Transient voltage stress of 400 kV urban system evaluated by numerical calculations

S. Pack, S. Kornhuber, F. Reisinger

Abstract--Overhead lines, high voltage cable systems and substations are important elements of the high voltage network. More and more close combinations of these elements are used in urban networks. This leads to new transient situations and a more complex transient behaviour in case of lightning or switching events. Additionally the requirements of a constant power supply ask for new efforts to predict impacts caused by interruptions.

Based on this fact this paper deals with investigations to evaluate the transient behaviour of a close combined 400 kV urban system. Numerical tools are basically a modern method to estimate transient stresses, help to optimize the insulation coordination and can simulate various circuit states. Thus, temporary faults can be reduced or avoided at all.

One of the major aspect of this work is the close connection of an overhead line, a cable section and a substation related to the 400 kV system. Additionally attention was paid to the transformers and the secondary side of the system, a 110 kV urban distribution network.

A number of calculations were carried out to get an overview of the transient stress caused by lightning or switching in numerous network nodes of the substation. Of additional interest have been different circuit states at the 400 kV GIS and the transient behaviour at the arrestors. Amplitudes and the energy consumption at the arrestors were taken into account.

These actual investigations were carried out to get useful information's about the transient stress in this important Viennese 400 kV substation, which was officially put into operation in May 2006. As an output of these investigations the results influence the strategy in running the network.

I. Introduction

The electrical energy consumption in Austria increases every year approx. by 3 %. To fulfil a reliable energy supply it is necessary to upgrade or rebuild important network nodes in the system. Especially in urban areas old air insulated systems are replaced by new gas insulated substations (GIS) to increase the distribution capacity and reliability.

More and more combined systems are in use, consisting overhead lines, cables and gas insulated. This leads to a new type of transient stress for the system components and needs a new approach for the insulation coordination. Various international working groups (like in IEC or in CIGRE) are discussing this important topic.

In this paper the transient behaviour of such a combined network system in Vienna is analysed, including a new 400 kV GIS (fig.1) and a connection to the 400 kV transmission power grid by an overhead-cable combination.

II. Description of the Combined Viennese System

The combined Viennese system is located in the north of Vienna and connected to the 400 kV air insulated transmission system of the Austrian Power Grid (APG). The observed network part can be split up in seven system groups (fig. 2) for the transient evaluation.

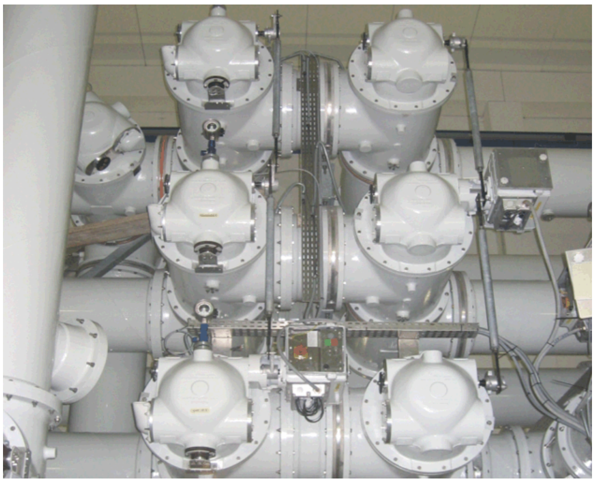

Fig. 1. 400 kV Disconnector in the new Viennese GIS

Part A: The air insulated 400 kV transmission network and the substation belongs to the Austrian grid operator. This network is approx. 15 km away from the new 400 kV Viennese substation. Additional substations of the Austrian Power Grid are more than 50 km away.

Part B: The overhead transmission line (9 km, double system) connects the air insulated 400 kV Austrian Power Grid substation and the cable bushing. For this line route the lightning density is given by 1.9 flashes per km² and year according to the measurements of the Austrian Lightning Detection and Information System (ALDIS).

Part C: The cable entrance is given by a 400 kV cable bushing and the location of a metal oxide arrester.

S. Pack, associated professor at the Institute for High Voltage and System Management, Graz University of Technology, 8010 Graz, Austria (e-mail of corresponding author: pack@hspt.tu-graz.ac.at).
S. Kornhuber, former scientific staff at the Test Institution for High Voltage Engineering Graz Ltd., 8010 Graz (e-mail: kornhuber@ieee.org).
F. Reisinger, head of the NT3 Devision of Wienstrom GmbH, 1020 Wien (e-mail: franz.reisinger@wienstrom.at).

