Setup of an outdoor hybrid AC/DC test line for corona measurements

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Abstract

While the installed capacity of remote renewables is increasing around the globe, the construction of new transmission lines is often delayed due to public opposition. Therefore many operators evaluate the option of an uprating of existing corridors. A conversion of existing tower infrastructure to hybrid AC/DC lines allows a significant capacity increase without low visual impact. Possible negative effects such as corona audible noise and electromagnetic fields will be a main factor for the acceptance and hence success of this conversion. However, only few experimental studies have been presented with regard to the corona effects of hybrid lines. Therefore, ETH and FKH have constructed an outdoor test line which allows to study these effects under realistic conditions.

The Däniken test line allows to measure the corona performance of a hybrid section of 35 m length for typical conductor bundles and operating surface gradients. The ground clearance, the AC-DC separation distance and the voltages can be varied in order to study different ratios of coupling between both sides. The safety system and voltage control is designed to be able to run autonomously for several days in order to capture long-time trends in changing weather and pollution conditions. Existing sensor concepts were upgraded in order to cope with harsh environmental conditions such as heavy rain, as these are often the worst case for corona effects.

1 Introduction

Many countries face a demand for higher transmission capacity while public opposition against new overhead lines causes significant construction delays. Through a partial DC conversion of existing double AC overhead lines to hybrid AC/DC lines allows for a significant transmission capacity upgrade without additional landscape disruption [1]. While a previous study shows a general favour of the public for a conversion compared to a new construction, the survey results have demonstrated that the public is very sensible with regard to negative effects, such as the impact of electric fields on humans and corona audible noise. Therefore a clear understanding and precise prediction of negative corona effects is of huge importance for the success of a hybrid conversion. Currently, hybrid lines are discussed in various countries around the globe [2]. While plenty of experimental data and operational experience has been published for AC corona in the past [3], only few measurements have been published with regard to DC and hybrid AC/DC corona effects, especially from large outdoor test setups. While AC corona loss and audible noise both increase with rain intensity [4], previous studies have shown that while in DC rain is still the worst case for corona loss, the audible noise is worst in dry weather due to pollution [5]. Furthermore, DC ions will not oscillate in the conductor vicinity due to the absence of an alternating field. Hence, the additional audible hum from the ion oscillation does not appear with HVDC lines [6], but the constant ion drift to ground will increase the ground level Poisson electric field. Additionally, ions will drift to adjacent AC bundles and earth wires, causing DC current component in these systems and their transformers. Furthermore, the energization of the DC side should cause a field bias on the AC bundle while the AC energization should cause an AC field ripple on the DC bundle. While these coupling effects could cause a significant change in the corona performance of hybrid lines, only very few studies exist to the authors knowledge.

Hybrid AC/DC lines have first been introduced by BPA in the 1980s [7]. In a first outdoor test series, it was shown that the AC audible noise is affected by the amplitude and polarity of a DC bias. However, in a later test series by EPRI [8], results regarding the effect of the bias polarity have been inconclusive, demanding for further tests. Furthermore, numerical studies of IREQ [9] have demonstrated that the ion current coupling between the AC and DC system could further increase the AC surface gradient and should therefore increase corona effects.

In this regard, measurements of EPRI [8] and ETH [10] have shown that the DC current in the AC side is increased if corona is present on both sides. In order to better understand these coupling effects between the AC and DC side, further indoor tests have been conducted at ETH [11]. The results have shown, that both the AC and DC audible noise can be increased through a field bias or ripple respectively, if the adjacent system is energized. Additionally, these results have raised the conclusion, that the corona is not only affected by the pure electrostatic field coupling but also increased by coincident ion drift.

Recent outdoor tests in Germany have studied the audible noise and ion current coupling on a full tower geometry. While very interesting data was collected for the bipolar DC corona coupling in grounded conductors [12], only few data points are available for a synchronous AC and DC energization in rainy conditions. Based on previous indoor

Figure 1 Overview of the Daeniken test setup (Photo: Joshu Jullier, Swissgrid AG)

results on the simultaneous corona on the AC and DC side [10, 11], this raises the question if this corona interference is negligible for full-size outdoor geometries and both sides could indeed be treated individually. Therefore, an outdoor test line was constructed to specifically investigate these coupling phenomena under realistic dimensions and weather conditions. The measurement equipment is designed for long-term testing in order to capture slow trends as pollution [5] as well as the dynamic corona characteristics during weather transitions for AC [13] and DC [14].

