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Derivative-Free Coolant Flow Distribution Solver for Thermal Management Systems

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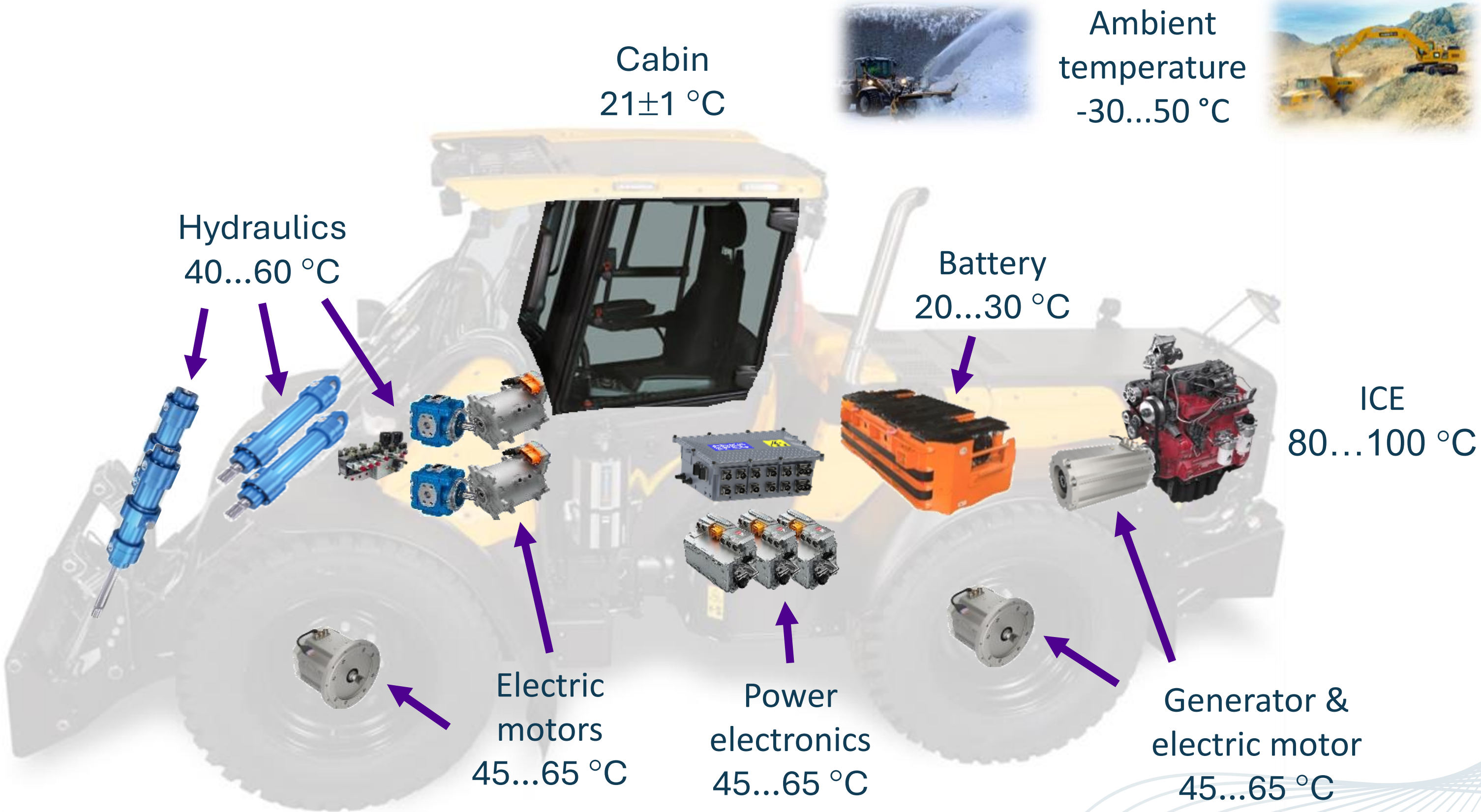
Thermal management in hybrid NRMM

- Components with distinct operating temperatures
- Thermal losses depend on load cycle
- Variable ambient conditions
- Thermal management affects efficiency, performance, and lifetime