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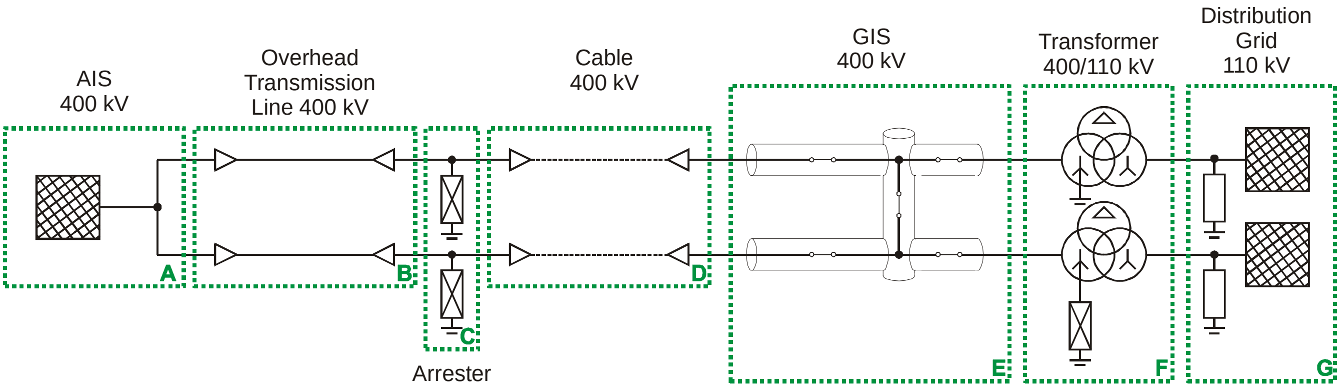

Fig. 2. Overview of the combined network
Air insulated transmission network 400 kV (A); overhead transmission line 400 kV (B), metal oxide arrester 400 kV (C), cable system 400 kV (D)
Gas Insulated Substation 400 kV (E), transformer 400 kV / 110 kV (F), Viennese distribution grid 110 kV (G)

Part D: The 400 kV cable system (5 km, three single phase) consists of a VPE cable to connect the overhead line to the GIS.

Part E: The 400 kV urban GIS consists of two similar substation parts symmetrically arranged, each with a cable entry and a direct feeder to the 400 kV/110 kV power transformer. The substations part can be coupled by a switch.

Part F: Two 400 kV/110 kV power transformers are connected directly to the GIS, whereby the neutral point of one of the transformers at the 400 kV level is grounded by a metal oxide arrester (reduction of the short circuit current during single line failures). The neutral point of the other transformer is directly grounded.

Part G: The 110 kV sides of the transformers are directly connected to a separate 110 kV GIS, which supplies the Viennese distribution network. The neutral points of the 110 kV transformers are not grounded (isolated network).

III. Basics of Calculation

The transient behaviour of combined system is mainly influenced by the differences of characteristic impedances of the network with distributed elements. Therefore three basic examples belonging to the presented combined Viennese network are described.

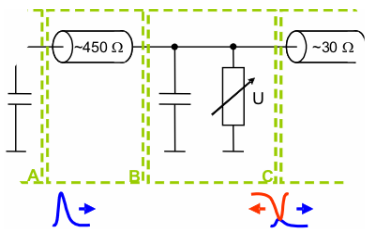

Fig. 3. Equivalent circuit for the reflection behaviour between an overhead line and the cable (section B-D of the analysed system)

The difference of the characteristic impedance at the cable bushing between an overhead line (approx. 450 Ω) and a cable (approx. 30 Ω) leads to a reflection coefficient of approx. 90 %. The incoming voltage impulse will be affected by the reflected voltage wave. In general a voltage step is given (increase or decrease), depending on the propagation direction. The capacity of the metal oxide arrester doesn't influence the transient effects (fig. 3) significantly. This configuration can be found in the section B-D.

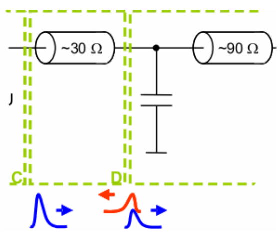

Fig. 4. Equivalent circuit for the reflection behaviour at the GIS entry (section D-E of the analysed system)

Also the difference of the characteristic impedance at the cable bushing close to the GIS influences the transient impulses depending on the propagation direction. The characteristic impedance of a cable (approx. 30 Ω) and the GIS (approx 90 Ω) leads to a reflection coefficient of approx. 50 %. The capacity of the cable bushing influences the impulses (fig. 4). See section D-E.

