Operation of aerial inspections vehicles in HVDC environments Part A: Evaluation and mitigation of high electrostatic field impact

M Heggo\textsuperscript{1}, K Kabbabe\textsuperscript{2}, V Peesapati\textsuperscript{1}, R Gardner\textsuperscript{1}, S Watson\textsuperscript{1} and W Crowther\textsuperscript{2}

\textsuperscript{1}School of Electrical Engineering and Electronics, The University of Manchester, Oxford Road, Manchester, M13 9PL, UK
\textsuperscript{2}School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, Oxford Road, Manchester, M13 9PL, UK

E-mail: mohammad.heggo@manchester.ac.uk

Abstract. Offshore high voltage DC (HVDC) wind farms offer a promising solution to growing energy demands in the future. Condition monitoring of substation assets is essential for reliable and resilient operation of electrical networks. Existing condition monitoring techniques for onshore substation and electrical network assets include regular and scheduled on-site visits by trained personnel to substation sites. However, such routine inspection is not a cost-effective solution for offshore sites. In cases where the accessibility to network assets becomes difficult, robotic and autonomous condition monitoring provides a solution. Such a robotic/autonomous solution would need to interact with the surrounding substation environment, without increasing the risk of electrical breakdown and flashovers between different energized components. In Part A of this paper, the effect of high electrostatic fields on an inspection unmanned aerial vehicle (UAV) is analyzed, with respect to: 1) AC corona emissions interference on the UAV, and 2) Air breakdown clearance characteristics. Both simulations and experiment results presented in the paper show the impact of corona emissions interference to both UAV autopilot and actuation sections, which requires a shielding mitigation solution. Also, experiment results show the limited effect of introducing a shielding solution on increasing the flashover risk between valve hall towers.

1. Introduction

High voltage direct current (HVDC) technology is currently drawing the researchers’ attention as a cost-effective solution for efficient power transmission, especially for offshore sites that use transmission cables [1]. Offshore wind turbines are expected to have 3000 full load hours per year compared to 2000 hours in case of onshore ones [2]. Therefore, operation and maintenance (O&M) is considered a dominant element in HVDC power grids to maintain stable power generation.

Compared to onshore sites, O&M of offshore wind farms is more expensive, since onshore O&M strategy relies on conducting frequent maintenance visits to the onshore sites and holding routine maintenance tasks, which seems to be impractical in the case of offshore sites [2]. This gives a rise of investigating a robotic inspection solution for offshore HVDC power stations [3], which can guarantee high accessibility to offshore assets with minimum human intervention.
One of the main HVDC system components is the valve hall or the converter station, which requires periodic monitoring of its devices [4]. Converter stations play an important role in HVDC grids through efficient power conversion from the AC to DC form at the offshore site for transmission and vice versa at the onshore site for power distribution [1] [4]. The conversion process takes place through valve towers that rely on either thyristor modules or insulated gate bipolar transistor (IGBT) modules [1].

All the converter station components are encapsulated inside a metallic structure known as valve hall to prevent electromagnetic interference (EMI) to surrounding wireless services [1] [4]. The main structure of a typical HVDC valve hall is shown in Fig. 1.

For a 3000 MW, ±500-kV converter station, the devices are rated to a voltage and current of 500 kV and 3 kA [6], respectively, which creates high EMI. These ratings are based on thyristor technology used in onshore HVDC substations. However, offshore HVDC substations will use IGBT technology which may generate different field strengths. Currently, there are no recorded EMI measurements for the HVDC converter stations using IGBT technology. Therefore, we rely on the thyristor module-based technology recorded data. Moreover, the valve halls in the offshore sites are subjected normally to lightning strikes, that can cause EMI to sensitive devices and equipment inside the converter station [7].

1.1. Electrostatic interference mechanisms

EMI inside converter substations can be divided into two parts: 1) Electrostatic field interference, and 2) Magnetic field interference. In Part A of this paper, the focus is on the impact of high electrostatic field interference, while Part B will focus on high magnetic field interference. High electrostatic field inside the valve hall can induce two types of risks: 1) Corona discharge current excitation, 2) Flashover between two valve towers. Simulation models in previous literature [8] were developed to calculate the maximum electric field on the surface of different assets inside the converter station, using numerical methods.

