Specific aspects of overvoltage protection in hydro power plant considering AIS and GIS connection to the transmission network

Bozidar Filipovic-Grcic, Viktor Milardic, Srecko Bojic, Bruno Jurisic

***Abstract*—Overvoltage protection of substations connecting hydro power plants (HPP) to the transmission network depends on numerous factors such as: type of HPP connection (air-insulated substation AIS or gas insulated substation GIS), overhead line/cable connection, location, and characteristics of installed equipment, specific operating conditions, and topology.**

This paper deals with analysis of overvoltage protection in the underground located HPP considering AIS and GIS connection to 220 kV transmission network with specific emphasis on lightning overvoltages. Detailed model for analysis of lightning overvoltages was developed, and simulations are carried out to determine optimum overvoltage protection configuration. Due to specific topology of HPP connection and underground location of step-up transformer, it is necessary to determine the level of transferred overvoltages over transformer to check the necessity for installing additional surge arresters for protection of generator.

***Keywords*: overvoltage protection, hydro power plant, GIS and AIS connection, lightning overvoltages, EMTP**

I. Introduction

Lightning overvoltages are one of the main reasons for interruption of power supply in the transmission network with overhead lines (OHL). In the case of hydro power plant (HPP) connection to the transmission network, lightning strikes to OHLs connecting HPP can cause outages and interruption of power supply. The outage of large hydro power plants from the electric power system results in unexpected costs of undelivered energy, and in some cases may endanger the stability of the system. For these reasons, it is necessary to pay special attention to the selection and dimensioning of HPP overvoltage protection and to check its effectiveness regarding lightning overvoltages [1],[2].

Spatial arrangements of HPP equipment and the type of connection to the grid may be quite different and, in some cases, very specific depending on the type of HPP, place in the HV network, operating regimes and very often, on local characteristics of the terrain where the HPP is located and particularly, of time when it was built, etc.

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Therefore, selection of HV equipment and overvoltage protection should be carried out carefully to obtain the optimal protection against lightning overvoltages while considering special HPP requirements and spatial limitations. This can be done using detailed wideband model in electromagnetic transient tool such as EMTP.

In this paper, high-pressure run-of-river and underground located HPP is considered, in the process of reconstruction, now with two refurbished generators (2x140 MVA), one connected to 110 kV network and another one to a higher network voltage, 220 kV. (Fig. 1.). Different overvoltage protection schemes of HPP are analyzed considering AIS and GIS connection to 220 kV transmission network. Existing old AIS connection is to be replaced by GIS type in the next step of the reconstruction.

Fig. 1. The view of generators in the underground engine room

The underground engine room with generators and step-up transformers was built as a complex building, which is reached through an access tunnel 520 m long. The HPP is equipped with two production units, Francis turbines with the installed flow of 2x55 m^3/s, with the nominal drop of 270 m.

Generally, the circuit breaker (CB) intended for generator synchronization to the grid can be located at the MV or at the HV side of a step-up transformer. The aspects of breaking currents and transient recovery voltage (TRV) ratings are given in IEEE/IEC 62271-37-013 [3] for generator circuit-breakers with rated voltages up to 38 kV, while IEC 62271-100 [4] covers requirements for CBs located on the HV side. In such case of considered type of HPP in this paper, the CB is installed on the HV side and connected by long HV cables to the step-up transformer.

In cases when TRV trough the CB is critical, surge arresters from both sides of the CB should be installed to reduce TRV or even, the CB with higher rated voltage could be selected, usually due to excessive TRV caused by out-of-phase switching [5],[6]. These TRV issues also affect an overall selection of the overvoltage protection.

II. Modeling AIS and GIS connection of HPP to the grid for simulation of lightning overvoltages

A. Configurations of considered AIS/GIS connections

Fig. 2 a) shows the original and still existing AIS connection of HPP to the transmission network. The 140 MVA salient pole generator with rated voltage 14.4 kV is located inside HPP.

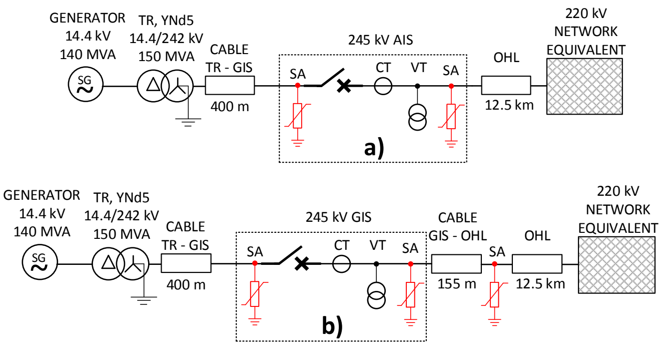

Fig. 2. Equivalent schemes of a) The existing AIS and b) The future GIS connection of HPP with indicated positions of surge arresters (SA)

The generator is connected to a two-winding 150 MVA, 14.4/242 kV step-up transformer. The 14.4 kV air-insulated buses connecting the generator to the step-up transformer are approximately 43 m long, with surge impedance of 133.4 Ω. Due to specific placement of equipment in HPP (generator and step-up transformer are located underground, while AIS/GIS is located above the ground), the cable connection from the power transformer to AIS/GIS is used.

