Calculations of Overvoltages in the Generator Electrical Circuit of a Power Station

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Abstract - **A short overview of a calculation of overvoltages in the generator main electrical circuit of a hydro power station is presented. A case of a generator connected to the step-up transformer through encapsulated lines has been studied. The most critical cases have been considered: lightning overvoltages transferred from the high- voltage circuit through the step-up transformer, overvoltages at a single-phase earth fault in the generator circuit and temporary overvoltages due to the single-phase earth fault followed by the load rejection. The calculations have been carried out by computer programs EMTP-ATP and MicroTran as well as by an analytical procedure. The results of the calculation are commented and compared.**

Keywords: Overvoltage, Lightning, Single-phase Earth Fault, Synchronous Generator, EMTP-ATP, MicroTran

I. INTRODUCTION

Overvoltages occurring in an electrical power plant are a substantial phenomenon that can damage insulation and consequently cause faults at the whole sequence of the plant's components thus jeopardising plant's operation and electric energy production. Hence, an analysis of overvoltages is an important prerequisite in prevention of negative consequences by setting suitable protection devices. Here in the first place overvoltages due to lightning strokes and switching activities are meant, but also temporary overvoltages due to failures of the voltage or turbine control devices [1].

The high-voltage (HV) side in a power plant is more exposed to overvoltages than the lower-voltage (LV) side. Despite of the fact that a HV substation is protected with a surge arrester, overvoltages can be transferred through the transformer to the LV side to which the generator is connected [2]. Consequently, surge protection of the LV side can be required. In order to obtain adequate settings of overvoltage protection devices in a power plant, elaborate calculations of electromagnetic transients at the plant's devices should be carried out.

In the paper, a short overview of a calculation of overvoltages in the generator main electrical circuit of a hydro power station is presented. A case of a generator connected to the step-up transformer through encapsulated lines has been studied. Like in most cases encountered in practice, there is no circuit breaker between the generator and the step-up transformer. Overvoltages can be generated in the generator circuit, or they can be transferred from the high-voltage circuit through the step-up transformer. The following most critical cases are considered:

a) lighting overvoltages transferred from the high-voltage circuit through the step-up transformer;
b) overvoltages caused by a single-phase earth fault in the generator circuit;
c) temporary overvoltages due to the single-phase earth fault followed by the load rejection.

The calculations have been carried out using two main versions of the EMTP computer program, ATP [3] and MicroTran [4] as well as by an analytical procedure.

II. LIGHTNING OVERVOLTAGES

Lightning overvoltages can directly endanger a generator connected to the overhead lines exposed to lightning strokes. However, generators with higher rated power are usually connected to the step-up transformer through encapsulated lines so they are not exposed to the direct lightning strokes. Nevertheless, in these cases there is also a risk of lightning overvoltages that are transferred from the HV side of the step-up transformer to the LV side. It is specially the case at transformers with a high transformer ratio, at which the difference of the withstand voltages i.e. insulation strengths is high.

A case of a generator connected to the network through a step-up transformer rated 400/15.75 kV is here analysed. Regardless to the fact that the 400 kV-side of the transformers can be well protected from lightning overvoltages by surge arresters, overvoltages transferred to the 15.75 kV-side can still endanger the generator.

Calculations of the transferred overvoltages have been carried out on a three-phase model of a substation, at which the step-up transformer should be in Yd5 connection (that is, secondary lags primary by 150°).

In the 400 kV- substation (Fig.1) there are double busbars to which the step-up transformers 1 and 2, the transmission lines 1 and 2, a connecting field, a network transformer (400/110/35 kV) and a measuring field are connected. Lightning overvoltages can get to the 400 kV-substation by the transmission lines 1 and 2, and besides, they can be transferred through the 400/15.75 kV step-up transformer to the 15.75 kV circuit, to which the generators are connected.