Reported simulation results in [8] show that the electric field inside a 800-kV converter station can reach to 1.5 MV/m in the healthy conditions. This value is expected to increase in case of faulty valve operation, which can increase corona discharge emissions. Different shielding mechanisms are proposed in [8] to avoid air breakdown incidences in faulty conditions, however
corona discharge current phenomenon remains a common hazard in HVDC valve hall. Therefore, in the case of navigating an inspection robotic platform between two valve towers, flashover risk between the valve towers is expected, due to the presence of a floating conductor in the middle.

The nature of high electrostatic fields inside a valve hall can induce a corona discharge current interference to any navigating robotic solution, that can affect its control and communication signals. Hence, a rigorous study should be made for high electrostatic field interference evaluation and mitigation inside converter stations, regarding introducing a remote inspection solution.

In this paper we mainly focus on the breakdown electric field limit which is 3 MV/m as a reference for corona discharge current excitation. Though partial discharge inception voltage (PDIV) is lower than the breakdown voltage, however PDIV value is dependent on several other factors like the robot orientation, electrode shape and robot material. Since the main focus of this study is identifying the most vulnerable parts of an inspection drone to corona interference, the breakdown electric field limit is sufficient at this stage of investigation. Future work can identify the criteria of the corona discharge current interference and excitation, which can then define the corresponding PDIV level.

1.2. Converter substation robotic inspection

Traditional inspections for power stations conducted by expert personnel involves meter readings, temperature measurements [9]. High electromagnetic field environment inside valve hall prevents these monitoring duties to be hold while the HV devices are active. Therefore, online premises monitoring using robots requires different sensors to be installed such as: high definition, thermal cameras and navigation sensors.

Robotic inspection for power substations and power line cables had been introduced and evolved over the last two decades [3], due to the increase in the need for autonomous remote monitoring devices inside these substations.

In [10], a biped line-walking robot was developed for powerline cables inspection, however the impact of the electrostatic field was not considered by the authors. In [11] and [12], a rolling robot was developed for inspection of 735 kV powerline cables. The robot was tested under high electrostatic field conditions, where the areas subjected to strong corona emissions were identified and shielded accordingly.
However, the environment of a converter station is different from powerline cables, which leads to different electrostatic field impact on the drone navigation. For example, the robot inside converter stations has shorter clearance distance available indoors than that available outdoors in the power line cable case, which increase the flashover risk.

In [9, 13–15] several designs for ground inspection robots had been proposed for HV substations, addressing electromagnetic interference problems to robot localization system. In [13], authors presented an inspection robot for the energized ceramic insulators used to sustain outdoors HV bus bars. Authors in [13] relied mainly on the clearance distance outdoors to mitigate the flashover risk. This clearance distance can reach up to 5 m. The clearances are the minimum distances required to avoid flashover in the event of an impulse voltage event, such as lightning and switching impulses. This method is impractical in case of indoor inspection inside the valve hall, since the inspection robot should navigate between two valve towers separated by maximum of 5 m distance, which leaves a smaller clearance distance between the robot and the device.

In [9] and [14], the electromagnetic interference to robot localization was investigated, where both radio frequency identification (RFID) and ultra-wideband (UWB) technology-based localization systems are proposed, respectively for EMI mitigation. In [15], authors used coded orthogonal frequency division multiplexing (COFDM) communication module to avoid EMI to communication signals. However, authors in [9, 14, 15] did not consider high electrostatic field interference to different control signals inside the robot.

Previous literature in [9,13–15] did not include the effect of the electrostatic field interference to the navigation control signals inside the robot and the effect of the shielding solution on air clearance distance inside a converter station. Also, a general simulation model is lacking in previous literature for high electrostatic field distribution over the inspection robot inside the valve hall, to identify the highest vulnerable parts to electrostatic field interference.

Furthermore, authors in [9, 13–15] focused on the use of ground robots for inspecting the converter stations, though multirotor vehicles can introduce a promising inspection solution in terms of high accessibility to the substation towers at different heights and with different camera shooting angles.

Multirotor vehicles had been previously used in inspecting warehouses as in [16]. As shown in Fig. 1, the internal structure of a converter station resembles that of a warehouse. However, the warehouse does not present any electromagnetic field interference to the multirotor vehicle as in the case of the valve hall inspection.

