Directions of Reducing the Computational Complexity in LSI Circuit Simulation

S.G. Rusakov, A.A. Lialinsky
Research Institute of CAD of VLSI
USSR Academy of Sciences
Moscow 105023/USSR

Reducing the computational complexity of circuit simulation algorithms is the main stimulus for the development of numerical analysis methods. Conditionally researches in this domain can be divided in two categories according to their purpose. The first one intends an improvement of methods and algorithms of simulation without quantity properties of mathematical models of an object [1]. Without excluding results of this research, the main purpose of the second category is to decrease the algorithm's complexity by speed enhancement in comparison to the growth of complexity of analyzed circuits, first of all at large dimensions of mathematical models. The main problem in reducing the computational complexity at circuit simulation of LSI and VLSI circuits is the problem of dimension. The solution of this problem is related to the use of the decomposition technique in modelling, the decomposition modelling (DM), and to partially or completely refusing from principles of 'standard' simulation [2-5]. Below the main directions of reducing the computational complexity are given in a structured form, and also a brief characteristic of basic problems concerning the development of DM models and algorithms. Leading concepts are hierarchical organization of computation and the hierarchy of models. Research results concerning a method of automating macromodel forming are briefly cited, also a new approach for economical representation of component equations and an autonomous version of the multiterminal subcircuit method and its use for parallelizing computational processes.

1. Structurization of the directions of reducing computational complexity

For the estimation of the timing complexity of circuit simulation problems the initial equation may be written as:

$$T_{sol} = T_{alg} + T_{fme} + T^{S}_{mod} \qquad (1)$$

where T_{sol} – time for the solution of the problem,
T_{alg} – time for the job of the algorithms for numerical solution,
T_{fme} – time for formulation of model equations,
T^{S}_{mod} – summarized computation time for model characteristics.

In terms of computational complexity ('comp') the expression (1) may be symbolically presented as:

$$comp_{Spr} = comp_{Alg} + comp_{fme} + \sum_{j=1}^{N} comp_{M_j} \quad (2)$$

Each term defines a possible direction for reducing the computational efforts to solve the problem ($comp_{Spr}$). These directions consist of (Fig.):

a) decrease of complexity of analysis algorithms ($comp_{Alg} \downarrow$);

b) decrease of complexity of mathematical models for analyzed circuit elements ($comp_{M_j} \downarrow$);

c) cutting down timing expenditure for the formulation algorithms of mathematical models ($comp_{fme} \downarrow$).

The consideration of equation (2) emphasizes another possibility of reducing the complexity: by decreasing the overall sum $\Sigma_{J=1...N}$ $comp_{Mj}$. Decreasing would be possible, for instance, by using simulation algorithms which work with a smaller number N in the computational process step or by using simplified models without reducing the overall precision of modelling. This direction may be defined as:

d) the choice of algorithms that allow the implementation of low complexity models.

The characteristics of the formulated directions of reducing the simulation effort are given below with a viewpoint regarding the application of the decomposition methods [2].

Reducing expenditure at the expense of implementation of more efficient methods for the formulation of circuit equations, firstly involves an optimization of the data structure of the simulation software, the improved programming of algorithms and the development of approaches that enable special ways of formulating for analyzed circuits. This means, there are various methods of linear system generation in a coded form by results of source circuit compilation. A lot of work is devoted to an elaboration of such methods. As a rule, the best effect is achieved by taking into account the software realization in a concrete computer and its operational system. These methods may be used together with decomposition approaches.

Various approaches of taking into account the structural peculiarities lead to various algorithmic directions of speed increase in the LSI simulation. These directions are:

- sparse matrix techniques, which take into account that the greater part of matrix coefficients of the corresponding linear equation system are null in the case of large sized circuits;
- the multiterminal subcircuit method where an initial circuit modelling is represented by the totality of interaction of subcircuits, and the high dimension problem being reduced to a successive solution of the lower dimension problem for each subcircuit;

