Neutral Earthing in Off-Shore Wind Farm Grids

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***Abstract*—The maintenance of offshore wind farms is more complicated than those onshore. The effort associated with cable repairs in terms of time and cost is much larger compared to similar tasks in conventional distribution grids. Current and voltage stress of the grid following the most common single phase to ground fault primarily affected by the type of transformer connection and the method of neutral earthing. Low impedance earthing leads to high fault currents but the voltage stress is limited. The high fault current, on the other hand, enables easy detection and quick clearance of the fault. Using simulation results, the authors show that for the medium voltage wind farm grid as well as for the 150-kV transmission link to the grid onshore, fault currents stay within acceptable limits in spite of solid earthing. As a result, grounding the neutral solidly offers itself as the most suitable neutral treatment method for offshore wind farms.**

***Index Terms*-- neutral earthing, neutral grounding, off-shore wind farm, unbalanced fault, single line to ground fault.**

I. Introduction

In Germany a number of medium and large offshore wind farms are planned. The installed wind power capacity, currently approaching the 25 MW mark, is projected to increase further up to some hundred MW [1]. The medium voltage networks linking up individual wind turbines in an offshore wind farm (OWF) have voltage levels of 33 kV or 20 kV. The medium voltage is then stepped up to 110 kV or 150 kV level to transmit the produced power using one or more high voltage (HV) cables to the point of connection with the rest of the grid. In simulations for this work a 150-kV transmission link is used. But the discussions and conclusions are applicable in equal measure to a 110-kV transmission link [2].

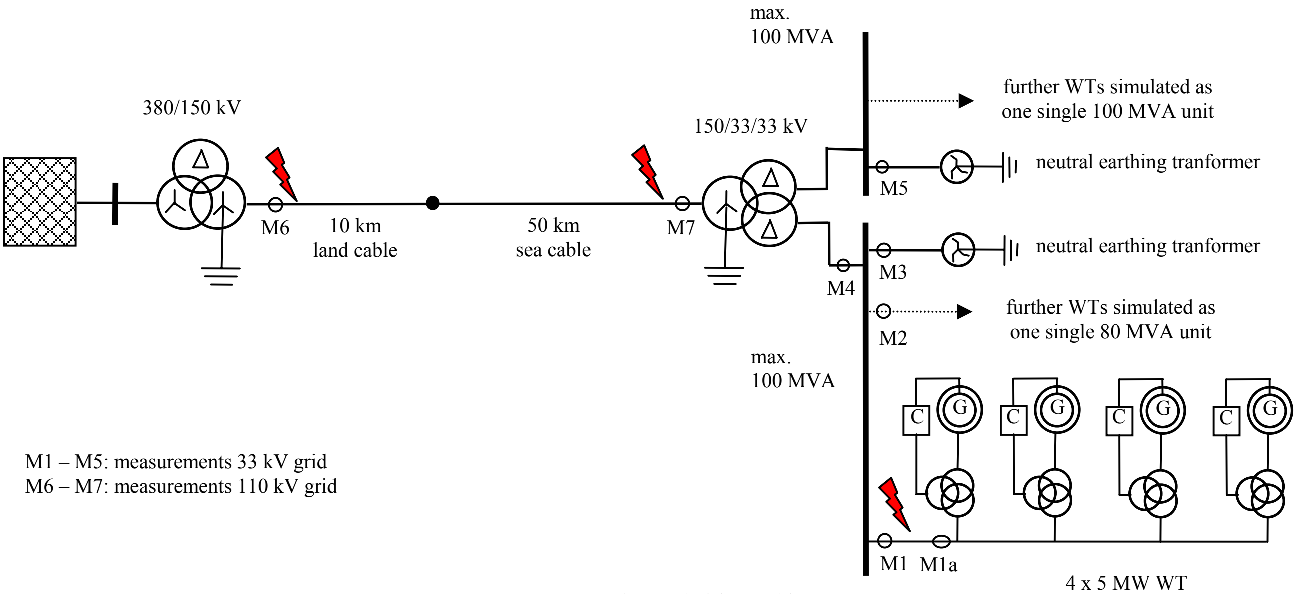

Fig. 1 Wind farm grid

For connection to the 400-kV grid obviously an additional transformer is needed. Another transformer is also used even if the wind farm is to be connected to the grid at 110-kV level. In northern Germany resonant grounding is used for the 110-kV network. But the cable link between the grid and the OWF has a high capacitive earth fault current exceeding the compensation limits. However, if a 110/110-kV transformer is

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included the zero sequence networks of the grid and the transmission link side are separated and thus the transmission cable does not contribute to the earth fault current.

