

Measurements for validation of high voltage underground cable modelling

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Abstract-- This paper discusses studies concerning cable modelling for long high voltage AC cable lines. In investigating the possibilities of using long cables instead of overhead lines, the simulation results must be trustworthy. Therefore a model validation is of great importance. This paper describes field test setups and measurements on an already installed cable line with several cross bonding points. These measurements are to be used for cable model validation, which are prepared using simulations. The proposed field tests should be used to validate the cable model for overvoltage problems. The verification shall be done both in the frequency domain and in the time domain.

Keywords: Cable lines, Cable model, Transient test, Cable measurements, Cable simulation.

I. INTRODUCTION

In recent years, interest towards using underground high voltage (HV) cables in power transmission, has increased considerably. In order to research the possibility of using large HV AC cable systems, it is necessary to have precise simulation models.

HV transmission cable models are to correctly represent the transient behaviour of underground cable systems. Small errors for short cables can become a larger problem when length of the cables and number of cross bonding points are increased. It is therefore important that differences between simulations and measurements are eliminated.

It has been recommended that the cable models be validated by use of a frequency response model with inverse Fourier transform [1]. The aim of this paper, on the other hand, is to describe necessary field tests, in order to investigate the accuracy of cable terminal conditions transient behaviour and build a comprehensive and precise model for HV AC cables.

Results from performed field test [2] have been used to validate various models through the years [3][4]. These field tests only include a fast-front impulse. This paper introduces

on the other hand more types of measurement setups that are important for acceptable cable model validation. Transient simulations in EMTD/PSCAD are used to prepare measurement setup for each proposed test.

II. PROPOSED MEASUREMENTS

The measurements should validate the models for most transient behaviour. The following overvoltages are considered [5]: (i)-Temporary overvoltages, (ii)-Switching overvoltages and (iii)-Lightning overvoltages. (i) can be caused by for instance earth faults and resonances.

According to IEC 60071-2 an impulse of $1.2 \times 50 \mu\text{s}$ can be used to simulate lightning overvoltages. In order to validate the model against all mentioned overvoltages, (i) and (ii) should also be considered. This paper describes three measurement setups. The first setup powers the cable at resonance frequency to validate a cable model for study of temporary overvoltages. The second setup uses a circuit breaker (CB) to validate a cable model for study of switching overvoltages. The third setup uses an impulse test to validate the cable performance and model calculations for the cable terminal conditions given in (1).

$$\begin{aligned} v_1(\omega) &= v_2(\omega) \cosh(\gamma(w) \cdot l) - i_2 Z_C(\omega) \sinh(\gamma(w) \cdot l) \\ i_1(\omega) &= \frac{v_2(\omega)}{Z_C(\omega)} \sinh(\gamma(w) \cdot l) - i_2 \cosh(\gamma(w) \cdot l) \end{aligned} \quad (1)$$

where γ is the complex propagation constant, l is the length of the transmission cable, Z_C is the characteristic impedance, v_1/i_1 is the sending end voltage/current and v_2/i_2 is the receiving end voltage/current.

All setups are prepared by simulations using the Gustavsen model, [6].

During simulations, the frequency domain is used for calculations of the propagation matrix $H(\omega)$ and the admittance matrix $Y_C(\omega)$. The cable terminal conditions are then calculated in time domain by use of a recursive convolution. The field test results are obtained directly in the time domain and can be transformed to frequency domain for model validation in the frequency domain.

A. Measurement preparation

In order to study how to measure the proposed overvoltages, transient simulations for a 400 kV cable system in Norhten Jutland, Denmark have been performed, see Fig. 1.

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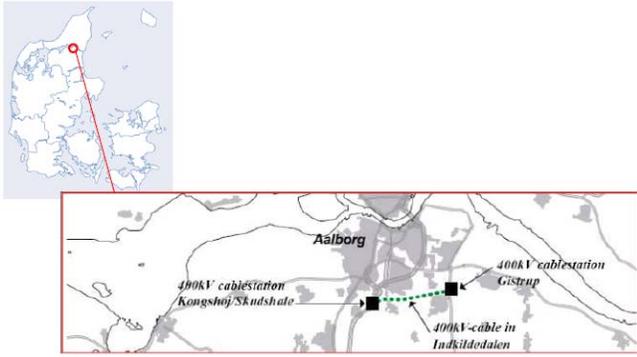


Fig. 1 Geographical placement of the measured 400 kV cable system.

