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# Circuit Modelling



Subtitle / Untertitel

# Kurzfassung

Kurzfassung auf Deutsch.

# **Abstract**

Abstract in English.

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# 1 Introduction

This chapter should include information about what circuit modelling wants to achieve as well as giving an overview of what this bachelor-thesis is about.

What is this thesis about?

Modelling and numerically solving systems that arise from electrical circuits with RLC elements. Furthermore it will briefly discuss on expanding this baseline with more complicated electrical components. What is the goal of this thesis?

The goal of this thesis is to give insight into industrial standards concerning circuit modelling. It aims to elaborate on the underlying concepts of MNA as well as on the most commonly used numerical methods.

## 2 Formulating a Mathematical Model

based on DAE lecture and modelling and discretization of elec circuit problems.

### 2.1 Network Topology

An electrical circuit is usually considered as a graph  $(N, E)$  where  $N = (n_0, n_1, n_2, \dots)$  are the Nodes and  $E = (e_{ij})_{ij}$  are the edges, where for some  $i$  and some  $j$  we have that  $e_{ij} = (n_j, n_k)$  is the edge from node  $j$  to node  $k$ . We can store this information in an *incidence matrix*  $\tilde{A} = (\tilde{a}_{ij})_{ij}$  which is defined by

$$\tilde{a}_{ij} = \begin{cases} 1 & \text{edge } j \text{ starts at node } i, \\ -1 & \text{edge } j \text{ ends at node } i, \\ 0 & \text{else.} \end{cases}$$

We call  $u = (u_0, u_1, u_2, \dots)$  the corresponding potentials to the nodes  $N$ . The difference of these potentials is the voltage at the associated edge. To fix the absolute values of these potentials we have to set one node to a fixed potential. We will do that by “grounding” the node  $n_0$ , this means we set the potential  $u_0 := 0$ . This grounding of a node allows us to remove the corresponding row from the incidence matrix to get the *reduced incidence matrix*  $A$ . The vector  $v = (v_{ij})_{ij}$  represents the voltages at the edges. For some  $i$  and some  $j$  the voltage at edge  $ij$  is  $v_{ij} = u_i - u_j$ .

We will later see, that the components of an electrical circuit, which will be installed along the edges, describe a relationship between the edges current and its voltage. Thus a current vector  $i = (i_1, i_2, i_3, \dots)$  containing the currents along the edges is required.



## 2.2 Energy Conservation Laws

To fully fix all the variables that arise in the model of an electrical circuit we will need some *conservation laws*:

- **Kirchhoff's voltage law (KVL):**

The sum of voltages along each loop of the network must equal to zero. Using the incidence matrix  $A$  this law can be formulated as

$$A^T * u = v. \quad (2.1)$$

- **Kirchhoff's current law (KCL):**

For any node, the sum of currents flowing into the node is equal to the sum of currents flowing out of the node. Using the incidence matrix  $A$  again, this law can be formulated as

$$A * i = 0. \quad (2.2)$$

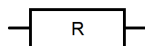
## 2.3 Electrical Components and their relations

Electrical components are described by equations relating their edge voltage  $v$  to their edge current  $i$ . We will mainly focus on so called RLC-networks which consist of resistors, capacitors, inductances, voltage sources and current sources. Diodes and Transistors as well as other electrical components can be described in a similar way, although these would lead to a more difficult analysis of the system.

- **Resistor**

Resistors "resist" the flow of current, which causes voltage to drop. This behaviour is described by the *resistance*  $R$  which is given in *Ohm* ( $\Omega$ ) and its reciprocal, the *conductance*  $G$ , which is given in *Simens* ( $S = \frac{1}{\Omega}$ ).

$$v = R * i \quad \text{or} \quad i = G * u.$$

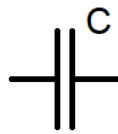


## 2 Formulating a Mathematical Model

- **Capacitor**

Capacitors "store" electrical energy by accumulating electrical charge. Their characteristic equations can be described directly using the stored charge  $Q$  or indirectly using the change in charge, which is nothing other than the current  $I$ . The *capacitance*  $C$  is given in *Farads* ( $F$ ).

$$Q = C * v \quad \text{and by derivation in t} \quad I = C * \dot{v}.$$



- **Inductor (Coil)**

An electric current flowing through a conductor generates a magnetic field  $\Phi$  surrounding it. This magnetic field causes a voltage drop dependant on the change in current. The *inductance*  $L$  is given in *Henry* ( $H$ ).

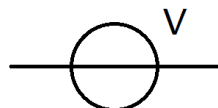
$$\Phi = L * i \quad \text{and by derivation in t} \quad v = L * \dot{i}.$$



- **Voltage Source**

A voltage source supplies the system with a voltage. It can either supply varying amounts of voltage (with the special case of alternating current AC) or a fixed amount of voltage. The unit of voltage is *Volts* ( $V$ ).

$$v = v_{src}$$

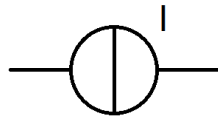


## 2 Formulating a Mathematical Model

- **Current Source**

A current source supplies the system with current. It can either supply varying amounts of current (with the special case of alternating current AC) or a fixed amount of current. The unit of current is *Ampere* ( $A$ ).

$$i = i_{src}$$



- Diode - to be filled with information after the rest is complete
- Transistor - unlike the other components which where all two-terminal components a transistor is a three-terminal component

## 2.4 Modified Nodal Analysis - MNA

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To analyse the network further we will sort the reduced incidence matrix  $A$  such that it has the block form

$$A = (A_R A_C A_L A_V A_I)$$

where  $A_R$ ,  $A_C$ ,  $A_L$ ,  $A_V$  and  $A_I$  all include the columns that are related to the resistors, capacitors, coils, voltage sources and current sources.

