Electromagnetic Disturbances of the Secondary Circuits in Gas Insulated Substation due to Disconnector Switching

Ivo Uglesic[1], Sandra Hutter[1], Viktor Milardic[1], Igor Ivankovic[2], Bozidar Filipovic-Grcic[2]

(1) Faculty of Electrical Engineering, University of Zagreb, Unska 3, 10000 Zagreb, Croatia (e-mail: ivo.uglesic@fer.hr, sandra.hutter@fer.hr, viktor.milardic@fer.hr), (2) Croatian Electrical Company, Transsmision Division, Ul. grada Vukovara 37, 10000 Zagreb, Croatia (e-mail: igor.ivankovic@hep.hr, bozidar.filipovic-grcic@hep.hr)

Abstract – **The paper describes problems with electromagnetic compatibility (EMC) of the secondary equipment in the 123 kV gas insulated switchgear (GIS). The causes for malfunctioning of the busbar protection during disconnector switching have been studied. Thorough measurements and computer simulations were conducted in order to determine magnitudes and frequencies of the transient voltages and currents in the secondary circuits. Although measured secondary transients had lower magnitudes than allowed, they caused malfunctioning of the secondary equipment, e.g. busbar protection. Continuous monitoring of the HV equipment's influence on the secondary equipment and implementation of some precautionary protection measures are recommended.**

Keywords – electromagnetic compatibility (EMC), transient enclosure voltage (TEV), busbar protection, gas insulated switchgear (GIS).

I. INTRODUCTION

Electromagnetic disturbances due to Very Fast Transient Overvoltages (VFTO) occurring in metal enclosed gas-insulated switchgear (GIS) are a well known problem.

Today, secondary equipment in HV switchgear is processor oriented, entirely electronic and very sensitive to disturbances. Also, it is located near the HV switching devices, which can cause harsh operating environment.

Cigre Working Group 23.02 stated in its Report on 2nd international GIS service experience survey that of the sample of 73024 CB/bay/year, 16% reported problems with maloperation of control, protection or secondary circuits, although in general, improved reliability of GIS in service was confirmed [1].

The influence of EM disturbances on the operation of relay protection devices, as well as propagation of transients in the secondary circuits has been studied for 123 kV GIS.

II. RELAY PROTECTION TESTING

After disconnector switching during normal substation operation, malfunctioning of busbar protection can occur which can result in disconnection of the whole substation. Testing was performed in order to determine causes that can lead to relay tripping.

In order to send a tripping command, the measuring system has to detect whether the fault is experienced inside or outside the protection zone. The busbar protection will send a command to open the circuit breaker if all three criteria (1 - differential current criteria, 2 - overcurrent criteria, 3 - direction criteria) are fulfilled during a certain time interval.

Fig. 1 shows an example of proper busbar protection operation. All three required criteria have been fulfilled during a certain time period. In this example, a 50 Hz current was injected from the testing device. Channel 1 shows that negative logic was implemented, which means that the signal is active if differential current is not present. With the presence of differential current, the signal obtains zero value and enables tripping. At this time instant an overcurrent signal is already present on channel 2. Channel 3 registers if current flows in the specified direction. This signal is present at regular intervals. The protection system measures signals separately, during positive and negative current half-period.

Testing on the busbar protection measuring system was repeated during disconnector switching operations. The module has tripped twice, when the disconnector was operated. Again, signals at the entrance to the protection system were recorded and all three criteria have been fulfilled during a certain time period (5 ms), although signals occurred at irregular intervals. The differential current criterion was fulfilled and saw-shaped overcurrent impulses are present during the entire interval. The processor is integrating the signal, if the frequency of the saw-shaped signal is high enough. The case in which all three criteria have been fulfilled during a certain time period (after approximately 50ms) is depicted in Fig. 2.

Fig. 3 shows signals at the entrance to the measuring system, also recorded during disconnector switching operation. Channel 1 represents current from cable 110 kV, which is one of the inputs into the measuring system.

