# OVERVOLTAGES IN MV CABLE NETWORKS OF OFFSHORE WIND POWER PARKS

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## ABSTRACT

*Switching overvoltages in the 33 kV cable system of an offshore wind power park are calculated. Earth fault conditions as well as pre charged cables have been considered. The benefit of surge arresters is discussed.*

## 1 INTRODUCTION

Because of the increased use of regenerative energies in Germany it is needed to install large wind power parks as offshore-units in the North Sea and the Baltic Sea. Following the normal layout, the generation (wind power generators) takes place on low voltage level, a medium voltage cable system connects the several feeders of the wind power towers. A high voltage cable transmits the energy to the mainland. Depending of the power and the distance, the transmission is done either with an AC three phase system or HVDC system.

In this report overvoltages in the medium voltage cable system that are produced from switching operations or that originate from earth faults, are determined. Also, an evaluation of the occurring overvoltages takes place in relation to the required withstand voltages of the connected equipment.

## 2 SYSTEM CONFIGURATION

The system configuration of a wind power park is shown in Fig.1. The different wind in-feed (generator and transformer) are connected over the medium voltage network. The transmission to the mainland is done through a 155 kV cable connection.

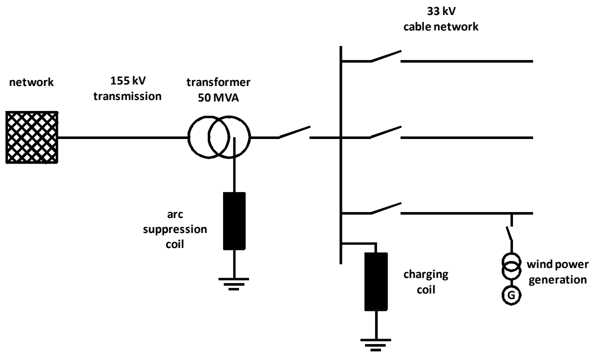

**Figure 1:** System configuration (simplified)

The used medium voltage cable network has an arc-suppression (Petersen) coil earthing to compensate a single phase earth fault. In addition it has a charging coil, which is connected to the medium voltage bus bar and compensates the capacitive charging current. In Fig.1 there is only one wind power tower shown as example, altogether there are 21 generators connected to the medium voltage bus bar over three cable tracks.

## 3 DATA OF EQUIPMENT

For the following simulations (switching operations, earth faults) the equipment is reproduced with equivalent electric circuits at operating frequency, because in these cases the damping by the effective resistance is lower, which means that the results on the safe side.

*Network:*
The network impedance is calculated by assuming the maximum three-phase short circuit current on the high voltage side (155 kV) as $I_k = 40$ kA, and assuming the impedance ratio of $L_{0Q}/L_{1Q} = 3.5$ and $R_{1Q}/X_{1Q} = 0.1$ and $R_{0Q}/R_{1Q} = 3$.

*Feeder Transformer:*
The deployed transformer with a power of $S_{OSUS} = 50$ MVA has the relative short circuit voltage of $u_{X12} = 11.16$ % and $u_{R12} = 0.30$ %, to determine the transformer impedance with a transformation ratio of $t_r = 155$ kV / 33 kV.

*Arc-suppression (Petersen) coil:*
The rated current of the Petersen coil lies in the range of $I_{rL1} = 20 – 100$ A at a voltage of $U_r = 19.05$ kV (phase - earth), the resistance of the coil is assumed $R_{L1} = 0.03\ X_{L1}$.

*Charging coil:*
The impedance can be determined when the resistance is assumed $R_{L2} = 0.03\ X_{L2}$ and the power of the coil of $S_{L2} =$ 470 kVAr with a rated voltage of $U_r = 33$ kV is considered.

