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System grounding of wind farm medium voltage cable grids

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Abstract — Wind farms are often connected to the interconnected power system through a medium voltage cable grid and a central park transformer. Different methods of system grounding can be applied for the medium voltage cable grid. This paper outlines and analyses different system grounding methods. The different grounding methods have been evaluated for two representative wind farms with different size. Special emphasis is put on analysis of isolated system grounding, which has been used in some real wind farm medium voltage cable grids. Dynamic simulations of earth faults have been carried out. The paper demonstrates for grids with isolated system grounding how the phase voltage can build up to a level of several times the system voltage due to re-ignition of the arc at the fault location. Based on the analysis it is recommended to use low-resistance grounding as the best compromise to avoid destructive transient over voltages and at the same time limit the earth fault currents in the wind farm grid to an acceptable level.

Index Terms — System grounding, wind farms, voltage rise, single-phase earth faults.

1. BACKGROUND

In Denmark wind farms has according to the traditional practice used in distribution systems often been established with isolated system grounding medium voltage cable grids. Abroad wind farms instead according to the traditional practice often have been established with (low) resistance grounding.

Within the last couple of years the first generation of "wind power plants" has been exposed to different kinds of faults. In the *Middelgrunden* wind farm several step-up transformers have faulted caused by switching voltage transients. Following several step-up transformers at the *Horn Rev* wind farm also have faulted, which lead to a replacement of all 80 wind turbine step-up transformers. At the same time the system grounding was changed from an isolated system to a kind of reactance grounding (via the wind farm auxiliary-supply transformer, designed with appropriate zero-sequence impedance).

The establishment of the first generation of wind farms (larger than 40 MW) in Denmark has in other words been exposed to different faults cases, which to a certain extent is believed to be influenced by the choice of the wind farm system grounding method.

2. SYSTEM GROUNDING METHODS

Different methods of system grounding in medium voltage networks are well-known. Basically the aim of choosing system grounding method is to find the best compromise between the different technical properties and the associated costs related to the specific system application. This should be judged case by case. Important technical properties to consider include fault current levels and over voltages.

This paper will focus on earth fault currents, fault re-ignition and reducing transient over voltages in case of single-phase to ground faults for different methods of system grounding.

Five different methods of system grounding have been analysed:

2.1. Isolated system

In the isolated system the network is without direct connection to ground. The only connections to ground are through the large zero sequence capacitance of the cables.

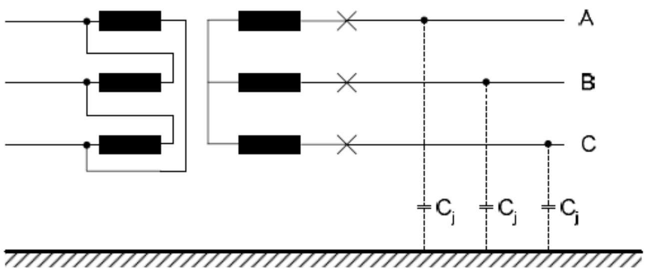

Figure 1. Isolated system grounding

The network zero-sequence impedance is approximately a pure capacitive impedance, which is much larger than the short circuit positive-sequence impedance. As a consequence single-phase earth fault currents are much smaller than short circuit fault currents, and depend on the cables and the length of the cable grid. Usually for wind farms single-phase to ground fault currents are smaller than load currents.

With respect to over voltages the isolated system has some major disadvantages, discussed further in section 3 and 4.

2.2. Direct (effective) grounded system

With direct grounded systems is meant systems with a direct connection via the transformer neutral to ground. Direct grounding is well-known and normally used in low voltage distribution networks. In transmission networks (above 100 kV) effective grounding – a special version of direct grounding, is well-known.

