Very Fast Transients in GIS: New approach towards analysis of the impact of the disconnector operation on the equipment

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***Abstract*-- Power equipment connected to Gas Insulated Substations (GIS) may be exposed to Very Fast Transients (VFT) due to disconnector operations. In the VFT study the common approach is based on single spark calculations only. In this paper the entire VFT process analysis has been involved for the assessment of the VFT impact on power equipment and a quantitative method of the assessment has been proposed. For the purpose of the method presentation the machine withstand voltage envelope has been used as an exemplary characteristics of the insulation withstand voltage for surges within wide frequency range. Exemplary study based on a typical HV GIS substation has been presented.**

***Keywords*: Gas Insulated Switchgear (GIS), Very Fast Transient (VFT), Disconnector Switching (DS), transformer insulation.**

I. Introduction

Very Fast Transients (VFT) resulting from breakdowns in Gas Insulated Substations (GIS) are characterized by the highest frequency in power system due to very short breakdown time in gas SF6. The most notable origins of VFT are disconnector operations [1]. During each of such an operation a number of re- or prestrikes occur due to relatively slow speed of the disconnector moving contact. Each of the breakdowns causes the VFT which propagates through the GIS, being reflected and transmitted at any discontinuity within the substation. The superimposition of the travelling waves constitutes VFT overvoltages (VFTO) which can influence both: the design of the disconnector in case of some Ultra High Voltage (UHV) substations and/or the withstand characteristics of dielectric insulation systems of some high voltage power equipment.

A. Single spark approach vs. entire process analysis

In insulation coordination practice related to VFT in GIS a standard approach is used which involves the so called single spark analysis, where the only one breakdown selected from the entire VFT process is taken into account. The breakdown selected is the most unfavourable one, assumed for the closing operation when the trapped charge voltage remaining on the load side of the disconnector is -1 p.u. The objective of this standard approach is to determine whether VFT exceeds insulation coordination level of the substation or the adjacent equipment such as bushings or transformers. For substations with higher rated voltage the margin between insulation coordination level and the rated voltage become lower and hence above 800 kV rated voltage the VFT tends to supersede the rated Lightning Impulse Withstand Voltage (LIWV) of the substation or the adjacent equipment.
In other cases, VFT does not exceed the LIWV and does not influence the design of the substation itself, but still can significantly stress the adjacent equipment insulation system due to very fast rise times and high recurrence rates, in case when the dielectric system is not designed for such surges.

B. VFT influence on HV equipment

VFT overvoltages in a GIS substation are always below the LIWV due to either the relatively high insulation coordination margin in case of substations up to 800 kV or due to the VFT dedicated protective measure [2] which in some cases is applied in UHV substations (e.g. disconnector with damping resistor). In consequence, in all GIS substations the existing lightning protection devices which are dedicated to Fast Transients, originated from lightning surges, are transparent for the Very Fast Transients.

According to CIGRE document related to electrical environment of transformer [3] VFT investigations can thus in some cases be recommended due to the steep front times and high recurrence rates of the phenomenon.

In this paper the step towards the quantitative assessment of the VFT influence on transformer insulation is proposed. Some exemplary analysis performed with use of the approach is presented on the basis of a typical HV GIS substation.

II. Impact of VFT on Transformer Insulation

A. Impulse withstand envelope

Withstand capability of the insulation as well as its aging processes are different under the stress of conventional lightning or switching voltage and the voltage of a very steep front time such as VFT in GIS. While many of the standard loads apply to the transformer insulation (such as LIWV or thermal overload) the VFT impulse strength criteria for equipment insulation are much more complicated. Such criteria take into account not only amplitude of the surges, but also parameters like the front steepness or repetitiveness of the

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phenomenon related to specific design of the equipment. For quantitative analysis of the VFT impact on the equipment, detailed characteristics of the dielectric insulation system in view of very high impulse steepnesses and recurrence rates have to be taken into account.

