Switching Restrikes in HVAC Cable Lines and Hybrid HVAC Cable/OHL Lines

F. Faria da Silva, Claus L. Bak, Per B. Holst

***Abstract*--The disconnection of HV underground cables may, if unsuccessful, originate a restrike in the circuit breaker, leading to high overvoltages, and potentially damaging the cable and near equipment.**

Due to the cable high capacitance and low resistance the voltage damping is slow, resulting, half a cycle after the disconnection, in a voltage of approximately 2 pu at the circuit breaker terminals. In case of restrike in that instant, it is theoretical possible to attain an overvoltage of 3 pu. The overvoltage can be even larger in hybrid cable-Overhead Lines (OHL), due to voltage magnifications in the junction point.

This paper explains the phenomenon for pure cable lines and hybrid cable-OHL lines, and uses Denmark's high voltage transmission grid, as planned for the year 2030, as test system.

The accuracy of different cable models, and the number of substations from the transient event requiring detailed modeling is also addressed. It is shown how cross-bonding the cables screens may affect the results and that the grid should be modeled for more than two busbars distance from the restrike event.

***Keywords*: Power System Transients; Power Cables; Restrikes; Modeling;**

I. Introduction

INSULATION coordination studies are normally performed when planning the installation of a cable or OHL. The disconnection of the cable and/or OHL and the correspondent transient recovery voltage (TRV), are typically addressed in such studies.

During the disconnection the circuit breaker must be able to withstand the TRV or a restrike may occur, resulting in a high undesirable overvoltage.

II. Capacitive Switching

A cable has a large capacitance. Consequently, its typical de-energisation resembles the de-energisation of a capacitor bank [1], which has been a well-studied phenomenon for many decades [2][3].

In a capacitive element the voltage lags the current by approximately 90º. As a result, the voltage has a peak value at the disconnection instant.

The de-energisation of a capacitive load is characterized by low energy dissipation and long decaying times. Therefore, the voltage on the capacitive load side remains almost equal to ±1 pu during the first cycles after the disconnection.

While the voltage on the load side remains almost constant, the voltage on the source side continues to oscillate at power frequency. Thus, half cycle after the disconnection, the voltage difference at the circuit breaker (CB) terminals reaches the theoretical maximum of almost 2 pu, shown in Fig. 1.

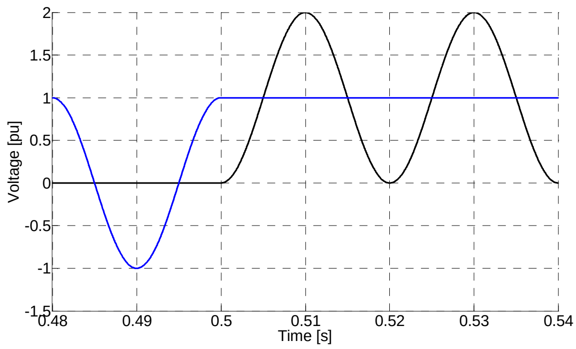

Fig. 1. Example of a capacitive load de-energisation. Vc: Voltage in the load side (blue); V_Brk: Voltage at the circuit breaker terminals (black)

The large voltage difference at the CB terminals may originate a restrike. If this happens, there is a transient overvoltage whose peak value is proportional to the voltage difference in the CB terminals at the restrike instant. Thus, the worst case is a restrike when the voltage difference at the CB terminals is maximum, i.e. half cycle after the disconnection.

As example, the overvoltage associated to a capacitor bank restrike in that instant, can in theory go up to 3 pu, even if it is normally inferior to 2.5 pu [3].

III. Simulation Model

A. Model Parameters

To simulate the switching restrikes, was modeled in EMTDC/PSCAD the transmission grid of West Denmark as planned to the year 2030. The network is characterized by the use of undergrounded HVAC cables at 150kV and OHL at 400kV [4].

The cables and OHLs are modeled by means of frequency-dependent phase models up to 2-5 busbars of distance from the analyzed node, the number of busbars is one of the

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Paper submitted to the International Conference on Power Systems Transients (IPST2011) in Delft, the Netherlands June 14-17, 2011

parameters being studied. The remaining cables/OHLs are modeled by means of pi-models. The voltage levels inferior to 150kV were not modeled, but were considered in the calculation of the equivalent grid.

The modeled network has a total of:

- 129 busbars;
- 27 OHL (400kV);
- 80 HVAC cables (165kV);
- 36 transformers

Fig. 13 shows the single line diagram of the restriked line and neighbor busbars. The line being restriked is installed between the NVV and BDK nodes and has a total of 47.5km

The EMTDC/PSCAD cable model was validated through comparison with measurements performed in a real 150kV single-core cable. The system conversion from PSS/E to EMTDC/PSCAD was confirmed by comparisons with PowerFactory simulations for steady-state conditions. For more details about the system and model validations consult [5].

