SURGE PROTECTION OF GENERATORS DIRECTLY CONNECTED TO A MEDIUM VOLTAGE NETWORK

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ABSTRACT

The paper presents the results of the surge protection study of a generator in a small hydro power plant that is directly connected to the overhead network. Overhead lines pass through to the area of high isoceraunic activity with high specific resistance of soil. Lightning striking overhead lines produce voltage transients that can harm insulation of a generator winding. The parameters for the generator model were obtained by calculation and measurement. The simulation model is presented, and results of the simulations are given. The improvement of surge protection is achieved by installation of additional surge arresters connected to generator terminals and at neutral point. It is recommended to conduct surge protection analysis for each generator which is designed to be directly connected to the overhead line.

1 INTRODUCTION

As renewable energy sources nowadays play an important role in the production of electrical energy, the number of small hydro power plants (SHPPs) has gone up. A generator is the most important and expensive element in a power plant and its protection should be designed very carefully. A generator fault could cause a long standstill in the energy production, since it should be very often transported and repaired in a factory.

Experiences have shown that faults in SHPPs occur more often than in large ones, due to simplified connective schemes and insufficient protection measures that are sometimes being implemented.

The reduction of surge level on values which are safe for insulation system of the generator is achieved by the principle of the insulation co-ordination. The service environment and the characteristics of the available protective devices should be taken into account [1], [2].

The paper presents an analysis of lightning overvoltages which can endanger the generator insulation, and it proposes measures of an improved surge protection.

2 GENERATOR DIRECTLY CONNECTED TO A MEDIUM VOLTAGE OVERHEAD NETWORK

It is well known that a generator transformer, as well as other power transformers, contributes to surge protection, primarily because they themselves are protected by surge arresters, and because the surge wave is reduced when transferred from one transformer winding to another.

Some small power plants are directly connected to a medium voltage distribution network, and their generators are more exposed to surges than large generators, that are somewhat protected by the step-up transformer and the interconnecting cable which could generally be several hundred meters long, [3]. If a steep transient voltage produced by the lightning is applied across the terminals of a generator, most of the wavefront will be distributed across the first few turns of the generator stator winding, thus overstressing these turns, [4], [5]. As the wave penetrates along the winding, the wavefront slopes off and the amplitude is reduced.

Lines in distribution network are often supported by wood, concrete or metal poles without a shielding wire, whose absence could be unfavorable regarding the surge protection, as lightning currents of high magnitudes can strike phase conductors. Also, the induced overvoltages, which result from the lightning strokes in the vicinity of the unshielded line, can reach remarkable magnitudes, as there is no grounded shielding wire which reduces the induced overvoltages, [6].

In some cases, the neutral point of the distribution network is isolated, and a single-phase fault could cause the significant voltage rise of the sound phases, [7]. The intermittent faults in such networks can cause long lasting transient overvoltages, with high amplitudes. In addition, the appearance of resonances is possible in networks with isolated neutral. The mentioned facts could make the efficient design of the surge protection more difficult.

3 MODEL FOR SIMULATION

Models of overhead line, cable, generator and surge arresters were used in EMTP simulations of lightning surges.

In the considered case study the double-circuit 10(20) kV overhead line is supported by concrete poles with metal consoles. The metal consoles are connected to a grounding system via concrete armature. The double-circuit line has no shielding wire, and all amplitudes of lightning currents can strike directly to upper phase conductors. When lightning strikes the phase conductor, it results in a significant increase of voltage, because of the impressed surge current. In almost all cases, a flashover occurs across the insulator to the grounded metal console.

Overvoltage waves, regardless of the origin, travel on the both sides of the line and reach, through the cable section, the switchgear of the SHPP and the generator, Fig. 1. The multiple reflections occur at the line–cable and generator connection points. Installed surge arresters in the switchgear of SHPP absorb the part of the energy of the lightning surge. The EMTP program, ATPDraw version, will be used for calculation of this complex transient event, [8].

Eleven spans of the one circuit of a double-circuit 10(20) kV overhead line were modeled. The model of line is terminated with an overhead line of a greater length to avoid reflections, Fig. 2.

The pole 1 of the double-circuit overhead line is depicted in Fig. 3. Following data are used for the model of the overhead line:

- Al/St conductor 50/8 mm^2, inner radius 0.16 cm, outer radius 0.48 cm, specific resistivity 0.5946 Ω/km;
- Specific earth resistance 2000 Ωm;

The used JMarti model includes skin effect and real transformation matrix. Parameters of each span were calculated in 10 points per 8 decades with an initial frequency of 10 Hz. Frequency matrix was calculated for 100 kHz.

