VoHB METHOD AND IT’S ROLE IN PA DESIGN

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SHORT CV

About T. Rahkonen

- Professor in “ Circuit theory and circuit design” at University of Oulu, Oulu, Finland
- PhD 1993: IC design, using CMOS delay lines for timing generation
- Research on predistortion, memory effects, EER and ET systems and switching amplifiers since 1996
- ca. 25 journal & 120 conference publications

Main publications

- J. Vuolevi et al.: Measurement Technique for Characterizing Memory Effects in RF Power Amplifiers. IEEE Trans. on MTT August 2001, pp. 1383-1389.
- J. Vuolevi, T. Rahkonen: Distortion in RF Power Amplifiers. Artech House 2003.
- J. Aikio, T. Rahkonen: Detailed Distortion Analysis Technique Based on Simulated Large-Signal Voltage and Current Spectra. IEEE Trans. on MTT October 2005

CONTENTS

1. SIMULATION NEEDS IN PA DESIGN

Power

losses
optimum load impedance

Efficiency

disastrously low with high peak power signals (class A: 50% at FS, 9% at -10 dB)
Ropt, non-overlapping V & I
heavy use of excotic structures (feedforward, Doherty, predistortion, envelope tracking..)

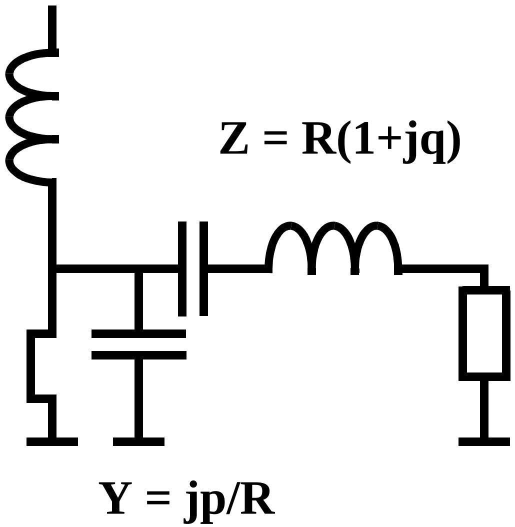
Linearity

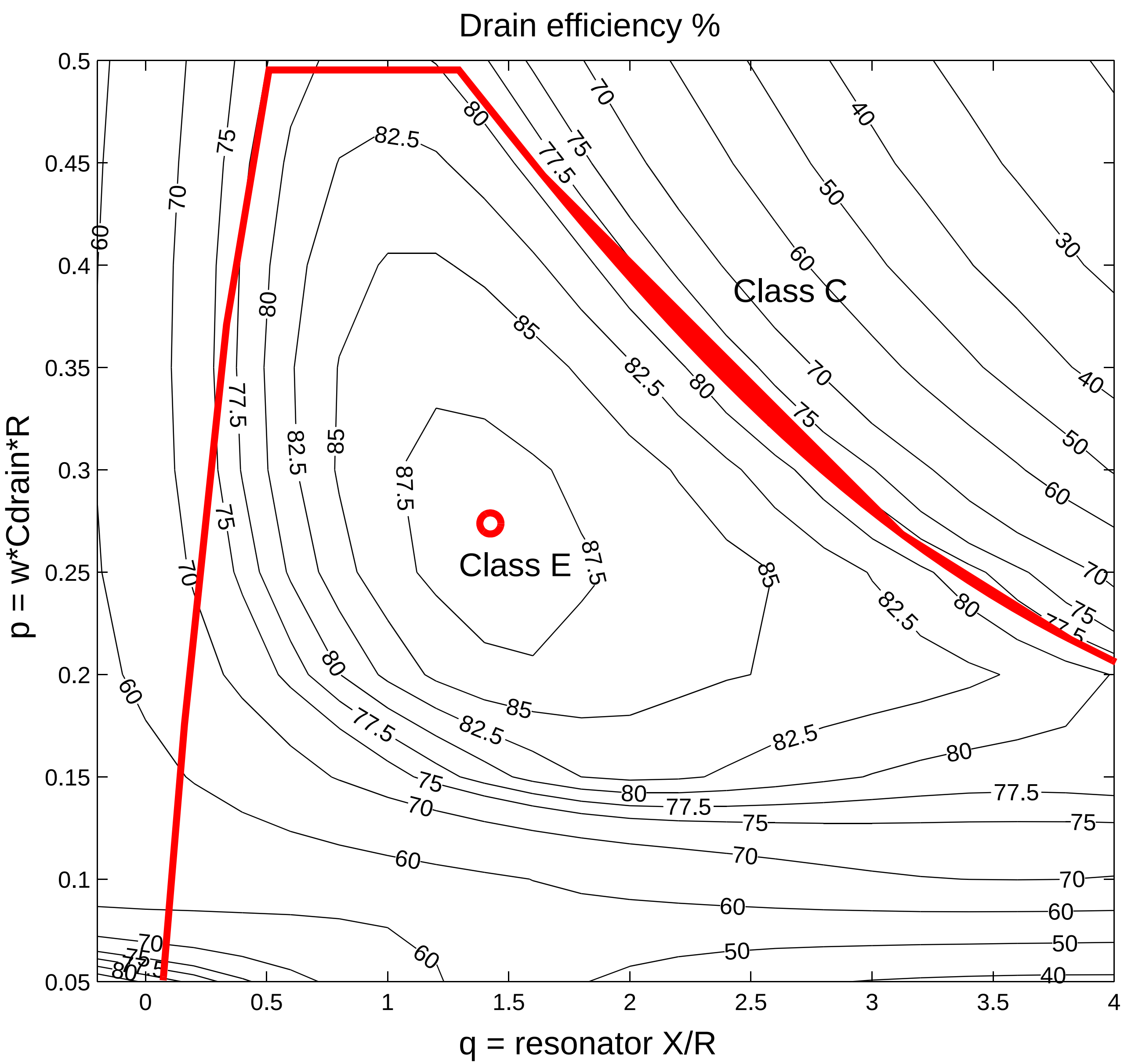
opposite to efficiency requirements
causes of memory effects
sweet bias points, cancellations, ...
now aiming at studying the perfomance of predistortion setups

Stability

large-signal system
exciting spurious oscillations without input RF signal

Pout & Efficiency vs, Zdrain





Harmonic load pull (performed by Volterra sweep)

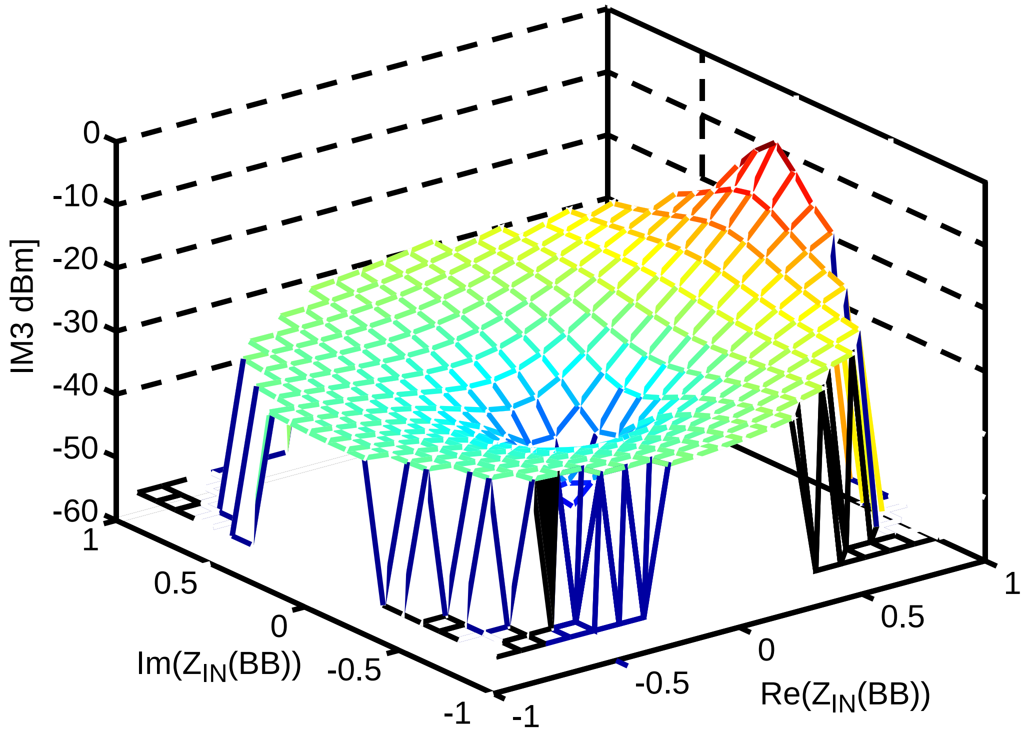
Fundamental Zg, Zd fixed

Large-signal op point ~ const

Nonlinearities ~ const

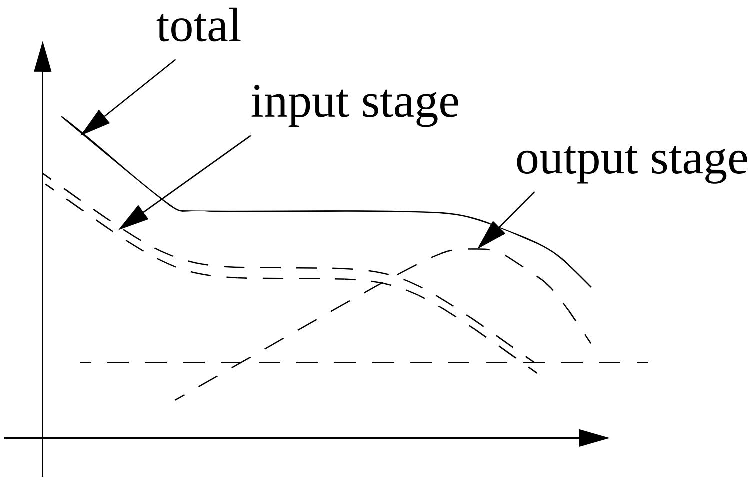
Sweeping Zg, Zd at BB, 2fo possible using Volterra