The cable system contains two times three 400 kV single conductor 1200mm^2 Al XLPE cables, each of them 7.48 km long with 9 main segments and 4 cross bondings. The cable properties are shown in Fig. 2.

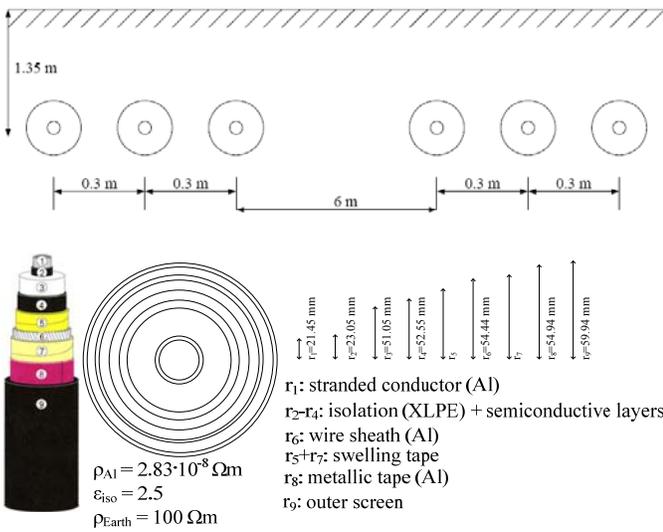


Fig. 2 Cable layout and properties.

All simulations use the Frequency Dependent Phase Model (The Gustavsen model) in EMTDC/PSCAD. The simulation model for the cable is shown in Fig. 3.

As temporary overvoltages can be caused by resonances, the model should be tested at resonance frequency for validating the model behaviour during such overvoltages. The resonance frequency should be obtained and measured. For this purpose an AC frequency variation test is performed. In this test an AC generator with variable frequency is used to power one of the outer phases. This is performed both for open circuit test and for short circuit test. The current in the cable system will have a maximum at resonance frequency for the open circuit test and a minimum at resonance frequency for the short circuit test. The test results are obtained in time domain and should be transformed to the frequency domain.

Time domain simulation results for the open circuit test are shown in Fig. 4. Frequency domain results are shown in Fig. 5, which indicates resonance at app. 2700 Hz and 4600 Hz.

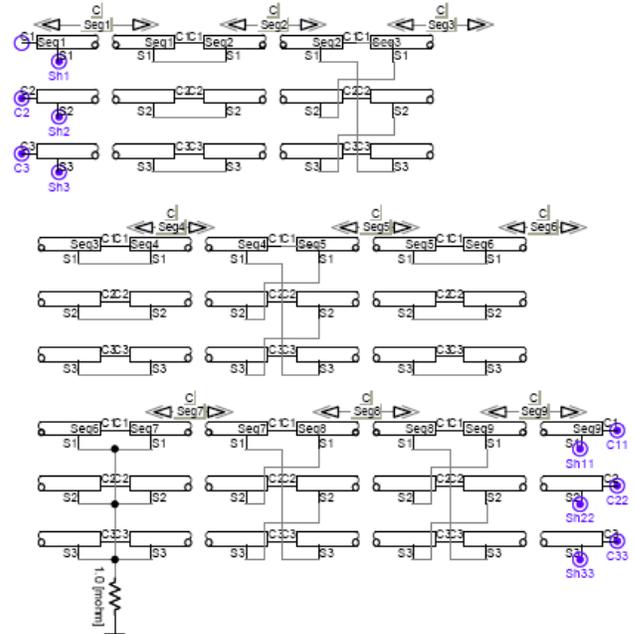


Fig. 3 The EMTDC/PSCAD simulation model for the measured HV cable in Denmark.

