HYPERRIDE
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Hybrid Provision of Energy based on Reliability and Resiliency by Integration of Dc Equipment

Work Package WP3

Hybrid grid enabling solutions

Deliverable D3.7

Microgrid MV DCCB 5 kV prototype (designed and laboratory tested)

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28/07/2021	v1.4	Gerhard Jambrich (AIT)	final version

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

DCCB	Direct Current Circuit Breaker
MOV	Metal Oxide Varistor
MV	Medium Voltage
MVDC	Medium Voltage Direct Current
TIV	Transient Interruption Voltage
TO	Test Object
VARC	Voltage source converter Assisted Resonant Current
VI	Vacuum Interrupter
VSC	Voltage Source Converter

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Executive Summary

Deliverable D3.7 of the HYPERRIDE project is a demonstration and laboratory testing of a 5 kV DC circuit breaker prototype. This report records the work done in order to achieve this goal.

The requirements on the prototype's current interruption capabilities are outlined in another task of the HYPERRIDE project and are dependent on the grid to be protected, i.e., the Medium Voltage Direct Current (MVDC) grid of RWTH Aachen.

A circuit breaker based on the Voltage source converter Assisted Resonant Current (VARC) principle has been designed to meet these requirements. The VARC breaking process uses an active current injection method where a Voltage Source Converter (VSC) excites the resonant branch of the circuit breaker to produce a resonant current through the main interrupter of the breaker. The resonant current counters the line current and the net current flowing through the main interrupter momentarily becomes zero. The current to be interrupted is commutated into an energy absorbing branch of the circuit breaker where the magnetic energy stored in the protected line is dissipated. This branch also clamps the voltage across the main interrupter.

This report documents the circuit breaker prototype setup and the relevant current interruption tests. Relevant details (such as largest interrupted current, breaker operation time and fault current suppression time) are also discussed.

It is concluded that a functioning circuit breaker prototype suitable for protecting the Aachen MVDC grid has been designed, built and tested by SCiBreak.

1 Introduction

1.1 Purpose and scope of the document

The purpose of Task T3.7 is to demonstrate the performance of the main circuit of the DC circuit breaker prototype that later will be developed for use in the German pilot of the HYPERRIDE project. This report documents the general requirements as well as the Aachen-grid specific requirements concerning an MVDC circuit breaker design. The report also details the main design steps of the VARC breaker. Moreover, the description of the test circuit used for measurements along with the measured test results are presented.

The work on the preparation of a circuit breaker for demonstration in the German pilot is divided into two tasks. This deliverable, D3.7, describes the first part, in which the main circuit of the circuit breaker is designed and tested.

It should be noted that the outcome of deliverable D3.6 would be tested as part of Task T3.7. The outcome of that particular deliverable is a prototype fast electromagnetic actuator along with a special Vacuum Interrupter (VI) and drive circuitry, developed by EATON. Since the deadline for this deliverable is later than the deadline of the current report, the design steps and test results of the EATON circuit breaker will have to be detailed in the report of D3.6.

1.2 Structure of the document

The structure of this report is outlined below.

Following the executive summary and the introduction, Section 2 details the general and target-specific requirements concerning the circuit breaker. In Section 3 the most important design steps and aspects are covered. Section 4 presents the tests done and the measured results. The document is concluded by Section 5.

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2 MVDC circuit breaker requirements

2.1 Definitions

Figure 1 shows the definitions of the different steps of the current breaking process, as per CIGRE Technical Brochure 683 "Technical Requirements And Specifications of State-Of-The-Art HVDC Switching Equipment", 2017 [1].

