THE COMPLETE TABLEAU APPROACH TO SIMULATE VLSI-NETWORKS

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Abstract: A new approach for the formulation of equations with application to circuit simulation, which is implemented in the circuit simulation program JANAP, is presented. The advantages of our method over the classical nodal and sparse tableau approaches are demonstrated.

Introduction

Since the early 1970's circuit simulation has evolved to a significant design aid for integrated circuit engineering. The present situation, however, reveals the need of more efficient simulation tools in terms of computer resources. So-called "Third-Generation" techniques offer possibilities to improve the efficiency of circuit simulation programs from the purely algorithmic point of view. Another important point is the availability of an efficient and flexible method to describe device and macro models.

The main goals of our new circuit simulation program JANAP (Just Another Network Analysis Program) are:

- to not impose restrictions on the description of the circuit elements
- to allow switches and boolean controlled elements [1] as basic circuit elements
- a flexible modeling technique of semi-conductor devices and macro models.
- to use state-of-the-art numerical methods.

Formulation of the network equations

Switches as basic circuit elements create some problems with capacitor-only nodes. This situation cannot be detected by static analysis of the network description. Another problem is charge conservation [2], which is of particular importance for the simulation of dynamic RAM's, switched capacitor filters, and similar MOS circuits.

The authors of [2] and [4] suggest to include the stored branch charge and flux as state variables in the system of equations. We include therefore all branch charges and fluxes in the system of equations to solve the charge conservation problem. Variables which are not required will be eliminated by general symbolic reduction as shown in the next chapter.

Further investigation into the problem with capacitor-only nodes leads to the general problem to describe a "capacity star" as is shown in Fig. 1. In addition to Kirchhoff's current and voltage laws the equation

$$q_1+q_2+q_3 = 0$$

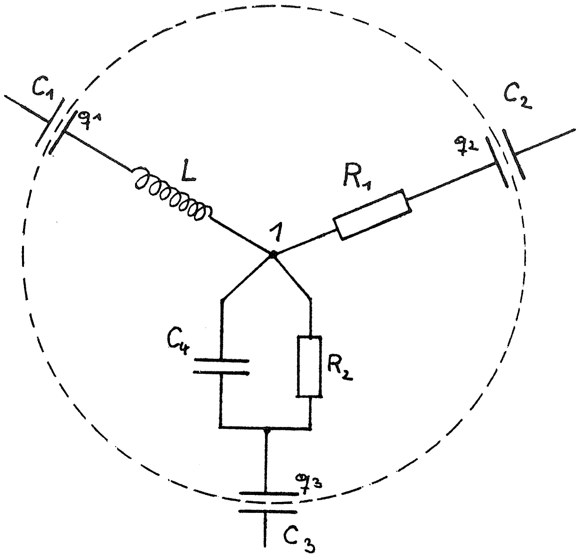


Figure 1: Capacity Star

must hold for the capacity star in the DC case. An easy formulation of this topology rule requires the "transportation" of this equation to the central node 1 of the capacity star by means of two utility branch values which are called herein "virtual charge" and "virtual flux".

Now we can describe each basic circuit element with six branch values connected by up to five branch equations. The branch values are:

- i current through branch
- v voltage at branch
- q stored charge within branch
- φ stored flux within magnetic field of branch
- r virtual charge to "transport" charges
- s virtual flux to "transport" flux

For an electric network with branches described with the above values the following Tellegen theorems [5] hold:

$$\mathbf{u}^T \cdot \mathbf{i} = 0$$
$$\mathbf{u}^T \cdot (\mathbf{q}+\mathbf{r}) = 0$$
$$(\boldsymbol{\varphi}+\mathbf{s})^T \cdot \mathbf{i} = 0$$
$$(\boldsymbol{\varphi}+\mathbf{s})^T \cdot (\mathbf{q}+\mathbf{r}) = 0$$

The characteristic equations of the basic circuit elements implemented in JANAP are summarized in Table 1.