IM3 vs. Zin(BB) on Smith chart



2. DETAILED DISTORTION ANALYSIS

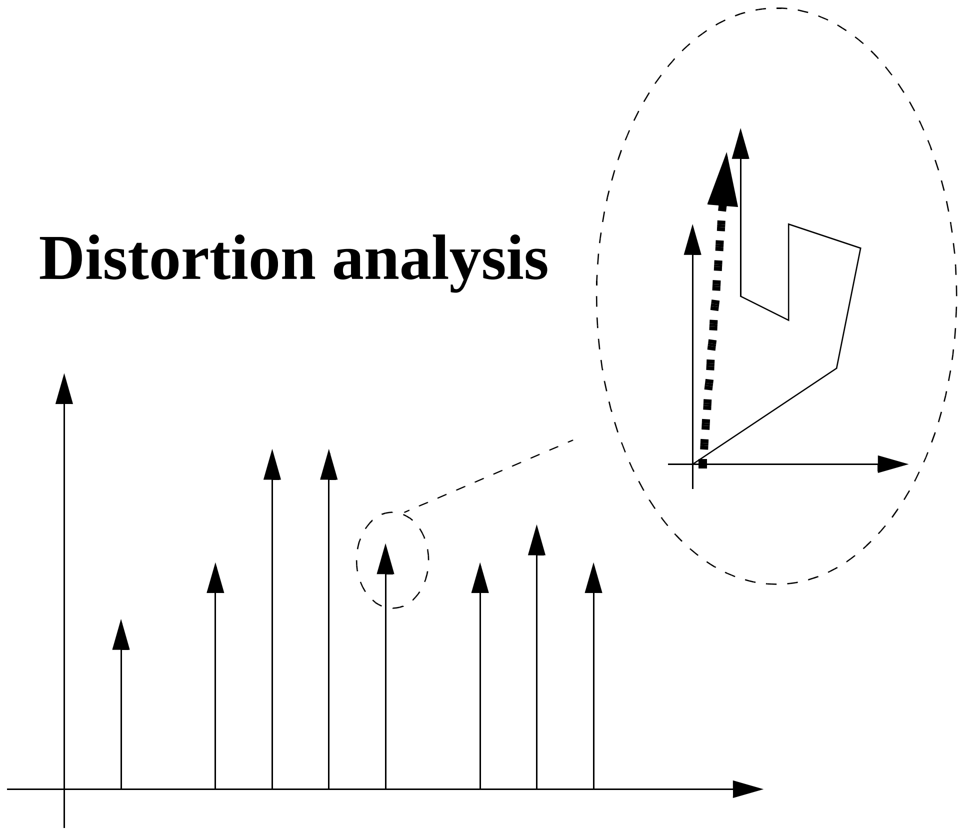
Noise analysis



Individual contributions are shown
to see what to improve

Cheap AC analysis

Distortion analysis

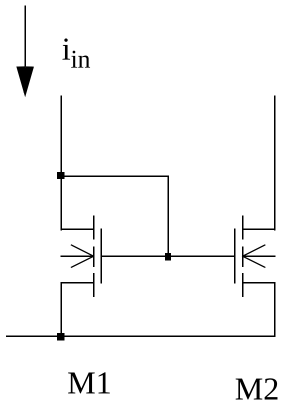


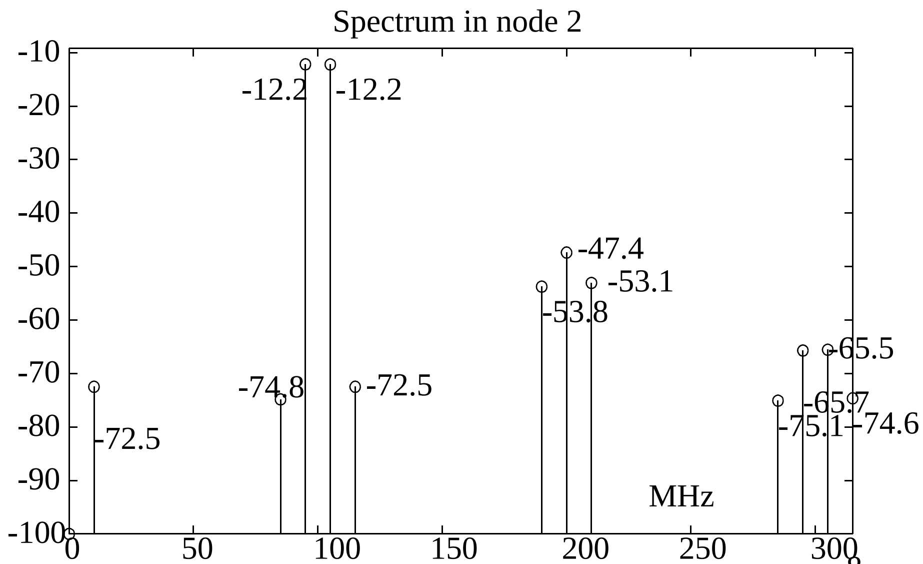
Typically, only total distortion is shown

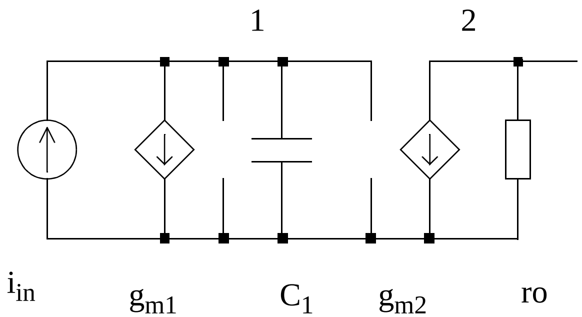
Multitude of contibutions, all having
amplitude and phase

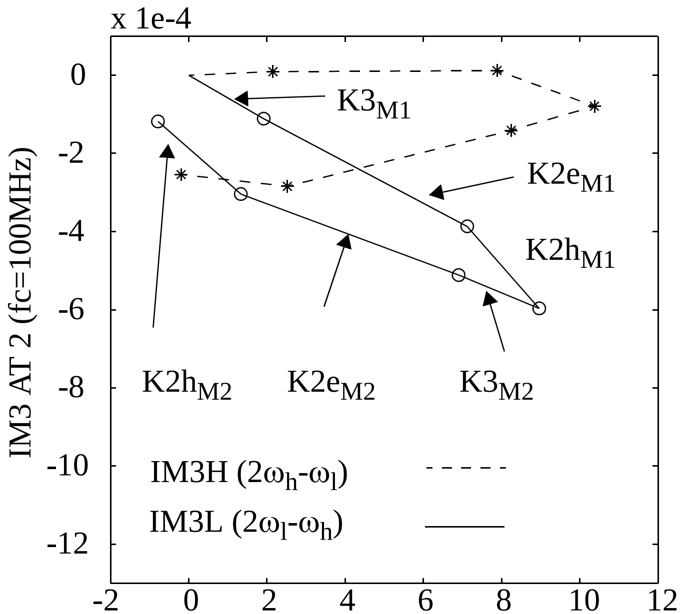
- Memory effects
- Use of harmonic & BB shaping
  for linearisation

