Construction of a DC Current Injection Generator for HVDC Long-Term Tests up to 5000 A DC at 660 KV DC Potential

Hallas, Martin; Wietoska, Thomas; Hinrichsen, Volker

(2019)

DOI (TUprints): https://doi.org/10.25534/tuprints-00014262

Publikationstyp: Konferenzveröffentlichung
Fachbereich: 18 Fachbereich Elektrotechnik und Informationstechnik
Quelle des Originals: https://tuprints.ulb.tu-darmstadt.de/14262

Construction of a DC Current Injection Generator for HVDC Long-term Tests up to 5000 A DC at 660 kV DC Potential

M. Hallas[1*], T. Wietoska[1], V. Hinrichsen[1]
[1]Technische Universität Darmstadt, Fraunhoferstraße 4, 64283 Darmstadt, Germany
*Email: hallas@hst.tu-darmstadt.de

Abstract: DC current injection at high voltage potential allows adequate testing of HVDC components according to their later operation. Several concepts are possible. To achieve high current and high voltage ratings by stacking of several components, capacitive current injection is a reasonable concept. It consists of a feeding unit, the transmission path and the rectifier at high voltage potential. It is shown how the components can be built and which technical parameters are required inside the generator. The overall goal of the project is the upscaling of the concept up to 5000 A DC current on a high DC voltage potential of 660 kV. Challenges and solutions during the design phase of the upscaled generator are discussed. Pictures of the generator components are shown, as well as first experiences with the upscaled generator. Summarized, the contribution demonstrates that this generator concept for DC current injection at high voltage potential is technically feasible for high equipment ratings.

1 INTRODUCTION

The design of HVDC equipment like gas insulated systems or cables always has to take space-charge accumulation in the insulation material into account. The main reason is the temperature dependency of the material's electrical resistance, which can cause space-charges and, therefore, after a certain charging time, locally high electrical field stresses. In conclusion, long-term tests on HVDC equipment like prequalification tests for HVDC cables or prototype installation tests for gas insulated systems always have to take into account high current and high voltage testing at the same time [1] [2]. Typically, AC current heating is used, since standard heating transformers can be used. However, there are some technical limits. Particularly, injection of high AC currents into large test loops requires high amounts of reactive power. Other aspects are customers' requirements for tests as close as possible to practice. Three current heating options are possible to test the later operation of the HVDC equipment in the laboratory [3]:

1. AC current heating with rated current
2. AC current heating with representative AC current
3. DC current heating with rated current

Option 1 will result in higher thermal stresses since the skin effect increases the losses in the assembly. Thermal stresses and electrical stresses due to space charges inside the equipment will be higher compared to regular operation. Therefore, suppliers of HVDC equipment would avoid option 1, since it leads to over-engineering of the equipment. Option 2 requires calculations and comparisons between DC and AC current temperature rise tests. It must be decided if the representative current shall be calibrated to the hot-spot temperature, the maximum temperature difference, the location of maximum electrical field stress, the location where electrical flashover will most likely occur or something else. The procedure can become difficult for complex assemblies, especially for gas insulated systems with several insulators and contact surfaces [3]. The chosen reference point for calibration also needs to be validated, which additionally increases the effort, especially when simulations are not accepted and laboratory tests are required. The overall procedure needs to be accepted by the customer and holds the risk of not being accepted by each customer, since differences of the overall temperature distribution in the test assembly between AC and DC current heating will always exist. Customers of HVDC equipment might therefore avoid option 2. Injection of DC current at magnitudes according to the later operation in the grid (option 3) is therefore the best choice to test HVDC equipment adequately. However, generators for this kind of testing are not commercially available so far [4].

2 DC CURRENT INJECTION

A basic sketch for injection of a current I_{DC} at high voltage potential U_{DC} is shown in Figure 1.