B. *Simulation Parameters*

The detail putted into a simulation is a compromise between accuracy and minimum complexity/running time.

Reference [6] recommends to model two-substations deep when simulating a line energisation/re-energisation/fault. This paper will demonstrate that for restrike studies in cable networks a deeper modeling may be required.

To show it four different system models were prepared. The differences between the models are the number of nodes modeled by means of FD-models:

- Model 1 - 5-substations deep
- Model 2 - 4-substations deep
- Model 3 - 3-substations deep
- Model 4 - 2-substations deep

To simulate the restrike, the CB is re-closed approximately half cycle after opening the first phase (phase A). Due to the re-charging of the cable's capacitance, the worse case is not exactly half cycle after the phase opening, but some hundreds of microseconds later. Therefore, the CB re-closing is simulated by means of statistical switching (50 simulations), based on a Gaussian distribution with a standard deviation of 1.8ms. Table 1 shows the maximum and average peak voltages obtained in the simulations.

Table 1. Maximum and average voltage (in pu) in the cable receiving end for the statistical switching

	Model 1	Model 2	Model 3	Model 4
Max. BDK-Ph A	2.328	2.321	2.248	2.274
Max. BDK-Ph C	**2.445**	**2.435**	**2.320**	**2.337**
Avg. BDK-Ph A	1.827	1.822	1.769	1.781
Avg. BDK-Ph C	1.832	1.829	1.757	1.746

The results show that the number of modeled substations is very relevant when simulating a cable restrike. In this example, the grid should be modeled up to at least 4-substation of the analyzed node, more than recommended in [6].

The difference between the models in Table 1 is explained by two factors: The nominal voltage in the busbar prior to the restrike and reflections in the near nodes.

The details put into the modeling slightly changes the steady-state voltage prior to the restrike event. The nominal voltage prior to the restrike is 0.989 pu for Model 1 and Model 2, and 0.981 pu for Model 3 and Model 4. As a result, the voltage at the CB terminals at the restrike moment is also larger for Model 1 and Model 2 than for Model 3 and Model 4. The small difference in the nominal voltages is not enough to explain the differences shown in Table 1, which are several times superior to 0.016pu.

The voltage is also influenced by reflections in the cables, OHLs and transformers installed in the vicinity of the restriked cable. The influence of the reflections can be accessed by comparing the voltage during the re-energisation for two different system-types. A first type equal to the one previously described where the entire grid is simulated through the use of FD-models and pi-models; and a second type where only the FD-models are used, whereas the remaining grid is simulated by means of an equivalent grid.

Fig. 2 to Fig. 4 show for the two system types, the voltage in the cable receiving end during a re-energisation.

The comparison shows that the voltages are initially equal for both system-types, deviating after a certain moment. The simpler the model, the sooner is the deviation.

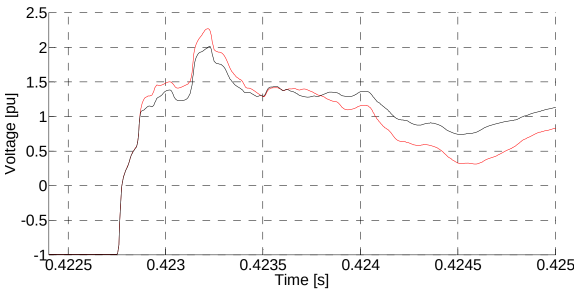

Fig. 2. Voltage in the cable receiving end after the restrike for Model 4. Red: Pi-models; Black: Equivalent grid

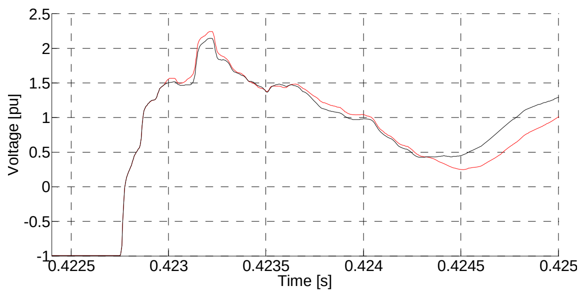

Fig. 3. Voltage in the cable receiving end after the restrike for Model 3. Red: Pi-models; Black: Equivalent grid

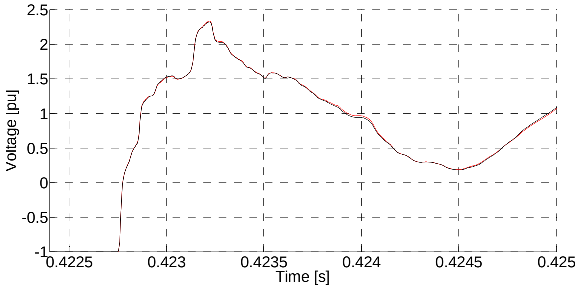

Fig. 4. Voltage in the cable receiving end after the restrike for Model 2. Red: Pi-models; Black: Equivalent grid

The equivalent grid model-type does not have reflections after a defined number of nodes. Therefore, the more complex the model is (i.e. the more nodes are modeled), the later is the deviation.