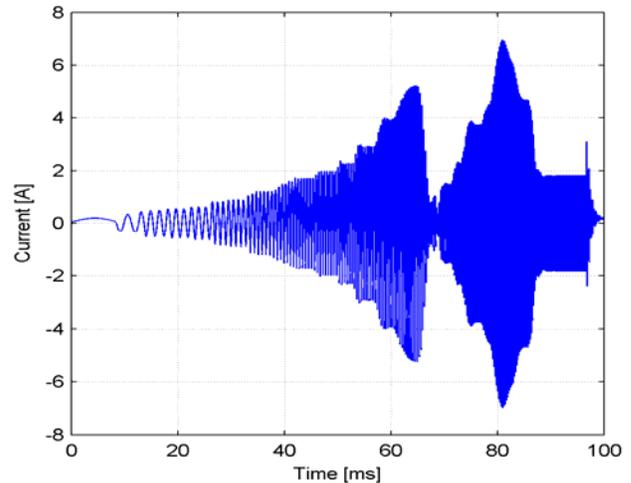


Fig. 4 Simulation results for frequency variation test. Input current on phase 1 for an input voltage of 100 V at 50 Hz-5000 Hz.

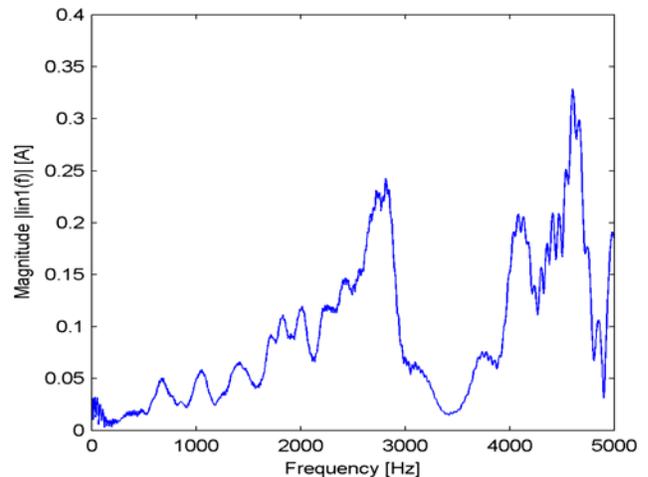


Fig. 5 FFT of simulation results for frequency variation test. Input current on phase 1.

For switching overvoltages an AC switching test is performed with a CB connecting the conductor of the powered phase. The test is performed as an open circuit to study the energizing process of the cable. In the switching test the CB is connected at the sending end at the output of the generator. The switching is performed during voltage peak, in order to obtain the largest transients possible. This test will show the transient behaviour of the cable during switching. If switching transients during field tests and simulations agree, the model can be trusted for studying switching overvoltages. The transient results are sensitive to the voltage value at the point of switching and the characteristic of the CB. This must therefore be modelled carefully.

The impulse test uses a fast front impulse with front time of 1.2 μs and half time of 50 μs . The impulse test will verify the cables behaviour during very fast transients and gives high harmonics, which can be used to validate the accuracy of the cable model. An example of simulation results for the voltage and current at the sending end of the energised phase is given in Fig. 6. These simulations are used to prepare the field tests. For validation purposes, the measured input voltage is used as an input for the simulation model.

