AN IMPROVED RELAXATION APPROACH FOR MIXED SYSTEM ANALYSIS WITH SEVERAL SIMULATION TOOLS

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Abstract: *This paper introduces a modified relaxation approach that allows to improve the convergence of iterations while analyzing mixed systems with different simulators. The method reduces the local feedbacks in the decomposed system by the use of rough models of parts in the neighboring parts of the system. This improvement is very important for mixed systems where optimal partitioning methods are not possible and the choice of the suitable types of coupling is also restricted.*

I. Introduction

Relaxation techniques are known to be successfully used for the electrical analysis of some types of circuits, mostly digital, and they were implemented in several programs as MOTIS [1], SPLICE [2], RELAX [3], etc. The main reasons that compel to choose relaxation iterations are:

1) Very high circuit size and complexity. In this case direct solution of the circuit equations, when all parts of the system are solved simultaneously, requires excessive CPU time and memory consumptions. On the contrary, relaxation techniques treat different parts of the circuit independently and they provide almost linear dependence of consumptions on the number of circuit equations.

2) Because of the multirate behavior of the circuit variables it is preferable to choose independent timesteps in different parts of the system. This can be realized easily when waveform relaxation method is used to simulate the dynamic circuit.

3) Relaxation algorithms easily allow parallel or consequent implementation on multiprocessor systems.

However, there are situations in which one must perform the relaxation iterations alike, whether the above reasons exist or not. This is the case in mixed system simulation where several parts of the system may exhibit different physical effects: electrical, thermal, structural, coupled-field, etc. To describe these effects we need various mathematical methods (ODE, partial derivative equations, finite elements etc.) and to simulate them we use some specially elaborated program tools. Other examples are the simulation of the "uniform-type" system when the numerical model for some part is not known but replaced with a call to a "real" device [4], and the mixed-level system simulation, for instance, circuit and device-level simulation [5].

As a result, under some circumstances, the simultaneous solution of the total system of equations becomes impossible. In the following we'll use the term "mixed system" to denote such type of a system to be simulated. Thus, the mixed system analysis requires the use of different program tools in one cycle of simulation.

If the processes in the given system are mostly unidirectional, this particularity doesn't invoke any extra problems. It's enough to simulate each part of such a system only once. In general, however, the different parts of the system might be "tightly coupled" and the global feedbacks in the system can also exist, so one has to repeat the simulation many times, i.e. perform iterations. Naturally, these iterations must converge to a desired solution and should do this as fast as possible.

Unfortunately, the diversity of the models in the different parts of the system compels crucial limitations for the use of optimal partitioning algorithms, overlapping of subcircuits and other methods implemented in most relaxation-based electrical simulators. Thus, alternative ways are needed to improve the convergence of relaxation iterations. In this paper we consider a new approach to accelerate the convergence of iterations that suppresses the local feedbacks in the decomposed circuit. The proposed method is based on rough (approximate) models of several parts being inserted into some neihboring parts of the mixed system. The accuracy of these models doesn't affect the final results of simulation but substantially improves the convergence properties.

The paper is organized as follows. In section II we consider the basic types of coupling that can be used in the decomposed mixed system. In section III we propose more general coupling schemes and investigate their features. Further we apply the modified type of coupling to a mixed system analysis and discuss the experimental results.

II. Basic local coupling in mixed systems

Since manifold forms and methods may be used to describe the parts in mixed systems, for the sake of convenience we shall suppose that the different parts of the system can also be represented by means of equivalent electrical circuits. In fact, we need the circuit description only for the inputs and outputs of these parts and for couplings between them. Let us consider the main possible ways of couplings with strong local feedback between the parts of the system. For simplicity, suppose that the system has only two parts, ***A*** and ***B***.