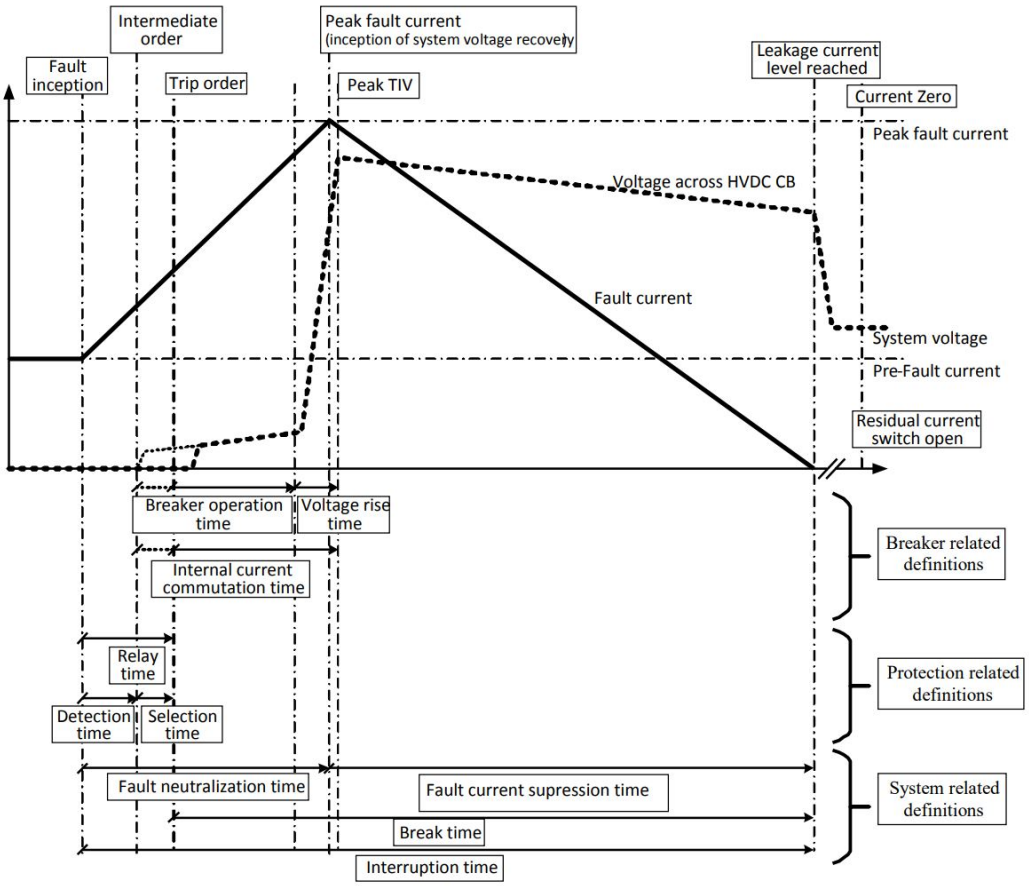

Figure 1: Definitions as per CIGRE working group A3/B4.34 TB 683.

2.2 Target grid

In this subsection the relevant characteristics of the grid to be protected by the circuit breaker prototype are discussed.

The grid in which the circuit breaker will operate is run by RWTH Aachen [2]. Currently, it has a ±2.5 kV symmetric monopole configuration and the nominal current is 1 kA. At a later point in time, an already existing mid-point conductor might be connected, to enable bipole operation.

Currently, an active front-end and dual-active-bridge converters are connected in a ring topology by Medium Voltage (MV) cables. Additional converters may be connected to the same network later on. Though the converter neutral points are available, the cables interconnecting

them are not used for energy transfer at the moment. Accordingly, the circuit breaker prototype is designed to clear pole-to-pole faults.

In normal operating conditions, the converters store a considerable amount of energy in their dc-link capacitors. Unless additional circuit elements are added a pole-to-pole fault can result in very high discharge currents rising very quickly. The high rate of rise of the fault current exceeds the capabilities of most Direct Current Circuit Breaker (DCCB) types. Therefore, the rate of rise will have to be limited by the addition of series reactors. The required inductance, and in effect the size, of this reactor depends on the operation time and peak fault current capability of the DCCB. For the prototype described herein the maximum interrupted current was set at 8 kA. The design steps are detailed in Section 3.

2.3 General requirements

The current breaker must be able to interrupt fault currents and normal load currents without adversely affecting the rest of the system. The latter design aspect is detailed in Section 3.2. A full set of requirements on a circuit breaker also includes requirements on personal safety, mechanical ruggedness, reliability, electromagnetic compatibility, breaker operating sequence etc. This document will, however, focus primarily on the fault-current interruption capability of the breaker. A full set of requirements on the apparatus will instead be established as part of the work in Task T3.1.