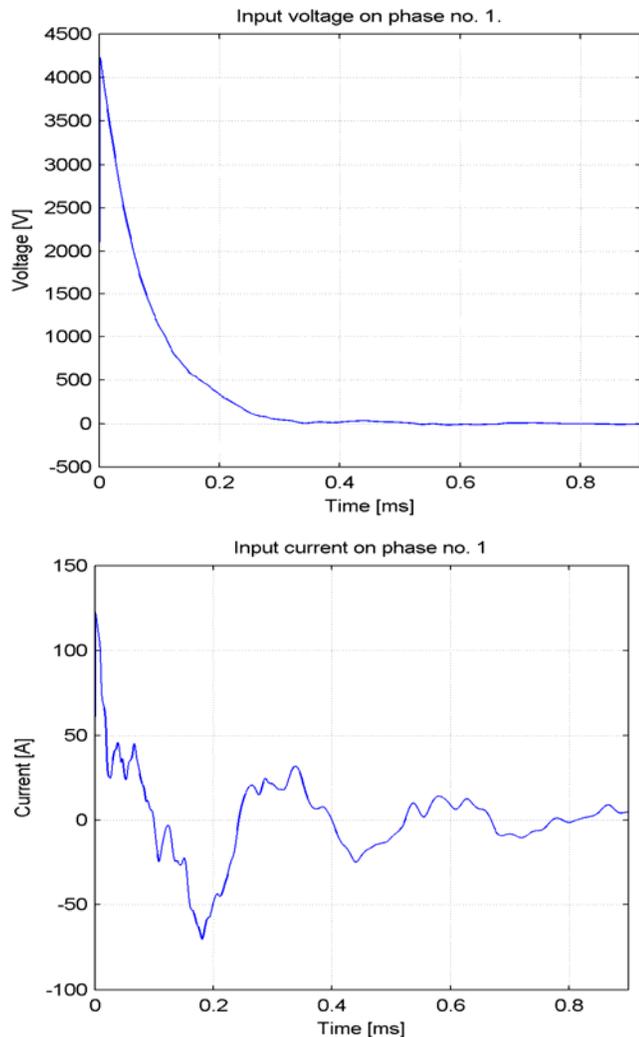


Fig. 6 Simulation results for impulse test. Input voltage and current on phase 1.

The model is very sensitive for the input parameters of the cable, so the cable must be modelled carefully in order to get simulations comparable to field test results. For the modelling part, the resistivity of the conductor is increased because of the stranded conductor. And the permittivity of the isolation is also increased because of semiconductive layers, [7].

B. Measurement setup

The measurement setup is shown in Fig. 7 where the load is different for the open and short circuit tests and the CB for the switching test should be placed at the output of the generator. For the open circuit test, the load is 500 Ω and for the short circuit test, the load is 5 Ω .

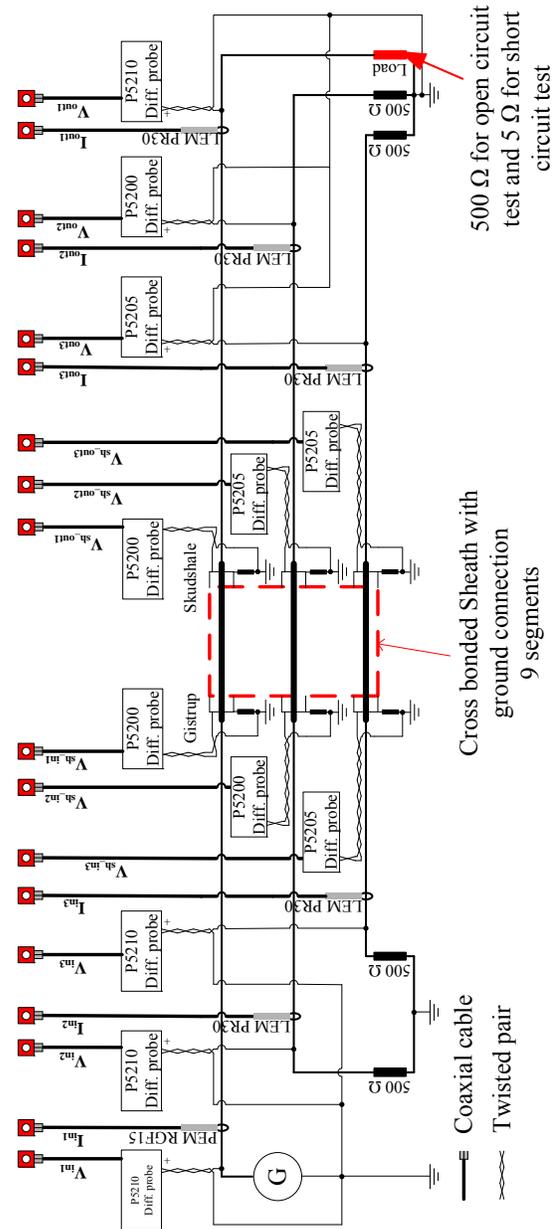


Fig. 7 Measurement setup for the field tests.