*33-kV-cable network*
The medium voltage cable network consists of marine cables N2XS(FL)2YRAA with different cross sections depending on the applied load. The entire cable network has a length of 17 km, starting from the medium voltage substation according Fig. 1 and is divided into three cable tracks. The average length between two wind power towers is $l = 810$ m. For the connection of the wind power towers the cross sections of 3x120 RM/16 and 3x240 RM/25 are used. The used cables have the following characteristic values: Rated voltage $U_r = 33$ kV; highest voltage for equipment $U_m = 36$ kV; Basic insulation level $U_{BIL} = 170$ kV

*Surge Arrester:*
In medium voltage systems generally the following types are used, depending on the place of installation:
Cable network: phase – earth $U_c = 36$ kV
Transformer: neutral – earth $U_c = 23$ kV

For the calculation of the overvoltages in case of earth faults characteristic values of current and voltage with a current steepness of $S_i$ = 30/60 µs are used, when the switching operation has higher frequencies, characteristic values with a steepness of $S_i$ = 8/20 µs are considered.

## 4 CALCULATION OF TRANSIENTS

To determine the maximum overvoltages in the medium voltage system only switching-on of cable sections and earth faults between phase and earth are considered. Several calculations have been performed as shown in Table 1.

| Case Nr. | Case | Description |
|---|---|---|
| I.1 | Three phase closing, no pre charge | Entire cable network |
| I.2 | | One complete cable track, two cable tracks already connected |
| I.3 | | First section of one track, two tracks connected |
| I.4 | | Last section of one track, two tracks connected |
| II.1 | Three phase closing, with pre charge | Entire cable network |
| II.2 | | One complete cable track, two cable tracks already connected |
| II.3 | | First section of one track, two tracks connected |
| II.4 | | Last section of one track, two tracks connected |
| III.1 | Single phase failure | Failure in voltage maximum |
| III.2 | | Failure in voltage zero |
| IV | Three phase closing on single phase failure, with pre charge | Complete cable track, two tracks already connected |

**Table 1:** Calculated cases

Because of the adapted earthing principle of the neutral it is possible, that after disconnection of cables the switched-off cables keep a capacitive charge. Reclosing with opposite phase to earth voltage leads to the highest overvoltages, which is especially critical during a single phase earth fault.

## 5 RESULTS

The calculations for the medium voltage system are made without connected wind power generation, which means, the circuit breakers on the high voltage side of the transformers in Fig. 1 are open, which also means that the cable network is not loaded. The voltage value (u = 46.69 kV) of the faultless phase during an earth fault corresponds to an earth failure factor of $c_E$ = 1.73, because of the arc-suppressing earthing (Petersen coil).

The simulations are made at the bus bar at a voltage of $U_b$ = 33 kV (phase - phase), so that the values refer to the peak value of the 33-kV-systemvoltage (1.0 p.u. = 33 kV $\times\sqrt{2/3}$ = 26.944 kV).

### 5.1 Three-phase closing, case I and II

Depending on the case, the connected cable network is either uncharged (case I), or it is assumed that a phase is charged with a maximum negative charging voltage. Connecting to a positive voltage will lead to high overvoltages. This is possible if due to a previous switching-off the cable network is still charged and then a reclosing takes place. For the calculations it is assumed that one phase of the connected cable network has the opposite voltage and is therefore connected in the opposing phase, while the other two phases are uncharged.

### 5.1.1 Complete 33-kV-cable system, case I.1; II.1

The switching-on of the entire cable network takes place according Fig. 2 through the circuit breaker S1 between the transformer and the medium voltage bus bar. The moment of the connection is always at the maximum of a phase voltage.

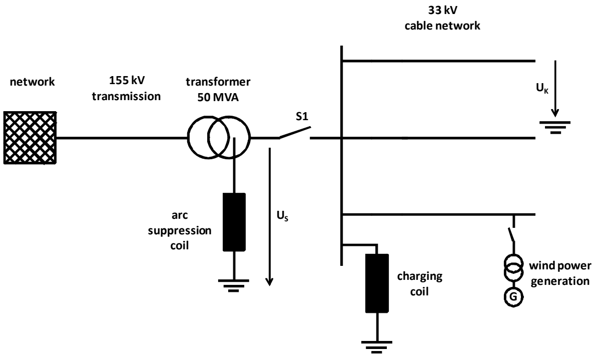

**Figure 2:** Switching-on of the entire cable network

Table 2 lists the maximum voltage values $U_S$ at the transformer and $U_K$ at the end of a cable track. The maximum voltages phase - earth result in $u_K$ = 52.89 kV (= 1.96 p.u.) and accordingly $u_K$ = 61.44 kV (= 2.80 p.u.). For the phase – phase voltages the values rise to $u_{KL-L}$ = 79.24 kV and accordingly 109.02 kV.