2 Setup & Instrumentation

2.1 Mechanical setup & electrical design

The mechanical setup of the outdoor test line is designed to allow maximum flexibility regarding possible conductor arrangements. The conductor height can be varied using electrical winches up to a maximum ground clearance of 8 m. Thereby the conductors can be lowered to ground level in roughly two minutes. This allows to access the measurement devices placed within the toroids, e.g. to change batteries. Also, the separation between the AC and DC bundle can be changed at ground through freely changing the clamp position of an additional tensioning wire. This allows to simulate different tower arrangements with typical separation distances of 6 to 12 m between AC and DC. The conductor bundles are strung between an existing set of four towers allowing a maximum length of 35 m as shown in **Figure 1**. The used double bundles are frequently used in several European countries. Likewise, the AAAC conductors have a cross-section of 600 mm^2 which is typical for existing AC bundles in Switzerland and therefore representative for a possible line conversion. The insulators were designed by Pfisterer Sefag AG based on a creepage length of 34 mm/kV for both AC and DC side. While pollution is expected higher for the DC side, it is assumed that a hybrid conversion will use insulators of equal length to switch sides in case of maintenance. The high voltage connection and the DC current measurement system are placed within a set of double toroids to avoid discharges from anything besides the conductors affecting the measurement of corona current, audible noise and PD.

2.2 Voltage supply & safety

The AC voltage supply is provided using a mobile gas-insulated Haefely-Trench TSSV 510-90-50 transformer with a maximum Voltage of 510 kV. The DC voltage supply is realized using an existing 1 MV Moser-Glaser AC outdoor transformer with a 400 kV HIGHVOLT outdoor rectifier diode and a smoothing capacitor. While the capacitive divider for the AC voltage measurement is directly included in the transformer bushing, the smoothing capacitor with a defined parallel resistance can be used for the DC voltage measurement and PD measurement.

* While both sources can be ramped up independently, they are coupled over a common safety circuit, which is monitored by a Yokogawa SmartDAC GP20 data recorder. The recorder is used to measure and control the voltages and currents on both sides and to survey the safety circuit. Tolerances are defined for the AC and DC voltages and the Yokogawa will automatically regulate the voltage to fulfill the tolerance conditions. If the maximum voltage or temperature of one of the sources is exceeded, the recorder will shut off both generators immediately. As both generators were not specifically designed for long-time use of multiple hours or even days, specific care was taken regarding their operating temperatures under load.

* Therefore, the heating curves of both generators were investigated for pure AC and DC as well as parallel operation, where current coupling might generate additional heat in the adjacent generator. These studies have shown that the temperature of the DC side is very steady with an negligible increase after several hours of operation at the maximum voltage of 400 kV in dry summer conditions. The AC generator, however, showed a significant temperature increase over time at the desired operating voltage of 265 kV. At this level, the maximum operating temperature specified by the manufacturer minus a safety factor of ten degrees was reached after eight hours in dry summer weather. It was verified, that the heating curve is almost identical under pure AC operation, compared to a hybrid operation with additional DC current potentially heating up the AC transformer. Therefore, the heating is mostly caused by the capacitive load of the overhead line and could only be compensated on the high voltage side. Hence, the on-time of the AC side is limited to roughly eight hours depending on the environmental conditions while the DC side is considered to be safe to run for several days. While the change of conductor pollution over time is assumed to be a long-time process for DC, the transient changes in rain intensity and drop distribution on the conductor show a much faster transition. Thus, while applying the DC voltage continuously adds a significant benefit, the maximum operation time of eight hours is considered sufficient for the AC side.

For safety, the whole test corridor is surrounded by a grounded fence which is included in the safety loop. Furthermore, the fence is equipped with multiple emergency stop switches and warning lamps during operation. If desired, both generators can be switched off remotely even if the recorder has no network access.