This paper presents a proposal of the method of possible analysis of the entire VFT phenomenon impact on equipment insulation. For the purpose of the method presentation, the impulse withstand voltage envelope applicable for machine insulation shown in Fig. 1 [4] has been used. Despite the fact that the insulation of rotating machine windings is much different from those of the transformers, it has been assumed that the general idea laid beneath this curve can in some cases illustrate the general dependence of the equipment dielectric insulation system on the surge steepness and repetition rate. The objective is thus to make use of this machine impulse withstand approach and to propose a new method for analysis of the impact of VFT overvoltages on the transformer winding. It should be noted however that in such studies the proper characteristics of the power equipment has to be involved.

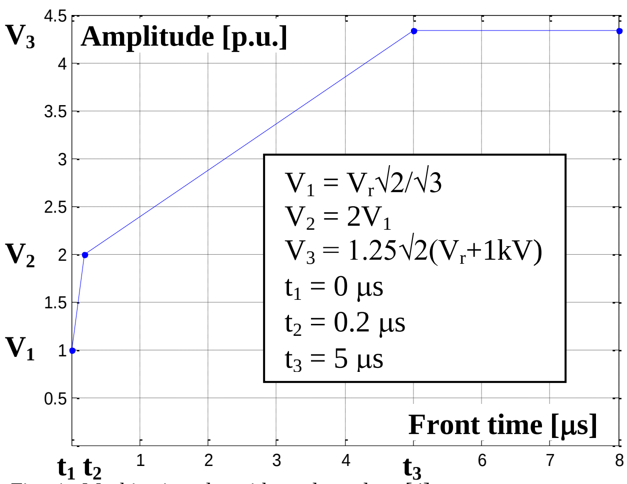

Fig. 1. Machine impulse withstand envelope [4]

The advantage of the exemplary voltage strength representation given in Fig. 1 is that voltage limits for short and long impulses are represented by a single envelope. When the front time voltage of the surge is short, the initial voltage distribution across the winding becomes highly non-linear. For extremely short front times, when the electrical length of the winding (total time of the impulse travelling through the winding) is comparable with the rise time, the initial voltage distribution analysis requires the application of the distributed parameters approach. In most typical cases however, the winding can be represented by lumped capacitances. In the case of the capacitive distribution most of the voltage appears between the first discs of the winding. Therefore the withstand voltage for short front time surges can be lower than it is for surges with longer front times.

Making use of this approach the quantitative measure of the VFT impact on transformer insulation can be proposed. It should be noted however, that for power transformer analysis the proper insulation characteristics has to be used.

B. *VFT quantitative assessment*

The goal of the quantitative assessment of the VFT process is to map the entire process into a single number and thus to define a functional *F*, which represents quantitatively the VFT influence on transformer insulation. Such an approach would be a useful tool for trapped charge behaviour analysis or VFT suppressing methods assessment, as it is shown in section IV.

For the purpose of VFT quantitative assessment the entire VFT process has been divided into small bits containing every single spark. For each of the spark the VFT overvoltage amplitude and VFT overvoltage front time have been determined. The amplitudes and the front times have been then compared to the envelope given in Fig. 1. Those events which amplitude turned out to be below the value of 1 p.u. (which is the case for most events) have been neglected. Only those events for which the amplitude exceeds 1 p.u. have been taken into account. For those latter cases it has been then distinguished whether the selected VFT overvoltage amplitude lay below the withstand value of the envelope for a given front time or whether the withstand value has been exceeded. For every event qualified, the quantity based on the energy characteristics of the overvoltage has been assigned, forming the final value of the functional *F*. The energy characteristics was assumed as the relation of the VFT overvoltage energy to the energy under LIWV conditions.

In this paper the exemplary study presenting the proposed approach is presented.

III. Modelling of Very Fast Transients

A. *Disconnector model for entire VFT analysis*

For the purpose of VFT analysis presented in the paper, a model for the entire VFT disconnector was developed [5]. In the model, not only one spark, but the entire process of the disconnector operation has been incorporated, including many re- or prestrikes.