| Parameter | Case I.1 | Case II.1 |
|---|---|---|
| $u_S$, kV/p.u. | 51.99/1.93 | 59.95/2.22 |
| $u_K$, kV/p.u. | 52.89/1.96 | 61.44/2.80 |
| $u_{KL-L}$, kV/p.u. | 79.24/2.94 | 109.02/4.05 |

**Table 2:** Maximum voltage at the connection of the entire cable network

### 5.1.2 Switching-on of entire cable tracks, case I.2

### and II.2

In this case it is assumed that two cable tracks are connected to the feeder already, the third one is switched on at the maximum voltage of a phase, which means that circuit breaker 2 will be closed. Fig. 3 shows the calculation results for these cases; they are listed in Table 3. Because of the charge reversals there is a reflection at the open end of the connected cable track, the result is a maximum value of $u_{K1}$ = 62.43 kV (= 2.32 p.u.).

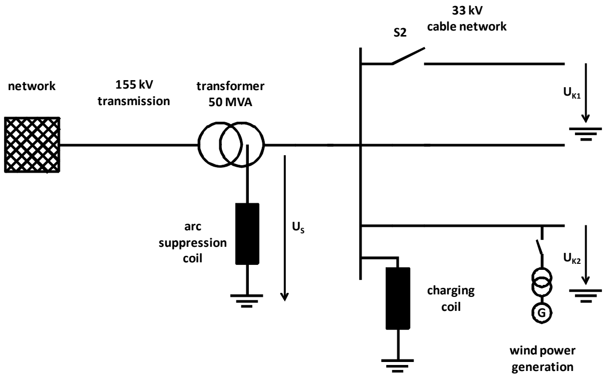

**Figure 3:** Switching-on of a cable track

| Parameter | Case I.2 | Case II.2 |
|---|---|---|
| $u_S$, kV/p.u. | 41.06/1.52 | 48.28/1.79 |
| $u_{K1}$, kV/p.u. | 62.43/2.32 | 83.09/3.08 |
| $u_{K1L-L}$, kV/p.u. | 97.31/3.61 | 132.38/4.91 |
| $u_{K2}$, kV/p.u. | 53.68/1.99 | 71.22/2.64 |

**Table 3:** Maximum voltages when switching-on of a cable track

### 5.1.3 Connection of single cable sections (first section), case I.3 and II.3

In this case only the first section of a cable track (average length of cable $l$ = 810 m) is switched-on, circuit breaker 2, the other two cable tracks are already connected. The switching status is visible in Fig. 4.

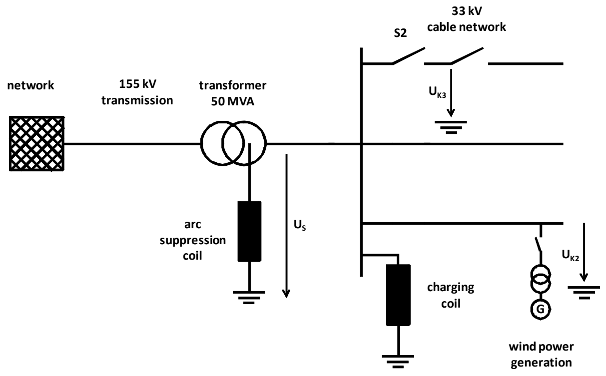

**Figure 4:** Connecting of a cable section (first section)

For the two cases I.3 and II.3, that where looked at, the maximum voltages according Table 4, results. In this case as well, the maximum voltages at the end of the connected cable section result in $u_{K3}$ = 51.66 kV (= 1.92 p.u.) and accordingly $u_{K3}$ = 67.69 kV (= 2.51 p.u.).