Figure 2 Weatherproof Wilson ion current plates

Figure 3 DC electric field measurement

2.3 DC corona current

The average DC current is a good indicator for the DC corona loss and average DC corona activity as well as the relative ion current coupling between the DC and AC side. Thus, the DC current is to be measured on high potential. Therefore, an IP 67 Extech E540 multimeter is placed in series between the voltage source and the test line. By use of a battery pack, the average on-time of the multimeter was extended to at least 50 days during Winter in the Swiss Alps [15]. This allows to conduct long-time tests without the need to lower the conductors regularly to change the batteries. Both the sensor and battery pack are placed in an IP67 Peli1150 protector case.
During commissioning, the multimeter was found to be very susceptible to errors if the DC component of the current to be measured is much smaller than its AC component. This is the case for the DC current on the AC side, which is in the low μA range while the AC charging current due to the line capacity reaches several ten mA. Therefore, additional low-pass filtering is necessary to avoid any influence of the AC voltage on the DC current measurement.

2.4 Ion current density

The ground level ion current is an important factor for the perception of electric fields. This is especially true as the ion current can be used as a reference to calibrate existing prediction models for the electric field. To measure this quantity, a set of sensors was designed based on the Wilson-plate concept [16]. Therefore, a measurement electrode is only connected to ground over a shunt resistor which allows the measurement of an ion current coupling to ground over a defined area. In contrast to a laboratory application, the plates are exposed to heavy rain and therefore have to be designed to be waterproof [17].
Hence, in order to avoid a short circuit of the measurement shunt through a conductive water path between the measurement electrode and the ground electrode, the measurement electrode is supported by outdoor insulators with a height of 6 cm. The guard ring is supported by steel rods of the same height to ensure a low contact resistance and shielding of the elevated measurement electrode. The dimensioning of the electrodes had to be designed as a compromise between spacial resolution, accuracy and handability. As a final design, the measuring electrode is 0.7 m times 0.7 m with the outer dimensions of the guard ring and base electrode of 1 m times 1 m. The outer shielding ring and the measurement electrode are separated by a gap of 2.5 cm in order to avoid shortening of the shunt resistor if water is bridging this gap. The edges of the guard electrode were added a fillet to reduce inhomogenities. With these dimensions, the plates are handable and allow 11 plates to be placed within the measurement corridor to investigate the lateral distribution of the ion current as shown in **Figure 2**. To ensure rigidity and resistance against corrosion, the plates were manufactured from stainless steel. A plastic foil is placed below and around the plates to avoid grass growing above the measuring electrode. A grounded aluminum mesh is then placed on top of the foil to ensure equal potential distribution. In order to maximize the signal-to-noise ratio, the shunt resistors are not equal, but chosen lowest directly below the DC line and highest at the outer end of the corridor. The voltage over the shunt resistors is then measured using Labjack T7Pro A/D converters connected to the measurement PC via Ethernet. The plates are connected radially as short as possible to the converter in the measurement box using coaxial cables and IP 67 proof TNC connectors against water submersion. In order to filter out the AC current from capacitive coupling, capacitors are added in parallel to the shunt resistors.

2.5 Electric field

The ground level electric field can be perceived as a nuisance and is therefore an important design criterion for a hybrid AC/DC line [8]. Regarding its measurement, various commercial probes are available, however most of them are designed for a different range of electric fields in indoor applications. Therefore, a set of four Monroe Electronics 1036F vibrating-type probes are installed as shown in **Figure 3**. Through a change of the standard aperture to

Figure 4 Noise measurement with super-cardioid microphone

a smaller size, the measurement range could be reduced to 100 kV/m. When pressurized air is connected to the probe, humidity and insects can be hindered from entering the sensor. Still, the probe has to be inverted to allow safe operation in rainy conditions according to [16].
Based on a prestudy in the HVL laboratory, two main concerns were raised [17, 15]. Firstly, it was shown in a small scale setup, that the correction factors for an inverted probe operation varies between the space-charge free case in contrast to a measurement with DC corona and hence space charges. Also, the DC electric field sensor was found to be prone to errors with regard to strong AC coupling. If the AC electric field at ground is high enough, the probe will be subject to a significant capacitive current. As this current can be magnitudes higher than the displacement current proportional to the DC electric field and not much lower in frequency, the probe cannot clearly differentiate between AC and DC electric field in a hybrid operation. Therefore, ETH is discussing the option of an in-house design of an electric field probe, where additional filtering of the raw signal can get rid of the AC component. Ideally, this probe is designed to be waterproof to avoid the inverted operation.