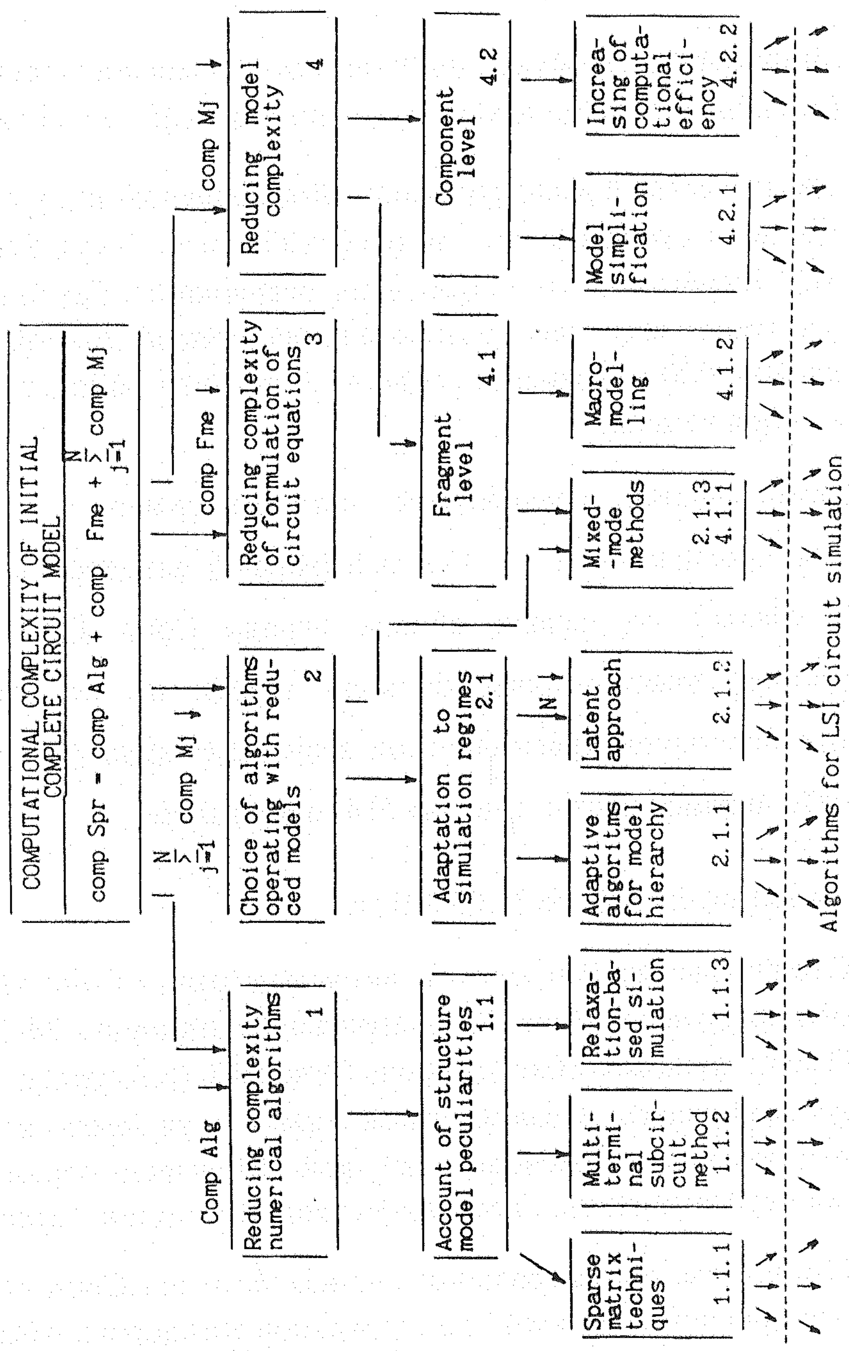

Fig. The main directions of decreasing computational complexity of LSI circuit analysis problems

- methods of timing analysis (MTA) providing a successive computational subprocess for one or more equations due to the use of relaxation approaches.

Reducing of the complexity of mathematical models of LSI elements can be performed at component or subblock levels (fig.). It is worthwhile considering two aspects at component level to decrease the computational expenditure:

- an enhancement of computational efficiency of models by saving their level adequateness and precision at the expense of economical programming and special computational approaches;
- simplification of component equations by a corresponding decrease of the characteristic precision (for instance, an implementation of look-up tables, piece-wise approximation and so on).

It should be pointed out that as a rule in practice it is useful, to combine specified methods at model synthesis, i.e. at model simplification to search for a possibility of economical performance of their characteristics. Reducing computational complexity at subblock level is achieved firstly at the expense of forming simpler models, i.e. implementation of macromodelling principles that allow to decrease the order of the circuit model considerably.