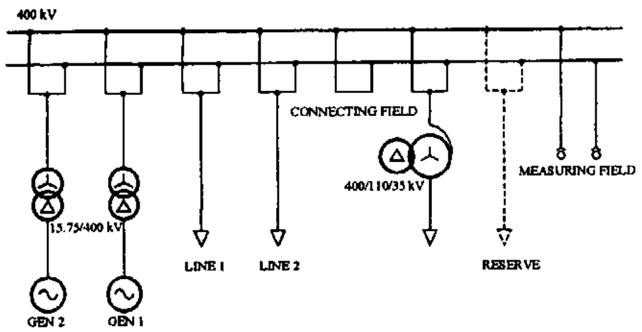

Fig. 1. Single-phase scheme of the plant and the substation

The analysis of both lightning overvoltages at the 400 kV substation and simultaneously transferred overvoltages to the 15.75 kV side has been carried out for the case of so-called dead-end station, at which to one of the busbars the transmission line 1, the step-up transformer 1 with the belonging generator and the network transformer are connected. At the same time, the transmission line 2 and the step-up transformer-generator 2 are out of operation. Described connection scheme is a very unfavourable configuration from the standpoint of overvoltage protection. Connection of the transmission line 2 as well as the block 2 acts in favour of decreasing the magnitude and steepness of incoming overvoltages. However, since the above described configuration of the dead-end substation is possible, especially in unfavourable meteorological and operating situations, the worst case has been simulated in which overvoltage protection should react satisfactory. Computer simulations have been carried out on a multi-phase model (Fig.2). All the phase conductors and the ground wire are modelled by matrices of high-frequency surge impedances, which are initially calculated from geometrical dimensions and the layout of the conductors. The switching substation at 400 kV and the 15.75 kV circuit are modelled by a three-phase model. At the step-up transformers in Yd5 connection, inductive and capacitive couplings between windings have been taken into account [5]. A voltage wave is initially transferred through the capacitive, and then through the inductive couplings between the windings.

The generator, which is connected to the step-up transformer through encapsulated lines, has been modelled by a concentrated capacitance.

Surge arresters are placed at three locations in the 400 kV-substation and have been modelled by a current-voltage characteristic based on the manufacturer data.

Lightning strokes to the transmission lines between the first five towers outside of the substation have been analysed. The voltages originating from lightning strokes at a greater distance from the substation are damped due to impulse corona and large resistance of the conductors at high frequencies. Determination of both parameters of the stroke current as well as the place of the stroke has been carried out by the statistical Monte Carlo method. A number of 7466 strokes to the first five spans outside of the substation had been simulated, and only 2.64% ended up at a single-phase conductor.

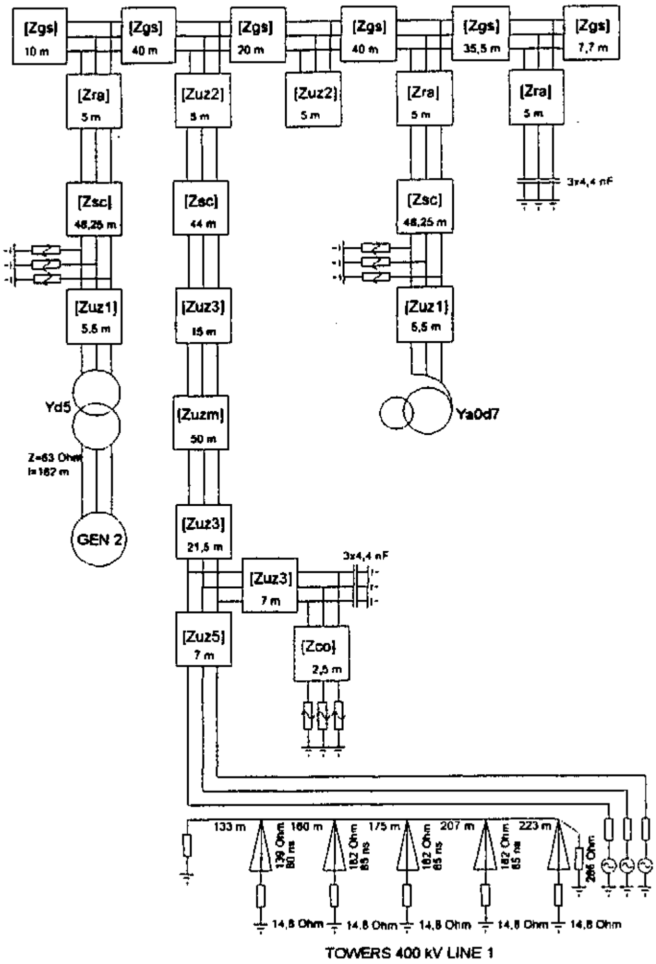

Fig.2. Multi-phase model of the HV substation and the generator circuit

The highest current that struck a phase conductor equals 14.27 kA and is of a 2.294/50 μs shape. The stroke took place at the first tower outside of the substation. It has been assumed that the lightning strikes the conductor of the phase designated as "*A*", in which the operating voltage in the moment of the stroke has maximum value of the polarity opposite to the overvoltage caused by the lightning.

