E8-262: Basics of Circuit Simulation/SPICE

Lecture: 4+5
Module 1: Electrical Challenges in High-Speed CPS

- Types of packages and PCBs
- Packaging Trends
- Review of Electromagnetic and Circuit basics
- Signal Integrity Introduction
- Power Integrity Introduction
- Electromagnetic Interference and Electromagnetic Compatibility Introduction
- Review of SPICE basics
- Lumped models, distributed RLGC, S/Y/Z parameters
Topics: Modified Nodal Analysis

- Parser
- Linear Element: DC Operating Point Analysis
- Linear Element: Transient Analysis
- +Non-linear Element: DC Operating Point Analysis
- +Non-linear Element: Transient Analysis
- Electromagnetic Models in SPICE
References


• William McCalla, Fundamentals of Computer-Aided Circuit Simulation, Kluwer Academic Publisher
History of SPICE:

http://www.omega-enterprises.net/The%20Origins%20of%20SPICE.html

- 1970: CANCER Project, R. Rohrer, L. Nagel and others – class project from Berkeley

- 1972-To Date: SPICE “Simulation Program with Integrated Circuit Emphasis”

- HSPICE owned by Synopsys; PSPICE owned by Cadence;

- TISPICE (TI), Lynx (Intel), PowerSPICE (IBM), Titan (Infineon), Mica (Freescale) ...
Sources:

- VName  N+  N-  V_value
- IName  N+  N-  I_value

DC Linear Elements:

- RName  N+  N-  R_value
- EName  N+  N-  NC+  NC-  E_val (VCVS)
- FName   N+  N-  NC+  NC-  F_val (CCCS)
- GName  N+  N-  NC+  NC-  G_val (VCCS)
- HName  N+  N-  NC+  NC-  H_val (CCVS)
Parser

Linear Elements in transient analysis:
• CName N+ N- C_value
• LName N+ N- L_value

Non-Linear Elements:
• Dname N+ N- Dmodelname
• Pname Nd Ng Ns Nb Pmodelname
• Nname Nd Ng Ns Nb Nmodelname
Example

* Test circuit to check the inverter performance

Vin 1 0 1
pm 2 1 3 0 pmos1
r1 2 0 5000
v1 3 0 2.5

<option post
.tran 0us 45ms 100us
.alter
Vin 1 0 sin (0 16.8 60 0ms 0 0)
*.dc VSource 1.88 1.89 0.01
.print v(0)
.print v(1)
.print v(2)
.print v(3)
.MODEL pmos1 cmosp ( W=10e-6 L=1e-6 )
.end
Linear Elements:
DC operating point analysis
## Resistor Stamp

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<tr>
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<th>1/R</th>
<th>-1/R</th>
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<tr>
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### Matrix

### RHS

**Dipanjan Gope**
Current Source Stamp

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Matrix

RHS

-Ik

+Ik
### Voltage Source Stamp

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**Matrix**

**RHS**

\[
V_k
\]
# G Stamp (VCCS)

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**Matrix**

**RHS**
**F Stamp (CCCS)**

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**RHS**
E Stamp (VCVS)

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RHS
# H Stamp (CCVS)

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**Matrix**

**RHS**
Matrix Solution

- Direct
  - Gaussian Elimination/ Sparse LU
  - Pkgs: Sparse1.3, SuperLU, Pardiso, MUMPS

- Iterative
  - Stationary Methods:
    - Gauss-Seidel
    - Gauss-Jacobi
    - Successive Over Relaxation (SOR)
  - Krylov subspace methods
LU Sparsity

Before LU

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Linear Elements: Transient Analysis
Transient Sources

- Pulse
- Exp
- Sin
- PWL
Integration Methods

• **Forward Euler**

\[
\frac{y(t_n + h) - y(t_n)}{h} = y'(t_n)
\]

• **Backward Euler**

\[
\frac{y(t_n) - y(t_n - h)}{h} = y'(t_n)
\]

• **Trapezoidal**

\[
\frac{y(t_n + h) - y(t_n)}{h} = \frac{1}{2} \left[ y'(t_n) + y'(t_{n-1}) \right]
\]

Other: Explicit and Implicit LMS
Capacitor Stamp

\[ Q = CV \]

\[ I = C \frac{dV}{dt} \]

\[ = C \frac{V(t) - V(t-h)}{h} \]

\[ = \frac{C}{h} V(t) - \frac{C}{h} V(t-h) \]

\[ = \frac{C}{h} (V^+ - V^-) - \frac{C}{h} \left[ V^+(t-h) - V^-(t-h) \right] \]
## Capacitor Stamp

### Matrix

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### RHS

- C/h \( v(t-h) \)
- -C/h \( v(t-h) \)
## Capacitor Stamp (MNA)

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### Matrix

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<td>i_k</td>
<td>C/h</td>
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</table>

### RHS

\[ C/h \cdot v(t-h) \]
Inductor Stamp

\[ V = L \frac{di}{dt} \]

\[ = L \frac{i(t) - i(t-h)}{h} \]

\[ = \frac{L}{h} i(t) - \frac{L}{h} i(t-h) \]
Inductor Stamp

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<td>i_k</td>
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Matrix

RHS

-L/h. i(t-h)
Non-Linear Elements:

DC Operating Point
Transient Analysis
Newton-Raphson

\[ f(v) = 0 \]

**Algorithm:**

\[ f(v_i) + f'(v_i)(v_2 - v_1) = 0 \]

