IMPACT OF DISCONNECTOR DESIGN ON VERY FAST TRANSIENT OVERVOLTAGES IN GAS-INSULATED UHV SWITCHGEAR

M. Szewczyk[1*], W. Piasecki[1], M. Stosur[1], U. Riechert[2], J. Kostovic[2]
[1]ABB Corporate Research Center, Poland
[2]ABB High Voltage Products, Switzerland
*Email: marcin.szewczyk@pl.abb.com

Abstract: The paper presents a novel approach for investigation of disconnector design impact on the Very Fast Transient (VFT) process in Gas-Insulated Switchgear. The approach is based on Trapped Charge Voltage (TCV) calculations for which the multi-spark model of the disconnector was employed. The model allows one to investigate the entire VFT process, including TCV statistical behavior of the disconnector. The results of the calculations indicate that the assumption of a real value of TCV can lead to additional safety margin in insulation co-ordination analyses and in consequence allow for reducing the total cost of UHV substations. For the approach presentation, the disconnector contact speed influence on the VFT process was investigated for a typical UHV 1100 kV GIS substation. Other parameters of the disconnector design, such as SF_6 gas pressure and dielectric design of the disconnector contact system, can also be investigated using the approach presented. Based on the case study presented in this paper, it can be concluded that the application of slow acting disconnector provides significant reduction of VFTO in UHV GIS substation. However, the VFTO reduction is achieved with the increase of both: the number of sparks and the sparking time. Thus, the optimization of the disconnector design parameters would provide the optimal reduction of VFTO.

1 INTRODUCTION

1.1 Very Fast Transients in UHV Gas Insulated Switchgear

Very Fast Transients (VFT) in Gas-Insulated Switchgear (GIS) can cause undesired phenomena of different types, including internal and external VFT overvoltages (VFTO). VFTO are generated mostly due to disconnector operations, in which many re- or pre-strikes occur due to relatively slow speed of disconnector moving contact. These phenomena can affect both internal design of the substation elements [1] and withstand characteristics of adjacent power equipment such as bushings and transformers [2].

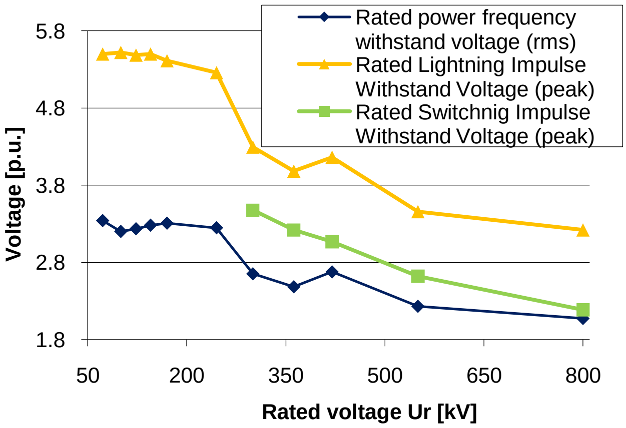

Figure 1: Withstand voltage levels for different rated voltage level

In UHV substations VFTO are of special concern. For the rated voltage beginning from 550 kV the ratio of the rated Lightning Impulse Withstand Voltage (LIWV) and the VFTO significantly decreases [3] – see Figure 1. Since LIWV is the base for GIS design, UHV GIS must be designed so that breakdowns caused by VFTO are improbable.

1.2 Trapped Charge Voltage impact on VFT process

When the disconnector opening operation is completed, after the occurrence of the last re-strike, the Trapped Charge Voltage (TCV) remains on the load side of the disconnector [4]. The trapped charge decay is a very slow process, taking hours or days, resulting from the charge leakage across the spacers. During the subsequent closing operation of the disconnector, the first pre-strike occurs when the source side voltage reaches its amplitude with opposite polarity of the load side voltage (Trapped Charge Voltage) resulting from the preceding operation. The VFT process depends on the voltage drop between the disconnector contacts just before a breakdown occurs, hence the VFTO amplitude is directly affected by the TCV value.