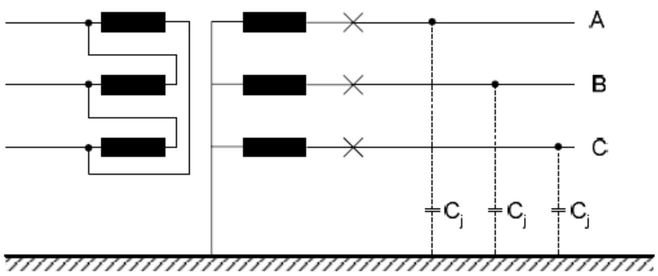

Figure 2. Direct (effective) grounded system

In direct (and effective) grounded systems single-phase earth fault currents is of the same size as short circuit currents. In other words single-phase earth fault currents will be relatively large (typically many kA). Cables, circuit breakers etc. must be designed for these large fault currents.

The effective grounded system is – as mentioned before, a special version of the direct grounded system. By grounding not all transformer neutrals in the network and by keeping impedance ratios within defined values (everywhere in the network, see table 2), the voltage rise on the healthy phases is said not to exceed 0.8 pu of the phase-to-phase voltage. Further single-phase earth fault currents is said to be approx. 0.6 pu of the three-phase short circuit fault current.

2.3. Reactance and resonance grounded systems

In reactance grounded systems the transformer neutral is connected to ground through a reactance.

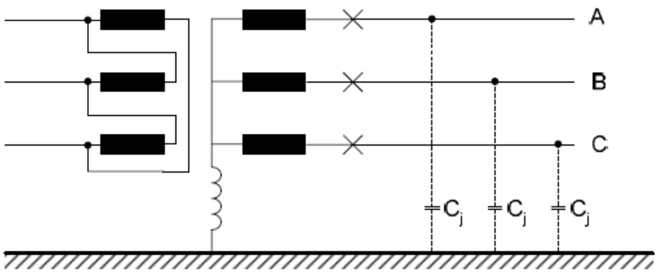

Figure 3. Reactance and resonance grounded system

By connecting the system to ground (through a reactance) it is possible to reduce the single-phase earth fault currents. To avoid destructive transient over voltages earth fault currents must be in the range of 0.25-0.6 pu of the network three-phase short circuit fault current. This is possible to achieve if impedance ratios is kept within defined values (see table 2).

A special case of reactance system grounding is when the reactance (inductance) is designed to exactly compensate the capacitive earth fault current; for this case, single-phase to ground fault current can be almost eliminated (reduced to a very small resistive current). If done, system grounding is said to be resonance grounded.

2.4. Resistance grounded system

In resistance grounded systems the transformer neutral is connected to ground through a resistance. Within resistance grounded systems two different methods are well-known; High-resistance grounding and low-resistance grounding.

High-resistance grounding has some similarities with isolated networks. The most characteristic relation is small single-phase earth fault currents (a few A), but properly designed the severe transient over voltages associated with isolated systems can be avoided. The high-resistance grounding method has not been treated in the latter analysis.

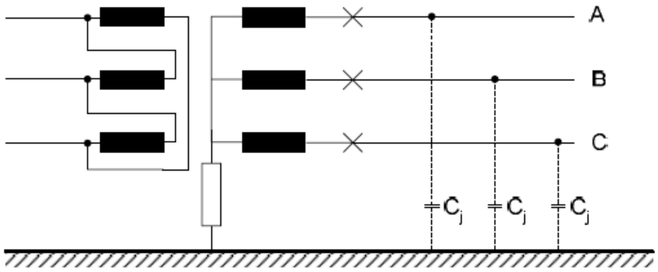

Figure 4. Resistance grounded system

Low-resistance grounding has the ability to reduce earth fault currents. By keeping impedance ratios within defined values (see table 2) earth fault currents is said to be within 200-1000 A.

As stated above the method of system grounding has significant impact on the magnitude of earth fault currents and the ability to reduce transient over voltages in case of earth faults. One consideration when selecting system grounding is therefore to try to achieve the best compromise between reducing earth fault currents and reducing possible destructive transient over voltages.