Diesel-electric hybrid sWille prototype

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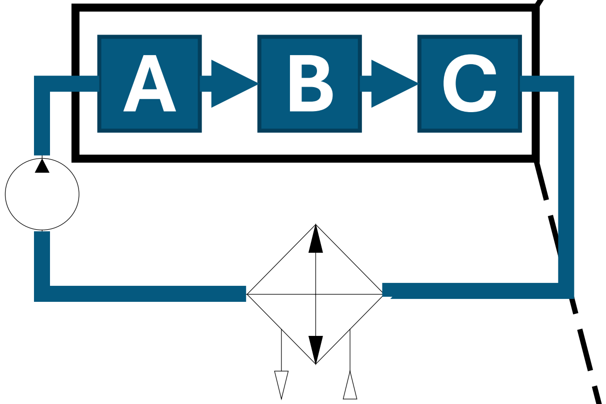
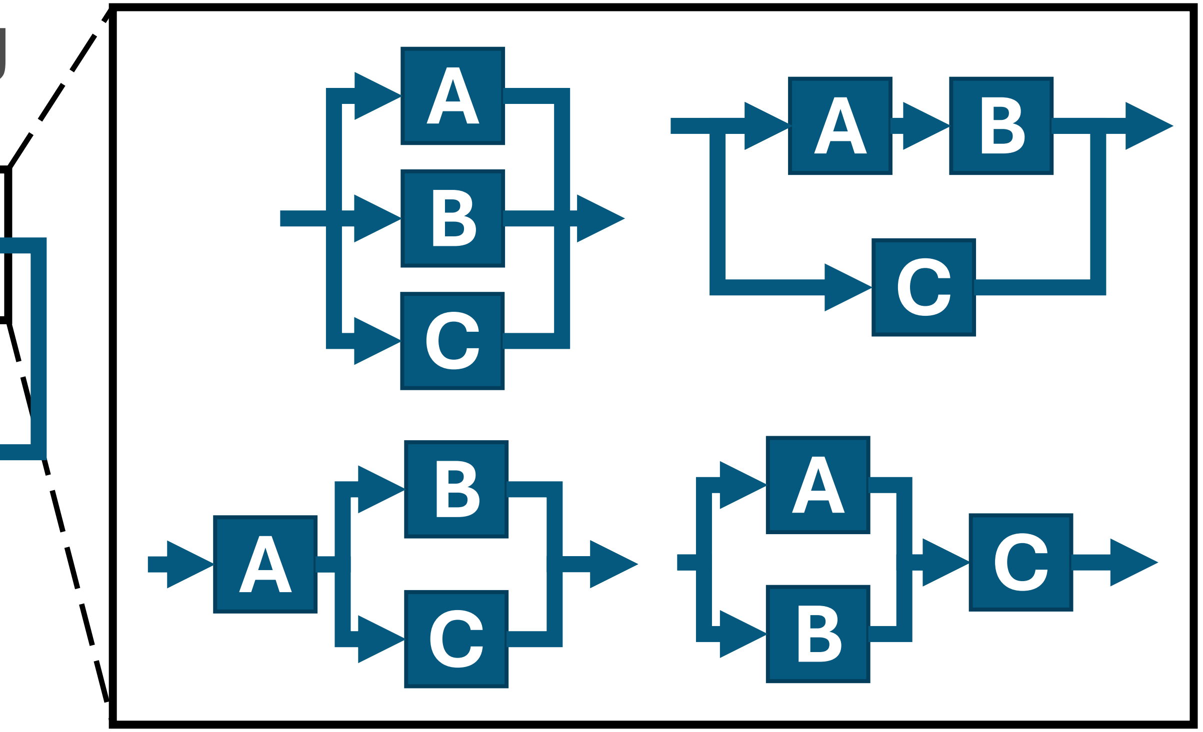
Configuration optimization

Consider single-circuit liquid cooling

- 3 components:
  - ➢ 19 valid configurations
- 11 components:
  - ➢ 10^{14} valid configurations



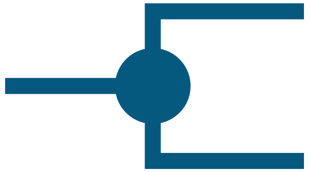


➢ Configuration optimization for thermal management systems

➢ Requires a fast coolant flow distribution solver

Steady-state coolant flow distribution

Node:



Edge:

