GENERATOR FOR CURRENT INJECTION ON HIGH DC POTENTIAL TO TEST HVDC EQUIPMENT

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Abstract: A new technical solution for a DC test current generator that injects a direct current on high voltage potential is presented. The concept is patented nationally [1] and internationally protected with PCT registration. So far, no commercial generators for this kind of testing are available. The solution is based on capacitive transmission from earth to high voltage potential. The generator isolates the high DC voltage, while it injects the high current in the test loop. For power transmission through the capacitors an AC current at kHz-frequency is used, while the high DC voltage is naturally blocked by the capacitor. At high voltage potential, the current is rectified and applied to the test loop. First prototypes for the new generator concept are demonstrated, which proves the technical feasibility of the design. Long-term-tests with this novel generator concept are shown, which proves the stability of the generator for continuous operation.

1 INTRODUCTION

The design of HVDC equipment like gas insulated systems or cables always has to take space-charge distributions in the insulation material into account. A main problem is the temperature dependency of the insulation material conductivity, which can cause space charges and therefore local high electrical field stresses. In conclusion, tests on HVDC equipment like prequalification tests for HVDC cables or GIL (gas insulated lines) always have to consider simultaneously high current and high voltage stress and shall thereby ensure the technical feasibility of the HVDC equipment for its total lifetime in the HVDC grid [2]. Therefore, power system users desire a test procedure as close to practice as possible.

However, a representative AC current heating is often used to heat the inner conductor of a cable (red conductor in Figure 1) due to limitation of the test equipment. A temperature gradient across the insulation material similar to that during the real DC current stress is important. Figure 1 shows the problem for a typical bipolar arrangement.

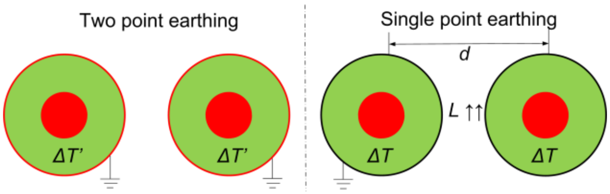

Figure 1: Heating with AC current. Cross-section of the cable; red areas carry current.

During testing induced currents and therefore heating of the outer sheath (red sheath in Figure 1, left) have to be avoided. The heating of the sheath would result in a "wrong" temperature gradient *ΔT'*, wherefore single point earthing of the sheath is mandatory. But the open sheath results in a current loop, where the inductance L increases with increased distance d between the conductors and higher lengths l of the test assembly. Assuming a length $l = 100$ m with typical GIL or cable dimensions and up to 5000 A rated current at 50 Hz, a power supply of approximately 780 kVA is required according to Equation (1).

$$L = \frac{\mu_0 l}{2\pi} \ln \frac{d}{r} \approx 1 \frac{\mu\text{H}}{\text{m}} \quad (1)$$

where: L = inductance of the current loop
l = length of the assembly
d = distance between conductors
r = radius of inner conductor

Reducing the length of the test assembly may solve the technical problem, but may also result in a lower temperature gradient due to cooling effects at the test set-up's boundaries. Usually the temperature is calculated for an infinitely long setup, because in practice usually long transmission lines occur [3]. This means adequate tests will also require a certain length giving the chance to neglect boundary effects.

Furthermore, complex geometries like segmented and stranded conductors are difficult to calculate, and additional experimental results to calculate a representative AC current have to be considered [4]. The additional experimental results also have to be accepted by the power system operator (the customer, respectively).

In conclusion the HVDC equipment is not tested under the same stress as it will appear in the real application in the DC grid. To overcome all such problems, simultaneous tests with DC current and DC voltage are desirable. The users of HVDC equipment would have a benefit from tests similar to the foreseen application. The supplier of the equipment could optimize his design according to the realistic stresses in the grid. But so far, no commercial generators for this kind of testing are available.

2 CURRENT INJECTION ON HIGH VOLTAGE POTENTIAL

The major problem in current injection is the power supply of the current source. Figure 2 shows the problem.

