# ASIZ - Analysis of switched-current filters in Z transform

*Documentation for version 2.0 (Windows)*

### Introduction

The ASIZ program analyzes switched-current (SI), switched-capacitor (SC) filters, or (almost) any periodically switched linear time-invariant network composed of capacitors, resistors, and voltage-controlled current or voltage sources, where the circuit stabilizes completely between the switching instants. The program can compute:

- Z-transform transfer functions.
- Poles and zeros.
- Frequency responses: Gain, phase, and group delay (approximated).
- Time-domain responses.
- Frequency response sensitivities.
- Effects of nonideal transistors in switched-current circuits.
- Errors due to component tolerances (sensitivity analysis).
- Output frequency spectrum.

The outputs of the analyses can be plotted on the screen and sent to a report file. The description of the circuit to be analyzed is read from a text file, but all the commands are given interactively.

### Input

The circuit to be analyzed must be described by its small-signal AC model (the normal structure for a SC circuit, and the circuit without the bias sources for an SI circuit). The circuit description is given by a text file, in the format:

First line: number of nodes in the circuit. Following lines: One element description per line:

- MOS transistor: M<name> <drain node> <gate node> <source node> <Gm> <Gds>
- Resistor: R<name> <node 1> <node 2> <resistance>
- Capacitor: C<name> <node 1> <node 2> <capacitance>
- Current source: I<name> <node +> <node -> <current>
- Voltage source: V<name> <node +> <node -> <voltage>
- Switch: S<name> <node 1> <node 2> <phase> [<phase>...]
- Transconductor: G<name> <node I+> <node I-> <node V+> <node V-> <Gm>
- Ideal operational amplifier: O<name> <input node> <input node> <output node>
- Voltage amplifiers:
- E<name> <node Vo+> <node Vo-> <node Vi+> <node Vi-> <Av>
- A<name> <node Vi-> <node Vi+> <node Vo> <Av>

The nodes are enumerated from 1 to the number of nodes, without missing numbers. 0 is the ground node. The phases are enumerated from 1 to the number of phases.

The description can be generated by the EdFil editor program. The program prefers a normalized circuit, with all the capacitances, resistances, conductances, and transconductances with values close to 1.

### Models for the elements

The MOS transistors can be n-channel or p-channel. The AC model is the same for both. A transistor is modeled by a transconductance Gm, a Gds conductance, a Cgs capacitance, and a Cgd capacitance. Gm and Gds are given in the netlist file, and the other parameters can be set in several ways in the mosfet parameters window.

Resistors can be used to convert currents into voltages and to model losses in switches and DC current sources. Capacitors can be used in the analysis of switched-capacitor filters, and the simulation of parasitic capacitance effects. Independent current sources feed the input signal to SI filters, and voltage sources are the inputs for SC filters. Transconductors can be used to model OTAs, and other functions. Voltage amplifiers can model finite-gain operational amplifiers in SC filters, and other functions. For convenience in using the EdFil editor, two formats are accepted ("E" and "A"). Ideal operational amplifiers are used in switched-capacitor filters and in precision switched-current filters.

The switching period is considered subdivided in a number of equal duration phases. A switch can be open or closed in any of these phases. The phase list in the description of the switch indicates in which phases it is closed.

Only one input can be applied to the circuit. Several signal sources can exist in the netlist, but the values of all them are considered as just scaling factors for the same input signal.

**Output**

The program computes nodal voltages in z-transform. In the AC small-signal model the relation between gate-source voltages and drain currents of MOS transistor is linear (and Cgs and other capacitances are also linear), and the output signal can be taken in a switched-current filter as the gate voltage of the transistor that produces the output current. Alternatively, more realistically, a resistor can be used to sample the output current. In this case, the results are also valid for large signals.