To mathematically describe the circuit we will use *modified nodal analysis* (or short MNA). MNA uses the node voltages as well as the currents of the coils and the voltage sources as unknowns and is based on the conservation laws

$$Ai(t) = 0 \tag{2.3}$$

## 2 Formulating a Mathematical Model

$$v = A^\top u(t) \quad (2.4)$$

as well as on the voltage-current relations of the electrical components. By replacing all edge-currents with their respective voltage-current relation and all edge-voltages with their node-potentials we obtain the MNA-equations

$$\begin{aligned} A_C C A_C^\top \dot{u} + A_R G A_R^\top u + A_L \dot{i}_L + A_V i_V + A_I i_{src} &= 0 \\ L \dot{i}_L - A_L^\top u &= 0 \\ -A_V^\top + v_{src} &= 0. \end{aligned}$$

In matrix form these read as

$$\begin{pmatrix} A_C C A_C^\top & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & 0 \end{pmatrix} * \begin{pmatrix} \dot{u} \\ \dot{i}_L \\ \dot{i}_V \end{pmatrix} + \begin{pmatrix} A_R G A_R^\top & A_L & A_V \\ -A_L^\top & 0 & 0 \\ -A_V^\top & 0 & 0 \end{pmatrix} * \begin{pmatrix} u \\ i_L \\ i_V \end{pmatrix} = \begin{pmatrix} -A_I i_{src} \\ 0 \\ -v_{src} \end{pmatrix},$$

where the diagonal matrices  $C$ ,  $G$  and  $L$  contain the capacities, conductivities and inductivities.

## 2.5 Energy bilanz??????????

may also not be relevant - leave out?

## 2.6 Charge/Flux oriented formulation of MNA

may not be too important - leave out?

Again using KCL 2.3 and the component equations we formulate a system of equations. **(more here)** What is flux and charge - explain either here or with the components

## 2 Formulating a Mathematical Model

$$A_C \dot{q} + A_R r(A_R^\top u, t) + A_L i_L + A_V i_V + A_I i(A^\top u, \dot{q}, i_L, i_V, t) = 0 \quad (2.5)$$

$$\dot{\phi} - A_L^\top u = 0 \quad (2.6)$$

$$v(A^\top u, \dot{q}, i_L, i_V, t) - A_V^\top u = 0 \quad (2.7)$$

$$q - q_C(A_C^\top u) = 0 \quad (2.8)$$

$$\phi - \phi_L(i_L) = 0 \quad (2.9)$$

Using

node potentials  $u$ ,

branch currents through voltage and flux controlled elements  $i_V$  and  $i_L$ ,

charges and fluxes  $q$  and  $\phi$ ,

voltage dependent resistors  $r$ ,

voltage and current dependent charge and flux sources  $q_C$  and  $\phi_L$ ,

controlled current and voltage sources  $i_{src}$  and  $v_{src}$ .

**Charge/flux oriented or conventional MNA?** On which formulation — charge/flux oriented or conventional — should the numerical discretization be based, if MNA is used for the automatic generation of network equations? From a structural aspect, the conventional MNA formulation yields a standard form of numerical integration problems, while the charge/flux oriented formulation does not. There are however several reasons, not to transform (4.1) into (4.2) before applying numerical discretization schemes, although they are analytically equivalent:

**Structure.** (4.1) is of linear-implicit nonlinear form, while (4.2) is of nonlinear-implicit nonlinear form. This may have an impact on the choice of a suitable integrator.

**Numerics.** Information on the charge/flux level is lost in the conventional approach, and charge conservation may only be maintained approximately in numerical integration schemes.

**Implementation.** Implicit numerical integration schemes for the conventional MNA equations (4.2) require second partial derivatives of  $q_C$  and  $\phi_L$ . These derivative informations, however, are not available in circuit simulation packages, may even not exist because of the lack of smoothness in transistor models.

**Figure 2.1:**

## 3 Differential Algebraic Equations

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### 3.1 Abstract Problem

$$F(t, y(t), y'(t)) = 0 \quad \forall t \in I \quad (3.1)$$

with  $F : \mathbb{R} \times \mathbb{R}^N \times \mathbb{R}^N \rightarrow \mathbb{R}^N$  sufficiently smooth. We will focus on linear time invariant systems of the form

$$Eu'(t) = Au(t) + f(t).$$

With  $E, A \in \mathbb{R}^{n \times n}$ . If  $E$  is regular, then this system is just an ordinary differential equation, thus we assume  $E$  to be singular to obtain a “true” DAE.

In the following chapters we will discuss important analytical properties of these systems. We will discuss the solvability and the index of these systems.

### 3.2 Types of DAEs

- **Linear systems with constant coefficients**  
are systems of the form

$$Ay'(t) + By(t) = f(t) \quad (3.2)$$

### 3 Differential Algebraic Equations

with  $A, B \in \mathbb{R}^{n \times n}$ ,  $A$  singular and  $f(t)$  a function.

- **linear time dependent systems**

$$A(t)y'(t) + B(t)y(t) = f(t)$$

with  $A(t), B(t), f(t)$  functions.

- **structured (non-linear) systems**

are semi-explicit systems of the form

$$y'(t) = f(t, y(t), z(t)), 0 = g(t, y(t), z(t))$$

with  $f$  and  $g$  functions.

For our analysis of electrical networks we will focus on linear systems with constant coefficients. (where do the other systems arise? what are they about?)

#### 3.2.1 Weierstraß-Kronecker Normalform

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To determine the solvability of a linear system with constant coefficients 3.2 we first need to introduce a Normalform for the system, the *Weierstraß-Kronecker Normalform*. This Normalform is dependant on the family  $\{A, B\} := \{\mu A + B | \mu \in \mathbb{R}\}$ , which is called the *matrix pencil* of the DAE.

**Definition 1.** The matrix pencil  $\{A, B\}$  is called regular if there exists some  $c \in \mathbb{R}$ , such that  $(cA + B)$  is regular ( $\det(cA + B) \neq 0$ ), otherwise it is called singular.

### 3 Differential Algebraic Equations

**Theorem 1** (Jordan Normalform). *For every matrix  $Q \in \mathbb{R}^{\times}$  there exists a regular matrix  $T \in \mathbb{C}^{n \times n}$ , such that*

$$T^{-1}QT = J = \text{diag}(J_1, \dots, J_r) \quad \text{with} \quad J_i = \begin{pmatrix} \lambda_i & 1 & & 0 \\ 0 & \lambda_i & \ddots & \vdots \\ & \ddots & \ddots & 1 \\ 0 & \dots & 0 & \lambda_i \end{pmatrix} \in \mathbb{C}^{m_i \times m_i}$$

*and  $n = m_1 + \dots + m_r$ .*

quote that from somewhere.

translate that:

The matrix  $J$  is called Jordan Normalform of  $Q$ , the  $J_i$  are called Jordan Blocks, where  $\lambda_i$  are the eigenvalues of  $Q$ . The matrix  $J$  is uniquely determined by  $Q$  except for the arrangement of the diagonal blocks. If  $Q$  possesses only real eigenvalues, then  $T$  can also be chosen from the reals.