Table 1 shows typical level of fault currents and voltage rises on healthy phases (50Hz) for different methods of system grounding in networks [1]-[4]. The level in table 1 is determined by the network impedance characteristics shown in table 2 [1]-[4].

Table 1, Characteristic fault currents and voltage rises of system grounding methods

Grounding method	Earth fault current [pu of 3-phase fault current]	Phase-earth voltage [pu of phase voltage]
Isolated	-	1.73 pu
Effective	> 0.6 pu	< 1.4 pu
Reactance	0.25-0.6 pu	<1.73 pu
Resonance	-	1.73 pu
Resistance	200-1000 A	<1.73 pu

Table 2, Impedance characteristics of system grounding types

Grounding method	X_0/X_1	R_0/X_1	R_0/X_0	R_0/X_{C0}
Isolated	(∞) - (- 40)	-	-	-
Effective	0 – 3	0 – 1	-	-
Reactance	3 – 10	0 – 1	-	-
Resonance	-	-	-	-
Resistance	0 – 10	30-60	≥ 2	≤ 1

3. THEORY FOR VOLTAGE RISE DUE TO SINGLE-PHASE TO EARTH FAULTS (ARCING GROUND) IN ISOLATED SYSTEMS

In a symmetrical, three-phase circuit the symmetrical components will be represented by three uncoupled equivalents for the positive sequence, negative sequence and zero sequence component.

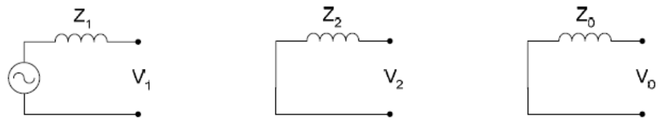

Figure 5. Symmetrical components, positive-, negative and zero sequence components

In short, in case of unsymmetrical faults e.g. single-phase earth faults, the three symmetrical components will be coupled and be represented by the equivalent shown fig. 6.

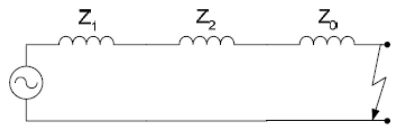

Figure 6. Equivalent for single-phase to ground fault

If the resistance in the network is ignored, the network zero sequence impedance will be mainly capacitive (as a consequence of the network capacitance to ground) and the positive and negative sequence impedances will be inductive (as a consequence of inductance in cables and transformers). If the fault impedance is assumed to be $Z_F = 0\ \Omega$, then the equivalent in figure 6 can be reduced to figure 7 in case of a single-phase to ground fault, where the fault arc is replaced by a circuit breaker.

It is seen, that the network positive- and negative sequence voltages now is represented by the voltages across the network reactance X_{1+2} and the zero sequence voltage V_0 is represented by the capacitance voltage.

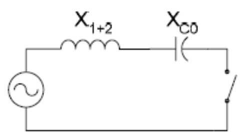

Figure 7. Simplified equivalent for single-phase to ground faults

Further the network zero sequence capacitance X_{co} will be much larger than the network inductance X_{1+2}. The earth fault current will therefore mainly be capacitive and lead the voltage by approx. 90°.

The non-linear circuit shown in figure 7 will do, that the zero sequence voltage and the phase-to-ground voltages at the two healthy phases will oscillate up to ±1 pu around the new 50Hz voltage (see figure 8, no. 1) until the transient oscillation is damped out. Within the first couple of ms after the fault has occurred the phase voltage on the two healthy phases can rise up to 2.73 pu. This phenomenon is verified by dynamic computer simulations later in section 4.