Only one of the two 3 phase cable systems is tested. The measured 400 kV cables are physically disconnected from the transmission line, which was grounded. Adjacent cable system is physically connected to the transmission line, and is therefore also grounded. This is shown in Fig. 8.

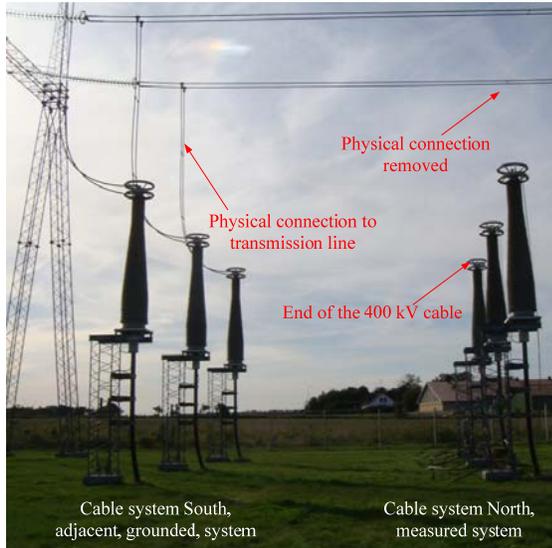


Fig. 8 Connections of the measured cable system.

The generator for the switching test is a 400 V AC generator. For the AC frequency variation test a Californian 1000 VA generator with variable frequency up to 5 kHz is used at 100 V. The frequency can only be varied in 9 steps which must be chosen beforehand. For both the AC switching test and the AC frequency variation test, two omicron CMC-256 test units with Enerlyzer are used. The CMC's are placed at each end of the cable and the triggering is synchronized by use of a clock controlled by a GPS signal.

The generator used for the impulse test is a HAEFELY PC6-288.1 surge tester. It is used to generate a 4.28 kV 1.2/50 μ s impulse. 6 identical Tektronix TDS 3014B oscilloscopes are used for measuring and the data is saved to be analysed by use of MATLAB.

For all tests, Tektronix HV probes are used. P5200 and P5205 for voltages up to 1.3 kV and P5210 for higher voltages. For current measurements LEM PR30 is used to measure currents up to 30 A and for the impulse test, a PEM RGF15 is used to measure the conductor current at the sending end of the energized phase.

The cable ends are placed 8 m above the ground, with 4 m between the phases in air. The generated voltage is connected by use of a measuring cable (not a coaxial cable) to the HV cable end. The current in this measuring cable is measured as phase 1 conductor current. Measured voltages also use such a measuring cable. For phase 2/3 sending end and phase 1/2/3 receiving end a grounding cable is connected between HV cable end and resistance. The current in the grounding cable is measured as conductor current, see Fig. 9.

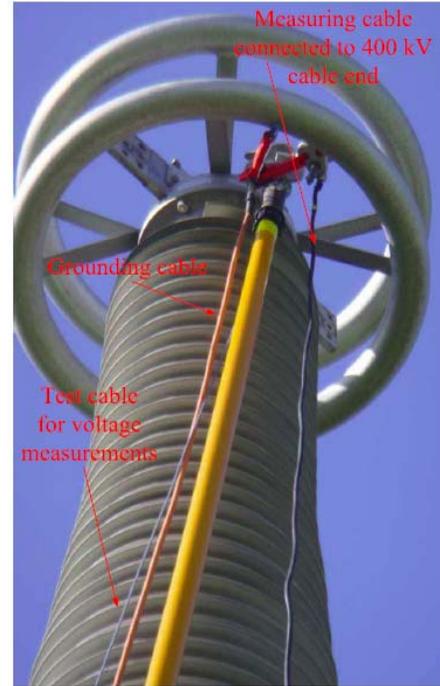


Fig. 9 Measuring and grounding cables connected to HV cable end.