Fig.3 shows overvoltages at the place of the stroke. No flashover to the grounded parts of the tower occurs. Overvoltages transferred to one phase of the LV transformer and overvoltages transferred to all three phases are shown in Fig.4 and Fig.5 respectively. The peak voltage in the substation (1108 kV) occurs at the voltage measuring transformer connected to the end of the busbars, while the voltages at the other parts of the 400 kV-substation are much lower.

At the LV side of the transformer, two fundamental frequencies of voltage oscillations can be noticed. The higher equals approximately 270 kHz, and the lower

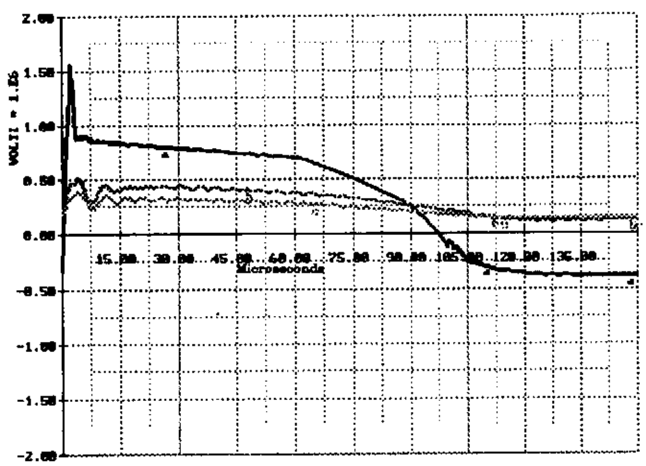

Fig.3. Conductor voltage at the place of the stroke, U_{Amax} = 1556 kV

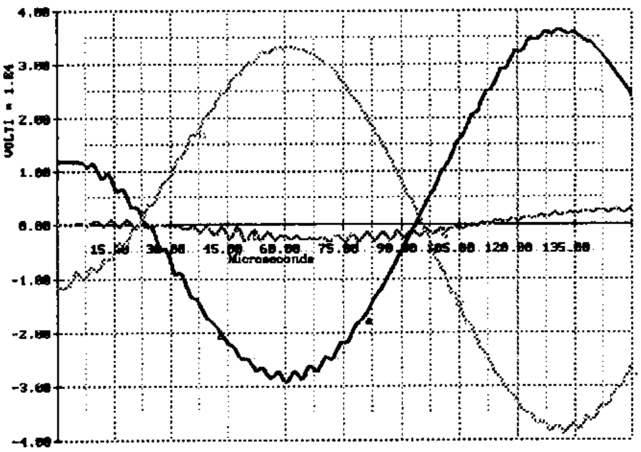

Fig.5. Voltages at the generator; U_{Amax} = 36.4 kV U_{Bmax}=–3.5 kV, U_{Cmax} = –40 kV

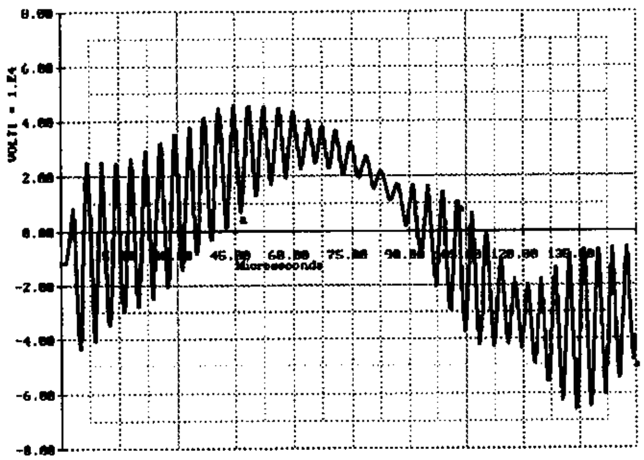

Fig.4. Voltage at the LV side of the step-up transformer in phase *C*, U_{Cmax} = - 66 kV