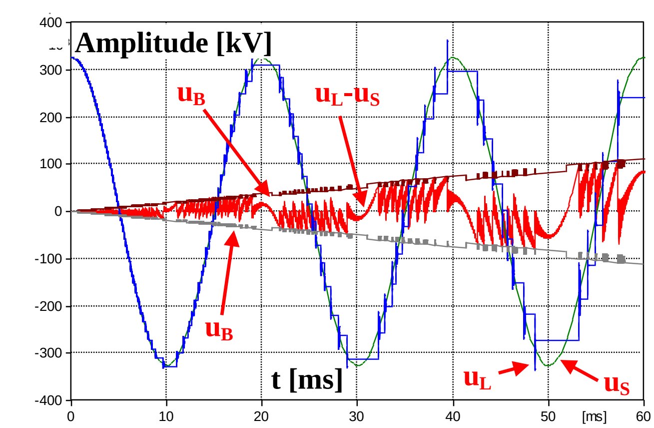

Fig. 2. VFT entire process, first 60 ms for opening operation; u_S – disconnector source side voltage, u_L – disconnector load side voltage, u_B – breakdown voltage, u_S-u_L – voltage across the contacts of disconnector

The idea of the model is based on the concept which is commonly applied for modelling of a Vacuum Circuit Breaker, as it is presented e.g. in [6]. The concept is to control the nonlinear resistance by using time controlled time dependent resistance. For the purpose of the model implementation the MODELS tool of the EMTP program has been used [7]. By means of the control procedure, a decision is being made whether the spark is to be ignited or extinguished (see Fig. 2).

The decision is based on the values of potentials on source and 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 the real disconnector and the rated power frequency withstand voltage across the isolating distance. Trapped charge is modelled by an additional capacitance, which is triggered by the ideal switch so that it does not influence travelling wave phenomenon constituting VFT.

B. *Disconnector model verification*

Verification of the entire VFT model has been performed based on the comparison between the simulation results and the results obtained in direct measurements performed with use of 420 kV GIS real disconnector. The test circuit set-up has been arranged according to IEC standard [8] as Test Duty 1. Exemplary resultant waveforms are presented in Fig. 3.

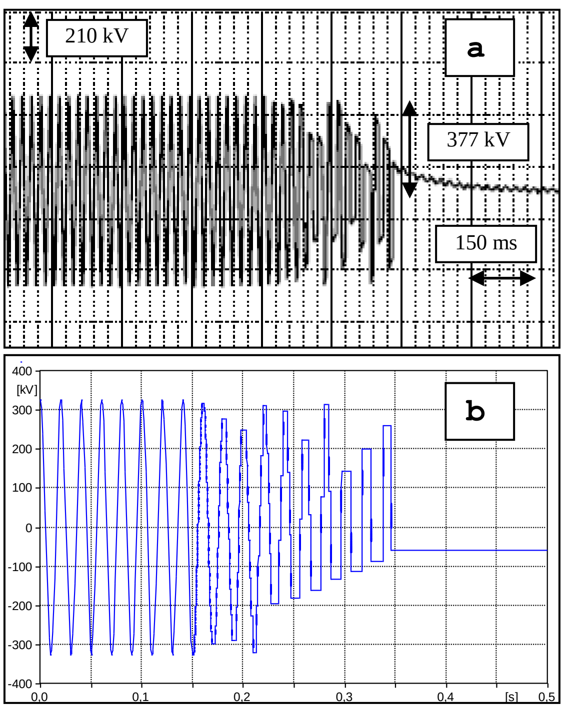

Fig. 3. Simulation results vs. measurements in Test Duty 1 for opening operation, load side voltage: a) measurements, b) simulation

Common step-wise patterns of the load side voltage, as well as the so called falling pattern (which is due to the contacts asymmetry) are visible. It can be noticed that after the opening operation the trapped charge voltage remains at the load side of the disconnector (Fig. 3b). This DC component is not visible in the measured waveform since the capacitive voltage dividers were used as the high voltage, high frequency sensors. On the low side of the dividers the high resistance input of the oscilloscope has been connected which brought about the typical differences between the two voltages (exponentially decaying trapped charge voltage, see Fig. 3a).