In the case of GIS (Fig. 2 b)), two cable connections are used, for OHL/GIS connection and for transformer/GIS connection. Inside GIS an SF_6 CB is placed together with other HV switching and measuring equipment (instrument VT and CT, disconnectors). Surge arresters are integrated inside GIS from both sides of the GIS cable connection. AIS/GIS is connected to a 12.5 km long 220 kV overhead line (OHL) (Fig. 2). Surge arresters are installed also at OHL/cable transition, while surge arresters are not installed at power transformer terminals due to direct cable connection from HV side and limited space at LV side. In the case of AIS (Fig. 2 a)) there is a direct connection to the OHL, while SAs are installed only at AIS/transformer cable connection and in the line bay at AIS/OHL connection, Fig 3.

B. Modeling of equipment inside the HPP

Since lightning overvoltages are high-frequency phenomena, the available data should be used to build the model suitable for the frequency range of interest. The generator is modeled using the synchronous machine model available in EMTP, with distributed capacitances added along stator windings to the ground (total capacitance of 0.672 µF). The neutral point is grounded over high-ohmic resistance.

The appropriate transformer models for analysis of lightning and transferred overvoltages are discussed in [7]-[11]. In this paper, a BCTRAN model extended with measured inter-winding capacitances and capacitances of windings to the ground was used, since no detailed frequency response measurements or geometry data was available for developing more complex and accurate black-box or a grey-box models [12]-[17].

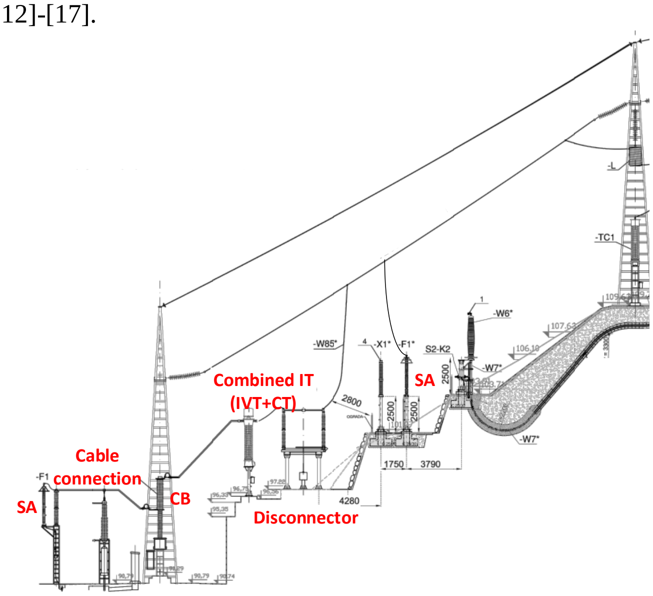

Fig. 3. The cross section of AIS connection to 220 kV OHL

In [7], it was shown that the extended BCTRAN model is accurate enough for frequencies up to few kHz or even higher (few tens of kHz) when the transformer geometry is not too complex, which is valid for the considered two-winding power transformer. In practice, the dominant frequency of lightning caused overvoltages at power transformer terminals in 220/110 kV AIS recorded by transient monitoring system is in the frequency range below 10 kHz [18]. In cases considered in this paper, the cable connection to the step-up transformer from the HV side will introduce the additional damping of lightning overvoltages. Figs. 4-7 show the comparison of measured end to end HV and LV windings SFRA [19] (sweep frequency response analysis) with simulated ones. As the available SFRA measurements (Figs. 4 and 6) are done with the open circuited windings, the first resonance peak (around 500-700 Hz) is different than the one obtained by the model.

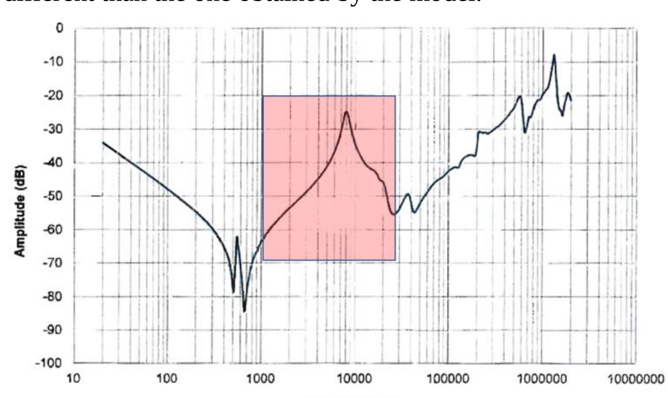

Fig. 4. SFRA measurement on HV winding (LV winding open-circuited)

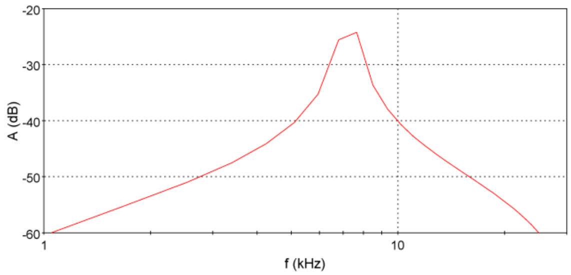

Fig. 5. SFRA simulation on HV winding (LV winding open-circuited)

