SWITCHING IMPULSE AND DC EVALUATION OF 800KV HVDC THYRISTOR VALVE STRESS SHIELDS

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Abstract: In order to satisfy insulation coordination and determine the minimum acceptable and optimised air clearances in company's 800kV direct current (DC) thyristor valve development, a comprehensive test campaign under switching impulse (SI) and DC was conducted to characterise a representative shielded thyristor valve structure with different size, shape and configuration of corona and stress shield. This paper outlines the test object design, the test methods and some results on a prototype thyristor valve stress/corona shield arranged in a representative dummy thyristor valve structure**.** The 50% probability of SI flashover ($U_{50\%}$ voltage) of different clearance was calculated using both the IEC method and another statistical method, from which a set of SI voltage withstand curves was calculated ($U_{10\%}$) for each test object configuration. DC breakdown (rapidly rising) and DC corona characterisation were carried out for air clearances ranging from 3 to 9m on all test object configurations. Corona observations and voltage inception were proved to be an effective method in DC breakdown prediction.

1 INTRODUCTION

Economic transmission of large quantities of power in the region of 6000MW, over long distances, is driving the need to develop HVDC technology up to 800kV and beyond, from the current levels of 500kV and 600kV. This significant increase in operating voltage presents some challenges in terms of converter and insulation design. Particular attention must be given to air clearance and to both optimisation and qualification test requirement to ensure that the valve structure is corona free in normal operation and to eliminate the risks of internal breakdown and external flashover under system and transient overvoltages.

For the purpose of satisfying insulation coordination and determine the minimum acceptable and optimised air clearances, comprehensive switching impulse (SI) and DC breakdown evaluations of a representative shielded thyristor valve structure were conducted with air clearances from ground plane and side walls up to 9m. This was particularly important for assessing the performance of different shield designs and configurations under DC (i.e. breakdown, corona inception) and SI (i.e. $U_{50\%}$ and $U_{10\%}$).

This paper outlines the test object design, the test methods and some relevant results on a prototype UHVDC thyristor valve stress/corona shield arranged in a representative dummy thyristor valve structure**.** The paper also addresses the issues of stray capacitance influencing the SI voltage grading along the test object and the mitigation employed to yield representative voltage distribution along the test object.

The SI tests were successfully conducted for air clearances ranging from 3 to 9m. The 50% probability of a flashover voltage ($U_{50\%}$) was calculated using both the IEC method [1] and another statistical method, from which a set of SI voltage withstand curves were calculated ($U_{10\%}$) for each test object configuration.

DC breakdown (rapidly rising) and corona characterisation were carried out for air clearances ranging from 3 to 9m on all test object configurations. Corona observations and inception voltage were proved to be an effective method in predicting DC breakdowns. Both SI and DC test results were adopted in recently completed UHVDC projects using similar stress / corona shield designs and configuration.

2 TEST OBJECT

The general geometry and testing site configuration of the test object is described in Figure1. There were 5 types of designs or modules consisting of flat plane and tubular shields [2]. Each individual test object is made of a set of three dummy valve modules sandwiched between two identical stress shields, suspended from a gantry via composite silicone suspension insulators. Stress shield design configurations comprised both smooth and tubular stress shields and a combination of both with a footprint of approximately 4m x 2m and height of 4m, and each of the three corona shields and upper/lower stress shields is separated by four 0.5m long composite insulators. The stress shields and dummy valve corona shields stack is about 4m tall, and is suspended by four strings of composite insulator over a height of 5m, to a frame structure of 6m X 6m, on which a grounded mesh was placed as an analogy of hall ceiling.

The practical thyristor valve hall was replicated by building a metal structure with the dimension of 24m x 24m x 24m with two sides covered with metal mesh to simulate side walls. The whole structure also served as a supporting structure to suspend the whole test object assembly. A diagonal bearing beam of 34m long was built on the top of structure, on which a telpher was assembled. The whole test object with its hanging structure affixed to the telpher hook. The telpher was controlled from ground thus the clearance to the two side walls and ground floor, as S_1, S_2 and H shown in Figure 1, could be easily adjusted. The 3-D impression of one test object and its suspension structure is shown in Figure 2.