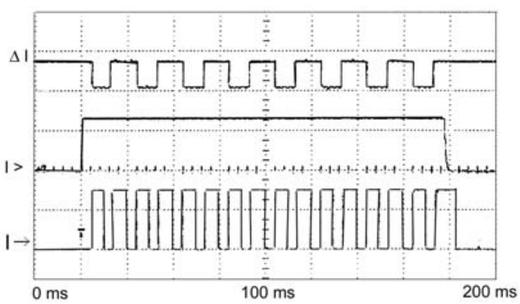


Fig. 1 Proper busbar protection operation initiated with testing device

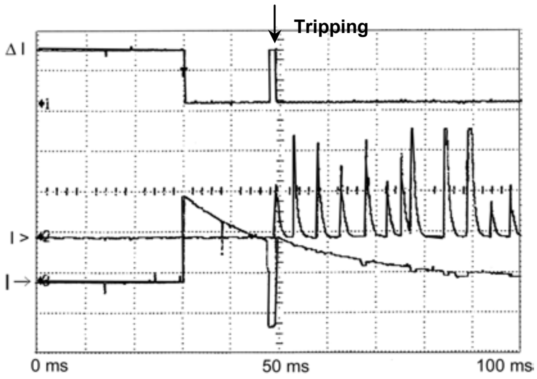
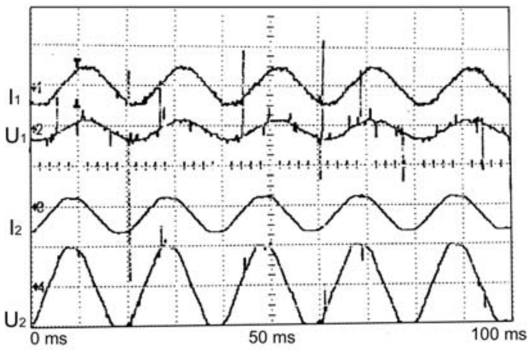


Fig. 2 Busbar protection operation initiated during disconnector switching operation.



Ch.1 - I_1 current from cable 110 kV,
Ch.2 - U_1 secondary voltage from module RWT80,
Ch.3 - I_2 current from transformer secondary 110/10 kV,
Ch.4 - U_2 voltage from transformer secondary 110/10 kV.

Fig. 3 Signals at the entrance in the measuring system (with superimposed HF interference).

It can be observed that HF interference is superimposed on 50 Hz frequency signal. Channel 2 represents voltage which the module sends as output signal in the measuring system. Channels 3 and 4 represent current and voltage from the secondary side of the power transformer.

On-site testing has demonstrated that disconnector switching operation can lead to the relay protection tripping.

III. MEASUREMENTS

Thorough measurements were conducted in order to determine magnitudes and frequencies of the transient voltages and currents in the secondary circuits [2].

Fig. 4 shows a one-line diagram of the 123 kV GIS testing configurations. During on-site EMC testing, applied voltage or current interference should not damage or put at risk normal operation of the equipment.

Transient enclosure voltage (TEV), induced impulse currents, transmitted voltages and currents in the secondary circuits were measured during disconnector switching operations located in the line feeder bay, at the following points (Fig. 5): enclosure at the point of GIS/cable junction and cable sheaths; ground straps; current transformer terminals; secondary circuits (differential protection control