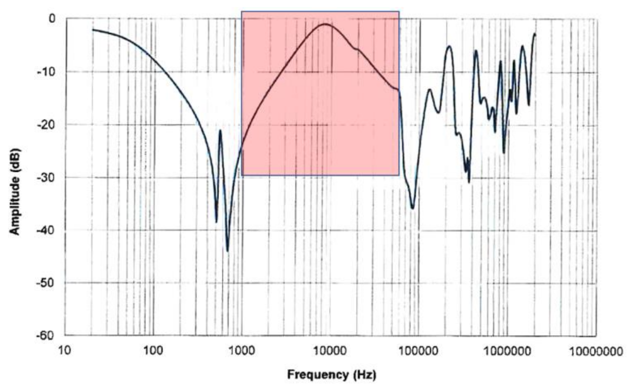

Fig. 6. SFRA measurement on LV winding (HV winding open-circuited)

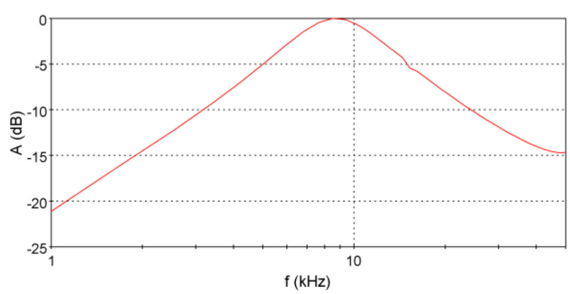

Fig. 7. SFRA simulation on LV winding (HV winding open-circuited)

Extended BCTRAN model represents only the short-circuit transformer behavior and does not represent the transformer core, which can be neglected when considering lightning overvoltages, as the frequencies of interest are in the range up to few tens of kHz. However, in the frequency range of the interest, the model and the measured response are matched (Figs. 4-7). Fig. 8 shows calculated impedance versus frequency between top of HV winding in phase A and corner of LV delta winding (connecting windings a-c and a-b), showing two resonance points up to 100 kHz.

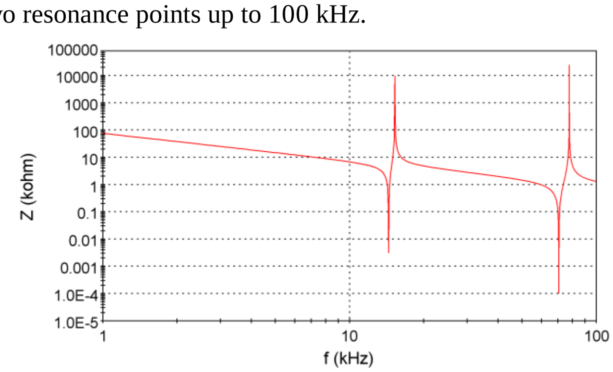

Fig. 8. Calculated impedance versus frequency between top of HV winding in phase A and corner of LV delta winding (connecting windings a-c and a-b)

Due to simple transformer geometry, the frequency response is not complex, and similar frequency responses with two resonant frequencies were obtained from measurements at similar power transformers. However, above 100 kHz, frequency response is much more complex, and it involves multiple resonant frequencies in the frequency range up to 2 MHz. Calculated frequency response obtained by extended BCTRAN model is not realistic and the model is not valid in this frequency range [7].

Therefore, it can be concluded that the model represents the transformer behavior accurate enough for the purpose of the observed simulations. This conclusion is in line with the existing literature, as already discussed. For the studies related to GIS switching operations, more detailed model shall be used, which is not in the scope of this paper.

The HV equipment inside the single-pole encapsulated GIS are modeled as concentrated capacitances with busbars in-between represented as distributed transmission line with surge impedance of 60 Ω [20],[21]. The surge arresters are modeled using *U-I* characteristic and added capacitance towards the ground. The 220 kV network equivalent is modeled as voltage source behind short-circuit impedances considering short-circuit power of the network. Cables and OHL are modeled using of frequency-dependent models. The OHL is equipped with two shielding wires. The data used for modeling are given in the Appendix I (Table V and VI).

III. Simulation Results – Lightning Overvoltages in AIS/GIS HPP Connection Considering Different Cases of Overvoltage Protection

Lightning overvoltages caused by lightning strike to the OHL in the vicinity of AIS/GIS are simulated. Efficiency of different overvoltage protections is analysed and levels of transferred overvoltages are investigated. The direct lightning strike to the OHL tower in the vicinity of the substation is simulated with the current amplitude of 200 kA. In this case, the back-flashover occurs in all phases at the struck tower. According to collected data from the lightning location system (LLS), the probability of occurrence of such lightning strike with a current of 200 kA is extremely rare [22]. Therefore, the overvoltage amplitudes obtained in the simulations represent the worst case that may occur in the HPP operation.

The second case considered includes a lightning strike to a phase conductor with the current amplitude of 14.7 kA. This “critical” current is obtained from electro-geometric model of the OHL, and it represents the highest amplitude of the lighting strike that can hit the phase conductor directly. Lightning strikes with higher currents, according to the used model, cannot directly hit the phase conductors due to the protection provided by the two shield wires of OHL. In this case, an insulator flashover occurs in the struck phase.