Inputs

System configuration

Prescribed pump flow Q_{in}

Edge pressure drop $\Delta p_j(Q_j)$

→ **Flow distribution solver** →

Outputs

Edge flow rates Q_j

Node pressures p_i

Assumptions

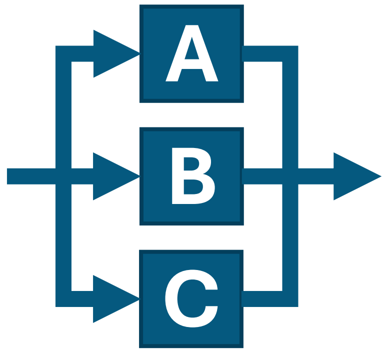
Monotone edge pressure drop functions

Series-parallel network structure

Constant fluid properties

Solving for total flow coefficient $K_{v,tot}$

Flow through turbulent orifice: $Q = K_v\sqrt{\Delta p}$



- Parallel connections:

$$K_{v,tot} = K_{v,A} + K_{v,B} + K_{v,C}$$

- Series connections:

$$\frac{1}{K_{v,tot}^2} = \frac{1}{K_{v,A}^2} + \frac{1}{K_{v,B}^2} + \frac{1}{K_{v,C}^2}$$

- Equivalent flow coefficient $K_{v,tot}$ is recursively determined for any series-parallel configuration

K_v method

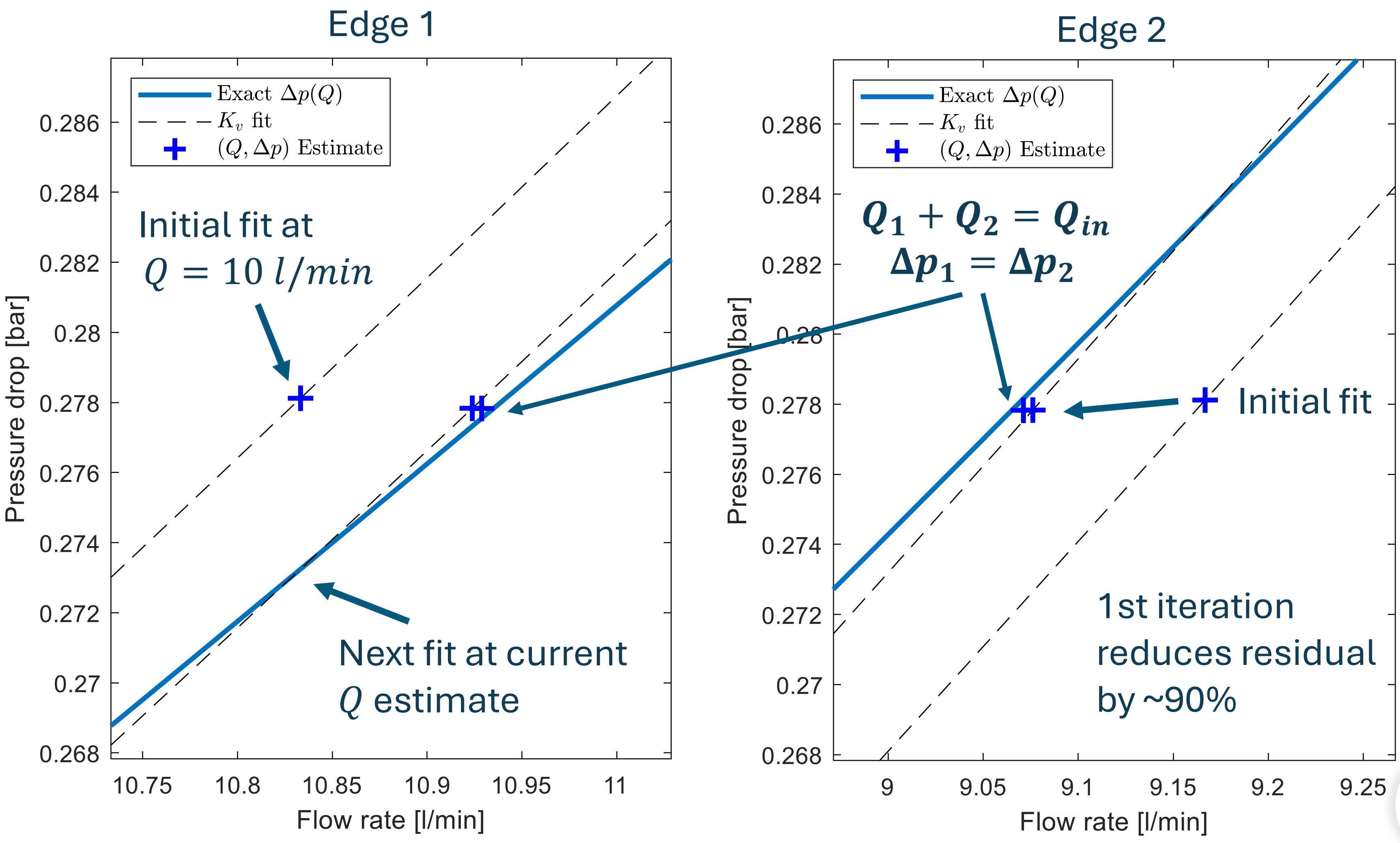
- Derivative-free, iterative flow distribution solver
- Starting from the pump outlet, for each node do:
  1. Compute $K_{v,i}$ at estimate Q_i for each leaving edge
  2. Determine the effective flow coefficient $K_{v,tot}$
  3. Compute the common pressure drop Δp_{tot}
  4. Compute the flow rate in each edge Q_i
- Stop when residual $||F||_2 < \text{tolerance}$

