The measurement of fast transients during shunt reactors 420 kV switching using electric field sensors

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***Abstract*- Shunt reactor switching is one of the most common switching manipulations in transmission system operation. The insulation system of shunt reactors is more stressed by switching impulses than other substation equipment for that reason. So there is important to perform switching without additional phenomena which can create worse conditions of the insulation stress. These phenomena can be C.B. re-ignition during shunt reactor switching-off, C.B. re-ignition when switching-on. The diagnostic measurements on 420 kV reactors based on overvoltage measurement were performed in two substations in the Czech Republic in years 2013-2014. The overvoltage detection was made using special e-field sensors developed in EGU HV Laboratory a.s. and FEE CTU in Prague. The accuracy of the measurement is warranted in bandwidth 5 Hz – 5 MHz. The results of the measurement are presented in the article.**

***Keywords*: reactor switching, overvoltage measurement, e-field sensors, reactor insulation stress, switching controllers, circuit breaker failures**

I. Introduction

Shunt compensations reactors are the most common switching equipment in substations of transmission system. The insulation system of shunt reactors is more stressed by switching impulses than other substation equipment for that reason. There is necessary to perform switching without additional insulation stress. This is extra important in case of the reactors directly connected to transmission voltage (245 kV, 420 kV etc.). Additional insulation stress is usually caused by phenomena like circuit breaker C.B. re-ignitions (re-ignitions) during shunt reactor switching-off, C.B. re-ignition when the reactor is switching-on.

The best condition for shunt reactors switching can be arranged by usage of controlled switching with controlled switching automatic device. That is absolutely true if the device is tuned properly. Any detuning of the control switching can lead to worse condition of reactor insulation stress.

There were performed some diagnostic overvoltage measurements of switching 420 kV reactors in two substations in Czech Republic within the years 2013-2014 with following aims:

- Investigation the proper operation of the circuit breakers switching the reactor (without C.B. re-ignitions)
- Evaluation of the controlled switching automatic
- Finding out the reason of the 420 kV reactor damage in the year 2013

II. Sensors for Overvoltage Measurement

Traditional method for high voltage measurement is usage of capacitor or resistor dividers which have galvanic connection with high voltage equipment. This is still commonly in operation in high voltage laboratories. This way of high voltage measurement is quite unsuitable for diagnostic measurement of high voltage equipment on-site in substations of transmission systems. The modern on-site diagnostic measurement technologies meet the following requirements:

- Diagnostic measurement system must be impacting operation equipment in the minimum (no) way.
- The installation of the diagnostic measurement doesn't interrupt the operation of any part of the high voltage system.
- The time of the measurement is as short as possible.
- The costs of the diagnostic are as low as possible

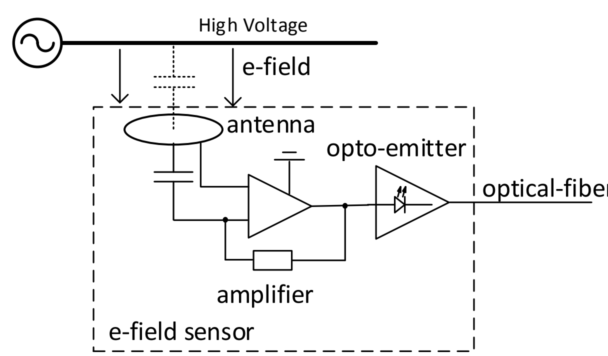

Fig. 1 Principal scheme of the e-field sensor for overvoltage measurement

These above mentioned requirements were challenge for development in R&D department of EGU-HV Laboratory a.s. At the present time the third generation of e-field sensor exists for overvoltage measurement as a result of the development.

The principal scheme of the e-field sensor is shown on Figure 1. The fundament of the sensor is the antenna which creates a major part of capacity of the divider. Discrete capacitor is the second part of the divider and its capacitance can influence the sensor sensitivity. The signal from this

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Fig. 2, E-field sensor (left) and 3-channel receiver unit with amplifiers and offset tuning

antenna is processed by amplifier with high input impedance and wide bandwidth of the signal amplification. Electrical signal is converted to optical one and then transmitted via optical fiber to the receiver unit. This unit is placed in shielding box in the measuring car and power supplied from UPS. Perfect protection against electromagnetic interference is guaranteed so there is no additional noise. The signal from the receiver unit is digitized and stored at the disk of the transient recorder.