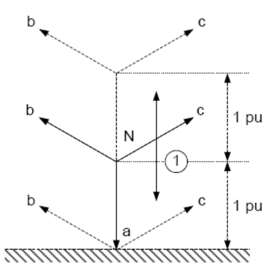

Figure 8. Transient oscillation in case of a single-phase to ground fault

When the arc current passes the natural current zero, the arc may extinguish, and the insulation potentially can re-establish the voltage withstand (the breaker at figure 7 will open). At the same time the zero sequence voltage is lagging the current by 90° and is at its maximum, i.e..up to 1 pu. The zero sequence voltage (the voltage across the capacitance in figure 7) – which actually means the isolated system is now "locked" with a new zero reference at 1 pu.

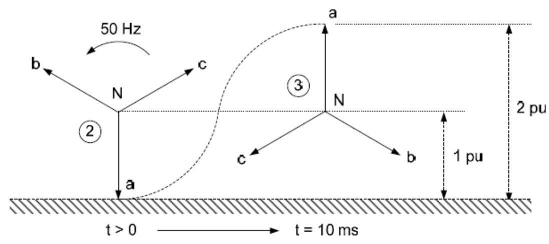

Figure 9. Voltage rise as a consequence of "locked" zero voltage

Within the next ½ period (10 ms) the faulted phase voltage will rise again – now up to 2 pu (see figure 9, no. 3).

If again assumed a fault re-ignition happens at voltage maximum (V_a = 2 pu), another transient oscillation can occur – now with a ± 2 pu oscillation for the zero sequence voltage and for the voltage at the healthy phases. This can result in very high transient oscillation on the healthy phases – theoretically now up to more than 3.5 pu.

These three steps (1-3) could theoretically go on forever. In practise the insulation in cables or transformers will break down at some point, creating a fault on a second phase which causes a protective CB trip and stop the ongoing voltage rise.

It appears above that if the zero sequence voltage can be discharged then the severe transient over voltages cannot build-up. This discharge must take place in the time span from the arc extinguish till the next voltage maximum on the (pre-) faulty phase (i.e. the time for risk of re-ignition). To ensure discharging an adequately resistance in the zero sequence system must be present. The decay of the zero sequence voltage will then be according to the below formula (1), where V_a is the phase to ground voltage before fault occurrence:

$$V_0(t) = V_a \cdot e^{\left(\frac{-t}{R_0 \cdot C_0}\right)} \tag{1}$$

It can be seen that the lower the resistance the faster decay of the zero sequence voltage and subsequently the lower the transient over voltages. Obviously this is one of the important properties of a resistance grounded network.

4. Simulation of Voltage Rise at Single-Phase to Ground Fault in Isolated System

To verify the transient voltage oscillations described in section 3, dynamic simulations of single-phase to ground faults and re-ignition of single-phase to ground faults have been carried out (see figure 10).

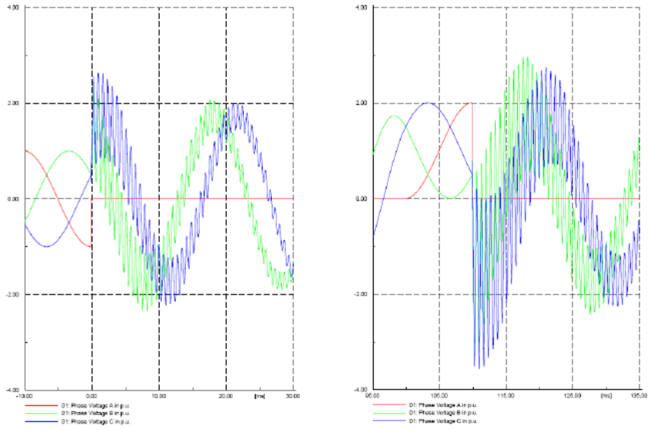

Figure 10. Simulation of transient voltage oscillations in case of single-phase to ground faults (left) and re-ignition of single-phase to ground faults (right).

The simulations show that the theoretical description of the voltage rise at single-phase earth faults is verified.

5. System grounding in wind farms

Two different wind farms have been analysed – *A* and *B* [5]. The purpose of the analysis has been to analyse fault currents and transient voltage rises at single-phase earth faults. For each wind farm five different grounding methods has been analysed.