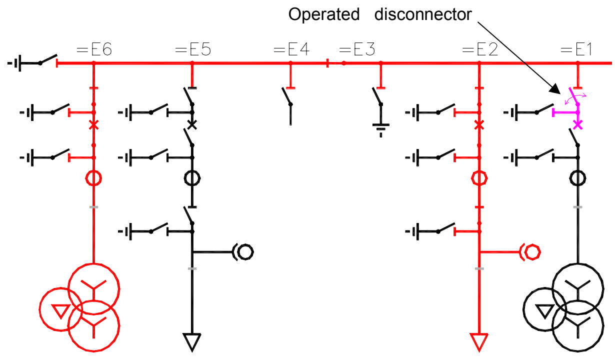


Fig. 4 One-line diagram of 123 kV GIS

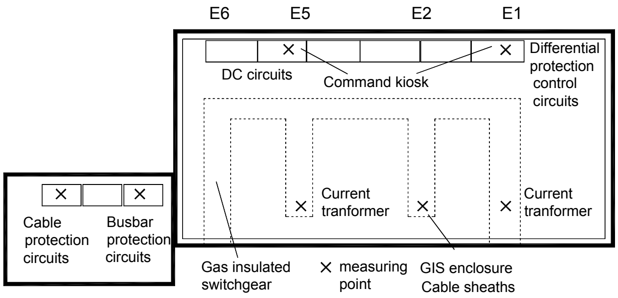


Fig. 5 Location of measuring points

circuits, busbar and cable protection circuits, and DC circuits).

A. External Transients at GIS/cable junction

During switching operation in the GIS, restrikes between contacts generate surges that propagate inside and outside the enclosure. Transients that appear on the outer side of the GIS cause transient enclosure potential rise (TEVR). Whole series of restrike sequences were recorded during disconnector closing and opening.

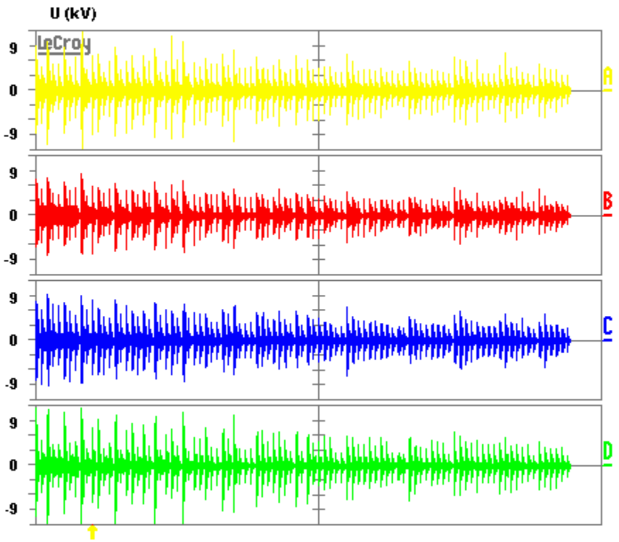
During measurements, more than a hundred repetitions of this phenomenon were recorded (Fig. 6). However, this number depends on the chosen trigger level, hence the actual number is even greater. It can be assumed that the duration of the whole process is more than 300 ms.

B. Transmitted Voltages and Currents in Protection Control Circuits

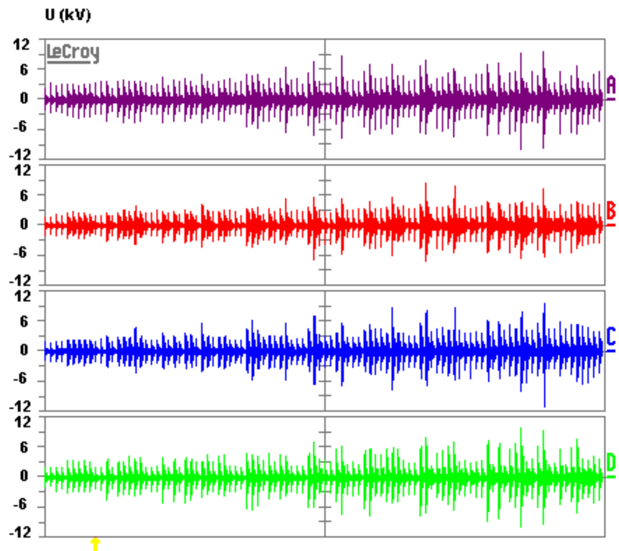
Impulse voltages and currents are transmitted in the measuring, protection and control circuits via conductive, inductive or capacitive coupling, and at the highest frequencies via radiative coupling (antenna effect) [3].

Fig. 7 shows typical a) voltage and b) current oscillograms recorded in current control circuits located in the busbar protection kiosk, caused by a single restrike (maximal measured voltage and current magnitudes at this location were 80 V and 20 A, respectively).

A wide band of frequencies can be observed in Fig. 7. However, the voltage oscillates with two dominant frequencies around 11 MHz and 48 MHz.