A gas insulated substation can be described by a coaxial wave guide, in which many inhomogeneous sections belonging to the transient behaviour are present. This leads to a huge number of reflections inside the GIS (e.g. tees, switches, measuring transformers). Transient impulses can also be coupled over the open switches. This situation can be found in the section E.

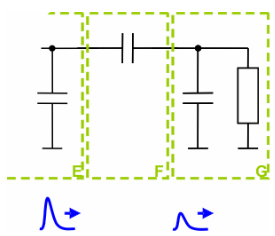

Fig. 5. Equivalent circuit for the reflection behaviour of the power transformer (section F of the analysed system)

A power transformer is an inductive coupling component between two network parts with different voltage levels and has also capacitive coupling between these two windings coils. Furthermore the differences of the characteristic impedance at the connection of the power transformer can lead to a significant influence to the transient behaviour (fig. 5). This configuration can be found in section F.

IV. Calculation of the Network

The described power network is modelled by using some given elements in ATP and by adapting components for this transient calculation. The boundary of the network was set at the 400 kV transmission substation (part A) and the 110 kV distribution network (part G), These network parts are represented by a termination with the characteristic impedance. The overhead transmission line and the cable system were modelled by using lossless lines. The gas insulated substation is represented by a lossless waveguide system with termination capacitances at disconnectors, switch gears, edges and tees.

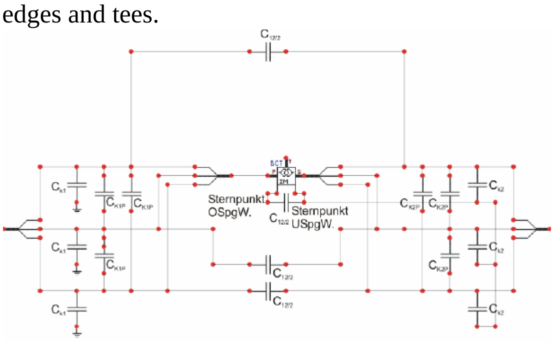

Fig. 6. Model of the power transformer according to CIGRE

The transformer is modelled by using the CIGRE recommendation [8]. For the metal oxide arrester the type 99 in ATP was used.

Two types of stress were taken into account. External transient stress is represented by lightning surges 25 kA, 1.2 / 50 µs. The source is modelled by using the Heidler approach and parameters in µs time domain. The values were adjusted to the recorded data of the Austrian Lightning Detection and Information System (ALDIS).

Internal stress of the system is given during opening or / and closing operations of switch gears in the GIS. For the evaluation the voltage rises are set to approx 50 kV/ns.

V. Results of the Calculation

A huge number of transient voltages were calculated for this transient evaluation of this combined Viennese high voltage system. Two representative examples of the project will be discussed below.

A. *Transient stress by lightning*

The overhead line model is stressed by impulses at various points in system 2. Due to the damping behaviour and the protection devices at the towers the transient stress at the cable entrance (part C) depends at the distance to the impact. The most critical situation is a direct strike to the cable entrance and will become even more important in a situation, when the coupling switch in the GIS is open. In fig. 7 and fig. 8 the results are shown.

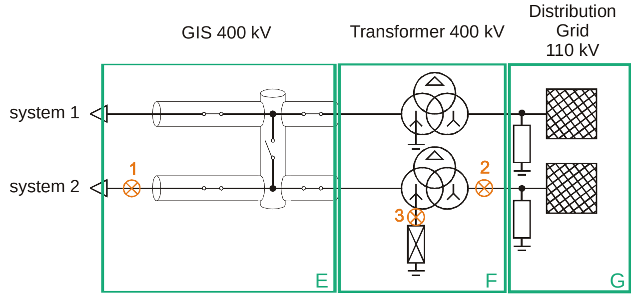

Fig. 7. Partial overview due to the calculated points at the observed network

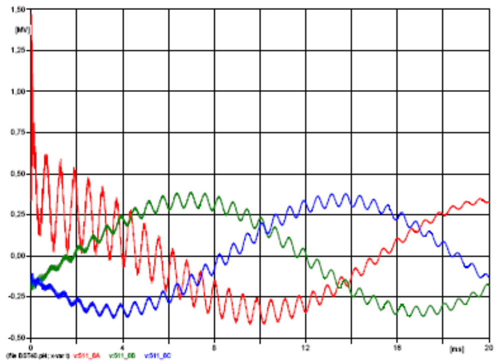

Fig. 8a Transient voltage stress (lightning) at point 1 (fig. 7)