The syntax of the JANAP input language allows to give nonlinear expressions in the description of the basic circuit elements which can depend on other branches.

Table 1: Basic Circuit Elements

	Element	i	v	q	φ	r	s
I	Current source	I		0	0	0	
V	Voltage source		V	0	0		0
R	Resistor		R·i	0	0		
G	Conductor	G·v		0	0		
C	Capacitor	$\frac{dq}{dt}$		C·v	0	0	
L	Coil		$\frac{d\varphi}{dt}$	0	L·i		0
S	Switch open	0		0	0	0	
	Switch closed		0	0	0		0
M	Coupling			$+k_{ij}\cdot\varphi_i$			
U	Universal	f	f	f	f	f	f

The "Universal Element" allows the specification of up to five nonlinear expressions for the branch values. With such an element one can describe in a very comfortable manner real voltage and current sources and also exotic elements like norators, nullators and memristors. This results in a reduction of the total number of elements of a circuit and therefore in a reduction of the total rank of the network equations. For instance, a diode model can be changed from three classical elements (Fig. 2) to one classical and one universal element (Fig. 3). This results in a reduction from 15 to 9 equations for the equivalent description.

$v_R=i_R\cdot R_S$

$q_R=0$

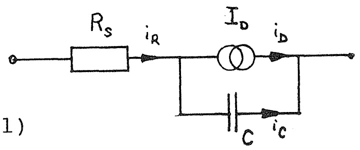
$\varphi_R=0$

$i_D=I_S\cdot(\exp(\frac{v_D}{n\cdot V_T})-1)$

$q_D=0$

$\varphi_D=0$

$r_D=0$



$$q_C=v_C\cdot[\tau_t\frac{I_S}{n\cdot V_T}\cdot\exp(\frac{v_C}{n\cdot V_T})+C_{jo}\cdot(1-\frac{v_C}{\Phi})^{-m}]$$

$i_C=\frac{dq_C}{dt}$

$\varphi_C=0$ $\quad q_D+r_D+q_C+r_C-q_R-r_R=0$

$r_C=0$ $\quad v_D-v_C=0$

$i_D+i_C-i_R=0$ $\quad \varphi_D+s_D-\varphi_C-s_C=0$

Figure 2: Diode model (classical elements)

Internally JANAP converts all classical circuit elements to a corresponding universal element.

The inclusion of charge and flux and its corresponding utility variables results in a superset of Kirchhoff's equations. We have the following topology equations:

$$\mathbf{A}\cdot\mathbf{i}=0$$

$$\mathbf{B}\cdot\mathbf{v}=0$$

$$\mathbf{A}\cdot\mathbf{q}+\mathbf{A}\cdot\mathbf{r}=0$$

$$\mathbf{B}\cdot\boldsymbol{\varphi}+\mathbf{B}\cdot\mathbf{s}=0$$

A is the cutset, **B** the loop matrix.

$v_R=i_R\cdot R_S$

$q_R=0$

$\varphi_R=0$

$$q_D=v_D\cdot[\tau_t\frac{I_S}{n\cdot V_T}\cdot\exp(\frac{v_D}{n\cdot V_T})+C_{jo}\cdot(1-\frac{v_D}{\Phi})^{-m}]$$

$$i_D=I_S\cdot(\exp(\frac{v_D}{n\cdot V_T})-1)+\frac{dq_C}{dt}$$

$\varphi_D=0$

$r_D=0$

$i_D-i_R=0$

$q_D+r_D-q_R-r_R=0$

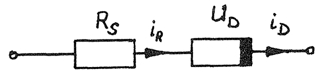


Figure 3: Diode model with universal element

The resulting system of equations of this so-called "Complete Tableau Approach" (CTA) is shown in Fig. 4.

Solution of the network equations

The system of equations owing to the CTA consists of six unknowns for each branch. Due to the simple structure of the defining equations a great number of theses values (most of the branch charges and fluxes) is known a priori and can be evaluated in the setup phase. This results in a reduction of the rank of the system of equations by about 40% for typical applications. There are many similiar situations, which can be easily solved by symbolic reduction of the system of equations.