2.3.1 Fault currents

Circuit breakers need time for a successful breaking operation. If the circuit breaker is equipped with a VI in the main current path, the contacts of the VI need to have a gap of certain size in order to successfully withstand the Transient Interruption Voltage (TIV) after interrupting the current. The contact separation of the VI takes time and if a fault is present in the protected grid, the current through the circuit breaker will increase during this time. How fast the fault current is rising depends on the driving electromotive force of the system and the resistance and inductance of the impacted line section (i.e. the resistance and inductance of the network components located between the power source and the fault).

If a current-limiting reactor is connected between the dc converter and the line, it limits the rate of change of currents flowing through it. In case of a fault, the fault-current is increasing more slowly than it would if the reactor was not connected. The current-limiting reactor effectively means there is more time available from fault detection till the occurrence of the peak fault current. As the fault current must not exceed the maximum permissible current through the circuit breaker, the reactor allows the use of a breaker with longer contact separation time for the VI.

Conversely, the lack of a current limiting reactor means that in case of a fault, the rate of rise of current may be too high for a circuit breaker. Given the time needed for the process during internal current commutation and contact separation of the VI, if the fault current grows so fast that it would exceed the maximum permissible current through the breaker, then the circuit breaker must not be used to protect against such faults.

2.3.2 Normal load currents

Normal currents are smaller in magnitude than fault currents. Load currents up to the nominal load current or up to the nominal load current times a reasonable safety factor (such as 1.1 or 1.2 , to account for some overload capability) should be considered normal currents.

The rate of change of normal currents is also smaller than those of the fault currents as the whole, protected system is present with its resistance and inductance between the power source and the load.

Therefore, breaking normal load currents impacts the circuit breaker design only in that respect that the components of the breaker that carry the normal load currents should have sufficient rated currents.

3 Design of a 5 kV VARC DC Breaker Prototype

3.1 VARC technology

SCiBreak's circuit breaker is of the VARC type. This section summarises the current excitation principles and provides an overview of the components of the prototype breaker VARC circuit, based on an earlier paper [3].

When the VI opens, the current through it continues to flow while an arc forms between the contacts (Figure 2). In order to extinguish the arc, the VSC excites the resonant circuit connected in parallel with the VI. With well-timed switching actions, the resonant current is increased until it reaches the magnitude of the initial current of the VI but is flowing in the opposite direction. At that instant, the arc current decreases to zero so the arc is quenched.

The magnitude of the increments of the resonant current is determined by the dc-link voltage of the VSC and the characteristic impedance of the resonant circuit. The occurrence of the switching events is timed according to the resonant frequency of the resonant circuit.

Let L, C, Z_{LC}, f_{LC} denote the inductance, the capacitance, the characteristic impedance and the resonant frequency of the resonant circuit, respectively. Then

$$Z_{LC} = \sqrt{\frac{L}{C}} \tag{1}$$

and

$$f_{LC} = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

Let U_{DC} denote the dc-link voltage of the converter.

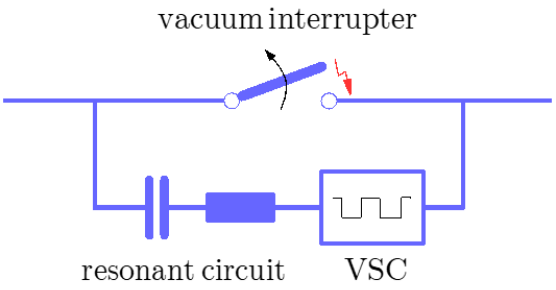

Figure 2: Resonant circuit.

As shown in Figure 3, the first switching of the converter (a step of U_{DC}) causes a resonant current with an amplitude of $I_0 = \frac{U_0}{Z_{LC}}$ (the losses are considered negligible for the sake of simplicity) to flow. Half a resonant period later the converter inserts the voltage source so that its voltage gets inverted with respect to the rest of the circuit. This difference of $2U_{DC}$ excites a current of $2I_0$, which sums up with I_0 from the previous half period to $3I_0$.

By consistently switching the converter to get a voltage reversal every half a resonant period, the resonant current can be built up (Figure 3).

Let n denote the number of reversals executed by the converter. The amplitude of the resonant current becomes $(2n+1)I_0$ after n reversals that take a time of $[(1/2+n)/2f]$.

