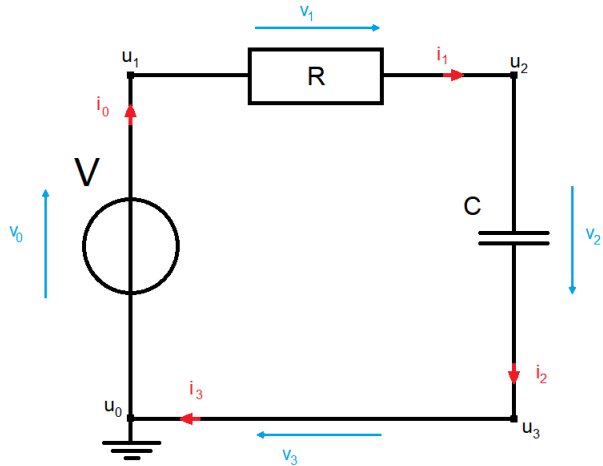


Circuit Modelling



Felix Dreßler

Example: Charging of a capacitor:



Formulating a Mathematical Model



Network Topology

For a circuit with l nodes and k edges, define the incidence matrix $\tilde{A} = (\tilde{a}_{ij}) \in \mathbb{R}^{k \times l}$:

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

By grounding node 0, i.e. $u_0 = 0$ we obtain the reduced incidence matrix $\rightarrow A$.

Formulating a Mathematical Model



Energy Conservation Laws

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

The sum of voltages along each loop of the network must equal to zero.

$$\rightarrow A^T u = v. \quad (1)$$

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




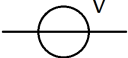
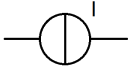
For any node, the sum of currents flowing into the node is equal to the sum of currents flowing out of the node.

$$\rightarrow A i = 0. \quad (2)$$

Formulating a Mathematical Model



Electrical Components and their Relations

Name	Symbol	Component Law
Resistor		$v = R i \quad \text{or} \quad i = G u$
Capacitor		$Q = C v \quad \text{and by derivation in t} \quad I = C \frac{d}{dt} v = C v'$
Inductor		$\Phi = L i \quad \text{and by derivation in t} \quad v = L i'$
Voltage Source		$v = v_{src}$
Current Source		$i = i_{src}$

Formulating a Mathematical Model



Modified Nodal Analysis - MNA

Rearrange reduced incidence matrix into

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

A_R , A_C , A_L , A_V and A_I ... columns related to components

Represent voltages:

$$v = A^T u$$

→ rearrange v into $v = (v_R, v_C, v_L, v_{src}, v_I)$ and i into $i = (i_R, i_C, i_L, i_V, i_{src})$. Rewrite component relations:

$$\begin{aligned} i_R &= G v_R = G A_R^T u, \\ i_C &= C v'_C = C A_C^T u'. \end{aligned}$$

Kirchhoffs current law:

$$A_C i_C + A_R i_R + A_L i_L + A_V i_V = -A_I i_{src}.$$

Kirchhoffs current law with component relations combine to

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

In matrix form:

$$\begin{pmatrix} A_C C A_C^\top & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & 0 \end{pmatrix} * \begin{pmatrix} u' \\ i_L' \\ i_V' \end{pmatrix} + \begin{pmatrix} A_R G A_R^\top & A_L & A_V \\ -A_L^\top & 0 & 0 \\ -A_V^\top & 0 & 0 \end{pmatrix} * \begin{pmatrix} u \\ i_L \\ i_V \end{pmatrix} = \begin{pmatrix} -A_I i_{src} \\ 0 \\ -v_{src} \end{pmatrix}. \quad (3)$$

→ differential and algebraic variables

Differential Algebraic Equations



Types of DAEs

In the most general form a DAE can be written as: Find $y : \mathbb{R} \rightarrow \mathbb{R}^n$ such that

$$F(t, y(t), y'(t)) = 0, \quad \forall t \in I \quad (4)$$

with $F : \mathbb{R} \times \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}^n$ sufficiently smooth and I the time-interval.

Linear systems with constant coefficients

find y such that

$$Ay'(t) + By(t) = f(t), \quad (5)$$

with $A, B \in \mathbb{R}^{n \times n}$, A singular, B regular and $f : \mathbb{R} \rightarrow \mathbb{R}^n$ a function in time. \rightarrow
differential and algebraic variables

Differential Algebraic Equations



Weierstrass-Kronecker normalform

Definition

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

Equivalence transformations lead to

$$\begin{aligned} u'(t) + Ru(t) &= s(t), \\ Nv'(t) + v(t) &= q(t), \end{aligned} \tag{6}$$

where N is a nilpotent matrix and the matrix R is regular.