The existence of mathematical model series, distinguished by complexity and precision, suggests new perspective directions allowing an effective use of models at various levels of complexity. Two types of methods for LSI simulation with various models can be emphasized:

- mixed-mode simulation methods;
- methods of model adaptation to a simulation regime.

The idea of the first method type is the simultaneous use of simplified models to simulate some VLSI blocks and precise models for the circuit analysis of the most important subblocks.

Methods of a mixed electrical-logic analysis of digital and analog-digital LSI circuits are the most spreading ones. The idea of adaptive simulation methods consists of the thesis that there is no necessity to use complete and precise models for all elements in all regimes to guarantee a given level of simulation error. For example, models with precise dynamic characteristics are not required at static mode simulation. The purpose of this class of algorithms is to reduce the expenditure value without lack of precision at the expense of a successful choice of model precision characteristics in correspondence to a simulation regime.

As a result of the organization simplicity the most widely used approach is the one to be defined as a limit case of adaptive methods. The latent approach allows to completely exclude calls to models of components or subblocks that do not change their state in a simulation interval. This approach based on the concept of 'latency' has an independent meaning and has already shown its economy in the simulation of the high order models of LSI circuits.

Each of the above-mentioned directions for the LSI circuit simulation (Fig.) has advantages from the viewpoint of complexity reduction in LSI simulation and relative disadvantages, as well as mathematical and software problems of realization. Each of these decomposition simulation directions is an object of partial researches because of the variety of approaches to their algorithmic implementations. Note that the family of the LSI simulation algorithms can be generated both by realization of these directions (Fig.) and the successful combination of different approaches typical for various directions. An adaptation of LSI simulation directions to parallel computations is the important factor in the evaluation of their perspective implementation.

2. Basic problems of the DM algorithm development

Sparse matrix methods (pos. 1.1.1) were investigated to a large degree and there is a considerable experience in their application. The multiterminal subcircuit method (MSM) may be regarded as one of the possible manners of taking into account an initially modelled structure sparseness. The main difference of MSM (pos. 1.1.2) from the sparse matrix technique is the subsequent use of one and the same memory arrays for different subcircuits and an autonomous formulation of the equations. The majority of work using MSM as a tool to solve the large dimension problem restricts research to formal matrix partitioning at the level of solving linear equations. The most perspective direction of MSM development is an algorithmic organization of independent computational processes that allow to consider their pecularities in a better way and in addition to reduce the simulation times. Computational problems of this kind are related to the wide use of MSM for the DM in nonlinear and timing levels [2,8,9]. Problems of theoretical researches and the practical algorithms using compound iterative processes and compound procedures of numerical integration are actual in this area. The elaboration of an autonomous version of an MSM algorithm is directly related to solving known problems of numerical character in using block methods at the nonlinear level, as well as in the implementation of the multirate integration methods in the time domain. The latter belongs to the most difficult in numerical ODE solution [10].

A perspective branch of LSI DM is the implementation of timing analysis methods (MTA) [3-7] (pos. 1.1.3). Occupying an intermediate position of precision versus productivity between logic- and circuit- (electrical) level analysis, MTA provides a speedup of calculations up to two orders of magnitude in comparison with traditional approaches for circuit simulation. The algorithmic structure of these methods corresponds to a decomposition of the initial system into partial equations and to excluding operations of the exact solution of a linear system. The specified decomposition is directly related with the use of relaxation solution methods of a nonlinear equation system at the level of numerical integration. Due to their construction these algorithms are close to approaches applied in the numerical solution of mathematical physics equations. Their common disadvantage is that there is a guarantee of convergence of the iterative processes only for the special mode system. The initial model matrix of analyzed LSI does not allow the assumption of symmetric and positive definition typical for mathematical physics. Therefore, the use of component models like these and macromodels that would provide the required structure of a simulating circuit becomes necessary. The main problem of elaboration and application of timing methods is the enhancement of their universality, and a direction of perspective algorithmic explorations is an expansion of the domain of convergence with saving stability properties of initial standard approaches. In the contrary case, the software will be specialized only for a certain type of circuits, and the total computational gain of decreasing the time-steps will not achieve a supposed efficiency in spite of the expenditure of reducing in each time step.

The branch of development of DM algorithms related to the application of various complexity models (pos. 2.1.1) is actually in the installation stage and is one of perspective ways of reducing computing times under saving the finite precision of simulation results. Problems of the algorithmic character to be solved at constructing adaptive algorithms are related to an organization of computational procedures with various complexity models and an algorithmic implementation of switching criteria for models of different levels in the calculation process.

