Insulation coordination for wind power plants

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Overview

• Insulation coordination definition
• Wind Power Plant characteristics
• Challenges of insulation coordination in WPPs
• Examples in EMTP-RV

✓ Temporary overvoltage due to SLGF
✓ Vacuum circuit breaker switching
✓ Direct lightning strikes
The goal of insulation coordination is uninterrupted and reliable power supply in all technical and atmospheric conditions.

Definition by IEC 60071-1:

- Insulation coordination is the selection of the dielectric strength of equipment in relation to the voltage which can appear on the system for which the equipment is intended and taking into account the service environment and characteristics of the available protective devices.

- The insulation in a power system (with all its components) should be designed on the way to minimize damage and interruption to service as a consequence of steady state and transient overvoltages and this should be done economically.
Wind power plant characteristics

- Transmission system: MVAC, HVAC, HVDC
- Collector system: MVAC cable network, different topologies
- Reactive compensation, filters at POI
- Main components:
  - wind turbine generators (Type 1 – Type 5)
  - vacuum circuit breakers
  - transformers (step-up and power transformer)
  - cables
WPP – typical layout

substation MV/HV transformer

feeder breakers

LV/MV step-up transformers

WTGs
Overvoltages in WPPs

Lightning transients
✓ Coupling through substation transformer
✓ From direct tower strikes

Switching transients
✓ Coupling through substation transformer
✓ Feeder energization
✓ Vacuum circuit breaker switching (VFFT due to prestrikes and restrikes)

Temporary overvoltages
✓ Ground faults
✓ Feeder islanding, loss of ground reference
✓ Can be higher than 1.73 pu

Continuous operating voltages
✓ Higher voltage at remote ends

Surge arrester selected to protect equipment from these

Surge arrester selected to survive these
Surge arrester typical placement in MV network

- adjacent to the substation power transformer
- on the feeder side of each feeder breaker
- at each interface between overhead and underground feeder sections
- at the end of each feeder and branch
+ LV surge arresters in the tower
## Insulation coordination steps

<table>
<thead>
<tr>
<th>Conventional process from standards (IEEE C62.22, IEC 60071)</th>
<th>Procedure for WPPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Select the surge arrester to be used (MCOV, TOV)</td>
<td>1. Select the available insulation level (limited range)</td>
</tr>
<tr>
<td>2. Determine the protective level of selected surge arrester</td>
<td>2. Select arresters needed to protect that insulation level</td>
</tr>
<tr>
<td>3. Determine the locations for surge arresters</td>
<td>3. Determine amount of TOV that can bewithstood</td>
</tr>
<tr>
<td>4. Determine the voltage at terminals of the protected equipment</td>
<td></td>
</tr>
<tr>
<td>5. Select equipment insulation level</td>
<td></td>
</tr>
<tr>
<td>Evaluate voltage protection margins</td>
<td></td>
</tr>
</tbody>
</table>

### TOV mitigation methods

if margins are inadequate, consider alternatives: different arrester locations, higher insulation level...
Temporary overvoltage due to SLGF
Example 1

Temporary overvoltage: single-line-to-ground fault, feeder disconnection and loss of ground reference

1. Ground fault on collector cable
2. Breaker trip, isolates collector feeder
3. WTGs do not see fault after collector breaker trips, may run-on

YD step-up transformers do NOT provide ground source for the cable network

Substation transformer is normal ground source
Example 1

- Overvoltage of healthy phases depends on grounding and WTG type

- TOV mitigating options:
  ✓ Transfer tripping (normally used in new WPPs)
  ✓ High-speed grounding switch
  ✓ Grounding transformer on each feeder

- The choice depends on WTG type
Example 1

WTG
ynD 0.69/33 kV

Grounding transformer
zig-zag

33 kV cable network

GB

voltage measurement

fault

VCB

dYn
33/132 kV

model in: arrester abb.dat

ZnO
66000

scope

breaker model

Vacuum circuit

scope

breaker model

Vacuum circuit

scope

breaker model

Vacuum circuit

model in: CABLE DATA cabledata5

model in: CABLE DATA cabledata4

model in: CABLE DATA cabledata6
Example 1 – GT 2 excluded

1. SLGF occurs at 20 ms on phase C
2. Feeder breaker opens at 100 ms – loss of ground reference
3. WTGs continue to generate

overvoltage limited
Example 1 – GT included

1. SLGF occurs at 20 ms on phase C
2. Feeder breaker opens at 100 ms – loss of ground reference
3. WTGs continue to generate

overvoltage remains limited
Vacuum circuit breaker switching
Practical problems with VCB switching in wind farms

• The first off-shore wind farms were faced with substantial transformer failures in a very early operation stage.