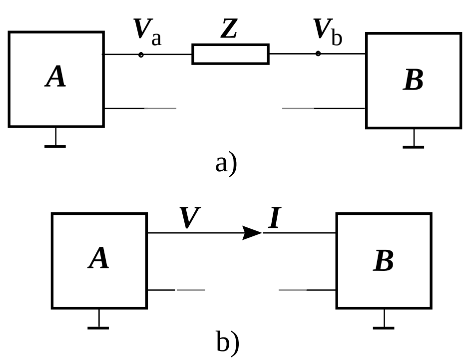

Fig.1 (a) Two parts connected by an element ***Z***. (b) Two parts connected direcly

In the first case the parts are connected by the resistive-type elements, as shown in Fig.1a. To perform the iterations, we can use the equivalent iterative circuit as in Fig.2a. This type of coupling is widely used in relaxation-based circuit simulators [6]. The equivalent circuit contains only voltage-controlled voltage sources (VCVS) and the resistive element ***Z*** is included into both parts of this circuit. The last peculiarity may produce implementation problems if the model of ***Z*** is rather compound (dynamic, nonlinear, distributed etc.) and implies a special form of mathematical description, inconsistent with the different program tools.

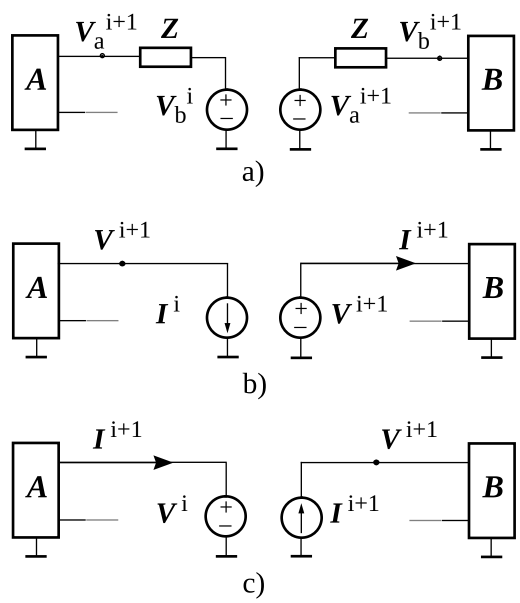

Fig.2 Basic types of coupling in the decomposed circuit

The second type of coupling (see Fig.1b) doesn't invoke any connecting elements between parts. The iterations can be organized in two ways as shown in Figs.2b, 2c. They both use different types of controlled sources: VCCS and CCVS.

If the mixed system contains many parts: ***A***, ***B***... and couplings between them, the different types of equivalent circuits like that shown in Figs.2a-c can be used together in one iteration process.

In any case we can't be sure that the considered iterations converge and/or the convergence is fast enough. Probably, among the reasons for slow or non-convergence there are: a) the equivalent iteration circuit badly reflects the "global" or informative feedbacks existing in the original system; b) the presence of strong local feedbacks produced by the controlled sources in the equivalent circuit itself. In the next section we'll show how to remove or reduce this second reason of non-convergence.

III. Modified local coupling

Note, that the local feedbacks can be reduced by changing the equivalent circuit in a way to suppress the alternating components of the controlled sources at the subcircuit ***A*** or ***B***. Now, we'll consider some modified iteration circuits that can provide this possibility.

