Development of Ferroelectric Capacitor Compact Model

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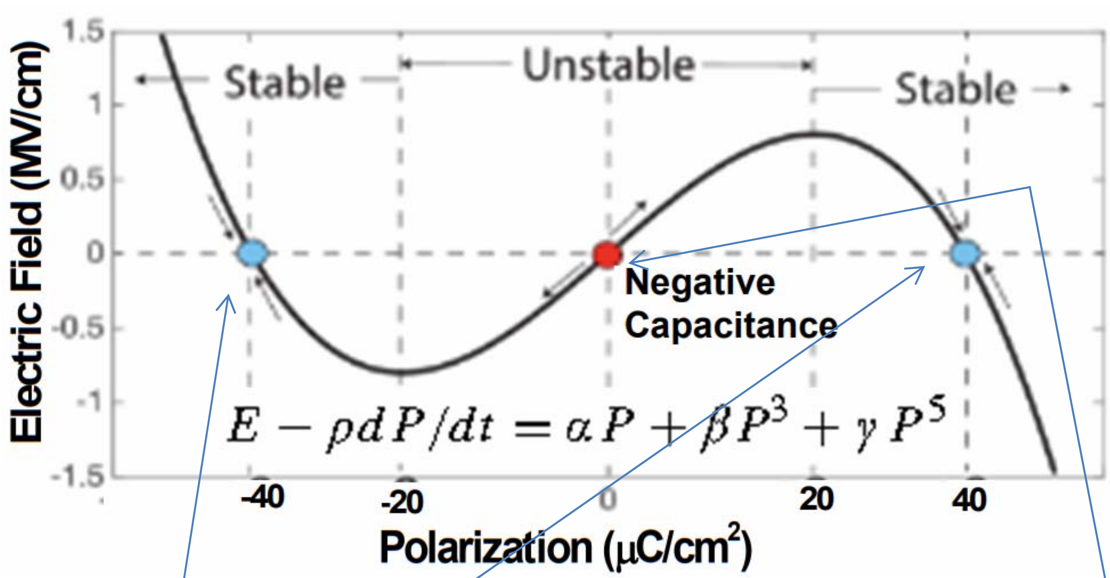
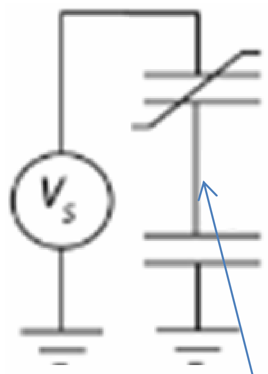
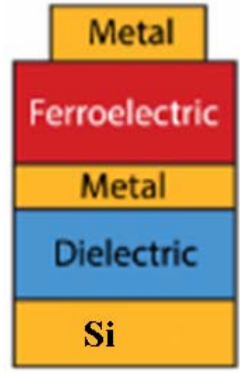
Ferroelectric (FE) Applications

Specific features of FE capacitance.   Low Power applications.





NCFET:



Two stable states: nonvolatile RAM

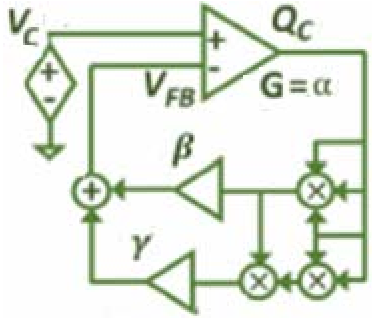
Negative capacitance: amplification in capacitance divider → NCFET

The research on the FE circuits requires effective tools including <u>computer models of nonlinear capacitances.</u>

Existing FE Spice Models

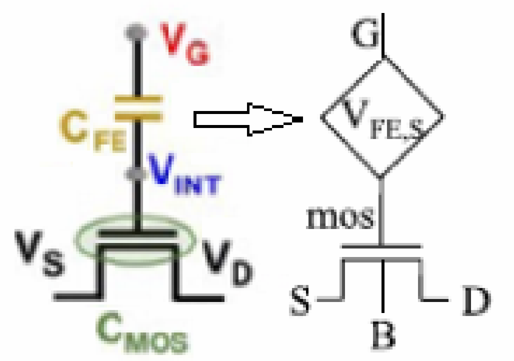
Landau-Khalatnikov equation: $V_C = -\alpha \cdot q + \beta \cdot q^3 + \gamma \cdot q^5$

A. Aziz model [IEEE Electron Device Letters, v. 37, no. 6, 2016]
Equivalent circuit with op-amps multipliers, buffers:



<u>Shortcomings</u>: high complexity, usage of imperfect devices, need for initial values in the transient and impossibility in the steady-state simulations under floating voltages in the capacitor subcircuit.