A. AIS connection of HPP to the grid

The basic insulation level (BIL) of the HV equipment in AIS at the HV side (network with U_m=245 kV) is 460 kV (1 min AC withstand voltage) and 1050 kV (standard LI withstand voltage 1.2/50 μs). The specified insulation levels of step-up transformer with respect to lightning overvoltages are 950 kV (HV side) and 125 kV (LV side). Onwards considering the construction time of the HPP and the complex current process of its reconstruction, there are significant differences in the age of the equipment now in service. The electrical insulation ages during the expected lifetime, owing to one or to combination of thermal, electrical, chemical and mechanical stresses. For this reason, for older HV equipment, a certain safety factor should be applied when comparing calculated overvoltages with BIL to ensure the safe and reliable operation. Two different overvoltage protection schemes are considered: A) - surge arresters installed only at cable/AIS transition; B) - surge arresters installed at the cable/AIS transition and in the AIS line bay. Overvoltage amplitudes are shown in Table I.

TABLE I
LIGHTNING OVERVOLTAGES IN THE CASE OF AIS HPP CONNECTION

Location	Lightning strike to tower		Lightning strike to phase conductor
	*A)	*B)	*A)
Disconnector in line bay	**1071.5 kV**	773.7 kV	693.9 kV
Combined IT in line bay	814.1 kV	645.4 kV	562.1 kV
AIS/cable connection	579.3 kV	571.04 kV	471.57 kV
Power transformer – HV side (phase-to-ground)	774.8 kV	731.12 kV	549.1 kV
Power transformer – LV side (phase-to-ground)	100.8 kV	83.5 kV	65.7 kV
Power transformer – LV side (phase-to-phase)	**186.8 kV**	122.13 kV	75.9 kV
Generator	10.4 kV	9.46 kV	21.2 kV

*A) - surge arresters installed only at cable/AIS transition; B) surge arresters installed at cable/AIS transition and in AIS line bay

Finally, in case A), when surge arresters are installed only at the AIS/cable transition, and event of lightning strike to the OHL tower, lightning overvoltages in the AIS are critical at the disconnector location at the entrance to the line bay (1071.5 kV) and on the LV side of the step-up transformer (186.8 kV). On all other points of the AIS overvoltages are within the permitted levels. In case of a lightning strike to the phase conductor, the lightning overvoltages in the AIS are within the permitted levels. Due to excessively high overvoltages in the case A), it is necessary to consider additional surge arresters at the entrance to the line bay (case B)). For this case, for a lightning strike to the OHL tower, lightning overvoltages in the HPP are within the permitted levels, but the levels of transferred overvoltages to the LV side of the step-up transformer are still quite high (122.13 kV). Therefore, for the protection against transmitted overvoltages, additional surge arresters could be installed at the secondary (LV, 14.4 kV) side of the step-up transformer. However, in this case it would require the reconstruction and opening of metallic enclosed air-insulated buses connecting the generator to the step-up transformer. Since existing old AIS connection is to be replaced by GIS type in the next step of future reconstruction of HPP, and in the GIS type, the overvoltages are lower as will be shown in the next chapter.

Surge arresters at the LV side of the step-up transformer were not installed. Overvoltage waveforms at power transformer terminals in the case B) in the case of lightning strike to tower are shown in Figs. 9 and 10. The dominant frequency of oscillations at secondary side of step-up transformer is around 15 kHz (Fig. 11).