The entire installation of the measurement diagnostic system is very easy and it takes about an hour. No operation interruption in substation is necessary. The e-field sensor is arranged at the insulating rod (Figure 3).

Fig. 3 E-field sensor at the 420 kV reactor

III. Measured Data Post-Processing

The insulation rod enables to be put near the sensor into measured high voltage point. The position of the sensor is very important because optimal position can eliminate interference of e-field to measurement signal (phase voltage) from other phases. The example of measured transients without interphase interference is in Figure 4. No other data post-processing is necessary in this case.

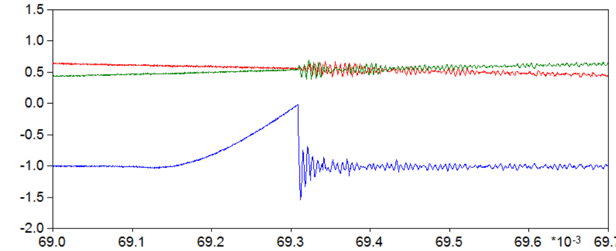


Fig. 4 Transient during switching-off 420 kV reactor with optimal positioning of the sensors, what can eliminate interphase interference of the e-field

The optimal positioning of the sensor isn't possible due to substation equipment layout sometimes. In that case the interference of the e-field from the other phases can't be fully eliminated. This influence isn't so important for the investigation of a character of the phenomena but if there is a requirement to evaluate values of the voltages data the post-processing have to be done.

The aim of the data post-processing is to transform measured voltages Vm_a, Vm_b, Vm_c to real voltages VR_a, VR_b, VR_c. The relationship of the interphase influence can be relatively easily investigated from voltage step *Vsmaa*, *Vsmab*,…. The meaning of the step voltages *Vsmaa*, *Vsmab*, etc. is clearly shown in Figure 5. There is demonstrated that the voltage step at phase B *Vsmbb* has the interfering response at phase C *Vmcc* and the voltage step at phase C (*Vsmbb)* has the interfering response at phase B (*Vsmcb).*

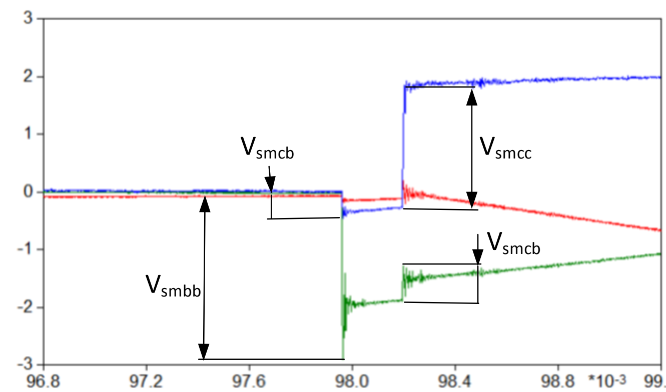


Fig. 5 Transient during switching-on 420 kV reactor with interphase interference of the e-field

For step voltages we can write the following equation (1)

$$\begin{bmatrix} Vsmaa & Vsmab & Vsmac \\ Vsmba & Vsmbb & Vsmbc \\ Vsmca & Vsmcb & Vsmcc \end{bmatrix} = \begin{bmatrix} Kaa & Kab & Kac \\ Kba & Kbb & Kbc \\ Kca & Kcb & Kcc \end{bmatrix} \begin{bmatrix} VsRa \\ VsRb \\ VsRc \end{bmatrix} \quad (1)$$

For the determination of real voltages we must calculate coefficients

Kaa, Kab, Kac … which are in the matrix K_{ij}. These coefficients must involve

a) the ratio of amplitudes
b) the shift between phases

The ratio of amplitudes responds the ratio of the steps voltages (2).

$$\begin{bmatrix} 1 & Kab/Kbb & Kac/Kcc \\ Kba/Kaa & 1 & Kbc/Kcc \\ Kca/Kaa & Kcb/Kbb & 1 \end{bmatrix} =$$

$$= \begin{bmatrix} 1 & Vsmab/Vsmbb & Vsmac/Vsmcc \\ Vsmba/Vsmaa & 1 & Vsmbc/Vsmcc \\ Vsmca/Vsmaa & Vsmcb/Vsmbb & 1 \end{bmatrix} \quad (2)$$

The simplest way how to find out the phase shift is iterated phase shift of measured signals to fixed signal with phase angle 120°. This iteration process changes the matrix coefficients to get result matrix K_{ij} in time when iteration is completed. This iteration process was performed in semi-automatic way when authors were changing the coefficients with comparison graph representation of fixed and measured signal. The automatic way of iteration is possible too with a bit effort to programming work.