Cable 10(20) kV XHE 49-A 3x(1x150/25 mm^2) was modeled in the same manner. Three cables were modeled: from the overhead line pole to the SHPP switchgear (2.27 km), from the switchgear to the generator (30 m) and from the generator to the neutral point cabinet (30 m), Fig. 1.

Each stator phase of the generator was modeled using surge impedance of 2270 Ω and resistance 0,001352 Ω/m. The surge impedance was calculated from the measured value of capacity (0.02395 μF) and inductivity (0.1235 H). Length of one phase winding is 917.44 m. The phase winding consists of 20 coils, and each coil of 16 turns. All 16 turns of the first coil are modeled in order to observe the voltage distribution along the turns by oncoming steep surges, Fig. 4. The series capacitances between the turns of a coil are calculated and measured (210 pF/m). The measurement was conducted on a part of insulated conductor of the stator winding, Fig. 5.

Surge arresters (SA) of different continuous operating voltages (U_C) and energy classes were modeled using [9]-[11]. Following SAs were selected:

- U_C=12 kV at the overhead line-cable connection;
- U_C=12 kV at the switchgear of the SHPP;
- U_C=11 kV at the generator terminals;
- U_C=7 kV at the neutral point cabinet.

The connecting leads of SAs installed on the pole were modeled with inductivity of 1 μH/m and the grounding resistance of the pole was 20 Ω.

In the switchgear of SHPP and in neutral point cabinet, connecting leads of SAs to reference earth were modeled with its resistance and inductivity of 10 μH.

SAs on generator terminals are directly connected with the generator housing and reference earth.

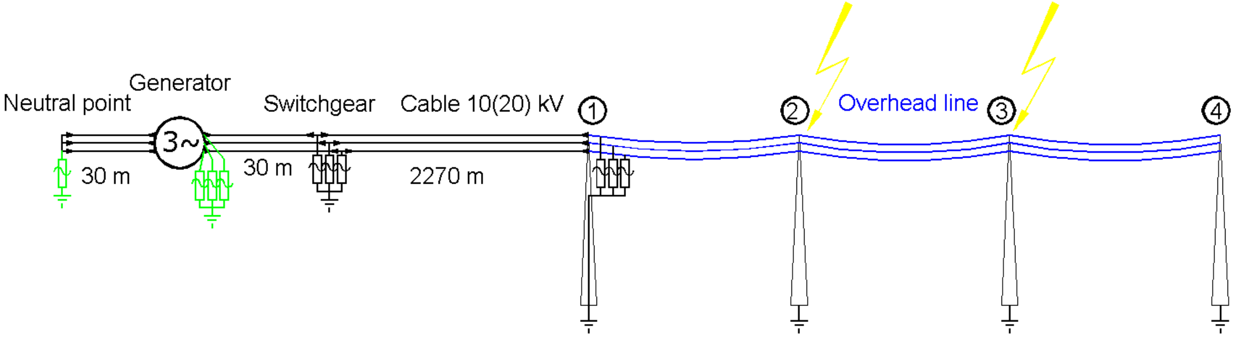

Fig. 1. Schematic diagram of the overhead line, cable and generators to consider transients