Dynamic simulations have been carried out using the DigSilent Power Factory computer simulation program.

5.1. Wind farm A (2 WT, 7.2 MW)

Wind farm *A* contains of two wind turbines of 3.6 MW each. The wind turbines are interconnected to a 1.5 km medium voltage cable grid.

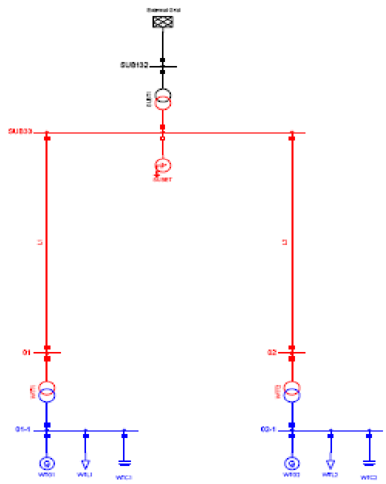

Figure 11. Wind farm A

Table 3 sums up the simulation impedance input values for the wind farm A substation earthing transformer (SUBET) and the impedance from transformer neutral to ground.

Table 3. Impedance characteristics of wind farm A

Grounding method	SUBET		Neutral impedance	
	R_0	X_0	R_N	X_N
Isolated	-	-	-	-
Effective	15 Ω	30 Ω	0 Ω	0 Ω
Reactance	15 Ω	300 Ω	0 Ω	0 Ω
Resonance	15 Ω	30 Ω	370 Ω	3.7k Ω
Resistance	15 Ω	30 Ω	95 Ω	0 Ω

Table 4 and table 5 sums up the impedance characteristics and earth fault currents and max transient phase voltage on the healthy phases in wind farm *A*. All values are measured at the wind farm substation medium voltage busbar.

Table 4. Impedance characteristics of wind farm A

Grounding method	X_0/X_1	R_0/X_1	R_0/X_0	R_0/X_{C0}
Isolated	(1.3 k)	-	-	-
Effective	3.6	1.8	-	-
Reactance	37	1.9	-	-
Resonance	(2.5 k)	(13 k)	(5.2)	(9.7)
Resistance	2.6	36	13.8	0.03

Table 5. Fault currents and transient over voltages of wind farm A

Grounding method	Earth fault current [faulted phase]	Max. phase voltage [healthy phase voltage]	
		Earth fault	Fault re-ignition
Isolated	6 A	2.7 pu	3.7 pu
Effective	1.3 kA	2.1 pu	2.0 pu
Reactance	0.2 kA	2.5 pu	3.5 pu
Resonance	0 A	2.6 pu	2.6 pu
Resistance	0.2 kA	2.1 pu	2.1 pu

In case of earth faults in wind farm A fault currents is found to be within the characteristic fault current values shown in table 1. Further transient over voltages is found to be up to 1 pu higher than the characteristic values.

In case of re-ignited earth faults transient over voltages for the effective-, resonance- and resistance grounding method is found to be at the level as the initial earth fault. For the isolated and reactance grounding method transient over voltages is found be in the range of 3.5-3.7 pu if an earth fault re-ignites. (It is known that 'fault re-ignition' in case of effective-, reactance- or resistance grounded systems may be somewhat hypothetically partly because of the size of the earth fault current (the arc will not extinguish) partly because protective relays usually will trip the faulty string instantaneous thereby preventing arcing faults. This comment applies also for case 5.2 below).

5.2. Wind farm B (20 WT, 72 MW)

Wind farm *B* contains of 20 wind turbines of 3.6 MW each. The wind turbines are interconnected to a 4.5 km medium voltage cable grid.