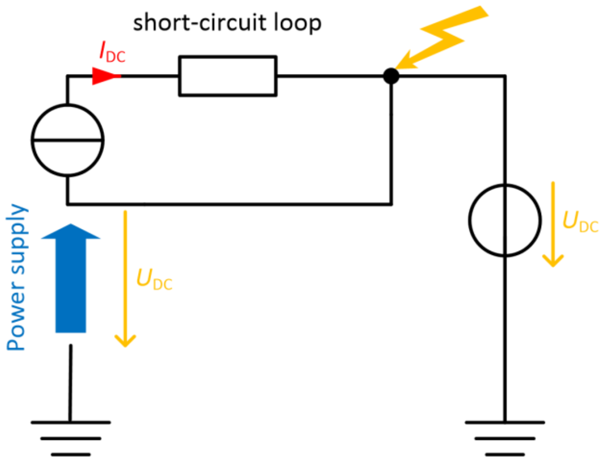

Figure 2: Current injection on high DC potential.

The DC current source has to operate on high DC potential. Therefore, an isolating platform for the current source is required. The current source feeds a short-circuit loop with the DC current I_{DC}. The short-circuit-loop of the test object can be modelled by a simple resistor. The power supply of the current source must be able to transfer the power as well as to isolate the high DC voltage U_{DC}. Several technical solutions to solve this task are possible, for example:

- Mechanical solutions with generator and drive, operated by insulating connections to ground like insulating rotating shafts or a pressurized air or hydraulic system

- Current injection with isolation transformer

One major problem of these solutions is the high weight and therefore material invest for transmitting high powers. E.g. for a mechanical solution two electrical drives and an insulating shaft are required. The drives or isolating transformers need high copper cross-sections to handle the currents for transmitting the power and heavyweight iron for magnetic coupling. The high weight on high voltage potential increases the costs. Another major challenge is the sensibility to space charge effects in the insulation material, which considerably reduces electrical strength. Especially in isolating transformers only small distances between primary and secondary winding can be realized to isolate the voltage [5]. Cascading of several isolating transformers is required to manage the voltage with larger safety margins, which also results in a higher material weight and thereby costs.

2.1 Capacitive current injection

A mechanically simpler and therefore more cost efficient solution with lower local electrical field stress is the capacitive current injection on high DC potential. Figure 3 shows the principle.

An AC/AC converter (2) is supplied by 50/60 Hz three-phase electric power, e.g. at a voltage of 400 V. The AC/AC converter generates a single phase electric power in the kHz frequency range. The advantage of the kHz-power-signal is that capacitors have a low impedance for this frequency, so that power can be transmitted. In order to reduce the current rating of the kHz-power-signal a voltage transformer is used (3). The kHz-power-signal is transferred from earth to high voltage potential through the current capacitor (6). The current capacitors at the same time isolate the high DC voltage U_{DC} from ground. The current capacitor (6) has to carry a kHz-current in the range of several ampere. This also results in heating of the current capacitors. To achieve a homogeneous potential grading several resistors