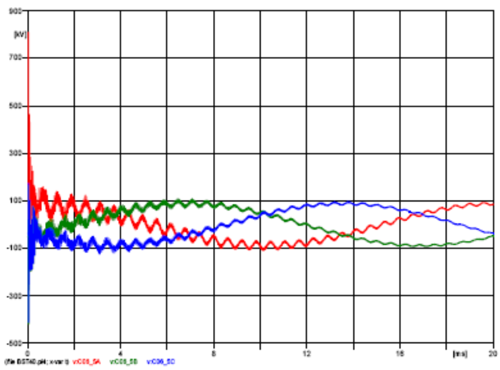

Fig. 8b. Transient voltage stress (lightning) at point 2 (fig. 7)

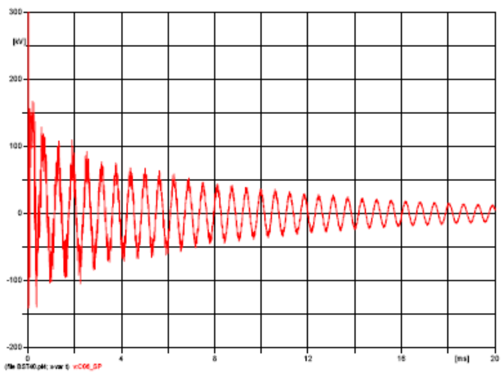

Fig. 8c. Transient voltage stress (lightning) at point 3 (fig. 7)

The lightning flash affects the phase A (red curve in fig. 8a and 8b) with superposed oscillations with amplitudes up to 1400 kV. The other two phases are also influenced by the capacitive and inductive coupling of the lines (amplitudes up to 500 kV). Furthermore the flash initiates a damped oscillation in the power network with a frequency of approx. 2 kHz. Additionally the flash itself and the oscillation lead to a stress at the neutral point of the power transformer metal oxide arrester (fig. 8c). A transient capacitive coupling in the power transformers can be recognized (fig. 8b).

B. *Transient stress by switching*

Due to the coaxial waveguide behaviour of GIS and to switching operations, switching over voltages could reach high values. For this calculation the coupling switch is closed at a specified time. In fig. 9 and fig. 10 the results are shown.

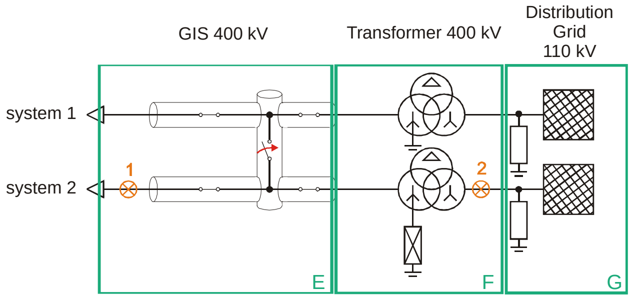

Fig. 9. Partial overview due to the calculated points at the observed network

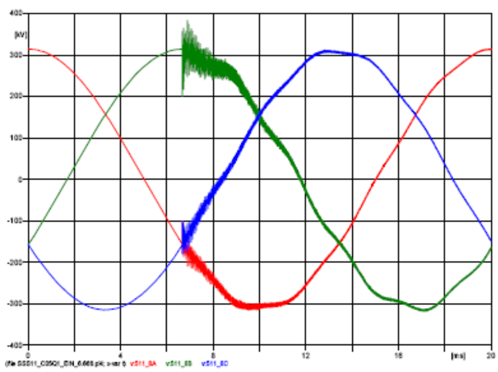

Fig. 10a. Transient voltage stress (switching) at point 1 (fig. 9)

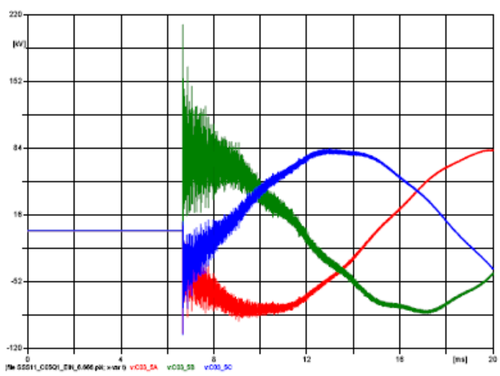

Fig. 10b. Transient voltage stress (switching) at point 2 (fig. 9)

The examples show superimposed oscillations with amplitudes up to 400 kV. The peak value of the transient voltage stresses depends on the switching time significantly.

Generally, the switching has minor effects to the transient stress in the 400 kV system. Again, the transient capacitive coupling in the power transformers could be well recognized (fig. 10b). The frequency of the transient pulses is approx. 100 MHz.