Navigation of shielded UAV inside HVDC valve hall is accompanied with introducing flashover risk. Air breakdown voltage characteristics inside HVDC valve hall were previously investigated in [17] [18]. The authors in [17] states that minimum air clearance inside ±500 kV is 4 m, while the clearance distance should be 8 m for ±800 kV valve hall. The impact of the presence of a floating conducting sphere in a long air gap was previously studied in [18]. In [18], experimental results prove a decrease of negative air breakdown voltage in presence of a floating conductor in the air gap. However, the floating conductor presence in the air gap increases the positive air breakdown voltage. In this paper, we will study the effect of the presence of a floating cross bar in both positive and negative air gaps. The cross bar simulates the presence of a completely shielded drone close to HV premises.

In this paper, an inspection multirotor vehicle solution is introduced for the inside of HVDC converter station. A systematic evaluation of valve hall electrostatic field impact on different UAV sections is presented. Corona discharge current interference to different UAV control signals is introduced, identifying the highest vulnerable drone subsections to corona interference. Also, flashover risk is evaluated between energized bus bars of the valve towers due to navigation of our shielded inspection drone. Both simulation and experimental models are provided to study corona emission impact and air breakdown voltage change.
In Section II, corona emission interference is studied. In Section III, flashover risk is investigated. In Section IV, the paper is concluded.

2. Corona Discharge

A typical UAV mainly consists of four subsystems: 1) Autopilot, 2) Communication, 3) Sensors payload, 4) Actuation. The main paper aim is identifying corona discharge current interference effect on each UAV subsystem, and also identifying the risk of introducing a shielding solution with respect to changing air breakdown characteristics between valve hall towers. Hence, two experimental setups were prepared to evaluate the risks of corona discharge current interference and air breakdown voltage changing.

2.1. Experimental Set-up

To test the corona discharge current interference on a UAV, a test rig was developed which used two spherical electrodes to generate an electrostatic field. The actual test rig and its descriptive figure are shown in Figs. 3 and 4, respectively.

Two metal spheres with equal diameters (0.2 m) and smooth curvatures were used and mounted 1.02 m apart. This distance is selected since the vertical distance between HVDC valve hall racks is from 1 m to 1.7 m [19]. One sphere was connected to an AC voltage source with root mean square (rms) value of (0 - 800 kV), while the other sphere was connected to the ground. The UAV was mounted between them on a wooden stand, midway between the two spheres. The UAV was secured to the mount so that it could not fly. The performance of the UAV subsystems was monitored remotely using QGroundControl software. The experiment is repeated for three times to validate our observations.
The voltage of the AC source is adjusted at the beginning of the test to 25 kV with a step increase of 20 kV. The drone is manually controlled using a wireless remote control (RC), which can adjust the drone throttle, yaw, pitch and roll through sending the correct pulse width modulated (PWM) signal. The PWM signals are processed in the drone autopilot and mapped to the speed controllers of the drone motors, which further translate those signals into PWM current for motor driving. For safety purposes, the drone throttle is adjusted to minimum and the drone propellers are removed during the experiment. Different drone sensors’ readings are sent through wireless communication and monitored through QGroundControl software.

2.2. Results

The drone motors preserve their nominal operation until the AC voltage exceeds 200 kV. At rms voltage levels above 200 kV, the drone motors stopped working, and the speed controller forced a software reset of the whole system. The speed controller of the motor has a protection mechanism in case of sudden increase of the motor current consumption above 30 A. To better understand the main reason of this software reset, the control signals are analyzed between the drone communication, autopilot and actuation sections.

The unloaded test allows safe margin for any possible increase in the current consumption due to external interference, which is not the case in the loaded test that is already high in current consumption. The current consumption is registered for the total current consumed by the drone motors and components. In the unloaded case, the nominal current consumption of the drone at minimum throttle is 1.4 A. The nominal width of the PWM signal output from the drone RC and flight controller are 982 µs and 1230 µs, respectively.

![Figure 5: Corona discharge current interference to UAV control signals at AC source voltage = 200 kV](image1)

![Figure 6: Corona discharge current impact on UAV current consumption at AC source voltage = 200 kV](image2)

In Fig. 5, the received PWM signal of the drone RC and the flight controller for the throttle control channel are mapped versus time. A spike can be observed at time instants 80 s and 120 s, simultaneously. Since, the drone throttle is preserved at its minimum level throughout the experiment, those spikes are expected to occur as a result of corona discharge current interference, which can affect the received communication signal and hence the resultant flight
controller signal. In Fig. 6, the current drawn by the motors is plotted versus time. Current spikes are observed at the same instants of spikes in the PWM control signals. However, the current exceeds 18 A in the second spike, which is more than the maximum current that can be drawn by the drone motor in unarmed case (i.e. without propellers). This shows the effect of the corona discharge inference on the motor speed controller performance.