$$K_{v,i} = \frac{Q_i}{\sqrt{\Delta p_i(Q_i)}}$$

$$\Delta p_{tot} = \left(\frac{Q_{in}}{K_{v,tot}}\right)^2$$

$$Q_i = K_{v,i}\sqrt{\Delta p_{tot}} = \frac{K_{v,i}}{K_{v.tot}} Q_{in}$$

Illustration of the K_v method



Two parallel edges
$Q_{in} = 20\ l/min$

Initial guess
$Q_1(0) = Q_2(0) = 10\ l/min$

Exact solution of the fitted K_v network at each iteration

Newton-based method as reference

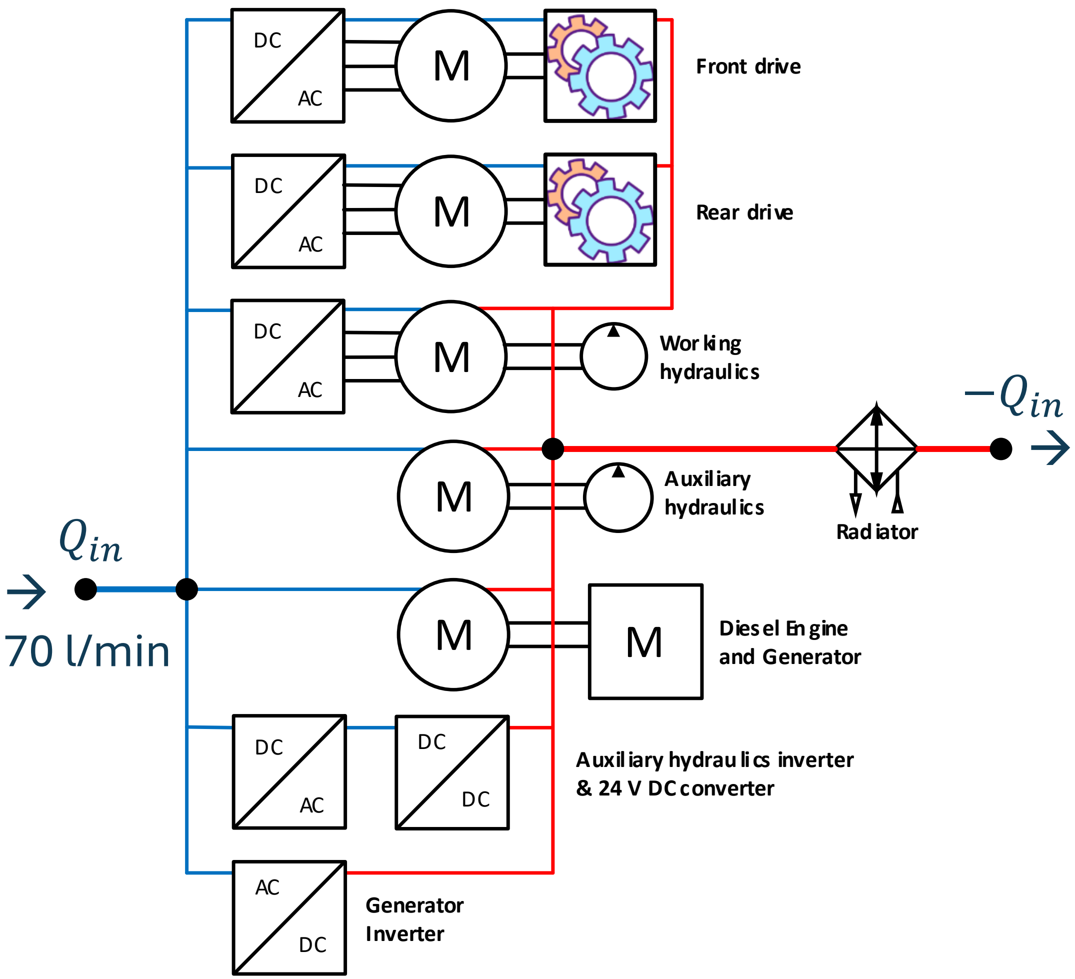
- Common in industry-standard water network solvers
- Root-finding algorithm for the system of nonlinear equations

