AN EXPERIMENTAL INVESTIGATION OF SWITCHING TRANSIENTS IN A WIND-COLLECTION GRID SCALE MODEL IN A CABLE SYSTEM LABORATORY

Muhamad REZA, Henrik BREDER,
Lars LILJESTRAND, Ambra SANNINO
ABB AB, Sweden
{muhamad.reza, henrik.breder,
lars.liljestrand, ambra.sannino}@se.abb.com

Tarik ABDULAHOVIC, Torbjörn THIRINGER
Chalmers University of Technology, Sweden
{tarik.abdulahovic, torbjorn.thiringer}@chalmers.se

ABSTRACT

With the background of experience from field investigations in cable networks, multiple pre-strikes and re-ignitions are known to occur during switching operations, causing high frequency, steep fronted transient voltages and currents.

Off-shore collection grids consist of vast amount of cables, with different length and connection points, which have low surge impedance compared with overhead lines. Consequently multiple pre-strikes and re-ignitions of switching apparatus with cables can cause transient overvoltages with higher time-derivatives than with overhead lines. The validation test circuits specified in the IEC standards developed for impulses due to fulmination on overhead lines do not consider the conditions of large cable grid and repetitive overvoltages due to switching. With the increase of cable grids and particularly wind parks, it has become important to characterize a collection grid cable system and the related transients during manoeuvres with different switching apparatus.

The main contribution of this work is the experimental verification of the transient overvoltage phenomena in cable systems. An attempt is made to characterize this phenomenon in terms of number of re-ignitions, the magnitude and the rate of voltage step.

INTRODUCTION

In overhead line (OHL) systems the transient overvoltages are often related to overvoltages caused by lightning and therefore electrical apparatus is currently tested with a standard lightning impulse – lightning impulse withstand level (LIWL) – of 1.2/50 μs surge. Surge arresters are used as a common protection for these transient overvoltages.

In a cable system like an offshore collection grid, transient overvoltages with multiple pre-strikes and re-ignitions with high time-derivatives can result from an interaction of different electrical apparatuses such as transformers, vast amount of cables – which have a low surge impedance relative to OHLs – with different length and connection points and switching devices, for example during circuit breaker operations in cable system: closing and opening breakers and switches [1-2]. There, the cables act as transmission lines for propagating waves with voltages appearing across the switching contacts or current flowing through the contacts.

Switching transients in three-phase systems can be extremely complex [3-4]. However, generally while opening and closing electrical contacts of any apparatus there is a time interval when the voltage withstand in the apparatus is low enough to allow re-ignitions during closing operations.

ABB WIND CABLE LABORATORY

Background

Characterization of the transients occurring due to switching operation can be made by computer simulation in an electromagnetic transient program provided that the models are verified. Verification can be obtained by field measurements or laboratory experiments. In the former, real-life conditions are recorded, however, it is difficult to record all necessary parameters to reproduce the exact conditions, and it is very difficult to test specific conditions due to commercial aspects (insurance and warranties) and risks involved. In laboratory environment, on the other hand, it may be difficult to realize a down-scaled test circuit that still is representative of the actual real-life conditions. However, if by realizing such test circuit, it would give full flexibility to change parameters, define different test scenarios, and even to test contingencies and faults, which are practically impossible to test in a real system.

Laboratory Setup

A laboratory environment resembling the collection grid in a wind park has been realized at ABB Corporate Research. A small section of a wind park is reproduced in the laboratory setup. Illustration of a wind park section is found in Figure 1 and a highlighted part is reproduced in the laboratory setup. The schematic diagram is shown in Figure 2. A total of 600 m cable has been installed.

The radial fork structure of the test laboratory presented in Figure 2 was intended for studies of reflection phenomena. However, hundreds of recurrent surges from re-ignitions in combination with multiple reflection points dramatically complicate the evaluation of the studies. During the study presented in this report, it was considered to reduce the number of wave reflection points in order to reduce the
complications during the evaluation of models and identification of the consequences of parameter changes. Consequently, the extra feeder SC3 and the extra windmill cable SC5 within the test setup were disconnected.

![Figure 1](image1.jpg)

**Figure 1** Illustration of a wind park and the part reproduced in the laboratory setup (highlighted area)

**EXPERIMENTAL SETUP**

The experimental setup was prepared at the ABB Wind Cable Laboratory. Figure 3 shows the circuit diagram. The installation of surge arresters at the protected transformer terminal is shown in Figure 4.