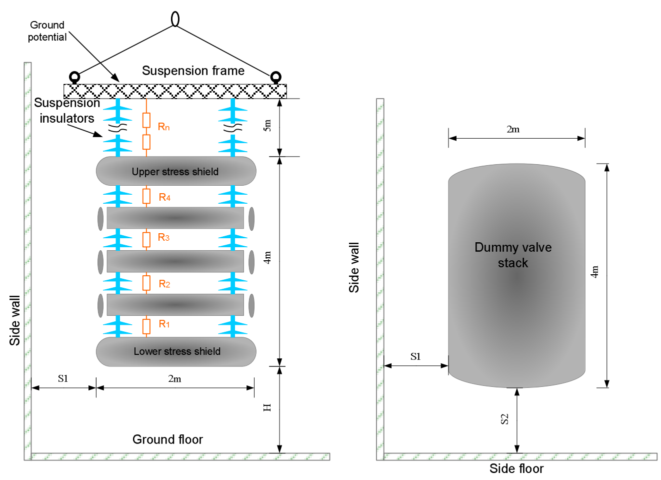

Figure 1, Test object configuration

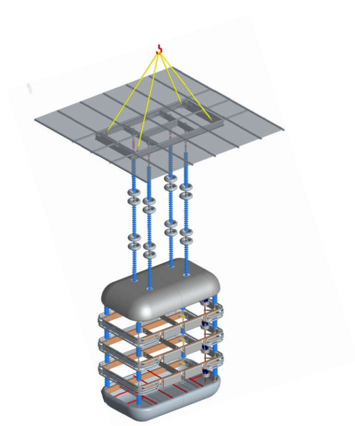

Figure 2, 3-D impression of test object Module 5 with suspension structure

3 DUMMY VALVE STACK VOLTAGE GRADING

In order to make the valve stress/corona shields of the stack to be subjected to appropriate DC and SI voltage during the test, the test object was voltage graded by using dimension resistors and capacitors respectively.

3.1 DC Voltage Grading

DC voltage distribution along the stack dummy valve Modules were graded by a few resistor stacks, R_1 to R_4 as shown in Figure 1. Another stack of grading resistors was connected from upper stress shield to the ground mesh ceiling. Top stack resistors consisted of 14-off of 143MΩ connected in series, and resistors connected among dummy modules were 8-off 50MΩ resistors. This DC voltage grading circuit makes the voltage at the upper stress shield is about 83% of the voltage applied to the bottom stress shield, and other 17% applied voltage between bottom and top stress shields are evenly shared by dummy modules.

3.2 SI Voltage Grading

SI voltage grading within the test object is more difficult in comparison with DC voltage due to the existence of stray capacitances among stress/corona shields and to ground. The correct voltage profile would only be obtained if the stray capacitances could be accurately computed among stress/corona shields and ground. The numerical computation method of boundary element method (BEM) was employed by using Alstom Grid “in-house” software for stray capacitance estimation [3], and an equivalent network of the test object under test was created on the basis of this calculation, as shown in Figure 3.

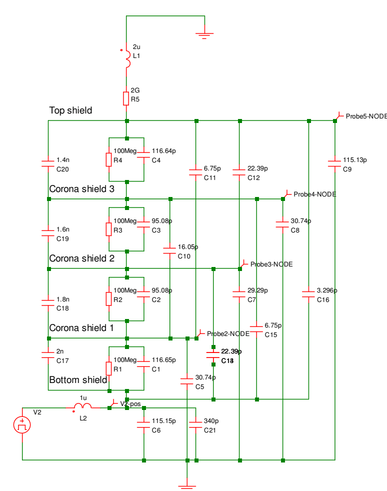

Figure 3, Equivalent circuit of test object and SI voltage grading circuit

In Figure 3, C_{17} ~C_{20} are four high voltage capacitors used with stray capacitor C_9 between upper stress shield and ground to grade SI voltage among corona/stress shields and voltage from upper stress shield (lower voltage) to ground. As the SI voltage at upper stress shield could be as high as 2,250kV if 3,000kV would be applied to bottom stress shield, it would be very costly and unrealistic to connect a physical capacitor from this point to the ground. In the test, the stray capacitor of upper shield to the ground/walls, C_9, was therefore used to act as the low voltage arm in this capacitive voltage divider. The simulation voltage distribution from above grading circuit is shown in Figure 4, in which the voltage amplitude at the upper stress shield is about 75% of the SI voltage at the lower stress shield, and the voltage difference between lower and upper stress shield are evenly shared by all modules.

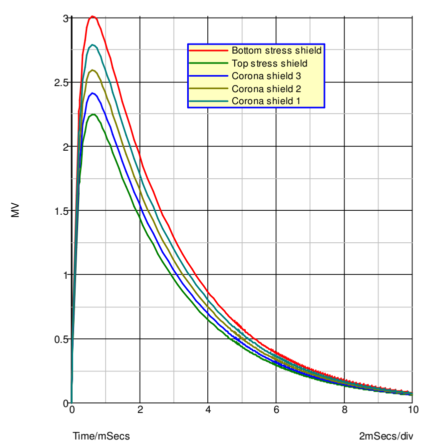

Figure 4, Simulated SI voltage distribution from grading circuit

The arrangement of the resistors and capacitors used for DC and SI voltage grading is shown Figure 5.