EXAMPLE: MOS CURRENT MIRROR

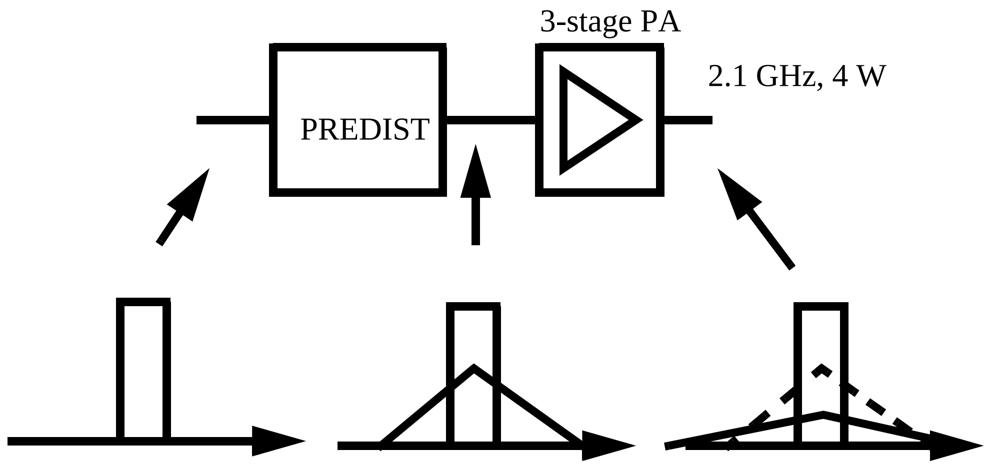




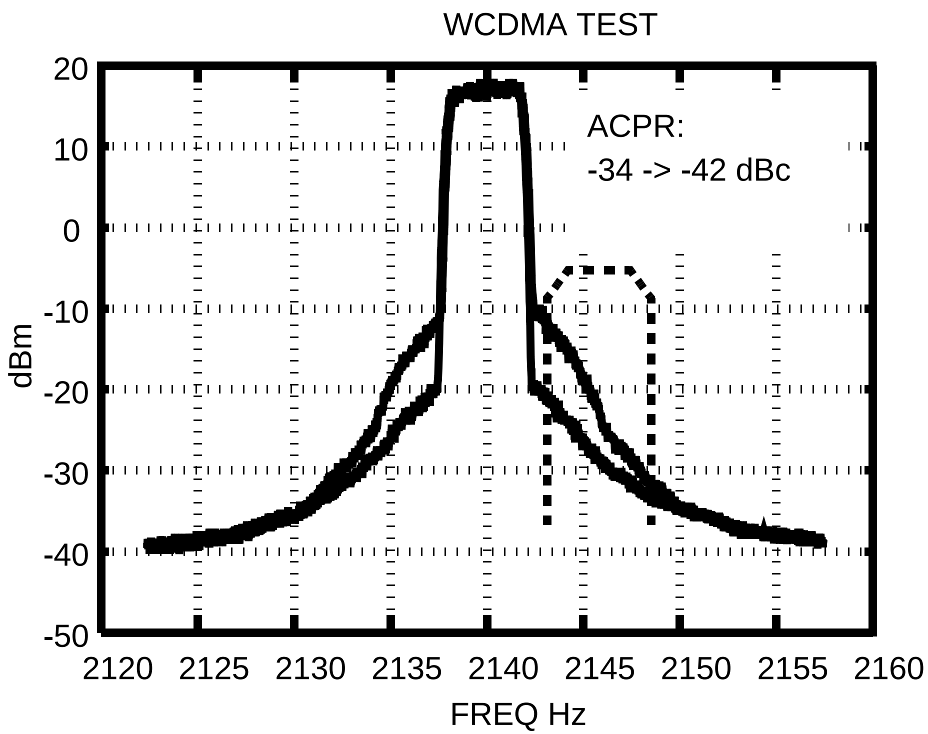


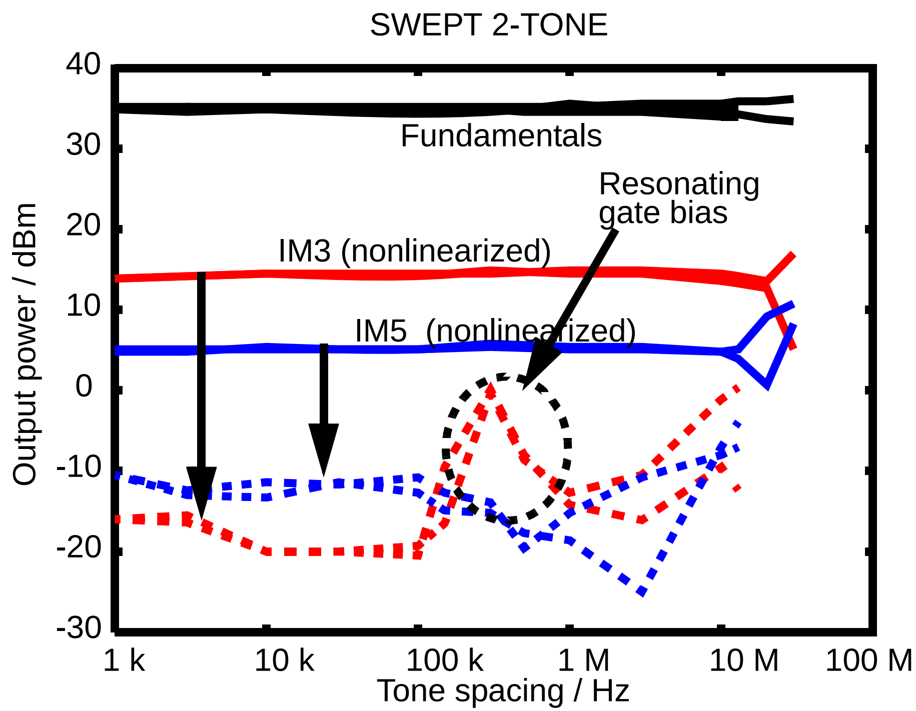


PROBLEMS IN PREDISTORTION



Achievable cancellation in predistortion depends on BW

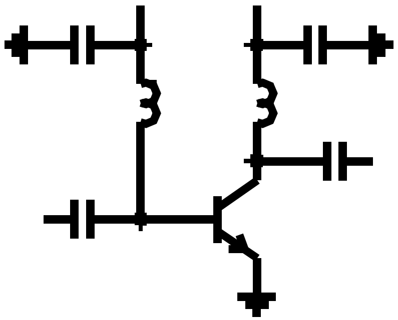




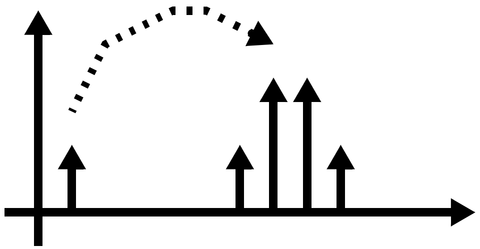
Rahkonen, Kursu INMMIC 2006

MEMORY EFFECTS

Upconversion of BB envelope

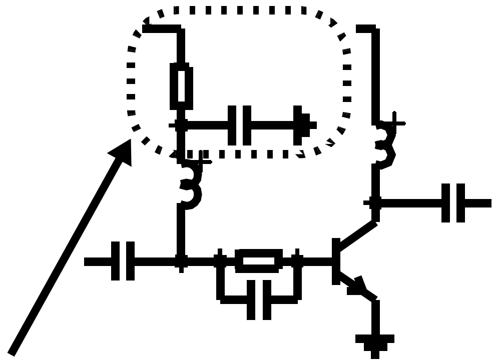


upconversion of envelope to IM3



$v_2 = i_{NL} * Z_{BB}(\Delta f)$

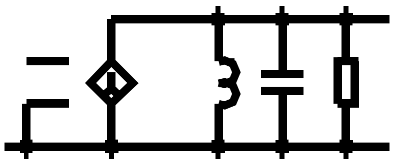
Bias shift due to envelope rectification



Envelope current appears as voltage and gets rectified, **causing Δf dependent DC bias shift**

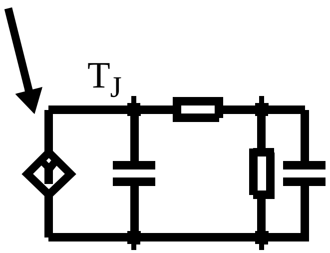
Gain tempco + thermal feedback

$Io = K*(1+k*T_J)*Vin$

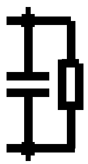


T_J

P_{diss}



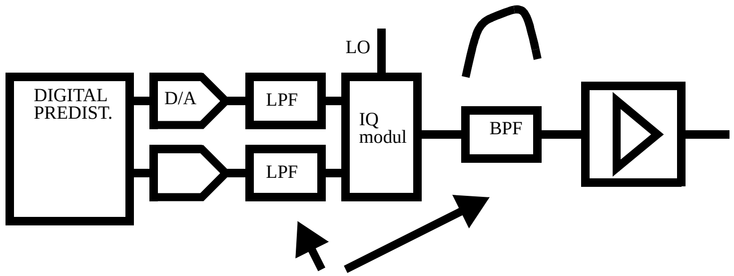
often < 1 Hz



C_{TH} R_{TH}

τ1 ~ 10 s
τ2 ~ 10 us

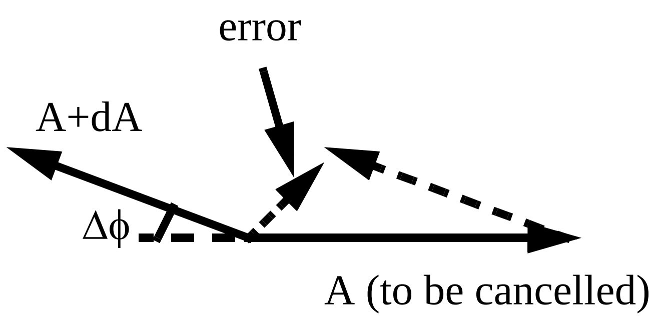
Filters between predistorter and PA

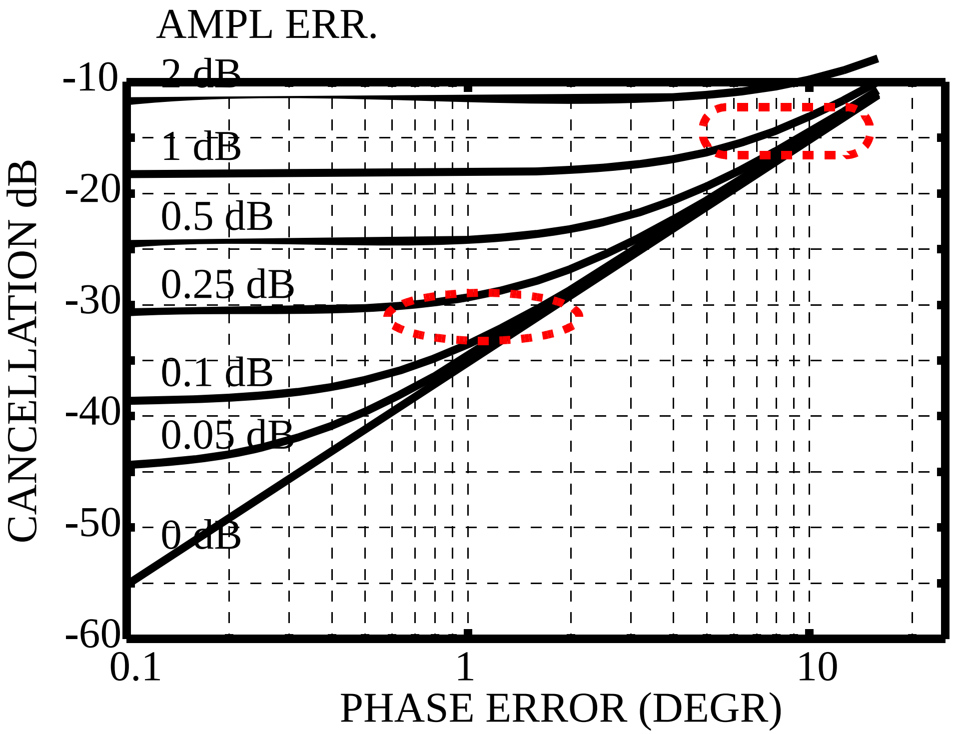


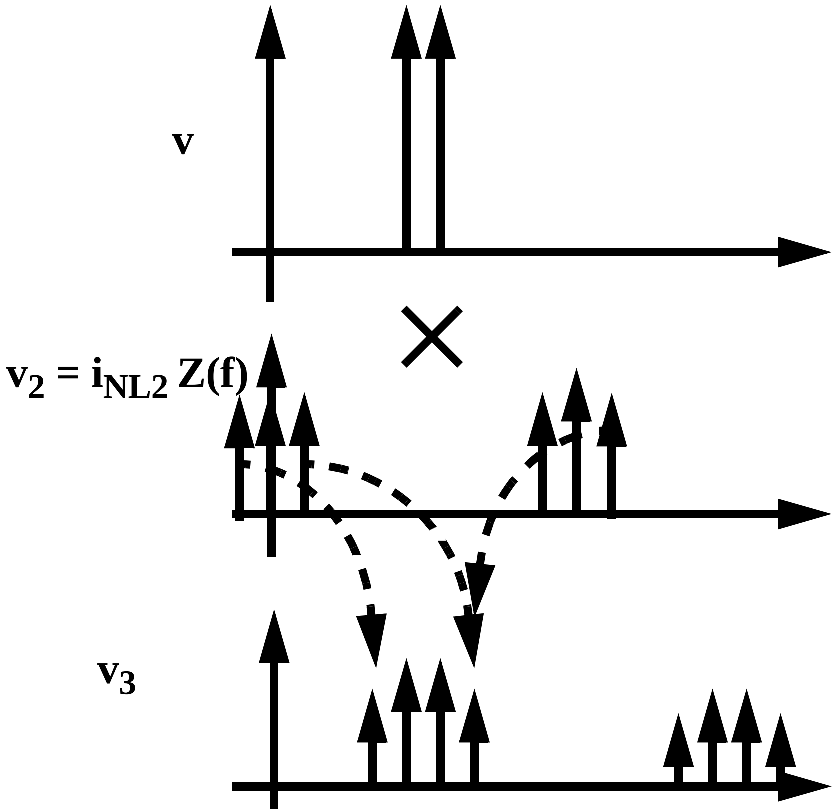
Flatness, ripple, and vector error of the filters

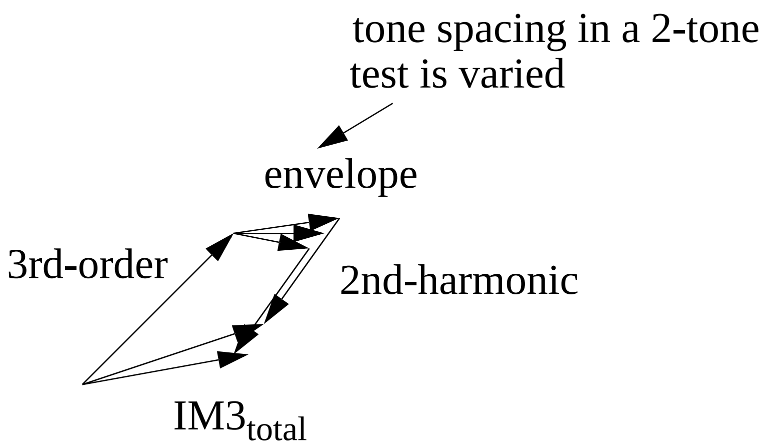
(Sundström)