First equation is an ODE \rightarrow unique solution $u(t)$ for any initial values. Construct explicit solution for second equation: $q(t) \in C^{k-1}([t_0, t_1])$:

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

\rightarrow differentiation index $v = k$.

Differential Algebraic Equations



Index of a Differential Algebraic Equation

Definition

Consider the differential algebraic equation (4) to be uniquely solvable and F sufficiently smooth. For a given $m \in \mathbb{N}$ consider the equations

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

The smallest natural number m for which the above system results in an explicit system of ordinary differential equations (ODEs), i.e. it has the form

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

Index Analysis of the Modified Nodal Analysis



Topological Conditions

- The resulting equations have index $\nu \leq 2$, if the circuit neither contains loops of only voltage sources nor cutsets of only current sources.
- They have index $\nu \leq 1$, if the circuit contains neither loops of capacitors and/or voltage sources nor cutsets of inductors and/or current sources.
- They have index $\nu = 0$, if every node in the circuit is connected to the reference node (ground) through a path containing only capacitors.

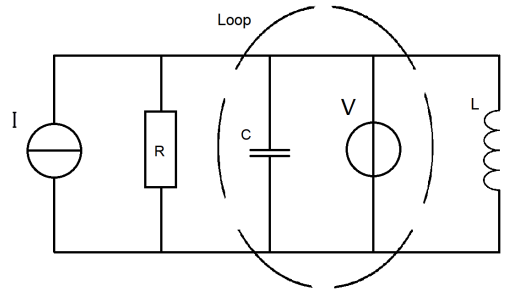
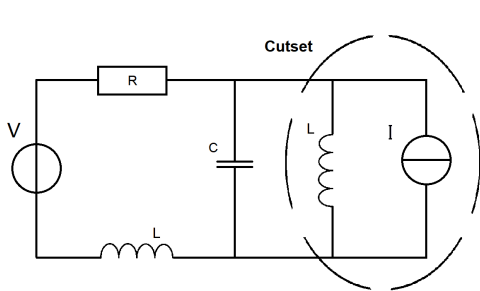


Figure: Illustration of a cutset and a loop.

Theorem (Index conditions)

Let the matrices of the capacitances, inductances and resistances be positive definite.

- If

$$\ker([A_R, A_C, A_V, A_L]^T) = \{0\} \quad \text{and} \quad \ker(A_V) = \{0\} \quad (7)$$

holds, then the MNA (3) leads to a system with index $\nu \leq 2$.

- If additionally

$$\ker([A_R, A_C, A_V]^T) = \{0\} \quad \text{and} \quad \ker([A_C, A_V]) = \{0\} \quad (8)$$

holds, then the system is of index $\nu \leq 1$

- If further

$$\ker(A_C^T) = \{0\} \quad \text{and} \quad \dim(v_{src}) = 0 \quad (9)$$

holds, then the system has index $\nu = 0$.

Numerical Solutions



Multistep Methods

Definition (Multistep method)

For given $\alpha_0, \dots, \alpha_k$ and β_0, \dots, β_k the iteration rule

$$\sum_{l=0}^k \alpha_l y_{m+l} = h \sum_{l=0}^k \beta_l f(t_{m+l}, y_{m+l}), \quad m = 0, 1, \dots, N - k \quad (10)$$

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.

Definition (generating polynomials)

$$\rho(x) := \sum_{l=0}^k \alpha_l x^l \quad \text{and} \quad \sigma(x) := \sum_{l=0}^k \beta_l x^l$$

Definition (Convergence order)

We say that a linear multi-step method is convergent of order $p \in \mathbb{N}$, if for a solution y of the problem and a vector $(y_j)_{j=0}^k$ created by an LMSM, we have that

$$\max_{0 \leq j \leq k} \|y(t_j) - y_j\| \leq Ch^p.$$

Where C is a constant not dependent on the step size h .

Definition (Consistency order)

A linear multi-step method is called *consistent with order p* , if for all functions $y(t) \in C^{p+1}[t_0, t_1]$

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

holds.

Numerical Solutions



Multistep Methods
Stability properties

Definition

1. The set

$$S := \{z \in \mathbb{C} : \rho(\xi) - z\sigma(\xi) = 0 \implies \xi \in \mathbb{C} \text{ and } |\xi| \leq 1. \\ \text{If } \xi \text{ has multiplicity greater than 1, then } |\xi| < 1\} \quad (11)$$

is called the region of stability of the method.