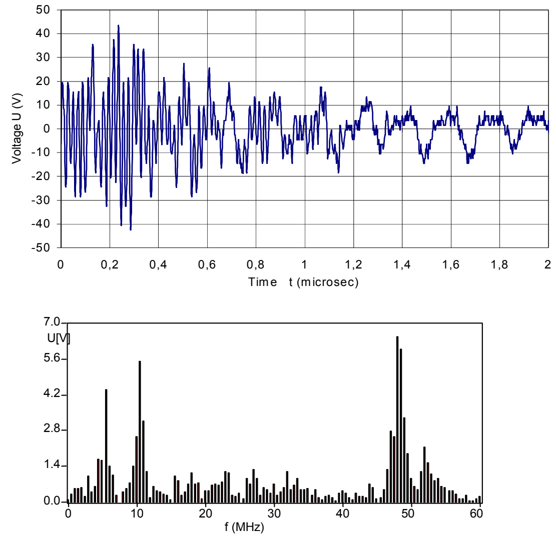


a) 95 samples, t = 260 ms

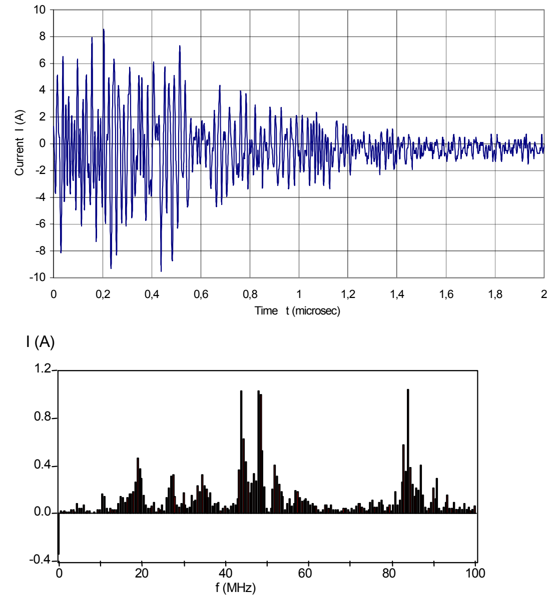


b) 100 samples, t = 234 ms

Fig. 6 External transient voltages at the GIS/cable junction (curve A) and on the cable sheaths (curves B, C and D) during disconnector a) closing b) opening



a)



b)

Fig. 7 a) Voltage and b) current during disconnector switching recorded in current control circuits located in busbar protection kiosks

Dominant frequencies observed on the current diagram are around 48 MHz and 86 MHz.

The entire disconnector switching operation, lasts a few hundred milliseconds. More than a hundred impulses with a duration of a few microseconds, are repeated with pauses of differnet durations in a range of milliseconds.

The overcurrent relay module takes into account RMS current value, so in some cases multiple repetition of the current impulses can be interpreted as a signal that led to busbar protection tripping.

C. Overview of Measurement Results

Measurement results have shown that in all cases high frequency voltages and currents appear, with a dominant frequency of 50 MHz occurring at different locations and with different magnitudes.

In some cases, currents had two dominant frequencies, one responding to the voltage frequency and the other twice as high.

Table I gives an overview of maximal transient voltages' and currents' magnitudes, with their corresponding dominant frequencies, measured at different locations.

According to standards IEC 801-4 [4] and IEC 17C 102 [5], testing procedures carried out on the secondary equipment have an acceptable disturbance level up to 2 kV.

All measured transients in the secondary circuits had magnitudes within the boundaries specified by the above mentioned standards.

Table I Maximal transient voltage and current magnitudes with dominant frequency(s).
U_N - voltage in normal operation, $\hat{U}$ - peak value of transient voltage, f_U - voltage dominant frequency(s),
I_N - current in normal operation, $\hat{I}$ - peak value of transient current, f_I - current dominant frequency(s).