Due to the statistical character of the VFT process, the Trapped Charge Voltage has also a statistical distribution. In state-of-the art approach used in co-ordination insulation calculations the single spark approach is used with the very conservative assumption of -1 p.u. of Trapped Charge Voltage [5]. This approach is used for verification whether

VFTO exceeds the Lightning Impulse Withstand Voltage (LIWV) of the GIS and/or adjacent equipment and can be a limiting factor for the proper dielectric design of the GIS elements such as the disconnector itself.

Based on the TCV distribution, a real value of the TVC can be used for single spark calculations. This can lead to an additional safety margin in the insulation co-ordination analyses and in consequence allow for reducing the total cost of UHV substations.

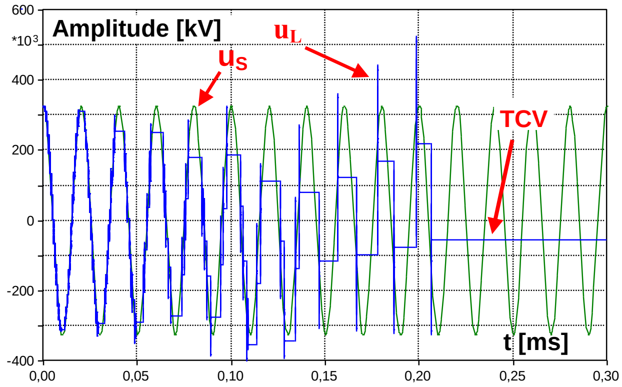

Figure 2: Very Fast Transient process; u_S – disconnector source side voltage, u_L – disconnector load side voltage, TCV – Trapped Charge Voltage

2 VFT MODELLING FOR TRAPPED CHARGE VOLTAGE CALCULATIONS

2.1 Multi-spark approach for disconnector modeling

For the purpose of the approach presented in this paper, the multi-spark disconnector model has been employed as presented in [6]. In the model, not only one spark, but the entire process of the disconnector operation is implemented, including many re- or pre- strikes.

The idea of the model is based on the concept which is commonly used when modeling of Vacuum Circuit Breaker, as it is presented e.g. in [7]. The concept is to control the nonlinear resistance by using time dependent resistance – see Figure 3. For the purpose of the model development the MODELS tool of the EMTP-ATP program has been used [8]. By means of the control procedure, a decision is being made whether the spark is to be ignited or extinguished – – see Figure 4.

The decision is based on the values of potentials on the source and on the load side of the disconnector, which are compared with the withstand voltage of the contact gap. The withstand voltage is calculated in each simulation step on the basis of moving contact velocity obtained from mechanical characteristics of a real disconnector and the withstand voltage characteristics of the disconnector contacts system. Trapped Charge Voltage is modeled with the use of an additional capacitance, which is disconnected by the ideal switch after the ignition of the first spark in the closing operation process.

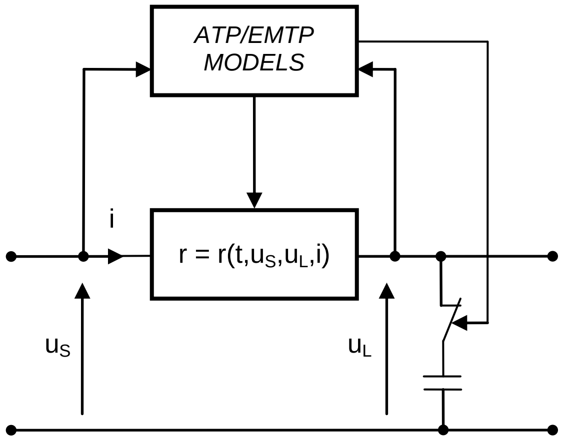

Figure 3: EMTP-ATP model of the disconnector [6]; r – TACS controlled time dependent resistance, u_S – disconnector source side voltage, u_L – disconnector load side voltage