Y. Li model [IEEE Trans. on Electron Devices, v. 64, no. 5, 2017]
Voltage source controlled by the gate charge of NCFET:



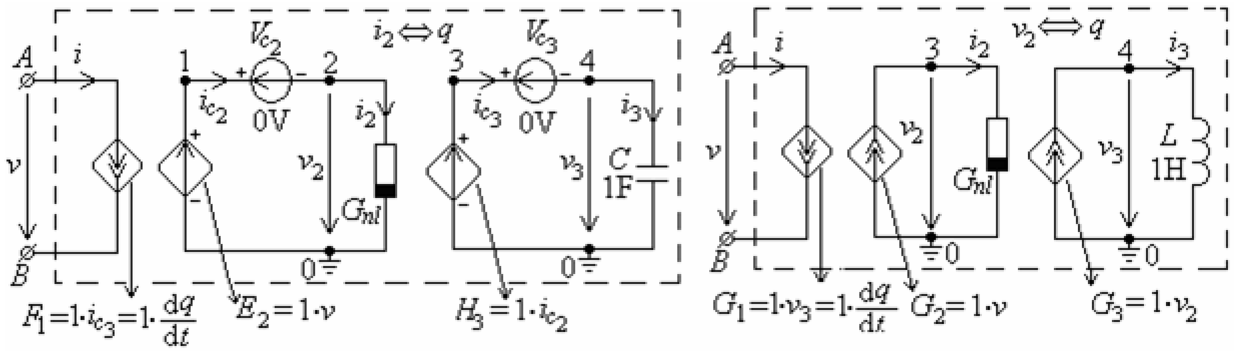
<u>Shortcomings</u>: difficulties in its extension to the series capacitors because the charge-voltage characteristic of the first capacitor should be included into all models of the series that prevents models autonomy.

Existing Capacitor Spice Models

Arbitrary nonlinear capacitor models

[M. Iordache Int. J. of Computers&Tech. 12(2) 2013]

comprise L, C elements, controlled sources G, F, E, H, nonlinear resistor G_{nl}.

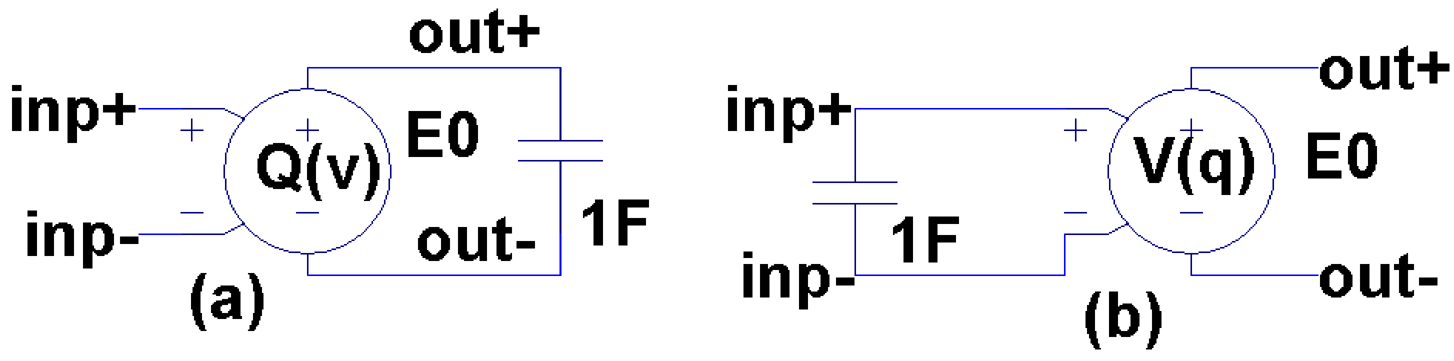


<u>Shortcomings</u>: nonlinear resistor model is not available in all Spice-like simulators

The Aim of Work

1) Models provide the simulation of nonlinear capacitor with arbitrary dependence charge on voltage or voltage on charge.
2) Models comprise linear elements, controlled voltage or current sources
3) The simulation of series of capacitors
4) Models are available in all types of analyses.