2.6 Audible corona noise

One of the main factors for the acceptance of an overhead line project is the audible noise [1]. While the test site does not have substantial traffic noise, a nearby factory creates a relatively constant background noise. Furthermore, bird noise can be substantial throughout the day. Therefore the audible noise measurement is mostly interesting at night were also the noise emission from the test site can be avoided. In order to further increase the signal-to-noise ratio, two concepts were developed.
Firstly, two optical fibre microphones are placed in the centre of the double bundle were the electric field is very low and the impact of the fibre on the surrounding electric field is negligible. However, the fibre is sensible to mechanical damage and can easily be damaged due to icing and heavy wind. Also, discharges on the fibre surface can occur in areas of high electric field, e.g. along the insulator or bushing, when the fibre becomes conductive due to precipitation or wind. While a microphone placed at mid-span captures its direct environment very clearly, discharges further along the line will be less strong and hence not act as a line source. While the fibre microphone is specified as waterproof , it is mounted with the aperture facing to ground to avoid the membrane being mechanically affected by the water. As the whole device is entirely made of synthetics and non-conductive, the measurement is not affected by alternating fields as for condenser microphones.
As a second option, two super-cardioid directional microphones are placed outside of the safety circuit aiming directly at the longitudinal conductor axis and hence away from the factory and adjacent conductor as shown in **Figure 4**. This placement allows to significantly reduce the background noises compared to the noise originating from the line. The microphones are grounded and placed behind the grounded fence to avoid any noise coupling from the AC line electric field. Although these microphones are suitable for outdoor use, they are not entirely waterproof and therefore equipped with a roof against rain directly entering the microphone facing upwards. Furthermore, damping foam was added to the ground directly below as well as on the roof to reduce background noise from rain. Both concepts use an additional windshield which is more resistant against environmental conditions and reduces the wind noise substantially.

2.7 Partial discharge & radio interference

While radio interference causes less annoyance since radio transmission is now mostly frequency modulated or digital [4], it is a very valuable indicator for corona activity. As the radio interference is based on the partial discharge (PD) pulses including an additional weighting function, also the PD itself can be measured instead. The AC transformer's capacitor can also be used for partial discharge coupling. Similarly, the smoothing capacitor of the DC side is insulated to ground and can therefore be switched to the measuring impedance as a coupling capacitor to measure PD using an Omicron MPD600. Furthermore, the current pulses can also be measured on high potential using a battery-powered oscilloscope connected via glass fibre, based on the concept of [18]. However, the energy consumption is too high for a continuous measurement. Hence, a small number of tests is planned to correlate the corona current pulse and audible noise measurement.

2.8 Optical investigation

For a visual inspection of the corona activity, a UViRCO Corocam 7 is used to observe the location and number of corona sources in daylight as shown in **Figure 5**. This includes the localization of partial discharges on the voltage sources and fittings in order to reduce background noise as well as the corona activity on the bundles. Further-

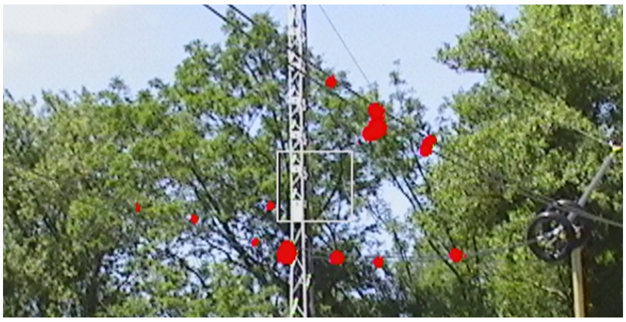

Figure 5 Visual corona inspection using the UViRCO Corocam 7

more, similar to previous laboratory investigations, long-exposure photography is used at night to visualize the distribution of the corona sources [10]. Regular inspections of the surface condition, conductor and insulator pollution as well as drop formation are scheduled as well.

2.9 Weather data

As corona is typically caused by dirt particles, rain drops and other precipitation, an accurate capture of the environmental conditions is of high interest. The Däniken test line is located roughly 400 m from the Gösgen nuclear power plant which is also home to a MeteoSwiss meteorological station providing measurement data of wind speeds, rain rate, temperature and humidity with the highest temporal resolution being 1/10 min. However, a previous investigation [17] has shown that rain sensors are typically designed to measure rather the amount of rain than the rain rate and, if yes, the range is rather aimed at the highest rain intensity and not very precise for typical rain rates below 10 mm/h. Furthermore, experience from the commissioning tests has shown that snow is not well captured by the rain sensors, as it takes a while for the snow to melt and its melted volume is quite small compared to rain. Also, wind speed and direction are rather turbulent due to nearby buildings and tree lines and therefore cannot be captured accurately by the nearby weather station. Therefore, ETH has scheduled to also measure the precipitation onset using an optical sensor which allows to also capture the onset of snow. Furthermore, measurements of the local wind speed and direction are conducted using a 3D-anemometer at the test site.