This paper focuses on the neutral earthing options for the MV grid as well as for the high voltage transmission link up to the point of connection with the grid. To show the time response of grid voltages and currents to single line to ground (SLG) faults, a realistic wind farm configuration has been used and faults at critical points have been simulated. The WT operating on a doubly-fed induction generator (DFIG) was modelled in detail to show their contribution to the fault current [3], [4].

The maintenance costs and the longer down times after a fault carry more weight in OWFs compared to an onshore system. As a result the priorities have to be set differently compared to the classical MV distribution networks. The fault has to be limited affecting a single element only. To achieve this objective fast switching and an effective limitation of voltage stress on the phases that are not directly affected by the fault is important. A SLG fault should not lead to a cascading failure of all machines or other grid elements.

II. SYSTEM DESIGN

The OWP grid used in this work consists of two parts, as shown in Fig. 1. The two 33-kV grids connected to the WTs and the 150-kV transmission link for transporting the power onshore. For the layout of these grids E.ON has given some recommendations, which will be explained below.

A. The 33-kV network

The offshore transformer (150/33/33-kV) should be designed as three winding transformer for OWF lager than 100-MW installed capacity. Between the two medium voltage terminals the short circuit voltage (u_k) should be relatively large, in the order of $u_k = 24$ % or above. With such a high short-circuit voltage value, for a fault in one of the MV networks the other is effectively shielded from the fault. It is recommended that the three-winding transformers have a YNd5d5 connection.

The zero-sequence networks of the 150-kV transmission link and the 33-kV grid are separated as a result of the type of transformer connection employed. A further advantage of this connection is that for any unbalanced fault outside the 33-kV network the voltage remains almost symmetrical. Also, the transformer does not offer a transfer path for the 3rd and 9th harmonics. Using this connection, the neutral at the 150-kV side can be grounded, but on the 33-kV side extra transformers are needed to create a neutral for grounding.

For wind farms larger than 200 MVA two three winding transformers should be used which may result in four 33-kV islands.

B. The 150-kV network

The onshore transformer should be connected as YnYn(d5). Sea cables are only available up to 245-kV nominal voltage at the moment. As a result, an additional transformer is always needed to connect an OWF with the 380-kV transmission grid. A transformer is also needed when connecting to a 110-kV grid with earth fault compensation, because the capacitive earth fault current of the long cable is too large to be fully compensated.

C. DFIG Model

The wind turbines are modelled with high accuracy [3]. The four turbines of 5 MW respectively are all modelled separately. The 80 MW WT is an aggregate model and represents 16 single 5 MW turbines. In the other medium voltage grid according to Fig. 1 one aggregate model of 100 MW is used. The basic control structure is shown in Fig. 2. Wind turbines do not contribute to the zero sequence current due to the connection of the step up transformer used. However, wind turbine control works so fast that it does not affect the currents supplied and the ensuing voltages. Furthermore, many wind turbines control the negative sequence current separately which is required to keep the negative sequence current of DFIG within limits. The control algorithm used for simulation includes all details relevant for SLG faults.

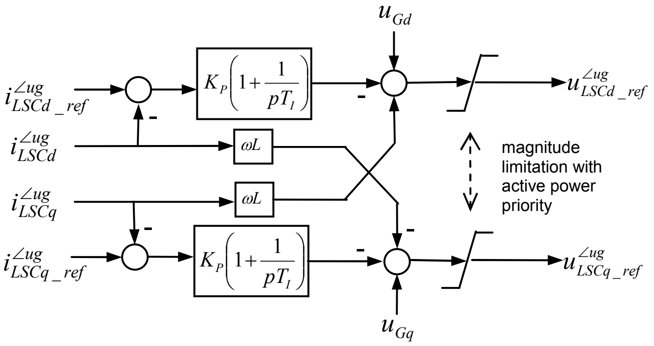


Fig. 2 LSC control diagram of DFIG wind turbine

III. ALTERNATIVE NEUTRAL EARTHING OPTIONS

A. The 33- kV network

1) Solid earthing

As it is well-known, solid earthing leads to large SLG fault current, which enables fast selective clearance of faults using a simple protection system. The amplitude of the SLG fault current can be influenced by the transformer zero sequence impedance (possibly including the earthing impedance). Fig. 3 shows the option of using neutral transformers in the main MV substation.

The zero sequence impedance can also be influenced by the number and location of the transformer neutrals used in the grid. In this case an option is using the neutrals of some of the wind turbine transformers, as shown in Fig. 4. This option is the best from the grid point of view, but at the moment no off-the-shelf product from any of the wind turbine manufacturer offers this possibility.