A transformation from  $A$  and  $B$  in 3.2 enables a separation into differential and algebraic variables.

aus buch seite 401

**Theorem 2.** *Let  $\{A, B\}$  be a regular matrix pencil. There exist  $P, Q \in \mathbb{C}^{n \times n}$  such that*

$$PAQ = \begin{pmatrix} I_d & 0 \\ 0 & N \end{pmatrix}, \quad PBQ = \begin{pmatrix} R & 0 \\ 0 & I_{n-d} \end{pmatrix}$$

*where*

$$N = \text{diag}(N_1, \dots, N_r) \quad \text{with} \quad N_i = \begin{pmatrix} 0 & 1 & & 0 \\ & \ddots & \ddots & \\ & & \ddots & 0 \\ 0 & & & 0 \end{pmatrix} \in \mathbb{R}^{n_i \times n_i}$$

*and  $R$  has Jordan Normalform.*



### 3 Differential Algebraic Equations

*Proof.* Because  $\{A, B\}$  is a regular matrix pencil, there exists  $c \in \mathbb{R}$  such that  $(cA + B)$  is regular. Set

$$\hat{A} := (cA + B)^{-1}A, \quad \hat{B} := (cA + B)^{-1}B.$$

Considering

$$(cA + B)^{-1}(cA + B) = I \implies (cA + B)^{-1}B + c(cA + B)^{-1}A = I,$$

we get that

$$\hat{B} = I - c\hat{A}.$$

Let  $J_{\hat{A}}$  be the Jordan Normalform of  $\hat{A}$ , this means that there exists a regular matrix  $T_1$  such that

$$T_1^{-1}AT_1 = J_{\hat{A}} = \begin{pmatrix} W & 0 \\ 0 & \tilde{N} \end{pmatrix}.$$

The matrix  $W$  contains the Jordanblocks with Eigenvalues which are nonzero, the matrix  $\tilde{N}$  contains the Jordan blocks with Eigenvalues equal to zero, thus  $\tilde{N}$  is *nilpotent*. The Jordan Normalform  $J_{\hat{B}}$  of  $\hat{B}$  is given by

$$T_1^{-1}\hat{B}T_1 = J_{\hat{B}} = \begin{pmatrix} I - cW & 0 \\ 0 & I - c\tilde{N} \end{pmatrix}.$$

The following two transformations will allow us to get the desired structure. First we will transform  $J_{\hat{A}}$  with

$$T_2 := \begin{pmatrix} W & 0 \\ 0 & I - c\tilde{N} \end{pmatrix}$$

in

$$T_2^{-1}J_{\hat{A}} = \begin{pmatrix} I & 0 \\ 0 & (I - c\tilde{N})^{-1}\tilde{N} \end{pmatrix}$$

### 3 Differential Algebraic Equations

and  $J_{\hat{B}}$  in

$$T_2^{-1}J_{\hat{B}} = \begin{pmatrix} W^{-1} - cI & 0 \\ 0 & I \end{pmatrix}.$$

Let now  $R$  be the Jordan Normalform of  $(W^{-1} - cI)$  and  $N$  be the Normalform of  $(I - c\tilde{N})^{-1}\tilde{N}$ , this means

$$T_W^{-1}(W^{-1} - cI)T_W = R \quad \text{and} \quad T_{\tilde{N}}^{-1}(I - c\tilde{N})^{-1}\tilde{N}T_{\tilde{N}} = N$$

Considering

Die Matrizen  $\tilde{N}$  und  $(I - c\tilde{N})^{-1}$  kommutieren. Daraus folgt

$$N^k = T_{\tilde{N}}^{-1}(I - c\tilde{N})^{-k}\tilde{N}^k\tilde{N}T_{\tilde{N}} = T_{\tilde{N}}^{-1}\tilde{N}^kT_{\tilde{N}}.$$

**Figure 3.1:** fig 1, i dont get why

The nilpotent matrix  $N$  thus has the nilpotency index  $k$ . A transformation with

$$T_3 := \begin{pmatrix} T_W & 0 \\ 0 & T_{\tilde{N}} \end{pmatrix}$$

transforms  $T_2^{-1}J_{\hat{A}}$  into the Jordan Normalform

$$J_{\hat{A}} := T_3^{-1}T_2^{-1}J_{\hat{A}}T_3 = T_3^{-1}T_2^{-1}T_1^{-1}\hat{A}T_1T_3 = \begin{pmatrix} I & 0 \\ 0 & N \end{pmatrix}$$

and  $T_2^{-1}J_{\hat{B}}$  into

$$J_{\hat{B}} := T_3^{-1}T_2^{-1}J_{\hat{B}}T_3 = T_3^{-1}T_2^{-1}T_1^{-1}\hat{B}T_1T_3 = \begin{pmatrix} R & 0 \\ 0 & I \end{pmatrix}.$$

Now set

$$P := T_3^{-1}T_2^{-1}T_1^{-1}(cA + B)^{-1} \quad \text{and} \quad Q = T_1T_3$$

to get the statement. □

### 3 Differential Algebraic Equations

**Definition 2.** The nilpotency index  $k$  from the Weierstraß-Kronecker Normalform of a matrix pencil  $\{A, B\}$  with  $A$  singular is called the Kronecker-Index of  $\{A, B\}$ . We write  $\text{ind}\{A, B\}$ . For  $A$  regular we set  $\text{ind}\{A, B\} = 0$ .

next lemma needs quotation, it is lemma 13.2.1

**Lemma 1.** The Kronecker-Index  $\text{ind}\{A, B\}$  is independant of the choice of the matrices  $P$  and  $Q$ .

Lemma 13.2.2 maybe

Using the findings above we are able to Transform the initial DAE 3.2 using the matrix  $P$  from 2. By multiplying  $P$  from the left we obtain

$$PAy'(t) + PBy(t) = Pf(t).$$

Setting

$$y = Q \begin{pmatrix} u \\ v \end{pmatrix}, \quad Pf(t) = \begin{pmatrix} s(t) \\ q(t) \end{pmatrix} \quad \text{with } u, s \in \mathbb{R}^d,$$

we get a system of the form

$$\begin{aligned} u'(t) + Ru(t) &= s(t) \\ Nv'(t) + v(t) &= q(t) \end{aligned} \tag{3.3}$$

The first equation is an ordinary differential equation of first order and possesses a unique solution  $u(t)$  in  $[t_0, t_l]$  for any starting values  $u_0 \in \mathbb{R}^d$ . Additionally setting  $q(t) \in C^{k-1}([t_0, t_l])$  then differentiating the second equation in 3.3 gives (**whyyyyyyyy??????**)