2. A linear multistep method is called

- *0-stable*, if $0 \in S$.
- *stable* in the point $z \in \mathbb{C}$, if $z \in S$.
- *$A(\alpha)$ -stable*, if it is stable in all z that lie within the set $\{z \in \mathbb{C}^- : |\arg(z) - \pi| \leq \alpha\}$ for $\alpha \in (0, \frac{\pi}{2})$.

Theorem

Let $f(t, y)$ be sufficiently smooth and the linear multi-step method be zero-stable and consistent of order p , then it is also convergent of order p .

Numerical Solutions



Consistent Initial Values

Index $\nu = 0$: no additional restrictions (ODE case).

Index $\nu = 1$:

Rewrite system into the form

$$\begin{aligned}y'(t) &= f(t, y(t), z(t)), \\ 0 &= g(t, y(t), z(t)).\end{aligned}$$

Conditions for consistent initial values $\rightarrow g(t_0, y_0, z_0) = 0$.

Index $\nu = 2$:

Rewrite system into the form

$$\begin{aligned}y' &= f(t, y(t), z(t)), \\ 0 &= g(t, y(t)).\end{aligned}$$

Conditions for consistent initial values

$$\begin{aligned}g(t_0, y_0) &= 0, \\ g_t(t_0, y_0) + g_y(t_0, y_0)f(t_0, y_0, z_0) &= 0.\end{aligned}\quad \text{(hidden constraint)}$$

Numerical Solutions



Implicit Linear Multistep Formulas
BDF-k Methods

The *backward differentiation formula (BDF)* is a family of implicit linear multistep methods.

$$\sum_{k=0}^s \alpha_k y_{n+k} = h\beta f(t_{n+s}, y_{n+s})$$

The BDF or BDF-k formulas for $k = 1, \dots, 3$ have the following form

$$k = 1 : hf_{m+1} = y_{m+1} - y_m \quad (\text{implicit euler})$$

$$k = 2 : hf_{m+2} = \frac{1}{2}(3y_{m+2} - 4y_{m+1} + y_m)$$

$$k = 3 : hf_{m+3} = \frac{1}{6}(11y_{m+3} - 18y_{m+2} + 9y_{m+1} - 2y_m)$$

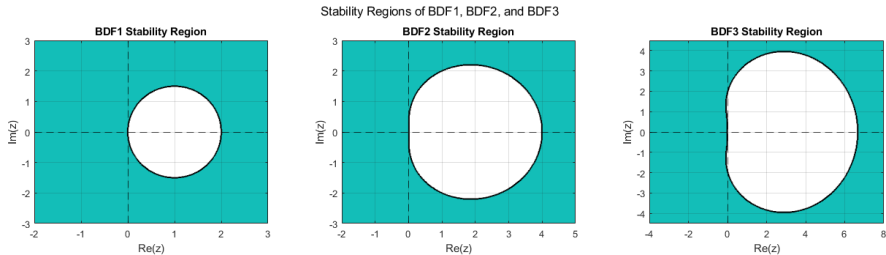


Figure: stability regions of BDF-schemes

Theorem

The BDF- k methods have consistency order $p = k$.

Corollary (Convergence rate)

The BDF- k methods with $k \leq 6$ are convergent with order k .

Numerical Solutions



Implicit Linear Multistep Formulas

Trapezoidal rule

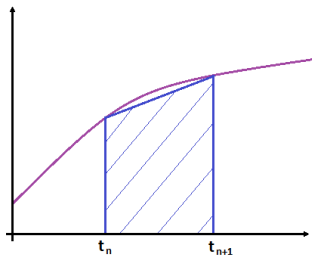


Figure: illustration of the trapezoidal rule

This procedure is repeated for small subsections of the interval $[a, b]$. Thus we obtain the iteration formula

$$y_{n+1} = y_n + \frac{h}{2}[f(t_n, y_n) + f(t_{n+1}, y_{n+1})].$$

The trapezoidal rule has convergence order $p = 2$.