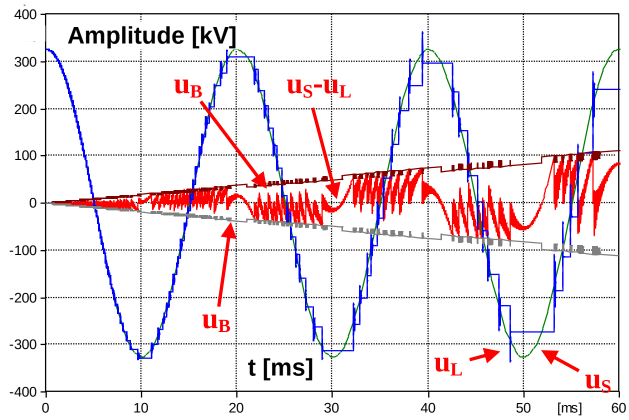

Figure 4: VFT entire process, first 60 ms for opening operation; u_S – disconnector source side voltage, u_L – disconnector load side voltage, u_B – breakdown voltage, u_S-u_L – voltage across the contacts of the disconnector

Design parameters of the disconnector, such as contact speed, SF_6 gas pressure and dielectric design of the disconnector contact system, influence the withstand characteristics of the disconnector and hence influence the Trapped Charge Voltage behavior of the disconnector.

2.2 Trapped Charge Voltage calculations

Trapped Charge Voltage distributions were calculated for opening operations of the disconnector, assuming different moving contact speed values, for the Test Duty 1 set-up (TD1). TD1 set-up has been arranged according to IEC standard [9] – see Figure 5.

EMTP-ATP controlling algorithm (implemented in the MODELS tool) controlled the sparks ignition process based on the withstand characteristics of the disconnector and the voltage between the disconnector contacts. After completing each of the disconnector operation (out of 1440 disconnector opening operations for a given phase and contact speed), the EMTP-ATP model returned the value of the TCV (as indicated in Figure 2). The TCV value was returned to the external controlling software which sent it to Matlab for the purpose of post-processing. Then, the distributions and cumulative distributions were calculated – see Figures 6-8.

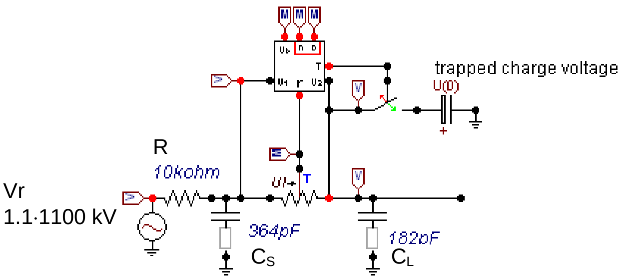

Figure 5: Test Duty set-up for Trapped Charge Voltage calculations; R – protective resistor, C_S – disconnector source side capacitor, C_L – disconnector load side capacitor

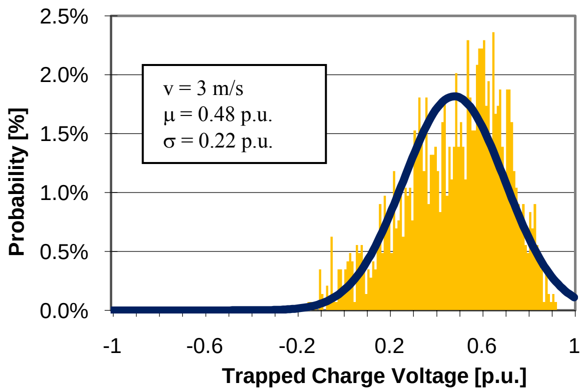

Figure 6: Exemplary distribution of Trapped Charge Voltage for contact speed 3 m/s; μ – mean value, σ - standard deviation

The simulations were performed for different values of the disconnector contact speed: 0.1, 0.3, 1.0, 1.5, 3.0 m/s.