2.3. COMSOL Simulations

To validate the experiment results, a simulation model using COMSOL software was developed. A computer-aided design (CAD) model of the UAV was imported which took into consideration the different materials used in construction. The simulation model is shown in Fig. 7.

The HV spherical electrode is connected to 200 kV voltage source. The distribution of the electric field over the drone surface at different azimuth angles with respect to z-axis is computed and shown in Figs. 8 - 9.

In Fig. 8-a, the electric field at the UAV autopilot edges exceeds 3 MV/m for an azimuth angle = 0 degrees. In Figs. 8-b, 9-a and 9-b the electric field at the UAV motor edges is registered to be 3.4 MV/m, 5.1 MV/m and 7.5 MV/m at different azimuth angles. This shows that both the surface of the drone autopilot and motor achieve an electric field above 3 MV/m, which is the electric field magnitude required for corona onset.

The simulation results explain the interference detected through our experiment to the control signals at the autopilot and actuation sections of the drone. Both autopilot and motor sections in the drone can achieve an electric field greater than 3 MV/m, which makes both sections highly vulnerable to corona discharge current interference. Though carbon fiber is used as a material
Figure 8: Electrostatic field impact at azimuth angle $\omega = 0$ degrees on (a) UAV autopilot section (b) UAV actuation section

Figure 9: Electrostatic field impact on UAV actuation section at (a) azimuth angle $\omega = 120$ degrees (b) azimuth angle $\omega = 240$ degrees

for the propellers in simulations, the electrostatic field distribution is maximum at the motor and autopilot edges as they are more conductive.

3. Air Breakdown Voltage

To avoid the corona discharge interference, a shielding solution is recommended. However, navigating a floating conductor inside the valve hall can introduce the risk of changing air breakdown characteristics inside the valve hall. Hence, an impulse test was conducted to evaluate the maximum change of the air breakdown voltage in the presence of a floating conductor.

The impulse DC test setup is shown in Fig. 10, where the drone model is tethered in the midway between two rod electrodes. The drone model is a cross aluminum bar which has the
same dimensions of a typical drone (0.5 m X 0.5 m) and thickness of 0.01 m, which represents the worst-case shielding scenario. The upper rod electrode is connected to a HVDC power supply, while the lower electrode is connected to ground. The two electrodes are separated by 1.7 m air gap distance. This distance is selected since the vertical distance between HVDC valve hall racks is from 1 m to 1.7 m [19].

In negative impulse test, the breakdown voltage between the two electrodes is found to be -1.158 MV and -1.126 MV in both absence and presence of the drone model, respectively. In positive impulse test, the breakdown voltage between the two electrodes is found to be 1.021 MV and 1.002 MV in absence and presence of the drone model, respectively.

The experimental results agree with the results introduced in [18], in case of negative air breakdown. In positive air breakdown, the aluminum cross bar floating conductor decreases slightly the breakdown voltage compared to a corresponding increase in case of using spherical conductor.

Within the realms of these tests, there has been no change to the breakdown voltage but further investigations would need to be done to confirm other parameters and probabilities. This is considered as a preliminary result, which needs further testing using real shielded drone
at different orientations and distances from energized electrodes.

4. Conclusion

Online monitoring of HVDC valve halls using inspection UAV is a promising solution, especially in offshore sites. The impact of high electrostatic field on different UAV components has been investigated in this paper, using simulation models and experimental setups. Both simulation and experiment results show that UAV autopilot and motor sections are highly vulnerable to corona emissions. Experiment results show the effect of corona discharge current interference on changing UAV motor speed and current, through interfering to control and communication signals. Failure in motor and autopilot sections can lead to uncontrolled UAV navigation that could harm expensive assets inside HVDC valve hall. Also, the results show the limited impact of introducing a shielded UAV solution on changing air breakdown characteristics inside HVDC valve hall. Both simulation and experimental models developed in this paper could be used for testing different inspection UAVs, which are used inside valve halls.

Future steps to current research include more experimental and simulation work to test real shielded UAV in high AC/DC electrostatic field. This work should investigate the immunity of the shield against high field and also, the shield impact on air breakdown characteristics inside HVDC valve hall.

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