Numerical Solutions



Numerical Examples

Example1

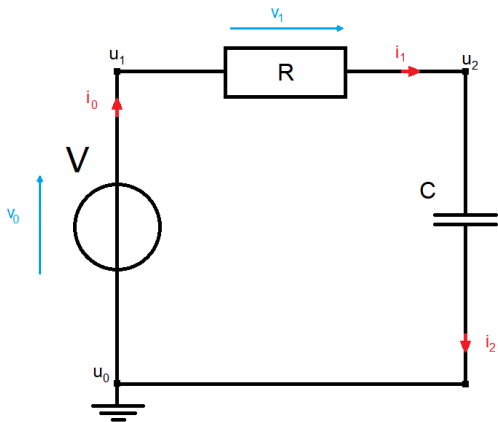


Figure: charging capacitor with series resistor and voltage source

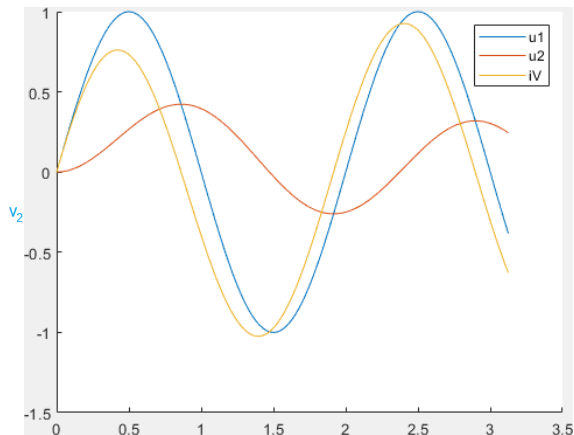


Figure: Exact solution for example 1.

h	k = 1		k = 2		k = 3		trapezoidal	
	err(u ₂)	err(i _V)	err(u ₂)	err(i _V)	err(u ₂)	err(i _V)	err(u ₂)	err(i _V)
0.1	4.620×10^{-2}	4.620×10^{-2}	9.567×10^{-3}	9.567×10^{-3}	2.852×10^{-3}	2.852×10^{-3}	3.344×10^{-3}	3.344×10^{-3}
0.05	2.339×10^{-2}	2.339×10^{-2}	2.454×10^{-3}	2.454×10^{-3}	3.645×10^{-4}	3.645×10^{-4}	8.367×10^{-4}	8.367×10^{-4}
0.025	1.178×10^{-2}	1.178×10^{-2}	6.264×10^{-4}	6.264×10^{-4}	4.928×10^{-5}	4.928×10^{-5}	2.092×10^{-4}	2.092×10^{-4}

Table: Resulting errors for the BDF-k methods and the trapezoidal rule.

Numerical Solutions



Numerical Examples
Gauss

$$y_{n+1} = y_n + hf(t_n + \frac{h}{2}, \frac{y_n + y_{n+1}}{2})$$

number of stages s	index $\nu = 1$		index $\nu = 2$	
	differential	algebraic	differential	algebraic
even		$s + 1$	$s + 1$	$s - 1$
odd	$2s$	s	s	$s - 2$

Table: Convergence order for Gauss method.

h	example 1			example 2		example 3	
	err(u ₁) (alg)	err(u ₂) (diff)	err(i ₀) (alg)	err(u ₁) (diff)	err(i _L) (diff)	err(u ₁) (diff)	err(i _V) (alg)
0.1	6.257×10^{-1}	1.041×10^{-1}	6.154×10^{-1}	6.589×10^{-3}	7.885×10^{-3}	6.257×10^{-1}	1.251×10^3
0.05	3.138×10^{-1}	5.181×10^{-2}	3.081×10^{-1}	1.649×10^{-3}	1.974×10^{-3}	3.138×10^{-1}	2.511×10^3
0.025	1.570×10^{-1}	2.578×10^{-2}	1.547×10^{-1}	4.123×10^{-4}	4.936×10^{-4}	1.570×10^{-1}	5.025×10^3

Table: Resulting errors for the Gauss method with one stage.

Definition

Let $y(t)$ be the exact solution of (4) and $\tilde{y}(t)$ be the solution of the perturbed system $F(t, \tilde{y}, \tilde{y}') = \delta(t)$. The smallest number $k \in \mathbb{N}$ such that

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

for all $\tilde{y}(t)$, is called the **perturbation index** of this system.

Dahlquist test problem as a model problem, find y such that

$$y' = \lambda y, \quad t > 0 \quad (12)$$

$$y(0) = y_0 \quad (13)$$

with $\lambda \in \mathbb{C}$ and y_0 fixed.

Thus the resulting linear multistep method is of the form

$$\begin{aligned} \sum_{l=0}^k \alpha_l y_{n+l} &= h \sum_{l=0}^k \beta_l \lambda y_{n+l} \\ \Leftrightarrow \sum_{l=0}^k [\alpha_l - h\beta_l \lambda] y_{n+l} &= 0 \end{aligned}$$