In Figure 6 an exemplary Trapped Charge Voltage distribution is depicted for contact speed of 3 m/s, including simulation results and the fitted normal distribution with mean value of 0.48 p.u. and standard deviation of 0.22 p.u. In Figure 7 normal distributions fitted to the simulation results for each value of contact speed assumed are shown. In Figure 8 cumulative distributions calculated for the distributions given in Figure 6 are presented.

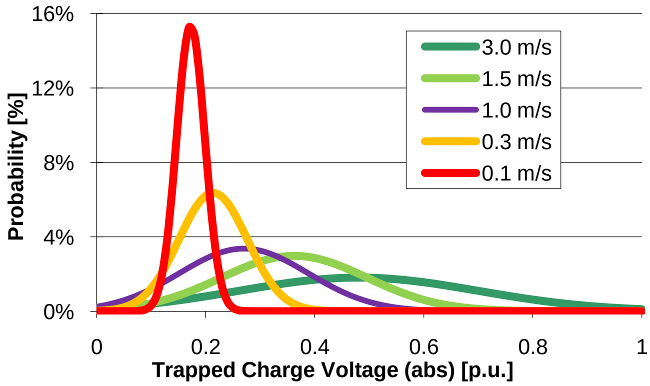

Figure 7: TCV normal distributions fitted to the simulation results for each contact speed

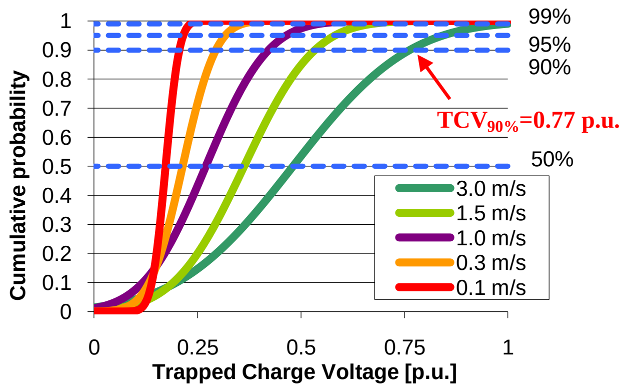

Figure 8: Cumulative TCV distributions calculated for the distributions given in Figure 7

As an example, for disconnector with moving contact speed of 3 m/s, the $TCV_{90\%}$ equals 0.77 p.u. (as indicated in Figure 8). Thus, there is probability of 90% that the Trapped Charge Voltage in an operation of the disconnector is less than 0.77 p.u. To put it in other words, in 90 % of the disconnector operations, the Trapped Charge Voltage remaining on the disconnector load side will be less than 0.77 p.u. Assuming slow acting disconnector (v = 0.1 m/s), and assuming the probability level of 99%, the Trapped Charge Voltage level becomes as little as $TCV_{99\%}$ = 0.24 p.u. (see Figure 8 and Table 1). Such a low TCV value provides an additional safety margin in insulation co-ordination analyses. This margin is even higher due to the fact that the calculations are performed for TD1 set-up, in which source voltage of 1.1 p.u. is used.

2.3 Trapped Charge Voltage calculations vs. measurements verification

The simulation results were compared to the results obtained in measurements in 1100 kV TD1 set-up according to IEC standard [9]. The comparison is presented in Figures 9-10 for Trapped Charge Voltage distributions and for sparking time distributions respectively. The measurements were performed for more than 500 opening operations of the disconnector.