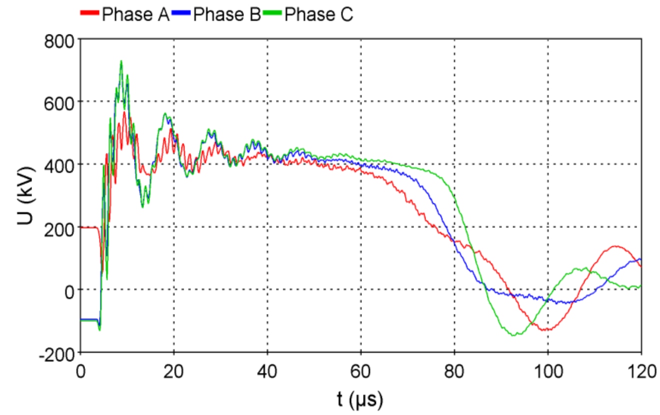

Fig. 9. Overvoltage waveforms on HV windings of step-up transformer

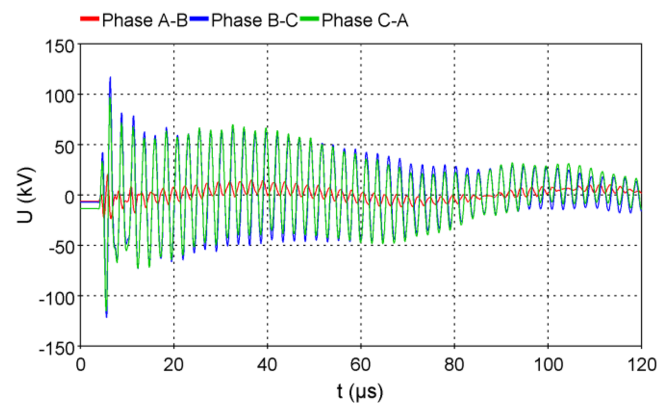

Fig. 10. Overvoltage waveforms on LV windings of step-up transformer

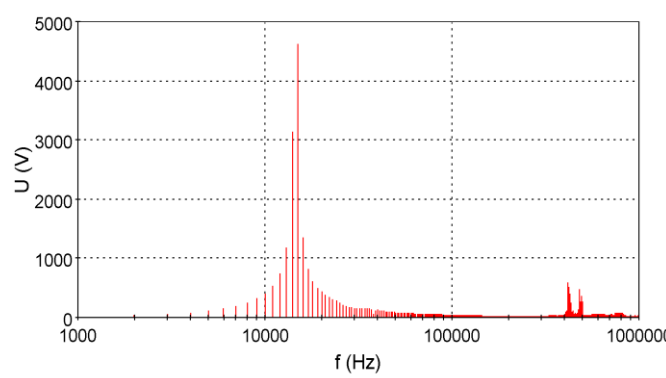

Fig. 11. Harmonic analysis of overvoltage at LV winding of step-up transformer (dominant frequency of oscillations around 15 kHz)

Furthermore, significant for analysis, is an average number of generator synchronizations to the grid. In the case of HPP with relatively large accumulation it can be approximately 130-150 per year, depending on HPP operating regime. This operating regime includes an open contact of CB during the generator synchronization. In the case of lightning strike to OHL which may occur before/during the generator synchronization, aside from power-frequency overvoltage stress during the synchronization, the switching or the lightning overvoltages may occur and superimpose to the AC voltage on the line side terminal of the CB. This event can cause flashover across the open contacts of the CB, and in some cases, it may even lead to the CB failure. Calculated overvoltage amplitudes for this case are shown in Table II.

TABLE II
LIGHTNING OVERVOLTAGES IN THE CASE OF OPEN CONTACTS OF CB

Location	Lightning strike to tower	
	A)	B)
Open contact of CB to ground	**3332.3 kV**	**1120.6 kV**
Instrument voltage transformer in line bay	**3200.6 kV**	957.0 kV
Disconnector in line bay	**3358.8 kV**	**1171.8 kV**

In the case A), lightning overvoltages to the ground on CBs, instrument transformers and disconnectors in line bay exceed the permitted levels (>3.2 MV). This is expected considering that in this case all parts of AIS from the line side of CB are not protected by surge arresters. Due to excessively high overvoltages obtained for the case A), it is necessary to consider protection with additional arresters that would be installed at the entrance to the line bay (case B). In this case, the overvoltages are significantly reduced, but they are still too high at open CB contacts and disconnectors in line bay. This is caused by the relatively large distances between the surge arresters and other HV equipment since AIS is located on a steep mountain slope with very specific and untoward terrain configuration, as shown in Fig. 3. In this case, HV equipment is arranged in steps along the slope of the mountain causing very long connecting conductors. Based on results, it is recommended to avoid long-term operation of the HPP with open CB contacts if the disconnector is in closed position, which is especially important during often thunderstorm conditions along the OHL route.

Data from LLS indicate high lightning activity along the OHL route, which in combination with high soil resistivity and ground resistance of towers frequently lead to insulator flashovers and faults. In period of 5 years, a total of 4263 cloud-to-ground lightning strikes were detected in the area of 1 km around OHL. Cumulative probability distribution of cloud-to-ground lightning current amplitudes is shown in the Fig. 12. Probability that lightning strike with current amplitude higher than 200 kA will hit OHL is very small, around 0.05%.

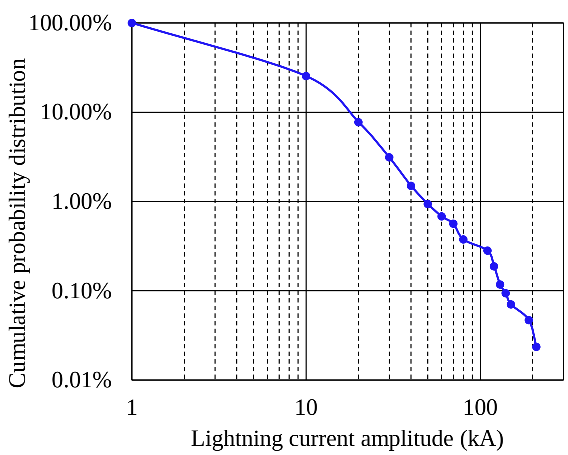

Fig. 12. Cumulative probability distribution of cloud-to-ground lightning current amplitudes around 220 kV OHL

The data collected from the lightning location system can be very useful tool to prevent such event, especially with if nowcasting option is available alarming operating personnel about incoming thunderstorms [23]. If such operating conditions cannot be avoided, it is recommended to switch off the disconnector in the line bay as soon as possible after switching off the CB and to do this manipulation when there is not lighting activity in the area.

In all the analysed cases, the calculated energies on the surge arresters do not exceed the maximum allowed limits. Figs. 13-15 show overvoltage waveforms at CB contacts, current and energy of surge arresters in the line bay for the case B) and lightning strike to tower.