C. *Peak values overview*

In tab. 1 a summarized overview of calculated peak values in the combined high voltage system is given. The highest values can be seen during the stress by lightning flashes in the 400 kV system and in the 110 kV grid. A few network situations (circuit states) can lead to peak voltages close to the insulation coordination level.

TABLE I
CALCULATED PEAK VALUES IN THE COMBINED NETWORK

system coordinate	lightning	switching
bushing cable (C)	1018 kV	---
bushing cable GIS	1482 kV	430 kV
GIS	1520 kV	504 kV
transformer	1560 kV	502 kV
neutral point arrester	300 kV	150 kV
110 kV grid	970 kV	217 kV

VI. RESULTS

The results of the external and internal transient stresses applied to a combined high voltage system can be summarized as followed.

A. *Influences by external stressing:*

The cable entrance (C-D) has to be protected by a metal oxide arrester. The ratio of the characteristic impedances has a positive influence.

The node cable – gas insulated substation (D-E) is stressed close to its BIL, approx. 50 % of the incoming wave is reflected.

Closer lightning discharges to the cable bushing lead to higher peak values inside the cable section.

Due to the size of the substation the atmospheric discharges to the overhead line cause no relevant reflections inside the system.

The transient behaviour of the system stress the arrester in the neutral point of the power transformer (400 kV).

A significant coupling of power transformer between the 400 kV and the 110 kV systems can be recognized.

B. *Influences by internal stressing:*

Inside the substation the open switch lead to high peak values during switching operation.

Active overhead lines represent high characteristic impedances for inside generated switching transients. Doubled peak values easily can be reached.

A significant coupling of power transformer between the 400 kV and the 110 kV systems can be recognized.

C. *Effects to the power grid system and customers*

Low frequency transients are initiated by atmospheric discharges in such combined systems.

The neutral point arrester acts as a fault current shunt during ground failures in the 400 kV network.

Transient effects belonging to the 400 kV system influences the voltage quality in the 110 kV distribution network.

VII. Conclusion

The evaluation of the transient behaviour of combined high voltage systems consisting overhead lines, cables and GIS is an important task. The new Viennese system is a typical example for the actual discussion of insulation coordination belonging to cable entries at substations. The calculated transient behaviour shows, that the nodes between two different system groups are the most endangered locations for transient stresses. Also the coupling of the power transformer between the 400 kV and 110 kV system has to be considered. Both, lightning and switching influence the powers system in a different way. Therefore no general conclusions can be made for the transient behaviour of such complex system. For a reliable performance of important network systems a numerical evaluation of the transient behaviour is essential.

VIII. Acknowledgement

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IX. References

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X. Biographies

Stephan Pack was born in 1958 in Graz, Austria. After the Gymnasium he studied Electrical Power Engineering at the Technical University Graz. Since 1985 he is working at the Institute of High Voltage Engineering and System Management and at the Test Institution of High Voltage Engineering Graz Ltd. at the Technical University Graz. In 1991 he received his doctor degree and 6 years later he finished his habilitation and became an associate professor in the field of high voltage engineering. Nowadays he is vice head of the institute and the head of the group high voltage technique. He is a member of CIGRE and OVE. His scientific work is characterized by the field of high voltage engineering, high voltage tests, insulation coordination, transients, numerical calculations, lightning and grounding. Since many years he is member of the national standard organization for lightning and national delegate for Austria in CIGRE for the committee C4 (System technical performance).

Stefan Kornhuber was born in Linz, Upper Austria in 1979. He graduated the Secondary technical and vocational school for electrical power engineering and power electronics, Linz, Austria, and studied at the Technical University of Graz. He reached the master degree in 2005. During his studies and after his graduation he worked at the Test Institution of High Voltage Engineering Graz Ltd. at the Graz University of Technology in the field of high voltage tests, transient calculations and overhead transmission line uprating until February 2006. Nowadays he is quality manager of Lemke Diagnostics GmbH, Germany, and project manager for online temperature monitoring systems for overhead transmission lines. He is a member of IEEE, OVE and VDE.

Franz Reisinger was born in Vienna, Austria, in 1947. He graduated from TGM, Vienna, and studied electrical engineering at the University of Technology, Vienna. His master degree he achieved in 1973. Since 1973 he has been working for the Viennese public utility company – electric utilities. He started at the network planning department. In 1978 he changed to the department which was responsible for planning, operation and extension of voltage transformation- and traction substations, hydroelectric power plants and grid switching stations. In 1988 he became 2nd vice head of the department and in 1997 1st vice head of the 380kV- and 110kV voltage transformation substations department. Since 2001 he is the manager of the voltage transformation- and traction substations department (NT4) at WIENSTOM GmbH.