### 3 Differential Algebraic Equations

**Beweis.** Angenommen, das Matrixbüschel  $\{A, B\}$  hat zwei verschiedene Weierstraß-Kronecker-Normalformen, d. h., es existieren reguläre quadratische Matrizen  $P, Q$  und  $\hat{P}, \hat{Q}$ , so dass gilt

$$PAQ = \begin{pmatrix} I_{d_1} & 0 \\ 0 & N \end{pmatrix}, \quad PBQ = \begin{pmatrix} R & 0 \\ 0 & I_{n-d_1} \end{pmatrix}, \quad (13.2.7)$$

und

$$\hat{P}A\hat{Q} = \begin{pmatrix} I_{d_2} & 0 \\ 0 & \hat{N} \end{pmatrix}, \quad \hat{P}B\hat{Q} = \begin{pmatrix} \hat{R} & 0 \\ 0 & I_{n-d_2} \end{pmatrix}. \quad (13.2.8)$$

Wir betrachten das Polynom

$$\begin{aligned} p(\lambda) &= \det(\lambda A + B) = \det(P^{-1}) \det(\lambda I_{d_1} + R) \det(Q^{-1}) \\ &= \det(\hat{P}^{-1}) \det(\lambda I_{d_2} + \hat{R}) \det(\hat{Q}^{-1}). \end{aligned}$$

Es gilt

$$\text{Grad}(p(\lambda)) = d_1 = d_2,$$

d. h., die ersten Blöcke in (13.2.7) und (13.2.8) haben die gleiche Dimension. Mit den regulären Matrizen  $\tilde{P} := \hat{P}P^{-1}$  und  $\tilde{Q} := \hat{Q}^{-1}Q$  ergibt sich aus (13.2.7) und (13.2.8)

$$\tilde{P} \begin{pmatrix} I & 0 \\ 0 & N \end{pmatrix} = \hat{P}AQ = \begin{pmatrix} I & 0 \\ 0 & \hat{N} \end{pmatrix} \tilde{Q}, \quad \tilde{P} \begin{pmatrix} R & 0 \\ 0 & I \end{pmatrix} = \hat{P}BQ = \begin{pmatrix} \hat{R} & 0 \\ 0 & I \end{pmatrix} \tilde{Q},$$

so dass gilt

$$\begin{pmatrix} \tilde{P}_{11} & \tilde{P}_{12} \\ \tilde{P}_{21} & \tilde{P}_{22} \end{pmatrix} \begin{pmatrix} I & 0 \\ 0 & N \end{pmatrix} = \begin{pmatrix} I & 0 \\ 0 & \hat{N} \end{pmatrix} \begin{pmatrix} \tilde{Q}_{11} & \tilde{Q}_{12} \\ \tilde{Q}_{21} & \tilde{Q}_{22} \end{pmatrix}$$

und

$$\begin{pmatrix} \tilde{P}_{11} & \tilde{P}_{12} \\ \tilde{P}_{21} & \tilde{P}_{22} \end{pmatrix} \begin{pmatrix} R & 0 \\ 0 & I \end{pmatrix} = \begin{pmatrix} \hat{R} & 0 \\ 0 & I \end{pmatrix} \begin{pmatrix} \tilde{Q}_{11} & \tilde{Q}_{12} \\ \tilde{Q}_{21} & \tilde{Q}_{22} \end{pmatrix}.$$

**Figure 3.2:**

### 3 Differential Algebraic Equations

Daraus folgen die Beziehungen

$$\tilde{P}_{11} = \tilde{Q}_{11}, \quad \tilde{P}_{12}N = \tilde{Q}_{12}, \quad \tilde{P}_{21} = \hat{N}\tilde{Q}_{21}, \quad \tilde{P}_{22}N = \hat{N}\tilde{Q}_{22}$$

und

$$\tilde{P}_{11}R = \hat{R}\tilde{Q}_{11}, \quad \tilde{P}_{12} = \hat{R}\tilde{Q}_{12}, \quad \tilde{P}_{21}R = \tilde{Q}_{21}, \quad \tilde{P}_{22} = \tilde{Q}_{22}.$$

Damit ergibt sich

$$\tilde{P}_{21} = \hat{N}\tilde{P}_{21}R = \hat{N}^2\tilde{P}_{21}R^2 = \dots = \hat{N}^{\hat{k}}\tilde{P}_{21}R^{\hat{k}} = 0 \quad \text{und} \quad \tilde{Q}_{21} = 0.$$

Hierbei ist  $\hat{k}$  der Nilpotenzindex von  $\hat{N}$ . Auf analoge Weise erhält man

$$\tilde{P}_{12} = \hat{R}\tilde{P}_{12}N = \hat{R}^2\tilde{P}_{12}N^2 = \dots = \hat{R}^k\tilde{P}_{12}N^k = 0,$$

wobei  $k$  der Nilpotenzindex von  $N$  ist. Aufgrund der Regularität der Transformationsmatrizen  $\tilde{P}$  und  $\tilde{Q}$  müssen die Blöcke

$$\tilde{P}_{11} = \tilde{Q}_{11} \quad \text{und} \quad \tilde{P}_{22} = \tilde{Q}_{22}$$

regulär sein. Ferner gilt jetzt

$$\tilde{Q}_{11}R = \hat{R}\tilde{Q}_{11} \quad \text{und} \quad \tilde{Q}_{22}N = \hat{N}\tilde{Q}_{22},$$

d. h.,  $R$  und  $\hat{R}$  sowie  $N$  und  $\hat{N}$  sind ähnliche Matrizen. Damit folgt, dass die Jordansche Normalform von  $N$  und die von  $\hat{N}$  aus den gleichen nilpotenten Jordan-Blöcken bestehen und somit den Nilpotenzindex  $\hat{k} = k$  besitzen. ■

**Figure 3.3:**

$$\begin{aligned}
 v(t) &= q(t) - Nv'(t) = q(t) - N(q(t) - Nv'(t))' = q - Nq' + N^2v'' \\
 &= q - Nq' + N^2(q - Nv')'' = q - Nq' + N^2q'' - N^3v''' \\
 &\vdots \\
 &= q - Nq' + \dots + (-1)^{k-1}N^{k-1}q^{(k-1)} + (-1) \underbrace{N^k v^{(k)}}_{=0} \\
 &= \sum_{i=0}^{k-1} (-1)^i N^i q^{(i)}(t)
 \end{aligned} \tag{3.4}$$

where  $k$  is the nilpotency index of  $N$ . This expression gives an explicit solution for  $v(t)$  in  $[t_0, t_l]$  with  $v(t) \in \mathbb{R}^{d-1}$ . It shows the dependency of the solution and its derivatives. The higher the Kronecker index  $k$  gets, the more differentiations of  $q(t)$  have to be performed.