approximately 7 kHz. The highest voltage occurs in the phase designated as *"C"* and equals 66 kV, although at the HV-side the lightning strikes phase *"A"*. This is a consequence of the Yd5 connection of the transformer. The generator has a relatively high capacitance (0.49 μF) due to its design, which acts in favour of damping of high-frequency oscillations, hence at the generator only the oscillations of 7 kHz can be noticed, and the voltage in the phase *C* reaches 40 kV maximum value. It is assumed that the insulation of the LV side of the transformer and the generator can withstand 110 kV and 68 kV respectively. In table 1 results of calculation of the overvoltages caused by strokes to a phase conductor are given for the first and the subsequent lightning stroke. In the table value of the highest overvoltage in each case is given.

Table 1. Overvoltages caused by the lightning strokes to the phase conductor of LINE 1

		5.5 kA 1.122/50 1. stroke	5.5 kA 0.39/50 subsq.str.	9.0 kA 1.623/50 1. stroke	9.0 kA 0.52/50 subsq.str.	14.27 kA 2.294/50 1. stroke	14.27 kA 0.677/50 subsq.str.
Voltage transformer at the end of the busbars (kV)		696	699	971	977	1108	1133
Conductor on the tower (kV)		678	679	867	1251	1556	2171
Step-up transformer HV side (kV)		640	641	733	738	765	762
Step-up transformer LV side (kV)	U_A	40	41	48	49	66	69
	U_B	17	18	30	33	42	46
	U_C	43	43	51	53	66	67
Generator (kV)	U_A	32	32	36	35	36	34
	U_B	2.5	2.8	3.2	3.3	3.5	36
	U_C	35	34	38	37	40	37

III. OVERVOLTAGES AT SINGLE-PHASE FAULT IN THE GENERATOR CIRCUIT

A single-phase earth fault in the generator electrical circuit has been analysed. At this fault, the steady-state voltage of the unfaulted generator phases increases by a $\sqrt{3}$ factor, due to the fact that the voltage increases from the phase voltage to the phase-to-phase voltage. Transient overvoltages in the unfaulted phases immediately after the single-phase earth fault depend on the moment in which the fault occurs. A case in which the highest overvoltages occur is chosen for the analysis.

Fig. 6 and 7 show time responses of the voltage in two unfaulted phases (*B* and *C*) in case of a single-phase earth fault at the phase *A*. The transient overvoltage following the fault reaches its peak value of –33.3 kV (6.3 kHz, phase *C*, Fig.7) and the steady-state voltage increases to 22.3 kV (50 Hz).

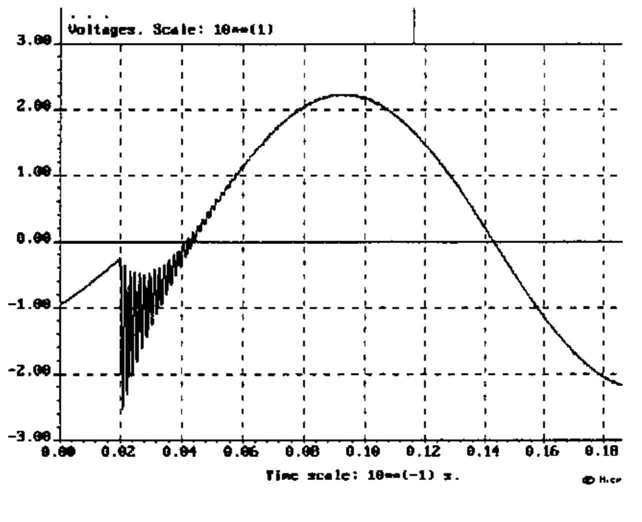

Fig.6. Voltage in the phase *B* (at a single-phase earth fault of the phase *A* at the moment t = 0.002 s)

