PSPICE MODELS OF SC-CIRCUITS WITH PERIODICAL NONUNIFORM INDIVIDUAL SAMPLING

Zdravko Atanassov Garmev*, Elissaveta Dimitrova Gadjeva**

*Melexis – BG, "Ami Bue" Str. No 84, 1612 Sofia, Bulgaria,
e-mail: zgy@melexis-bg.com

**Department of Electronics, Technical University of Sofia, "Kliment Ohridski" Str. No 8, 1000 Sofia, Bulgaria, e-mail: egadjeva@tu-sofia.bg

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In the present paper, computer models are proposed for the investigation of SC-circuits with peroidical nonuniform individual sampling. The application of SC-circuits with this sampling type introduces an additional degree of freedom with a possibility for program tuning of the circuit parameters. The equivalent circuit of switched capacitor element is based on modeling of capacitor charge increment for each of the subintervals within the whole cycle of controlling signals. This representation leads to a multiphase capacitor model in the frequency domain based on z-transform of the signals in the discrete-time domain. This leads to an acceleration of the frequency-domain analysis in comparison with the Fourier component determination of the results from the time-domain analysis. A specific feature of the switch model is the necessity of parameterization of its characteristics in the case of peroidical nonuniform individual sampling. The developed approach is illustrated by the analysis in the frequency domain of a bandpass SC-filter with characteristics, allowing tuning/trimming by different clock sequences, applied on the separate switch groups.

1. INTRODUCTION

The switched-capacitor circuits are widely used in the development of contemporary electronic devices. One of the advantages of SC-circuits consists in the possibility for circuit characteristics variation using the characteristic dependence on the effective commutation frequency in different circuit branches. It is achieved by grouping a number of phase sequences (m) in a more general phase cycle [1]. The defined in this way phase cycle is repeated as shown in Fig. 1. In this way, an easy digital control is achieved on the characteristics of the analog part of the system, by selecting the number of the phase sequences (p), which are to be activated. The traditional simulation approach of such type of circuits and the assessment of the efficiency of the designed circuit is the time-domain analysis, followed by Fourier analysis for obtaining the frequency-domain characteristics. This approach is characterized by a low speed of simulation in the case of complex systems. In that reason, it is important to develop SC-models which allow the increasing of simulation speed.

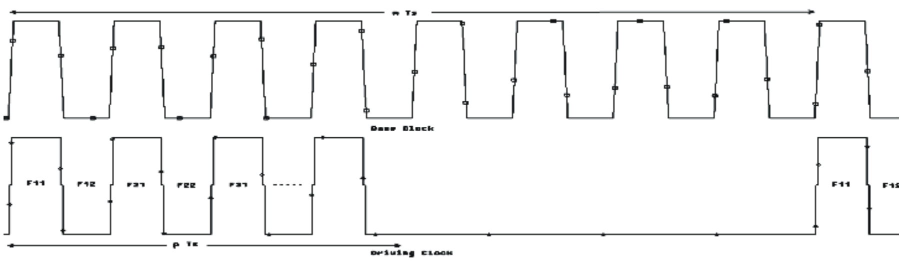

Fig. 1

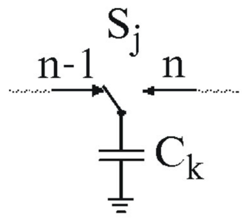

Fig. 2

2. GENERAL PRINCIPLES FOR SC-CIRCUIT MODELING

The SC-circuit analysis in the discrete-time domain is reduced to the analysis in continuos-time domain using equivalent behavioral models of the SC-components.

As the SC-circuits have two (or more) phases of operation, the model describing the system behavior, consists of subcircuits describing the circuit behavior in each of the phases. The transition of the system from one phase to the next phase is characterized by a charge transfer from the first to the next circuit configuration by the switched capacitors. After the commutation, a new voltage is established on the capacitor (Fig. 2). The charge transfer leads to the influence of the current phase to the next, and it has to be modeled. The transferred charge is proportional to the capacitor voltage difference for the successive phases and to the capacitor value.

$$\Delta Q_{n,k} = \left(U_{Ck,n} - U_{Ck,n-1}\right)C_k \tag{1}$$

where $\Delta Q_{n,k}$ is the charge difference and $U_{Ck,n}$ и $U_{Ck,n-1}$ are the voltages of the capacitor C_k, for the current phase (n) and the previous phase (n-1).