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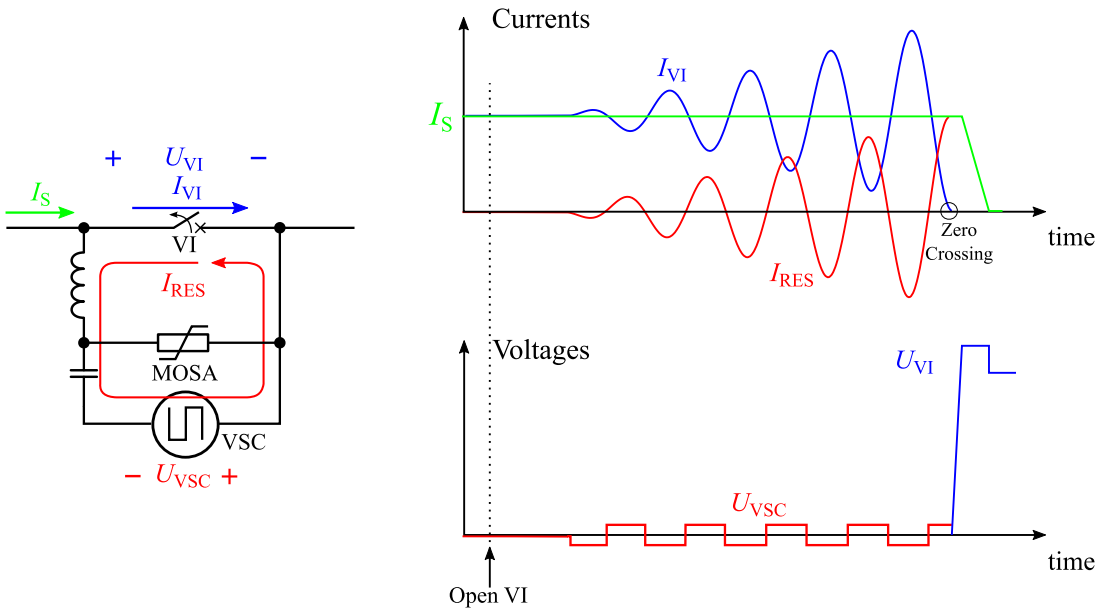

Figure 3: VARC principle.

3.2 Metal-oxide varistor

Once the current through the VI ceases to flow, the line current has been commutated to the capacitor in the resonant circuit. In order to prevent the capacitor from being overcharged, an MOV has to clamp the capacitor voltage. The MOV is also needed to suppress the line current and to dissipate the magnetic energy stored in the protected line.

The MOV is usually selected such that its discharge voltage level is approximately 1.5 times the system nominal voltage. The lower the discharge voltage, the longer the current suppression takes and the higher the energy dissipated in the MOV. On the other hand, the MOV discharge voltage cannot be too high either, otherwise the components of the circuit breaker or the protected system are subjected to excessive voltage stresses.

There are several variants of how the components of the VARC circuit breaker can be connected. SCiBreak's circuit breaker uses the circuit shown in Figure 4 (the 'Surge arrester' of Figure 4 is realised by the MOV).

3.3 Passive components of the resonant circuit

The design of the resonant circuit and the electromagnetic properties of the components depend on the MOV selection, the maximum current to be interrupted (denoted by I_{BR}) and the desired resonant frequency.

The MOV discharge voltage and the largest current determine an impedance Z_{BR}.

$$Z_{BR} = \frac{U_{MOV}}{I_{BR}}$$

The circuit must be able to generate a current pulse with a magnitude of at least I_{BR}. The capacitor voltage at the instant of the current reaching I_{BR} should remain below the discharge voltage of the MOV. Therefore,