**Newton-Raphson (NR):**

\[ v_2 = v_1 - \left[ f'(v_1) \right]^{-1} f(v_1) \]
Diode Stamp

\[ i_D = i_D^{\text{pre}} + \left( \frac{\partial i_D}{\partial V_D} \right)^{\text{pre}} (V_D - V_D^{\text{pre}}) \]

\[ i = \left( \frac{\partial i_D}{\partial V_D} \right)^{\text{pre}} V_D + i^{\text{pre}} - \left( \frac{\partial i_D}{\partial V_D} \right)^{\text{pre}} V_D^{\text{pre}} \]

\[ = G_0 V_D + I_0 \]

conduclance \rightarrow current source
### Diode Stamp

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#### Matrix

#### RHS

$I_0$
Diode Stamp

\[ I_D = I_S \left( e^{\frac{V_T}{nV_T}} - 1 \right) \]

\[ \frac{dI_D}{dV} = \frac{I_S}{V_T} e^{\frac{V}{V_T}} \]
Level I Stamp for MOSFET

\[ I_{ds} = I_{ds}(V_{gs}, V_{ds}) \]

\[ = \left( \frac{W}{L} \right) k'(V_{gs} - V_{T} - \frac{1}{2} V_{ds}) V_{ds} \]

Assume \( V_{T} \neq f(V_{ds}) \) for simplicity.

\[ \frac{dI_{ds}}{dV_{gs}} = g_m = \frac{W}{L} k' V_{ds} \]

\[ \frac{dI_{ds}}{dV_{ds}} = g_{ds} = \frac{W}{L} k' (V_{gs} - V_{T} - V_{ds}) \]
MOSFET Stamp

\[ I_{DS} = I_{DS}^{p_{ne}} + \left( \frac{2I_{DS}}{V_{DS}} \right) (V_{DS} - V_{DS}^{p_{ne}}) + \left( \frac{2I_{DS}}{V_{GS}} \right) (V_{GS} - V_{GS}^{p_{ne}}) \]

\[ \Rightarrow I_{DS} = g_{DS} V_{DS} + g_{m} V_{GS} + \left( I_{DS}^{p_{ne}} - g_{m} V_{GS} - g_{ds} V_{DS}^{p_{ne}} \right) \]
### MOSFET Stamp

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<th>Ns</th>
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**Matrix**

**RHS**
Newton-Raphson Challenges

- Oscillatory functions
- Bad initial guess
- Derivative error
- Discontinuity
Electromagnetic Models in SPICE:
All Linear Models 😊
Heavily Coupled Models 😞
Lumped vs. Distributed

https://ccrma.stanford.edu/~jos/NumericalInt/Lumped_vs_Distributed_Systems.html
RLGC Models: Lumped

- R, L, G, C (and coupling elements) extracted using quasi-static analysis

**Accuracy?**

1. Approximation of distributed effect by Lumped Elements: Not Accurate

2. Distributed problem is solved in EM tool and the result expressed as Lumped elements:
   Fairly Accurate
   - Quasi-static EM tool: Not accurate at high frequency
   - Full-wave EM tool: Sometimes not accurate in lumped element conversion using fitting
Transmission Line Models: Distributed

\[ R(f) \approx R_o + \sqrt{f}(1 + j)R_s \]

\[ G(f) \approx G_o + \frac{f}{\sqrt{1 + (f/f_{gd})^2}}G_d \]

\[ G\omega = G_o + \sum_k Gd_k \frac{j\omega}{j\omega + \omega_k} \]

```
Wtest win 0 wout 0 N=1 RLGCMODEL=WE1 L=0.3
+ INCLUDEGDMIN=yes
.MODEL WE1 W MODELTYPE=RLGC, N=1
+ Lo = 3.8e-07
+ Co = 1.3e-10
+ Ro = 2.74e+00
+ Go = 0.0
+ Rs = 1.1e-03
+ Gd = 0.0
+ wp = 0.07
```

**Accuracy?**
1. 2D approximation: cross-section unchanged in length
2. TEM approximation in cross-section
S/Y/Z Models: Distributed

**S-parameter example**

```
*OPTION post
.probe v(n2)
P1 n1 0 port=1 Zo=50 ac=1v PULSE 0v 5v 5n 0.5n 0.5n 25n
P2 n2 0 port=2 Zo=50
.ac lin 500 1Hz 30MegHz
.tran 0.1ns 10ns
* reference node is set
S1 n1 n2 0 mname=s_model
* S parameter
.model s_model S TSTONEFILE = ss_ts.s2p
Rt1 n2 0 50
.end
```

```
! touchstone file example

! # Hz S MA R 50.0000
0.00000 0.637187 180.000 0.355136 0.00000
0.355136 0.00000 0.637187 180.000
......
! # Hz S DB R 50.0000
0.00000 -3.91466 180.000 -0.99211 0.00000
-0.99211 0.00000 -3.91466 180.000
......
! # Hz S RI R 50.0000
0.00000 -0.637187 0.00000 0.355136 0.00000
0.355136 0.00000 -0.637187 0.00000
......
! 2-port noise parameter
! frequency[Hz] NF[Min[dB] GammaOpt (M) GammaOpt (P) RN/Zo
0.0000 0.29166 0.98916 180.00 0.11055E-03
0.52632E+08 6.2395 0.59071 -163.50 0.32868
0.10526E+09 7.7698 0.44537 175.26 0.56586
......
! end of file
```

**Accuracy?**

1. Accurate but time expensive both in extraction and simulation.
PEEC: Lumped or Distributed?

Geometry

Conductor

Accuracy?
1. Accurate but time expensive
2. Conventional SPICE do not support delay elements