C. *Gas insulated substation model*

Exemplary study presented in this paper has been performed based on a typical 400 kV GIS substation shown in Fig. 4. The three bays of the substation have been selected for the calculation: the source bay supplied from the system, the disconnector bay with the disconnector operated and the transformer bay in which the VFT overvoltage has been calculated at the transformer terminals. The dashed line in Fig. 4 shows the calculated configuration.

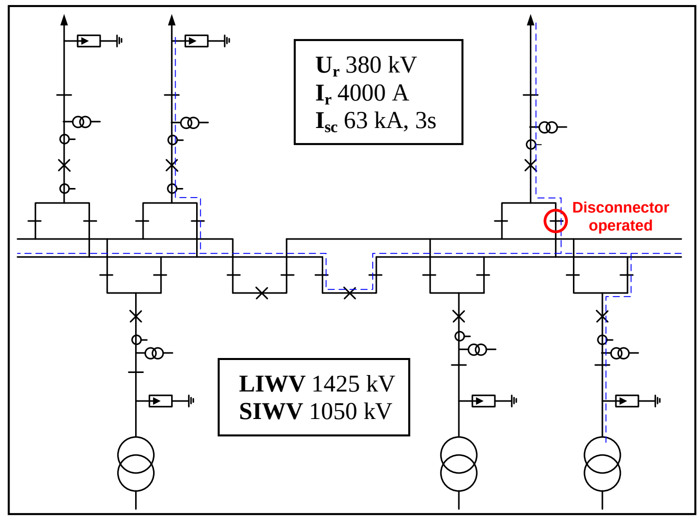

Fig. 4. Single line diagram of HV GIS substation with calculated configuration marked with the dashed line

For the purpose of the substation modelling the state of the art of GIS modelling for VFT analyses has been used, as described e.g. in [9]. GIS sections have been modelled as equivalent circuits composed of distributed parameter lines defined by surge impedance and travelling times. The sections lengths have been determined based on the manufacturer's drawings of the GIS. Insulators, bushings, voltage and current transformers and circuit breaker chambers have been modelled as lumped capacitances. As a transformer model, a simple capacitive representation based on manufacturer data provided was used. This approach allows one to analyse transients in the substation without the analysis of internal voltage distribution within the transformer itself.

In Fig. 5 exemplary VFT overvoltage waveforms are presented for closing and opening disconnector operation in the GIS substation under the consideration. For the closing operation with the trapped charge -1 p.u. (Fig. 5b) it is clearly visible that more than one of the prestrikes has a significant amplitude.

IV. Exemplary Study

Quantitative assessment of VFTs impact on transformer insulation has been performed for the closing operation of the disconnector with use of the entire VFT process modelling. One of the important factors characterizing the VFT process has been taken into account, namely the trapped charge behaviour of the disconnector. The study has been performed according to the description given in section II for the entire VFT process assessment and has been based on a typical HV GIS substation layout outlined in section III (see Fig. 4).