The matrix can be then inverted and real voltages evaluated by the equation (3).

$$VR_i = \sum K^{-1}_{ij}\, Vm_j \quad (3)$$

IV. Results of the Measurement of Reactor Switching Transients with Non-Synchronized Switching

As an object of the measurement was selected a shunt reactor 420 kV switched with circuit breaker without controlled switching. There were noticed phenomena like re-ignition in former times. The aim of that measurement was to confirm re-ignition appearance, investigate overvoltage and reactor insulation stress.

The reactor switching on/off was repeated 8 times for statistical reasons. Each manipulation was sensed with e-field sensor and digitized with transient record sample rate 5 MSample/s. The sensor layout in this case was optimal so the interphase interference was very small and no data post-processing was done.

A. Switching-on

Without using the switching controller the value of overvoltage has probabilistic character. The circuit breaker re-ignition is caused by early ignition of the arc before C.B. contact junction. This can be an indication of reducing of the insulating capability of the space in C.B. chamber or C.B. contact erosion. An occurrence of pre-ignitions mainly depends on 50 Hz instantaneous voltage value, the most probability of the pre-ignition is in time of voltage maximum (amplitude). If there are pre-ignition with voltage lower than amplitude it is a confirmation of the bad state of the circuit breaker (Figure 6 – pre-ignition L1).

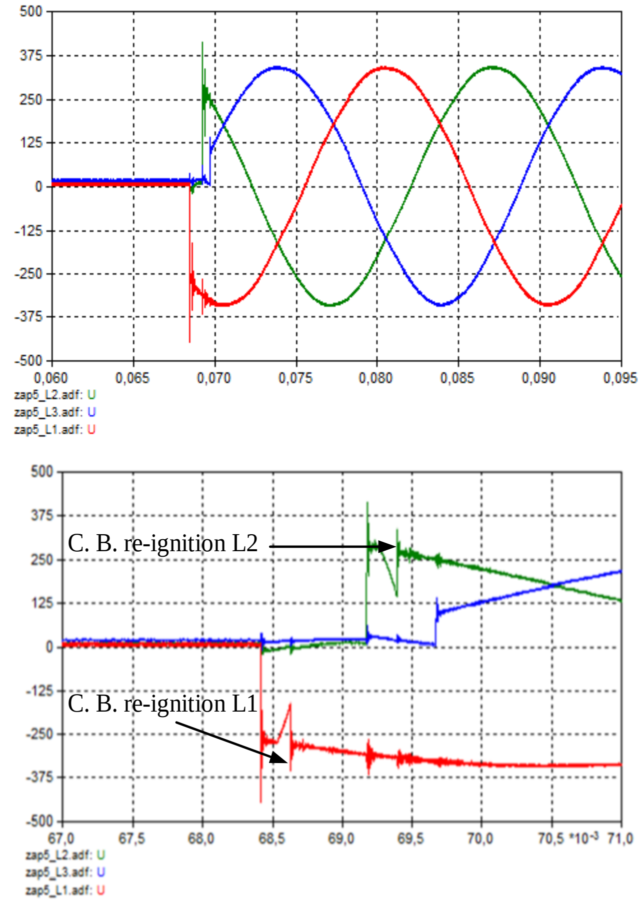


Fig. 6 Reactor switching-on with C.B. re-ignition

The non-standard state of the C.B. in phase L1 was confirmed in test case No.7, when the double re-ignition was recorded (See Figure 7).