III. MEASUREMENT RESULTS

In order to estimate the noise voltage because of surrounding transmission systems, the disturbance from surrounding transmission lines is evaluated by performing measurements of noise currents and voltages for the non operating cable system. This evaluation indicates that the surrounding noise does not affect the measuring results and can be ignored.

There were performed four identical tests for each test setup. This was done in order to have a base for comparison and not only one less reliable measuring result. All four tests give fairly the same results, which indicates that the measurements are reliable and can be used as a foundation for cable model validation.

A. AC frequency variation test

The AC frequency variation test uses fixed frequency steps. The most important measurement is the current on the energized phase (phase 1). The peak of the current in the open circuit test will give the resonance frequency for the cable capacitance and the inductance in the cable and load. For the short circuit test, the current reaches minimum at resonance frequency. The field test results from the open circuit test for phase 1 is shown in Fig 10.

The resonance frequency is 2.3 kHz and 4.7 kHz. At these two frequencies, the current is at maximum because of interaction between the capacitance of the cable and the inductance of the cable. The same resonance frequency should also be obtained using an acceptable simulation model for the cable.

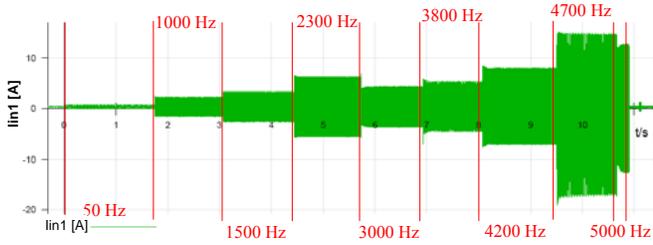


Fig. 10 AC frequency variation field test results for the open circuit test. The figure shows measured conductor current at the sending end of phase 1.

Knowing the correct resonance frequency will give correct simulation results when studying resonance problems because of using long HV underground cables and shunt reactors for capacitive current compensation.

B. AC switching test

The AC switching test can be used to validate transients during connection of a breaker connected to a cable. The reason for such a switching test is to obtain information of the cable energizing process. An AC switching test is therefore performed to validate the accuracy of the switching transients of the cable model.

The field test results from the open circuit test for phase 1 is showed in

Fig. 11.

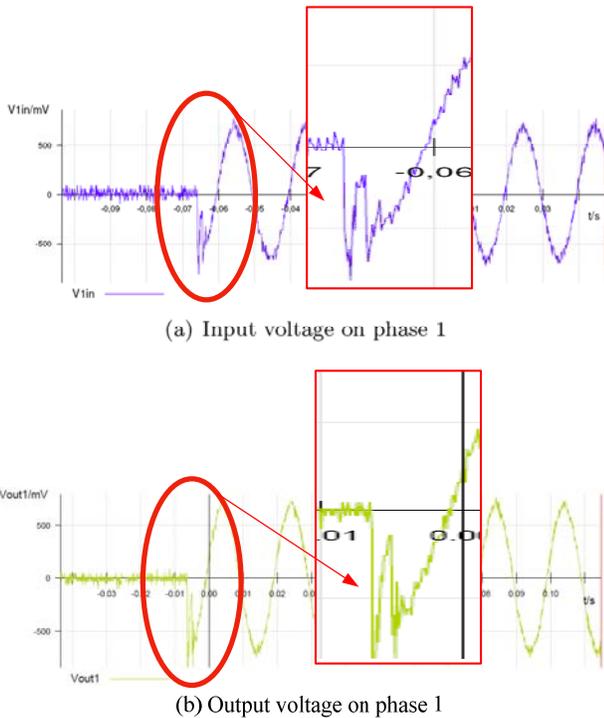


Fig. 11 AC switching field test results for the open circuit test. The figure shows measured conductor voltage at both ends of the cable.

The conductor voltage measurements for the switching test show some transient voltage during the first 4.5 ms. After that time, the conductor voltage has reached steady state value. The simulated connection of the cable should give the same switching transients during the energizing of the cable.