The reasoning can be extended for the results shown in Table 1, where the systems are modeled by a mix of FD-models and pi-models. The substitution of a pi-model by a FD-model changes the reflection coefficients and the travelling times, resulting in different peak overvoltages.

IV. Shunt Reactor Influence

Shunt reactors are typically installed together with cables. Shunt reactors can be connected either to the busbar or directly to the cable. The location of the shunt reactor influences both the waveform after the disconnection and the likelihood of a restrike.

Fig. 5 shows a possible waveform for the de-energisation of a cable and shunt reactor together. The voltage is no longer a decaying DC, but a decaying AC oscillation at resonance frequency. As a result, for reactive power compensation inferior to 100%, the maximum voltage difference at the CB terminals is no longer half cycle after the disconnection, but later. Equation (1) can be used to calculate, for a 50Hz cable, the moment of the maximum voltage difference at the CB terminals in milliseconds.

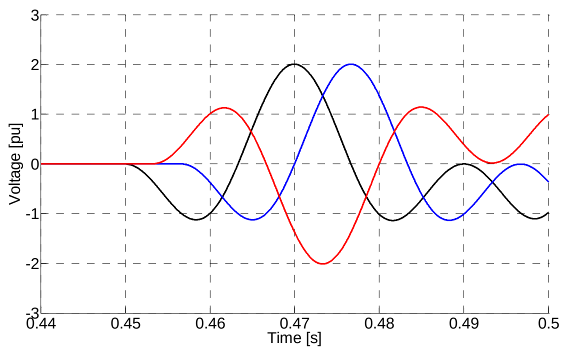

Fig. 5. Voltage difference at the CB terminals during the de-energisation of cable+shunt reactor for the disconnection sequence Phase A-Phase C- Phase B. Black: Phase A; Red: Phase C; Blue: Phase B

$$t = \left| \frac{1800}{180 - 3.6 f_r} \right| \qquad (1)$$

For the example shown in Fig. 5, the resonance frequency of the cable+shunt reactor system is 25Hz. Thus, after the disconnection the voltage in the cable side oscillates at 25Hz, while the voltage in the source side continues to oscillate at 50Hz.

The voltage at the CB terminals is the difference of these two oscillatory waves. For that reason, the maximum voltage difference at the CB terminals is no longer half cycle after the disconnection instant, i.e. 10ms, but one cycle later or 20ms.

A restrike of the CB half cycle after the switch off would originate a 1.297 pu overvoltage. If the restrike happens one cycle after, when the voltage difference at the CB is maximum, the overvoltage is of 2.285 pu.

So, as expected, if the restrike happens when the voltage at the CB terminals is maximum (i.e. ≈2 pu), the overvoltage has an amplitude equal to the one obtained when the shunt reactor is connected to the busbar. But, as the maximum voltage difference occurs later in time, the restrike is less probable.

V. Hybrid cable-OHL

The previous section explained the restrike for a cable-line. The existence of hybrid cable-OHL is becoming more common, and it is therefore necessary to study the phenomenon for this type of line.

To study it, are analyzed eight different hybrid line configurations:

- Case 1: ½ cable - ½ OHL
- Case 2: ⅓ cable - ⅔ OHL
- Case 3: ⅔ cable - ⅓ OHL
- Case 4: ½ OHL - ½ cable
- Case 5: ⅔ OHL - ⅓ cable
- Case 6: ⅓ OHL - ⅔ cable
- Case 7: ⅓ cable - ⅓ OHL - ⅓ Cable.
- Case 8: ⅓ OHL - ⅓ Cable - ⅓ OHL
- Case 9: Pure OHL

The total line length (cable+OHL) is equal for all nine cases (47.5km). The reactive power compensation provided by the shunt reactors installed in both ends of the cable is corrected in function of the cable length and the restrike continues to be forced in the same side of the line.

Statistical switching is again used to simulate the CB restrike. Table 2 shows the obtained maximum and average overvoltage values for the different cases.

