by typing "madcat" at the Matlab command prompt. MADCAT opens with the graphical user interface shown in Fig. 4. MADCAT searches for a directory named "\project" under the current Matlab working directory. MADCAT takes it as the circuit file directory if it exists; otherwise, the circuit file directory is set to C:\. The user may specify the MADCAT circuit file directory through the user interface.   The default filename is "example1.txt" and the default analysis type is DC Bias (single-point analysis). The user may change the file name and/or analysis type and then clicks "Continue." Clicking "Exit" will terminate MADCAT and return the user to the Matlab command window.
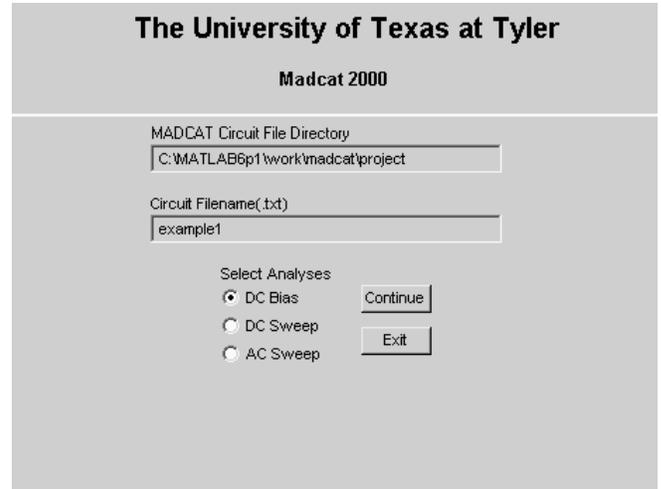

Fig. 4. MADCAT main menu.

DC BIAS ANALYSIS: DC Bias (single-point) analysis of a circuit is performed by simply clicking "Continue."   This performs a dc analysis with all independent voltage and current sources set to fixed values specified in the circuit file. Results are displayed on the Matlab command window.   DC bias-point analysis of the circuit of Fig. 1 gives the following results. "V(node)" gives the voltage at the specified circuit node in V; "I(branch)" gives the specified branch current in A. The MADCAT main menu reappears after a dc bias-point analysis.

DC bias-point analysis for file example1 :

V(1) = 10
V(2) = 4.48
V(3) = 8.48
I(1) = -0.0536
I(2) = 0.046
I(3) = 0.0112
I(4) = 0.0076
I(5) = 0.0348
I(6) = 0.0424

DC SWEEP ANALYSIS: DC Sweep analysis displays a graph of a selected branch current or node voltage vs. the swept value of an independent voltage or current source. Choosing "DC Sweep" as the analysis type at the main menu brings up the dc sweep menu in Fig. 5.
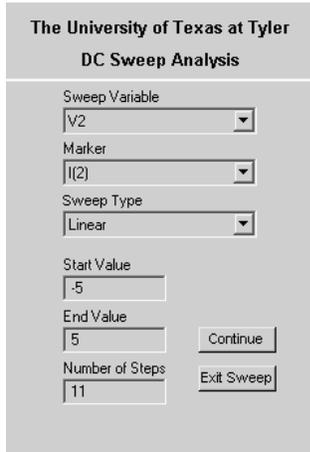

Fig. 5. DC Sweep Analysis menu.

"Sweep Variable" provides a drop-down list of all independent voltage and current sources in the network. The user may choose one source whose dc value is swept while any other sources remain fixed. "Marker" provides a drop-down menu of all node voltages and branch currents; the user chooses the node voltage or branch current to be displayed as a function of the sweep variable. "Sweep Type" allows either linearly-spaced or logarithmically-spaced sweep steps. Clicking "Continue" starts the dc sweep analysis; clicking "Exit" will return the user to the main menu. DC sweep analysis of the circuit of Fig. 1 with the parameters of Fig. 5 gives the following results shown in Figure 6.

AC SWEEP ANALYSIS: AC sweep analysis displays a graph of a selected branch current or node voltage as a function of frequency. Both magnitude and phase of the selected variable are displayed.

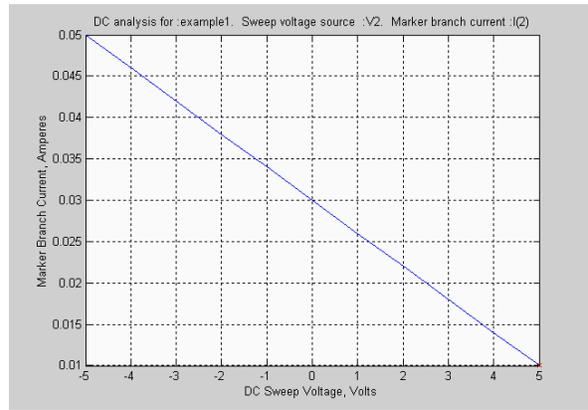Choosing "AC Sweep" from the main menu brings up the AC Sweep Analysis menu shown in Fig. 7.