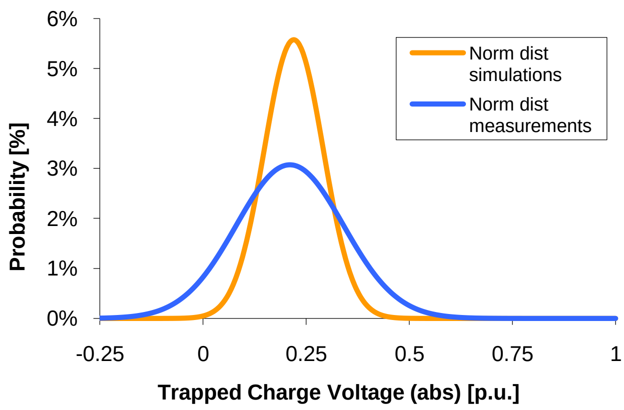

Figure 9: Trapped Charge Voltage distributions simulated and measured for 1100 kV TD1 set-up, for disconnector contact speed v = 0.4 m/s (see also Figure 7)

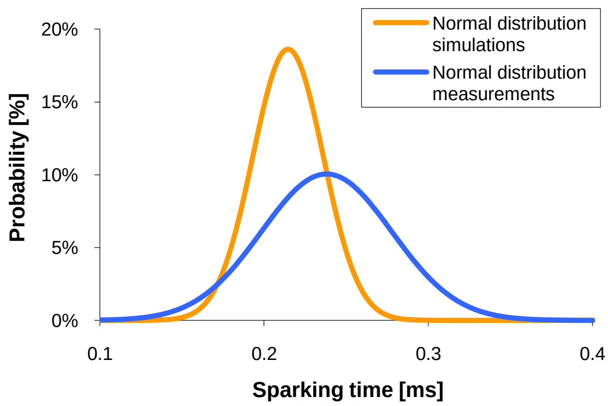

Figure 10: Sparking time distributions simulated and measured for 1100 kV TD1 set-up, for disconnector contact speed v = 0.4 m/s

3 TRAPPED CHARGE VOLTAGE IMPACT ON VFTO IN UHV GIS SUBSTATION

3.1 Scope of the simulations

The values of the Trapped Charge Voltage for probability of 99% were used for VFT calculations in a typical UHV 1100 kV GIS substation. The TCV values are presented in Table 1.

Table 1: Trapped Charge Voltage for 99% probability according to Figure 8

Contact speed [m/s]	0.1	0.3	1.0	1.5	3.0
$TCV_{99\%}$ (abs) [p.u.]	0.24	0.36	0.55	0.68	1.00

The value of the $TCV_{99\%}$ for contact speed equals 3 m/s corresponds to the state-of-the-art conservative approach of -1 p.u. typically used in insulation co-ordination analyses.

The VFT process has been characterized by the following parameters: VFT overvoltage (VFTO), number of sparks during the VFT process, and the sparking time. The parameters were calculated during the disconnector closing operation for exemplary 1100 kV GIS substation on the disconnector load side.

3.2 UHV GIS substation modeling

For the purpose of VFT calculations for different levels of the TCV, the model of an exemplary UHV 1100 kV GIS substation has been developed. The calculations were performed for the closing operation of the disconnector.

Modeling principles employed for the model development of a typical UHV GIS substation are based on the state-of-the-art modeling approach presented e.g. in [5]. Closed circuit breakers and disconnectors are modeled as GIS busbars, by means of surge impedance characterized by associated length and surge velocity. GIS components have been represented as lumped capacitances and suitable surge impedances. Sparks during the disconnector operation are modeled as a nonlinear resistance according to the description in section 2.1, given by the formula:

$$R = R_a + R_0 \cdot e^{-t/\tau}, \qquad (1)$$

where: R_a = Arc resistance in Ohm (Ω)
R_0 = Resistance of opened gap in Ohm (Ω)
τ = Time constant leading to the spark propagation specific for breakdown in SF_6 in seconds (s)

Ohmic losses have been neglected. Detailed models description is given in [5].

3.3 Simulation results

The simulation results are presented in Figures 11-13. Each value represents VFT calculations for closing operation of the disconnector in the UHV GIS substation for selected TVC values of 50%, 90%, 95%, and 99% (according to Figure 8). For the slow acting disconnector the VFTO level significantly decreases with respect to that for the fast acting one.