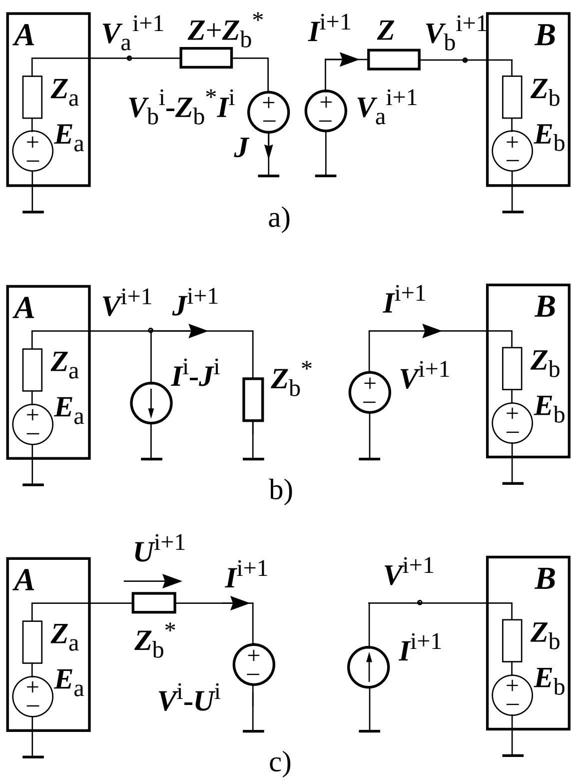

Fig.3 Modified types of coupling in the decomposed circuit

To explain the principle of the method in the easiest form we start with a linearized system that doesn't restrict the applicability of our approach to nonlinear system. Let, the linearized input characteristics of ***A***, ***B*** be described by the input resistances $\boldsymbol{Z}_a$, $\boldsymbol{Z}_b$. In this case we can represent the original model (Fig.1a) by the equation:

$$(\boldsymbol{Z}_a + \boldsymbol{Z} + \boldsymbol{Z}_b)\,\boldsymbol{I} = \boldsymbol{E}_a - \boldsymbol{E}_b, \qquad (1a)$$

where $\boldsymbol{E}_a$, $\boldsymbol{E}_b$, decsribe some internal energy sources in ***A***, ***B***. Similarly, the equation

$$(\boldsymbol{Z}_a + \boldsymbol{Z}_b)\,\boldsymbol{I} = \boldsymbol{E}_a - \boldsymbol{E}_b \qquad (1b)$$

describes the original model of second type (Fig.1b). Let also $\boldsymbol{Z}_b^*$ be some additional resistance which we'll use below. In these denotions for each considered case we can construct the modified iterative circuits that have some new features.

Thus, the iteration circuit in Fig.3a generalizes the case of Fig.2a and transforms to it when $\boldsymbol{Z}_b^* = 0$. To prove the consistency of this approach we must show that if iterations converge then the modified circuit produces the result, satisfying (1a). If $\boldsymbol{V}_b^{i+1} = \boldsymbol{V}_b^{i} = \boldsymbol{V}_b$, $\boldsymbol{I}^{i+1} = \boldsymbol{I}^{i} = \boldsymbol{I}$, $\boldsymbol{V}_a^{i+1} = \boldsymbol{V}_a$, then from Fig.3a we have:

$$(\boldsymbol{Z}_a + \boldsymbol{Z} + \boldsymbol{Z}_b^*)\,\boldsymbol{J} = \boldsymbol{E}_a - \boldsymbol{V}_b + \boldsymbol{Z}_b^*\boldsymbol{I} \qquad (2)$$

$$(\boldsymbol{Z} + \boldsymbol{Z}_b)\,\boldsymbol{I} = \boldsymbol{V}_a - \boldsymbol{E}_b \qquad (3)$$

$$\boldsymbol{V}_a = \boldsymbol{E}_a - \boldsymbol{Z}_a\boldsymbol{J} \qquad (4)$$

$$\boldsymbol{V}_b = \boldsymbol{E}_b + \boldsymbol{Z}_b\boldsymbol{I}\ . \qquad (5)$$

Substracting (3) from (2) and then substituting (4), (5), we get $\boldsymbol{J} = \boldsymbol{I}$. Further, the addition of (2) and (3) yields (1a).