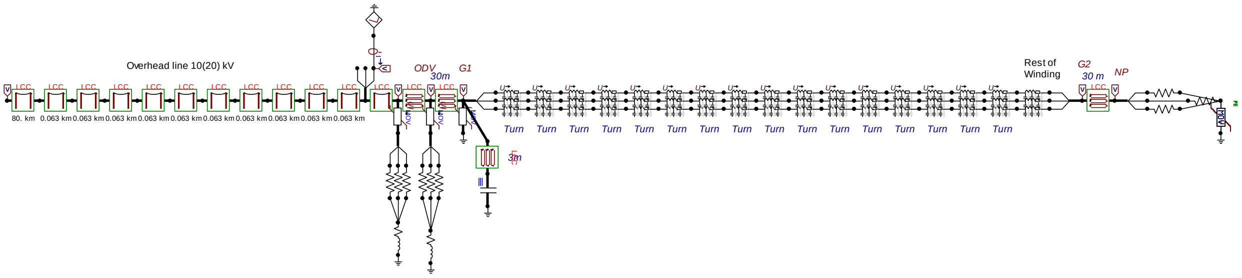

Fig. 2. Three phase model in ATPDraw

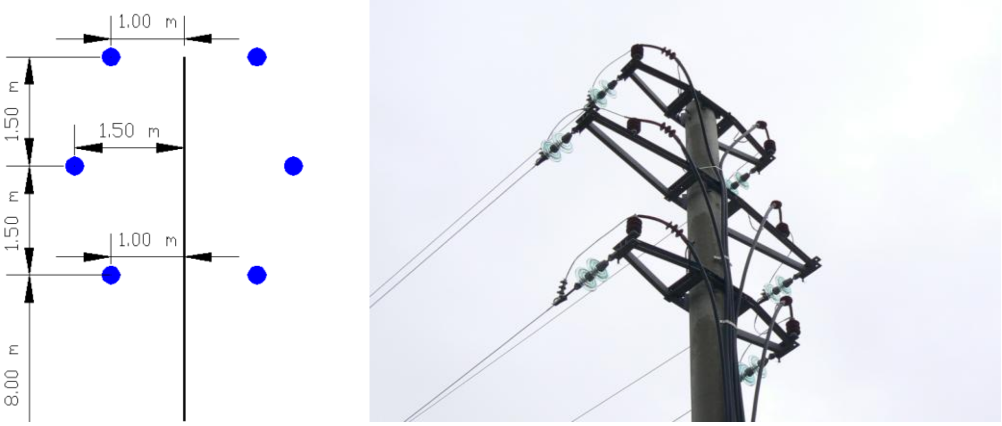

Fig. 3. Pole 1 of the double-circuit 10(20) kV overhead line

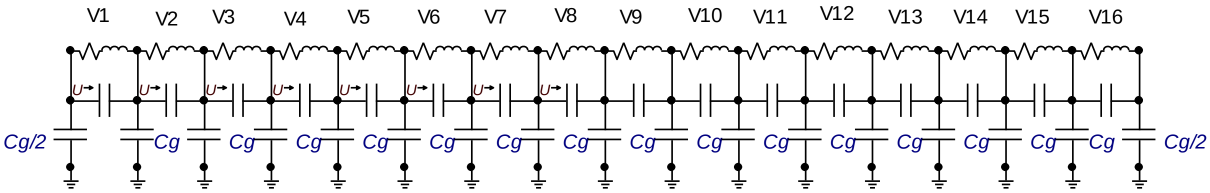

Fig. 4. Model of the first coil of one phase of the stator winding

Fig. 5. Part of insulated conductor of the stator winding

4 RESULTS OF SIMULATION

The first and the subsequent stroke were simulated in the calculations. The first stroke is usually of the higher amplitude and smaller steepness than the subsequent one.

Two cases were simulated:

Case A - The 10 kA lightning stroke terminating at phase conductor at the pole 2 in front of the overhead line-cable connection with and without flashovers;

Case B - The 70 kA lightning stroke at the phase conductor at the pole 3.

4.1 Lightning stroke without flashover

The 10 kA stroke at the pole 2 with maximum steepness of S_m = 65 kA/μs without the occurrence of flashover was modeled. According to [12], only 5% of the lightning strokes have a greater steepness. A very unfavorable case of a lightning stroke at the pole 2 in front of the overhead line-cable connection is assumed and the flashover across the insulator is avoided due to the vicinity of SAs installed at the pole 1. Lightning striking poles far away from the pole 2 (even with amplitudes smaller than 10 kA) will certainly cause a flashover across the insulator. The flashover reduces the amplitude of the surge, and that is convenient from the point of surge protection.

First simulations were conducted for SAs installed at the overhead line-cable connection and at the switchgear of the SHPP. Such arrangements of SAs placement was during the fault of stator winding insulation that was caused by lightning surges.

Fig. 6 and Fig. 7 depict the overvoltages at the generator terminals that reach values above the withstand voltage. Relatively small amplitude of lightning striking the first few spans would most likely damage the insulation of generator stator winding.

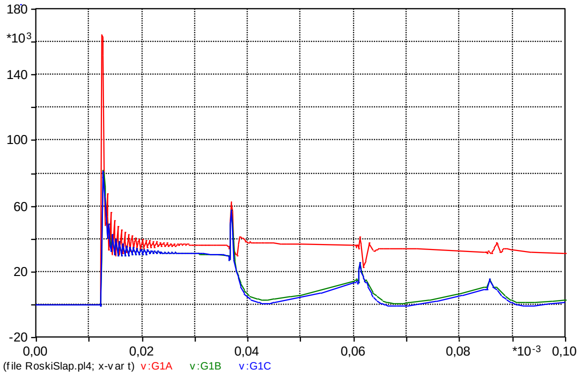

Fig. 6. Voltages at the generator terminals to the reference ground (V_{amax}=164.4 kV; V_{bmax}=82.0 kV; V_{cmax}=81.2 kV)