CANCELLATION ACCURACY - MEMORY EFFECTS









3. VOLTERRA ANALYSIS

Reasoning

- Polynomial modelling makes it easy to track mixing between harmonic bands
- Symbolic analysis grows out of hand -> need numerical tools

Visualization methods

- Vector plots of different contributions
- Different types of analysis

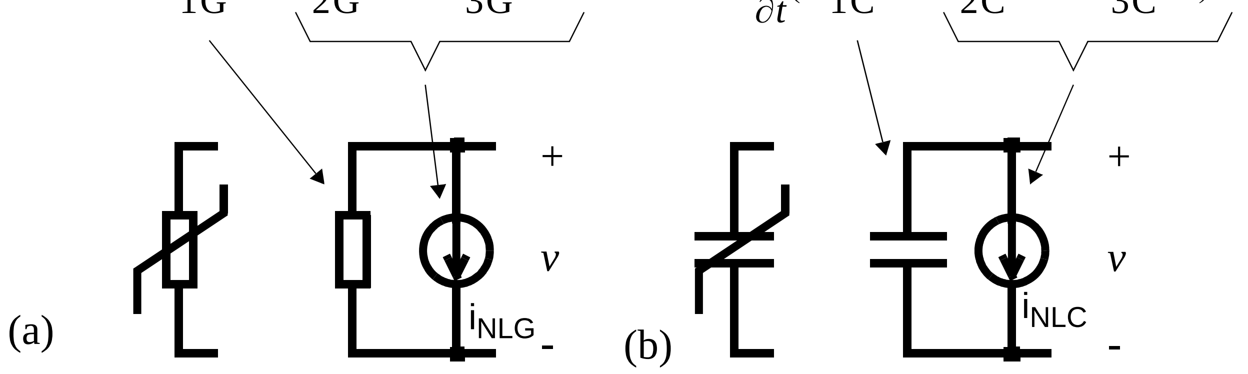
Numerical Volterra analysis / Implementation in APLAC

- 5th-order general Matlab SW NLSIM (Heiskanen)
- VoHB: Combined fitting and analysis on top of harmonic balance of Aplac (Aikio)

Volterra basics

Nonlin VCCS -> lin comp. + distortion current source

$$i = K_{1G}v + K_{2G}v^2 + K_{3G}v^3 \qquad i = \frac{\partial}{\partial t}(K_{1C}v + K_{2C}v^2 + K_{3C}v^3)$$



$$v = v_1 + v_2 + v_3 + \ldots$$

$$v^2 = v_1^2 + 2v_1 \cdot v_2 + v_2^2 + \ldots$$

Time domain

$$i(t) = K_1 \cdot v + K_2 \cdot v^2 + K_3 \cdot v^3 + \ldots$$

$\otimes$ means convolution

Frequency domain

$$I(f) = K_1 \cdot V + K_2 \cdot (V \otimes V) + K_3 \cdot (V \otimes V \otimes V) + \ldots$$

$$V = V_1 + V_2 + V_3 + \ldots$$ signals = sums of all order signals

$$I(f) = K_1 \cdot V + K_2 \cdot (V \otimes V) + K_3 \cdot (V \otimes V \otimes V) + \ldots$$

1st-order $= K_1 \cdot V_1$

2nd-order $+ K_2 \cdot (V_1 \otimes V_1) + K_1 \cdot V_2$

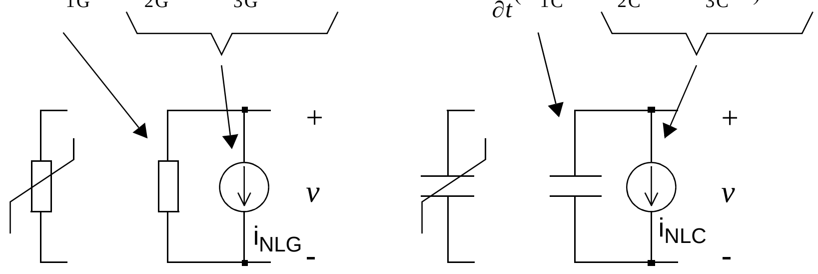
3rd-order $+ K_3 \cdot (V_1 \otimes V_1 \otimes V_1) + 2K_2 \cdot (V_1 \otimes V_2) + K_1 \cdot V_3$

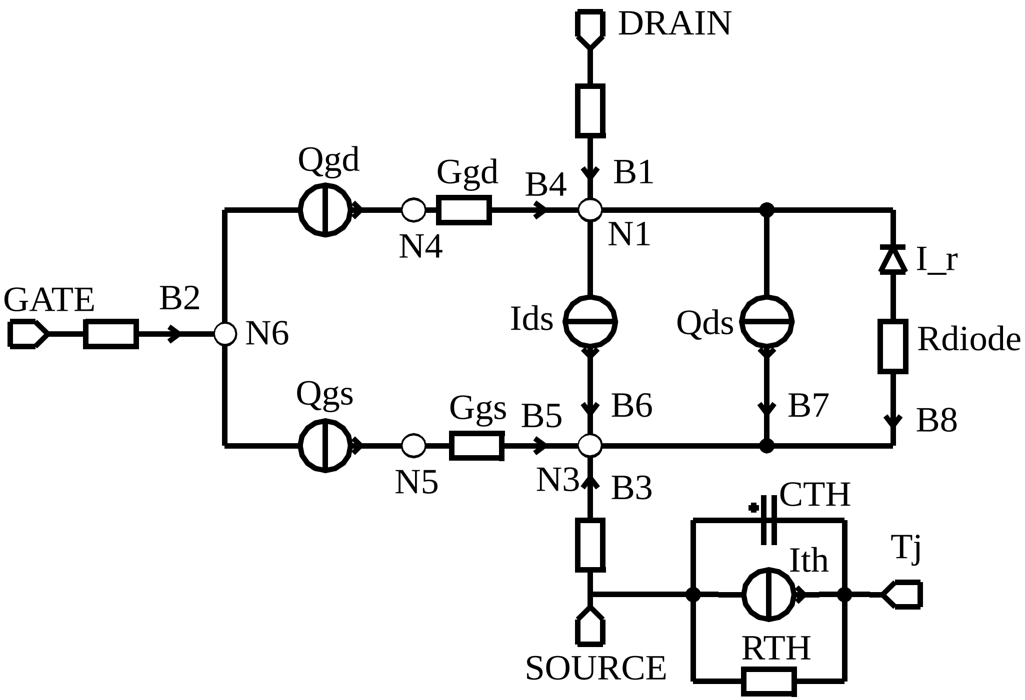
4th-order $+ K_4 \cdot (V_1 \otimes V_1 \otimes V_1 \otimes V_1) + 3K_3 \cdot (V_1 \otimes V_1 \otimes V_2)$
$+ 2K_2 \cdot (V_1 \otimes V_3) + K_2 \cdot (V_2 \otimes V_2) + K_1 \cdot V_4$

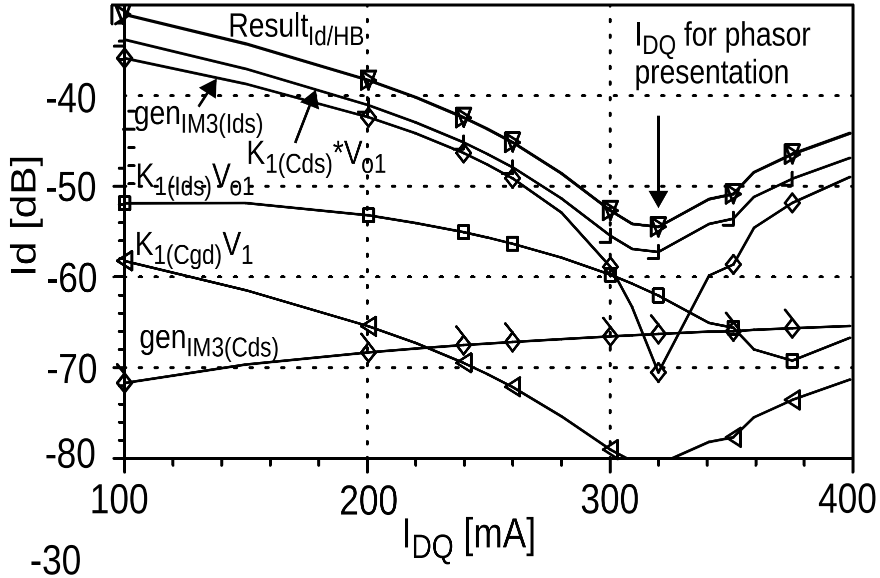
Aikio, IEEE Trans. MTT Oct 2005

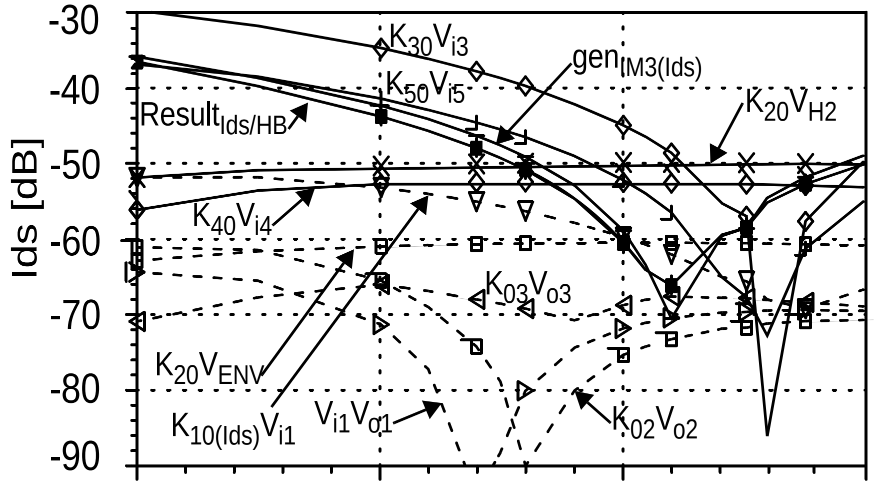
VISUALIZATION METHODS - IM3 BIAS SWEEP

$$i = K_{1G}v + K_{2G}v^2 + K_{3G}v^3 \qquad i = \frac{\partial}{\partial t}(K_{1C}v + K_{2C}v^2 + K_{3C}v^3)$$