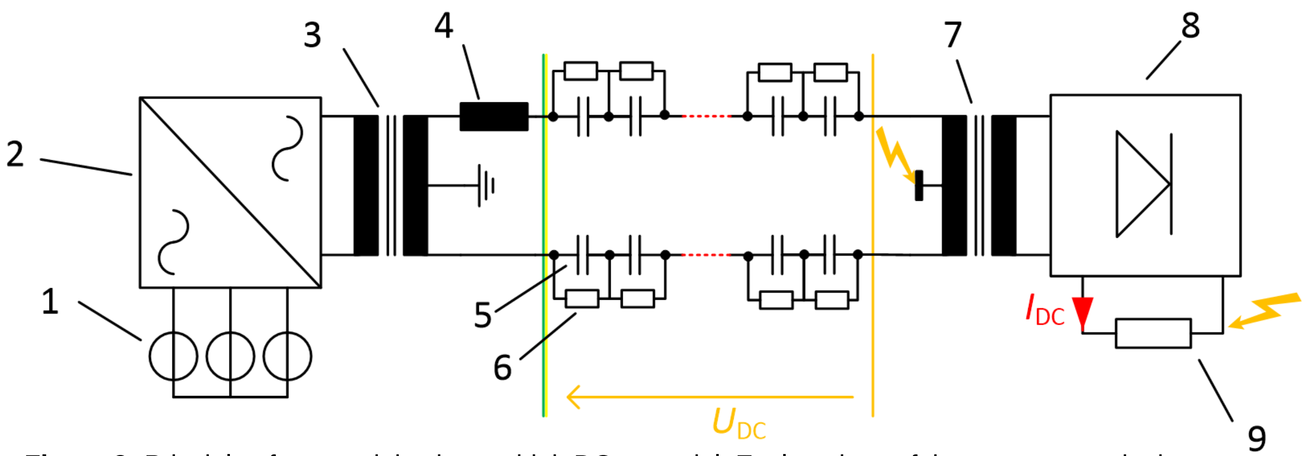

Figure 3: Principle of current injection on high DC potential. Explanations of the components in the text.

(6) are connected in parallel to the capacitors. In conclusion the current capacitors (5) and the resistors (6) have a similar behaviour as an ohmic-capacitive voltage divider. To avoid reactive power flow in the circuit a compensation reactance (4) is used. The compensation reactance (4) and the current capacitor (5) form a resonant circuit. The resonant frequency of the circuit is equal to the frequency of the kHz-power-signal to minimize the reactive losses. On the high voltage side, the transmitted kHz-power-signal is fed into a current transformer (7) to generate the required high current. Behind the current transformer a rectifier (8) converts the kHz-power-signal to a DC current I_{DC}. The current I_{DC} can then be injected into the test sample (9).

A sketch of a real assembly in a high voltage laboratory can be seen in Figure 3. On earth potential a feeding unit with converter, coil and transformer can be seen (1). AC/AC converters for kHz-frequencies and high electric powers of 100 kW and more are available in the market for induction heating units. The two current capacitors (2) between high voltage potential and ground look similar to standard voltage dividers. On high voltage potential an isolated platform (3) with the transformer and the rectifier is shown. In Figure 3 the isolated platform is positioned on top of the bushings from the device under test (4).

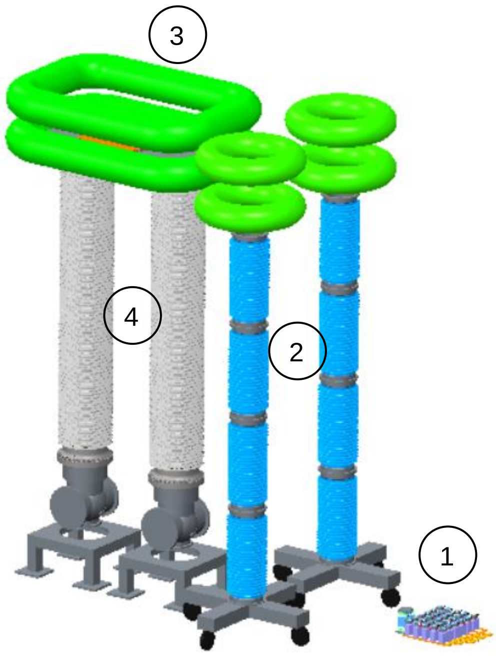

Figure 3: CAD model of current injection on DC potential.

Due to the kHz-frequency, all parts like the transformer and the rectifier can be built very compact, which reduces the total weight and therefore the costs. The current capacitors can be designed similar to voltage dividers and are therefore very cost efficient. Due to the resistive potential field grading, the total insulation distance from high voltage to earth is used to withstand the DC voltage.

2.2 Rectification on high DC potential

Any concept for high DC current injection needs a rectifier and therefore electronic devices on high voltage potential. The generation of the high current in the low-ohmic short circuit loop requires a voltage between the terminals of only a few volts (e.g. 15 V). Usually diodes for rectification are used to fulfil this task. But the threshold voltage of rectification diodes is at least 0.7 V. Considering a rated current of 5000 A the power losses of a B2U-rectifier can be calculated in best case according to Equation 2.

$$0.7\ \text{V} \cdot 5000\ \text{A} \cdot 2 = 7\ \text{kW} \tag{2}$$

Cooling power losses of 7 kW would result in bigger additional cooling devices on high voltage potential. Modern voltage converters use a different approach to reduce the power losses in the rectifier. Today synchronous rectifiers with MOSFETs in parallel to the diodes are used, because of their low drain-source resistance. In conducting mode, the MOSFET is switched on, in blocking mode it is switched off. The switching of the MOSFETs is timed with an additional control unit [6]. The procedure reduces the power losses in the foreseen generator application by a factor of approx. 8 compared to B2U rectification. This results in a much lower effort for the isolating platform.