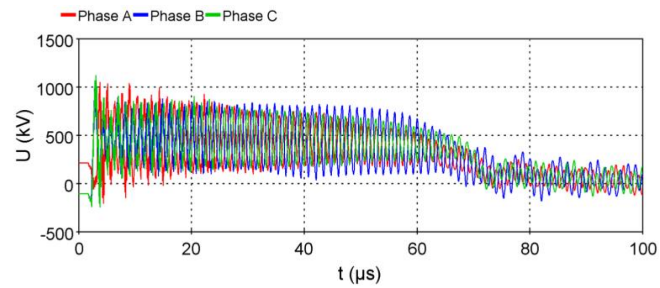

Fig. 13. Overvoltage waveforms at open CB contacts

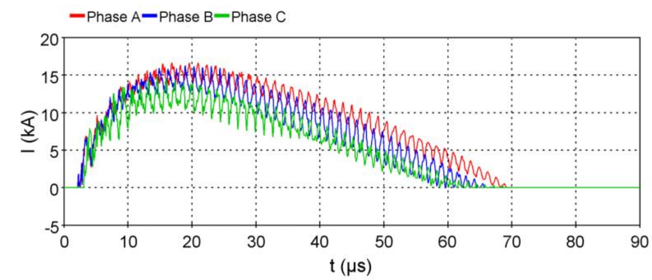

Fig. 14. Currents through surge arresters in the line bay

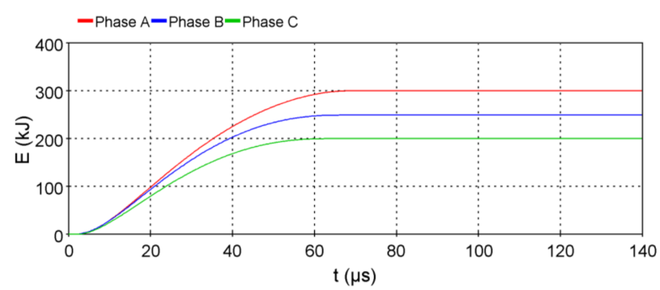

Fig. 15. Energy stress of surge arresters in line bay

B. *GIS connection of HPP to the grid*

Calculated overvoltage amplitudes in the case of GIS connection of HPP to the grid is shown in Table III. Based on the simulations results, the following can be summarised. In the case of a lightning strike to the OHL tower, the lightning overvoltages in the 220 kV switch yard are within the permitted levels. Overvoltages at HV equipment inside the HPP are 5-55% lower compared to the AIS case (Fig. 16). In all of analysed cases, the calculated energies on the surge arresters do not exceed the maximum allowed limits.

Fig. 17 shows overvoltage waveforms at HV side of step-up transformer in the case of lightning strike to the phase conductor (producing flashover at the struck tower in phase A). The dominant frequency of oscillations at secondary (LV) side of step-up transformer is around 18 kHz (Fig. 18).

TABLE III
LIGHTNING OVERVOLTAGES IN THE CASE OF GIS HPP CONNECTION

Location	Lightning strike to tower	Lightning strike to phase conductor
Cable/GIS connection – from the transformer side	447.6 kV	387.2 kV
Cable/GIS connection – from the OHL side	447.9 kV	387.3 kV
OHL/cable transition	512.8 kV	455.6 kV
Power transformer – HV side (phase-to-ground)	697.3 kV	489.3 kV
Power transformer – LV side (phase-to-ground)	64.7 kV	40.7 kV
Power transformer – LV side (phase-to-phase)	105.6 kV	49.6 kV
Generator	9.13 kV	15.9 kV

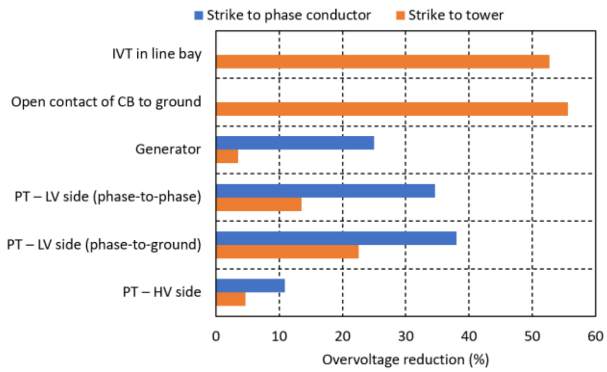

Fig. 16. Overvoltage reduction on HV equipment inside the HPP (GIS connection compared to AIS connection)

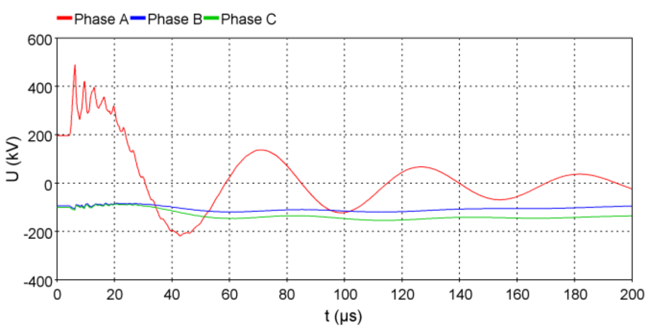

Fig. 17. Overvoltage waveforms at HV side of step-up transformer

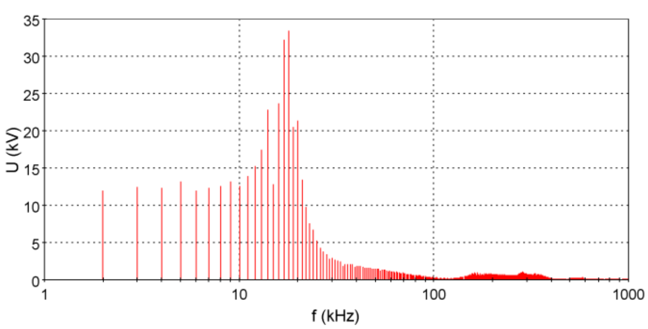

Fig. 18. Harmonic analysis of overvoltage at HV winding of step-up transformer in phase A (dominant frequency of oscillations around 18 kHz)

Surge arresters integrated into the GIS effectively protect HV equipment in the case of lightning overvoltages encountering open CB contacts (Table IV). This is caused by the small distances between CB and the arresters, compared to much larger distances in AIS case.