4 TEST RESULTS AND DISCUSSION

4.1 Switching Impulse Voltage Breakdown Tests

SI tests were performed on stress/corona shield modules with a corresponding air clearances of 3~9 meters. The standard switching impulse voltage suggested by IEC60060-1:1989 was applied to test objects at positive and negative polarity at each individual test.

In the test, the 50% probability of flashover voltage U_{50} was found by using the voltage up-and-down method detailed in IEC60600-1:1989. The breakdown/withstand voltage results were then corrected for temperature and humidity. The standard deviation σ was calculated. In each test, there were more than fifteen successful impulse applications; the 50% flashover voltage is therefore simply calculated by averaging the prospective crest values of all impulses [1].

Figure 5, Resistive and capacitive grading connection

Additionally, a more complicated calculation, which is explained by Kuffel [4] and used by Ukrainian Transformer Institute (VIT), was also implemented.

U_{50} is calculated by the method of:

$$U_{50} = U_o + \Delta U \left(A/N \pm 0.5 \right) \quad (1)$$

Whilst the standard deviation is determined by:

$$\sigma = 1.62 AV \left(\frac{NB - A^2}{N^2} + 0.029 \right) \quad (2)$$

Where U_o is initial level of voltage applied to test object two or more times. ΔU is the averaged values of difference between neighbouring voltages.

For instance in one test, the total number of shots is n, the total numbers of breakdowns and withstands are n_b and n_w respectively.
if n_b>n_w, then n_i=number of withstands at level j
if n_w>n_b, then n_j=number of breakdown at level j
In equation (1),
if n_i=n_{bi}, use negative sign
if n_i=n_{wi}, use positive sign.
where,

$$N = \sum_{i=0}^{k} n_{iw} \text{ or } \sum_{i=0}^{k} n_{ib}$$

$$A = \sum_{i=0}^{k} i \times n_{iw} \text{ or } \sum_{i=0}^{k} i \times n_{ib}$$

$$B = \sum_{i=0}^{k} i^2 \times n_{iw} \text{ or } \sum_{i=0}^{k} i^2 \times n_{ib}$$

Then the measured 50% breakdown voltage is corrected to U_{50corr} corresponding to standard reference atmosphere by

$$U_{50corr} = U_{50} / K_t \tag{3}$$

K_t is atmospheric correction factor, which is the product of air density and humidity correction factors, as explained in IEC 60600-1:1989.

4.2 SI test results

The SI test results for rod-plane electrode and stress/corona shields of Module 1, 2 (flat plane) and 3(tubular) were compared in Figure 6. Each individual test object is seen possessing a consistent increment in U_{50} when the air clearance increased. From the three test objects, Module 2 gives the highest U_{50} at all test clearances.

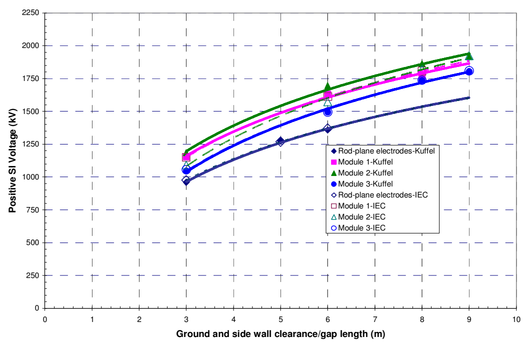

Figure 6, U_{50} of test objects and rod-plane electrodes

Module 3 shows the lowest SI U_{50} compared to the other modules at all air clearances. Regarding the flashover positions, Module 3 is also very different from modules 1 and 2, where the large majority of breakdowns occurred from the lower corona shields with positive polarity and from lower stress shield with negative polarity.

According to the model developed by Rizk [5] and the basis of the continuous leader inception and propagation, the tubular structure of the lower stress shield is likely to exhibit the highest electric field values in localised specific areas in comparison with the flat plane design version of the lower stress shield. As a consequence it is conceivable that a tubular design for the lower stress shield will always generate the lowest inception voltage under positive and negative polarity. This assumption is also in line with the subsequent DC breakdown tests and corona observations, where the lower stress shield of tubular design initiated all DC voltage breakdowns and had the lowest corona discharge inception voltage (DIV). However, this hypothesis needs to be proved by the analysis of electric field test data fed into the FEA model.