After the system of equations has been reduced by the above mentioned method the Jacobian matrix is computed symbolically, as far as possible. Deriviates, which cannot be determined symbolically must be computed with numeric differentiation, however this does not occur very frequently. Each element of the Jacobian matrix can be classified as follows:

0
constant
equation
numeric computation required

After this step the worst case sparsity pattern of the Jacobian matrix is known. Parts of the factorization of the Jacobian matrix can already be done in the setup phase.

It should be noted that it is not possible to compute all branch values (e.g. the virtual values in purely resistive networks). Studies of circuits containing switches show another problem. An open switch can result in a deconnection of two parts of the circuit. Than we have two independent ciruits. This results in an extranous redundant node-equation. Therefore the system of equations is overdetermined but not contradictionary. Contradictions can occur in situations like short cutting a voltage source. These problems have to be tackled with a modified sparse matrix code (e.g. [6], [7]).

The final system of equations is solved with an adaptively damped Newton scheme. Transient simulation is accomplished by fully implicit backward difference formulae with automatic time step and order control [3]. According to [2] the inclusion of charge and flux results in better performance during the transient solution. Latency is automatically accounted for with zero order integration and bypassing of Jacobian matrix evaluations. Informations about the elements which are contained within one subcircuit are used to determine the latent blocks.

Conclusion

The formulation of the network equations used by JANAP has been presented, which offers a great flexibility in the description of circuits.

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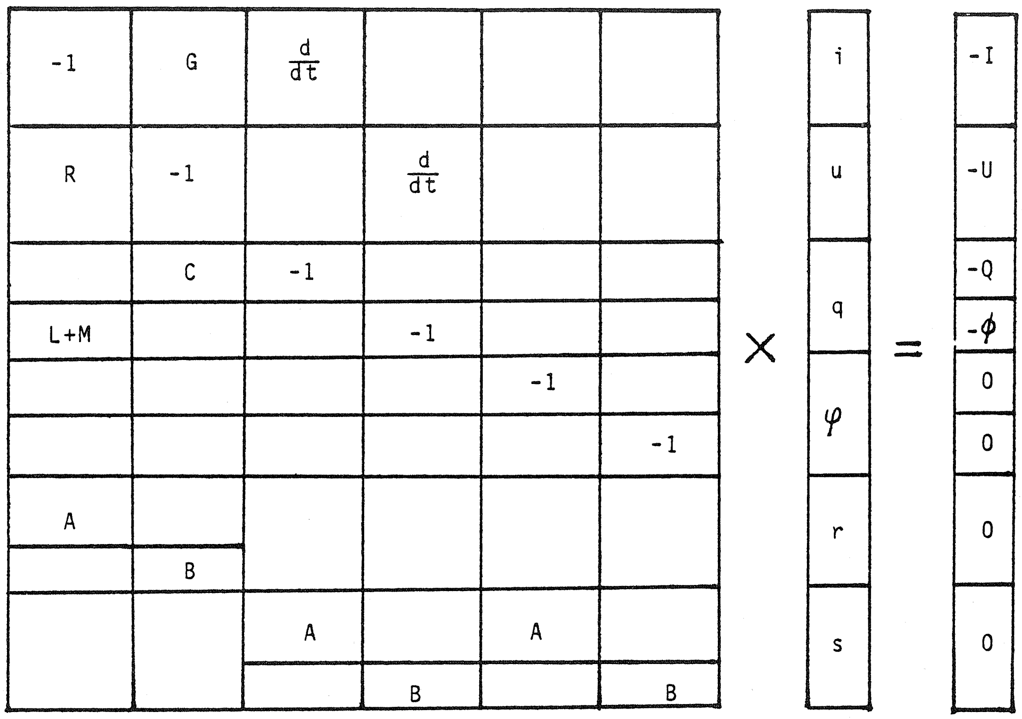

Figure 4: System of equations for CTA