| Parameter | Case I.3 | Case II.3 |
|---|---|---|
| $u_S$, kV/p.u. | 37.49/1.39 | 43.11/1.60 |
| $u_{K3}$, kV/p.u. | 51.66/1.92 | 67.69/2.51 |
| $u_{K3L-L}$, kV/p.u. | 79.63/2.96 | 103.98/3.86 |
| $u_{K2}$, kV/p.u. | 45.63/1.69 | 59.22/2.20 |

**Table 4:** Maximum voltages at the connection of a cable section (first section)

### 5.1.4 Connection of a cable section (last section), case I.4 and II.4

As opposed to section 5.1.3, in this case the last section of a cable track is connected through switch S3 according Fig. 5. The rest of the cable system is already connected to the feeder. Depending on the operating conditions before the connection (with or without pre-charge) the maximum voltages according Table 5 result with the following values: $u_{K1}$ = 46.36 kV (= 1.72 p.u.) and 64.07 kV (= 2.38) respectively.

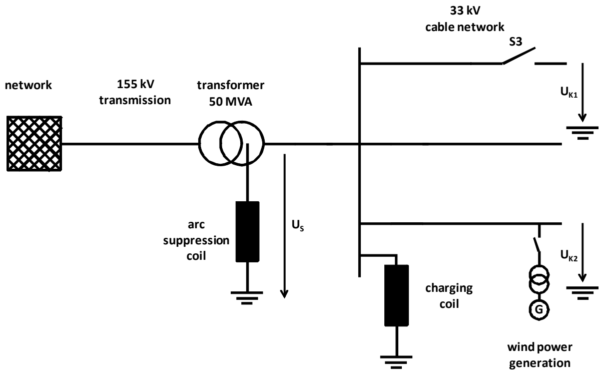

**Figure 5:** Connection of the cable section at the end of the cable track

| Parameter | Case I.3 | Case II.3 |
|---|---|---|
| $u_S$, kV/p.u. | 33.77/1.25 | 38.37/1.42 |
| $u_{K1}$, kV/p.u. | 46.36/1.72 | 64.07/2.38 |
| $u_{K1L-L}$, kV/p.u. | 73.79/2.74 | 92.66/3.44 |
| $u_{K2}$, kV/p.u. | 38.17/1.42 | 44.28/1.64 |

**Table 5:** Maximum voltages at the connection of a cable section (last section)

### 5.2 Single phase faults, case III.1and III.2

If there is a single phase fault, the phases that are not concerned by the fault, rise according to the earthing of the star point. Generally higher overvoltages are to be expected in a network with an isolated star point or a resonance earthed star point, compared to a network with a low ohmic earthing. For this reason the calculated voltage values are a conservative estimation.

The single phase fault according Fig. 6 is initiated at the end of a cable track, the distinction is made between the occurrence of the fault at maximum voltage (case III.1) and at voltage zero crossing (case III.2). The maximum voltages in the tables refer to the faultless phase.

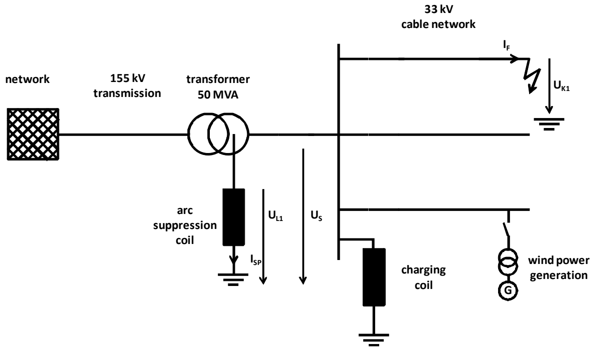

**Figure 6:** Occurrence of a single phase fault at the end of a cable track

The maximum voltages result depending on the moment of connection as $u_{K1}$ = 84.60 kV (= 3.14 p.u.) and accordingly 48.71 kV (= 1.81), table 6.

| Parameter | Case III.1 | Case III.2 |
|---|---|---|
| $u_S$, kV/p.u. | 79.15/2.94 | 48.62/1.80 |
| $u_{K1}$, kV/p.u. | 84.60/3.14 | 48.71/1.81 |
| $u_{K1L\text{-}L}$, kV/p.u. | 84.57/3.14 | 48.71/1.81 |