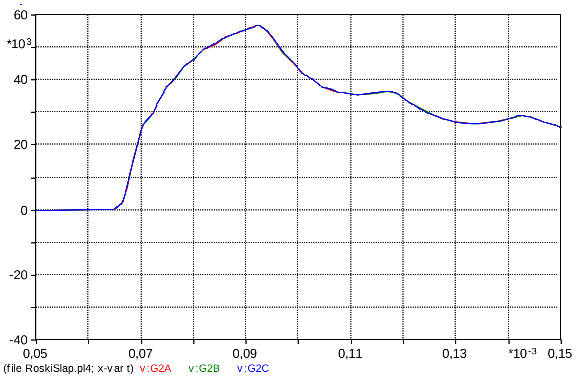

Fig. 7. Voltages at the end of the generator stator windings to the reference ground (V_{amax}=56.8 kV; V_{bmax}=56.8 kV, V_{cmax}=56.8 kV)

In the simulations that follow, beside existing SAs, additional SAs, marked in green color in Fig. 1, were installed at the terminals of generator (U_C=11 kV, energy class 4,) and at the generator neutral point (U_C=7 kV, energy class 2).

Fig. 8 shows the voltage at the generator terminals, and the Fig. 9 the voltage at the ends of the generator winding.

It is obvious from Fig. 8 and Fig. 9 that the SAs installed at the generator terminals and at the generator neutral point considerably reduce overvoltage at the generator, which should protect its insulation to the ground.

Insulation of stator coil to the ground was tested in high voltage laboratory by short (1 minute), $2U_N+1$=22 kV withstand voltage according to the IEC standards [4], [5], Fig. 10. It was shown that insulation of a new coil withstands much higher voltage (to the ground) than the requested value defined by the above mentioned IEC standards.

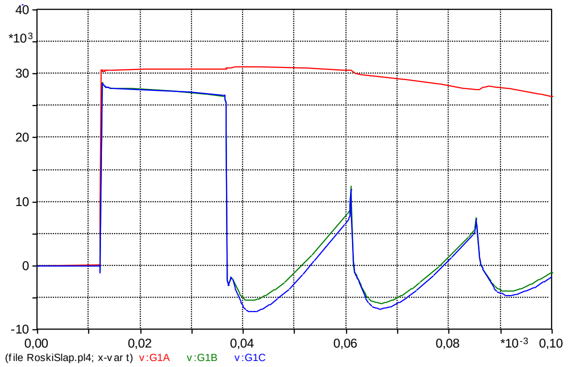

Fig. 8. Voltages at the generator termninals to the referent ground (V_{amax}=31.1 kV; V_{bmax}=28.5 kV, V_{cmax}=28.5 kV)

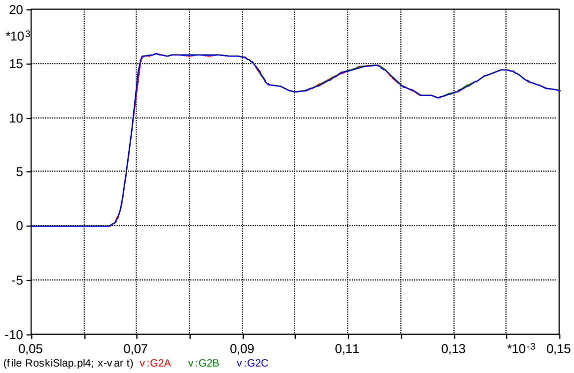

Fig. 9. Voltages at the end of the generator stator windings to the referent ground (V_{amax}=15.9 kV; V_{bmax}=15.9 kV; V_{cmax}=15.9 kV)

The voltage distribution along the first few turns of the first coil of the generator stator winding was also considered. Fig. 11 shows the maximal overvoltages at the first turn V_{1max}, between the first and second turn V_{2max}, the second and third turn V_{3max}, the third and fourth turn V_{4max}, and the fourth and fifth turn V_{5max} of the first coil of the stator winding. The highest overvoltage amplitude occurs at its first turns, as expected.