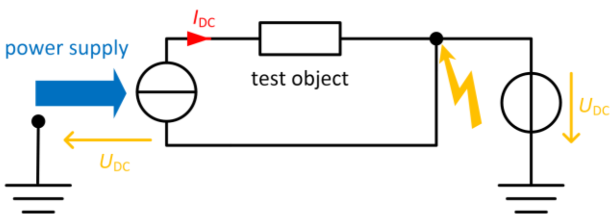

Figure 1: Basic sketch of DC current injection at high voltage potential [4]

A resistor represents the test object. The current source has to generate the high DC current at high voltage potential. The power supply of the current source has to fulfil two tasks. First, it has to transmit power for the current source. Secondly, it has to insulate the high voltage stresses between the test object and ground [4].

2.1 GENERATOR CONCEPTS

To solve the task sketched in Figure 1, several technical solutions are possible. Typical concepts would be [3]:

(1) isolating shaft

(2) isolating transformers [6]

(3) hydraulic current injection

(4) inductive DC current injection [5]

The solutions have advantages and disadvantages. Concept (1) needs a special isolating shaft, which is difficult to design. Higher power and voltage ratings make this task even more challenging. The insulating transformers in concept (2) have to be designed for the total rated power. This results in a very heavy assembly, which insulates the voltage stress only in small spaces between primary and secondary winding. The power ratings of concept (3) are limited to the power ratings of the hydraulic engines and their efficiency. For this concept, especially very large testing loops with high currents are challenging since the isolating hydraulic pipes have to be iron free, and the power demand for cooling devices to prevent oil overheating increases. The transmission path of concept (4) needs to fulfill higher current and voltage ratings than the test object, since it is stressed with AC current, which results in higher temperature differences across the DC insulation. Special designs and therefore higher costs might be necessary to implement the concept [3].

2.2 CAPACITIVE CURRENT INJECTION

To achieve high voltage and high current ratings with conventional parts available in the open market, the capacitive current injection offers a high efficiency solution. Figure 2 shows the developed basic circuit [4].

The solution is based on capacitive transmission of a high frequency current at moderate amplitude from ground to the high voltage potential. There, the current is stepped up and rectified. A DC current of several kilo-amperes amplitude at a voltage of only a few volts is the result. In conclusion, the capacitors build the insulation for the high DC voltage while they transmit the high frequency current to the rectifier at high voltage potential. Prototypes have shown good performance of the overall concept [3] [4].

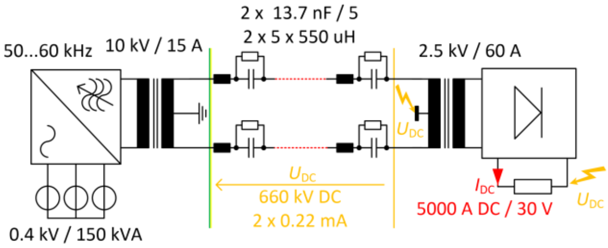

Figure 2: Capacitive current injection generator

The ratings of the circuit are also shown in Figure 2. The frequency is set to 50…60 kHz, low enough to avoid unwanted high frequency effects and high enough to benefit from low capacitive impedances. The current rating in the transmission path is limited to the current capability of the used components. A maximum value of 15 A resulted as a reasonable limit. A maximum voltage of 10 kV in the transmission path seems also reasonable, since this voltage level can still be handled efficiently, especially between primary and secondary windings of the transformers. The capacitance of the transmission path has to be on one hand as low as possible to allow fast polarity reversals in the transmission path, and on the other hand as high as possible to minimize the capacitive impedance. As a good compromise, a value of approximately 5.5 nF of the total capacitance is reasonable. The resistance of the parallel resistor follows similar design rules. It has to be as high as possible to reduce the ohmic losses, but shall be as low as possible to allow the polarity reversal. The inductance value depends on the value of the capacitance. Since lower capacitances are used, higher inductances are required to achieve a resonant frequency in the range of the operating frequency of 50…60 kHz. Large single inductances with high frequency ratings are difficult to design. Because of the strong influence of the proximity and other high frequency effects, high temperatures arise at the inductor. Furthermore, the high frequency resonant voltage at the terminals increases with increasing inductance. In conclusion, several smaller inductances in series are easier to handle and are therefore used in the concept of Figure 2.