Based on the results presented in Figures 11-13 the VFTO reduction factor can be expressed as the ratio of VFTO for a given disconnector contact speed (hence given TCV level), and given TCV probability, to the VFTO at the TCV of -1 p.u. The results presented in that way are depicted in Figure 14. The relation between VFTO level and the voltage value when the spark occurs is linear, thus the relations depicted in Figure 14 for VFTO are of the same character as the relations of TCV in the TD set-up depicted in Figure 8. In Figure 14 the reduction of as much as 20% is visible for the disconnector contact speed reduced to the value of 0.1 m/s. It has to be mentioned however, that such a speed reduction would lead to the increase in both sparking time and the number of sparks

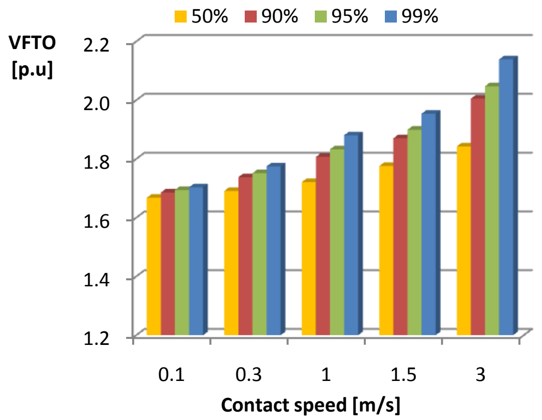

Figure 11: TCV and contact speed impact on VFTO disconnector load side

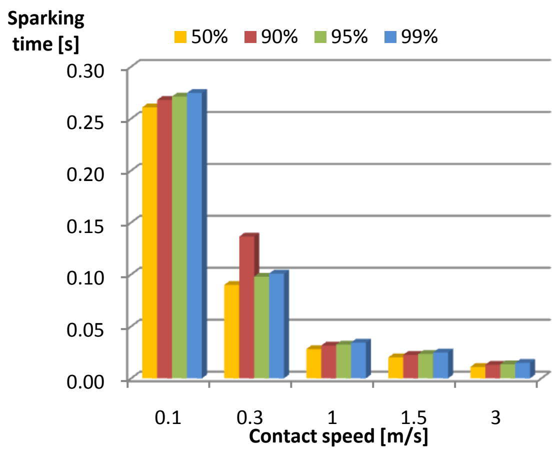

Figure 12: TCV and contact speed impact on sparking time

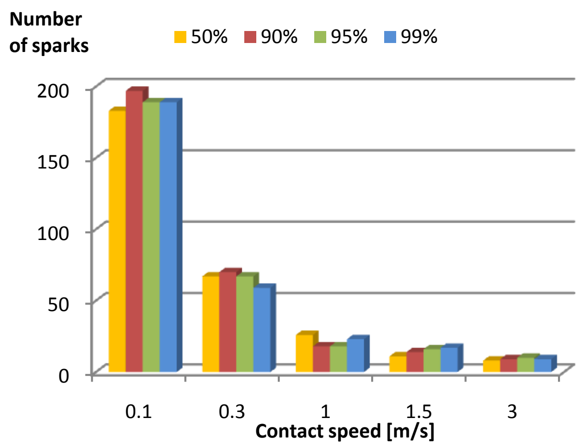

Figure 13: TCV and contact speed impact on number of sparks

during the disconnector operation process (see Figures 12-13). The optimum design of the disconnector should be considered to achieve significant VFTO reduction with acceptable sparking time and number of sparks.