![Figure 2](image2.jpg)

**Figure 2** Wind Cable Laboratory schematic diagram

![Figure 3](image3.jpg)

**Figure 3** Circuit diagram of the experimental setup

![Figure 4](image4.jpg)

**Figure 4** Installation of surge arresters (ZnO) within the experimental setup

The experimental setup consisted of the following major components:

- Power cable: XLPE, trefoil, core diameter for 240 mm² aluminum:18.1 mm, insulation thickness 5.5 mm, diameter over insulation 30.7 mm, cross-section of screen 35 mm², outer diameter of cable 40 mm, and capacitance 0.31 μF/km. The nominal voltage is 20 kV.
- Transformers, TX1: 1250 kVA, 20.5/0.41 kV, oil-immersed, Dyn11. TX2: 1000 kVA, 20/0.69 kV, oil-immersed, Dyn11.
- Switching apparatus: 12 -24 kV vacuum breakers, e.g. rated power frequency withstand voltage 28 kV, rate of rise of transient recovery voltage (TRV) 0.34 kV/μs and peak TRV 20.6 kV.
- Protective elements: ZnO surge arresters with continuous operating voltage 14.3 kV, characteristic points of 1 mA at 17.2 kV and 10 kA at 28.5 kV.
- Voltage measurement: three 10,000:1 voltage dividers, 20 MHz bandwidth and three 2,500:1 voltage dividers, 20 MHz bandwidth.
- Current measurement: Current transformer 100 ns usable rise time, max. peak current 50 kA and max rms current 200 A.
- Transient recorder: 50 MHz sampling rate.
- Control system: The laboratory is equipped with a sequence control system as standard being phased locked to the fundamental voltage where all sequence controlled output signals are programmed by means of a digital controller given as numerical input to the lab process central controller. The resolution of the outgoing raw signal from the sequence controller is 50 μs. The total precision is dominated by output relays with 7 ms operating time before the breaker pulse output, in the order of ± 0.1 ms.
- Load: A battery of low voltage air core coils configured to the reactance \( X_l = 0.10 \) at 50 Hz connected at Node 1 (Transformer TX1).

During the test reported in this paper, the operating voltage is set at 12 kVₐ₋ₐ, i.e. 60% of the transformer rating.
TEST CASES AND WINDMILL OPERATION

Switching operations in the medium voltage (MV) collection grid should be performed in a controlled sequence involving minimum stress to the windmill system under all mechanical and electrical considerations. Here some components such as the low voltage (LV) breakers and contactors, blade pitch, converters, grid fault ride through functions, and the MV breaker can be controlled.

Operating the MV breaker located in a windmill connection point can be made in combination with control of the other components. From an electrical point of view the operation is preferably made during minimum load i.e. with the windmills stopped, minimum load condition or generator disconnected.

Nevertheless, regardless of the reason for switch/breaker operations, the corresponding load cases defined for the MV breaker can be categorized in “no load” and “load” case. Switching under load can e.g. occur due to faults or temporary instability. “No load” cases involve the capacitive currents in an energized system. Capacitive load has to be considered in particular while operating switches and disconnectors with low operating speed.

In this study, the opening and the closing of the breaker at no load or with inductive load connected are considered and tested. Four test cases are then defined as listed in Table 1.

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Load Case</th>
<th>Switching Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No load</td>
<td>Closing</td>
</tr>
<tr>
<td>2</td>
<td>No load</td>
<td>Opening</td>
</tr>
<tr>
<td>3</td>
<td>Inductive load</td>
<td>Closing</td>
</tr>
<tr>
<td>4</td>
<td>Inductive load</td>
<td>Opening</td>
</tr>
</tbody>
</table>

Studies of pre-strike and re-ignition conditions in circuit breakers with cables on both sides have shown that all load currents with both resistive and inductive dominance give rise to transients, however a mainly inductive load current provide the worse cases. In the actual experiments, a load has been selected giving a current essentially larger than the typical chopping current of a breaker and to a magnitude that corresponds to the order of equal or less than the installed power, resulting in 80 % of the installed power at the selected operating voltage point.