Location	Comment	U_N [V]	$\hat{U}$ [V]	f_U [MHz]	I_N [A]	$\hat{I}$ [A]	f_I [MHz]
Enclosure		0	12800	20; 47	-	-	-
Cable sheath		0	14380	20; 47	-	-	-
Command kiosk	current circuits	0	400	-	-	-	-
	diff. busbar protection	0	240	23; 47	1	90	23; 47
	DC circuit 220V	$\pm$ 110	$\pm$ 80	23	-	-	-
Current transformer	bay E5	0	368	48	1	115	48; 90
	bay E1	0	228	50	1	105	50; 70
Busbar protection kiosk	voltage circuits	$100/\sqrt{3}$	76	3; 18	0	22	18
	current circuits	0	80.5	48	1	20.5	48; 86
	DC circuit 24 V	$\pm$ 12	$\pm$ 30	27; 52	-	-	-
Cable protect. kiosk	voltage circuits	$100/\sqrt{3}$	56	16	-	-	-

IV. Computer Simulations

Additionally, computer simulations were performed on the model, containing three phases in one encapsulation and taking into account mutual coupling between phases, with the help of the EMTP-ATP program.

Inner VFTO and transmitted voltages in the secondary circuits were calculated during disconnector switching operations, for the same substation layouts on which measurements were carried out (Fig. 4).

A. Applied Models

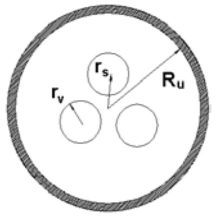
Bus ducts (Fig. 8) were represented as lossless distributed parameter transmission lines [6] with the following high-frequency surge impedance matrix, calculated with the support routine CABLE CONSTANTS in the EMTP-ATP program [7]:

$$Z_S = \begin{bmatrix} 105.6 & 18.8 & 18.8 \\ 18.8 & 105.6 & 18.8 \\ 18.8 & 18.8 & 105.6 \end{bmatrix} \quad [\Omega]$$

Electrical arc in the disconnector during sparking was simulated with its conductance-dependent parameters described with the Cassie and Mayr arc equation:

$$\frac{dg}{dt} = \frac{1}{\Theta(g)}\left(\frac{i_s^2}{P(g)} - g\right) \qquad (1)$$

where g is the arc conductance, i_s is the arc current, P is the arc cooling power and Θ is the arc thermal time constant.



$r_v = 0.04$ m,
$r_s = 0.144$ m
$R_u = 0.3$ m

Fig. 8 Bus duct cross-section

Parameters $P(g)$ and $\Theta(g)$ are conductance dependent. $P(g)$ is defined for two rates that correspond to the ignition and burning phase:

a) Ignition:

$$P_i = 1.015\ g^{0.827} \quad (\mathrm{MW}) \qquad (2)$$

b) Burning:

$$P_b = 15\ g^{2.5} \quad (\mathrm{MW}) \qquad (3)$$

The time constant Θ determines the rate of change with which the arc conductance obtains its stationary value. In the calculations a constant value of $\Theta(g) = 1\mu$s was assumed, because of its negligible influence on the very fast transients. Parameters P_i, P_b and Θ are selected as recommended in [8].

The power transformer was modeled, as proposed in [9] with the total equivalent capacitance:

$$C_T = C_e + C_b = \sqrt{C_g C_s} + C_b \qquad (4)$$

where C_s represents equivalent series capacitance of the winding, C_g is the shunt capacitance between winding to the grounded core and transformer tank, and C_b is capacitance of the terminal bushing. C_s and C_g were computed from the transformer geometry according to [10]. For the considered transformer with the nominal power of 40 MVA and with continuous disc winding, computed values were C_s = 66 pF and C_g = 3700 pF. The leakage inductance of the winding was 174 mH.

Inner transients are transmitted to the outer side of the GIS enclosure at the GIS/cable junction and at the gas to air bushings. The model of the gas to air bushing contains an ideal transformer that enables connection of three transmission lines: the bus duct inside enclosure, the enclosure outer side (surge impedance to ground) and an overhead wire, as shown in Fig.9. A similar approach was used for modeling of the GIS/cable junction.