The z-transform of the charge difference is obtained in the form:

$$\Delta Q_{n,k}(z) = C_k U_{Ck,n}(z) - z^{-K} C_k U_{Ck,n-1}(z) \tag{2}$$

where $K = \Delta T/T$, ΔT is the phase duration , T is the period of the phase sequence.

If the phases are of the same duration, $K = 1/N$, where N is the number of phases. Based on the dependence $z = e^{sT}$, the representation in the s-domain for the transferred charge is obtained:

$$\Delta Q_{n,k}(s) = C_k U_{Ck,n}(s) - e^{-\frac{s}{NF}} C_k U_{Ck,n-1}(s) \tag{3}$$

where $F = 1/T$ is the frequency of the main phase sequence.

In the cases when the frequency dependence of the OpAmp open-loop gain is not taken into account, the OpAmp is modeled by a voltage dependent voltage source (VCVS). It is included in each of the subcircuits S_1, S_2, …, S_N representing the successive phases.

Taking into account the frequency dependence of the OpAmp open-loop gain, the influence of current phase on the next phase has to be assessed. If one-pole approximation of the transfer function (1.5) is used

$$H(s) = \frac{U_{out}(s)}{U_{in}(s)} = \frac{A_0}{1 + s/p} \tag{4}$$

where A_0 is the DC gain and p is the approximating pole, the output voltage has the form [2]:

$$U_{out}^{k}(s) = A_0\left(1 - e^{\frac{pT}{N}}\right)U_{in}^{k}(s) + e^{\frac{(p-s)T}{N}}U_{out}^{k-1}(s) \tag{5}$$

Each of the switches S_k, k=1,2,..., m is defined with a parameter n_k – number of clock periods in a clock cycle when the switch is closed. The ratio n_k/n defines the transferred charge and the corresponding circuit characteristics. If the switch S_{ij} connected between nodes i and j, is closed in the phase q, it is modeled by a short circuit between nodes $i^{(q)}$ and $j^{(q)}$ in the *SC*-model.

3. MODELING OF SC-CIRCUITS WITH NONUNIFORM PHASE SEQUENCE

In the SC-circuits with nonuniform phase sequence, a variation of the circuit characteristics can be achieved using corresponding sequence control (Fig. 1).

The multiphase models of *SC*-circuits with nonuniform phase sequences consist of subcircuits modeling all phase sequences in a phase cycle. *SC*-models are derived in the paper for the case of m sequences with a two-phase commutation of each sequence. The results can be easy generalized for the case of multiphase commutation. The modeling of nonuniform phase sequence leads to a (2m)-phase *SC*-models of the components. The switch model allows connections between each of the its even or odd ports depending on the phase number, which corresponds to a closed switch. In order to model nonuniform switching, controlling parameters depending on the digital control, are used in the switch model. These parameters define the connections which have to be realized for the corresponding conditions.

4. COMPUTER REALIZATION IN THE ORCAD ENVIRONMENT

The approach is illustrated for the number of sequences m=8 and two-phase commutation for each of the sequences. In this case the expression (1.3) has the form:

$$\begin{aligned}
\Delta Q_{1,k}(s) &= C_k U_{Ck,1}(s) - e^{-\frac{s}{2F}} C_k U_{Ck,16}(s)\\
\Delta Q_{2,k}(s) &= C_k U_{Ck,2}(s) - e^{-\frac{s}{2F}} C_k U_{Ck,1}(s)\\
&\dots\\
\Delta Q_{16,k}(s) &= C_k U_{Ck,16}(s) - e^{-\frac{s}{2F}} C_k U_{Ck,15}(s)
\end{aligned} \tag{6}$$

The corresponding computer model corresponding to (1.6) is shown in Fig. 3, where only the last and the first subcurcit are depicted. The rest of the subcircuits are modeled in a similar way. The model consists of resistors and voltage controlled dependent sources of GLAPLACE type. The pins of the capacitor are denoted by A and B. Buses A[1..16] and B[1..16] are used for placing of pins of multiphase capacitor model. The capacitor parameters are defined as attributes. The symbol of the multiphase switched capacitor is shown in Fig. 4. The model is defined as a hierarchical block.