$$F(p,Q) = \begin{bmatrix} AQ - Q_{in} \\ A^T p - \Delta p(Q) \end{bmatrix}$$

← Flow continuity at nodes
← Pressure balance between edges

- Newton step $x_{k+1} = x_k - J(x_k)^{-1} F(x_k)$
- **Derivatives** of the pressure drop functions in each edge are needed
- Jacobian is a block-matrix with diagonal dominance → yields convergence

sWille cooling circuit



- Seven parallel edges connected in series with supply and return
  - **9 edges, 4 nodes**
- Edge flow rates, node pressures are solved → **12 variables**
- Outlet node as reference, $p_4 = 0$

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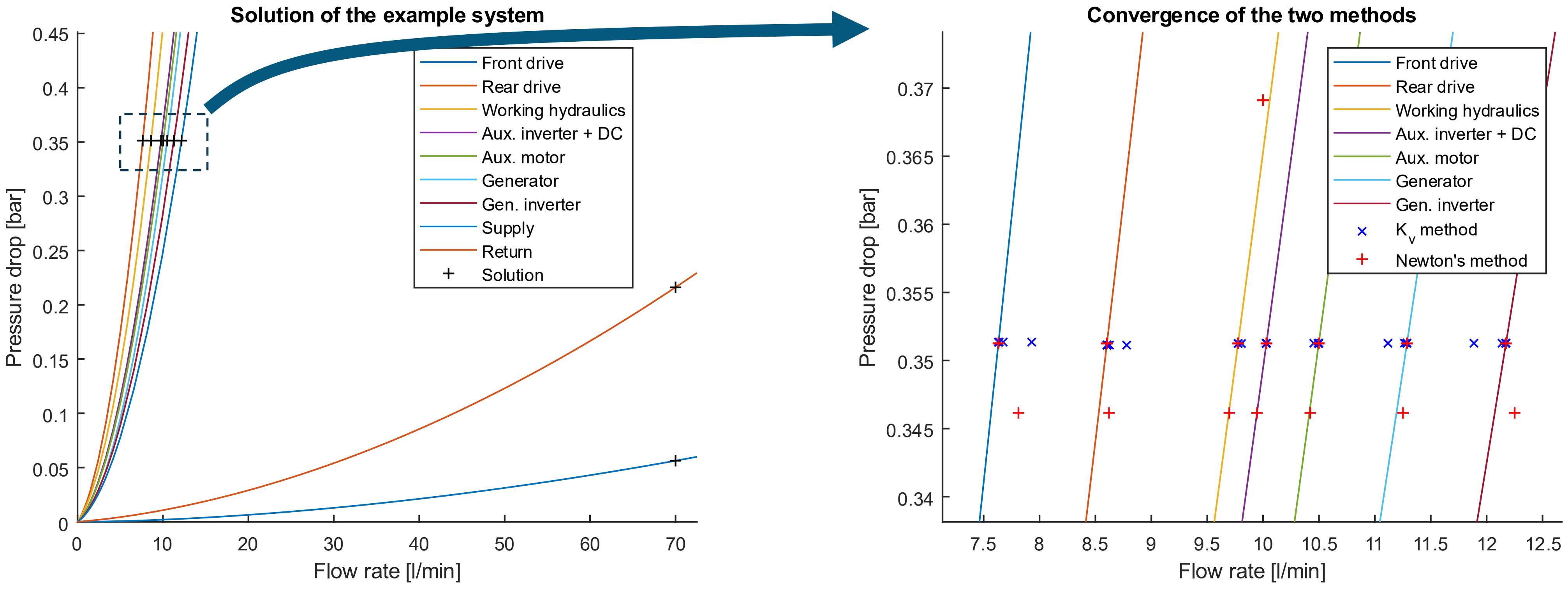
Solution of the sWille cooling circuit