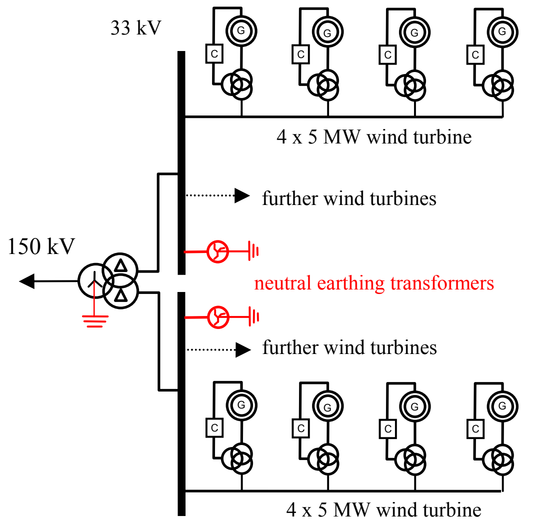


Fig. 3 Earthing option with neutral transformer

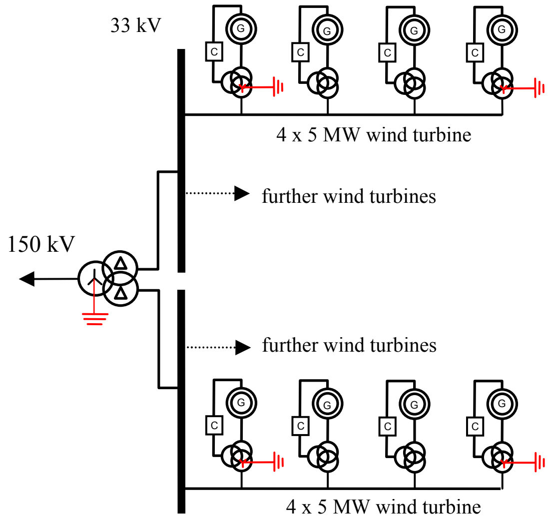


Fig. 4 Earthing option with neutral of wind turbine transformers

So an optimum balance between SLG fault currents and over voltages has to be struck. Very high fault currents can lead to damage at the fault location and excessive current along the short-circuit current path. The fault current can be limited using appropriately chosen transformer and grounding impedance during the design stage. Generally the earth fault factor should be restricted to a value equal or below 1.4 p.u. and the SLG fault current should stay within the allowable limit. Although each setup under consideration will have its unique features, the allowable values offshore will generally be different from those of a comparable onshore networks.

In summary, effective grounding offers the benefit of fast fault detection (faster than 150 ms) and the possibility of selectively clearing the fault. On account of the short fault clearing time, the thermal stress at the fault location remains acceptable and only a small over voltage is experienced.

2) *Isolated neutral*

Operating the network with an isolated neutral point is not a practical option. The 33-kV cables have a capacitive earth fault current of about 3.6 A/km. With a total cable length of about 25 km in each medium voltage grid, the total earth fault current would reach 90 A. This amount of current is greater than the standard allowable limit for isolated grids [5]. A single line to ground fault cannot be detected properly in such a grid and fast fault clearing is not possible. The excessive voltage stress with overvoltages reaching about 1.73 p.u. during fault would pose a danger to the whole grid. The transient voltage stress would also be relatively high. Due to all these reasons an isolated neutral is not recommended for the 33-kV wind farm grid. An apparent benefit vis-à-vis the enumerated disadvantages would be the fact that no grounding transformer would be needed in the 33-kV grid.

3) *Compensation coil (resonant grounding)*

The benefits of resonant grounding are well known [6]. However, for an underwater cable grid these advantages do not come to bear. The relatively small fault current with a small ohmic part is not easy to detect and locate. This makes fast, selective fault clearance in the grid impossible while the fault is not self-healing. Additionally, during the fault the danger of a follow-up fault induced by the high earth fault factor, which can reach values of up to 1.73 p.u., is high. Compared to an isolated grid, just like the solidly grounding option an extra grounding transformer would be needed.

B. *The 150-kV network*

For the transmission link an effective grounding proves to be the only solution, i.e. solid non-switchable grounding of both transformer neutrals. If the fault currents exceed 10 kA, current limiting impedance (pure resistor or an impedance) has to be connected to the neutral. With this solution, an earth fault factor around 1.1 p.u. can be maintained (see simulation results), and the danger of over voltage kept negligible. Both neutrals have to be grounded to make sure that in the event of staggered fault clearing, first on the one side then on the other, not all neutrals are lost and the grid is not isolated for a short time. With one side grounding only, the earth fault factor during the fault would reach 1.3 p.u. The system protection would be more complicated as there is no zero sequence current from the ungrounded side. With grounding on both sides, a dangerous voltage stress for the high voltage sea cable can be avoided and faults can be cleared faster than 150 ms.