3 GENERATOR DESIGN

The CAD model of the capacitive current injection generator is shown in Figure 3. The generator consists of the feeding unit (AC-AC converter) at earth potential, the transmission path with two capacitors and the rectifier at high voltage potential [3] [4].

Figure 3: CAD model of the capacitive current injection generator

3.1 FEEDING UNIT

The feeding unit consists of a regulating transformer to control the magnitude and an AC-AC converter to control the frequency. The basic circuit is shown in Figure 4.

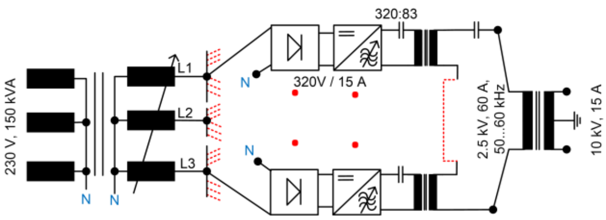

Figure 4: Feeding unit circuit

Pulse-width modulation converters to directly control the magnitude are not used, since this solution would produce higher electromagnetic noise, which might disturb other laboratory measurements. The converter has to fulfill several tasks. It shall provide the power with high efficiency and at a low noise level. High efficiency can be implemented by using MOSFETs as switching components. A disadvantage of MOSFETs is that only lower voltage ratings are available compared to IGBTs. Therefore, the DC link voltage has to be limited to approximately 320 V. Several converters are used in parallel to reduce the ratings of each converter to levels, which can easily be handled. The summation of all converters is achieved by transformers with parallel connection of their primary windings and series connection of their secondary windings. As long as the transformer voltage ratios are equal, all modules are equally stressed. This is physically given by the same current flowing through each secondary winding, which results in identical current stress in each primary winding. Due to phase shifts during the MOSFET switching, as well as phase shift due to the summation of all voltages, the resulting voltage may contain a DC offset. High DC offsets may cause saturation of transformers and must be avoided. To suppress the DC offset, blocking capacitances are introduced into the circuit.

If the converter noise level in the laboratory needs to be reduced, a sinusoidal multi-level converter could be a reasonable option as an alternative.

3.2 CAPACITIVE TRANSMISSION PATH

The transmission path is shown in Figure 2. The main components of the circuit are capacitors and inductances.

3.2.1 Capacitors

The capacitors must be chosen to the current rating. The capacitors are stacked and assembled in closed housings. The temperature rise of each capacitor should not exceed the specified limits. This may occur, since stacking and enclosing increase the temperature rise. The parallel resistors heat the assembly additionally, so that high temperatures may be reached.

During the design period, two different types of capacitors were particularly considered [7] [8]. Temperature rise tests under defined thermal conditions were performed. The test showed that the temperature rise of [7] is twice the temperature rise of [8] for 15 A at 50…60 kHz. Since the second type of capacitor also showed a better performance and had lower capacitance, type [8] was finally selected for the generator.

First prototypes with stacked capacitors and parallel resistors were built. Comparable to the later application, they were stacked in an enclosure filled with oil. The oil increases dielectric strength and reduces the risk of partial discharges. Also the thermal heat transfer is optimized with the oil. Temperature rise tests at the prototypes with high frequency current showed hot-spot temperature rises of 24 K, which is more than twice the temperature rise compared to the first development tests. Application of a DC voltage will further increase the temperature rise. But as the expected overall temperature rise was much lower than the specified limits, the capacitors were nevertheless used for the construction of the current injection generator.

3.2.2 Inductors

The inductors are required to operate the circuit at resonant frequency. The inductors are directly positioned between the capacitors, which results in very limited space for the inductors. During the design phase, several types of inductors were investigated. An inductance of approximately 500 µH for 15 A current at 50…60 kHz is required. The difficulty from these ratings can be seen in the results of temperature rise tests, shown in Figure 5. The first types of inductors were N87 ferrite-core inductors. They offer compact design, and only few windings are needed for the required inductance. The stray field is very low, because of the high permeability of the ferrite. But ferrite cores have technical limits, which can be seen in the temperature rises in Figure 5.