Fig. 6. Results of dc sweep analysis of the circuit of Fig. 1 with voltage source V2 swept from –5 to +5V. The displayed variable is the current in branch 2.

Fig. 7. AC Sweep Analysis menu.

"Marker" selects the node voltage or branch current to be displayed. "Sweep Type" determines whether the frequency sweep is logarithmic or linear. "Plot type" selects a linear or dB magnitude plot. "Display option" allows the user to choose between "Complete solution" (in which results are graphed only after all calculations are completed) or "Step-by-step" (in which results are plotted as they are calculated). Clicking "Exit Sweep" returns the user to the main menu; clicking "Continue" starts ac sweep analysis. An example result of analysis of the circuit of Fig. 2 with the parameters of Fig. 7 is shown in Fig. 8:
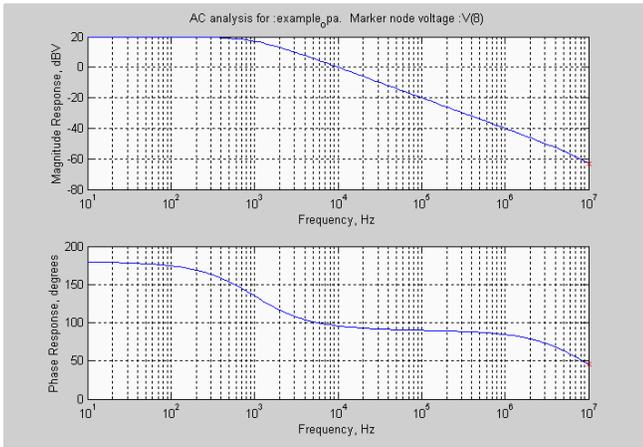
Fig. 8. MADCAT ac analysis of the circuit of Fig. 2. The excess phase shift above 100kHz is due to the limited gain-bandwidth product of the model of the operational amplifier.

HOW MADCAT WORKS

Circuit-analysis texts stress systematic methods for setting up network equations for solution. One method for finding the unknown branch currents in a network of b branches and n nodes to is to apply Kirchhoff's Current Law (KCL) at n–1 nodes and Kirchhoff's Voltage Law (KVL) around b–(n–1) loops or meshes.[1] This gives a unique solution for the b branch currents. Node-to-node voltages may then be calculated for resistive branches (and reactive branches in ac analysis) by Ohm's Law. Systematic rigorous approaches suitable for computer implementation are based upon loops, branches, or cutsets.[2] MADCAT relies on a modified nodal approach which uses elements of each. This methodology is best illustrated with some simple examples.

SIMPLE DC CIRCUIT WITH INDEPENDENT SOURCES: Figure 9 shows a simple dc circuit involving resistors and independent sources.
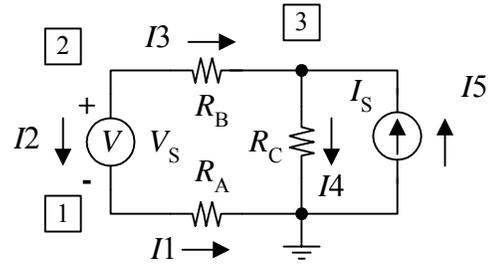

Fig. 9. Simple dc circuit with assigned node and branch numbers. Node numbers are enclosed in boxes.

	FROM NODE	TO NODE	BRANCH CURRENT	VALUE
RA	1	0	1	$<R_A>$
VS	2	1	2	$<V_S>$
RB	2	3	3	$<R_B>$
RC	3	0	4	$<R_C>$
IS	0	3	5	$<I_S>$

KCL states that the sum of all currents flowing from and to a node must be zero. Adopting the convention that a current flowing from a node is positive and a current flowing to a node is negative gives the following equation for the nodes of Fig. 9:

$$
\begin{aligned}
I1 - I2 &= 0 && \text{Node 1} \\
I2 + I3 &= 0 && \text{Node 2} \\
-I3 + I4 - I5 &= 0 && \text{Node 3}
\end{aligned}
\qquad (1)
$$

Eqs. (1) may be expressed in matrix form:

$$
\begin{bmatrix}
1 & -1 & 0 & 0 & 0 \\
0 & 1 & 1 & 0 & 0 \\
0 & 0 & -1 & 1 & -1
\end{bmatrix}
\begin{bmatrix}
I1 \\ I2 \\ I3 \\ I4 \\ I5
\end{bmatrix}
=
\begin{bmatrix}
0 \\ 0 \\ 0
\end{bmatrix}
\qquad (2)
$$

The coefficient matrix of 1s, –1s, and 0s is known as a reduced incidence matrix.[2] Each row of the reduced incidence matrix represents one node. MADCAT builds a row by placing a 1 in each column corresponding to a branch current flowing from that node and a –1 in each column corresponding to a branch current flowing to that node.