The voltages in the adjoint network are also available. It must be observed that some "voltages" in the adjoint network (at "high impedance" nodes) have no physical meaning, because they belong to capacitive nodes fed by current sources. Those "voltages" are used only for sensitivity calculations, where their "infinite" values are multiplied by "zero" conductances, producing finite (and correct) current values. When voltage sources are used, additional variables are computed in the adjoint network, indexed with numbers above the numbers of nodes. They represent the negative of the currents in the voltage sources in the adjoint network, and are used in sensitivity calculations. Note that the adjoint network is not physically realizable, because in it the capacitors retain the voltage of the next phase, not of the last.

The voltages computed can be interpreted as the responses of a periodically switched Gm-C circuit, where the currents (and, in the normal circuit, voltages) are allowed to reach the steady state between the switching instants.

There are restrictions on the topology of the circuits that can be analyzed: All the resistive portions must have a connection to the signal ground at all the phases and current sources cannot be connected to purely capacitive nodes (or the program will produce singular equation systems). This normally happens in any practical circuit topology. In some switched-capacitor circuits, capacitors are left floating at some phases. The program does not accept this. Additional switches or resistors, or phases in the switches, must be added to keep all the parts of the circuit with well-defined voltages in all phases.

**Program operation**

*Netlist:*

The program begins by presenting text fields to be filled with the name of the input netlist file and the number of phases. The file name can be selected in a file selection window. The button "Read" starts the reading of the file.

*Analysis:*

After the reading, a window with several analysis parameters is presented. Usually only the output node and the sampling parameters are used. The others rarely must be changed. The button "Analyze" starts the analysis.

At the end of the analysis, the computed denominator, or characteristic polynomial of the circuit, is listed, and windows pop up with numerator parameters and several display options. Once the numerator parameters are set to the desired values, the different analyses can be made in any order. All the windows can be accessed through the menu in the main window.

*Frequency response:*

The frequency response can be plotted for any transfer function. It is plotted in the program main window, with several options selectable in the frequency response parameters window. The same plot is also used for the display of error limits (sensitivity) and spectral components (see below).

*Transient response:*

Time responses for several test inputs can be plotted, also for any transfer function. They are plotted in a secondary window. The transient response parameters window holds the controls for the several options. The input signal can be read from a file. The file is a text file, where at each line is a pair of numbers. The first is a time, and the second a value. The signal is considered as piecewise-linear using 0, 0 and the given points as corners. The first point cannot have 0 as time, and no two points can have the same time (points like these will be ignored). The signal is considered as 0 after the last point given.

*Poles and zeros:*

Poles and zeros of any transfer function can be computed and plotted in a window or listed. Along with the frequencies, the unit circle is also plotted for reference. The poles and zeros parameters window controls how the poles and zeros are computed and displayed.

*Output spectrum:*

The output spectrum components for a sinusoidal input at a given frequency can be plotted, superimposed on the main frequency response plot. The spectrum computation can be started from the output spectrum parameters window, or directly from the frequency response window, by pressing the “e” key. All the spectrum components that are in the frequency range selected for the main transfer function are computed. The output spectrum is available only for normal transfer functions.

*Sensitivity:*

Sensitivities from a transfer function in relation to the variation of a selected group of circuit parameters can be computed, and plotted along with the gain and phase curves in the frequency response (main) window, as errors in decibels and degrees superimposed on the curves shown. The errors can be computed as deterministic deviations (sum of the errors due to all the selected parameters) or statistical deviations (square root of the sum of the squares of the errors due to all the selected parameters). All the selected parameters are assumed to have the same variability. Note that the sensitivities of just one nodal voltage, the one specified in the analysis parameters window at the start of the program, are available after the initial analysis, although frequency responses of any nodal voltage are always available without recalculation. The computation of errors due to a large group of parameters may be slow. The sensitivities of the transfer function in relation to the values of all the selected elements can be listed, by pressing "s" when the cursor is at the desired frequency in the frequency response graph. In the present version, sensitivities for unsampled input are not available (see "sampling" below).