Table 2. Maximum and average voltage in the hybrid line receiving end for the statistical switching

	Pure Cable	**Case 1**	**Case 2**	**Case 3**	**Case 4**
Max. BDK-Ph A	2.328	**3.4175**	**4.4308**	3.8817	2.5682
Max. BDK-Ph C	**2.445**	2.7190	4.2434	**3.9079**	**2.7667**
Avg. BDK-Ph A	1.827	2.7919	3.5095	3.1174	2.0001
Avg. BDK-Ph C	1.832	2.0818	2.8968	2.7032	2.1171
	Case 5	**Case 6**	**Case 7**	**Case 8**	**Case 9**
Max. BDK-Ph A	2.4935	2.5381	2.6972	2.5112	**1.9911**
Max. BDK-Ph C	**2.6730**	**2.7633**	**2.8285**	**2.6415**	1.2658
Avg. BDK-Ph A	1.9506	1.9785	2.1144	1.9193	1.5208
Avg. BDK-Ph C	2.0654	2.0921	2.0964	1.9372	1.1216

Several differences are noticed when comparing the results obtained for a pure cable line and a hybrid line configuration:

- The restrike of a hybrid line results in a larger overvoltage than the restrike of a cable or OHL;
- The overvoltage is larger if the restrike occurs in the CB attached to a cable;

As part of the cable is substituted by an OHL there is a decrease of the total line capacitance and less energy to be damped. Thus, the voltage difference at the CB terminals half cycle after the disconnection is smaller, as can be observed in Fig. 6, and one would expect a lower overvoltage. Except that the simulations show exactly the opposite, an increase of the overvoltage by 81% when comparing case 2 with a pure cable line.

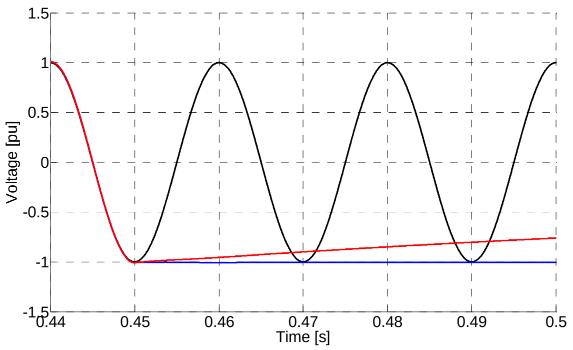

Fig. 6. Comparison between cable and OHL TRVs. Black: Source voltage; Blue: Cable voltage; Red: OHL voltage

The increase of the overvoltage is a result of reflections/refractions in the cable-OHL junction point(s).

The reflected and refracted voltages are calculated by (2) [7], where V_1 is the sending voltage, V_2 is the reflected voltage, V_3 the refracted voltage, and Z_A and Z_B the surge impedance of the lines.

$$V_3 = V_1 \frac{2Z_B}{Z_A + Z_B}$$
$$V_2 = V_1 \frac{Z_B - Z_A}{Z_A + Z_B} \tag{2}$$

The surge impedance of an OHL is typically larger than the surge impedance of a cable. As a result, the voltage is reduced when a wave flows from the OHL into the cable and magnified when a wave flows from the cable into the OHL [8].

Substituting the cable and OHL surge impedances into (2), are obtained (3) and (4) for an incident wave flowing from the cable into the OHL and (5) and (6) for an incident wave flowing from the OHL into the cable.

$$V_3 = V_1 \cdot 1.755 \tag{3}$$
$$V_2 = V_1 \cdot 0.755 \tag{4}$$
$$V_3 = V_1 \cdot 0.245 \tag{5}$$
$$V_2 = V_1 \cdot (-0.755) \tag{6}$$

Equation (3) shows that the voltage would ideally increase 1.755 times for a restrike in the cable end, explaining the voltage increase in cases 1 to 3.

In the same way that a voltage increase is expected when a restrike occurs in the cable side of a hybrid line, a voltage decrease would be expected if the restrike happens in the OHL end (see (5)). But the simulations contradict the equation, showing an increase of the voltage magnitude.

The voltage is reduced when flowing from the OHL into the cable, but it is later reflected back in the cable receiving end, being then reflected and refracted in the junction point. In this process the voltage builds up, and would in theory, for a lossless cable and OHL, reach the same peak value that would be obtained if no cable was presented [7].

In the simulations the voltage surpasses this theoretical maximum value, meaning that not are being considered all factors. Usually, when analysing reflections and refractions in a cable-OHL line, the cable length is very small when compared with the OHL length. A typical study-case is a lightning hitting the OHL and propagating into the substation through a short cable, this is the situation in [7][8] and [9].

In this situation the wave reflection in the OHL end is not considered, as the OHL travelling time is too large when compared with the cable travelling time. In the cases studied in this paper, the cable and OHL travelling times have the same order of magnitude, making necessary to consider the wave reflections in the OHL end and subsequent reflections/refractions in the junction point.

Fig. 7 shows the voltage in the junction point and cable receiving end, for the re-energisation of a hybrid OHL-cable line. In this particular example, the OHL is connected to an ideal voltage source, resulting in a reflection coefficient of -1 at the OHL sending end; the voltage difference at the CB terminals at the restrike instant is of 1.936 pu.

The restrike occurs at 0.4650s and the waves travelling times are respectively 55.5µs and 176µs for the OHL and cable. As a result, at approximately 0.4654s the voltage that was first reflected at the cable receiving end reaches the junction point and is both refracted to the OHL and reflected back to the cable, reaching the cable receiving end at approximately 0.46556s. At this point the voltage analysis becomes more complicated, since all the refractions and reflections start to superimpose upon each other.