TABLE IV
LIGHTNING OVERVOLTAGES IN THE CASE OF OPEN CONTACTS OF CB

Location	Lightning strike to tower
Open contact of CB to ground in GIS	497.3 kV
Instrument voltage transformer in GIS	452.2 kV
Cable/GIS connection – from the OHL side	451.3 kV
OHL/cable transition	569.9 kV

IV. CONCLUSIONS

This paper deals with analysis of overvoltage protection in the underground located HPP considering AIS and GIS connection to 220 kV transmission network with specific emphasis on lightning overvoltages. The CB intended for generator synchronization to the HV power grid is connected by long cable to the HV side of step-up transformer and located outside of the underground engine room.

For such specific HPP configuration, a detailed model for analysis of lightning overvoltages was developed, and simulations are carried out to determine the optimum of overvoltage protection for AIS/GIS connections to the grid. It was shown that lightning overvoltages are more severe in the case of AIS kind of connection. Due to excessively high overvoltages, it is necessary to consider additional surge arresters at the entrance to the line bay. For a lightning strike to OHL tower, lightning overvoltages in the HPP are within permitted levels, but the levels of transferred overvoltages to the secondary side of the step-up transformer are still quite high. Therefore, for the protection, additional surge arresters could be installed at the secondary side of the step-up transformer, but such kind presents certain difficulties in its own implementation. Onwards, in the case of a lightning strike, overvoltages are still too high at open CB and disconnector contacts in the line bay. This is caused by the relatively large distances between the surge arresters and other HV equipment, since AIS is located on a steep mountain slope with very specific terrain configuration. Based on results, it is recommended to avoid long-term operation of the HPP with open CB contacts if the disconnector is in closed position, which is especially important during thunderstorm conditions along the OHL route. In that sense, the data from lightning location system can be very useful tool to prevent such event, especially with if nowcasting option is available alarming operating personnel about incoming thunderstorms.

In comparison of two types of considered connections, lightning overvoltages are lower in the case of GIS connection. Surge arresters integrated into the GIS effectively protect HV equipment in the case of lightning overvoltages encountering open CB contacts. This is caused by the small distances between CB and the arresters and additional OHL/cable connection, compared to much larger distances in the AIS type of connection. In the considered case, TRV at CB is critical, so surge arresters from both sides of the CB inside the GIS should be installed to reduce excessive TRV caused by out-of-phase switching. These TRV issues affect an overall selection of the overvoltage protection, particularly selecting and controlling an appropriate energy capability of surge arresters.

V. Appendix

TABLE V

Data used for modelling GIS and generator

GIS data	
Cable connection	50 pF
Surge arrester	200 pF, U_c=154 kV, U_r=192 kV, I_n=10 kA
Circuit breaker	220 pF
Earthing switch	45 pF
Current transformer	40 pF
Disconnector	70 pF
Voltage transformer	100 pF

Generator data			
S_n	140 MVA	No. of poles	20
cosφ	0.9	I'_{f0}	495 A
U_n	14.4 ± 5% kV	U_{fn}	276 V
I_{gn}	5613 ± 5% A	I_{fn}	994 A
R_n *at neutral point*	1660 Ω	*C stator winding to ground*	0.6717 μF/ph.
X_d	1.11 pu	X_0	0.15 pu
X_q	0.61 pu	X_2	0.25 pu
X_l	0.14 pu	T'_{do}	8.34 s
R_s	0.002631 Ω	T'_d	2.34 s
X'_d	1.11 pu	T''_{do}	0.146 s
X''_d	0.21 pu	T''_d	0.096 s
X''_q	0.30 pu	T''_{qo}	0.157 s

TABLE VI

Data used for modelling power transformer

Transformer data			
S_n	150 MVA	$C_{HV\text{-}LV}$	2097 pF/ph.
U_{n1} / U_{n2}	242 / 14.4 kV	$C_{HV\text{-}N}$	1106 pF/ph.
I_{n1} / I_{n2}	357.9 / 5013 A	$C_{LV\text{-}N}$	5619 pF/ph.
connection	YNd5	$C_{HV\text{-}LV} + C_{HV\text{-}N}$	3204 pF/ph.
u_k	13.05 %	$C_{HV\text{-}LV} + C_{LV\text{-}N}$	7716 pF/ph.
P_{Cu}	441.61 kW		
P_{Fe}	57.27 kW		
i_m	0.059 %		

VI. References

[1] D. Subedi and M. Lehtonen, "Lightning Overvoltages in Electrical Power System of a Power Plant", *20th International Scientific Conference on Electric Power Engineering (EPE)*, 2019, pp. 1-4, doi: 10.1109/EPE.2019.8777933.