The convergence of the considered iterations in the form $\boldsymbol{V}_a^{i+1} = \boldsymbol{W}\,\boldsymbol{V}_a^{i} + \boldsymbol{k}$ (where $\boldsymbol{W}$ is an iteration or companion operator and $\boldsymbol{k}$ is independent of $\boldsymbol{V}_a^{i}$, $\boldsymbol{V}_a^{i+1}$) is characterized by the expression:

$$\boldsymbol{W} = [(\boldsymbol{Z}_a + \boldsymbol{Z} + \boldsymbol{Z}_b^*)\,(\boldsymbol{Z} + \boldsymbol{Z}_b)]^{-1}\boldsymbol{Z}_a\,(\boldsymbol{Z}_b - \boldsymbol{Z}_b^*). \qquad (6)$$

Note, that if $\boldsymbol{Z}_b^* = 0$ then (6) coincides with the known estimation for the iterations from Fig.2a. Further, the norm of $\boldsymbol{W}$ substantially decreases and the convergence of modified iterations accelerates when $\boldsymbol{Z}_b^* \approx \boldsymbol{Z}_b$. In this case the controlled source parameter $\boldsymbol{V}_b^{i} - \boldsymbol{Z}_b^*\boldsymbol{I}^{i} \approx$
$\boldsymbol{V}_b^{i} - \boldsymbol{Z}_b\,\boldsymbol{I}^{i} = \boldsymbol{E}_b$ produces almost no local feedback during the iterations.

The modified iterations for the case of Fig.2b are shown in Fig.3b and they turn to the first when $\boldsymbol{Z}_b^* \to \infty$. If the convergence is reached then KCL and KVL equations have the form:

$$\boldsymbol{Z}_a^{-1}\,(\boldsymbol{V} - \boldsymbol{E}_a) + \boldsymbol{I} = 0 \qquad (7)$$

$$\boldsymbol{Z}_b\,\boldsymbol{I} = \boldsymbol{V} - \boldsymbol{E}_b \qquad (8)$$

The excluding of $\boldsymbol{V}$ from (7), (8) yields (1b) which proves the consistency of the modified iterations.

For this case the companion operator $\boldsymbol{W}$ may be expressed as:

$$\boldsymbol{W} = - [\boldsymbol{Z}_b (\boldsymbol{Z}_b^* + \boldsymbol{Z}_a)]^{-1}\boldsymbol{Z}_a (\boldsymbol{Z}_b^* - \boldsymbol{Z}_b) . \qquad (9)$$

If $\boldsymbol{Z}_b^* \to \infty$ then (9) simplified to $\boldsymbol{W} = - \boldsymbol{Z}_b^{-1} \boldsymbol{Z}_a$ that is the companion operator for the basic iterations shown in Fig.2b. For $\boldsymbol{Z}_b^* \approx \boldsymbol{Z}_b$ we have $\boldsymbol{W} \approx 0$ and the value of the controlled current source turns to $\boldsymbol{I}^i - \boldsymbol{J}^i \approx \boldsymbol{Z}_b^{-1} (\boldsymbol{V}^i - \boldsymbol{E}_b) - \boldsymbol{Z}_b^{*-1} \boldsymbol{V}^i \approx -\boldsymbol{Z}_b^{-1}\boldsymbol{E}_b$.

At last, the equivalent circuit shown in Fig.3c generalizes the iteration circuit from Fig.2c. They both coincide when $\boldsymbol{Z}_b^* = 0$. After the iterations have been finished, the modified circuit is described by the equations:

$$(\boldsymbol{Z}_a + \boldsymbol{Z}_b^*) \boldsymbol{I} = \boldsymbol{E}_a - \boldsymbol{V} + \boldsymbol{U} \qquad (10)$$

$$\boldsymbol{U} = \boldsymbol{Z}_b^* \boldsymbol{I} \qquad (11)$$

$$\boldsymbol{V} = \boldsymbol{E}_b + \boldsymbol{Z}_b \boldsymbol{I} \qquad (12)$$

Substituting (11) and (12) into (10), we come to (1b) which proves the consistency of the modified circuit. The companion operator in this case has the form:

$$\boldsymbol{W} = - (\boldsymbol{Z}_a + \boldsymbol{Z}_b^*)^{-1} (\boldsymbol{Z}_b - \boldsymbol{Z}_b^*). \qquad (13)$$

If $\boldsymbol{Z}_b^* = 0$ then (13) coincides with the estimation of $\boldsymbol{W}$ for the case of Fig.2c; the condition $\boldsymbol{Z}_b^* \approx \boldsymbol{Z}_b$ makes $\boldsymbol{W} \approx 0$ and turns the parameter of controlled voltage source to $\boldsymbol{V}^i - \boldsymbol{U}^i = \boldsymbol{Z}_b \boldsymbol{I}^i + \boldsymbol{E}_b - \boldsymbol{Z}_b^* \boldsymbol{I}^i \approx \boldsymbol{E}_b$.