Current in each resistive branch is given by:

$$[V(\text{FROM}) - V(\text{TO})]G_{\text{branch}} - I_{\text{branch}} = 0 \qquad (3)$$

where V(FROM) is the voltage at the FROM node of the branch, V(TO) is the voltage at the TO node of the branch, and G_{branch} is the conductance of the branch. The conductance is the reciprocal of the branch resistance R_{branch}. The equations corresponding to the resistive branches of Fig. 9 may be written:

$$\begin{bmatrix} G_A & 0 & 0 \\ 0 & G_B & -G_B \\ 0 & 0 & G_C \end{bmatrix}\begin{bmatrix} V1 \\ V2 \\ V3 \end{bmatrix} + \begin{bmatrix} -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 \end{bmatrix}\begin{bmatrix} I1 \\ I2 \\ I3 \\ I4 \\ I5 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \qquad (4)$$

where $G_A = 1/R_A$, $G_B = 1/R_B$, and $G_C = 1/R_C$. The matrix of coefficients multiplying the node-voltage vector $[V1\ V2\ V3]^T$ is a nodal admittance matrix.[2] MADCAT determines the coefficients of a row of the nodal admittance corresponding to a resistive branch by placing a value of $1/R_{\text{branch}}$ in the location corresponding to the FROM node and a value of $-1/R_{\text{branch}}$ in the location corresponding to the TO node. A value of -1 is placed in the location corresponding to the branch current in the coefficients multiplying the branch current vector $[I1\ I2\ I3\ I4\ I5]^T$.

The nodal approach must be modified for independent voltage and current sources. An independent voltage source forces a voltage differential to appear between the two nodes to which it is connected. The equation arising from V_S is:

$$V2 - V1 = V_s \qquad (5)$$

An independent current source fixes the current of its branch. Thus the equation arising from I_S is:

$$I5 = I_s \qquad (6)$$

The overall network equations for network of Fig. 9 are as follows, including two augmented lines added to handle the independent sources:

$$\begin{bmatrix} G_A & 0 & 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & G_B & -G_B & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & G_C & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 1 & -1 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}\begin{bmatrix} V1 \\ V2 \\ V3 \\ I1 \\ I2 \\ I3 \\ I4 \\ I5 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ V_S \\ I_S \end{bmatrix} \qquad (7)$$

Eq. (7) may be expressed in compact form as AX=B, where A is the [n+b, n+b] coefficient matrix, X is the column vector of unknowns, and B is the column vector of known quantities. X can be found by matrix inversion ($X = A^{-1}B$).

DC BIAS-POINT ANALYSIS: Eq. (7) is solved once with fixed values for independent sources in vector B.

DC SWEEP ANALYSIS: One independent voltage or current source is chosen by the user as the sweep variable. The value in vector B representing the independent source is stepped through a user-defined range, and the solution vector X is computed at each step.

CAPACITORS AND INDUCTORS IN SWEPT-FREQUENCY AC ANALYSIS: Figure 10 defines currents and voltages in branches containing capacitance or inductance. Such branches are handled like resistive branches with the conductance of the resistor (1/R) replaced by the admittance of the capacitor (j2πfC) or the inductor (1/j2πfL), where f is frequency in Hz. The admittances of reactive elements in the nodal admittance matrix must be changed as frequency is stepped.

$$j\,2\pi f\,C\,[\,V(A)\text{-}V(B)\,] - Ib = 0 \qquad\qquad (1/\,j2\pi f\,L)\,[\,V(A)\text{-}V(B)\,] - Ib = 0$$
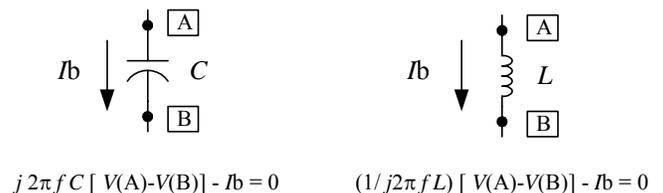
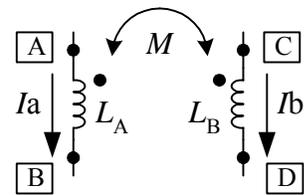Fig. 10. Definition of branch voltage and current relationships for inductors and capacitors.

PHASE FOR INDEPENDENT SOURCES IN SWEPT-FREQUENCY AC ANALYSIS: Phase angle may be specified for independent ac sources. The value of the independent source in B is replaced by its complex rectangular form. For example, a voltage source of 5V with a phase angle of 36.9° would be represented as 3+j4.