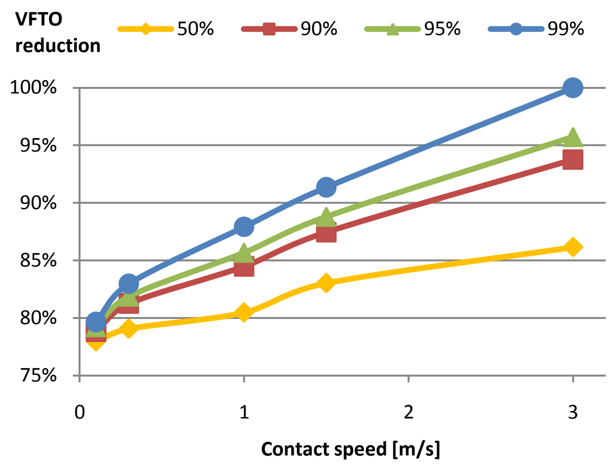

Figure 14: VFTO reduction as a function of disconnector contact speed

4 CONCLUSIONS

In this paper the approach is presented which allows one to investigate the disconnector design impact on the Very Fast Transient (VFT) process in Gas-Insulated (GIS) UHV Switchgear. Design parameters such as contact speed, SF_6 gas pressure, and the dielectric design of the disconnector contact system, can be investigated with the approach presented. The approach is based on the circuit modeling which is a common practice used in the insulation co-ordination analyses. For that purpose the multi-spark disconnector model has been employed and adapted for the Trapped Charge Voltage (TCV) simulations.

Simulation results were verified based on the measurement results for the 1100 kV Test Duty 1 set-up according to the IEC standard.

The cumulative Trapped Charge Voltage distributions lead to the conclusion, that the value of -1 p.u. TCV is a very conservative assumption. The assumption of a more realistic value of the TCV, can lead to more realistic insulation co-ordination calculations and in consequence allow for reducing the total cost of UHV substations. This can be achieved by the reduction of the clearances and hence the size of the substations when the lower VFTO levels are considered.

The application of slow acting disconnector provides significant reduction in the VFTO. Moreover, both: the number of sparks and the sparking time could be analyzed and used as input for the insulation coordination analyses.

5 REFERENCES

[1] U. Riechert, U. Krüsi, D. Sologuren-Sanchez, “Very Fast Transient Overvoltages during Switching of Bus-Charging Currents by 1100 kV Disconnector,” CIGRÉ Report A3-107, 43rd CIGRÉ Session, August 22-27, 2010, Palais des Congrès de Paris, Paris, France

[2] K. Johansson, U. Gäfvert, G. Eriksson, L. Johansson, “Modeling and Measurements of VFT Properties of a Transformer to GIS Bushing”, A2.302.2010, CIGRE 2010

[3] IEC 6271-203 High-Voltage Switchgear and Controlgear – Part 203: “Gas-Insulated Metal-enclosed Switchgear for Rated Voltages Above 52 kV”

[4] G. Ecklin, D. Schlicht: “Overvoltages in GIS Caused by the Operation of Isolators”, Proceedings of the Brown Boveri Research Centre, Baden, Switzerland, September 3-4, 1979, pp. 115-128

[5] D. Povh, H. Schmitt, O. Volcker, R. Witzmann, P. Chewdhuri, A. E. Imece, R. Iravani, J. A. Martinez, A. Keri, A. Sarshar, “Modeling and Analysis Guidelines for Very Fast Transients”, IEEE Power Engineering Review, Volume: 17, Issue: 13, 1996

[6] M. Szewczyk, M. Stosur, W. Piasecki, M. Fulczyk, M. Florkowski, M. Steiger, J. Kostovic, "New Disconnector Model for Very Fast Transient Studies in High Voltage Gas Insulated Substations," in Proc. 2010 EEUG (European EMTP-ATP User Group) Conf., pp.154-163

[7] J. Helmer, M. Lindmayer, “Mathematical Modeling of the High Frequency Behavior of Vacuum Interrupters and Comparison with Measured Transients in Power Systems,” in Proc. 1996 International Symposium on Discharges and Electrical Insulation in Vacuum (ISDEIV), vol. 1, pp. 323-331

[8] H. W. Dommel, W. S. Meyer: “Computation of Electromagnetic Transients,” Proceedings of the IEEE, vol. 62, no. 7, July 1974, pp. 983-993

[9] IEC 62271-102, “High-Voltage Switchgear and Controlgear – Part 102: Alternating Current Disconnectors and Earthing Switches”