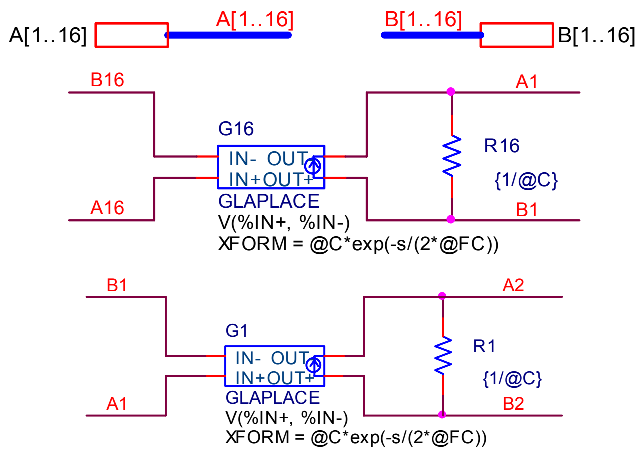

Fig. 3

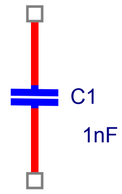

Fig. 4

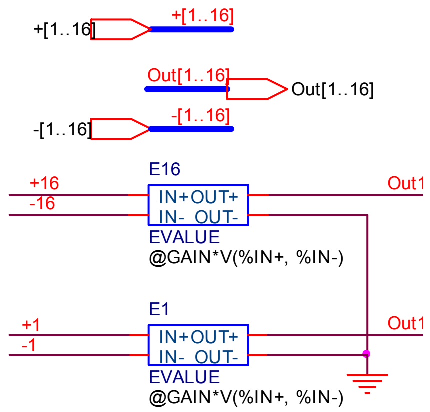

Fig. 5

In order to increase the simulation efficiency, a corresponding PSpice model is created and attached to the symbol shown in Fig. 4, using the PspiceTemplate attribute. It corresponds to the input language of the circuit editor and has the form:

X^@REFDES %A1 %A2 %A3 %A4 … %B13 %B14 %B15 %B16
+ @Implementation PARAMS: C=@Value FC=@Fc

The model taking into account the open-loop DC gain is based on the VCVS of EVALUE type included in each of the phases. The OpAmp gain is defined as a parameter in the form: @GAIN*V(%IN+, %IN-). The resulting computer model is shown in Fig. 5, where only the last and the first subcurcit are depicted.

The symbol of the OpAmp is shown in Fig. 6. The model is defined as a hierarchical block. Similarly to the SC-capacitor, a PSpice hierarchical model based on subcircuit definition, is constructed in order to increase the simulation efficiency.

A computer OpAmp model taking into account the frequency dependence of the open-loop gain, corresponds to the equation (5), is also constructed (Fig. 7). The elements of GVALUE and GLAPLACE type of the ABM library are used for this purpose. The node number reduction is achieved in the computer model shown in Fig. 7, based on equivalent circuit with current sources. The direct modeling of (5) using voltage sources is ineffective, as a large number of inner nodes are introduced. The specific feature of the SC switch models in the case of nonuniform switching is the necessity of model parameterization in order to define the corresponding connections.

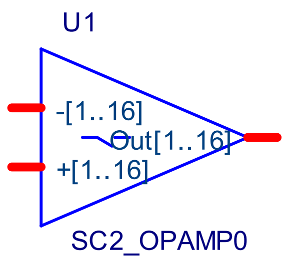

Fig. 6

Fig. 7

The specific feature of the SC switch models in the case of nonuniform switching is the necessity of model parameterization in order to define the corresponding connections. Another speciality is the introducing of "dummy" resistors of large value in order to ensure a DC path to each of the nodes. A part of the model (phases 3 and 6) are shown in Fig. 8. The symbol of the switch is shown in Fig. 9. The switches, which are active in the odd half-period of the clock signal, are modeled similarly.