IV. SIMULATION RESULTS

A. *Case studies*

The offshore wind farm investigated in this study consists of two medium voltage 33-kV grids connected to the three winding transformer and a 150-kV transmission link, transmitting the wind power to the 150/400 kV step up transformer. The single line diagram is shown in Fig. 1. All simulations are performed in time domain using three phase instantaneous values with the software package DigSilent/PowerFactory as a platform.

In the MV grid a single line to ground fault in phase 1, as shown in Fig. 1, was simulated. The zero sequence impedance of the grounding transformer was assumed as 5 Ohm (given by the manufacturer, which appears in the zero-sequence equivalent circuit with the factor 3).

In the 150-kV transmission link a single line to ground fault on the onshore end of the cable was simulated. Then the effect on the short-circuit current of an open neutral at the transformer offshore was investigated

B. The 33-kV grid

The fault occurs at t = 0.05 s and is cleared at t = 0.2 s. Fig. 1 shows the currents and voltages at the measurement points M1-M4, in the medium voltage grid.

Fig. 5a) shows the voltages in the faulted medium voltage grid in point M1. The voltage in the “healthy” phases rises during the fault to about 1.4 p.u. With the chosen grounding transformer, the objective of keeping the voltage stress low has been attained.

The voltages at the wind turbine terminal, shown in Fig. 5b), increase during the fault to the same value as at the substation. After the circuit breaker is open, the wind turbines continue to operate in an island mode. The voltage increases immediately to a value greater than 1.7 p.u. and then the wind turbine control causes the voltage to rise to 2.3. p.u. The cable with the wind turbines connected, loose any neutral grounding at t = 0.2 s and the fault is still there. The earth fault factor in the medium voltage cable rises to the 1.7 p.u. and the voltage at the low voltage wind turbine side rises above 1.1 p.u. as their power output has to be zero at that time.

The fault current, shown in Fig. 5c), reaches an RMS value of 3.42 kA that represents an acceptable value for the cables under investigation.

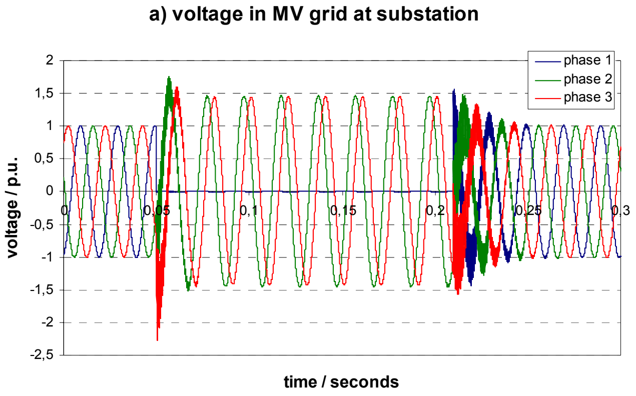
The current at the substation side in the faulted cable, shown in Fig. 5d), point M1, is still 3.28 kA. It is a value that can easily be detected by the protection system.

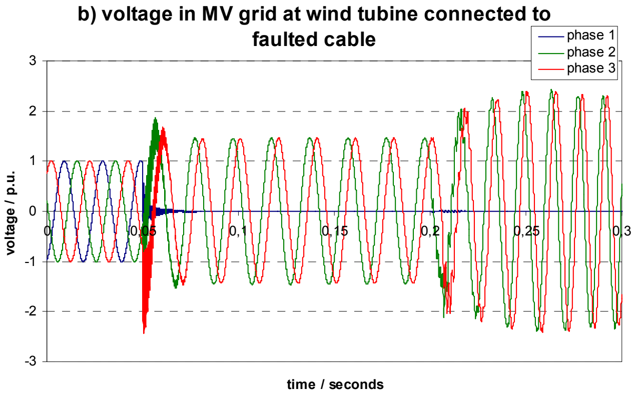
The wind turbines do not contribute towards the fault currents, as they do not feed the zero sequence. The currents of the wind turbines connected to the faulted cable (Fig. 5e, point M1a) and of the aggregate wind turbine (Fig. 5f, point M2) only change a little. The currents contain only positive and negative sequence components.