*Sensitivities with gain sensitivity discounted:*

It is possible to discount the gain sensitivities at a given frequency from the sensitivity calculations, by pressing the corresponding button in the sensitivity analysis parameters window. After the initial plot, move the cursor to the desired frequency and press "s". This is useful to separate gain errors from errors that distort the gain frequency response. The technique is more clearly meaningful in filters derived from LC doubly terminated networks, where at the frequencies of maximum gain only the flat gain sensitivities affect the gain.

*Correlated elements:*

For the statistical deviation computation, groups of correlated elements can be specified. These elements have their sensitivities added and are treated as a single element in the computation. To select correlations, select a group "a".."z" before selecting elements with the mouse left button. All the elements marked with a same letter will belong to a group of correlated elements. To make elements uncorrelated with the others, select the "*" group before selecting the elements with the mouse. The current selection of elements and correlations can be saved to a file or read back.

*References:*

Frequency responses and transient responses can be saved as references (the commands are in the pop-up menus of the windows), and plotted along with others of the same circuit or of another circuit for comparison. Sensitivity curves cannot be saved as references.

*Report file:*

All the computed results can be saved in a report file. The messages window can also be saved in the report file. For the frequency response, a table is generated containing: frequency, gain, phase, group delay, gain error, phase error, minimum gain limit, and maximum gain limit, as columns of values. The errors are listed only if the sensitivity analysis is selected.

*MOS transistor parameters:*

It is possible to include parasitic effects in the circuit in a simple way using the commands in the mosfet parameters window. Once an item is changed, the circuit must be read again and reanalized.

**Direct commands in the windows**

*Pole/zero graph:*

- Cursor keys, +, -: Move the graph and changes the scale.
- Shift+Left mouse button: Move the cursor.
- G: Toggles the drawing of a grid.
- Mouse left button: Dragging the mouse defines zoom area.

*Frequency response graph:*

- Horizontal cursor or Shift+Left mouse button: Cursor.
- A, R, +, -: Change the horizontal and vertical scales.
- Vertical cursor keys, <(,), >(.): Panning.
- L: Changes the horizontal scale between logarithmic and linear.
- F: Toggles the drawing of phase curves.
- T: Toggles the drawing of group delay curves.
- V: Lists the linear absolute gain at the cursor frequency.
- Mouse left button: Dragging the mouse defines zoom area.
- G: Toggles the drawing of the grid.
- C: Changes colors.
- S: List all the selected sensitivities at the cursor frequency, and, if the discount of gain sensitivities is enabled, plots a new graph.
- E: Plots the spectrum components for an input at the cursor frequency.
- W: Lists the same spectrum.

(G and C affect the other plots also, when they are redrawn).

*Transient response graph:*

- Horizontal cursor or Shift+Left mouse button: Move the cursor.
- A, R, +, -: Change the horizontal and vertical scales.

- G: Toggles the drawing of a grid.

The direct commands in graph windows only work when the graphs are valid. If some parameter is changed in some window that invalidates a graph, it remains unchangeable until redrawn.

Each graph has a menu of options, presented before the plotting and accessible through the graph menu, where scales and other parameters can be directly specified.

**Observations**

*Graphics mode:*

The program is optimized for at least 800x600 pixels.

*User interface:*

The program uses the normal Windows interface.

*Poles and zeros:*

The default tolerances and initial approximations in the poles and zeros parameters window are sufficient for most usual cases, but they can have to be changed in some cases. The most usual problems are with groups of closely spaced roots that the program interprets as a multiple root or of a multiple root that the program interprets as a group of closely spaced roots. The parameter of "magnitude tolerance" can be adjusted to guide the routine to the correct result: Smaller values force multiple roots and higher values force distinct roots. The routine can also have problems of convergence. It will lower the tolerance for the roots until they can be found. Poles and zeros are computed in the $z^{1/N}$ domain, where N is the number of phases. A complete turn around the unit circle corresponds to N times the switching frequency.