The concept of the rectifier is shown in Figure 4.

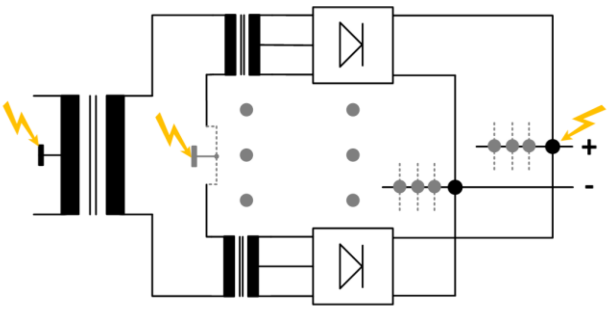

Figure 4: Rectification on DC potential.

Instead of one single high current transformer with rectifier a modular concept is used. One module is composed of a transformer and a rectifier. All primary windings of the transformers are connected in series, all secondary windings in parallel. This results in a homogeneous current distribution in each module due to the same magnetic flux in each transformer. Each parallel rectifier module represents a current source for several amperes. All these currents sum up to the total test current. Assuming 100 modules in

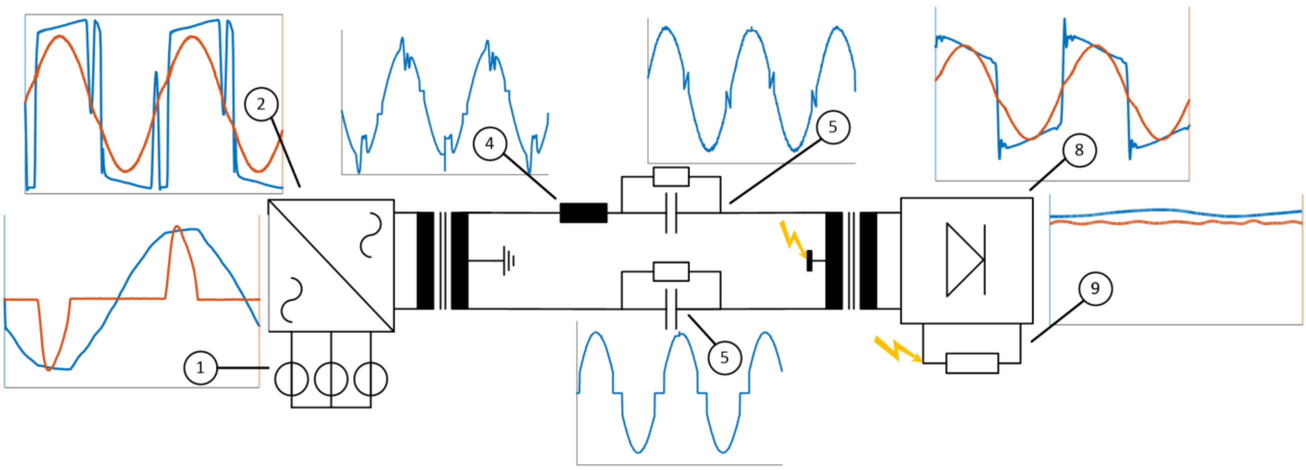

Figure 5: Current injection on DC potential (qualitative oscillograms - blue = voltages / red = currents).

parallel, each one has to generate only 50 A DC current to achieve a 5000 A test current. Each module is connected to a busbar to collect the current ("+" and "-" in Figure 4). The modular concept also allows easy scaling of the rectifier by using standard components for each module. The rectifier is a M2U rectifier to reduce the number of electronic parts and thereby the losses. Also the reference potential for each part in the circuit can easily be connected to the high voltage DC potential. This means no electronic parts are floating in case of transient voltages from the test sample.