$$Z_{LC} I_{BR} < U_{MOV} = Z_{BR} I_{BR}$$

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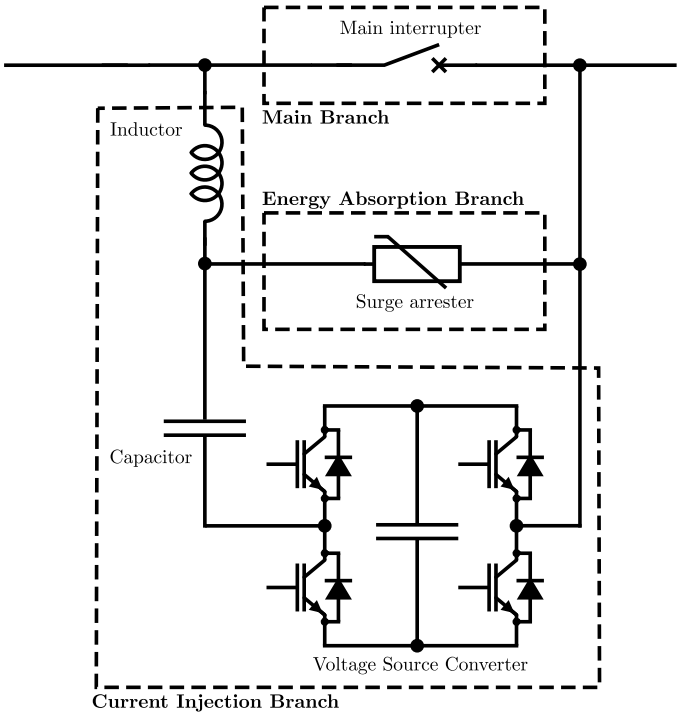

Figure 4: VARC circuit breaker topology.

The characteristic impedance Z_{LC} needs to be lower than Z_{BR}. But taking a possible reignition of the VI into account, Z_{LC} should be as high as possible; in case of a restrike in the VI, practically only Z_{LC} is limiting the current.

The Aachen grid is a nominal 5 kV system ($\pm$ 2.5 kV), but the midpoint is not used at the moment and has a high impedance to ground, so using an MOV with 9 kV of discharge voltage is quite close to the practice described in Section 3.2 (i.e. setting the MOV discharge voltage level to 1.5 times the system voltage).

If a fault occurs between the positive and negative poles right next to the converter, the dc-link capacitors are discharged very quickly, resulting in very large currents. In order to use the prospective VARC breaker with maximum 8 kA at interruption, current-limiting reactors are needed to be installed in the Aachen grid.

This means that

$$Z_{BR} = \frac{U_{MOV}}{I_{BR}} = \frac{9\,\text{kV}}{8\,\text{kA}} = 1.13\,\Omega$$

The resonant frequency has been set to 14 kHz. It was estimated that current interruption with the circuit breaker components SCiBreak has is still possible with a resonant frequency in the 14–15 kHz range. On the other hand, increasing the resonant frequency as much as possible permits the most compact circuit breaker design.

By inserting Z_{BR} into 1 and 14.3 kHz into 2, approximate values for the inductance and capacitance of the resonant circuit are retrieved.

$$L_{LC} = \sqrt{\frac{Z_{BR}}{2\pi f_{LC}}} = 12.5\,\mu\text{H} \tag{3}$$

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$$C_{LC} = \sqrt{\frac{1}{2\pi f_{LC} Z_{BR}}} = 9.89\,\mu F \tag{4}$$

As Z_{LC} shall be smaller than Z_{BR} (but not smaller than 0.9 Z_{BR}), the inductance and capacitance of the resonant circuit can differ a bit from the computed values.

3.4 Test setup

3.4.1 Passive components

The capacitor of the resonant circuit was 10 µF. The inductance of the circuit was measured to be 12.4 µH; this includes the inductor and the inductance of the leads. Inserting these values into (1) yields a Z_{LC} of $1.11\,\Omega$; Z_{LC} is smaller than Z_{BR}.

Inserting 10 µF and 12.4 µH into (2) yields 14.3 kHz. This was the frequency that was measured during testing.

The used MOV had a clamping voltage of 9 kV. This corresponds to the design aspect mentioned in Section 2.3 and does not jeopardise the rest of the system (Section 2.2) by imposing too severe overvoltages.