Summarizing, we can say that all the considered modified iteration circuits from Figs.3a-c are generalizations of the conventional cases shown at Figs.2a-c and they all transform to the latters under some values of $\boldsymbol{Z}_b^*$. Furthermore, the choice $\boldsymbol{Z}_b^* \approx \boldsymbol{Z}_b$ considerably improves the convergence of the modified iterations. It also makes the local feedback "unidirectional" since the parameters of the controlled sources in the left part of circuit become almost constant.

Although the simplest case of linearized iterations was considered here, this approach can also be used to analyze nonlinear dynamic systems. In this case the values $\boldsymbol{I}$, $\boldsymbol{V}$, $\boldsymbol{U}$, $\boldsymbol{E}_a$, $\boldsymbol{E}_b$ etc. must be treated as time functions. Since this method deals with local feedbacks, it can also easily be generalized for more complex systems with N>2 parts involved in the iteration process, and many couplings may exist between every two parts of this system.

To implement these modified iterations in mixed system simulation one must use the "rough" input model of $\boldsymbol{B}$ while analyzing the part $\boldsymbol{A}$, if $\boldsymbol{B}$ in each iteration is analyzed after $\boldsymbol{A}$. More general, if during analyzing of part $\boldsymbol{X}_i$, $1<i<N$, one takes the results from $\boldsymbol{X}_1 ... \boldsymbol{X}_{i-1}$ found on the current iteration and the results from $\boldsymbol{X}_{i+1} ... \boldsymbol{X}_N$ that found at the previous one, then the convergence can be improved by the use of the rough input models of $\boldsymbol{X}_{i+1} ... \boldsymbol{X}_N$ while simulating $\boldsymbol{X}_i$, as shown in Figs.3a-c. Naturally, we must be able to describe these rough models in terms appropriate for the $\boldsymbol{X}_i$ analyzer.

IV. An example of mixed system simulation

To illustrate the above approach consider the analysis of a mixed system "electrical circuit - piezoelement" (Fig.4). For the electrical part we used Eldo v.4.3.1 analyzer (Anacad) and ANSYS 5.0 program (Swanson An.Sys.) was used for the piezoelement simulation.