The so-called 'latent' approach finds a considerably wider implementation (pos. 2.1.2), that it can be regarded, as already mentioned, as the limit case of the mentioned adaptive principle of the work with models. Using this approach excludes the request of component or subblock models with unchanged states in the studied time interval, i.e. the 'time' sparseness of simulation is taken into account. The popularity of this approach is due to its simulation economy and the simple computational organization. Computational problems to be accounted for in realizing this approach are related to a potential appearence of unstability in the integration. It is necessary to determine an effective and reliable criterion of the latent state and exit conditions, organization of event dispatching for calculations.

The purpose of mixed-mode simulation methods (pos. 2.1.2) is to enhance the computational efficiency due to the use of various mathematical techniques for various subblocks of the circuit. The mixed analysis may be performed at different simulation levels. Logic simulation [11-13] is the most widely used one. Problems of algorithmic realization of these methods are especially related to the development of mathematical and software interfaces which provide the combined use of heterogeneous models. The methods have already got practical spreading.

The synthesis of mathematical models, both for components and for LSI subblocks, is performed traditionally on the base of a qualified consideration of the simulation object. This tendency leads to model simplification, too. Much experience of theoretical and practical researches led to the requirement of component library models and macromodels (MM) [15] . Together with these results the current level of circuit simulation programs requires the application of formalized approaches of model forming. First of all, it belongs to macromodelling and especially to obtaining macromodels of LSI subblocks (pos. 4.1.3). The necessity of the operative development of these macromodels dictates the demand for methods and tools to automate this process. The problem of automating the macromodel forming is the leading one for the macromodelling of LSI subblocks. It is directly connected to the problem of formalized construction of nonlinear dynamic macromodels from an overall component-level model.

Considerable resources of the computable effort economy may be used at the simplification of component models. The main direction in this case is a transformation of the initial component equation to a simplified one (pos. 4.2.1) with a corresponding lack of precison. In this case piece-wise approximation, look-up tables and other forms of simplified representation can be used. A new definition of the problem to be solved is the development of methods to enhance the computational efficiency of the model due to the implementation of special economical methods of their characteristic representation (pos. 4.2.2). The development of formalized methods for the transition to simplified models may be included in the problems of algorithmic character.

3. Autonomous version of multiterminal subcircuit method (MSM)

The main concepts of elaborating an autonomous version of an MSM algorithm [2,8,9] in distinction from formal methods of matrix partitioning are the following:

- application of compound computing procedures for organizing independent numerical processes;
- decomposition of initial systems immediately at the nonlinear and time equation solution levels.

To decompose the initial equations the vector of circuit variables x is represented by the components of the vector of terminal variables y and the vectors of internal variables z_i : $x = [z_1, z_2, .., z_n, y]$, $i = 1,..,n$; n being the number of subcircuits. While implementing MSM in circuit analysis programs the behavior of the whole circuit is modelled by a set of nonlinear algebraic equations relatively to the vector y:

$$f(y) = 0 \qquad (3)$$

and for i -st subcircuit with the help of the set of equations:

$$g_i(z_i, y_i) = 0 \qquad (4)$$

By analogy while modelling dynamical regimes the differential equations:

$$f(\dot{y}, y, t) = 0 \qquad (5)$$

relative terminal variables represent behavior of the overall circuit in the time domain and the equations:

$$g_i(\dot{z}_i, z_i, \dot{y}_i, y_i) = 0 \qquad (6)$$

describe the dynamical regimes for each i-st subcircuit. Here y_i is a component of vector y, playing the role of terminal variables for i-st subcircuit.

The multilevel algorithm of statical behavior analysis by MSM uses the compound iteration procedure of the type Newton-Newton for providing independent computational subprocesses to solve equation (4) at each iteration step for the system (3). In distinction from partitioning at the linear level the autonomous algorithm provides additional economy of memory and permits to accelerate the analysis by taking into account pecularities of separate subcircuits. To reduce computational times the principle of agreed reducing the norms of the errors for subcircuit equations is used. It means the establishment of a stopping criterion for subcircuits in accordance with the predicted norm $\|f\|$ or the norm $\|y\|$ at each iteration step of solving equations (3) for the terminal variables. For the hierachical organization of computational processes while modelling the dynamical behavior by MSM a new conception of composite methods of numerical integration is proposed [20]. The composite method uses this organization of calculations when the steps of one method ('outer') include series of operations of another ('inner'). The possibility of using compound methods for solving the problem of multirate integration of system (5), (6) in accordance with the character of transient processes in LSI is shown. The algorithms that provide synchronization of the whole process of integration with automatic choice of different step sizes for different subcircuits are elaborated. In the class of compound methods a computation procedure is proposed which involves semiexplicit Rosenbrock methods at the upper level (5) and an implicit integration method at the lower level (6). The computational advantages of its usage are shown. Also the possibility of implementation of integration methods with different order of accuracy in compound methods is shown. The simplification of using the concept of latency at the subcircuit level in the last case is stated.