*Global and Partial numerators:*

The global transfer function of a switched circuit with N phases is the composition of N×N partial transfer functions, from each phase at the input to each phase at the output. The denominator of all the functions is the same, but the numerators are different. The program computes all the partial numerators and adds them to obtain the global numerator (The sampling operation divides the sum by N in the frequency response, and the time separation of the phases does the same in the transient response. Due to this, the global numerator coefficients, as listed, appear multiplied by N). Zeros, frequency responses, sensitivities, and transient responses can be computed for all the partial transfer functions. Usually the designed digital transfer function of a filter is one of the partial transfer functions. Note that in these cases the gain appears divided by the number of phases, as a partial transfer function output is zero at the other output phases. Usually, a look at the transient response turns clear what is happening.

*Switched-current filters:*

All the biasing DC current sources must be omitted from the description (remember: ALL the sources are AC). They can also be substituted by resistors representing their output resistances, but it is more practical to set a convenient value for Gds in the mosfet parameters window. All the capacitances, resistances, and transconductances shall be normalized to values around 1 for good accuracy in the analysis. Independent scaling factors can be used for capacitances and transconductances.

*Switched-capacitor filters:*

Finite-gain voltage amplifiers and voltage sources can be used directly. Alternatively, a current source or a transconductor with a resistor in parallel with its output is equivalent to a voltage source or a voltage amplifier, for capacitive loads. Note that the ideal operational amplifier is really ideal, and reduces the size of the systems of equations that the program solves when used. Impedance normalization shall be used, with capacitors having values around 1 F.

*Sensitivities:*

In proper switched-current filters, the sensitivities to all the capacitances are always null (or low, if parasitic capacitances, as Cgd, are included). As default, the program marks the transconductors to have their sensitivities computed, because only they are significant in ideal SI filters.

*Sampling:*

Three sampling methods are available:

- Sample/hold: The input and output are considered sampled at the beginning of each phase and held for the phase interval. This is the usual sampling method. Filters will exhibit the usual sin(x)/x gain distortion caused by the output sampling.

- Impulse: The input is considered sampled at the beginning of each phase and held for the phase interval. The output is considered sampled by a unitary impulse function at the beginning of each phase. Filters will present the ideal digital transfer function. Note that the program assumes that the output is sampled at all the phases. This can cause some confusion if impulse sampling is used, because even if the output varies only once per period, the output exhibits N impulses per period. This causes the appearance of extra zeros in the transfer function (at multiples of the sampling frequency, if all the impulses are equal). The artifact can be eliminated by zeroing the output (with switches) at all the phases, except the one where the output changes.

- No sampling: The effects of direct signal feedthrough through the circuit are considered. It is assumed that the time constants in the path are negligible, so effects of input variations propagate instantaneously. Frequency responses, transient responses, and spectra will be computed considering the signal feedthrough. Sensitivity analysis is not available (yet) in this case.

Note that other sampling methods can be analyzed, by using explicit sampling circuits added to the input or output. A sample/hold circuit can be made with a switch, a capacitor, and a buffer circuit.

*Output spectrum:*

For usual filters, the output spectrum components appear at all the frequencies in the form n × <sampling frequency> ± <input frequency>, and the amplitudes agree with the main transfer function amplitudes at those frequencies. This is not always true, because modulation effects can affect the spectrum components, causing some of them to disappear or to assume different values. The program considers all these effects.

*Group delay:*

The group delay is computed by the numerical differentiation of the phase curves, and so is more precise if more points are used. (The exact computation is possible, and may be included in a future version.) Spikes may appear at 360 degrees phase transitions if not enough segments are used.

*Circuits with cancelled unstable poles:*

If a transfer function has cancelled poles out of the unit circle, as happens with balanced structures without common-mode feedback, the program can have problems when plotting the transient response. Usually, numerical residues of the analysis will excite the unstable poles, and the transient response will diverge after some time. The effect is very dependent on numerical details, as the interpolation radius used. Note that these circuits have only theoretical interest. This note is just to explain the apparent error.

*Valid results:*

It must be noted that the program assumes that all the elements are linear (small-signal model). The results are valid for large signals only if certain topological restrictions (switched-current or switched-capacitor techniques) are followed. Also, the program assumes that switching transients are much faster than the switching period, and that the continuous-time circuits formed at any phase are stable.