The Kronecker index  $k$  shows, that  $k$  differentiations are required to receive an ordinary differential equation.

### 3.3 Index of a Differential Algebraic Equation

The Index of a DAE gives us insight about it's numerical properties and in general about the solvability. In general, the higher the index, the harder it is, to solve the system.

We will consider two types of index concepts, the differentiation index and the perturbation index.

**Definition 3** (differentiation index). *Consider the differential algebraic equation 3.1 to be uniquely locally solvable and  $F$  sufficiently smooth differentiable. For a given  $m \in \mathbb{N}$  consider*

$$\begin{aligned} F(t, y, y') &= 0, \\ \frac{dF(t, y, y')}{dt} &= 0, \\ &\vdots \\ \frac{d^m F(t, y, y')}{dt^m} &= 0. \end{aligned}$$

*The smallest natural number  $m$  for which the above System results in an explicit system of the form*

$$y' = \phi(t, y)$$

*from which  $y$  can be determined is called **differentiation index**.*

In the previous chapter we have already discussed, that for a DAE with constant coefficients 3.2 and a regular matrix pencil  $\{A, B\}$  we need  $k = \text{ind}\{A, B\}$  differentiations to receive an ordinary differential equation. This means that the Kronecker index  $k$  is equal to the differentiation index in the case of a DAE with constant coefficients.

### 3 Differential Algebraic Equations

**Definition 4** (perturbation index). Let  $y(t)$  be the exact solution to 3.1. This problem has the **perturbation index**  $k \in \mathbb{N}$  along  $y(t)$ ,  $t_0 \leq t \leq T$  if for all  $\tilde{y}(t)$  with  $F(t, \tilde{y}, \tilde{y}') = \delta(t)$  the inequality

$$\|y(t) - \tilde{y}(t)\| \leq C \left( \|y(t_0) - \tilde{y}(t_0)\| + \sum_{j=0}^k \max_{t_0 \leq \xi \leq T} \left\| \int_{t_0}^{\xi} \frac{d^j \delta}{d\tau^j}(\tau) d\tau \right\| \right)$$

for the smallest number  $k$ .

for lin const nilpot ind = ind + proof

**Bemerkung 13.3.5.** Im Fall linearer differential-algebraischer Systeme (13.2.1) mit regulärem Matrixbüschel  $\{A, B\}$  kann die DAE

$$A(y'(t) - \tilde{y}'(t)) + B(y(t) - \tilde{y}(t)) = \delta(t)$$

nach Folgerung 13.2.1 transformiert werden in

$$\begin{aligned} u'(t) - \tilde{u}'(t) + \hat{R}(u(t) - \tilde{u}(t)) &= \delta_1(t) \\ N(v'(t) - \tilde{v}'(t)) &= \delta_2(t). \end{aligned} \tag{13.3.29}$$

Aus der Lösungsdarstellung von (13.3.29), vgl. (13.2.11), folgt, dass der Störungsindex  $pi$  gleich dem Kronecker-Index  $k$  ist. Mit Bemerkung 13.3.1 gilt damit  $k = di = pi$ .  $\square$

Bezüglich des Störungsindex von (13.3.8) gilt der

**Figure 3.4:**

## 4 Index Analysis of the MNA

der ane satz do + proof hopefully

seite 22 kap 7 netw top and dae ind for rlc - modelling and discretization circ prob

In the linear case, the capacitances, inductances and resistances are symmetrical positive definite (We consider them as matrices in this case). In the nonlinear case ... . Then it is called an RLC network.

In our further analysis we will only consider such RLC networks.

### 4.1 General Index analysis

Assuming the system only contains linear elements or is linearized at an operating point in order to investigate the system behaviour then the corresponding network equation represent a DAE with constant coefficients 3.2. Ww will denote  $x = (u_L i_V)^\top$ .

- **ODE-case:**

The matrix  $B$  is regular in 3.2. This is the case if

ODE-case:  $B$  regular. This holds, iff the circuit contains no voltage sources and there are no nodes which have no path to ground via capacitors. In this case, system (6.1) represents a

**Figure 4.1:**

, then the system represents a linear-implicit system of ODEs and can be transformed into the explicit ODE system

$$\dot{x} = B^{-1}(-Ax + f(t))$$



## 4 Index Analysis of the MNA

- **DAE-case:** The matrix  $B$  is singular in 3.2. In the following we will assume  $D$  to be regular. Multiplying with  $D^{-1}$  from the left side produces nevermind that's the same as we did in the 3.2 chapter. - reference to that an explain in these terms. - page 20

### 4.2 Topological Conditions

For this we consider RLC networks with independent voltage and current sources (**what does that mean?**). To obtain the perturbation index of the MNA we perturb the right-hand side of

reference to Tischendorf

From analyzing the MNA some conditions to the circuit topology can be obtained. We will be considering the impact of loops containing only capacitances and voltage sources as well as cutsets containing only inductances and current sources.

**Theorem 3** (Index-1 condition). [Tischendorf2004Topological] *Let the matrices of the capacitances, inductances and resistances respectively be positive definite. If the network neither contains inductance-current-source cutsets nor (controlled?) capacitance-voltage-source loops, then the MNA leads to an index-1 DAE.*

**Theorem 4** (Index-2 condition). [Tischendorf2004Topological] *If the Network contains inductance-current-source cutsets or capacitance-voltage-source loops except for capacitance-only loops, then the MNA leads to an index-2 DAE.*

## 5 Numerical Solutions

As we are usually interested in finding real (or complex) valued solutions of our systems we also have to look into solving them numerically. This chapter focuses on the numerical solution of the mentioned systems.

We will first focus on methods used to solve a more general problem

$$y'(t) = f(t, y), \quad t \in [t_0, t_l], \quad (5.1)$$

$$y(t_0) = y_0. \quad (5.2)$$

For this we presume that the function  $f(t, y)$  is continuous and Lipschitz, thus *Picard-Lindelöf* gives us, that for every  $y_0$  it is uniquely solvable in  $[t_0, t_l]$ .