CONTROLLED SOURCES: Figure 11 illustrates the implementation of controlled sources in MADCAT with their defining equations.

MUTUAL INDUCTORS: Mutual inductors are handled as a special case of inductive branches. Fig. 12 defines the voltage and current relationships of a pair of mutually-coupled inductors L_A and L_B. The mutual inductance is included in the row for L_A by adding a coefficient of M/L_A in the column corresponding to the branch current Ib; the effect of mutual inductance on L_B is included by adding a coefficient of M/L_B in the column corresponding to the branch current in L_A.

MADCAT IN CURRICULAR USE

MADCAT was independently tested by junior and senior students in 2001 and 2002. During that time one legitimate bug producing incorrect ac analysis results was uncovered;

$$(1/j\,2\pi f L_A)\,[\,V(A)-V(B)\,] - Ia - (M/L_A)\,Ib = 0$$
$$(1/j\,2\pi f L_B)\,[\,V(C)-V(D)\,] - Ib - (M/L_B)\,Ia = 0$$

Fig. 12. Definition of branch voltage and current relationships for mutually-coupled inductors.

this affected circuit files in which a capacitor or inductor was defined as a circuit element after a mutual inductor had been defined. These students generally had no difficulty in creating MADCAT files or running MADCAT using the instructions from the User's Guide. One student found some errors in the User's Guide; these errors have since been corrected. The chief problem in using MADCAT appeared to be linked to MADCAT's minimal syntactic or topological checking. (MADCAT will detect unknown circuit elements and duplicated branch numbers). Nodes with only one connection, missing controlling node (or branch) information for controlled sources, and failure to include the .end statement were the most-frequent causes of difficulties with MADCAT. Students found that MADCAT results matched
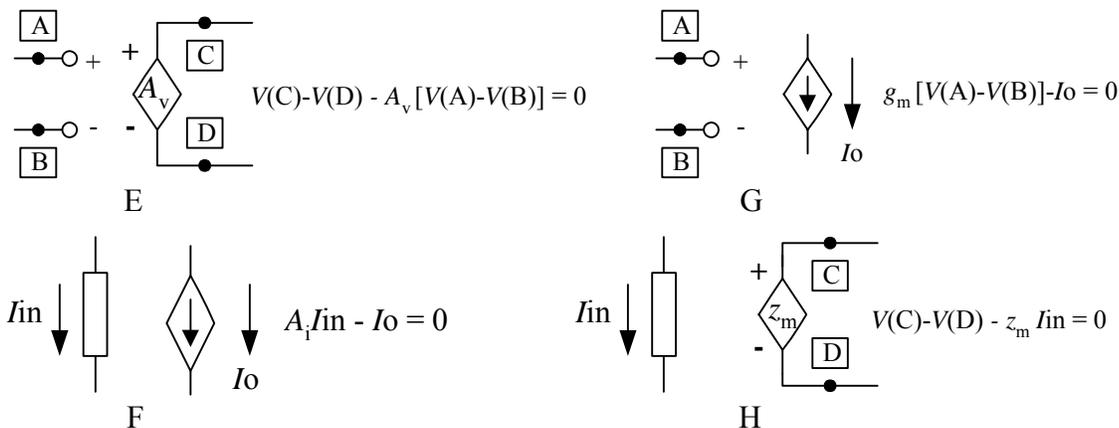

Fig. 11. Controlled sources supported by MADCAT and their defining equations. Available source types are defined in Table 1.

those of PSpice.

MADCAT has been used in teaching EENG 3304 (Linear Circuits I) in the summer terms of 2001 and 2002. Students have quickly learned to use it and have reported it to be useful in understanding the role of network topology in circuit analysis. The chief problem reported with MADCAT has been related to its limited syntax checking (such omissions as missing controlling nodes or branches for controlled sources, missing component values, and a missing .end statement at the end of the circuit file).

REFERENCES

1. Nilsson, James W. and Susan A. Riedel, Electric Circuits, Sixth Edition, Prentice-Hall, 2001.

2. Chua, Leon O. and Pen-Min Lin, Computer-Aided Analysis of Electronic Circuits. Prentice-Hall, 1975.

BIOGRAPHICAL INFORMATION

David Beams is an Assistant Professor of Electrical Engineering at the University of Texas at Tyler. He received the B.S. degree in Electrical Engineering in 1974 and the M.S. degree in 1977, both from the University of Illinois at Urbana-Champaign. He was employed in industry for 16 years. He received the Ph.D. degree from the University of Wisconsin–Madison in 1997. He is a licensed PE in Wisconsin and Texas and holds or shares four patents.

Kau Teng Lim graduated summa cum laude in 2000 with the BSEE degree from the University of Texas at Tyler. He is currently employed with Lopez Garcia Group, a consulting engineering firm in Dallas.

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