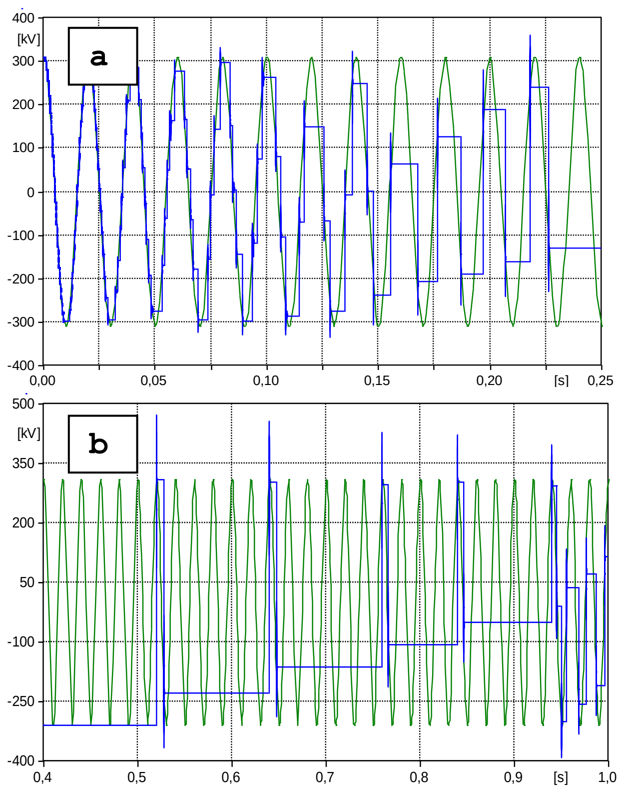

Fig. 5. VFT due to disconnector switching – source side voltage (continuously alternating) and load side voltage (step wise) for: a) **opening** (restrikes), b) **closing** (prestrikes) operation at disconnector terminals

Calculation results are presented in Fig. 6 in a form of the so called dot-plots of VFT overvoltage amplitude. Dot plots stands for that each of the dots represents the amplitude of a single VFT overvoltage in a given VFT process.

The three processes have been selected, all of them for closing operation of the disconnector. In the first case, the standard -1 p.u. value of trapped charge voltage has been assumed (see Fig. 6a). In the second case, the trapped charge voltage has been lowered to the value of -0.6 p.u. (see Fig. 6b). For the third case, the value of -0.2 p.u. trapped charge voltage has been assumed (see Fig. 6c). In real conditions the value -0.3 p.u. of trapped charge voltage is much more likely to occur than the most unfavourable value of -1 p.u. used in insulation coordination practice [10].

In Fig. 6a_1-c_1, the dot plots of the VFT overvoltage amplitudes are presented in domain of the time of the disconnector operation (from 0 to 1.5 s). In Fig. 6a_2-c_2, the dot plots of both the amplitudes and the front times have been presented, together with the insulation withstand envelope assumed (as described in section II). Those events, for which the amplitude exceeds the withstand level are highlighted in red. Those events which are below the withstand voltage, but still exceed the 1 p.u. value, are black coloured. The remaining ones are green coloured. For each of the event the value has been assigned based on the description given in section II, forming the resultant quantitative functional F of the entire VFT process. For the exemplary withstand envelope assumed, the quantitative measure has been calculated (see Fig. 7b).

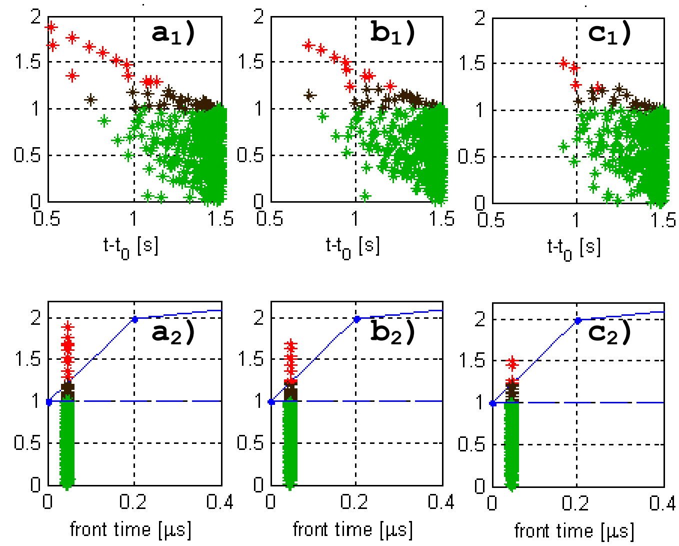

Fig. 6. Dot-plots of the VFT overvoltage for closing operation, different levels of trapped charge; $a_{1\text{-}2}$) -1 p.u., $b_{1\text{-}2}$) -0.6 p.u., $c_{1\text{-}2}$) -0.2 p.u.; a_1-c_1) VFT overvoltage amplitude vs. time, a_2-c_2) VFT overvoltage amplitude and front time over the withstand envelope