**Table 6:** Maximum voltages and currents in case of a single earth fault in the voltage maximum

### 5.3 Reclosing of a cable track during a single phase fault, case IV

High overvoltages during reclosing are to be expected when during a unipolar fault a faultless cable is disconnected and then reconnected. The consequence is that the pre-charge of the cable has the value of $u_0$ = 1.73 p.u. (phase-to-phase voltage) and this process leads to higher overvoltages than the calculations according case II. With the switching-on with pre-charge according case II.2 (connection of an entire cable track when two are already connected) the highest overvoltage ($u_{K1}$ = 83.09 kV) occur. Fig. 7 shows the single line diagram. The connection of the cable track is made by the circuit breaker S2, the single phase fault exists already in the connected power supply unit, fault position K2.

The maximum voltages according Table 9 result. In this case the maximum voltage is $u_{K1}$ = 121.38 kV (= 4.50 p.u.) at the end of the connected cable track. The voltage at the bus bar is with $u_S$ = 73.67 kV (=2.73 p.u.) much smaller, because at this position there is no complete reflection. The given values have been determined without surge arrester in the network, in Table 7 they are designated as case IVa.

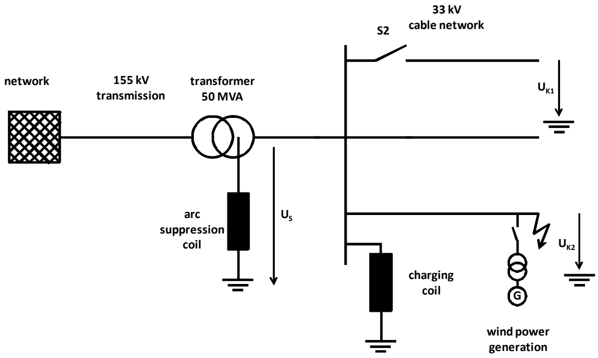

**Figure 7:** Reclosing during an existing single phase fault

| Parameter | Case IVa | Case IVb |
|---|---|---|
| $u_S$, kV/p.u. | 73.67/2.73 | 75.20/2.79 |
| $u_{K1}$, kV/p.u. | 121.38/4.50 | 88.96/3.30 |
| $u_{K2}$, kV/p.u. | 89.90/3.34 | 98.33/3.65 |

**Table 7:** Maximum voltage at reclosing of a cable track (single phase fault)

The simulation under the given circumstances leads to the highest overvoltages. Therefore in a second step surge arresters phase to earth at each end of the three cable tracks are considered, in addition a surge arrester at the transformer neutral to earth is applied. Under these circumstances the maximum voltages are considerably reduced, a reduction from $u_{max}$ = 121.4 kV to $u_{max}$ = 98.3 kV can be observed. The residual voltage for a current wave 8/20 µs is taken into consideration for the surge arrester phase to earth ($U_c$ = 36 kV). The surge arrester between the transformer star point and the earth ($U_c$ = 23 kV) is taken into account with a current wave shape of 30/60 µs.

## 6 EVALUATION

The equipment used in the 33 kV network has a highest voltage for equipment of $U_m$ = 36 kV with the following test values according IEC 60071-1, 2006-01:

Rated withstand voltage (1 min): $U_W$ = 70 kV
Lightning impulse withstand voltage: $U_{BIL}$ = 170 kV.

The calculated overvoltages have to be compared with these values, taking a safety margin under consideration.

Based on the rise times, the results of the different simulations can be assigned to the two voltage waveforms slow/fast. With the help of IEC 60071-2, 1996-12, an insulation co-ordination under consideration of the calculated overvoltages is made by determining the needed withstand voltages.