MSM has pecularities of 'natural' parallelism due to the character of its computational organization and the initial data structure. It must be noticed that at the present time intensive work is done to establish standard circuit simulators on computers with parallel architecture. Among a number of computational problems to be solved one of the major practical problems is to imply efficient vectorization of algorithms for LU-decomposition of sparse matrices, the possible approach is proposed, for example, in the paper [14]. To a certain degree MSM is an alternative version. It allows a simple implementation of the vector representation for basic numerical procedures on vector computers, including different architectures. Using MSM implies the execution of superoperations on operands of N_i size, where N_i is the number of variables of the i-st subcircuit. For providing the simultaneous work at N_i variables for each subcircuit vectorizable numerical procedures of MSM have been developed. The upper estimations of the accelerated coefficient and efficiency coefficient for parallel MSM realization on a processor matrix have been also obtained.

The advantages of the autonomous version MSM appear with separating the algorithms into several flows of commands, i.e. with parallel computations for different subcircuits on different processors. This approach supposes independent computational processes in the frames of asynchronous computations. It is known that the initialization of the short timing processes can not only decrease but as well increase the overall time of the program exploitation, because the additional loss in initialization exceeds the gain from parallel execution.

Various algorithmic versions of MSM were analyzed for asynchronous computations, among which the most widely used algorithm, the formal matrix partitioning, and the discussed autonomous version of MSM were compared. The parallel schemes of asynchronous computations for both MSM versions were elaborated for statical as well as for dynamical behavior simulation. Computational advantages of the autonomous version of MSM have been shown and in comparison with formal partitioning the estimation of relative efficiency has been obtained. It is as follows:

$$E_{aut/par} = (4\,K_{ex} + K_w)/(2\,K_{ex} + K_w) * ITER_{av}$$

where $ITER_{av}$ is the average amount of iterations for one call of the subcircuit, K_w and K_{ex} are the normalized time coefficients of waiting for data and data exchange respectively.

The arguments given above concerning a lower number of exchanges on iteration or integration steps permit to come to a conclusion of the perspectiveness of using an autonomous version of MSM for parallel computers including multitransputer arrays becoming widely used as accelerators of workstations.

4. The forming of the macromodels (FMM) of LSI subblocks

The main achievements in macromodelling have been received for typical constructive completed MSI and SSI circuits. In distinction from such circuits for monolithic

LSI circuits in many cases necessary experimental data are absent, principle scheme and parameters are not invariant when changing from one scheme to another. The above mentioned pecularities are the reason for special problems of forming MM (FMM) of LSI subblocks and identification of their parameters. Among the problems to be solved which determine the effectiveness of LSI macromodelling, we must emphasize the automation process for the reduction of models providing necessary operativeness.

The analysis [17] defines the usefulness of constructing algorithms for automatic forming MM by obtaining the reduced models of circuit fragments from their complete mathematical models. The method FMM has been elaborated [2, 16] which provides the synthesis of nonlinear dynamical MM of the subblocks from their initial complete models. The results of macromodelling in this case are the 'input-output' relations received by the exception of the internal variables, i.e. vector-function

$$I_M = g(\dot{y}, y) \tag{7}$$

which is obtained from the overall mathematical model of the subcircuit given by the equations

$$\begin{aligned} &f(\dot{y}, y, \dot{x}, x) = 0 \\ &I_p = h(\dot{y}, y, \dot{x}, x) \end{aligned} \tag{8}$$