3 DEVELOPMENT TESTS ON THE GENERATOR CIRCUIT

So far the generator concept described in Chapter 2 was realized in a prototype with a rated voltage of 60 kV DC and a rated current of 30 A. The operating frequency of the AC/AC-converter was $\approx$ 50 kHz. The prototype has proven the technical feasibility of the concept.

Figure 5 shows oscillograms taken on the prototype. Only the qualitative behaviour of the circuit shall be demonstrated, therefore no absolute numbers are given. Blue curves represent voltages, red curves represent currents.

For the prototype a simple AC/AC-converter with DC link capacitor was used. The oscillogram of the power supply (1) shows a typical power input for the rectifier. After the DC link capacitor IGBTs convert the DC voltage to a rectangular AC voltage (2). The current is nearly perfectly sinusoidal, because only the current of the resonance frequency is transmitted. Other frequencies are damped. The AC voltage across the capacitors (5) and the inductor (4) are in phase opposition and compensate each other. The voltage spikes in the inductor voltage (4) result from the reactive back feeding. At the high voltage side, the rectangular voltage arrives (8) and is converted to the DC current (9). Therefore, in the rectifier module (9) parallel transformers increase the current and the parallel synchronous rectifier generates the DC current. The output current is voltage controlled depending on the resistance of the test sample.

For the first development loop, the prototype was tested for long-term performance. Two separate long-term tests were performed. The current feeding long-term test should prove the continuous current operation of the generator. The high voltage stress test should prove the long-term stability of the generator for DC voltage (e.g. space charge effects).

3.1 Current feeding

The current feeding long-term test was performed for 300 hours. For measuring the current on the isolating platform the high voltage source was switched off.

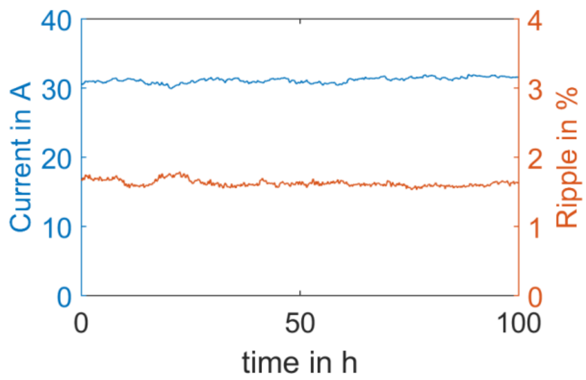

Figure 6: Magnitude and ripple of the output current.

Figure 6 shows a graph for a 100 hours' time slot. The output current is mainly constant. The deviation of the output current and ripple is caused by the fluctuation of the feeding electrical grid. The ripple current is very low due to the high frequency. In conclusion the result from the current-feeding long-term test is optimal. The current feeding of the source is constant, and no current drops or current decreases due to heating of the test assembly could be observed.

3.2 High Voltage stress

The high voltage long-term test was performed for 1000 hours. During the test, the output current of the current source was approximately 30 A. The current source operated at 60 kV high voltage potential. Figure 7 shows a graph for a 100 h time slot.

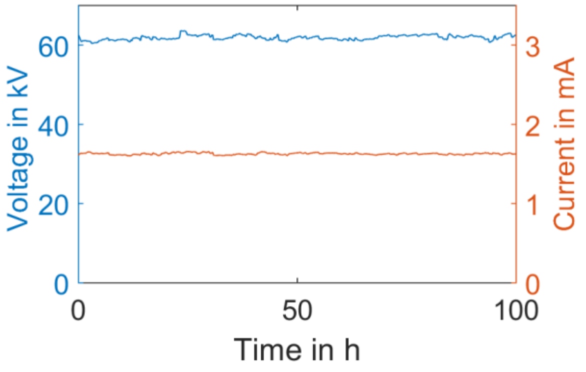

Figure 7: High voltage stress and current high voltage to earth through the field grading resistors.

