Using range arithmetic in evaluation of compact models

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Outline

- Introduction
- Interval based Simulation flow
- Simulator design
- Simulator models library
- Testing strategy
- Conclusion
- Future work
Process Variations

- For electronic circuit design we can define 3 variable quantities related to the circuit behavior:
  - **Design parameters**: are related to circuit structure, it is designer responsibility to change them to get optimum performance.
  - **Range parameters**: usually define the range of operation for the circuit, like supply voltage or temperature range.
  - **Statistical parameters**: describes the random variations which occur during the manufacturing process, they are modeled in form of probability density functions.

- Process variations become particularly important at smaller process nodes (< 65 nm) as the variation becomes a larger percentage of the device geometry.

- It causes measurable and predictable variance in the output performance of all circuits.
Account for Process Variations

- Circuit simulations is used to expect the behavior of electronic circuits before doing manufacturing.
- Monte-Carlo is a computational algorithm that rely on repeated random sampling to obtain numerical results for difficult or impossible to obtain a closed-form expression, or infeasible to apply a deterministic algorithm.
- Monte-Carlo simulation is used to account for process variations in the design stage.
- Many runs needed to obtain the distribution of an unknown probabilistic entity.
- For big circuits this takes long time, may be weeks.
- We need to replace MC simulation with interval based simulation.
Modal Arithmetic

In modal arithmetic the following two operators are defined for interval $X=[a,b]$ where $b>a$
- $\text{dual}(X) = [b,a]$
- $\text{opp}(X) = [-a,-b]$

We use modal arithmetic in our work to bound output results.
Interval Based Simulation flow

Traditional simulation flow

Proposed interval based simulation flow
Simulator Parts

- Front end process the design to get interval parameters.
- The solver formulate and solve the equations which describe the design.
- Models library contains mathematical equations define characteristic of each component in the design.
- Back end process the results and display it in a proper way.
Solver flow

- Flow for steady state and transient simulation
- Use Newton's method for interval system of non-linear equations.
- Interval Gauss-Seidel used to solve the system of interval linear equations.

$t = 0$

$t = t + h$

Time domain integration

Models evaluation

Linearization

Solve linear eqn

Newton Converge?

Yes

Store the solution

No

Finish?

Yes

Generate outputs

No
Models Library

- **Sources**
  - Independent current source
  - Independent voltage source

- **Passive elements**
  - Resistor
  - Capacitor
  - Inductor

- **Active elements**
  - Simple diode model
  - Simple MOSFET transistor model
  - Advanced MOSFET transistor model
Resistor Model

Voltage difference across Ohmic resistor is:

\[(v_1 - v_2) = I.R\]
Resistor Model

- This example shows how modal arithmetic enhances the results.

![Resistor Circuit Diagram]

- $I_1$: [0.9, 1.1]
- $R_1$: [9, 10]
- $R_2$: [18, 22]
Resistor Model

- This simple circuit is represented using modified nodal analysis as follow:

\[
\begin{bmatrix}
G_1 & -G_1 \\
-G_1 & G_1 + G_2
\end{bmatrix}
\begin{bmatrix}
v_1 \\
v_2
\end{bmatrix}
= \begin{bmatrix} I_1 \\
0, 0
\end{bmatrix}
\]

Where \( G = 1 / R \)

- Classical results

\[
V_1 = [21.354545, 41.677778]
\]
\[
V_2 = [11.647933, 33.959671]
\]

- Modal results by replacing \(-G_1\) with \(\text{opp}(G_1)\)

\[
V_1 = [24.300000, 36.300001]
\]
\[
V_2 = [16.199999, 24.200001]
\]
Simple diode model

- Diode is a two-terminal electronic component with asymmetric conductance.
- Model is defined on regions.
- If regions boundaries (Vbr, Vd) are defined as intervals, we can use monotonic behavior, then we compute output current twice (using end points).
  - Minimum input with the minimum edge of the region, and maximum input with the maximum edge of the region
- Results are the union of the two outputs.

* Picture from Wikipedia
**Simple MOSFET model**

- MOSFET is a type of transistors.
- It is a four terminal electronic device and used for amplifying or switching electronic signals.
- We use a simple model to describe the MOSFET basic characteristics.
- The simple MOSFET model is defined on regions, with one equation for the output current in each region.
- The voltage on the terminals defines the region of operation.
- In case we have interval threshold (boundary), we compute twice and use the same technique used to calculate diode output.

* Picture from Wikipedia
BSIM4 MOSFET Model

- BSIM4 is an accurate compact model for MOSFET transistors.
- It is widely used by electronic circuit industry.
- It has more than 900 model parameters, and 7500 lines of code.
- Results obtained so far from the interval model is not good.
- The model still need more work and investigation to probe the problem.
Testing

- **Unit testing**: tests interval results for each element or model alone and compare it versus single point results with sweeps.

- **RLC network testing**: tests simulator behavior with linear elements only.
  - This mainly tests functionality of interval matrix solver.

- **Simple circuits**: this test show how each component is integrated within the simulator, and how much Newton’s algorithm can handle non-linear elements.

- **Big circuit**: this test show how much our simulator is reliable (capacity and speed).
Conclusion

- We have introduced simulation flow that uses interval computations.
- Basic models library is created.
- Modal arithmetic is used to enhance results.
Future work

- Work to enhance BSIM4 results
- Begin circuit testing with the simulator.
- Support small signal analysis along with steady state and transient analysis.
- Compare affine arithmetic results to modal interval arithmetic results.