Regarding the withstand voltage, or the voltage applied that the test object could withstand (i.e. 0% probability of a flashover), U_0, can be derived from the 50% flashover voltage data by the method suggested in references [1, 4]

$$U_0 = U_{50} - 3\sigma \tag{4}$$

(σ is the standard deviation of the test results)

In practice, for a better optimisation of air clearances the 10% SI flashover voltage probability, U_{10}, may preferably be used to evaluate withstand performance, which is also derived from the U_{50} value by:

$$U_{10} = U_{50}(1 - 1.3z) \tag{5}$$

where z is the conventional deviation of the flashover voltage. For the air insulated systems like the tests described in this report, z=3% can be used. For the normal distribution of flashover voltage, both methods could be used. If a 3% standard deviation is used, above two equations become:

$$U_0 = 0.91 \times U_{50} \tag{6}$$

$$U_{10} = 0.96 \times U_{50} \tag{7}$$

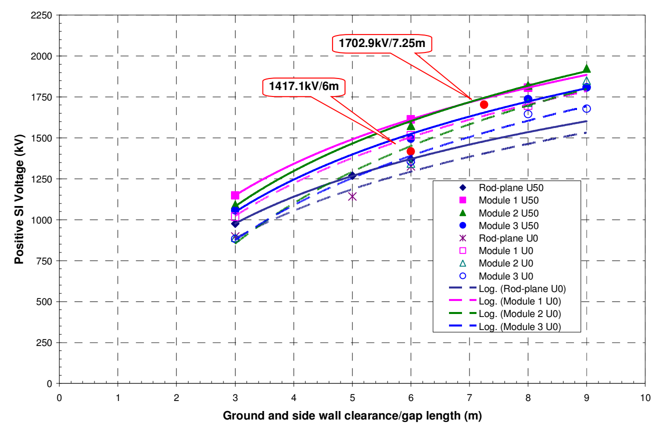

Figure 7, SI withstand voltage (U0%) for Modules 1, 2 and 3 and rod-plane electrode system

The hybrid stress shield design, module 5, has been deployed for ±500kV and ±660kV practical project, and its withstand verification tests of were carried out as well. The withstand voltages at air clearances of 6m and 7.25m are shown in Figure 7 for comparison purposes.

4.3 DC Voltage Breakdown Tests

DC voltage breakdown tests were conducted at positive and negative polarities. In the test, a protective resistor of 200kΩ was connected between test object and the DC generator to limit the current in case of flashover. To reduce the possible corona discharge and flashover from the testing configuration, the high voltage connection was made of aluminium extraction tube with a diameter of 450mm, as shown in the photo of Figure 8.

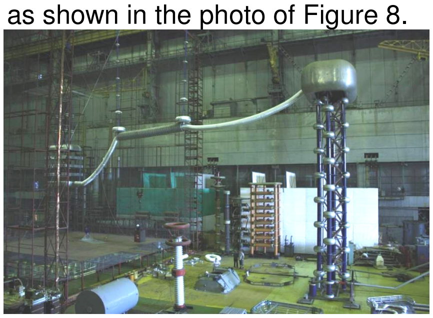

Figure 8, Setup of DC voltage breakdown test

The testing voltage was ramped up constantly at the rate of 100kV per 5~7 second till breakdown occurred. Each test object at the given clearance was subjected to 5 or more breakdown test and the corresponding breakdown voltage for each air clearance was obtained by averaging all the test results.

4.4 DC breakdown test results

The breakdown voltages after atmospheric factor corrections were plotted in Figure 9 against air clearances to ground and side walls.

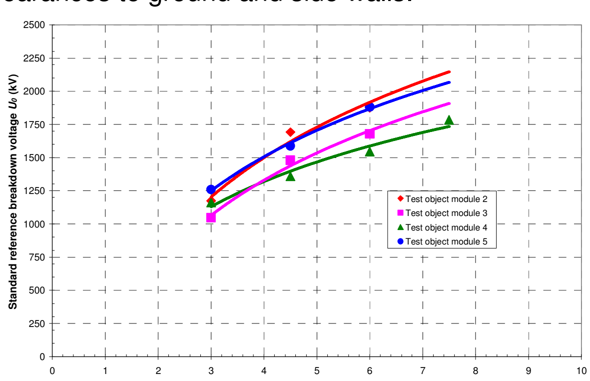

Figure 9, DC breakdown voltages for different air clearances

From the graphs in Figure 9, it is noticed that module 2 and 5 gave significantly higher breakdown voltages than module 3 and 4 except for some the inconsistent values for module 5 at 7m air clearances. By verifying the breakdown positions on above four test objects, it was noticed that, for module 3 consisting of tubular stress/corona shields, all the breakdowns took place from the lower stress shield corner nearest to the side walls. As discussed in the SI tests, it was implied that the tubular lower stress shield in the whole structure of module 3 represented the weakest link as it exhibits the highest stressed and thus leads to the lowest breakdown voltages in comparison with the smooth lower stress shield design.