Figure 7 shows the applied DC voltage and the current from high voltage to earth through the field grading resistors ((6) in Figure 5). Figure 7 shows constant current and voltage magnitudes. The deviations of voltage and current are caused by the fluctuation of the electrical grid. Figure 7 also shows one major advantage of the capacitive concept. DC applications often have exponential decreasing currents, what means, that space-charge effects influence the field distribution [2]. Figure 7 shows a constant DC current. This means no polarisation currents are visible and therefore mainly the ohmic field grading resistors define the potential distribution across the insulation distance. Therefore only locally low electrical field stresses occur and the overall design is robust against space charge effects.

In conclusion also the voltage stress test shows an ideal behaviour. Therefore, the design seems very stable for high voltage applications.

3.3 Temperature rise during long-term tests

During the long-term tests the heating of the total assembly was monitored with an infrared camera. Figure 8 shows the test results for the current feeding long-term test.

No high voltage stress was applied for the photographs of Figure 8. The assembly was cooled with forced air ventilation due to its high temperature. At the front the current capacitors and grading resistors can be seen. The current through the current capacitors was approximately 6 A. This also results in heating of the current capacitors. Figure 8 shows a total heating of the assembly. Typically, current capacitors are applicable in a temperature range of 75 °C – 85 °C. This shows the necessity for an adequate thermal design of the current capacitors. Upscaling the concept has to consider this problem.

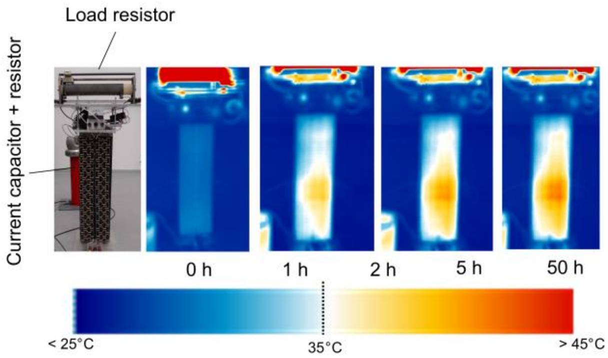

Figure 8: Heating of test assembly during long-term test.

4 FUTURE WORK

Upscaling the concepts will require further investigations. Besides the thermal design of the current capacitors, further investigations on the concept are required. The most important ones are:

- Optimization with regard to partial discharges
- General upscaling effects

UHF PD measurement in the frequency range up to approx. 1.5 MHz is manageable with the presented concept. The switching operations take place in the kHz-frequency range and therefore do not influence the measurement. This has been proven by first UHF PD measurements on a short stretch of a test sample, which was fed by the DC current of the prototype generator.

Conventional PD measurements according IEC 60270:2000 will be mainly influenced by the used AC/AC converter. So far, with the used rectangular converter the PD measurement is affected. The rectangular impulses create frequency impulses in the kHz range, where conventional PD measurements also take place. It is assumed that a sine wave converter with connected filter will improve the behavior enormously. In this case the frequency interference occurs mainly at one single frequency. The affected frequency can then easily be filtered out by the PD measurement software.

So far only low voltages and currents have been realized. The target is to build a generator for approximately 650 kV DC and 5000 A DC.

Upscaling of the concept by combining several modules is the next challenge.

5 CONCLUSIONS

Testing of HVDC equipment as close as possible to its foreseen application results in the necessity for simultaneous testing with DC voltage and DC current. A new generator concept for capacitive current injection is shown. The concept is based on the fact that current capacitors are reasonably conductive for high-frequency AC currents, whereas the DC voltage is blocked naturally by the capacitors. The major advantages of the concept are the low material weight and the natural potential field grading. For the total assembly exclusively standard components like commercial converters, parts from voltage dividers, standard synchronous rectifier elements etc. can be used. Due to the high applied frequency, the rectifier can be very simple to achieve a low ripple. In addition, synchronous rectifiers are used to reduce the power losses at high voltage potential. The technical feasibility of the concept has been proven in several long-term tests. The generated high current allows for UHF PD measurements on the connected device under test. So far, consistently positive experience could be collected. The generator concept will be upscaled to approximately 650 kV DC and 5000 A DC.

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