TEST RESULTS AND ANALYSIS

This paper focuses on the occurrence of the transient overvoltage phenomenon in cable systems. Detail analysis of the phenomena is not the scope of this report. Nevertheless, typical results of voltage measured at transformer TX1 terminals (Node 2 in Figure 3) obtained from the four test cases are listed in Table 1 and also shown in Figure 5 to Figure 8 and some remarks can still be made. Figure 5 shows the closing of the breaker at no load. The switching time is adjusted so the withstand voltage of the breaker reaches the maximum rated peak voltage when the voltage is at its maximum at one phase. If that condition is fulfilled, the pre-strike current is at its maximum value, and additional pre-strikes will produce the maximum transient overvoltages. In Figure 6, the switching time of the opening operation for the no load case is chosen so the no load current in one phase is at its maximum when the breaker starts separating contacts. Since the no-load current represents the magnetizing current of the transformer, the current lags 90° and the voltage re-strikes are superimposed on the fundamental frequency voltage when it is at its maximum. Figure 7 shows the closing of the breaker at inductive load. The switching time is adjusted as it is in the case 1. In Figure 8, opening of the breaker with inductive load is shown. The breaker switching instant in this case is chosen so the phase current in one phase is at the current chopping level when the contacts starts to separate. This ensures that the transient recovery voltage will reach the breaker withstand voltage very short time after the contact separation producing a re-strike. It takes much longer time for the breaker to build up the withstand voltage to the level higher than the transient recovery voltage produced by re-strikes compared to the no-load case. This increases the magnitude and the number of re-strikes compared to the no-load case. It can be observed that the voltage over the transformer TX1 is limited by the surge arresters to the level of 20 kV.

Strikes resulting from breaker operation depend to a large extent on the time instant of opening and closing of the contacts of the breaker [4-5]. In this experiment the opening and the closing of the breaker is performed in such a way that the worst case scenario is achieved. It was assessed that the time instant of opening and closing of the breaker contacts results in the voltage transient of the highest magnitude. Moreover, the breaker used in the experiment is also stochastic and probabilistic characteristics (e.g. probability of arch quenching, etc.). To take this into account, after the switching time instant resulting in the highest/steepest voltage transient is obtained for each test case, 2-4 extra shots are additionally performed with the exact same instant time. Transients resulting from a typical test sequence are quantified in terms of number of reignitions, the magnitude and the rate of voltage step, and shown in the following section.

Measured transient overvoltages versus LIWL

In OHL systems, transient overvoltages often occur as a result of lightning strikes and according standard equipment test procedures are designed around the typical 1.2/50 μs impulse (LIWL = Lightning Impulse Withstand Level) due to fulmination. When the results of transient overvoltages measured in the cable laboratory are compared to this LIWL, Table 2 is obtained.
Table 2 Recorded transient overvoltages* during laboratory experiment versus standard LIWL ($U_n = 12$ kV) [6]

<table>
<thead>
<tr>
<th>Case</th>
<th>Number of strikes (#)</th>
<th>Voltage step magnitude (kV)</th>
<th>Voltage step 10%-90% steepness (kV/μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Closing at no load</td>
<td>2-3</td>
<td>10.5-11</td>
<td>13-30</td>
</tr>
<tr>
<td>2 Opening at no load</td>
<td>3**</td>
<td>7.5**</td>
<td>12**</td>
</tr>
<tr>
<td>3 Closing with inductive load</td>
<td>10-30</td>
<td>10-13</td>
<td>14-27.5</td>
</tr>
<tr>
<td>4 Opening with inductive load</td>
<td>230-323</td>
<td>41.5-43</td>
<td>82.5-88</td>
</tr>
<tr>
<td>5 LIWL</td>
<td>1</td>
<td>75</td>
<td>62.5</td>
</tr>
</tbody>
</table>

* Only voltage steps with the magnitude more than 5 kV and the 10%-90% value steepness more than 5 kV/μs are identified as strikes. ** Only one shot (from several) in this case resulted in recorded strikes (more than 5 kV in magnitude and 5 kV/μs in steepness), a result only a single value displayed.

CONCLUSIONS

The experiments verify the occurrence of repetitive pre-strikes and re-ignitions determined by the electrical circuit and the point on wave of switching. With a ZnO-type surge arrester alone as protection device, the experiments show that a high number of repetitive voltage transients below the arrester protection level can occur at the incoming terminals of the transformer. Repetitive voltage transients with higher time derivatives than the standard lightning impulse test have been recorded and analyzed.

ACKNOWLEDGMENT

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REFERENCES