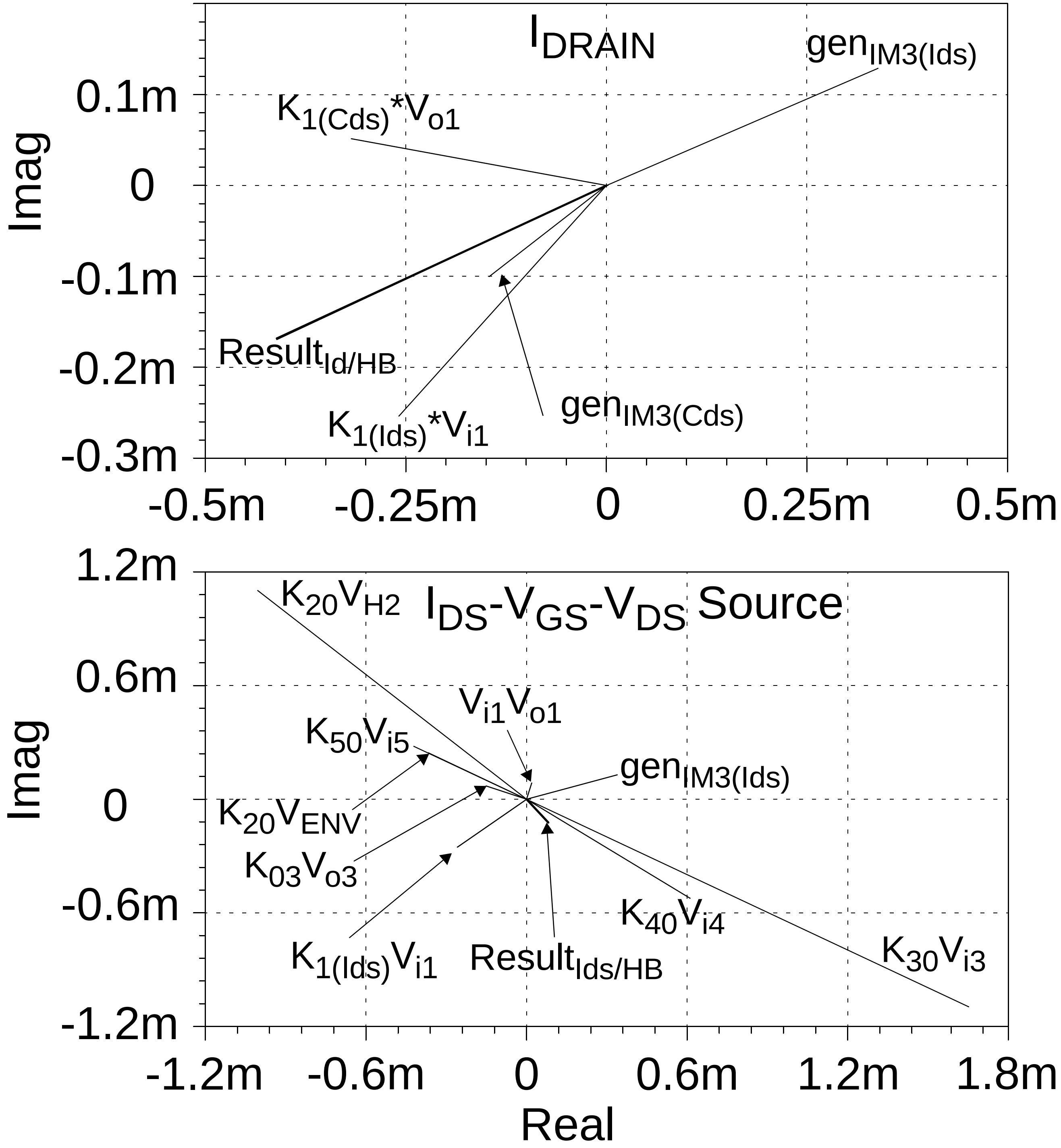






Gives a detailed view of what is causing memory effects, for example

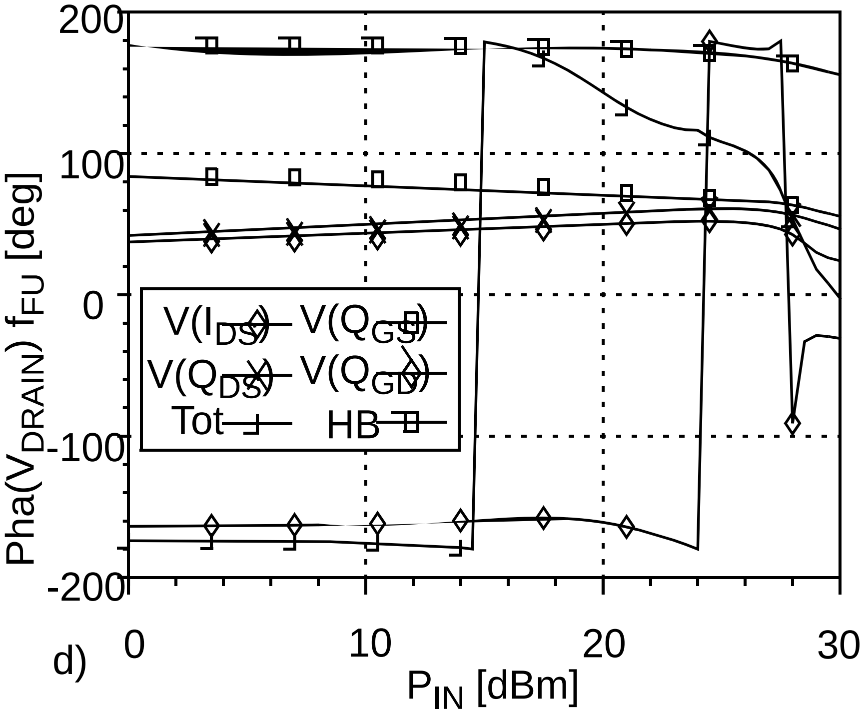
IM3 VECTOR SUM AT POINT POWER

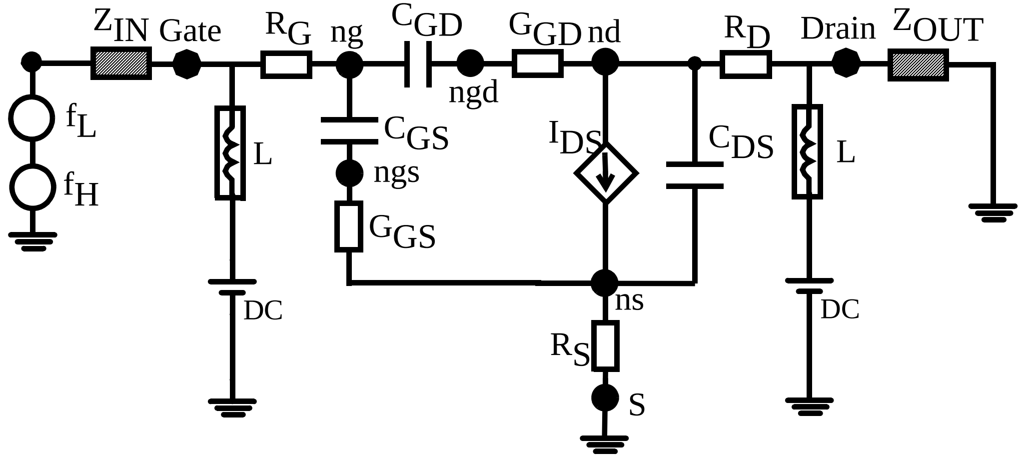


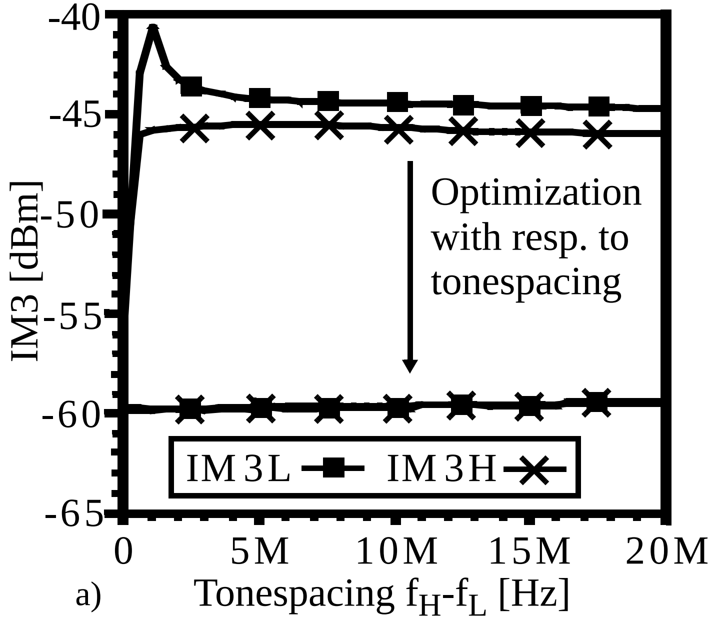
FUNDAMENTAL AMAM/AMPM

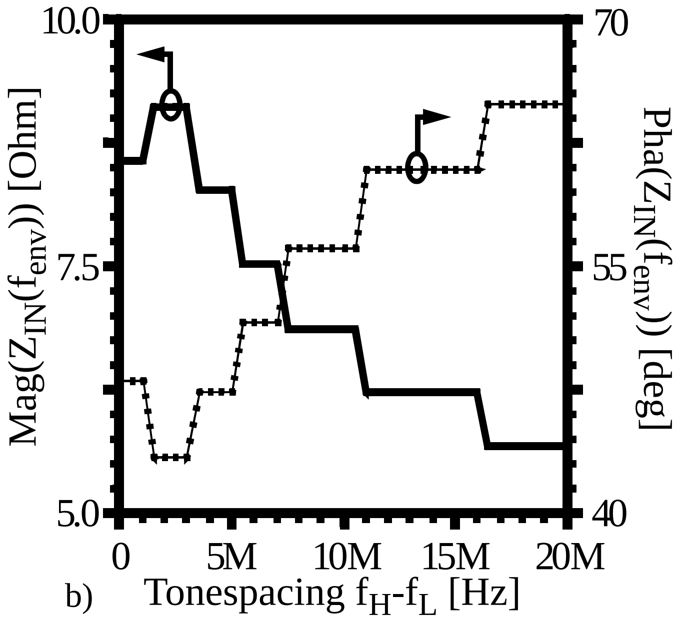
HARMONIC LOAD PULL

- ANALYSIS OF ANY TONE
- AM/AM, AM/PM
-





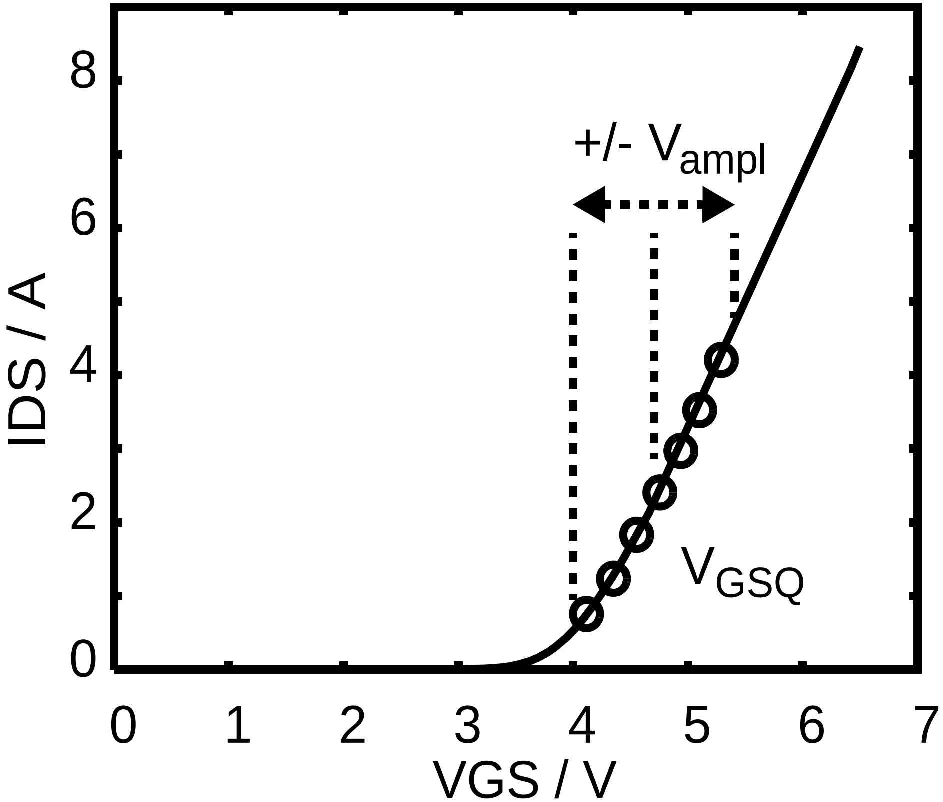




4. BUILDING POLYNOMIAL MODELS: I-V Curve Fitting

Pick *m* data points from the I-V curve and perform normal LSE fitting - sensitive to bias & ampl.