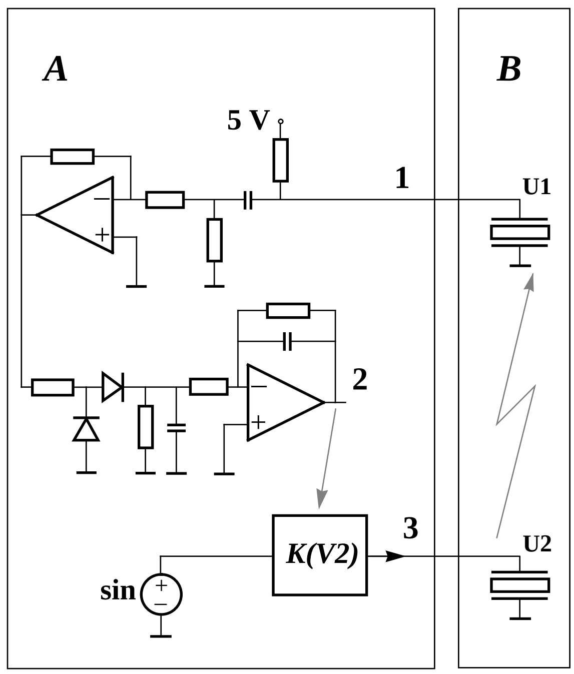

Fig.4 The example of a mixed system

The considered automatic gain-controlling system contains the piezoelement U1 that receives the acoustic vibrations coming from the transmitting element U2 through a stiff media. The received oscillations are then transformed into an electrical signal that is amplified and detected. The output of the detector after additional amplification and filtering controls the amplifier with the gain factor $\boldsymbol{K}(\boldsymbol{V2})$ = $\boldsymbol{K0}/(1+300\boldsymbol{V2})$. The resulting sine voltage of the frequency 100kHz is then applied to the transmitting piezoelement U2.

The input voltage is firstly applied to the top and bottom surfaces of U2, that produces the deformations creating the flat acoustic wave in the neighbourhood of U1. The acoustic pressure together with the voltage across U1 provoke the change of its charge. In its turn, the resulting current influences the voltage of node 1. The controlling system tries to maintain the constant magnitude of oscillations in node 1.

Hence it follows that:

1). The simulation of the given system totally in one program, either in Eldo or in ANSYS is impossible due to both the inconsistency of the input language and the incompatibility of the mathematical models of the parts. Furthermore, we don't dispose of the piezoelement macromodel that could be used in circuit simulators.

2). The considered system is tightly coupled and it has both global and local feedbacks. The global gain controlling loop runs through all the elements of the system. The local coupling between the $\boldsymbol{K}(\boldsymbol{V2})$ amplifier and U2 is "almost" unidirectional since the charge movement in U2 doesn't affect the output voltage of the amplifier. However, this is not the case for node 1 where the voltage substantially depends on the charge variability in U1, and this charge in its turn strongly depends on the applied voltage.

3). The suitable type of coupling in the decomposed circuit is that shown in Fig.2b. The first type (Fig.2a) cannot be realized since the original circuit (Fig.4) corresponds to the case of Fig.1b and we can't include the models of the electrical circuit components into Ansys. The third type of coupling (Fig.2c) is not possible here because we can't apply the current correctly distributed between different finite elements of U1 and U2 models.

As it was anticipated, the iterations realized according to Fig.2b, diverge very quickly. E. g. the forth iteration of V(2) yields values of about 1.0E8 V.

This inconvergence results from the fact that the input electrical impedance of U1 is of capacitance type while the output of electrical part from this point is almost resistive, so the multiple differentiation of the initial error is occurred during iterating.

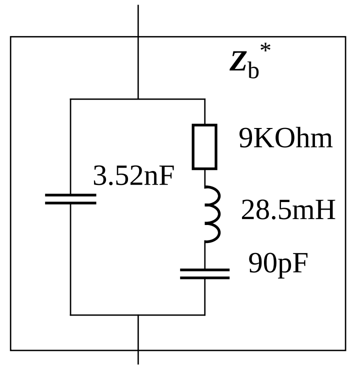

Fig.5 The rough circuit model of piezoelement

To provide the convergence we must realize the modified iteration scheme shown in Fig.3b. The simple C-RLC linear circuit (Fig.5) is used as a rough model of piezoelement U1. Fig.6 illustrates the

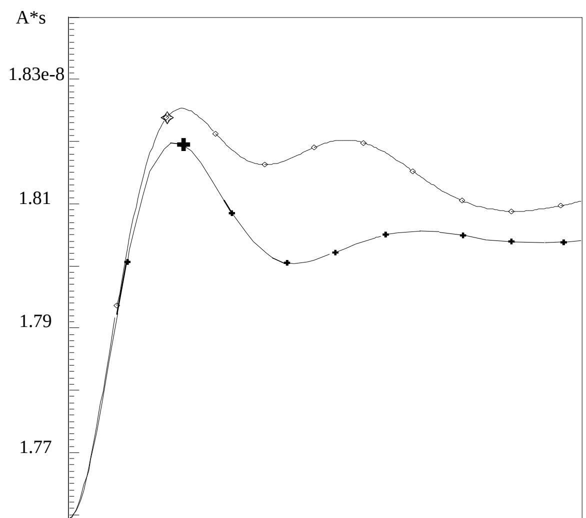

Fig.6 Charge responses of the ANSYS model (✧) and the rough circuit model (✚) of piezoelement U1

responses (charge vs. time) on the 5V step function for both U1 finite element ANSYS model and the rough model shown above. Further, fig.7 shows the results of the first 6 modified iterations. Though the rough circuit