3.4.2 Setup

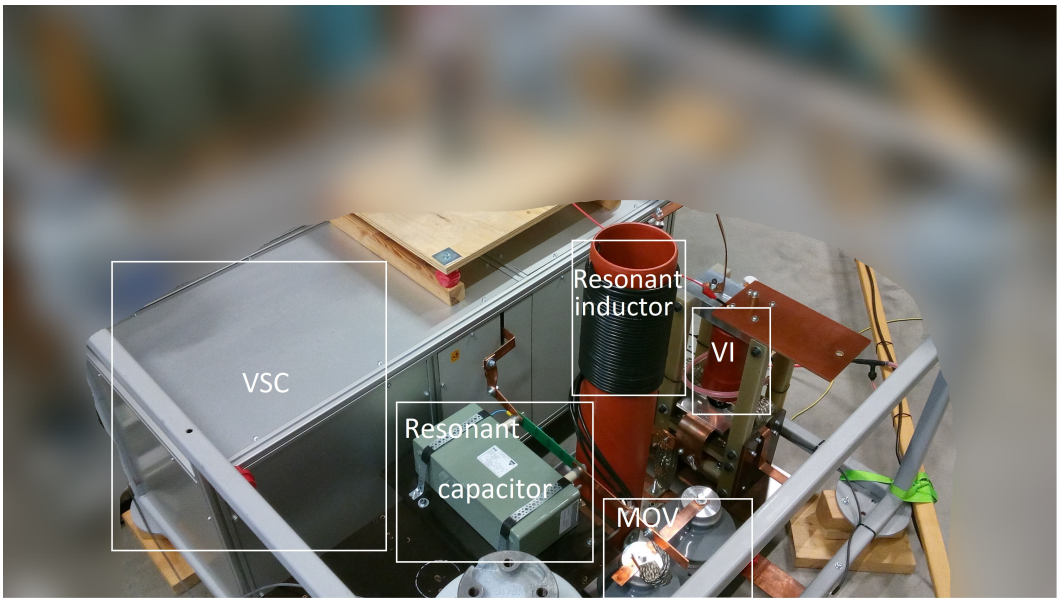

Figure 5: Circuit breaker prototype.

Figure 5 shows the whole circuit breaker prototype. The components of the setup can be identified as the ones shown in Figure 4 (the VI and the MOV correspond to the 'Main interrupter' and the 'Surge arrester' of Figure 4, respectively).

Figure 6 offers a closer look at the resonant circuit and MOV of the circuit breaker prototype.

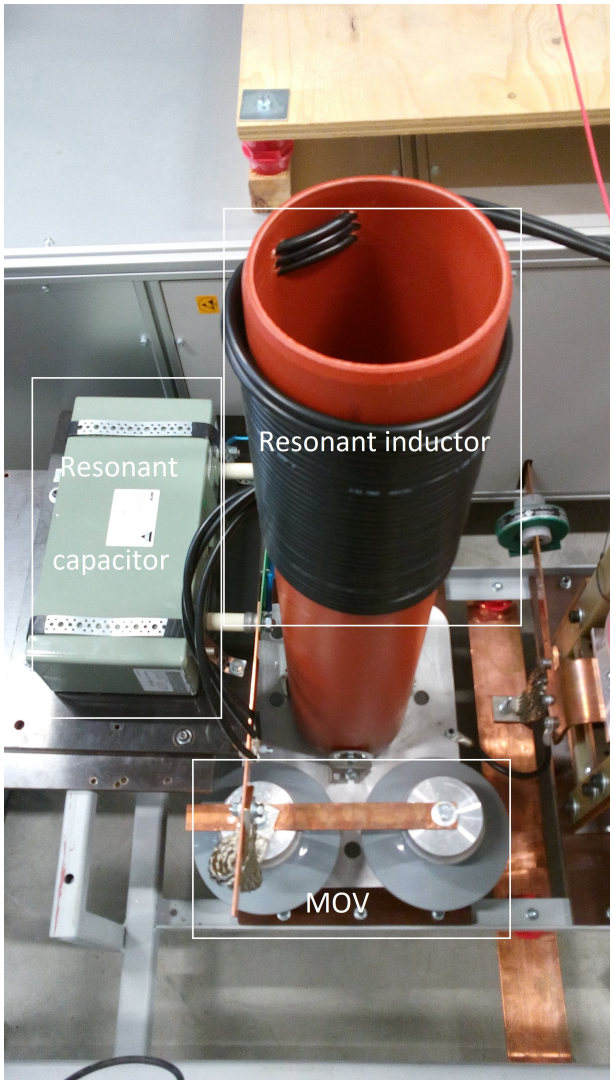

Figure 6: Resonant tank and MOV.

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4 Measurements

4.1 Test circuit

The test circuit used in the SCiBreak laboratory is of a type using a pre-charged capacitor bank. It allows for conducting fault- and load current interruption tests whilst being compact and cost-effective as compared to, for instance, a short-circuit current generator [4].