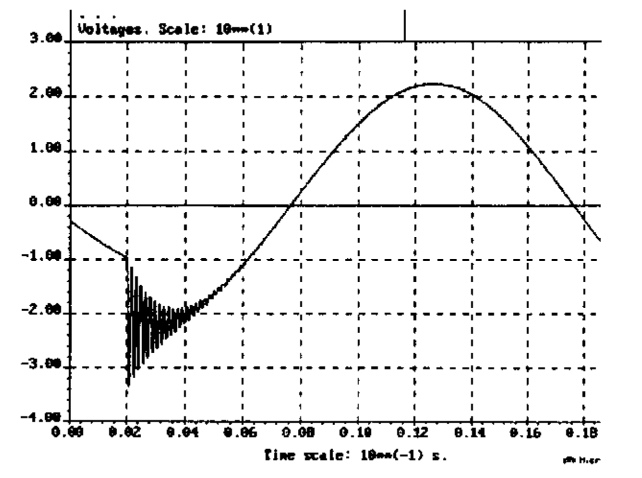

Fig.7. Voltage in the phase *C* (at a single-phase earth fault of the phase *A* at the moment t = 0.002 s)

IV. OVERVOLTAGES AT SINGLE-PHASE FAULT FOLLOWED BY LOAD REJECTION

A combined fault consisting of the following events has been analysed: a single-phase earth fault at the first phase occurs at a location between the generator and the step up transformer; after that, at t=0.15 s, the circuit-breaker at the high-voltage side of the step-up transformer is switched off by the protection system (the single-phase earth fault is still present). As the worst possible case, an excitation system fault resulting in lack of excitation control is assumed.

Due to the fault sequence described above, the voltage in the unfaulted phases increases, and in time an additional voltage increase occurs owing to load rejection of the uncontrolled generator-set (the speed increases due to unchanged driving torque, and the excitation remains unchanged). The voltage increases:

a) in the unfaulted phases of the generator due to the single-phase earth fault;

b) due to the uncontrolled excitation, which after load rejection should normally be adjusted by the regulator to a much lower value to keep the generator's voltage at the nominal value;

c) due to an overspeed of the water-turbine.

Normally excitation control would react (practically within several hundred milliseconds or at most 1 second) in a way that the voltage does not exceed the nominal value (hence only an initial voltage rise due to switching overvoltages and increased phase-to-phase voltages in unfaulted phases is possible), and the turbine governor would react gradually, within few seconds, redirecting the water out of the turbine.

In Fig.8 and 9 the beginning of voltage transients due to the load rejection are shown. These overvoltages are the highest in case of switching off a reactive load, and somewhat lower in case of switching off the nominal load at S_n and $\cos \varphi_n$. However, these overvoltages are still lower than ones due to the speed rise in case of lack of excitation control.

In table 2 speed and the highest values of voltage in the unfaulted phases after the single-phase earth fault followed by switching off the main circuit breaker is shown for three different fault duration times. It is by that

Table 2. Increase of speed and voltage of the unfaulted phases after the single-phase earth fault followed by load rejection.

Time	**Speed**		**Max. phase voltage**	**Overvolt. factor**
t (s)	**n (rpm)**	**% n_n**	$\hat{U}$ **(kV)**	$k_p=\frac{\sqrt{3}\hat{U}}{\sqrt{2}U_n}$
1	665.1	110.8	31.0	2.41
1.685	720	120	33.95	2.64
2	744.6	124.4	35.9	2.79

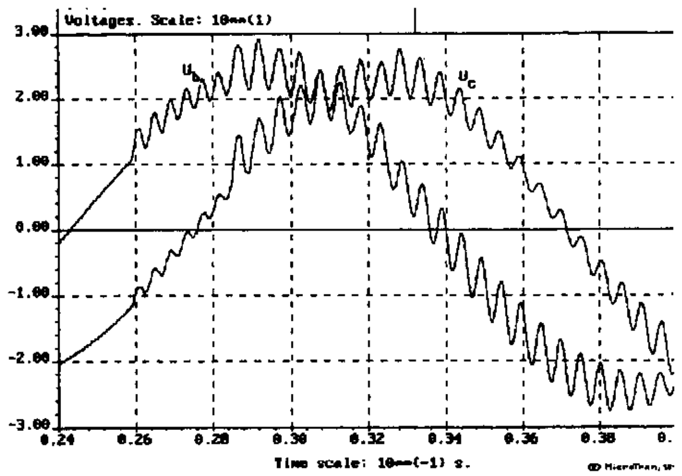

Fig.8. Overvoltages in the unfaulted phases *B* and *C* after switching off the circuit breaker, which follows after a single-phase earth fault of the generator