Nonlinear sources

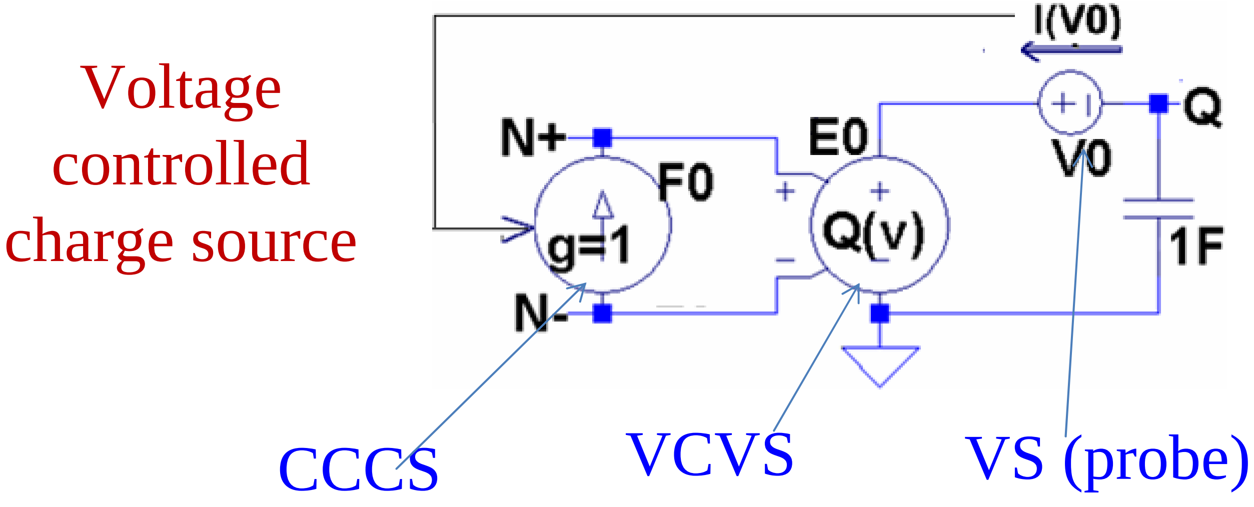


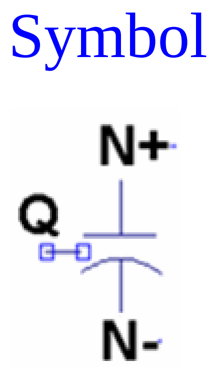
Voltage controlled charge source Q(V)

Charge controlled voltage source V(Q)

Charge on C=1F is equal to voltage,
VCVS E0 provides the nonlinear function Q(V) or V(Q).

Voltage controlled capacitor model

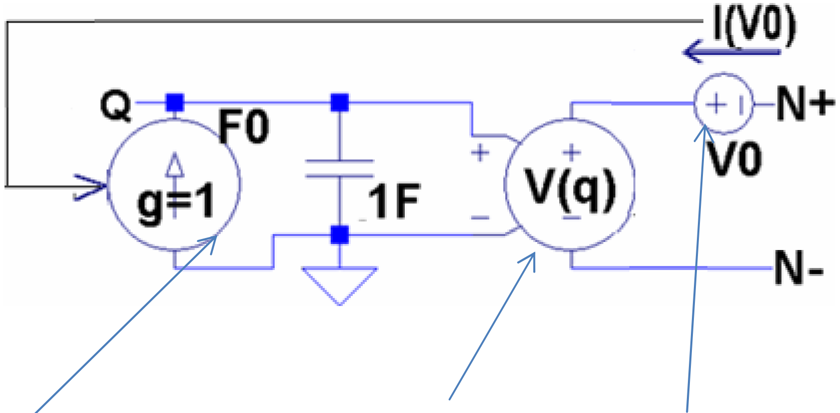




- N+, N- are terminals, $Q=f(V_{N+} - V_{N-})$
- CCCS F0 current equals to current of C=1F
- "charge" node Q provides the capacitor charge analysis via the voltage waveform at node Q