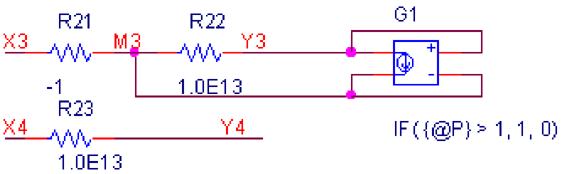

Fig. 8

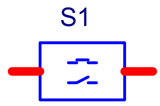

Fig. 9

5. EXAMPLE

The SC-filter with peroidical nonuniform individual sampling [1] shown in Fig. 10, is investigated as an example.

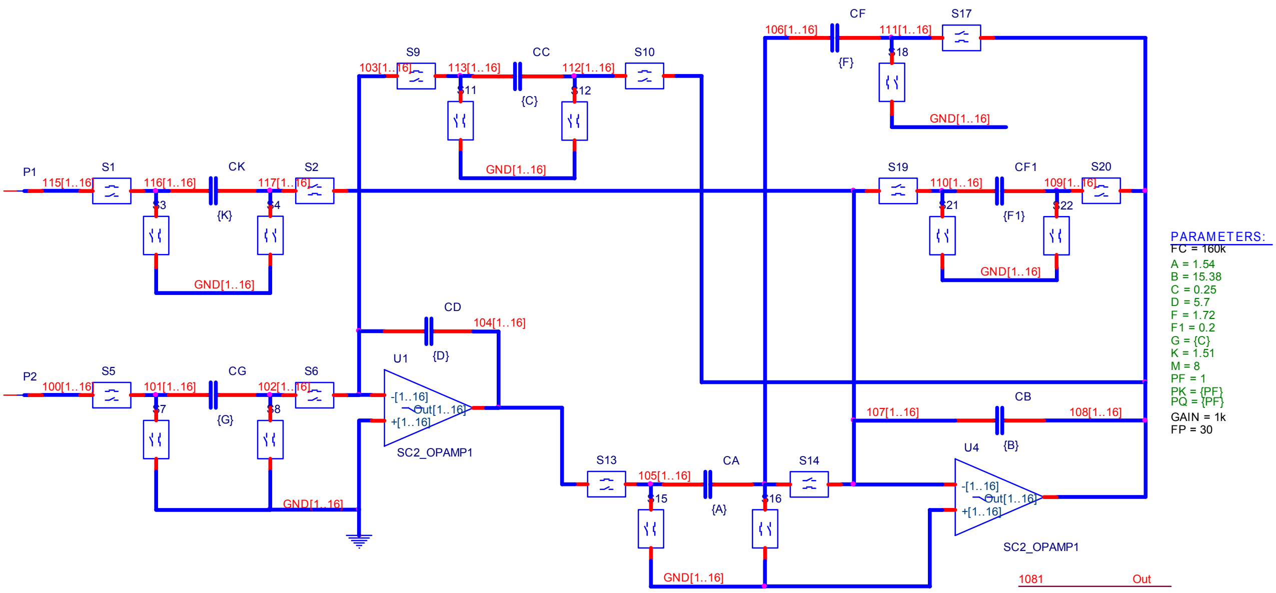

Fig. 10

The circuit has two inputs – one as an input of a low-pass filter and another as an imput of bandpass filter. The pole frequency, the gain, as well as the quality factor can be controlled by variation of corresponding circuit parameters PF, PK and PQ. The circuit is investigated using frequency-domain and parametric analyses. The results for the control of the gain, pole frequency and quality factor Q of the low-pass filter are shown in Fig. 11, Fig. 12 and Fig. 13 respectively. The results for the quality factor control of the band-pass filter are shown in Fig. 14. The comparison between The simulated results are in a good agreement with the measurements performed in [1].

6. CONCLUSION

Computer models are developed for analysis of SC-circuit with peroidical nonuniform individual sampling. Multiphase macromodels are prposed for the SC building blocks: capacitors, OpAmps and switches. The possibilities for program tuning of the circuit parameters (pole frequency, gain, quality factor) are presented. The proposed principles of modeling can be used to frwquency domain analysis of discrete-type circuits using the standard PSpice-like simulators. The comparison between the measured characteristics given in [1] and the simulated results are in a good agreement. It gives the possibility of assessment the developed filter circuits at earlier design stage. The proposed computer symbol and model libraries can be enlarged with models corresponding to concrete components and can serve as a computer-aided design tool.