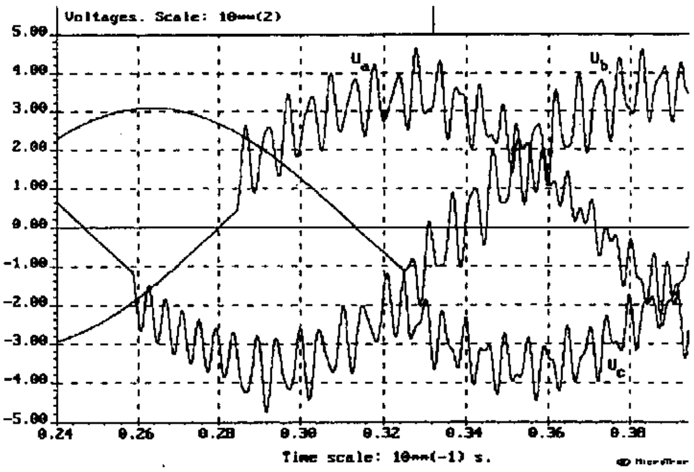

Fig.9. Overvoltages at the HV-side of the transformer after switching off the circuit breaker, which follows a single-phase earth fault of the generator.

assumed that the driving torque remains unchanged (nominal) and the excitation is uncontrolled. It can be noticed that after 1.685 seconds a voltage higher than the overvoltages in chapter III occurs. The results are calculated by the MicroTran software package. The overvoltage factor k_p is expressed as a ratio to the generator nominal voltage (U_n).

According to the generator data, the nominal operating point is defined by the following values: S_n = 155 MVA, P_n = 138 MW, Q_n = 70.7 Mvar, U_n = 15.75 kV, I_n = 5688 A, I_{f0} = 667.5 A. Known parameters which can affect the calculation are:

- reactances x_d = 90%, x_d' = 24%, x_d'' = 19%, x_p = 13%
- armature resistance r = 0.18%
- time constants T_{do}' = 6s, T_d'' = 0.073 s, T_q'' = 0.27 s
- moment of rotor inertia J = 287100 kgm^2.

The current of the unloaded transformer (with ratings 155 MVA, 400/15.75 kV, YNd5 connection, u_k = 12.91%) equals 0.312 % and 1.079 % of the nominal current at U_n and 1.1 U_n respectively.

A. Increase of voltage due to load rejection

Currents of the generator and transformer at load rejection and the resulting speed rise can be estimated with the following assumptions in two extreme variants:

a) the magnetising current of the step-up transformer is no higher than 10 % of the generator's nominal current ($I < 0.1\ I_n$); the calculation is carried out as if the generator were unloaded;
b) the magnetising current of the step-up transformer is substantially higher than 10 % of the generator's nominal current (for example $I = 0.5\ I_n$); in the calculation a drop of the generator's voltage due to the loadings is taken into account.

At estimation of the maximum flux density that can occur at the load rejection, the no-load characteristic of the generator should be known. The following should be noticed:

- generator's excitation current under no-load condition at the nominal voltage U_n and frequency f_n is I_{f0} = 667.5 A;
- generator's armature voltage under no-load condition at the f_n and the nominal excitation current I_f = 1238 A = 1.855 I_{f0} equals U = 1.255 U_n.

If the transformer is not significantly saturated, one can expect that the transformer will not draw high magnetisation current at the generator's load rejection. Let's assume for example that the transformer's magnetisation current is less than 10% of the nominal generator current. It is a realistic assumption for a step-up transformer, which is regularly designed to have lower nominal flux density (up to 1.65 T), compared to other power transformers which have a nominal flux density of 1.73-1.78 T and consequently higher magnetisation currents can be expected.

According to known data, the no-load current of the transformer is 1.079 % of the nominal transformer current at the voltage equal 1.1 U_n. It is expected that the no-load current at 1.255 U_n is substantially higher than this value, but still lower than 10 % of the nominal current. Therefore only the no-load losses should be taken into account, and the current losses can be neglected.