Due to the wave reflection in the OHL sending end, the peak overvoltage depends on the cable and OHL traveling times. Fig. 8 shows, keeping the OHL length constant, the peak overvoltage associated to a restrike for different cable lengths. In this example the lines are lossless and no damping is present.

Fig. 8 shows that the voltage has an erratic value for a cable and OHL with similar lengths. The voltage starts to increases constantly for cables 2.5 longer than the OHL, because of the much longer wave traveling time in the cable when compared with the OHL.

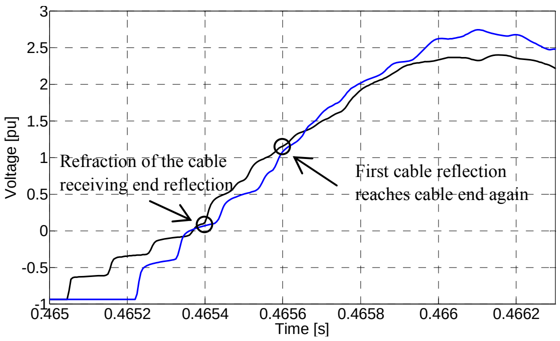

Fig. 7. Voltage in the junction point and cable receiving end during the re-energisation of OHL-cable line

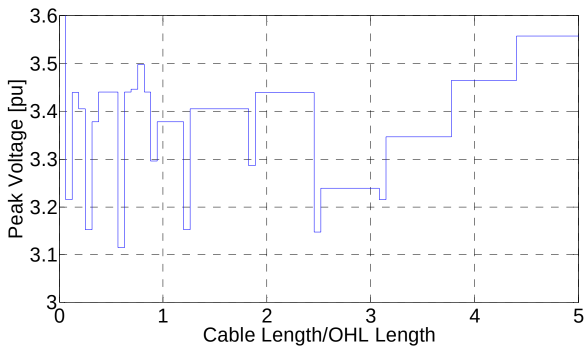

Fig. 8. Maximum overvoltage in function of the cable length due restrike

VI. The Influence of Cross-Bonding Points

In the previous simulations the cables were bonded in both-ends. The cross-bonding of the cable screen, action normally done for long HV cables, can dramatically change the simulation outcome.

The restrike/re-energisation of a cable is a high-frequency phenomenon, resulting in large currents flowing into the cable's screen, inducing voltages in the conductors.

Fig. 9 shows the voltage in the end of a cable line during a restrike for different bonding types. In the both-ends bonded cable the voltage is reflected only on the cable ends, while in the cross-bonded cable the voltage has several small reflections in each of the cross-bonding points.

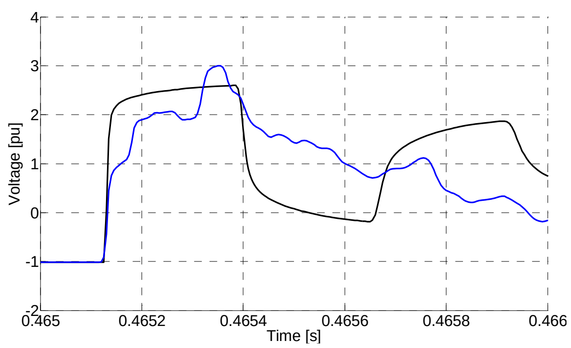

Fig. 9. Voltage in the cable receiving end for a pure cable line. Black: Both ends bonding; Blue: Cross-bonding

Fig. 10 shows the voltage in the cable and OHL receiving ends, for a hybrid line consisting of a cable and OHL of equal lengths.

Fig. 9 shows a peak voltage larger in the cross-bonded cable than in the both-ends bonded cable. Thus, one would expect that in the hybrid line the maximum voltage would also be larger when using a cross-bonded cable, but as seen in Fig. 10.b that is not true.

The maximum overvoltage in the cross-bonded cable end, i.e. the junction point, does not occur when the first wave impulse reaches that point, but hundreds of microseconds after the cable energisation/re-energisation.

In this example the cable and the OHL have equal lengths, meaning that the OHL travelling time is less than the cable charging time. Thus, when the cable maximum voltages reaches the OHL receiving end the voltage in that point has already decreased due to reflections in the OHL receiving end and joint point.