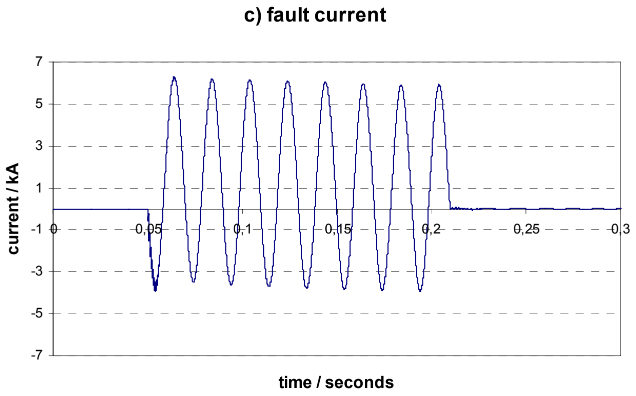
The currents at the 150/33/33 kV transformer (point M4) as shown in Fig. 5g) increase in two phases and contain also positive and negative sequence currents only.

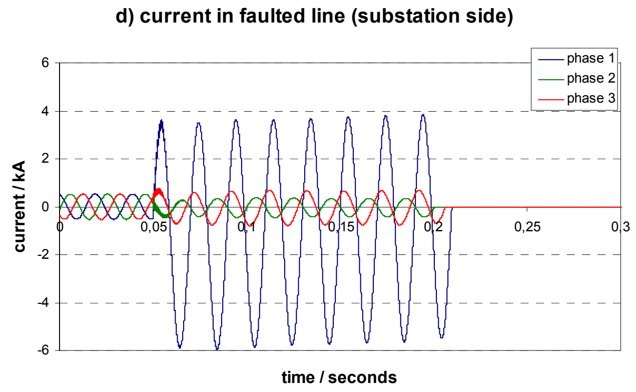
The total zero-sequence current $3*I_0$ at the grounding transformer (M3) is almost as large as the fault current (Fig. 5h). The zero sequence voltage (Fig. 5i) during the fault is about 0.65 p.u. and after the fault is cleared, it recovers (discharges) quite quickly, with high frequent transients.

Due to the fairly high short circuit voltage of the transformer (24 %) between the two medium voltage sides of the three winding transformer, the fault has almost no influence on the “healthy” phases of the medium voltage grid. The voltages at position M5 decrease during the fault only slightly to 0.9 p.u. and recovers to normal level after the fault is cleared quite fast (Fig. 5j).

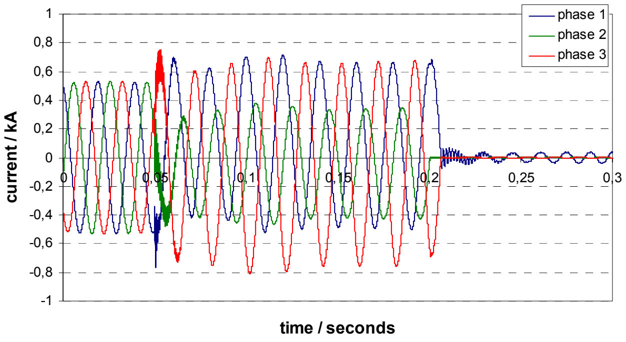

a) voltage in MV grid at substation


b) voltage in MV grid at wind tubine connected to faulted cable

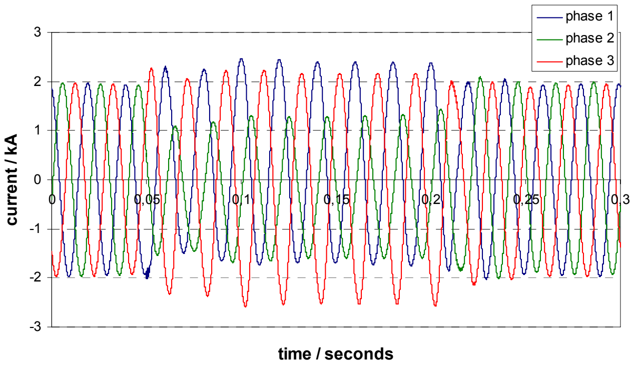

c) fault current


d) current in faulted line (substation side)

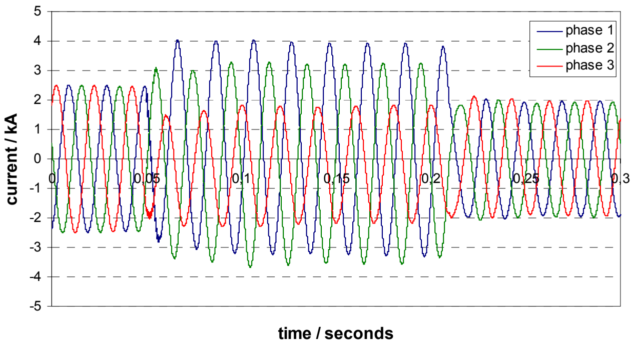
e) current in faulted line (wind turbine side)