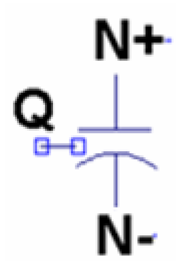
Charge controlled capacitor model

Charge controlled voltage source



CCCS VCVS VS (probe)

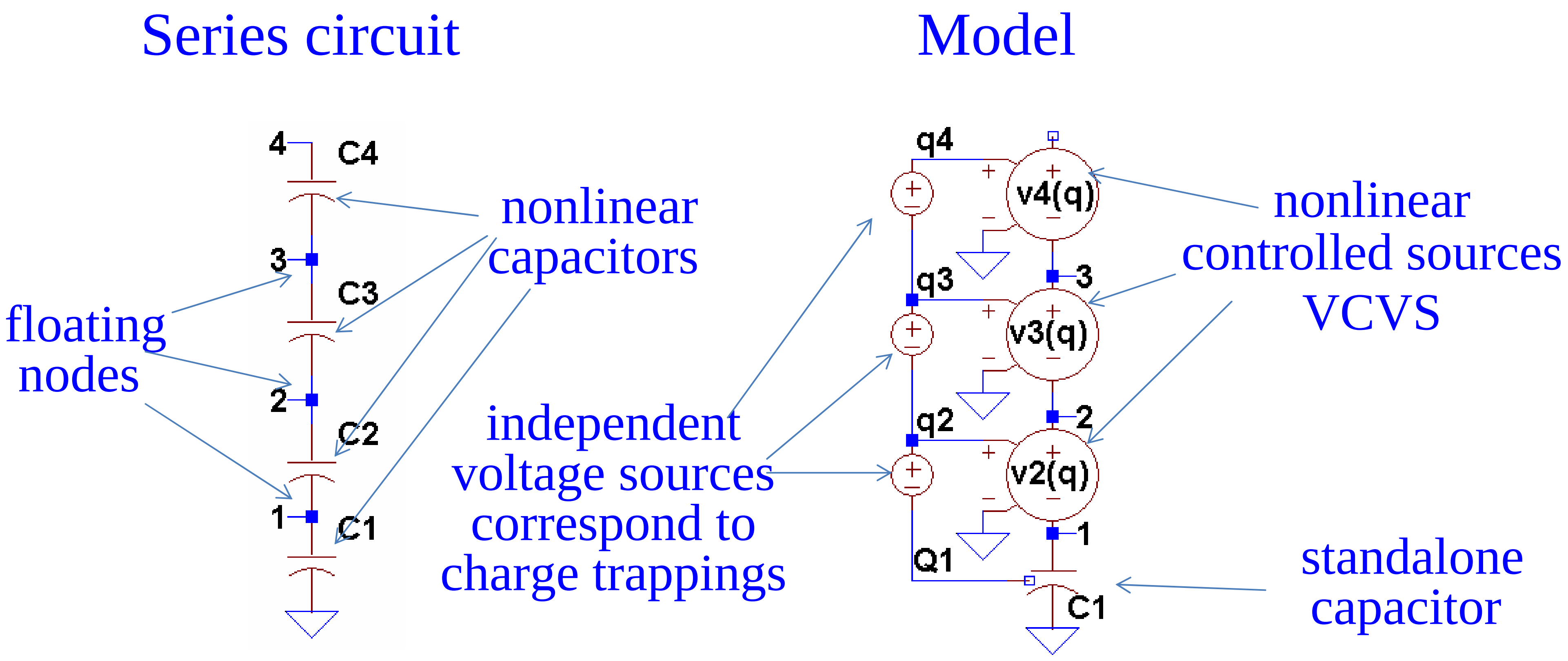
Symbol



- N+, N- are terminals, V=f(Q)
- CCCS F0 current equals to current of capacitor
- “charge” node Q provides the capacitor charge analysis via the voltage waveform at node Q and IC