The enclosure, ground straps and simplified earthing grid are modeled for calculation of TEV from their surge impedance and corresponding length [6].

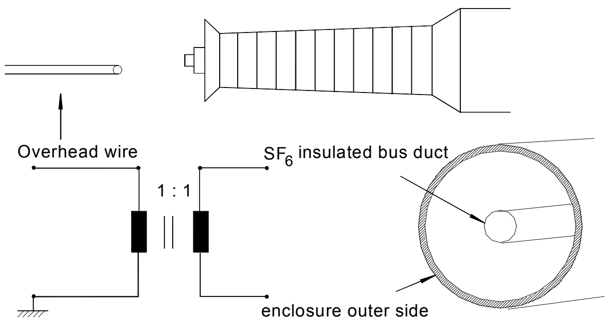


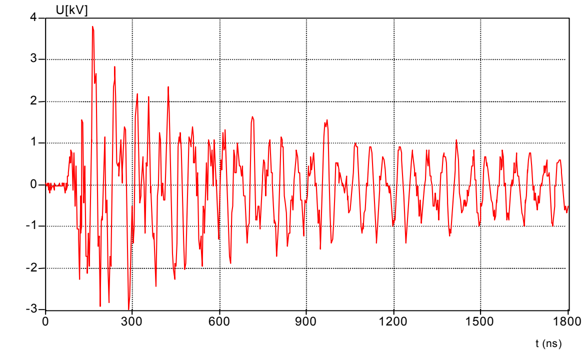
Fig. 9 Model of the gas to air bushings

Surge impedance for each enclosure section was calculated from its medium height above the ground and its outer radius.

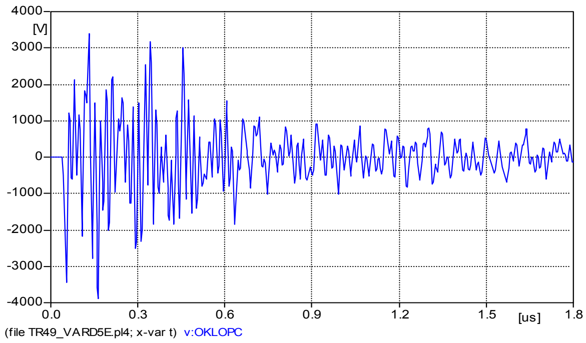
B. Calculation Results

Evaluation of calculated results for external transients has to take into account complexity of the model and unsymmetrical geometry of components outside the enclosure. Usually, for the substations that are already in operation it is difficult to obtain all necessary details for more accurate calculations.

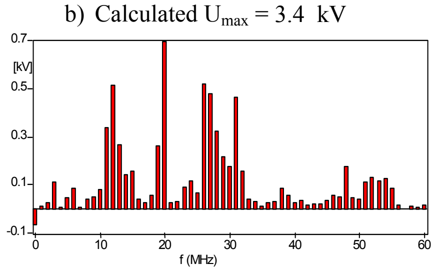
Measured and calculated results for the external transients were compared in the time and frequency domains (Fig.10 and Fig. 11). Results have shown that inner transients in this case do not place high dielectric stress on adjacent equipment and the transformers' insulation. However, due to their high frequency and multiple repetition in a short time period they are a source of disturbances to the secondary circuits.