$$I_D = K_0 + K_1 v + K_2 v^2 + K_3 v^3$$

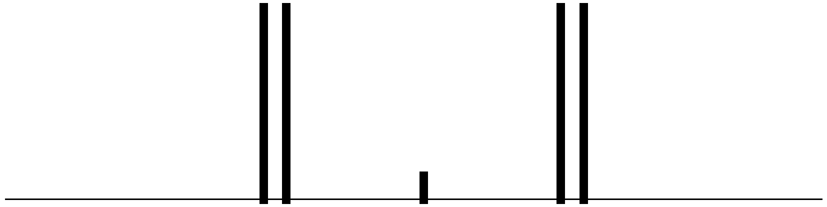


$$\underset{M}{\begin{bmatrix} 1 & v_1 & v_1^2 & v_1^3 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & v_m & v_m^2 & v_m^3 \end{bmatrix}} \cdot \underset{K}{\begin{bmatrix} K_0 \\ K_1 \\ K_2 \\ K_3 \end{bmatrix}} = \underset{I}{\begin{bmatrix} i_1 \\ \vdots \\ i_m \end{bmatrix}}$$

$$K = (M^T \cdot M)^{-1} \cdot (M^T \cdot I)$$

Spectral Fitting (core of VoHB)

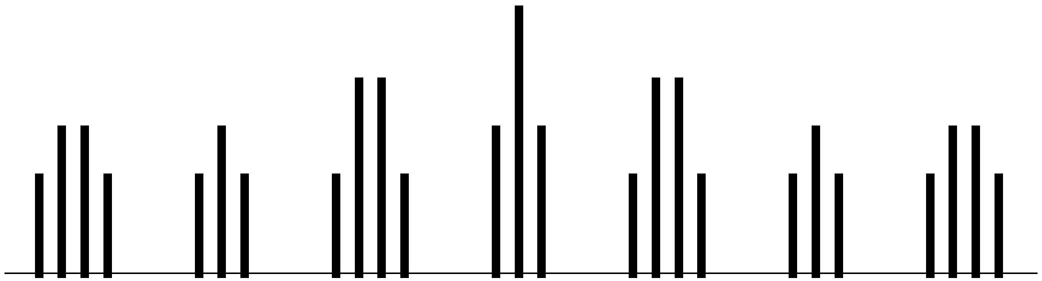
K1·**V**



+ K2·(V⊗V)

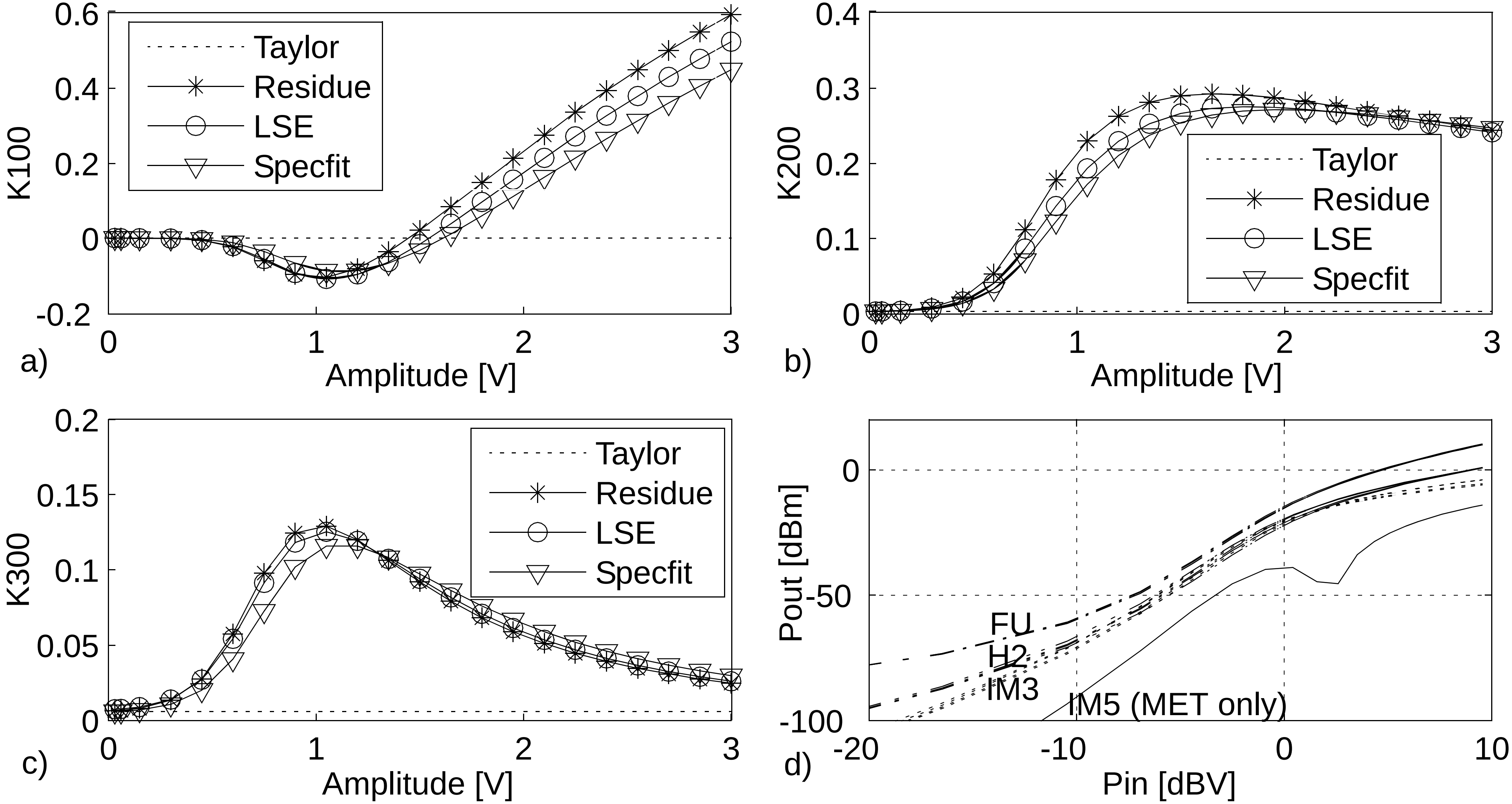
+ K3·(V⊗V⊗V)

= I



```
pw = [1  1 1 1 1 1  1 1 1 1 1  1 1 1 1 1  1 1 1 1 1   0 0 0 0 0  0 0 0 0 0 ; ... % enable mask
         0  1 2 3 4 5  0 0 0 0 0  1 2 3 4 2  1 1 1 2 3  0 1 0 2 1  0 3 2 1 0 ; ... % vi
         0  0 0 0 0 0  1 2 3 4 5  1 1 1 1 2  2 3 4 3 2  0 0 1 0 1  2 0 1 2 3];     % vo
         0  0 0 0 0 0  0 0 0 0 0  0 0 0 0 0  0 0 0 0 0  1 1 1 1 1  1 1 1 1 1 ];    % t

[icoeff]  = fitIds(Idsac,Vgsac,Vdsac,Tac,pw);   % fit id-vgs-vds values

--------------------------------------------------------------
function [coeff] = fitIds(y, x1, x2, t, pow) %%%%%  polynomial fit of  Id-Vgs-Vds-T

M = [];
for i=1:length(pow(1,:))
   if pow(1,i) == 1, M = [M  (x1.^pow(2,i)).*(x2.^pow(3,i)).*(t.^pow(4,i))]; end
end

  if(1>0)
   MMI = (M'*M);  fprintf(1,'Condition number: %1.2e \n', cond(MMI));
   coeff   = inv(MMI)*(M'*y);
  else
   [Q,R] = qr(M);  %% QR factorizations
   coeff   = R\‹R'\‹M'*y));
   est = M*coeff;
   err = y - est;
   coeff  = coeff  + R\‹R'\‹M'*err));
   [mr,nr] = size(R); R = R(1:nr,1:nr);
   MMI = inv(R); MMI = MMI*MMI'; fprintf(1,'Condition number:  %1.2e \n', cond(MMI));
  end
```