By contrast, module 2, 4 and 5 which contain flat plane smooth lower and upper stress shield but either flat or tubular corona shields, the breakdown locations varied from stress shield to corona shields. However for module 4, the breakdown voltage is unexpectedly low for air clearance larger than 4.5m. It has not been possible to explain the cause for this discrepancy.

4.5 Corona Observations under DC

Corona observations as a function of DC voltage application were conducted after each DC breakdown test sequence on each test module for each air clearance. The voltage application were constantly raised up to corona discharge inception and increased in steps but kept below breakdown voltage. When significant discharges were identified, the corresponding DC voltage was recorded as corona discharge inception voltage (DIV) for quantitative analysis of DC test breakdown results. The corona discharge activities were recorded by using a UV Camera (CoroCAM) as soon as they occurred in voltage ramping up.

The DIV levels under positive DC stress for the four test objects for different air clearances are presented in Figure 10. Module 3 was once again, showed to be exhibiting significantly lower DIV levels in comparison with other three modules. It also showed that corona discharges were always initiated from the lower tubular stress shield where the highest testing voltage appeared in the whole test object.

For Modules 2, 4 and 5, the first corona discharge always took place from the lowest corona shield, nearest to the side walls and ground plane. These corona shields exhibit relatively higher electric stressed due to their closer proximity to ground potential. The discharges were therefore much more prominent on the upper corners of the flat corona shield corner or the upper tubular section of the tubular corona shield corner. As the voltage was correspondingly graded along the test object, both for SI and DC stresses respectively, higher SI U50%, DC breakdown and DIV level were consistently obtained with Modules 1, 2, 4 and 5 compared to Module 3.

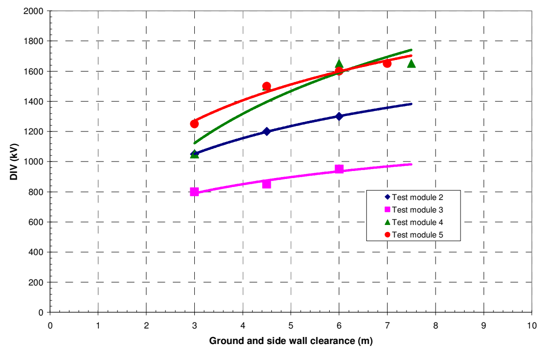

Figure 10, Corona DIV for the different Modules at different air clearances

However, the first initiation of corona discharge on the corona shield corner cannot alone explain the results for the negative SI U50% test result by leader inception [6,7], where most of the air breakdown took place from the lower stress shield rather than the corona shields. The leader propagation (speed) might hold the justification for this situation as one can easily notice the difference between positive and negative corona patterns (i.e. streamer path and path numbers) at their respective DIV levels.

5 CONCLUSIONS

Following conclusion could be drawn from above results and relevant discussion:

- The 50% flashover voltage of module 1, 2 and 3 were successfully conducted at the clearance ranging from 3 to 9m. U_{50} of each test module was calculated by IEC method and the method used by VIT and Kuffel. The results from both methods are agreed very well;
- Regarding to U_{50} results, the test module 3 (tubular design) gave the lowest values among the module 1, 2 and 3, and is about 14% lower than the module 2;
- SI withstand voltages, U_0 of above test objects were calculated by Kuffel's method. Again the test module 3 gives the lowest withstand voltages. IEC standard recommended method suggested for U_{10} (i.e. 10% flashover probability) agrees linearly well with the results of U_0 for the normal distribution. It would be therefore acceptable to use U_0 in engineering practice although it's not suggested in the latest version IEC 60600;
- DC voltage breakdown tests were conducted on test module 2, 3, and two hybrid modules 4 and 5, in which module 2 and 5 have the relatively higher DC breakdown voltages. As expected, the values of module 3 are significantly low;
- Corona observations were performed at different voltages and clearances. Module 5 has the highest corona discharge inception voltage (DIV) at all clearance. The corona discharges always firstly initiated from the lower corona module's bending corner. Whilst module 3 gives the lowest DIV, some of even 40% lower than that of module 5. It was also noticed that corona in module 3 always occurred from lower stress shield around lower part of the corner. This factor could explain why the module 3 has the lowest DC breakdown voltages, probably as well the lowest SI results.

6 REFERENCES

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