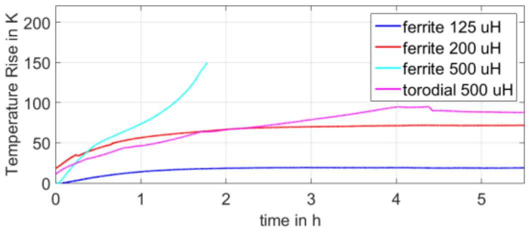

Figure 5: Temperature rise tests of inductors. Irregularities of the temperatures result from adjustment of the test current.

Smaller inductance values show good performance, but temperature increases strongly with increasing inductance. The hot-spot temperature arises at the ferrite core. The losses increase with higher flux density. Beyond a certain temperature limit, the core losses increase significantly. For the required rating, the ferrite cores also showed effects of thermal runaway, resulting in very high temperatures and gob odor. Consequently, the inductors would have to be upscaled, or several inductors would need to be operated in series. Alternatives were researched in order to fulfill the requirements. Cylindrical coils are not suitable because the stray field causes eddy currents in metal parts, which decreases the inductance and increases power losses. The best results were achieved with toroidally wound air coils with litz wire. Air coils do not show thermal runaway. The temperature rise at the required ratings still reaches high levels, but can be handled by the use of adequate materials. Furthermore, the temperature rise can be reduced with increased litz wire diameter. The limited space requirements can also be handled with the toroidal design.

The transformers in the converter, the transmission path and the rectifier also increase the overall inductance and further help reducing the resonant frequency. But these inductances are low compared to the required overall inductance.

3.3 RECTIFIER

The rectifier needs a transformer, which is able to transform 15 A/10 kV to levels of 5000 A/30 V at kHz-frequency. One single transformer is hardly technically possible. Therefore, a modular concept was chosen to split the electrical stresses over several modules. Figure 6 shows the circuit [3]. The 2.5 kV voltage is divided over 100 transformers of 25 V primary voltage. Each transformer must be able to insulate the voltage between primary and secondary winding. One 25 V/ 60 A transformer feeds two M2 rectifiers, so that no open circuit in the transformer occurs in case of a failure of one rectifier. In the beginning, the M2 rectifier was planned as synchronous rectifier, since this offers high potential to reduce power losses. During the upscaling process, this idea had to be revised. Figure 7 shows the main reason for it.

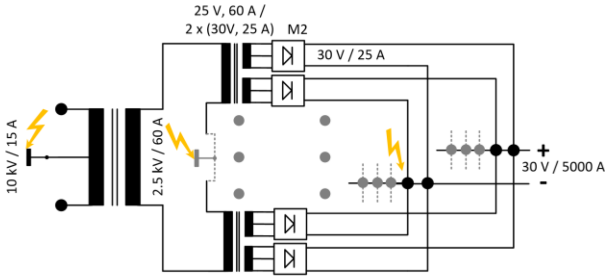

Figure 6: Rectifier circuit [3]

The MOSFETs in the synchronous rectifier have to be switched on (time t_{ON}) and off (time t_{OFF}) during the conducting phase of the rectifier by a controller. The switching process results in losses. Since many modules need to be controlled in parallel, the control unit has to be slowed down with RC low-passes. The main reasons are stray parameters in the circuits, which caused failure switching of the controller. The RC low-passes homogenize the stray parameters and reduce their influence. But the time to switch the MOSFETs on and off (t_{ON} and t_{OFF}) increases, which in turn increases the overall losses. In conclusion, the losses of a parallel synchronous rectifier are only slightly lower compared to normal rectifier diodes. Furthermore, the active controller forms a weak point for electromagnetic interferences (EMI). Damages in case of neighbored gas discharges in high-pressurized SF_6 could be observed. Furthermore, the MOSFET switching causes notable noise for other sensitive laboratory measurements (e.g. partial discharge measurement). In conclusion, conventional Schottky diodes were chosen, since their losses are similar, they are less sensitive to EMI effects, and no other measurements are disturbed.