If the step-up transformer under nominal condition has a flux density higher than 1.7 T, then due to load rejection very high magnetisation currents, order of 50% I_n can be expected. In this case, the generator cannot be considered as unloaded. Generator's operating point is at a flux density lower than 1.255 B_n due to the voltage drop at the generator's stator leakage (Potier's) reactance as well as due to the armature reaction. As the current is in this case practically thoroughly reactive, the voltage drop $U_p = x_p \cdot I$ directly reduces generator's induced voltage by $U_p = 0.13 \cdot I$ (pu). Hence, at I = 50% I_n a value U_p = 6.5 % is obtained. If the armature reaction due to the assumed generator's current of 50 % I_n is taken into account as well, the voltage at the generator's terminals would be only 12 % higher than the nominal voltage at $f = f_n$ = 50 Hz. If the transformer were not saturated i.e. if the generator were unloaded, this voltage increase would be 25.5 %. The same can be applied to the flux density of the transformers. It is clear that for the generator the magnetic condition obtained from the induced voltage is relevant, and for the transformer the condition obtained from the generator's voltage is relevant.

B. Total expected voltage increase due to load rejection

The most probable variant of saturation rate will result in loading the generator with a step-up transformer's current equal 0.1-0.2 I_n, which means that the flux density in the transformer equals 1.2-1.23 B_n. In this case generator's voltage will increase to 1.2-1.23 U_n due to load rejection after opening the main circuit-breaker at the HV-side of the step-up transformer as well as due to unchanged (uncontrolled) excitation of the generator. This increase occurs instantaneously. Due to the speed increase, both the voltage and the frequency increase proportionally to the speed, which adds to the voltage increase. Let us assume that the speed increase after approximately 2 seconds is 25% of the nominal speed for the considered moment of inertia of the generator-set, assuming a constant (nominal) drive-torque. Accordingly, a total voltage increase of approximately $1.22 \cdot 1.25 = 1.53\ U_n$ after 2 seconds can be expected, which means more than 50 % of the nominal value. It should be noticed that this is valid only in case of the excitation system fault, i.e. assuming that the excitation is not controlled (i.e. decreased).

Regarding the steady-state voltage at the combined fault, it increases by a $\sqrt{3}$ factor at the unfaulted generator phases, due to the fact that the voltage increases from the phase voltage to the phase-to-phase voltage. If a realistic no-load curve of the generator is taken into account, i.e. if the saturation effect is considered, the voltage in the generator's phases increases after 2 seconds to $1.73 \cdot 1.53 = 2.65\ U_{n(ph)}$, i.e. from $U_{n(ph)} = 9.093$ kV to 24.1.kV (rms).

If these values are compared to the results calculated by the MicroTran, smaller differences can be observed which is a result of the fact that in the used version of the MicroTran program [4] generator's saturation could not be characterised by a no-load curve. The results from the MicroTran show higher values of maximum voltage comparing to the results obtained by the analytical analysis here presented (2.79 $U_{n(ph)}$ in table 2, instead of 2.65 $U_{n(ph)}$).

V. CONCLUSION

A calculation of critical overvoltages in the circuit of a generator connected to a 15.75/400 kV step-up transformer has been carried out. The following cases of overvoltages have been analysed: lighting overvoltages transferred from the HV side of the step-up transformer, overvoltages due to a single-phase earth fault and temporary overvoltages due to a single-phase fault followed by load rejection in case of an excitation system fault.

The lightning overvoltages transferred through the transformer to the generator circuit depend on overvoltage protection at the HV side, design of the step-up transformer as well as configuration of the generator circuit. For calculation of the transferred lightning overvoltages capacitive coupling between windings is especially important since the highest overvoltages are transferred through them in the beginning.

The transferred lightning overvoltages have been calculated for the worst cases of a lightning stroke to the first five line spans outside of the substation, obtained by a simulation using the Monte Carlo method. Due to an appropriate overvoltage protection at the HV side of the substation, overvoltages have not exceeded the withstand voltages of the insulation in the generator circuit in any of the analysed cases. Due to a high capacitance of the generator, overvoltages at the generator are lower than these at the LV side of the step-up transformer in both magnitude and frequency.

The calculation of overvoltages for the single-phase earth fault at the generator (presented worst case) has shown that these overvoltages are not particularly dangerous for the generator insulation.

Temporary overvoltages for the combined fault including a single-phase earth fault followed by opening the circuit-breaker and an excitation system fault, are barely lower than the power frequency test voltage, which is very unfavourable for the generator insulation. This indicates a need for special attention to the excitation system design as well as design of the overvoltage protection system. Calculation of temporary overvoltages is also a prerequisite to determine nominal rating of metal-oxide surge arresters if they are to be installed in the generator circuit.

VI. REFERENCES

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