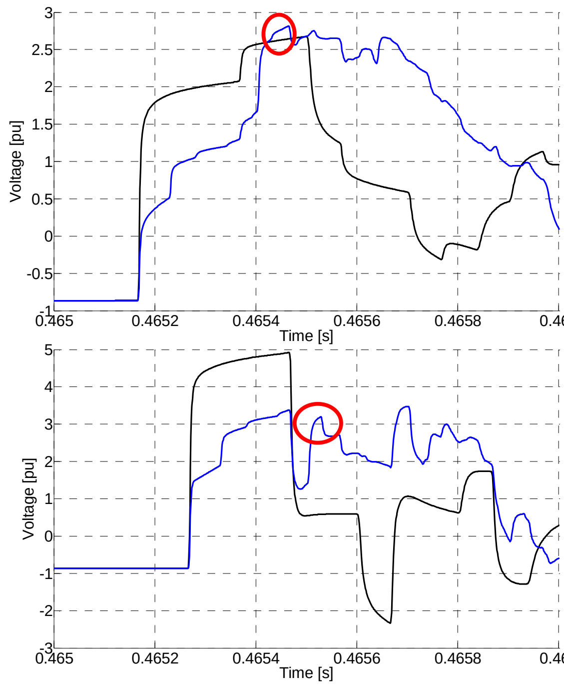

Fig. 10. Voltage in the cable (upper graph) and OHL (lower graph) receiving ends for a hybrid cable-OHL line. Black: Both ends bonding; Blue: Cross-bonding

Therefore, one cannot say that the use of cross-bonding will result in a decrease or increase of the overvoltage value. As example, in Fig. 10 the cable and the OHL have the same length, but if the OHL was sufficiently long the voltage would be larger in the hybrid line with the cross-bonded cable.

Another important parameter is the length of the cross-bonding minor sections.

Previously, the cross-bonded cable was modeled as having only one major section, divided into three minor sections. For a long cable, this model is oversimplified, as one should expect minor cable sections no longer than 3.3km [10].

A more detailed model having the cable divided into three major sections, each of them subdivided into three minor sections was designed.

Fig. 11 compares the voltage in hybrid-line receiving end, when simulating a cable bonded in both ends with a cable with one major cross-bond section and one with three major cross-bond sections. The peak magnitude is approximately 1.7 times larger when using three major sections than when using a single major section.

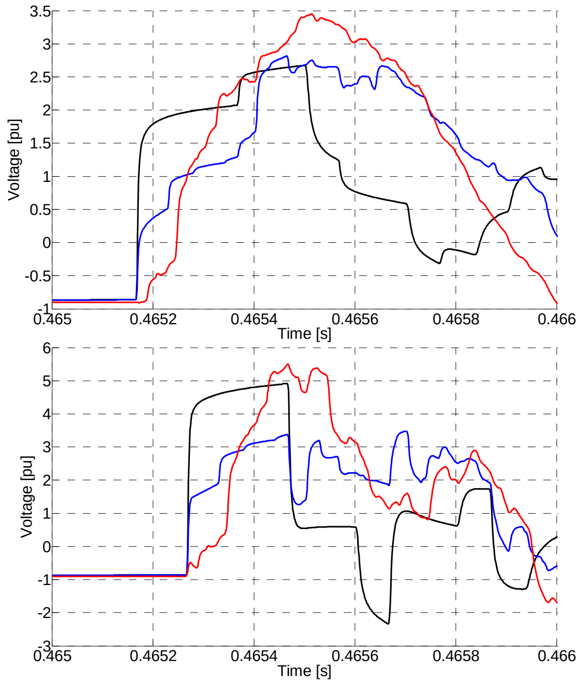

Fig. 11. Voltage in the cable (upper graph) and OHL (lower graph) receiving ends for a hybrid cable-OHL line. Black: Both ends bonding; Blue: Cross-bonding (1 major section); Red: Cross-bonding (3 major sections)

Table 3 gives the maximum and average overvoltage values for the different cases when modeling the cable with three major sections.

Fig. 12 compares the peak overvoltage when modeling three major cross-bonded sections and one major cross-bonded section. For these particular examples the overvoltage is larger when modeling three major sections.

Table 3. Maximum and average peak voltages in the hybrid line receiving end for statistical switching, when modeling the cable with three major cross-bonding sections

	Pure Cable	Case 1	Case 2	Case 3	Case 4
Max. BDK-Ph A	2.4678	3.8031	4.4912	3.8074	2.5879
Max. BDK-Ph C	**2.6890**	**4.2958**	**4.5722**	**4.3005**	**2.8152**
Avg. BDK-Ph A	1.9215	2.9764	3.5082	2.9798	2.0244
Avg. BDK-Ph C	2.0138	3.2172	3.2254	3.2207	2.1616

	Case 5	Case 6	Case 7	Case 8
Max. BDK-Ph A	2.5604	2.5923	2.7915	2.5866
Max. BDK-Ph C	**2.7987**	**2.8868**	**2.9968**	**2.7459**
Avg. BDK-Ph A	1.9961	2.0199	2.1612	1.9758
Avg. BDK-Ph C	2.1527	2.1691	2.2090	2.0245

