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Scaling Laws of Fully Superconducting H-Bridge Converter

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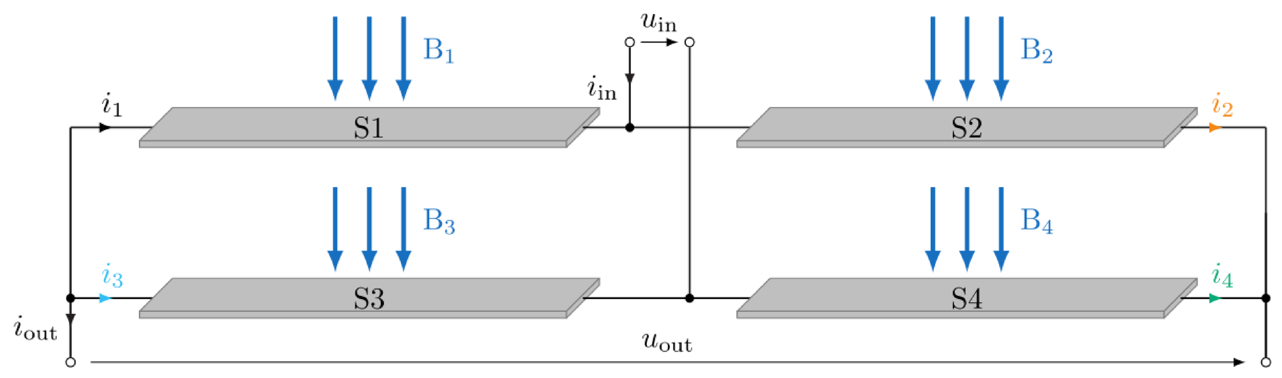
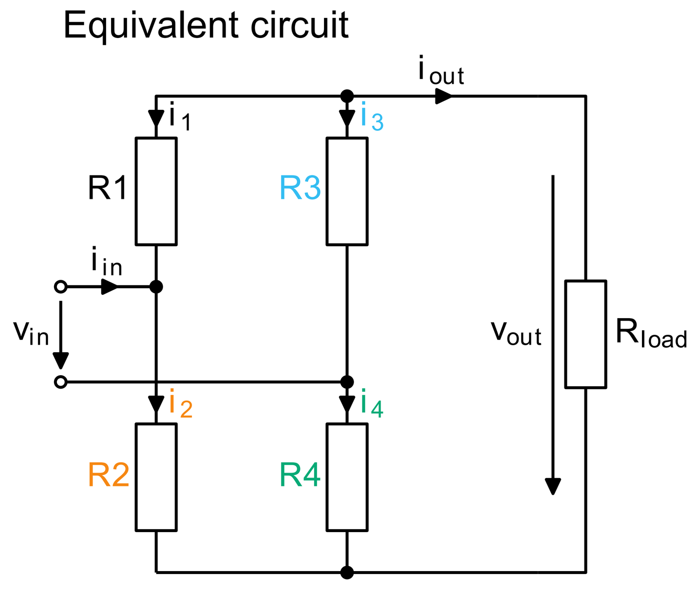
Introduction

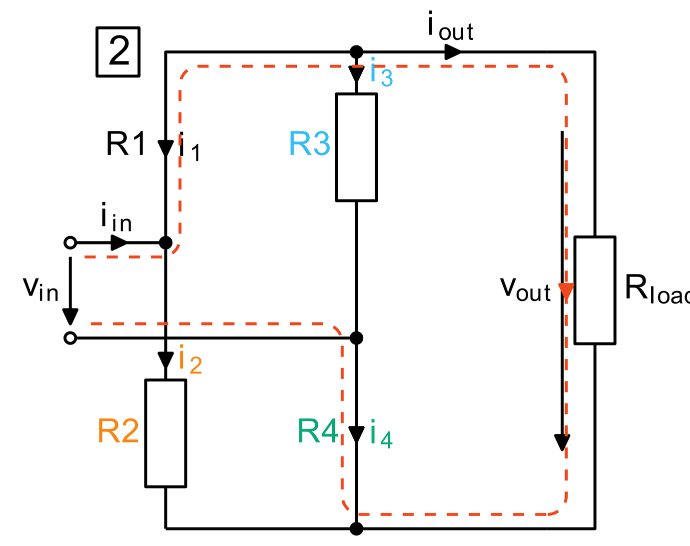
Schematic of bridge rectifier with superconducting switches