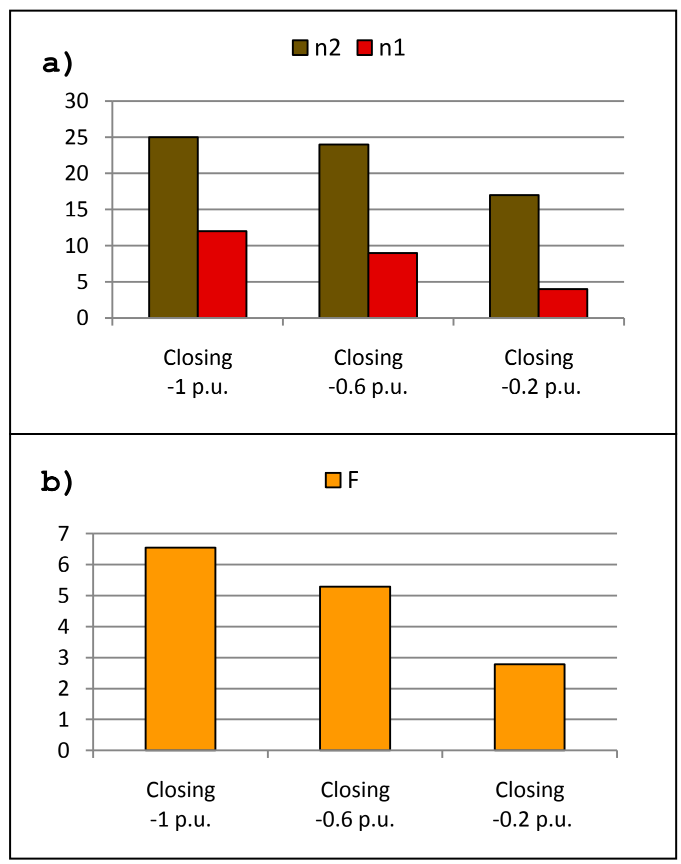

Fig. 7. a) Number n_1 of VFT overvoltage exceeding withstand envelope (red coloured) and number n_2 of VFT overvoltage exceeding 1 p.u. only (black coloured), b) value of the VFT quantitative measure, functional F

In Fig. 7 the resultant numbers are presented. In Fig. 7a the numbers of the sparks leading to VFT overvoltage of certain amplitude are depicted. In Fig. 7b the values of VFT quantitative measure *F* for the three cases analyzed are presented.

V. Conclusions

In the paper the possible assessment method of VFT impact on the equipment insulation has been presented. For the purpose of the method presentation, the machine withstand envelope has been used as a reference characteristics and the study based on the exemplary HV GIS substation has been performed. The objective of the paper was to make use of such characteristics to present the approach based of the entire VFT process analysis. It should be noted however that in each specific case the proper characteristics of the withstand voltage of the equipment analyzed has to be used.

The presented new approach allows one to assess quantitatively the overall impact of the switching process on the adjacent equipment. The approach substantially extends the standard single spark calculations used in insulation coordination practice.

Results of the exemplary study shown in Fig 7b are in agreement with the expectations based on the VFT understanding. Those VFT overvoltages which exceed insulation characteristics of the equipment are to be avoided by properly designed GIS elements or by means of protective measures applied. In each case the proper insulation characteristics of the equipment has to be used. Significant reduction of the VFT overvoltages can be achieved by means of the trapped charge voltage reduction.

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