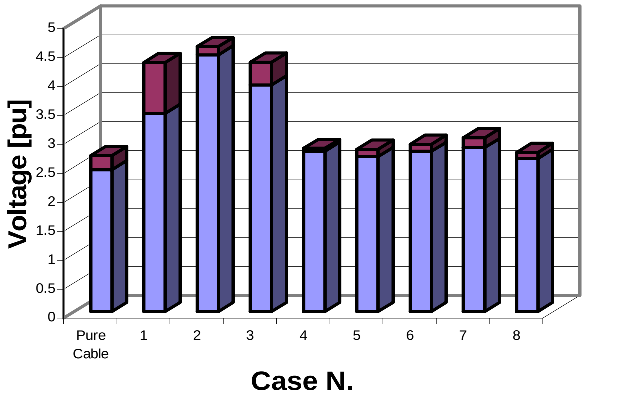

Fig. 12. Peak overvoltage for the pure cable and the eight hybrid cases. Blue: 1 Cross-section; Purple: 3 cross-sections

The ground resistance should also be characterized as precisely as possible, since it can originate small differences in the peak values (see [11] for lighting impulse examples).

VII. Countermeasures

Besides the use of surge arresters, other countermeasures can be applied in order to minimize the overvoltage.

A. Hybrid Line Opening Sequence

Comparing the different cases, it can be noticed that for two hybrid lines with equal cable and OHL lengths the overvoltage will be substantially lower if the restrike happens in the CB attached to the OHL (compare Case 1 with Case 4, Case 2 with Case 5 and Case 3 with Case 6 in Table 2 and Table 3).

Thus, when opening a hybrid line, the CB attached to the cable should be opened first. As a result, even if the CB fails to open the restrike will be small and not represent a risk for the system. One or two cycles after the opening of the cable's CB, it can be opened the OHL's CB.

B. Insertion of a cable between the OHL and the substation

It is common to have the connection between the OHL and the substation made through a short cable. This cable may reduce the overvoltage amplitude, as explained in section V.

Using Case 2 as example, the insertion of a 500m cable after the OHL would reduce the overvoltage in 0.251pu, from 4.5722pu to 4.3212pu.

C. Have the shunt reactor directly connected to the cable

Section IV shows that when de-energising a cable together with a shunt reactor, the maximum voltage at the CB terminals occurs later, reducing the likelihood of a restrike.

VIII. Conclusions

This paper explained the restrike phenomenon for a cable-based network, and several conclusions can be taken from the shown results.

The modeling detail is particularly relevant when simulating a restrike and an accurate simulation may require a modeling depth larger than recommended by the standard [6].

A restrike of a hybrid line results in larger overvoltages than the restrike of a pure cable/OHL line. For the same length, the overvoltage associated to a restrike of a hybrid-line can be more than two times the overvoltage associated to the restrike of an equivalent pure cable line. This large difference is consequence of reflections and refractions in the joint cable-OHL node, which originates a voltage magnification when an electric wave flows from a cable to an OHL.

The maximum overvoltage is a function of several factors (e.g. reflection factor, waves speeds, initial voltage at the CB terminals), and its calculation requires the use of simulation tools.

The cable modeling is very important, and simplifications should not be used. During a restrike part of the current flows in the cable's screen and the reflections in the cross-bonded points will affect the final simulation outcome. As a result, it is necessary to model accurately all cross-bonding points.

Three countermeasures that can be used to reduce the restrike overvoltage value were presented.

IX. Appendix

Table 4 and Table 5 show the used modeling parameters for respectively the cable and OHL.

Table 4 - Cable Parameters (trefoil foirmation)

Cross-section Area [mm2]	800
Conductor outer radius [mm]	16.85
Conductor resistivity [Ohm.m]	3.122-8
Insulation outer radius [mm]	35.05
Insulation relative permittivity	2.796
Screen outer radius [mm]	35.479
Screen resistivity [Ohm.m]	1.72e-8
Outer Insulation outer radius [mm]	41.5
Outer Insulation relative permittivity	2.3

Table 5 - OHL Parameters (flat formation)

Conductor geometric mean radius [m]	0.073
Conductor DC resistance [Ohm/km]	0.0257
Conductor SAG [m]	8.5
Distance between conductors [m]	5.5
Conductors height [m]	24
Ground wires radius [m]	0.007
Ground wires resistance [Ohm/km]	0.2892
Distance between ground wires [m]	17

X. References

[1] *IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers*, IEEE Standard C37.012-2005, 2005

[2] I. B. Johnson, A. J. Schultz, N. R. Schultz, R. B. Shores, "Some Fundamentals on Capacitance Switching", Power Apparatus and Systems, Part III. *Transactions of the American Institute of Electrical Engineers*, Vol. 74, Issue 3, 1955

[3] *IEEE Guide for the Protection of Shunt Capacitor Banks, IEEE Standard*, IEEE C37.9-2000, 2000

[4] ELINFRASTRUKTURUDVALGET, "Technical Report on the future expansion and undergrounding of the electricity transmission grid", 2008