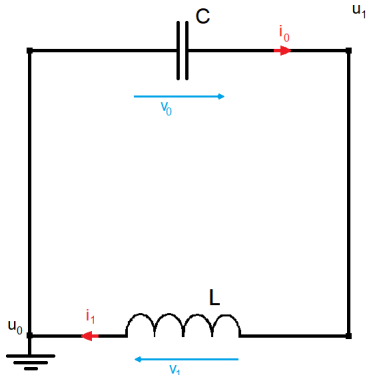


Figure: LC-circuit

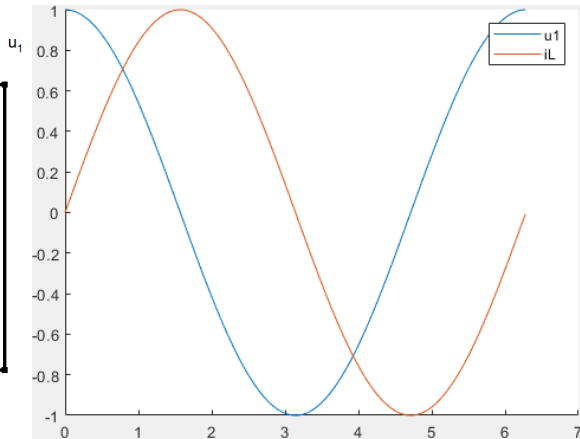


Figure: Exact solution for example 2.

$$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} * \begin{pmatrix} u_1' \\ i_L' \end{pmatrix} + \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} * \begin{pmatrix} u_1 \\ i_L \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}.$$

h	k = 1		k = 2		k = 3		trapezoidal	
	err(u ₁)	err(i _l)	err(u ₁)	err(i _l)	err(u ₁)	err(i _l)	err(u ₁)	err(i _l)
0.1	2.659×10 ⁻¹	2.106×10 ⁻¹	1.686×10 ⁻²	1.917×10 ⁻²	1.286×10 ⁻³	1.042×10 ⁻³	4.007×10 ⁻³	5.140×10 ⁻³
0.05	1.446×10 ⁻¹	1.125×10 ⁻¹	4.266×10 ⁻³	5.067×10 ⁻³	1.501×10 ⁻⁴	1.131×10 ⁻⁴	1.003×10 ⁻³	1.301×10 ⁻³
0.025	7.543×10 ⁻²	5.817×10 ⁻²	1.070×10 ⁻³	1.294×10 ⁻³	1.460×10 ⁻⁵	9.674×10 ⁻⁶	2.507×10 ⁻⁴	3.268×10 ⁻⁴

Table: Resulting errors for the BDF-k methods and the trapezoidal rule.

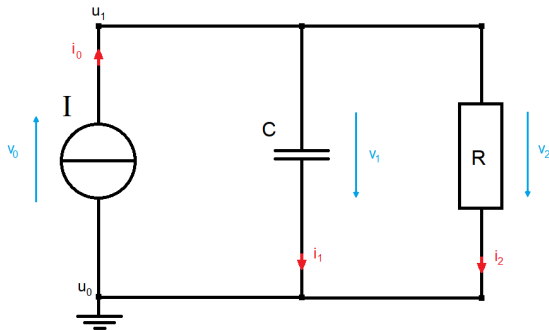


Figure: Current source with capacitor and resistor.

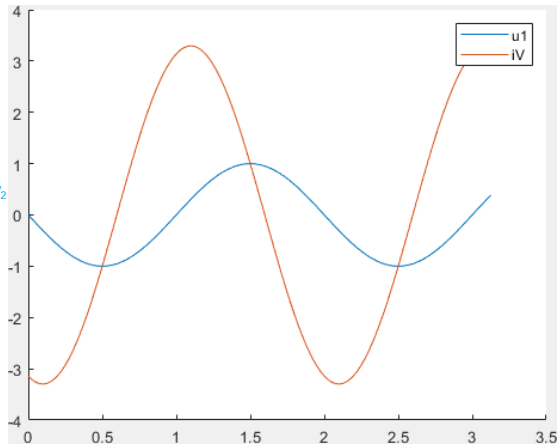


Figure: Exact solution for example 3.

$$\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} * \begin{pmatrix} u_1' \\ i_V' \end{pmatrix} + \begin{pmatrix} 1 & -1 \\ 1 & 0 \end{pmatrix} * \begin{pmatrix} u_1 \\ i_V \end{pmatrix} = \begin{pmatrix} 0 \\ -\sin(\pi t) \end{pmatrix}.$$

h	k = 1 err(i_V)	k = 2 err(i_V)	k = 3 err(i_V)	trapezoidal err(i_V)
0.1	4.894×10^{-1}	1.023×10^{-1}	2.403×10^{-2}	5.219×10^{-2}
0.05	2.462×10^{-1}	2.577×10^{-2}	3.034×10^{-3}	1.295×10^{-2}
0.025	1.233×10^{-1}	6.456×10^{-3}	4.029×10^{-4}	3.232×10^{-3}

Table: Resulting errors for the BDF-k methods and the trapezoidal rule.