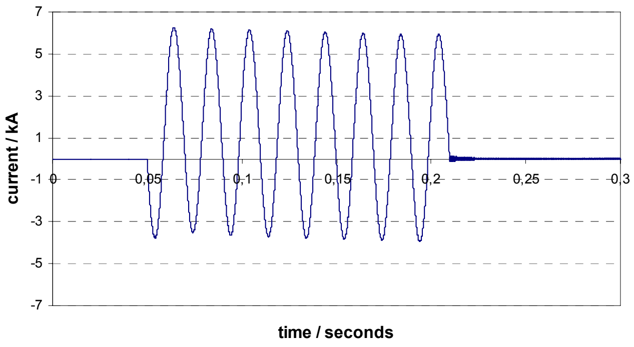
f) currents at substitute wind turbine



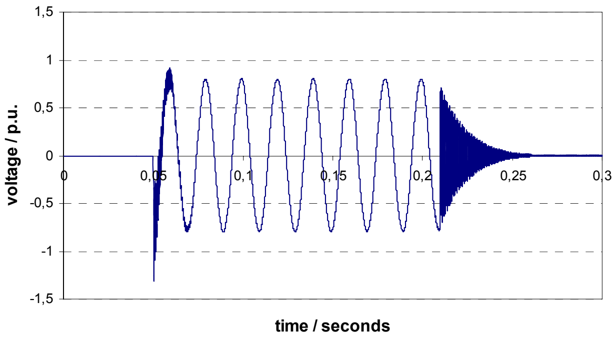
g) currents at 150/33/33 kV transformer (33 kV side)



h) 3*I0 at neutral transformer



i) zero sequence voltage at neutral transformer



j) voltages in unfaulted MV grid

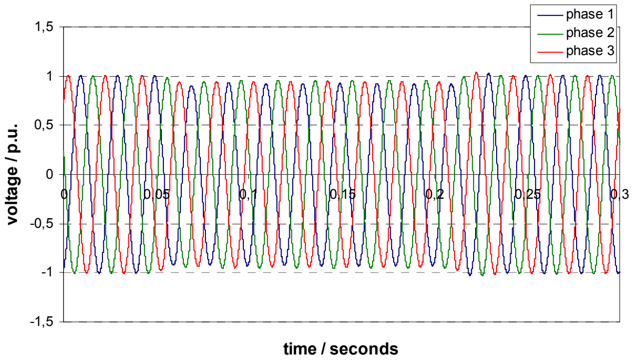


Fig. 5 Currents and voltages in the medium voltage grid with a single line to ground fault, according to Fig. 1. (Measuring M1-M5)

C. The 150-kV network

In the 150-kV transmission link two SLG earth faults in phase 1, one close to the onshore transformer and another close to the offshore transformer, were simulated and different grounding options were studied and compared to one another. In all cases, the charging current of the cable was compensated by 80 % with two compensation coils, 40 % in each side of the transmission link.

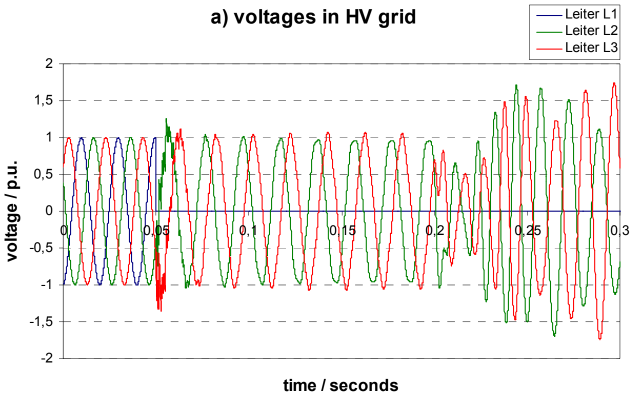
The first case, shown in Fig. 6, is a fault close to the onshore transformer in phase 1. The neutrals of both the onshore and offshore transformers were grounded solidly. The fault was assumed to occur at t = 0.05 s with the circuit breaker onshore opening at t = 0.2 s. The circuit breakers offshore opened a further 50 ms later at t = 0.25 s.

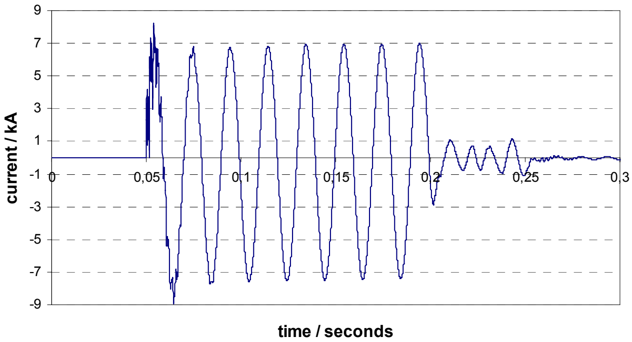
The voltage, shown in Fig. 6a (position M5), increases during the fault to about 1.1 p.u. After the circuit breaker opened onshore, the voltage initially decreases and then increases to about 1.7 p.u. due to the action of wind turbines voltage control, which controls the positive sequence voltage only. After opening the circuit breaker offshore the compensation coils start to oscillate with the cable capacitance connected parallel.