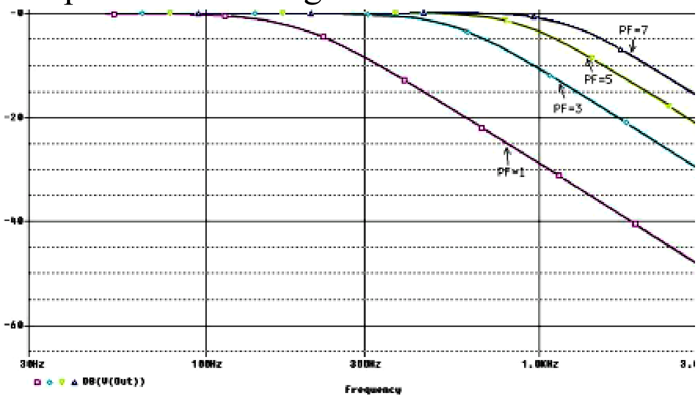

Fig. 11

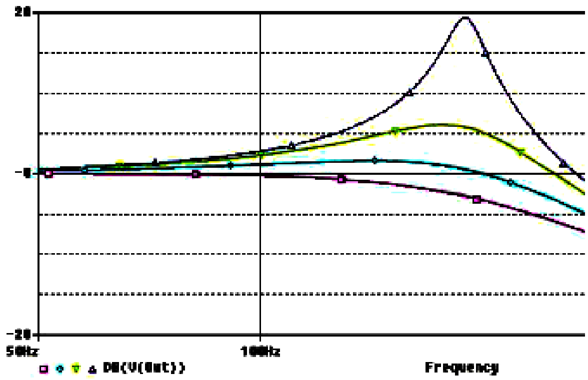

Fig. 13

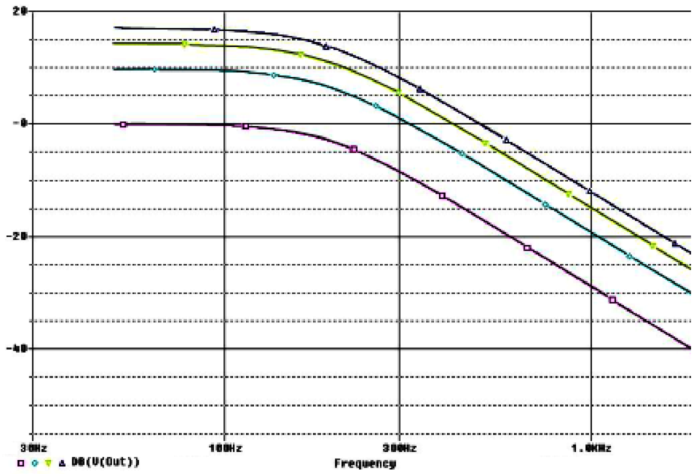

Fig. 12

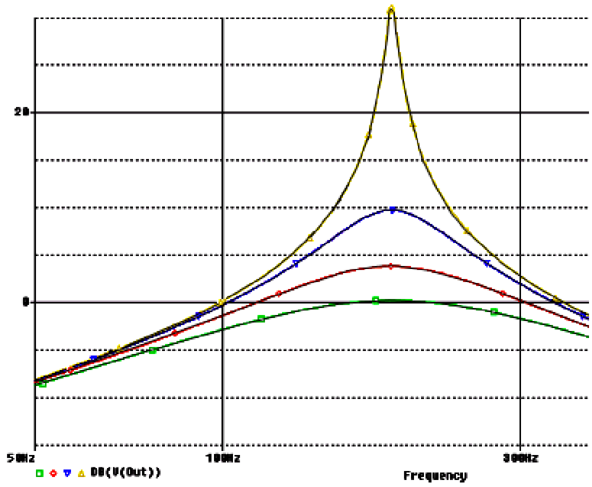

Fig. 14

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