The capacitor bank, consisting of a number of capacitors (C_1-C_N), is charged to a predefined voltage level. The stored energy is released into the Test Object (TO) via an inductor (L) when a making switch (S_1-S_2) connects the capacitor bank in series with L and TO.

The maximum capacitor voltage is 7 kV and the TIV of the TO is limited by the voltage withstand capability of L to 170 kV. The highest current peak attainable with the test circuit is 19 kA. The maximum energy stored in the circuit is 170 kJ.

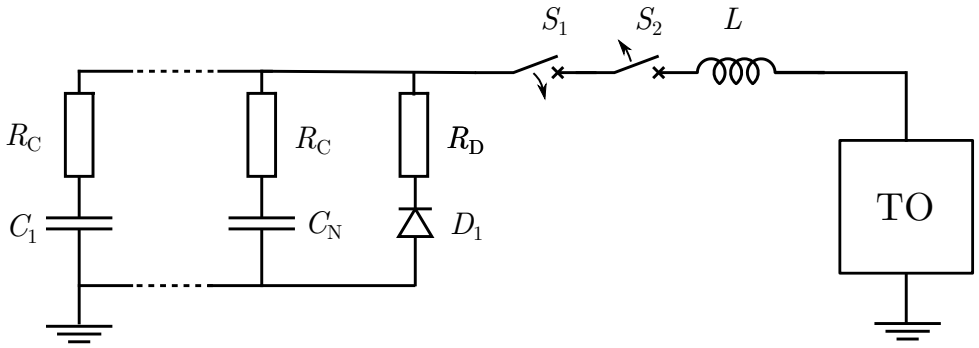

Figure 7: Test circuit connection.

The component values are summarized in Table 1.

Table 1: Charged capacitor test circuit.

Symbol	Value	Unit	Description
N	10		Number of parallel capacitors
C	690	µF	Unit capacitance
L	800	µH	Series reactor
R_c	250	mΩ	Current-limiting resistor
R_d	30	mΩ	Free-wheeling diode resistor

4.2 Fault current interruption

Figure 8 shows that the largest line current interrupted was measured to be 7.8 kA. The peak TIV was 10.9 kV and the MOV clamped the voltage to 9.3 kV.

The breaker operation time spans the interval from trip order till the voltage across the VI starting to steeply increase (see Figure 1). The breaker operation time and the fault current suppression time of the shown test were 1.2 ms and 800 µs, respectively. The circuit breaker measures the current through the VI internally and based on the rate of change of the current, it estimated when the current would reach the maximum permitted level. The trip order was issued autonomously.

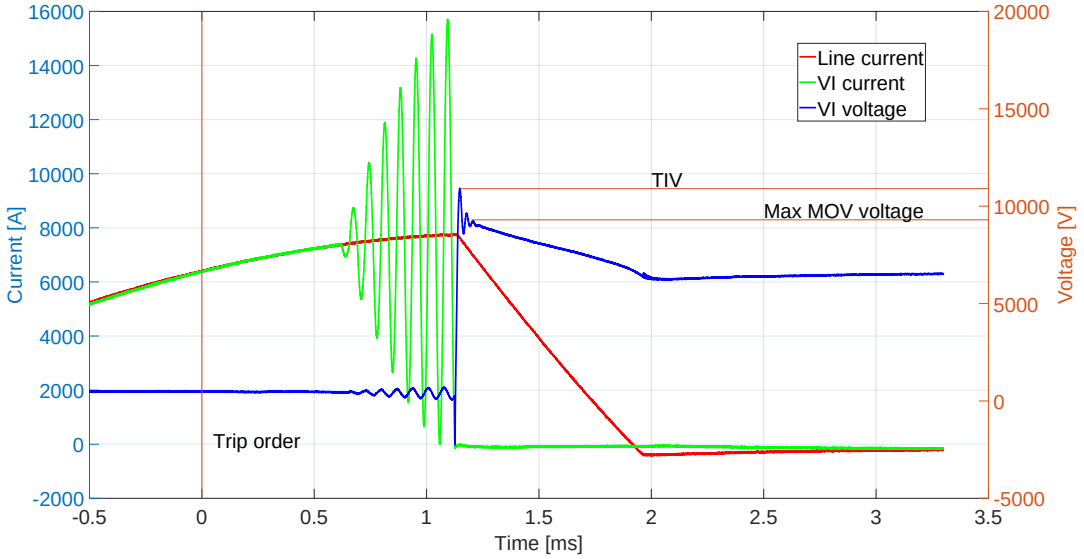

Figure 8: Fault current interruption.