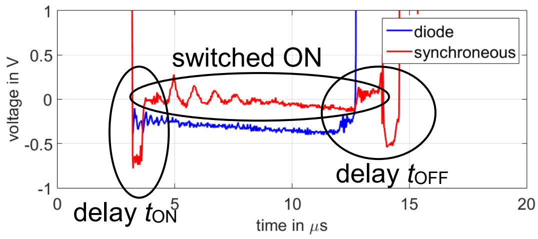

Figure 7: Voltage drop across rectifier configurations

Due to the high frequency in the kHz range, the current ripple of the rectifier is very low, without much effort for smoothing with capacitors and inductors. Current ripples of less than 0.5 % have been measured. With increasing testing loops, these levels can be further reduced.

In case of failure the diodes will be short-circuited. In order to avoid the total current flow of 5000 A through the short-circuited diodes, fuses are integrated in each rectifier module.

4 CONSTRUCTION

Based on the fundamental findings of chapter 3 the main components of the generator were manufactured to achieve ratings up to 5000 A DC current at 660 kV DC potential.

4.1 AC-AC CONVERTER

A 30 kW prototype of the converter is shown in Figure 8. The 3-phase 50 Hz supply voltage is fed into 6 parallel circuits. Each circuit is equipped with an overload detection, a rectifier and a DC link capacitor. The DC voltage is applied to the converter boards, which operate in parallel. Each converter board output is given to a transformer primary winding. The secondary windings of the transformers are connected in serial. If more power is required, several racks would have to be connected in serial to test larger test loops. The driver circuits to switch the MOSFETs are connected to the converter boards. All drivers are controlled by the same controller to ensure that the converters switch simultaneously. The input terminal is located at the top rack unit. The output of the rectifier is a rectangular voltage, since this voltage shape is easy to achieve.

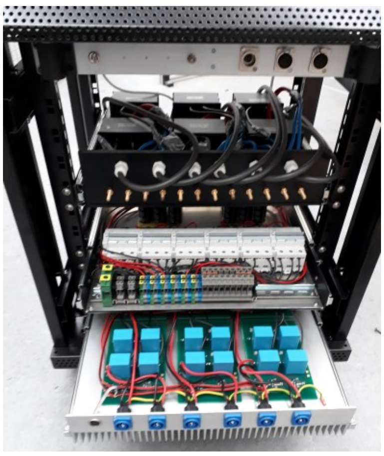

Figure 8: 30 kW AC-AC converter

4.2 CAPACITIVE TRANSMISSION PATH

The internal and external assembly of one 150 kV capacitor is shown in Figure 9. Several of these capacitors are stacked for higher voltage levels.

The capacitors are mounted on insulating bars. The connections as well as the parallel resistors are soldered. In order to control the electrical field at the sharp edges of the connection points, each connection point is shielded by a sphere. The assembly is mounted in hollow insulators, which are then filled with oil. This improves the dielectric strength as well as the thermal heat transfer. The toroidal coil is assembled below the capacitors. To insulate the resonant voltage of the inductor, the electrical potentials need to be insulated with insulating plates. The toroidal coil consists of several litz wire layers, which are twisted to achieve homogeneous current distributions among the layers.

Figure 9: 150 kV transmission path capacitor with inductance: internal capacitor stack (top left), internal inductor (top bottom), housing (right)

4.3 RECTIFIER

One individual rectifier module as well as the connection of several parallel modules to form the 5000 A rectifier are shown in Figure 10.

Each module consists of four rectifiers operating in parallel and provides a maximum current of 100 A. The transformer at the top provides the voltage for each M2 rectifier. The rectifier board is directly mounted on cooling devices. The rectifier board output is connected to the plus and minus busbars of the module. The modules are connected in an array, which is connected to the main 5000 A plus and minus busbars. Additional electronics at the front of the rectifier feed the auxiliary circuits, such as measuring devices or fans.