Numerical Methods work by discretization, this means we divide the time-intervall into

$$t_0 < t_1 < \dots < t_N \leq t_l$$

and consider approximations  $y_m \approx y(t_m)$  for  $m = 1, \dots, N$ . Gitterpunkte, Schrittweite, äquidistant, nicht äquidistant.

### 5.1 Single-Step-Methods

The first class of numerical methods we will have a look at are single-step methods. These methods use the previous approximated value  $y_j$  and (for implicit methods) also the current approximated value to determine the current value through a *procedural function*. ... waht does implicit and explicit mean?

## 5 Numerical Solutions

**Definition 5.** A numerical method to approximate a differential equation 5.1 on a time-grid  $t_0, \dots, t_l$  with the intermediate values  $y_0, \dots, y_l$  is called a single-step method if it is from the form

$$y_{j+1} = y_j + h_j \phi(t_j, y_j, y_{j+1}, h_j). \quad (5.3)$$

With the procedural function  $\phi$ . If  $\phi$  is not dependent on  $y_{j+1}$  then the method is called explicit, otherwise it is called implicit.

### 5.1.1 Consistency and Convergence

To compare different single-step methods we have to define some notions to compare their quality. This leads to the definition of the error of the method, its consistency and its convergence.

**Definition 6.** Let  $\tilde{y}_{m+1}$  be the result of one step of 5.3 with the exact start-vector  $y_m = y(t_m)$  then

$$le_{m+1} = le(t_m + h) = y(t_{m+1}) - \tilde{y}_{m+1}, \quad m = 0, \dots, N-1 \quad (5.4)$$

is called the local discretization error of the single step method at the point  $t_{m+1}$ .

The error encodes how far off the numerical method is from the true value of the solution. In real applications this solution is usually not known. This shows how important error bounds for numerical methods can be.

**Definition 7.** A single-step method is called consistent if for all initial value problems 5.1

$$\lim_{h \rightarrow 0} \frac{||le(t+h)||}{h} = 0 \quad \text{for } t_0 \leq t \leq t_l \quad (5.5)$$

## 5 Numerical Solutions

holds.

It is called consistent of order  $p$ , if for a sufficiently smooth function  $f$

$$||le(t+h)|| \leq Ch^{p+1} \quad \text{for all } h \in (0, H] \quad \text{and} \quad t_0 \leq t \leq t_1 - h \quad (5.6)$$

holds with  $C$  not dependent on  $h$ .

Consistency aims to give insight in how similar the problem that the numerical methods solves it to the real problem that we want the solution from.

**Definition 8.** A single-step method is called convergent, if for all initial value problems 5.1 for the global discretization error

$$e_m = y(t_m) - y_h(t_m)$$

holds that

$$\max_m ||e_m|| \rightarrow 0 \quad \text{for} \quad h_{\max} \rightarrow 0.$$

The single-step method is called to have the convergence order  $p$ , if

$$\max_m ||e_m|| \leq Ch_{\max}^p \quad \text{for} \quad h_{\max} \in (0, H] \quad \text{with} \quad t_0 \leq t_m \leq t_1$$

with the constant  $C$  not dependent on the step size  $h$ .

As the name suggests convergence tries to quantify how far off a numerical solution is from the real solution of a system.

### 5.1.2 Runge-Kutta Methods

A very prevalent family of numerical single-step methods are the *Runge-Kutta* methods. ...  
Whats the idea behind those methods?

## 5 Numerical Solutions

**Definition 9.** Let  $s \in \mathbb{N}$ . A single-step method of the form

$$y_{m+1} = y_m + h \sum_{i=1}^s b_i f(t_m + c_i h, y_{m+1}^{(i)}) \quad (5.7)$$

$$y_{m+1}^{(i)} = y_m + \sum_{j=1}^s a_{ij} f(t_m + c_j h, y_{m+1}^{(j)}) \quad (5.8)$$

is called a Runge-Kutta Method with  $s$  steps.

We usually collect the coefficients into the vectors and matrices  $c = (c_1, \dots, c_s)$ ,  $A = (a_{ij})_{ij}$  and  $b = (b_1, \dots, b_s)$ .

If  $A$  is a strictly lower triangle matrix, this means for all  $j \geq i$  holds  $a_{ij} = 0$  then the Runge-Kutta method is explicit, otherwise it is implicit. In general implicit Runge-Kutta methods might need more computational effort because to calculate  $y_m^{(i)}$  a nonlinear system of equations has to be solved. But in contrast those methods can also lead to very good stability characteristics.

**Lemma 2.** A Runge-Kutta method is consistent, if and only if

$$\sum_{i=1}^s b_i = 1$$

The coefficients of a Runge-Kutta method are usually represented in the *Butchertableau*, which was introduced by John C. Butcher and has the following form.

$$\begin{array}{c|ccc} c_1 & a_{11} & \dots & a_{1s} \\ \vdots & \vdots & & \vdots \\ c_s & a_{s1} & \dots & a_{ss} \\ \hline & b_1 & \dots & b_s \end{array} \quad \text{of in matrix form} \quad \begin{array}{c|c} c & A \\ \hline & b \end{array}$$

## 5.2 Multistep-Methods

based on chapter 4 of book num gew dgl steif nichtsteif

Linear multistep methods use approxiamtions  $u_{m+l}$  along the gridpoints  $t_{m+l}$ ,  $l = 0, 1, \dots, k-1$  to calculate the new approximation  $u_{m+k}$  at  $t_{m+k}$ . WE will first discuss topics related to the order of the methods depending on its parameters, stability and convergence.

**Definition 10.** For given  $\alpha_0, \dots, \alpha_k$  and  $\beta_0, \dots, \beta_k$  the iteration rule

$$\sum_{l=0}^k \alpha_l u_{m+l} = h \sum_{l=0}^k \beta_l f(t_{m+l}, u_{m+l}), \quad m = 0, 1, \dots, N-k \quad (5.9)$$

is called a linear multistep method (linear  $k$ -step method). It is always assumed that  $\alpha_k \neq 0$  and  $|\alpha_0| + |\beta_k| > 0$ . If  $\beta_k = 0$  holds, then the method is called explicit, otherwise implicit.