4.3 Load current interruption

The nominal current of the Aachen grid is 1 kA. The measurement of the circuit breaker breaking such current is shown in Figure 9. The TIV was measured to be 7.9 kV and the MOV clamped the voltage to 7.2 kV. The breaker operation time and the fault current suppression time of the shown test were 1.2 ms and 150 µs, respectively.

It is not visible on Figure 9, but the arcing voltage of the VI during breaker operation is in the range of 20 – 30 V. The inductive voltage drop across the VI is more significant (it is approximately 100 V).

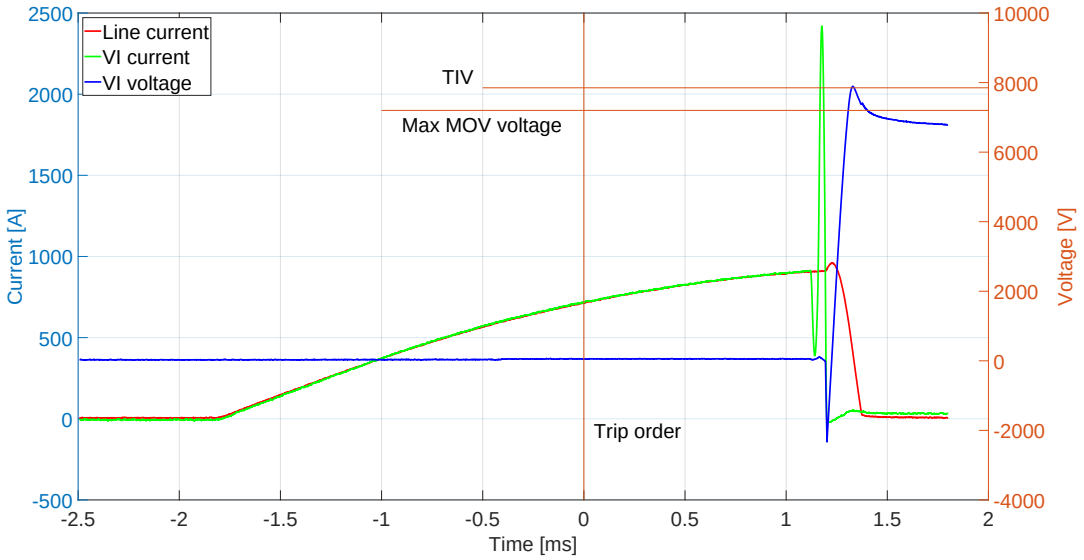

Figure 9: Load current interruption.

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5 Conclusion

A 5 kV DC circuit breaker prototype has been designed according to the requirements outlined in Section 2. The principle of the VARC circuit breaker and the design steps of the prototype of D3.7 have been detailed in Section 3. The prototype has been built and tested in SCiBreak's laboratory. The test results presented in Section 4 show that the prototype is able to interrupt both nominal load currents and fault currents according to design specifications.

As for the relevant future work, other deliverables (e.g. D3.9) of the HYPERRIDE project will be using the demonstrator of this deliverable.

References

[1] C. Franck, R. Smeets, and M. A. 34, “Technical requirements and specifications of state-of-the-art hvdc switching equipment,” *CIGRE WG A3/B4. 34, Report No. 683*, 2017.

[2] M. Stieneker, J. Butz, S. Rabiee, H. Stagge, and R. W. D. Doncker, “Medium-voltage dc research grid aachen,” in *International ETG Congress 2015; Die Energiewende - Blueprints for the new energy age*, 2015, pp. 1–7.

[3] L. Ängquist, S. Nee, T. Modeer, A. Baudoin, S. Norrga, and N. A. Belda, “Design and test of vsc assisted resonant current (varc) dc circuit breaker,” in *15th IET International Conference on AC and DC Power Transmission (ACDC 2019)*, 2019, pp. 1–6.

[4] S. Nee, T. Modeer, L. Ängquist, S. Norrga, and A. Baudoin, “Tank test circuit for fast dc circuit-breakers,” in *15th IET International Conference on AC and DC Power Transmission (ACDC 2019)*, 2019, pp. 1–4.

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