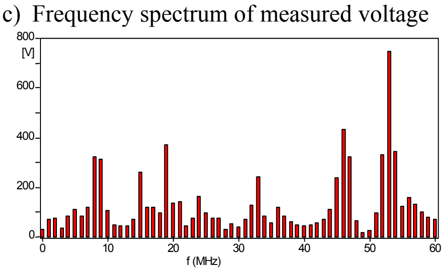
a) Measured U_{max} = 3.8 kV



b) Calculated U_{max} = 3.4 kV

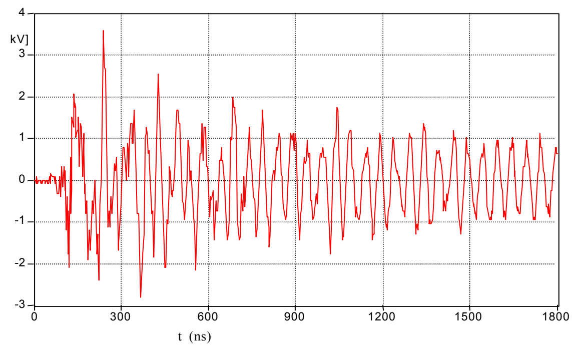


c) Frequency spectrum of measured voltage

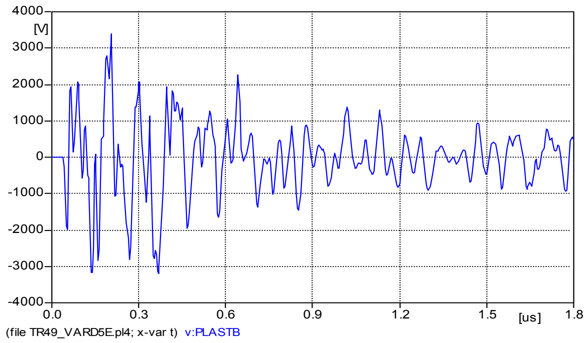


d) Frequency spectrum of calculated voltage

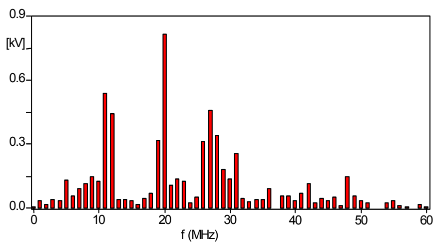
Fig. 10 Transient enclosure voltage



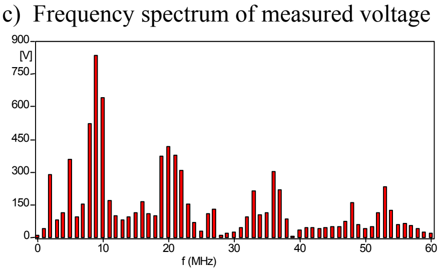
a) Measured U_{max} = 3.6 kV



b) Calculated U_{max} = 3.4 kV



c) Frequency spectrum of measured voltage



d) Frequency spectrum of calculated voltage

Fig. 11 Transient voltage on cable sheat

Computer simulations can be used for assessment of the possible transient level and their frequency spectrum that can occur in the GIS.

The frequency spectrum of calculated transient enclosure voltage differs somewhat from that measured, although a dominant frequency of around 50 MHz is often measured in other cases (Table I). Arrangement and modeling of the ground straps has a considerable influence on the calculation of the external transients, and especially on the frequency spectrum, due to the wave reflections at short distances. It can be observed that the transients are strongly damped in both cases.

VI. CONCLUSIONS

EMC problems due to disconnector switching have been analyzed on the existing 123 kV GIS.

Measurements were conducted on some characteristic points in GIS, in order to determine the level of the EM disturbances.

Measurement results have shown that in all case studies, high frequency voltages and currents occur, with a dominant frequency of 50 MHz, regardless of very different disturbance magnitudes occurring in different locations (ranging from 14.4 kV in one case to 30 V in another).

Malfunctioning of the busbar protection during disconnector switching in the GIS has been thoroughly studied and measurements have established that all three necessary criteria for busbar protection operation are fulfilled in this case. Multiple repetition of the current impulses can cause busbar protection tripping due to integration of these input signals in the overcurrent relay module.

Measured overvoltages and currents have lower magnitudes than allowed by the standards. In general, they should not place dielectric stress on the insulation or cause the secondary equipment to malfunction.

However, busbar protection malfunction has occurred during on-site testing, which demonstrates a need for continuous monitoring of the transient overvoltages and current levels in the secondary circuits. In the GIS operation continuous monitoring of the HV equipment's influence on the secondary equipment and implementation of some precautionary protection measures are recommended.

Attention should be focused on the implementation of protection measures, electromagnetic disturbance mitigation methods and on site EMC equipment testing.

Comparison of the external transients computer simulations with field measurements showed that calculations could be used for assessment of the overvoltage level that may occur in the GIS.

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