C. Impulse test

The impulse test uses fast front impulse to energize phase 1 of the crossbonded cable. Voltage and current of all three phases was measured. The field test results for conductor voltages at the sending end for phase 1 are shown in Fig. 12

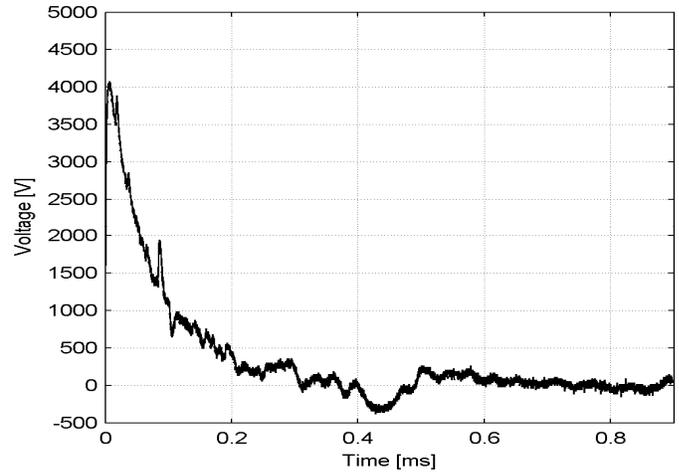


Fig. 12 Impulse field test results for conductor voltages at the sending end of the cable. Input voltage on phase 1.

The voltage in phases 2 and 3 is induced from phase 1, in the closed circuit of phases 2 and 3. The voltage at the receiving end is delayed in time because of the cable time constant. There is a voltage drop over the cable because of the cable parameters, which are frequency dependent. The distributed cable parameters are represented in the frequency domain as (2).

$$Z(\omega) = R(\omega) + j\omega L(\omega) \quad (2)$$

$$Y(\omega) = G(\omega) + j\omega C(\omega)$$

where Z is the series impedance matrix, Y is the shunt admittance matrix, R is the series resistance, L is the series inductance, G is the shunt conductance and C is the shunt capacitance per unit length of the cable system.

The measured conductor voltages at the receiving end are shown in figure Fig. 13.

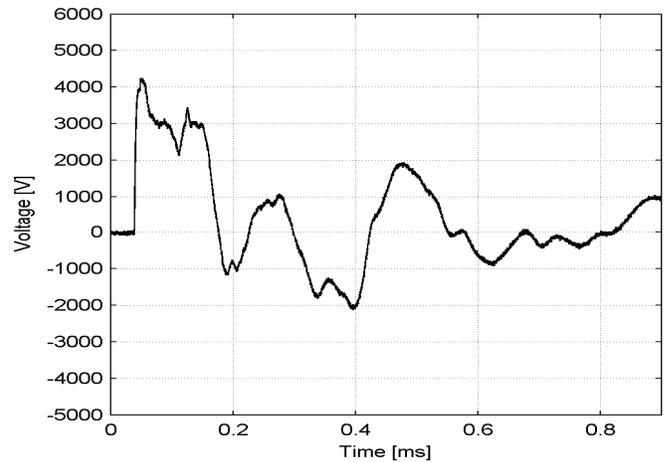
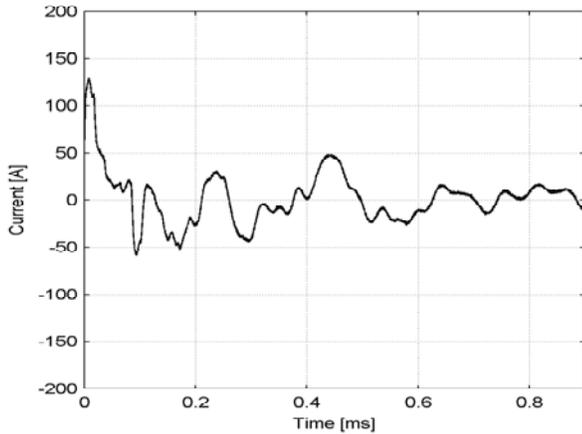