*Analysis method:*

The analysis method used by the program was described in the paper: "Systematic nodal analysis of switched-current filters," by A. C. M. de Queiroz, P. R. M. Pinheiro, and L. P. Calôba, proceedings of the 1991 IEEE ISCAS, Singapore, pp. 1801-1804, June 1991. A more detailed description appeared in the paper "Nodal analysis of switched-current filters," IEEE Transactions on Circuits and Systems-II, vol. 40, no. 1, January 1993, pp. 10-18. A still more detailed description is in the book "Switched-Currents: An Analogue Technique for Digital Technology," edited by C. Toumazou, N. C. Battersby, and J. B. Hughes, and published by the IEE in 1993.

*Main revisions:*
Version 2.0: Porting of the DOS version to Windows using Delphi.
Version 1.6: The input for the transient analysis can be read from a file.
Version 1.5: Discount of gain sensitivities implemented.
Version 1.4d: Bugs in the treatment of voltage sources, noise input without sampling, and a possible cause of crash in the transient plotting removed. Single-precision version of the program removed.
Version 1.4c: Noise input in the transient response added.
Version 1.4b: Time limit in the transient response eliminated.
Version 1.4a: Approximate group delay computation included, and listing of the gain values, for easy dynamic range equalization of SI filters.
Version 1.4: Direct signal feedthrough considered, with the "None" sampling option. General rewriting of internal procedures. The transient responses saved in the report now contain the values at the two extremes of each phase interval, and will plot correctly in a XY plotter program.
Version 1.3a: An optimization in numerical procedures increased significantly the analysis speed. 2-3x for two-phases circuits, and more for more phases.
Version 1.3: Output spectrum calculation included. Retaining of the frequency response graph (command "X") added. Corrected potential problem in the saving of the sensitivity selection.
Version 1.2d: Corrected a bug in the number of phases in references.
Version 1.2c: Frequency responses and sensitivities are now available for the partial transfer functions. The sensitivity calculation was optimized, and is now 2 or 3 times faster.
Version 1.2b: The impulse input now lasts for one entire period, and the plotting of the input in the transient response is optional.
Version 1.2a: More correlated groups. Most recent versions compiled with slightly changed interface.
Version 1.2: Groups of correlated elements in the statistical deviation.
Version 1.1b: Sensitivities can be listed.
Version 1.1a: Voltage sources included.
Version 1.1: Memory allocation improved to allow the analysis of larger circuits. The program now accepts circuits of up to 200 nodes and 16 phases, resulting in systems of up to 400 equations.

*Files on the compressed distribution file*

Asizw.exe - The ASIZ program.
Asizw.pdf - Documentation for the ASIZ program.
Examples.pdf - Description of the examples.
Asizfaq.pdf - Some questions and their answers.
Edfilw.exe - Circuit schematic editor.
Edfilw.pdf - Documentation for the EdFil program
*.cir - Schematic circuit files for EdFil.
*.net - Netlist files.
*.val - Value list files for EdFil.

*Distribution and use*

The ASIZ program can be distributed freely for educational purposes, as long as no charge is made, it is not changed in any way, and reference to its use is made in any work done with its help.

For commercial utilization, a registration fee is required. Contact the author. The author believes that the program works correctly, but cannot assume responsibility for losses caused by flaws in the program that escaped his attention. The most current version of the program and auxiliary files can be obtained at:
http://www.coe.ufrj.br/~acmq/ASIZ.html.

Users are encouraged to send a letter or e-mail to the author telling how the program is being used. Comments, suggestions and questions about the program utilization shall be sent to:

Dr. Antonio Carlos M. de Queiroz
Programa de Engenharia Elétrica
COPPE - Universidade Federal do Rio de Janeiro
CP 68504
21945-972, Rio de Janeiro, RJ, Brazil
or, via e-mail, to acmq@ufrj.br

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