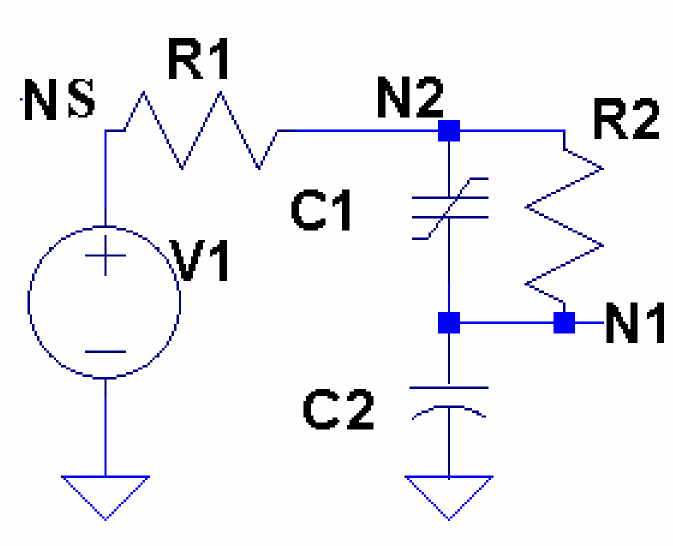
Spice Model for Series Capacitors

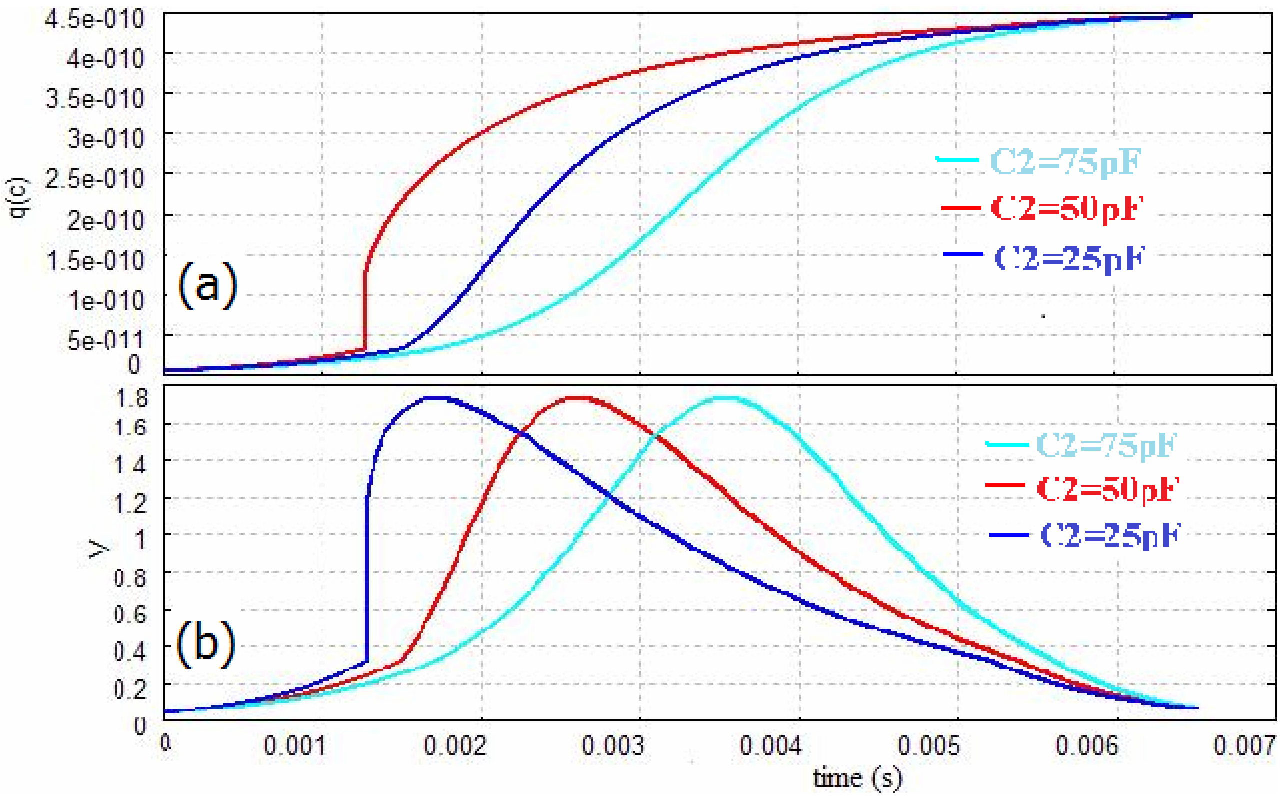
Internal floating nodes of series capacitors lead to the singularity in DC analysis. To overcome such challenges we apply an approach based on nodal charge balance equations: $Q(C_{i+1}) = Q(C_i) + q_i$



Testing Results 1

Instability analysis in the circuit with leakage resistance.