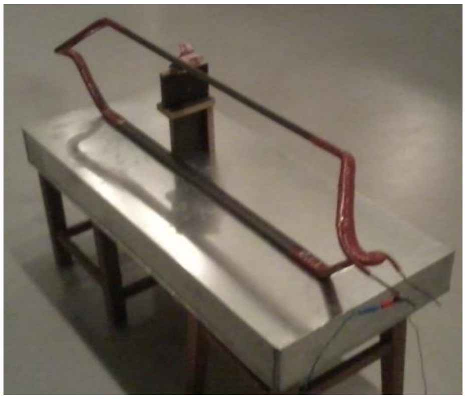

Fig. 10. Testing of the coil of the stator winding

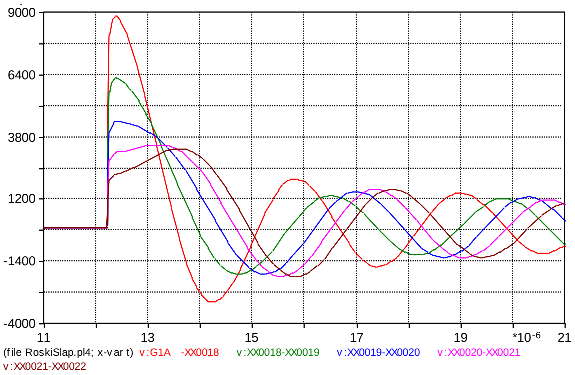

Fig. 11. Voltage wave shapes on the first five turns of the coil (V_{1max}=8.86 kV; V_{2max}=6.29 kV; V_{3max}=4.47 kV; V_{4max}=3.47 kV; V_{5max}=3.32 kV)

Insulation between the turns was tested in a high voltage laboratory, by short (1 minute) 15 kV withstand voltage (RMS). Comparing the calculated overvoltages and the RMS values of the test withstand voltage, it can be concluded that the insulation between the turns should withstand overvoltage amplitude.

4.1.1 Protective capacitors

Further improvement of surge protection of the generator insulation, especially between the turns of the first coil, can be achieved by adding protective capacitors. Fig. 12 shows the voltage at the first five turns of the first coil with the 0.25 µF protective capacitor connected per phase.

Connecting cable (2 m length) between the terminals of the generator and capacitor causes the first peak of oscillation that can be seen in Fig. 12.

In order to avoid such oscillation the all connecting cables should be as short as possible (not longer than 2 m).

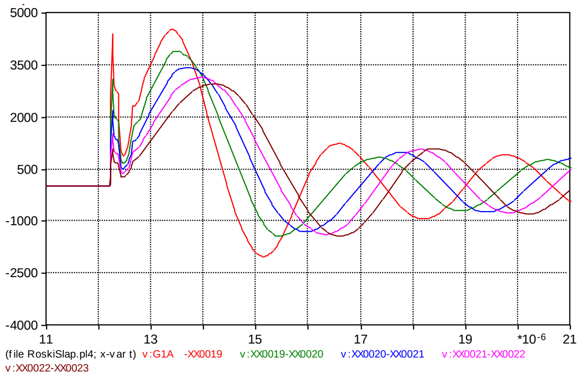

Fig. 12. Voltages on the first five turns of the coil (V_{1max}=4.54 kV; V_{2max}=3.91 kV; V_{3max}=3.43 kV; V_{4max}=3.15 kV; V_{5max}=2.97 kV)

4.2 Lightning stroke with flashover

By simulating a 10 kA lightning stroke with the maximum steepness of S_m=65 kA/µs, and taking into account the possibility of flashover it was shown that the overvoltages in all cases have lower values. This was completely in line with the expectations, since the overvoltage wave energy has been taken away by the flashover, so consequently, the overvoltage amplitude at all observed points was lower.

Next simulation was the lightning stroke of 70 kA with the maximum steepness of S_m=40 kA/µ. A very unfavorable case of a lightning stroke to the pole 3 in front of the overhead line–cable connection was assumed. In that a case, the flashover occurs across the insulators strings in all the three phases of the stroked pole 3 as well as at the pole 2 and in the two phases of the pole 4 and pole 5. Also, it is shown that the SAs installed at the generator terminals and at the generator neutral point considerably reduce the overvoltages at the generator. Such protection is sufficient to prevent insulation damage. As in previous simulations, the highest surge appears between the first turns of the firs coil of the stator winding. Comparing the calculated overvoltage amplitude and the RMS value of the withstand test voltage, it can be concluded that the insulation between the two turns can withstand such surges.

5 CONCLUSIONS

Surge protection of each generator, which is designed to be directly connected to the overhead line, has to be analyzed very carefully. Selection of surge arresters for the generator protection should take into account all possible temporary overvoltages.

Beside the surge arresters installed at the entrance of the switchgear the most effective protection of the generator ensure surge arresters connected with generator terminals. Also, surge arrester should be installed at the generator neutral point.

Further improvement of surge protection of the generator insulation, especially between the turns of the first coil, can be achieved by adding protective capacitors.

In the considered case it was concluded that protective capacitors are not neded.

6 REFERENCES

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