## 5 Numerical Solutions

Durch die Forderung  $|\alpha_0| + |\beta_0| > 0$  ist die Schrittzahl  $k$  eindeutig festgelegt. Im Falle  $\beta_k = 0$  lässt sich die Näherungsfolge  $\{u_{m+k}\}$ ,  $m = 0, 1, \dots, N - k$ , direkt berechnen. Die Verfahrensvorschrift (4.2.1) liefert demzufolge für jedes äquidistante Gitter  $I_h$  eine eindeutig bestimmte Gitterfunktion  $u_h(t)$ . Ist  $\beta_k \neq 0$ , so hat man zur Bestimmung von  $u_{m+k}$  ein i. Allg. nichtlineares Gleichungssystem der Form

$$u_{m+k} = h \frac{\beta_k}{\alpha_k} f(t_{m+k}, u_{m+k}) + v, \quad (4.2.2)$$

zu lösen, wobei der von  $u_{m+k}$  unabhängige Vektor  $v$  durch

$$v = \frac{1}{\alpha_k} \sum_{l=0}^{k-1} \left( h \beta_l f(t_{m+l}, u_{m+l}) - \alpha_l u_{m+l} \right)$$

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4 Lineare Mehrschrittverfahren

gegeben ist. Zur Lösung von (4.2.2) verwendet man für nichtsteife Systeme Funktionaliteration, d. h.

$$u_{m+k}^{(\varkappa+1)} = h \frac{\beta_k}{\alpha_k} f(t_{m+k}, u_{m+k}^{(\varkappa)}) + v, \quad \varkappa = 0, 1, \dots$$

Unter der Schrittweitereinschränkung

$$h \left| \frac{\beta_k}{\alpha_k} \right| L < 1, \quad (4.2.3)$$

wobei  $L$  eine Lipschitz-Konstante für  $f(t, y)$  darstellt, konvergiert die Folge  $\{u_{m+k}^{(\varkappa)}\}$  bei beliebig vorgegebenem Startvektor  $u_{m+k}^{(0)}$  gegen die eindeutige Lösung von (4.2.2). Für ein nichtsteifes Anfangswertproblem ist die Bedingung (4.2.3) an  $h$  keine wesentliche Einschränkung.

Ein lineares Mehrschrittverfahren setzt sich zusammen aus zwei Bestandteilen:

1. Der *Startphase* zur Berechnung der Näherungswerte  $u_1, \dots, u_{k-1}$  in den Gitterpunkten  $t_l = t_0 + lh$ ,  $l = 1, \dots, k - 1$ , die mit einem Einschrittverfahren, z. B. mit einem expliziten Runge-Kutta-Verfahren, oder mit Mehrschrittformeln niedriger Schrittzahlen und sehr kleinen Schrittweiten bestimmt werden können.
2. Der *Laufphase*, d. h. einer Mehrschrittformel (4.2.1) zur sukzessiven Berechnung der Approximationen  $u_{m+k}$  in den Gitterpunkten  $t_{m+k}$ .

**Figure 5.1:**

A linear multi-step method consists of two parts:

1. In the *starting-phase* approximations  $u_1, \dots, u_{k-1}$  for the first  $k - 1$  gridpoints  $t_l = t_0 + lh$ ,  $l = 1, \dots, k - 1$  are calculated using a single-step method. For example using an explicit Runge-Kutta Method or a multi-step method with fewer steps.

## 5 Numerical Solutions

2. In the *run-phase* the multi-step formula is used to determine new approximations  $u_{m+k}$  for the gridpoint  $t_{m+k}$

For theoretical analysis of the multi-step methods we consider the generating polynomials

$$\rho(x) := \sum_{l=0}^k \alpha_l x^l \quad (5.10)$$

$$\sigma(x) := \sum_{l=0}^k \beta_l x^l \quad (5.11)$$

Eine zentrale Rolle bei der theoretischen Untersuchung linearer **Mehrschrittverfahren** spielen die beiden *erzeugenden Polynome*

$$\begin{aligned} \rho(\xi) &:= \alpha_k \xi^k + \alpha_{k-1} \xi^{k-1} + \cdots + \alpha_0 \\ \sigma(\xi) &:= \beta_k \xi^k + \beta_{k-1} \xi^{k-1} + \cdots + \beta_0. \end{aligned}$$

Sie wurden erstmals von Dahlquist [79] zur Stabilitätsuntersuchung linearer **Mehrschrittverfahren** verwendet. Mit den erzeugenden Polynomen lassen sich die Konsistenzbedingungen (4.2.7) in der Form

$$\rho(1) = 0 \quad \text{und} \quad \rho'(1) = \sigma(1). \quad (4.2.11)$$

**Figure 5.2:**

### 5.2.1 Consistency and Convergence

local discretization error - def 4.2.2

**Definition 11.** Let  $\tilde{y}_{m+k}$  be the result of one step of the multi-step method 5.9 with the start-vectors  $y_m = y(t_m)$ . This means

$$\alpha_k \tilde{u}_{m+k} = \sum_{l=0}^{k-1} (h \beta_l f(t_{m+l}, y(t_{m+l})) - \alpha_l y(t_{m+l})) + h \beta_k f(t_{m+k}, \tilde{u}_{m+k}).$$



## 5 Numerical Solutions

Then

$$le_{m+k} = le(t_{m+k}) = y(t_{m+k}) - \tilde{u}_{m+k}, \quad m = 0, 1, \dots, N - k$$

is called the local discretization error (local error) of the linear multi-step method 5.9 at the point  $t_{m+k}$ .

We will assign the linear difference operator

$$L[y(t), h] = \sum_{l=0}^k (\alpha_l y(t + lh) - h\beta_l y'(t + lh)) \quad (5.12)$$

to the local discretization error. Using this we gain the following definition.

**Definition 12.** A linear multi-step method is called **preconsistent** if for all functions  $y(t) \in C^1[t_0, t_l]$

$$\lim_{h \rightarrow 0} L[y(t), h] = 0$$

holds. It is called **consistent**, if for all functions  $y(t) \in C^2[t_0, t_l]$

$$\lim_{h \rightarrow 0} \frac{1}{h} L[y(t), h] = 0$$

holds. It has the **consistency order p**, if for all functions  $y(t) \in C^{p+1}[t_0, t_l]$

$$L[y(t), h] = \mathcal{O}(h^{p+1}) \quad \text{for } h \rightarrow 0$$

holds.

### 5.2.2 Convergence and stability

## 5 Numerical Solutions

**Definition 13.** A linear multi-step method is called zero-stable if all solutions of the difference equation

$$\sum_{l=0}^k \alpha_l u_{m+l} = 0$$

are bounded.

**Theorem 5.** A linear multi-step method is zero-stable, if and only if the polynomial  $\rho(x)$  fulfills the root-condition, this means:

1. All roots  $\bar{x}$  of  $\rho(x)$  are within the unit-circle  $|\bar{x}| \leq 1$  in the complex plane.
2. All roots  $\bar{x}$  with  $|\bar{x}| = 1$  are singular.

from circuit book below, above from modelling book

### 5.3 Implicit linear multi-step formulas

These kinds of multi-step methods are conventionally used to numerically solve the systems obtained using modified nodal analysis.