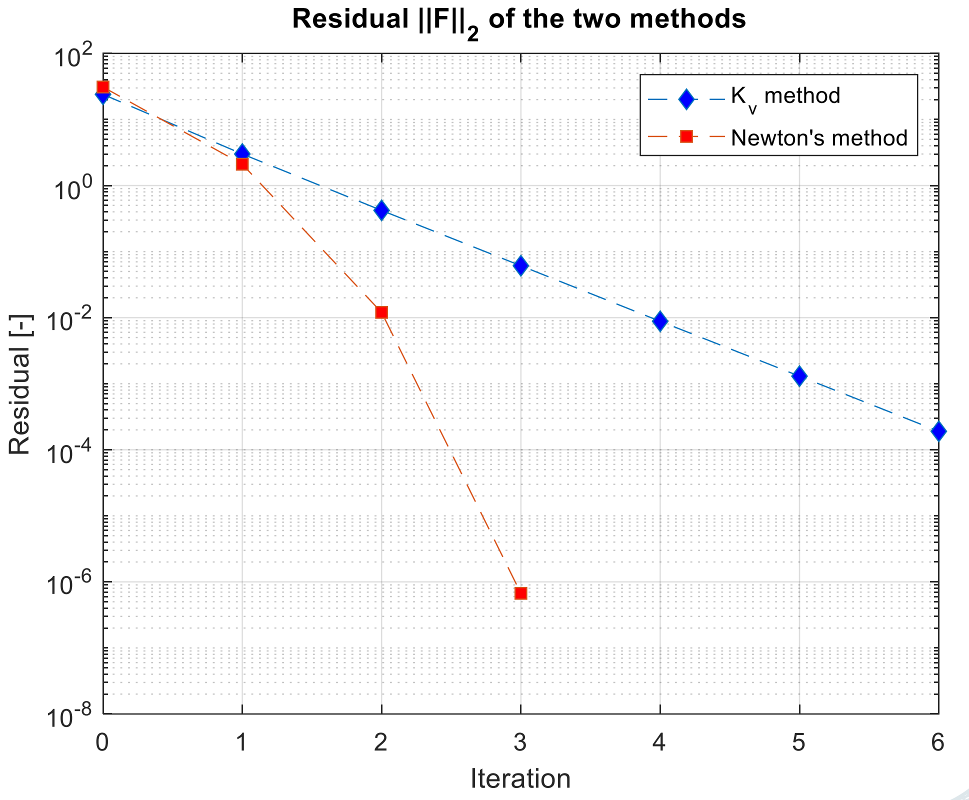


- Equal pressure drop in parallel edges
- Equal flow rate in series connections

Computational results

$$F(p,Q) = \begin{bmatrix} AQ - Q_{in} \\ A^T p - \Delta p(Q) \end{bmatrix}$$

- K_v method solves the system **8.6x faster**
- Newton takes fewer iterations
- Convergence speed increases at each iteration
- K_v method reduces the residual by approx. one order of magnitude per iteration



Average execution time and required iterations

Method	t [ms]	n	Speed-up factor
Newton	1.6	3	-
K_v method	0.21	6	**8.6**

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Conclusions

- Derivative-free method to solve flow distribution in series-parallel networks
- K_v method rapidly solves the flow distribution in liquid cooling systems
- Step towards system-level configuration optimization algorithms for thermal management systems

Thank You!

Save the date: 1-3 June 2027, Location: Tampere, Finland

https://events.tuni.fi/sicfp2027/

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