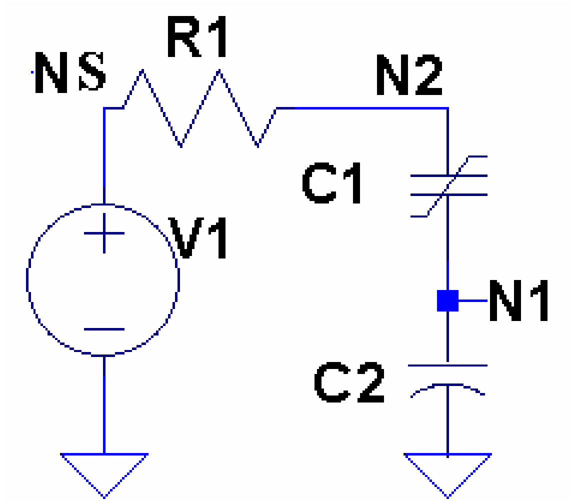


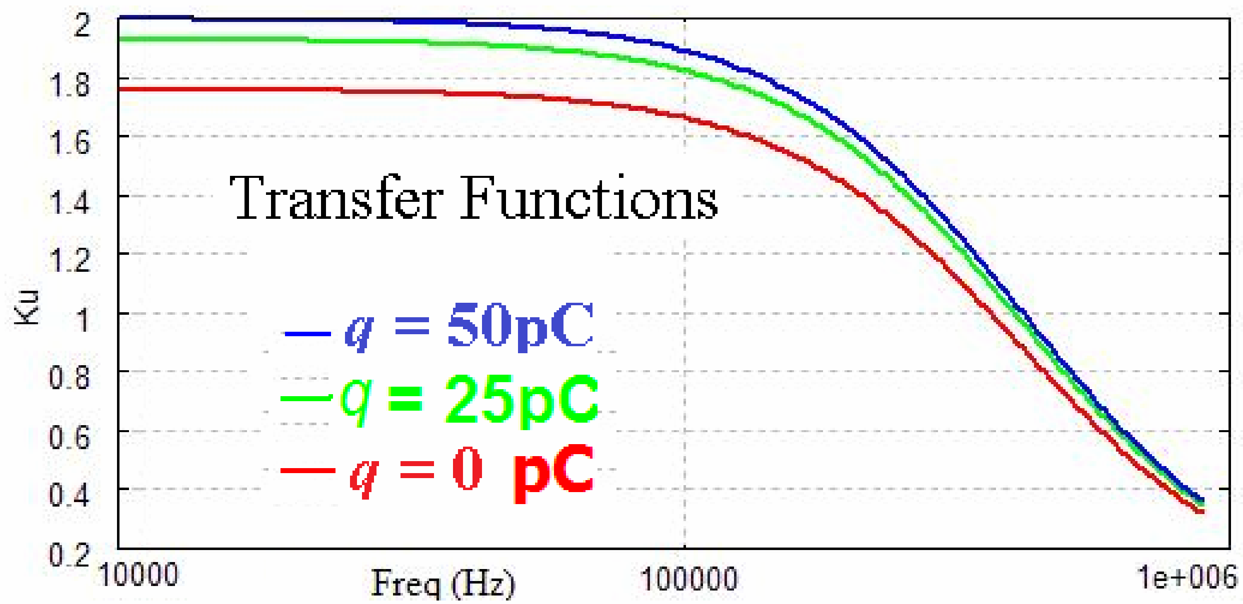
Transitions from the neighborhood of unstable point in the circuit, (a) FE capacitor charge, (b) N1 voltage.

Testing Results 2.

AC analysis in the circuit with floating node.

- to test the model of the series capacitors,
- to analyze the impact of trapped charges;
- to model the behavior under steady-state simulation.





Conclusion

1. **Spice models of arbitrary nonlinear capacitors to be applied to FE circuits are proposed.**
2. **Models for standalone “charge on voltage” and “voltage on charge” capacitors comprise “charge” terminal which enables analyzing charge waveforms, setting charge initial conditions and using charge-controlled sources.**
3. **Nonsingular model for series capacitors takes into account trapped charges of internal nodes.**
4. **The efficiency of the approach is demonstrated by the simulation of typical FE circuit configurations.**

Thank you