Equivalent circuit



Switching pattern for positive half wave



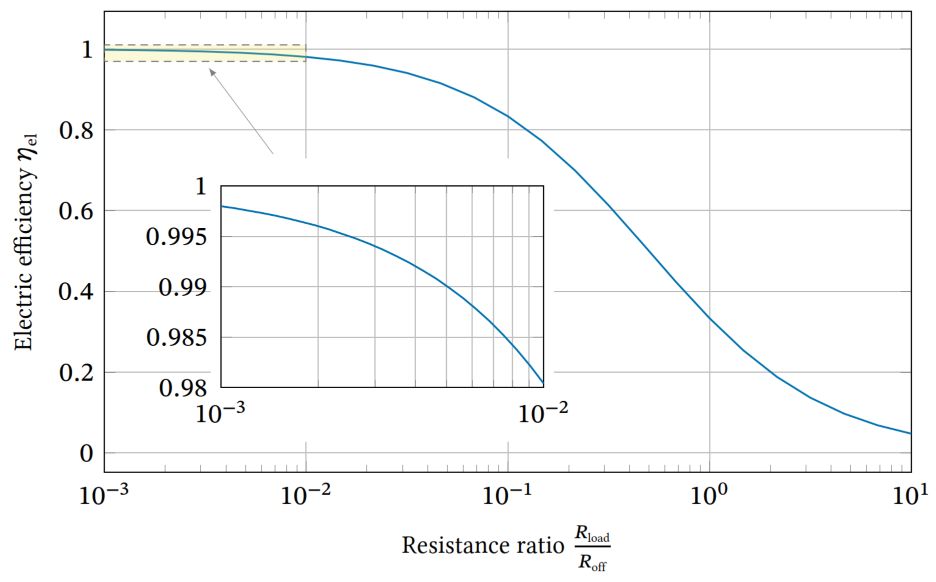
- Fast superconducting switching units based on dynamic resistance
- Multiple switching units combined into a fully superconducting power inverter
- **Objective**: Estimation of conductor lengths for a fully superconducting inverter based on dynamic resistance measurement data

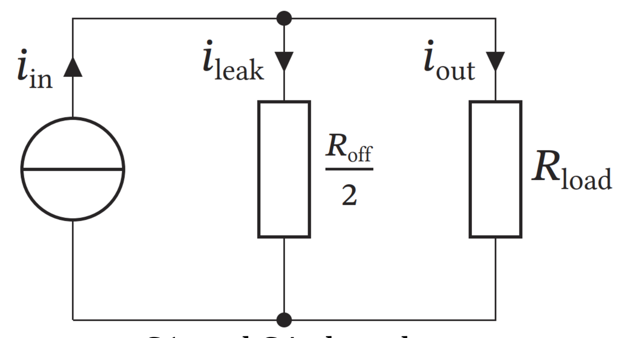
Model and Scaling Laws

Efficiency

since the resistance in on-state is zero, no voltage drop occurs across the switch and the output voltage is equal to the input voltage.

$$\eta_{el} = \frac{P_{out}}{P_{in}} = \frac{v_{out} \cdot i_{out}}{v_{in} \cdot i_{in}} = \frac{i_{out}}{i_{in}} = \frac{1}{1 + \frac{2R_{load}}{R_{off}}}$$