[2] H. Ren, Y. Wu, "Study on Lightning inrush overvoltage of 500 kV GIL-GIS Hydropower Station" *Journal of Physics: Conference Series*, 2021, Vol. 1920, doi: 10.1088/1742-6596/1920/1/012006.

[3] IEC/IEEE 62271-37-013:2021 *High-voltage switchgear and controlgear* – Part 37-013: *Alternating current generator circuit breakers*

[4] IEC 62271-100:2021 *High-voltage switchgear and controlgear* – Part 100: *Alternating-current circuit-breakers*

[5] *Cigre Technical Brochure* 716, "System condiditons for and probability of out-of-phase – background, recommendations, developments of instable power systems", joint working group A3/B5/C4.37, January 2018

[6] D. Braun, G. Koeppl, "Transient Recovery Voltages During the Switching Under Out-of-Phase Conditions", *International Conference on Power Systems Transients* – IPST, New Orleans, USA, 2003

[7] B. Jurisic, A. Xemard, O. Moreau, I. Uglesic, F. Paladian, S. Lallechere, "Comparison of transformer models on a practical case of lightning overvoltages", *International Conference on Lightning Protection*, Bologna 2016

[8] H. K. Hoidalen, A. C. O. Rocha, "Analysis of gray Box Modelling of Transformers", *Electric Power Systems Research*, 107266, Vol. 197, August 2021

[9] B. Jurisic, T. Zupan, B. Filipovic-Grcic and L. Teklic, "Setup for measuring and simulating high-frequency overvoltages of power transformer," 2019 *2nd International Colloquium on Smart Grid Metrology* (SMAGRIMET), 2019, pp. 1-5, doi: 10.23919/SMAGRIMET.2019.8720391.

[10] M. Popov, L. van der Sluis, R. P. P. Smeets, "Complete analysis of Very Fast Transients in Layer-type Transformer Windings", *International Conference on Power Systems Transients* (IPST), Lyon, France, 2007.

[11] M. Popov, L. van der Sluis, R. P. P. Smeets, "Evaluation of surge-transferred overvoltages in distribution transformers", *Electric Power Systems Research*, Volume 78, 2008, pp. 441-449, ISSN 0378-7796, doi: 10.1016/j.epsr.2007.03.015.

[12] D. Filipović-Grčić, B. Filipović-Grčić and I. Uglešić, "High-Frequency Model of the Power Transformer Based on Frequency-Response Measurements," in *IEEE Transactions on Power Delivery*, vol. 30, no. 1, pp. 34-42, Feb. 2015, doi: 10.1109/TPWRD.2014.2327061.

[13] A. Holdyk, B. Gustavsen, "External and Internal Overvoltages in a 100 MVA Transformer During High-Frequency Transients", *International Conference on Power Systems Transients* (IPST), Cavtat, Croatia, 2015.

[14] H. K. Høidalen, A. C.O. Rocha, "Analysis of gray Box Modelling of Transformers", *Electric Power Systems Research*, Volume 197, 2021, 107266, ISSN 0378-7796, doi: 10.1016/j.epsr.2021.107266.

[15] T. A. Papadopoulos, A. I. Chrysochos, A. I. Nousdilis, G. K. Papagiannis, "Simplified measurement-based black-box modeling of distribution transformers using transfer functions", *Electric Power Systems Research*, Volume 121, 2015, pp. 77-88, ISSN 0378-7796, doi: 10.1016/j.epsr.2014.12.003.

[16] B. Gustavsen, "Wide band modeling of power transformers," *IEEE Power Engineering Society General Meeting*, 2004., 2004, pp. 1791 Vol.2-, doi: 10.1109/PES.2004.1373186.

[17] N. Chiesa and B. Gustavsen, "Frequency-Dependent Modeling of Transformer Winding Impedance From R(ω)/L Measurements," in *IEEE Transactions on Power Delivery*, vol. 29, no. 3, pp. 1511-1513, June 2014, doi: 10.1109/TPWRD.2014.2301597.

[18] B. Jurisic, B. Filipovic-Grcic, T. Zupan, G. Levacic, "Statistical analysis of non-standard overvoltage waveforms measured at 220 kV terminals of a power transformer", *Electric Power Systems Research*, Volume 197, 2021, 107318, ISSN 0378-7796, doi: 10.1016/j.epsr.2021.107318.

[19] IEC 60076-18:2012, Power transformers - Part 18: Measurement of frequency response, Edition 1.

[20] IEC TR 60071-4:2004 *Insulation co-ordination - Part 4: Computational guide to insulation co-ordination and modelling of electrical networks*, Edition 1, 2004.

[21] J. Kessel, V. Atlason, C. L. Bak J. Lund, "Lightning simulation of a combined overhead line/cable connected GIS", *29th International Conference on Lightning Protection*, Uppsala, Sweden, 2008.

[22] B. Franc, B. Filipovic-Grcic, I. Uglesic, "Application of Lightning Location System Data for Designing the External Lightning Protection System", *International Colloquium on Lightning and Power Systems*, Lyon, France, 2014.

[23] H. Foroozan, B. Franc, F. Pandzic, N. Pletikosa, "Development of an intelligent lightning hazard system for a wind farm in Croatia with machine learning methods", 15th *CIGRE Symposium on power system management*, Cavtat, Croatia, 2022.