• In the first large offshore wind farms Horns Rev and Middelgrunden (Denmark), almost all of the transformers had to be replaced due to insulation failures.

• It is suspected that the switching of the vacuum circuit breakers (VCB) caused the transformer failures.

• In order to investigate this phenomenon, a laboratory setup was built, designed to give an insight into high frequency transients generated during breaker switching in offshore wind farms and similar cable systems.

„ELECTRICAL TRANSIENT INTERACTION BETWEEN TRANSFORMERS AND THE POWER SYSTEM“, CIGRE WG A2/C4.39
Vacuum circuit breaker switching

$u_d(t)$
dielectric strength of the inter-contact gap
Restrike phenomena during breaking of small inductive current
Restrikes caused by VCB switching

Figure 10: Voltage restrikes at transformer TX1 (oil-insulated) with surge capacitor protection – simulation.

Figure 11: Voltage restrikes recorded in measurements (left) and simulation (right) – oil-insulated tr.
Example 2 – Failure of power transformer 110/25 kV

Failure of 25 kV winding
Example 2 – EMTP-RV model

- Detailed model of VCB
- Detailed model of power transformer (high-frequency behaviour)

MV cable network (capacitive load)
Simulation results

VCB voltage

- DEV1/VCB_ph_a@vb
- DEV1/withstand_U_new@control
- -1*DEV1/withstand_U_new@control
Simulation results

VCB current
Simulation results

VCB current
Simulation results

Overvoltage at 25 kV winding of power transformer
Simulation results

Overvoltage at 25 kV winding of power transformer
Direct lightning strike to wind turbine
Damages caused by direct lightning strike
Lightning and surge protection for the wind turbine
Placement of the SPDs

Example: protection for the generator

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPD according to EN 61643-11/IEC 61643-11</td>
<td>type 2/class II</td>
</tr>
<tr>
<td>Nominal AC voltage ($U_n$)</td>
<td>480 V (50/60 Hz)</td>
</tr>
<tr>
<td>Max. continuous operating voltage ($U_c$)</td>
<td>600 V (50/60 Hz)</td>
</tr>
<tr>
<td>Nominal discharge current (8/20 µs) ($I_n$)</td>
<td>15 kA</td>
</tr>
<tr>
<td>Max. discharge current (8/20 µs) ($I_{max}$)</td>
<td>25 kA</td>
</tr>
<tr>
<td>Voltage protection level ($U_P$)</td>
<td>≤ 3 kV</td>
</tr>
<tr>
<td>Temporary overvoltage (TOV)</td>
<td>900 V / 5 sec.</td>
</tr>
</tbody>
</table>
Example 3 – Direct lightning strike to WT blade

Single WTG 3 MVA operating in the vicinity of substation 22/110 kV.

Lightning current 100 kA

Blade 40 m

Tower 80 m

WTG 3 MVA

TR1 0.69/22 kV 3 MVA

22 kV cable 2 km

TR2 22/110 kV 15 MVA

110 kV network

0.7 kV cable 80 m

SPD

Grounding resistance 50 Ω (ionization included)
Example 3 – lightning current distribution / ionization

Lightning current

Current through grounding resistance

Potential rise at grounding resistance

Grounding resistance
Example 3 – overvoltages at TR1 and WTG terminals

Overvoltages at 0.69 kV side of TR1

Transferred overvoltages at 22 kV side of TR1

Overvoltages at WTG terminals
Example 3 – SPD connected in neutral point of TR1 and ideally grounded

Overvoltages at 0.69 kV side of TR1

Transferred overvoltages at 22 kV side of TR1

Overvoltages at WTG terminals
Conclusion

• Different approaches for reducing TOVs due to SLGF are investigated. Simulations have shown that application of grounding transformer efficiently reduces TOVs during SLGF.

• EMTP-RV simulations confirmed the fact that VCB switching produces VFTOs which are not high in magnitude, but due to high frequency, the distribution across the transformer winding is nonlinear. This may cause dielectric breakdown of transformer insulation system.

• The results of direct lightning strike simulation indicate that use of appropriate SPDs is crucial in order to protect the vulnerable electronic equipment. However, the efficient operation of SPDs depends on grounding resistance value which should be kept as low as possible.
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