[5] F. Faria da Silva, "Study of High Voltage AC Underground Cable Systems", Ph.D. dissertation, Dept. Energy Technology, Univ. Aalborg, 2011 (to be published)

[6] *Insulation Co-ordination - Part 4: Computational guide of insulation co-ordination and modelling of electrical networks*, IEC TR 60071-4, 2004

[7] Allan Greenwood, "Electrical Transients in Power Systems", John Wiley & Sons, 2nd edition, 1991

[8] Lou van der Sluis, "Transients in Power Systems", John Wiley & Sons, 2001

[9] CIGRE Working Group B1.05, "Transient Voltages Affecting Long Cables", April 2005

[10] CIGRE Working Group B1.07, "Statistics of AC Underground Cable in Power Networks", December 2007

[11] CIGRE Working Group B1.18, "Special Bonding of High Voltage Power Cables", October 2005

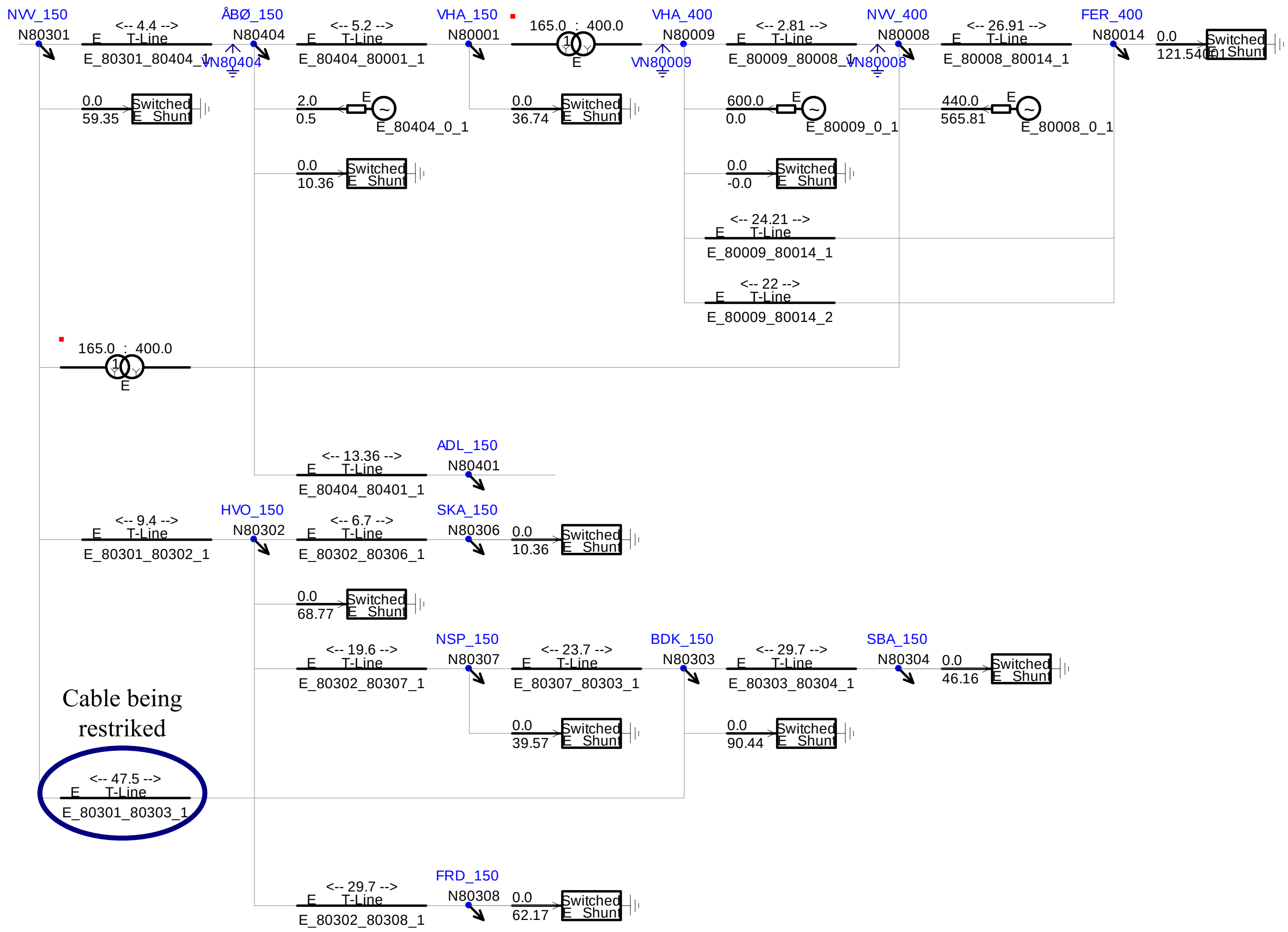

Fig. 13. Single-line diagram of the studied line are surrounding busbars (the arrows represent connection points to the equivalent grid)