Accuracy of polynomial models - class C LDMOS example

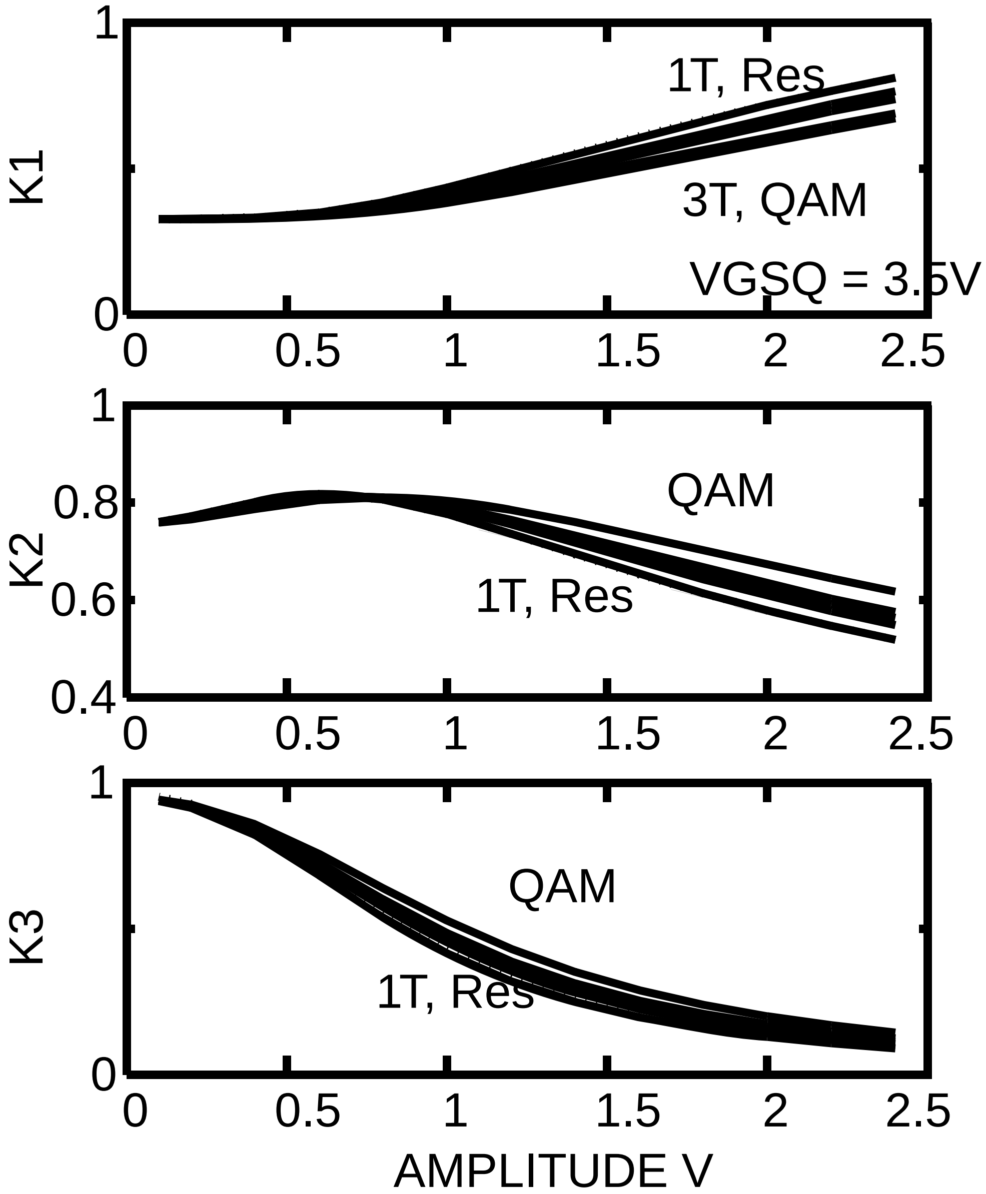


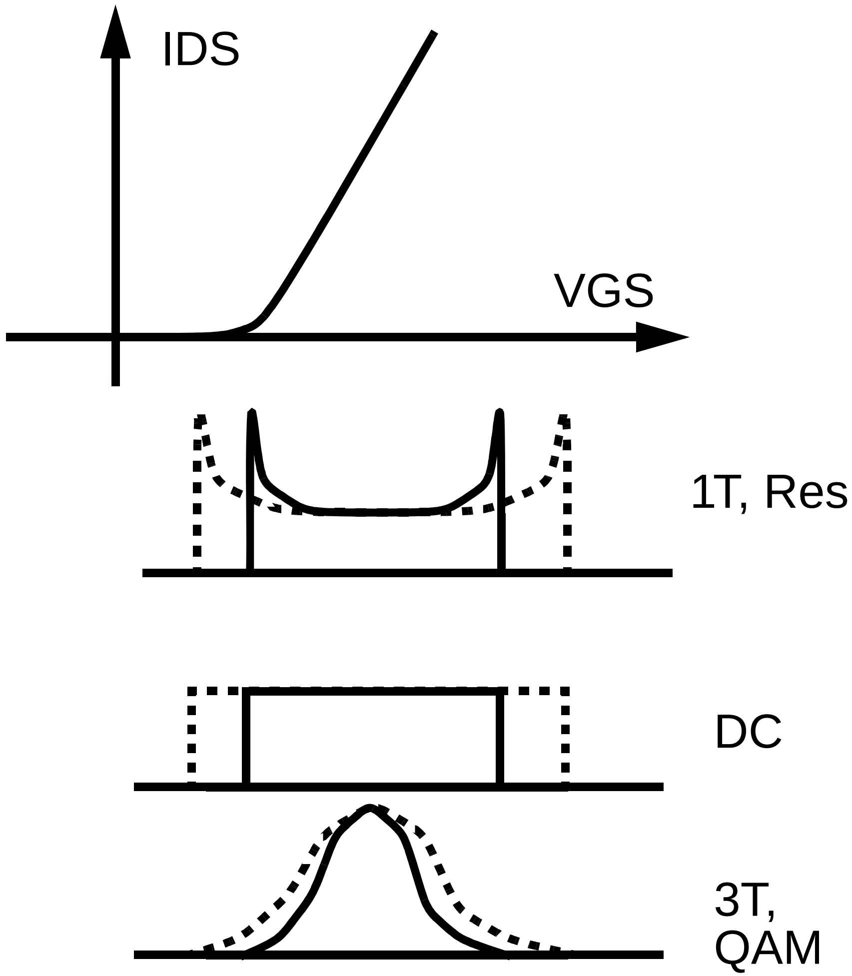
$$i(t) = K_{100} \cdot v + K_{200} \cdot v^2 + K_{300} \cdot v^3$$

Rahkonen, ISCAS 2003

Different training signals:

$$I_D = K_0 + K_1 v_{GS} + K_2 v_{GS}^2 + K_3 v_{GS}^3$$





5. IMPLEMENTATIONS OF VOLTERRA ANALYSIS

NLSIM: $i(t) = K_1 \cdot v + K_2 \cdot v^2 + K_3 \cdot v^3 + \ldots$

- Solve 1st order voltage spectrums as

$$V_1 = Y^{-1} \cdot I_{in}$$

- Calculate 2nd order current spectrum as

$$I_{NL2} = K_2 \cdot (V_1 \otimes V_1)$$

- Solve 2nd order voltage spectrums as

$$V_2 = Z_T \cdot I_{NL2}$$

- Calculate 3rd order currents as

$$I_{NL3} = K_3 \cdot (V_1 \otimes V_1 \otimes V_1) + 2K_2 \cdot (V_1 \otimes V_2)$$

- Solve 3rd order voltages as

$$V_3 = Z_T \cdot I_{NL3}$$

....

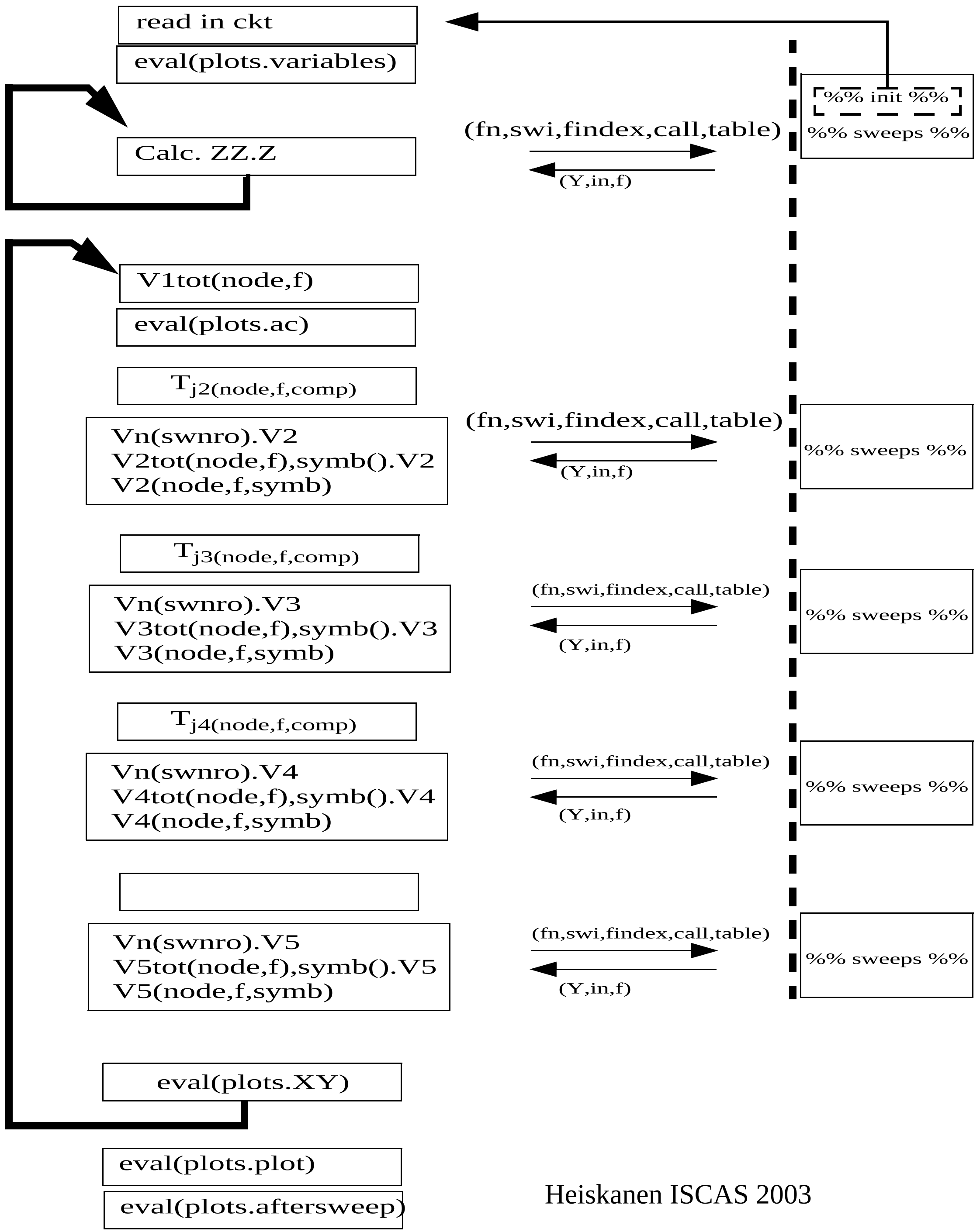
- Store results term-by-term basis

MATLAB SIMULATOR
NLSIM

$$v(t)\cdot v(t) \leftrightarrow V(f)\otimes V(f)$$

i3 = K3*conv(v1,conv(v1,v1))
+ 2*K2*conv(v1,v2)

- **netlist-> y-matrix**
- **multiport**
- **envelope injection**
- **poss. to multitone**
- **non-optimised implmt.**