Here x(t) and y(t) are vector-functions of the internal and external circuit variables. In case of the nodal analysis I_p is the vector of terminal currents of the subcircuit and I_M is the vector of the macromodel currents. The dimensions of vectors f and x correspond to the number of internal variables and dimensions I_M and y to the number of external terminals of the subcircuit. In the proposed approach the ideas of the pertubation method are implemented for the purpose of the FMM in multiterminal type. The approach gives in fact possibilities to lead the forming of dynamical macromodel to a static problem. In this variant the computational efforts for solving approximation problems in the time domain are excluded in comparison with the traditional definition of the problem. In the work [16] the formula of calculating matrices of terminal capacitances MM has been received in the following form:

$$C_{eq} = [\partial h/\partial\dot{y} + \partial h/\partial\dot{x} * \partial x/\partial y] - \partial h/\partial x * (\partial f/\partial x)^{-1} [\partial f/\partial\dot{y} + \partial f/\partial\dot{x} * \partial x/\partial y] \tag{9}$$

The conditions for the application of MM obtained by this method and the estimation of dynamical errors are determined. Due to the account of the peculiarities of LSI macromodelling the method has some advantages such as:

- the structure of the obtained MM is suited for circuit simulation programs;

- while forming MM the circuit and parameter information at component level is implemented;
- there is a possibility of saving initial physical and geometrical parameters of components that provide a practical application of such MM in the design of LSI circuits;
- in distinction from the majority of electrical macromodels for the analysis of digital LSI circuits the possibility of accurate description of terminal current is conserved.

An important advantage of the method consists of formalized computational procedures, making up basic algorithmic provision for automation of the process of obtaining MM. This method was used for the construction of a number of MM, among them electrical macromodels of digital MOS LSI library elements. The application of the obtained MM decreases the computational effort of MOS LSI modelling by 2.5-4 times in comparison with the analysis using overall models. The errors in determination of the transient response were limited by 10-15%.

5. Increasing of computational efficiency of mathematical models for integrated circuit components

The new approach to formalized decrease of model order with the exception of internal variables has been proposed. Two aspects of decreasing of the model's computational complexity are discussed:

- model reduction with admissible loss of accuracy;
- effective organization of computational operations for model equations.

These approaches were illustrated on the popular Ebers-Moll model for a bipolar transistor with ohmic resistances from the transistor active region to its collector, emitter and base terminals, respectively.

The inclusion of these resistances into the equivalent circuit adds three nodes for each transistor. Therefore the application of nodal analysis to circuit equation formulation leads to a bigger increase of the dimension of the system equations in comparison with the simple Ebers-Moll model. If the recommended approach is implemented for formalized reduction from the Ebers-Moll model with resistances to the simpler model then the possibility of setting full system parameters is served and the computational expense is nearer to a simpler model. It is proposed for the exception of internal variables in a static model to apply special functions [19], in particular, the implicit function $g(x) = e^{x-g(x)}$ is applied for the Ebers-Moll model with ohmic resistances. The single description of processes with linear and exponential mechanisms is provided with its help. For elementary functions these equations are not solved. The current-voltage characteristic of a diode with resistance is a typical illustration of the equation of the same type: $y = x - A \ln y$. The solution of that equation with the use of the g-function is given by the following expression: $y = A * g(x/A - \ln A)$. The values of the g-function are calculated by the application of chain fraction for interval approximation. The g-function is implemented to build-up an economical static model of bipolar transistors. The computer time decreased from 20 to 50% already on the stage of the formulation of the circuit model equations.

The main problem of the evaluation of a dynamical model consists of forming the matrix of capacitances for the equivalent circuit. This matrix must take into account in a correct form the influence of exceptional resistances r_E, r_C, r_B. For this purpose it is proposed to use the described method of obtaining the simpler model from full equivalent circuits. In this case the expression (9) determines the algorithm of calculation capacitancies mentioned and has the following form:

$$C_{eq}(y) = \partial h/\partial x * (\partial f/\partial x)^{-1} [\, C_{init} \,] (\partial f/\partial x)^{-1} * \partial h/\partial x$$

where C_{init} is the initial capacitance matrix of the transistor model. The analytical descriptions for the matrix values of terminal capacitances C_{eq} are obtained.

As a result of the combination of these elaborated approaches for increasing computational effectiveness the methodology of obtaining simplified models from initially full models with the exception of internal nodes is presented. The main computing economy is attained on a stage of solving systems of equations in connection with a significant decrease of the dimension of circuit models. Moreover so, the excluded internal nodes are sources of small time constants, then it allows to expect minimizing the number of steps of integration due to the exception of internal nodes.

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