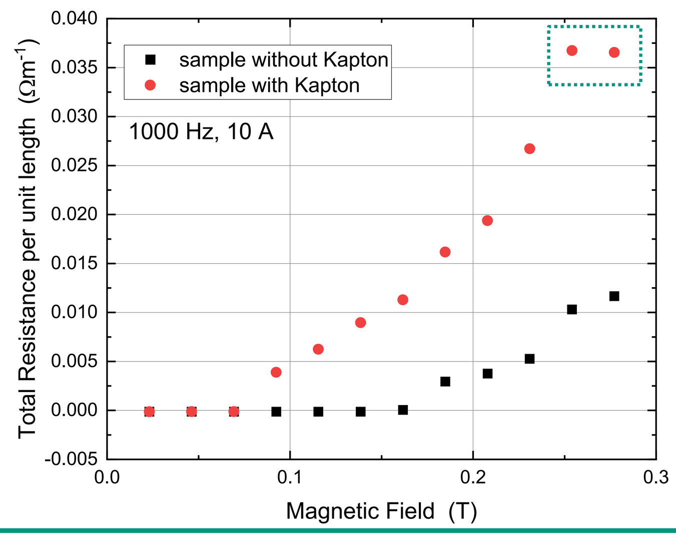




S1 and S4 closed

$R2 = R3 = R_{off}$

Dynamic resistance



Leakage Current / Voltage

is dependent on the off-state resistance R_{off} and the load resistance R_{load}

$$i_{leak} = \frac{2R_{load}}{R_{off}} i_{out}$$

Example: $i_{leak} = 0.01 i_{out}$, $v_{out} = 10\,\text{V}$, $i_{out} = 10\,\text{kA}$

$$R_{load} = \frac{10\,\text{V}}{10\,\text{kA}} = 1\,\text{m}\Omega \qquad R_{off} = \frac{2R_{load}}{0.01} = 0.2\,\Omega$$

$$R_{off,tape} = 16 \times R_{off} = 3.2\,\Omega \qquad l_{tape} = \frac{R_{off,tape}}{R_{tot}}$$

Datasheet	Fujikura
Width	12 mm
Ic	880 A
Substrate	Hastelloy C276, 38 μm ± 3 μm
Silver	2 μm top / 1 μm bottom
Sc	2.8 μm

Demonstrator Design and Optimization

Objective: Design of a fully superconducting H-bridge inverter with an output voltage 10 V and a current of 10 kA.

Step 1
Current capacity
Determines number of parallel HTS tapes.

$$I_t = 0.8 \times 800\,\text{A}$$
$$N_{pt} = \frac{i_{out}}{\gamma I_c} = \frac{10\,\text{kA}}{0.8 \times 800\,\text{A}}$$

16 parallel tapes

Step 2
Output voltage / Leakage current
Determines minimum off-state resistance.

$$i_{leak} = 0.01\, i_{out}$$
$$R_{load} = \frac{\mathbf{10\,V}}{10\,\text{kA}} = 1\,\text{m}\Omega$$
$$R_{off} = 2R_{load}\frac{i_{out}}{i_{leak}}$$
$$\mathbf{R_{off,min} = 0.2\,\Omega}$$
$$\mathbf{R_{off,tape} = 16 \times 0.2\,\Omega = 3.2\,\Omega}$$

Step 3
Tape length of one switch
In active magnetic field

$$R_{tot} = 35\,\text{m}\Omega\text{m}^{-1}$$
(at 1000 Hz / 207 mT)
$$l_{tape} = \frac{3.2\,\Omega}{0.035\,\Omega\text{m}^{-1}} = 91.43\,\text{m}$$

16 x 91.43 m = 1.45 km

Step 4
Tape length of the whole circuit
4 switches and interconnection (additional 10 %)

6.3 km

Parameter	HTS tape (old)	HTS tape	HTS tape
Width (mm)	12	12	**48**
Critical current (A)	338	**800**	**3200**
Off-state resistance (mΩm^{-1}) (measured)	119.8	**35**	**35**
Number of parallel tapes per switch	37	16	4
Sc length per switch (m)	2300	1448	90.5
Total length (km)	10.1	**6.3**	**0.398**

- For a 10 V / 10 kA demonstrator with a state of the art superconductor a total of 6.3 km of superconducting tape is needed
- Less parallel strands are needed to meet the design current capacity
- 40 % reduction in tape length compared to a superconductor with ~0.5 Ic
- Further optimization:
  - Prospect width of 40 mm to 120 mm from various manufacturers
    - Higher critical current, therefore less parallel tapes
    - Same dynamic resistance

Conclusion and Outlook

- Upscaling of a superconducting inverter based on experiments and measurements towards an output of 10 V and 10 kA.
- The required conductor lengths depend heavily on the critical current of the superconductor. State-of-the-art conductors require lengths of 6.3 km.
- The use of wider superconductors significantly reduces the length of the superconductor in the magnetic field by 90%.
- Experimental investigation of wide superconductors is necessary in order to build a larger demonstrator.