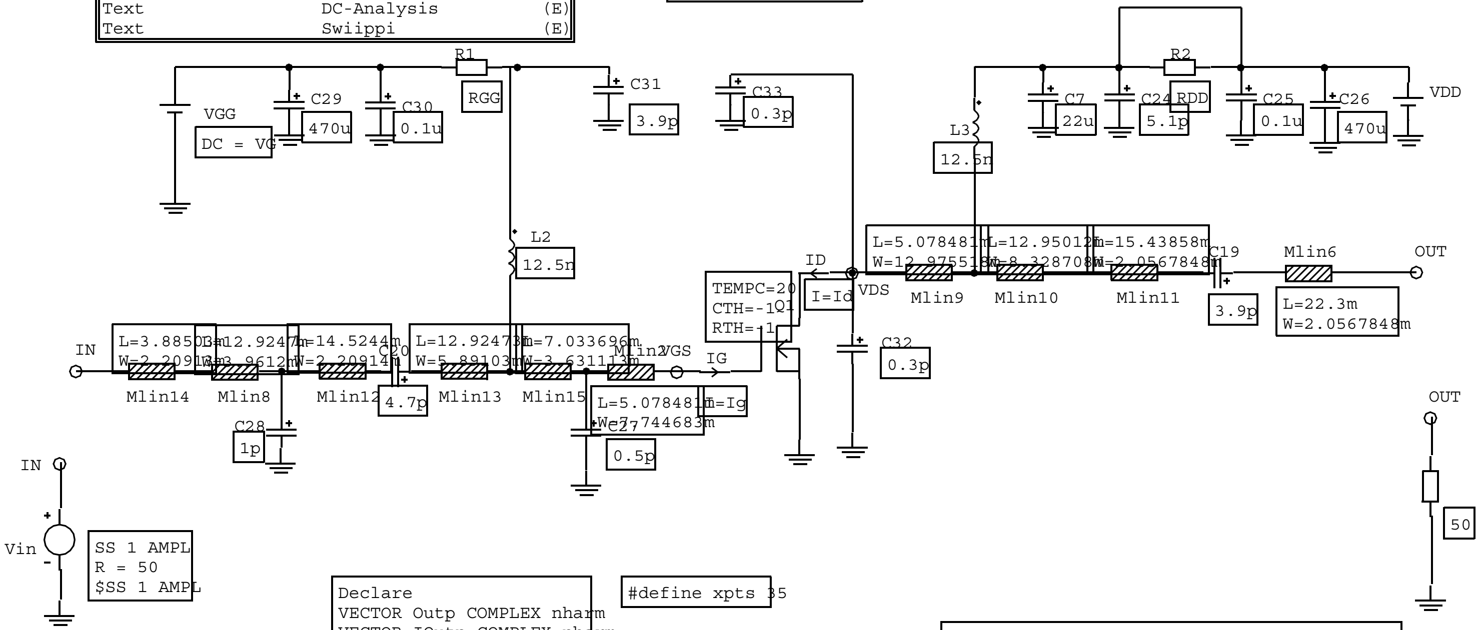
Heiskanen ISCAS 2003

VoHB: APLAC i code:
(now mostly on c lang)

```
Text                  pre                        (E)
MSub                  TLX                        (E)
T$xt                  Variabl$s                  (E)
OptimM$thod           Tuning                     (D)
Circuit Diagram       [...]                      (E)
Text                  d$f                        (E)
D$clare               [VECTOR Outp COM...]       (E)
Text                  DC-Analysis                (E)
Text                  Swiippi                    (E)
```

```
MSub TLX
ER = 2.55
LEVEL = 1
H = 0.7618867m
TAND = 0.0019
T = 35u
```

```
#define nharm 5
Prepare TONE 1 nharm
```




```
#define xpts 35
```

```
Aplacvar k

For l 1 xpts

call AMPL = 10^((l-1)/22)

Sw$$p "sika" SS
+ FO=FREQ
+ WINDOW 0
+ X "FREQ" "Hz" 0 (nharm+1)*FREQ
+ Y "sika" "dB"  -60 20

Call Outp=Spectrum(out)

EndSweep

call F1A[l-1]=mag(Outp[1])
call F1P[l-1]=pha(Outp[1])
call H3[l-1]=mag(Outp[3])

call signal[l-1]=AMPL
call gain[l-1]  = F1A[l-1]/AMPL

EndFor

Sweep "Power sweep"
+ LOOP xpts APLACVAR k LIN 0 1
+ WINDOW 1
+ X "Uin"  "V" 0 0.5
+ Y "Uout"  "V" 0 1
+ WINDOW 2
+ X "Uin"  "V" 0 0.5
+ Y "Gain"  "V" 0 5

Display Window 1
+ VECTOR xpts
+ XY "Uout" signal F1A Mark$r 1
+ XY "H3"   signal H3 Mark$r 2
+ XY2 "AM/PM" signal F1P Mark$r 3

Display Window 2
+ VECTOR xpts
+ X "Uin" signal
+ Y "Uout" gain Mark$r 1

EndSweep
```

```
Declare
VECTOR Outp COMPLEX nharm
VECTOR IOutp COMPLEX nharm
VECTOR Inp COMPLEX nharm
VECTOR Igg COMPLEX nharm
VECTOR Ud COMPLEX nharm
VECTOR POUT REAL xpts
VECTOR ROUT REAL xpts
VECTOR ZOUT COMPLEX xpts
VECTOR ZIN  COMPLEX xpts
VECTOR signal  REAL xpts
VECTOR F1A REAL xpts
VECTOR F1P REAL xpts
VECTOR F1R REAL xpts
VECTOR F1I REAL xpts
VECTOR I1A REAL xpts
VECTOR H2 REAL xpts
VECTOR H3 REAL xpts
VECTOR H4 REAL xpts
VECTOR H5 REAL xpts
VECTOR gate REAL xpts
VECTOR curr REAL xpts
VECTOR gain REAL xpts
VECTOR vgdd REAL xpts
```

```
Aplacvar RGG =12.5 opt step 100
Aplacvar RDD = 12.5 opt step 100
Aplacvar VG 3.79 opt st$p 0.01
Aplacvar VD 28 opt step 0.1
Aplacvar AMPL = 20m
Aplacvar FREQ = 2140Meg
```

```
Analyze DC

Sweep "DC-analysis" DC

Print
+ S "DC_analysis" LF LF
+ S "Vds  =" REAL Vdc(VDS) LF
+ S "Vgs  =" REAL Vdc(VGS) LF
+ S "Id =" REAL Idc(Id) LF
+ S "Ig =" REAL Idc(Ig) LF LF
$+ S "Tj =" REAL (Vdc(VDS)*Idc(Id)*Rthjs + Ta) LF
$+PUBLICS

EndSweep
```

3000 lines of code ... →

Fitting + Volterra on top of Harmonic balance

Simulation procedure:

2-tone HB

↓

$V_1(\omega)$ Spectra

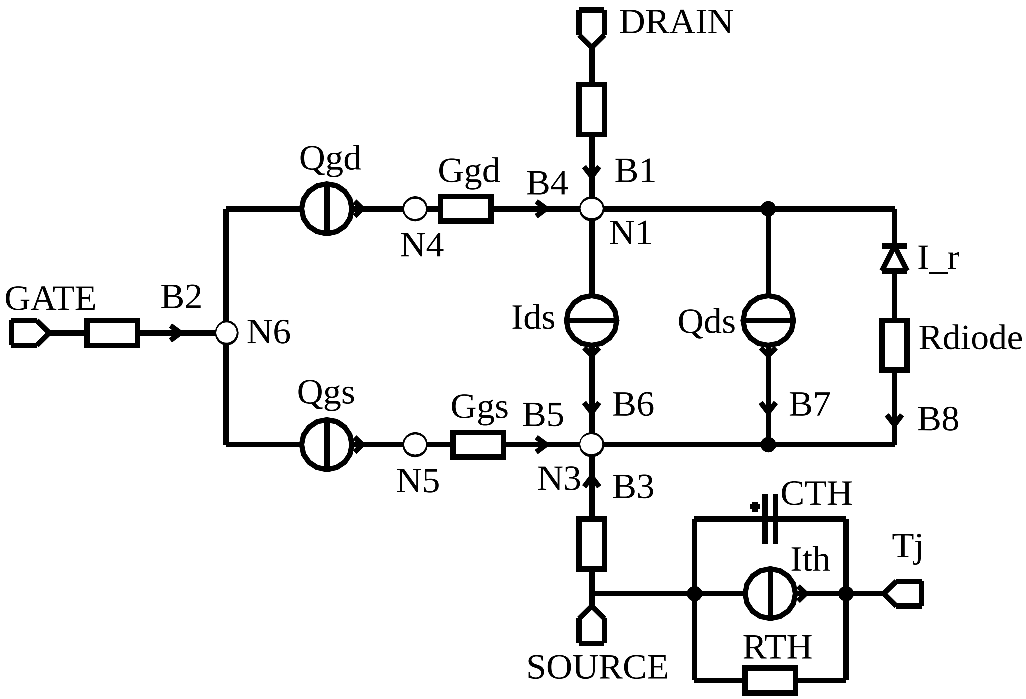
↓

Fit Polynomial I-V, Q-V using convol. spectra

↓

Calc. vectors and plot

Intrinsic MET model:



J. Aikio, T. Rahkonen:
IEEE Trans. on MTT, vol. 53 , no. 10 , October 2005, pp.

Frequency domain fitting + contribution analysis

$$v_1(t) \cdot v_2(t) \leftrightarrow V_1(f) \otimes V_2(f) \quad ,$$

$$i(t) \ = \ K_0 + K_{10} \cdot v(t) + K_{20} \cdot v(t)^2 + K_{30} \cdot v^3(t)$$

$$\begin{bmatrix} V_1(f) \ V_2(f) \ V_3(f) \end{bmatrix} \cdot \begin{bmatrix} K_{10} \\ K_{20} \\ K_{30} \end{bmatrix} = \begin{bmatrix} I_{ds}(f) \end{bmatrix} \quad .$$

Solve K = $(V^T V)^{-1} (V^T I)$

Use K to calculate IM3 current as a sum of contributions

$$\begin{aligned} I_{DS}(f_{IM3}) \ = \ & K_{10} \cdot V_{i1}(f_{IM3}) + 2K_{20} \cdot V_{ENV}(f_{IM3}) + 2K_{20} \cdot V_{H2}(f_{IM3}) \\ & + K_{30} \cdot V_{i3}(f_{IM3}) + K_{01} \cdot V_{o1}(f_{IM3}) + K_{02} V_{o2}(f_{IM3}) \\ & + K_{03} \cdot V_{o3}(f_{IM3}) + K_{11} \cdot V_{i1} V_{o1}(f_{IM3}) \\ & + K_{21} \cdot V_{i2} V_{o1}(f_{IM3}) + K_{12} \cdot V_{i1} V_{o2}(f_{IM3}) \end{aligned}$$

6. GOING ON

Polynomial fitting + Volterra into Aplac

- c implementation using AIF interface
- arbitrary number of VCCS -> multidevice analysis
- new convolution algorithm supports multitone analysis

Extensions

- Harmonic load pull using Volterra (i implementation ready)
- Yet new ways of finging polynomial coefficients

To be done in the next episode

- Complex transmitter structures: Feedforward, Doherty amplifier, ET, ...
- Usability in large signal stability analysis ?