- Step 1: Determination of the representative overvoltage $U_{rp}$, The representative withstand voltage gives the value of a specific voltage category (form), in detail these are:

- Step 2: Determination of the co-ordination withstand voltage $U_{CW}$. This voltage is determined from the representative overvoltage $U_{rp}$ by multiplication with the co-ordination factor $K_c$, the deterministic co-ordination factor is for all voltages $K_{cd} = 1.0$.
- Step 3: Determination of the needed required withstand voltage $U_{rW}$. This voltage considers firstly a safety factor and secondly a correction factor, which depends on atmospheric conditions.
- Step 4: Conversion into the standardized withstand voltages.
- Step 5: Selection of the standardized rated withstand voltages. In the columns of Table 8 the maximum voltage values are marked “bold“ and respectively “colored”, when the corresponding standard value is over traversed.

Bearing the previous steps in mind, the maximum overvoltage values for all cases according the voltage categories can be determined. These values are given in table 8; the upper value of a row refers to the results without pre-charge, the lower to the results with pre charge. For the evaluation of the maximum voltages with regard to the required voltage tests, the following values result:

Short-term power frequency voltage (phase - earth and accordingly phase - phase):
$U_{Wmax}$ = 76.5 kV and 76.9 kV with pre charge
$U_{Wmax}$ = 39.3 kV and 61.3 kV without pre charge

Lightning impulse voltage (phase – earth and phase - phase)
$U_{BILmax}$ = 92.4 kV resp. 142.0 kV with pre charge
$U_{BILmax}$ = 70.6 kV resp. 108.7 kV without pre charge

These voltage values have to be compared with the test values ($U_W$ = 70 kV und $U_{BIL}$ = 170 kV). Following basic results can be derived:

- The evaluation shows that the analyzed switching operation (earth fault, case IV) under consideration of a pre-charge is not covered by the short term power frequency voltage.
- Switching operations without pre-charge (case I.2) stress the insulation phase- phase as well, but there is still sufficient safety margin to the rated value with $U_W$ = 61.3 kV for the outer isolation.
- Switching operations that have overvoltages with high frequencies, a sufficient distance to the test value should exist.

Mind that in this examination the calculations have been made with a rated voltage of $U_b$ = 33 kV. With the application of surge arresters (phase - earth) at the end of a cable track, the overvoltage shall be kept under the maximum admissible voltage values.

## 7 SUMMARY

Simulations of transient processes in the 33 kV cable network of an offshore-wind power park show that high overvoltages during switching operations occur when cable sections with pre-charge are connected at opposite polarity. This is especially critical when the switching operations take place during an earth fault. Surge arresters that are installed at the end of the cable tracks limit the overvoltages.

| step | | Type of overvoltage | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | temporary | | | | slow front | | | | fast front | | | |
| | | phase – earth | | phase – phase | | phase – earth | | phase – phase | | phase – earth | | phase – phase | |
| | | inner | outer | inner | outer | inner | outer | inner | outer | inner | outer | inner | outer |
| 1. | $U_{rp}$ | 36 | 36 | 41.4 | 41.4 | 121.4<br>62.4 | 121.4<br>62.4 | 122.1<br>97.3 | 122.1<br>97.3 | 67.7<br>51.7 | 67.7<br>51.7 | 104.0<br>79.6 | 104.0<br>79.6 |
| 2. | $U_{CW}$ | 36 | 36 | 41.4 | 41.4 | 121.4<br>62.4 | 121.4<br>62.4 | 122.1<br>97.3 | 122.1<br>97.3 | 67.7<br>51.7 | 67.7<br>51.7 | 104.0<br>79.6 | 104.0<br>79.6 |
| 3. | $U_{rW}$ | 41.4 | 37.8 | 47.6 | 43.5 | 139.6<br>71.8 | 127.5<br>65.5 | 140.4<br>111.9 | 128.2<br>102.2 | 77.9<br>59.5 | 71.1<br>54.3 | 119.6<br>91.5 | 109.2<br>83.6 |
| 4.a | $U_W$ | 69.8<br>35.9 | 76.5<br>39.3 | 70.2<br>56.0 | 76.9<br>61.3 | - | - | - | - | - | - | - | - |
| 4.b | $U_{BIL}$ | - | - | - | - | - | - | - | - | 85.5<br>65.5 | 92.4<br>70.6 | 131.6<br>100.7 | 142.0<br>108.7 |

**Table 8:** Voltage values for the calculation of the necessary withstand voltages