The conventional approach can be split into three main steps:

1. Computation of consistent initial values
2. numerical integration based on multi-step schemes
3. transformation of the DAE into a nonlinear system and its numerical solution by Newton's procedure (????????????????will not be discussed further because not very specific)

**Consistent initial values**

## 5 Numerical Solutions

**Consistent initial values.** The first step in the transient analysis is to compute consistent initial values  $(x_0, y_0)$  for the initial time point  $t_0$ . In the index-1 case, this can be done by performing a steady state (DC operating point) analysis, i.e. to solve

$$\mathcal{F}(0, x_0, t_0) = 0 \quad (10.2)$$

for  $x_0$  and then set  $y_0 := g(x_0)$ . If there are no controlled sources, the Jacobian  $\partial\mathcal{F}/\partial x$  of (10.2) with respect to  $x_0$  reads

$$\frac{\partial\mathcal{F}}{\partial x} = \begin{pmatrix} \tilde{G}(A_R^\top u_0, t_0) & A_L & A_V \\ -A_L^\top & 0 & 0 \\ -A_V^\top & 0 & 0 \end{pmatrix}$$

with the definition  $\tilde{G}(A_R^\top u, t) := A_R G(A_R^\top u, t) A_R^\top$  already introduced in Section 4. Since  $\ker(\partial\mathcal{F}/\partial x) = \ker(A_R, A_L, A_V)^\top \times \ker(A_L, A_V)$  holds, the matrix is only regular, if there are neither loops of independent voltage sources and/or inductors, nor cutsets of independent current sources and/or capacitors. If these topological conditions are violated, no steady state solution can be computed, and so most circuit analysis programs check and refuse these circuit configurations. Additional assumptions are implied in the case of controlled sources. But note that in the nonlinear case the Jacobian matrix also may become numerically singular, e.g. due to vanishing partial derivatives or in the case of bifurcation.

An approach always feasible in the index-1 case is to extract the algebraic constraints using the projector  $Q_C$  onto  $\ker A_C^\top$ :

$$\begin{aligned} Q_C^\top(A_R r(A_R^\top u, t) + A_L j_L + A_V j_V + A_I i(u, j_L, j_V, t)) &= 0 \\ v(u, j_L, j_V, t) - A_V^\top u &= 0. \end{aligned}$$

If the index-1 topological conditions hold, this nonlinear system uniquely defines for  $t = t_0$  the algebraic components  $Q_C u_0$  and  $j_{V,0}$  for given (arbitrary) differential components  $(I - Q_C)u_0$  and  $j_{L,0}$ . The derivatives  $\dot{y}_0$  have then to be chosen such that  $A\dot{y}_0 + f(x_0, t_0) = 0$  holds.

**Figure 5.3:**

### Nunmerical integration.

#### 5.3.1 BDF-schemes and trapezoidal rule

chapter 9.2 numerik book

The most commonly used numerical methods for solving the systems that arrise in electrical circuits are the BDF-scheme and the trapezoidal rule.

## 5 Numerical Solutions

### BDF-schemes

$$\begin{aligned}
 k = 1 : \quad & hf_{m+1} = u_{m+1} - u_m \\
 k = 2 : \quad & hf_{m+2} = \frac{1}{2}(3u_{m+2} - 4u_{m+1} + u_m) \\
 k = 3 : \quad & hf_{m+3} = \frac{1}{6}(11u_{m+3} - 18u_{m+2} + 9u_{m+1} - 2u_m) \\
 k = 4 : \quad & hf_{m+4} = \frac{1}{12}(25u_{m+4} - 48u_{m+3} + 36u_{m+2} - 16u_{m+1} + 3u_m) \\
 k = 5 : \quad & hf_{m+5} = \frac{1}{60}(137u_{m+5} - 300u_{m+4} + 300u_{m+3} - 200u_{m+2} \\
 & \quad + 75u_{m+1} - 12u_m) \\
 k = 6 : \quad & hf_{m+6} = \frac{1}{60}(147u_{m+6} - 360u_{m+5} + 450u_{m+4} - 400u_{m+3} \\
 & \quad + 225u_{m+2} - 72u_{m+1} + 10u_m)
 \end{aligned} \tag{9.2.4}$$

Durch Einsetzen in die Konsistenzbedingungen (4.2.7) und (4.2.8) erhält man:

**Satz 9.2.1.** *Die BDF-Methoden (9.2.4) besitzen die Konsistenzordnung  $p = k$ . Die Fehlerkonstante ist gegeben durch*

$$C_{p+1}^* = -\frac{1}{k+1}. \quad \square$$

**Figure 5.4:**

## 5 Numerical Solutions

### trapezoidal Rule

#### 2.4.3 Explizite Runge-Kutta-Verfahren bis zur Ordnung vier

Ausgehend von den in der Tabelle 2.4.2 aufgeführten Konsistenzbedingungen wollen wir in diesem Abschnitt explizite RK-Verfahren mit minimaler Stufenzahl bis zur Ordnung  $p = 4$  herleiten. Dabei setzen wir voraus, dass die Knotenbedingung

$$c_i = \sum_{j=1}^{i-1} a_{ij}, \quad i = 1, \dots, s,$$

also insbesondere  $c_1 = 0$  gilt. Sie vereinfacht die Herleitung der Ordnungsbedingungen für Verfahren höherer Ordnungen. Das einzige einstufige explizite RK-Verfahren der Konsistenzordnung  $p = 1$  ist dann das explizite Euler-Verfahren. Zweistufige RK-Verfahren der Ordnung  $p = 2$  haben wir bereits in Beispiel 2.2.1 betrachtet. Sie sind durch das Parameterschema

$$\begin{array}{c|cc} 0 & & \\ c_2 & c_2 & \\ \hline & 1 - 1/(2c_2) & 1/(2c_2) \end{array}, \quad c_2 \neq 0$$

gekennzeichnet. Für den Knoten  $c_2 = 1/2$  erhält man das Verfahren von Runge (1895), das für ein Quadraturproblem in die Mittelpunkregel übergeht. Für  $c_2 =$

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2 Einschrittverfahren

1 bekommt man das Verfahren von Heun (1900), das für ein Quadraturproblem in die **Trapez**regel übergeht.

**Figure 5.5:**