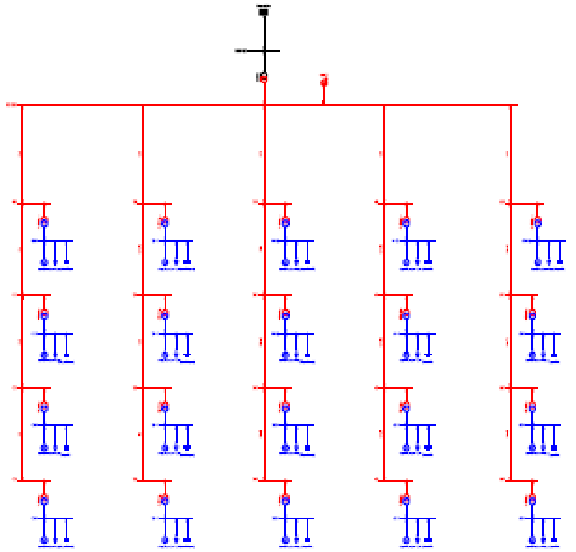

Figure 12. Wind farm B

Table 6 sums up the simulation impedance input values for the wind farm B substation earthing transformer (SUBET) and the impedance from transformer neutral to ground.

Table 6. Impedance characteristics of wind farm B

Grounding method	SUBET		Neutral impedance	
	R_0	X_0	R_N	X_N
Isolated	-	-	-	-
Effective	1 Ω	3 Ω	0 Ω	0 Ω
Reactance	1 Ω	3 Ω	0 Ω	0 Ω
Resonance	1 Ω	3 Ω	12 Ω	120 Ω
Resistance	15 Ω	30 Ω	15 Ω	0 Ω

Table 7 and table 8 sums up the impedance characteristics and earth fault currents and max transient phase voltage on the healthy phases in wind farm *B*. All values are measured at the wind farm substation medium voltage busbar.

Table 7. Impedance characteristics of wind farm B

Grounding method	X_0/X_1	R_0/X_1	R_0/X_0	R_0/X_{C0}
Isolated	(0.3 k)	-	-	-
Effective	2.7	0.9	-	-
Reactance	8.3	0.9	-	-
Resonance	-	-	-	-
Resistance	-	54	3.5	0.2

Table 8. Fault currents and transient over voltages of wind farm B

Grounding method	Earth fault current [faulted phase]	Max. phase voltage [healthy phase voltage]	
		Earth fault	Fault re-ignition
Isolated	0.2 kA	2.3 pu	3.7 pu
Effective	9.9 kA	1.7 pu	2.1 pu
Reactance	5.1 kA	2.1 pu	3.1 pu
Resonance	19 A	2.4 pu	2.7 pu
Resistance	0.8 kA	2.3 pu	2.4 pu

In case of earth faults in wind farm B fault currents is also found to be within the characteristic fault current values shown in table 1. Further transient over voltages is still found to be higher than the characteristic values in table 1.

Transient over voltages in the resistance grounded system caused by re-ignited earth faults only show a small increase compared to transient over voltages at the initial earth fault. For other grounding methods increases between 0.3-1 pu in case of earth fault re-ignition are observed.

In the isolated grounded system transient over voltages as high as 3.7 pu is possible in case of earth fault and earth fault re-ignition.

6. Conclusion

Throughout dynamic simulations two different wind farms have been analysed with respect to system grounding. For both wind farms it has been shown, that the best compromise for reducing earth fault currents and transient over voltages is obtained by low-resistance grounding of the internal medium voltage cable grid. Therefore low-resistance system grounding is recommended to be applied in wind farms with an internal medium voltage cable grid. The design must be in accordance with the impedance characteristic in table 2.

For the rare case where possibility of continuous operation of the wind turbines despite an earth fault has priority another grounding method like the high-resistance grounding method may be considered.

Even though resonance grounding from the perspective of the issue of this paper seems attractive this method has other disadvantages (risk of Ferro-resonance, more complex, and more expensive) which usually makes it not recommendable for wind farm collection grids.

Isolated system grounding is not recommendable due to risk of very high transient over voltages in case of single-phase earth faults followed by single-phase earth fault re-ignition.

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