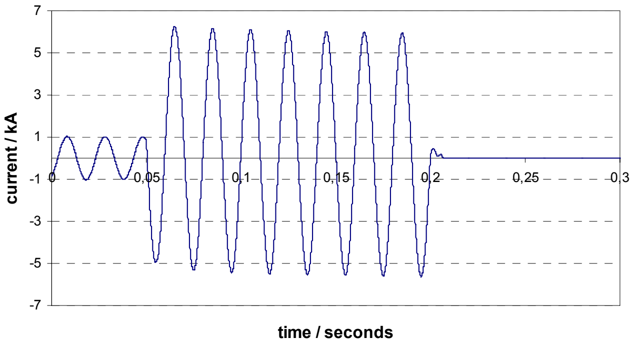
The fault current, Fig. 6b), reaches an RMS value of about 5 kA. This is acceptable for the 150 kV cable and large enough to be detected by a protection system.

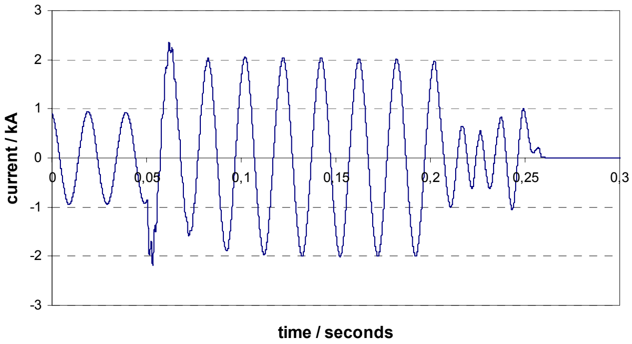
The current in the faulted cable at the onshore side, Fig. 6c (position M6), attains an RMS value of about 4 kA, much greater than the current in the faulted cable at the offshore side, Fig. 6d, (position M7), which is about 1.4 kA.

The voltage in the medium voltage grid, Fig. 6e) decreases during the 150 kV cable fault although the wind turbines attempt to support the voltage during this stage. After the circuit breaker offshore opens, the wind turbines are separated from the onshore grid. Subsequently the voltage increases within the MV grid despite the WT voltage control.


a) voltages in HV grid


b) fault current


c) current in faulted phase (onshore)


d) current in faulted phase (off-shore)

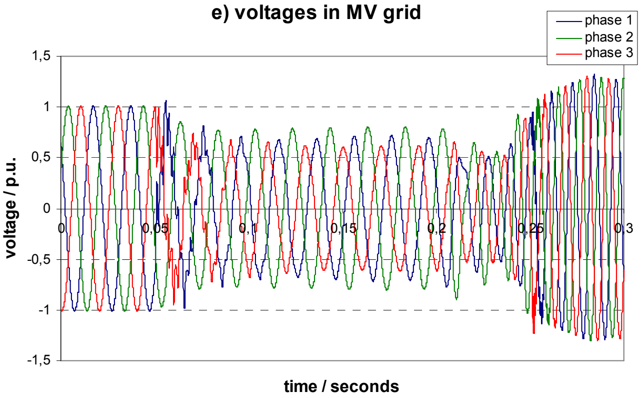

e) voltages in MV grid

Fig. 6 Voltages and currents in 150-kV high voltage transmission link during a single line to ground fault in phase 1 onshore, as shown in Fig. 1 (both transformer neutrals within the link are grounded solidly, measuring at M6 and M7)

The second case, shown in Fig. 7, is a fault close to the onshore transformer in phase 1. The neutral of the onshore transformer is solidly grounded and that of the offshore transformer is isolated. The fault is assumed to occur at t = 0.05 s and the onshore circuit breaker opening takes place at t = 0.2 s. The circuit breakers offshore open 50 ms later at t = 0.25 s.

The earth fault factor in this case turns out to be about 1.3 p.u. during the fault and when the circuit breaker on the onshore side opens, it rises to 1.7 p.u. immediately. Then, due to the parallel resonance between cable capacitance and compensation coils the voltage rises further to about 3-4 p.u.