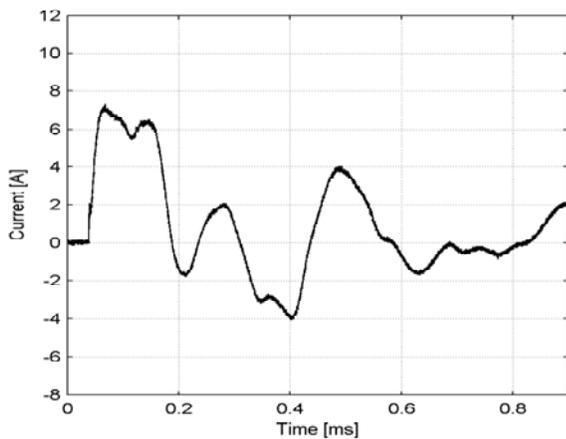
Fig. 13 Impulse field test results for conductor voltages at the receiving end of the cable. Output voltage on phase 1.

The first peak of the conductor voltage on phase 1 at the receiving end happens after a short delay and is 4260 V.

The conductor current both at sending and receiving end has also been measured. The test result for sending and receiving end of the conductor current on phase 1 is shown in Fig. 14. The test results in Fig. 12, Fig. 13 and Fig. 14 should be transformed to the frequency domain, using for instance FFT. Then the terminal conditions in (1) can be validated.



(a) Input current on phase 1



(b) Output current on phase 1

Fig. 14 Impulse field test results for conductor currents at the sending and receiving end of the cable for phase 1.

In order to validate the simulation model also sheath voltages at both sending and receiving end of the cable have been measured. The results for the sheath voltages can be used for sheath overvoltage studies [8] and the results for the conductor current can be used for studies of large fast transient currents, such as during lightning overvoltages as well as for validating the terminal conditions.

The applied voltage has been measured and can be used to generate an identical impulse test using the simulation program, where the margin of accuracy for both amplitude and time must be taken into consideration. The simulated response of the cable in terms of cable terminal conditions for both conductor voltage/current and sheath voltage can then be validated by the measured results, both in time and frequency

domain. By this method, it is possible to identify which parts of the simulation model need improvements. Large differences in both frequency and time domain give indication of too much simplification of the model or wrong parameters. Large differences in only time domain give indication of inaccurate time domain implementation when using recursive convolution to calculate the voltage/current relationship of (3), [6].

$$Y_C(\omega)v - i = 2i_i = 2H(\omega)i_{re} \quad (3)$$

where i_i is the incident current and i_{re} is the reflected current.

IV. CONCLUSIONS

In this paper, field test setups for acceptable HV AC cable model validation have been proposed. The three setups of AC frequency variation test, AC switching test and impulse test should cover the most recognized overvoltage problems encountered in a transmission line operation and are based on simulations for a specific cable system case. Furthermore the impulse test can be used to validate the accuracy of the simulation model.

When using the measurement for cable model validation the field test results and simulations should agree within a predefined accuracy. A profound comparison of field test results and simulations, for validation of cable models, is a part of an ongoing future work. When appropriate agreement has been reached, the cable model is regarded as acceptable for studying transmission systems with long HV underground cables.

Field tests have been performed based on the described setups. Field test results are introduced in order to verify the importance of each test setup. All results indicate a trustworthy foundation to be used for cable model validation.

The impulse response test should be the first one used for cable model validation. When the model accuracy has been validated by such impulse response measurements, calculation of resonance frequency can be verified by use of the AC frequency variation test and models of switching transients caused by switching with CB can be verified by use of the AC switching test. All three tests should be used to validate the cable model, in order to obtain correct simulation results for overvoltage studies.

Furthermore a fourth test would be recommended before planning of long HV underground cables. This test is not used for overvoltage studies, but is a DC inrush test where the DC component caused during start up of long HV cables connected to a shunt reactor is validated. By validating the correct DC component in the simulation program, it is possible to study problems such as zero missing (the problem of opening breakers during failure because of large DC component).

V. ACKNOWLEDGMENT

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