2.10 Data storage concept

As the setup is scheduled to conduct long-time tests to capture various environmental conditions and slow trends such as pollution, large amounts of data have to be captured, filtered and stored safely. Therefore a data concept was developed [15, 19]. First, all measurement data is collected locally by a single measurement PC. A Matlab script will average data to measurement points of 2 seconds in batches of 10 minutes which are then saved. The whole measurement is monitored by a watchdog script which checks the connection of the measurement devices regularly and will reconnect if necessary. If the size of the data packages is 10% smaller than expected, an e-mail warning is sent. The offline data is stored in a cloud-synced folder. This allows to synchronize data with the remote ETH network access storage without data loss in case of connection loss. An additional ping function will regularly communicate the time stamp with an FTP server, which will regularly check this ping and send an e-mail warning if ping was not updated in a while and therefore data could not be synced.

3 Commissioning & results

As an exemplary measurement from the operation, the results for a hybrid energization are depicted in **Figure 6**. The selected results show the ground level ion current for all 11 ion plates as well as the corona current in the DC conductor. During the operation, first only a DC voltage of 300 kV was applied in the morning for roughly 30 min. While the DC voltage was kept constant, an AC voltage of 265 kV was applied after this phase for 1.5 h. Then again the AC voltage is set back to zero while the DC voltage remains constant. Under these specific conditions, the pollution in winter was very low and the conductor mostly dry with some condensation remaining from the morning dust. Therefore, the absolute levels of corona current and also the ground level ion currents are rather low. However, when switching on the AC voltage, a jump in both these effects was measured without any drastic change in the weather conditions. As expected, the ion current was measured highest for the ion plates closest to the DC conductor (6-8). This behavior can possibly be explained based on the theory that the additional AC ripple causes an earlier corona onset of the DC conductor, as shown previously for laboratory conditions in [11].

4 Conclusion & outlook

A new hybrid AC/DC test line was constructed which allows to investigate the distinct corona characteristics for various weather conditions and pollution over longer time periods. As one of the most interesting test cases, the DC corona activity and audible noise should be investigated in summer when pollution and dry weather corona is highest. Furthermore, the interference between AC and DC corona should be investigated in rain, when corona is naturally present on both systems.

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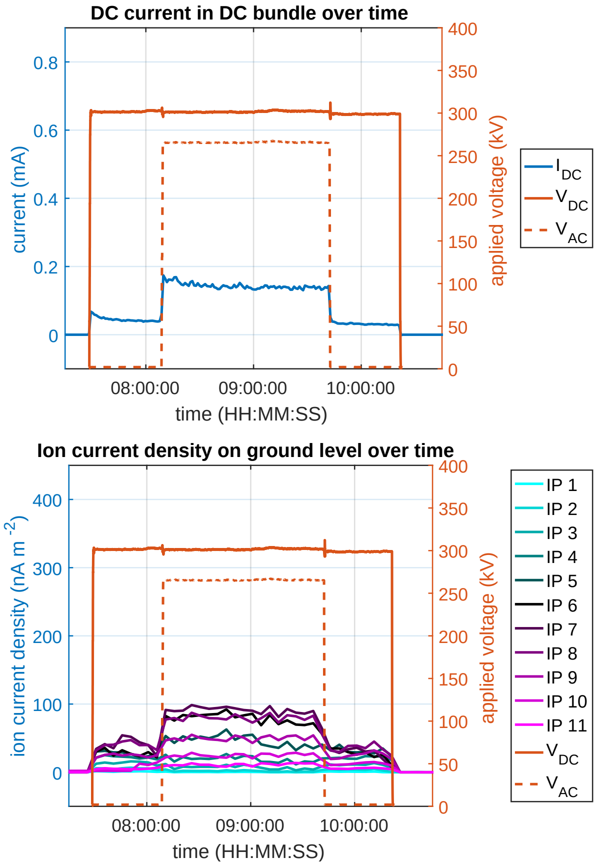

Figure 6 Ground level DC ion currents (left) and DC corona current (right) under DC and hybrid operation

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