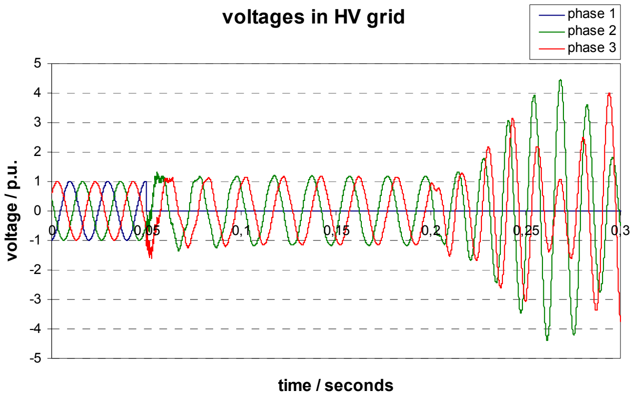


Fig. 7. Voltage in 150-kV high voltage transmission link during a single line to ground fault in phase 1 onshore, as shown in Fig. 1 (onshore transformer neutral within the link solidly grounded, offshore transformer neutral within the link isolated)

V. CONCLUSION

In this paper the available neutral earthing options for the MV grid in the offshore wind farm as well as for the high voltage transmission link between the wind farm and the point of connection with the grid has been analysed. Each star point treatment option has its pros and cons. On balance, however, the study reached the conclusion that a solid grounding for the medium wind farm grids as well as for the 150 kV transmission link stands out to be the best solution for offshore wind farm circuits.

Using the solidly grounding option the earth fault factor within the 33-kV network can be limited to about 1.4 p.u. The single phase to ground short circuit current reaches a value of about 3.4 kA. This fairly high current, however, is still within acceptable limits for cables and can be easily detected and quickly cleared by the protection system. This is the basic requirement for a fast and selective fault clearance.

The neutral earthing using a grounding transformer at the main substation in the 33-kV grids leads to a satisfactory result with regard to the current and voltage stress. However, there is the risk of loosing the neutral transformer and thus the effective grounding in case of a fault. One possible alternative could be to connect both medium voltage substations. This will lead to an earth fault factor of slightly over 1.4. Another problem is a faulted feeder after it is switched off at the main substation. This switching is faster than the fault clearing at the wind turbines. After the feeder is switched off, the grid behind the feeder becomes an isolated grid with four or five wind turbines remaining in operation. As the fault is still not cleared, in this line, the voltage at the “healthy” phases reaches 1.7 p.u. The only way to solve this problem is to place a neutral into each feeder. This could be done by changing the type of connection of the wind turbine transformer and use the neutrals at the 33-kV side for grounding. The grounding transformer at the main medium voltage substation is then no longer needed.

The simulations for the 150-kV transmission link have shown that solid grounding is needed in both ends. If the offshore neutral is not grounded and the circuit breaker on the onshore side opens first, the grid is isolated for a short time. After switching on the wind farm side, the possibility of a resonance in the transmission link is also fairly higher than in a grounded network. When both sides are grounded, the earth fault factor is limited to 1.1 p.u. and the fault current turns out to be about 5 kA, both being optimal values. Optimal in this context implies a good detection (excitation and opening) for the main and reserve protection system and no adverse effects on any parts of the system. This includes the cable shield, which is usually designed to withstand 10 kA short-circuit current for a duration of 1 s. As current magnitudes of 5 kA for a duration of 150 ms pose no threat to the cable, the main focus within the offshore wind farm grid is the maintenance of the earth fault factor within limits.

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VII. BIOGRAPHIES

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Jens Paetzold (1963) received the Dipl.-Ing. and the Dr.-Ing. degree in Electrical Engineering from the Technical University of Dresden/Germany in 1989 and 1994. From 1993 to 1998, he worked with the IPP-company VEBA Kraftwerke Ruhr AG in Gelsenkirchen at the division of electrical engineering. Since 1998, he is the head of the department of electrical engineering at E.ON Engineering GmbH in Gelsenkirchen (former PreussenElectra Engineering GmbH). His research interests are focused on power system stability and control. He is a member of VDE.

Istvan Erlich (1953) received his Dipl.-Ing. degree in electrical engineering from the University of Dresden/Germany in 1976. After his studies, he worked in Hungary in the field of electrical distribution networks. From 1979 to 1991, he joined the Department of Electrical Power Systems of the University of Dresden again, where he received his PhD degree in 1983. In the period of 1991 to 1998, he worked with the consulting company EAB in Berlin and the Fraunhofer Institute IITB Dresden respectively. During this time, he also had a teaching assignment at the University of Dresden. Since 1998, he is Professor and head of the Institute of Electrical Power Systems at the University of Duisburg-Essen/Germany. His major scientific interest is focused on power system stability and control, modeling and simulation of power system dynamics including intelligent system applications. He is a member of VDE and senior member of IEEE.