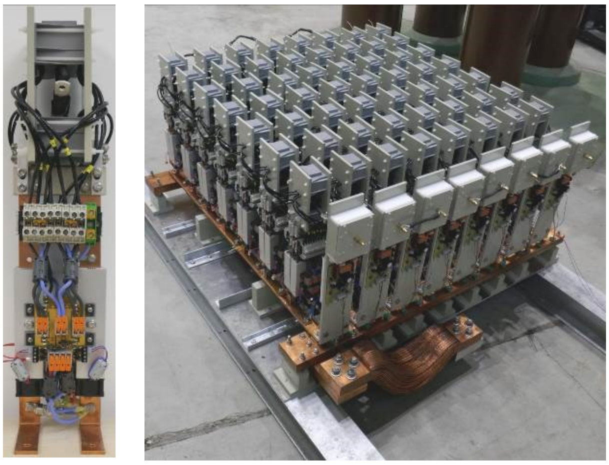

Figure 10: 100 A module (left) and 5000 A DC rectifier (right)

5 COMMISSIONING

Each component has to successfully pass a commissioning procedure. The commissioning of the overall assembly is still in progress.

The AC-AC converter successfully generated its specified power rating at ohmic loads. The temperature rises of its components were much lower than the allowed limits. The capacitive transmission path was tested with 15 A at 50…60 kHz and 150 kV DC voltage. For this purpose, two capacitors as shown in Figure 9 were connected in parallel and short circuited at both top electrodes. High DC voltage was applied to the top electrodes, while the high frequency current flew through the loop from earth electrode one to earth electrode two. The components successfully withstood the stresses. Each 100 A module as well as the final 5000 A rectifier were successfully tested. The current distribution among the rectifier modules was determined to be ± 5%.

Further service experience must now be made with the components. Especially the long term performance is of interest, because the generator has to operate in long time cycles (e.g. continuously for one year). In the final step the full assembly has to be built up to operate the generator at the specified ratings of 5000 A and 660 kV.

6 CONCLUSIONS

In this contribution a new generator concept has been presented that is capable to inject a DC current of 5000 A at a high DC potential of 660 kV. The technical parameters have been given, together with some particular challenges during the design and construction phase. The main components of the generator have been explained in detail. So far, the generator concept seems to be technically feasible.

Assembly and commissioning of the final 5000 A / 660 kV generator is still in progress. Each individual component was tested successfully. Converter, transmission path and the 5000 A rectifier are able to operate at the required technical ratings. Further experience, especially tests on long term performance, with the new generator concept and the generator design have to be gained and will be reported later.

ACKNOWLEDGMENTS

The authors gratefully acknowledge support of this work by the IWB-EFRE-Program by the State of Hessen (Funding Code 20002558).

EUROPEAN UNION
European Regional Development Fund
Investing in your future

HESSEN

REFERENCES

[1] C. Neumann et. al. “Some thoughts regarding prototype installation tests of gas-insulated HVDC systems” CIGRÉ Winnipeg 2017
[2] IEC 62895:2017 “High voltage direct current (HVDC) power transmission - Cables with extruded insulation and their accessories for rated voltages up to 320 kV for land applications - Test methods and requirements”
[3] M. Hallas, V. Hinrichsen “General overview of AC and DC current injection on high voltage potential for HVDC long-term tests” CIGRÉ Hakodate 2019
[4] M. Hallas, T. Wietoska, V. Hinrichsen “Generator for Current Injection on High DC Potential to Test HVDC Equipment” ISH Buenos Aires 2017
[5] W. Schufft, S. Schiering “Developmets in Power Engineering and their Demands on High-Voltage Test Equipment” ELECO 1999.
[6] B. Yang, “Device for Testing Load of superconducting High-Voltage DC Cable”, patent WO2014046467 A1.
[7] Vishay MKP1848C55012JK2 “Metallized Polypropylene Film Capacitor” www.vishay.com accessed 09.02.2019
[8] Vishay MKP386M482250YT3 “Metallized Polypropylene Film Capacitor” www.vishay.com accessed 09.02.2019

This is a post-peer-review, pre-copyedit version of an article published in "Proceedings of the 21st International Symposium on High Voltage Engineering". The final authenticated version is available online at: https://doi.org/10.1007/978-3-030-31680-8_140