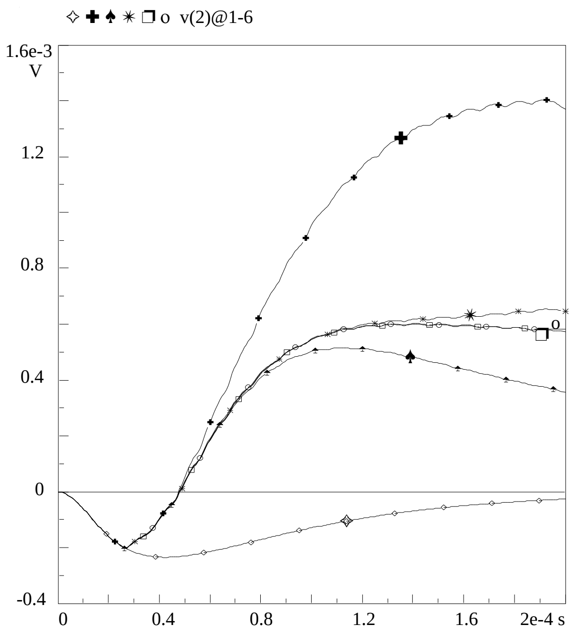

Fig.7 Results of first 6 iterations for modified type of coupling (convergence)

model is very inaccurate, the iterations converge fast enough and the results of 5-th and 6-th iterations almost coincide that can be considered as an exact solution.

It is important that we can't use the rough U1 model directly in the circuit simulator instead of the finite-element ANSYS model since it doesn't provide the

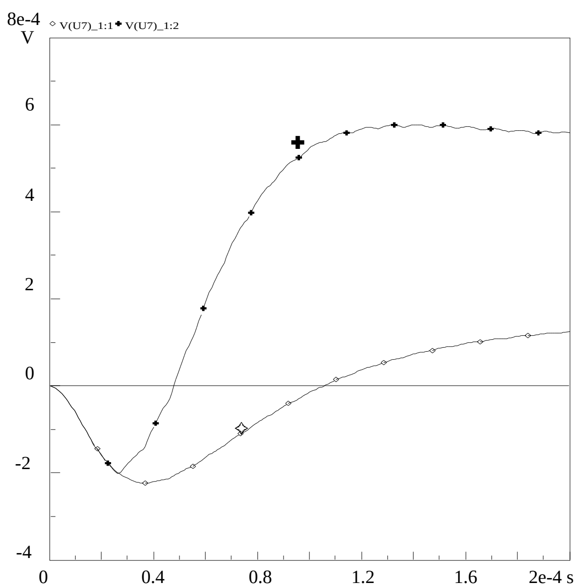

Fig.8 The result of Eldo simulation with "rough" U1 model (◇) and the solution from coupled simulation (✚)

sufficient accuracy. Figs.8 shows the result obtained in this way and the "exact" solution for node 2. Thus, for the given example the modified iteration approach has no alternatives.

V. Conclusion

In this paper we introduced a new approach that allows to improve the convergence of iterations while analyzing mixed systems with different simulators. The useful effect results from the reduction of the local feedbacks in the decomposed system. This is very important for mixed systems where optimal partitioning methods are not possible and the choice of the suitable types of coupling is also restricted.

To reduce the problems of global feedback we can use any other methods like time windowing, timestep refinement, multilevel iteration etc. that can be combined easily with the proposed approach.

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