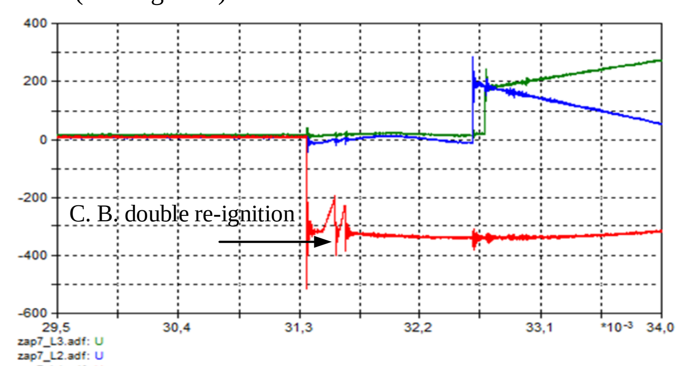


Fig. 7 Reactor switching-on with double C.B. re-ignition

B. Switching-off (de-energizing)

Switching-off the reactor is more significant from the point of view of overvoltage value when re-ignition occurs. Re-ignition happens if the C.B. recovery voltage rises more rapidly than electric strength of the insulation between C.B. contacts. The value of overvoltage of the re-ignition depends on:

1. Value of the voltage of LC self-oscillation of the reactor
2. 50 Hz instantaneous voltage value in network, U_f
3. Voltage difference between U_f and maximum value of LC oscillations

The re-ignitions were observed in five cases from the total of seven recorded switching-off tests (one test case wasn't recorded).

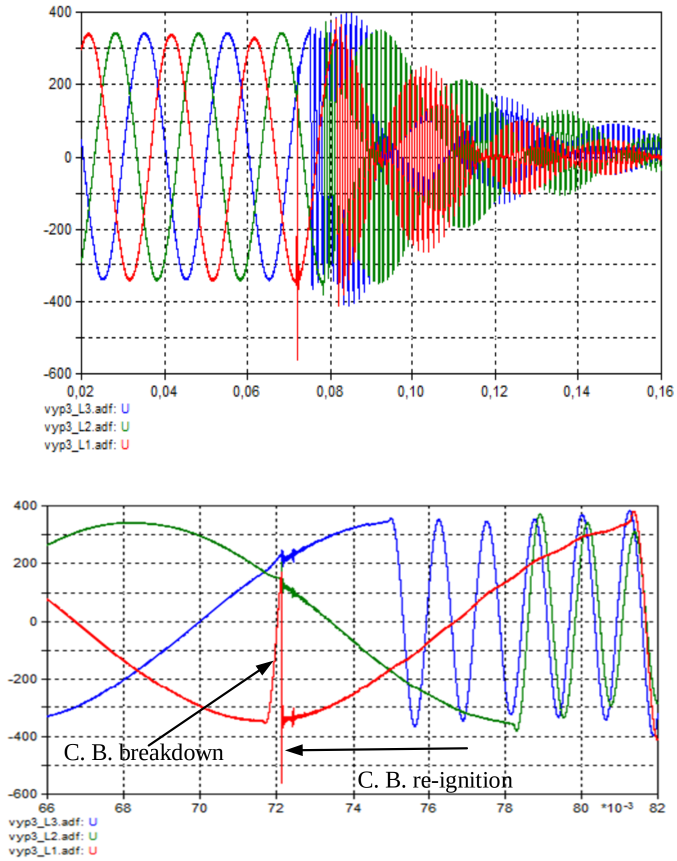
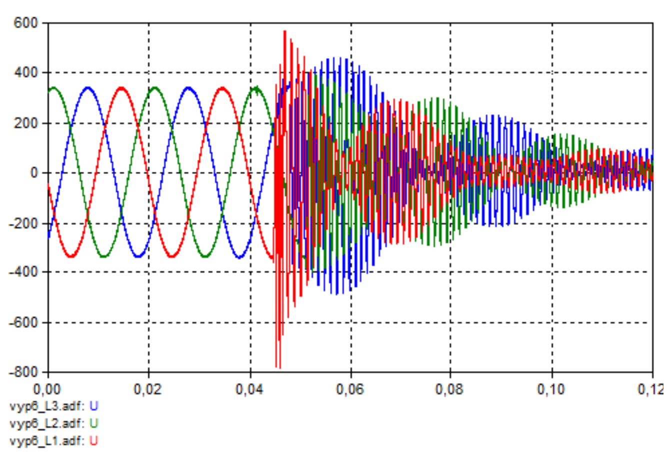


Fig. 8 Reactor de-energizing with C.B. re-ignition

The record with re-ignition is presented in Figure 8. The occurrence of multiply re-ignitions is possible in the case of very poor insulation conditions. We present such case of phenomenon when four times re-ignition was recorded in Figure 9. It confirms the observation of re-ignitions in phase L1 when reactor was switched-off.



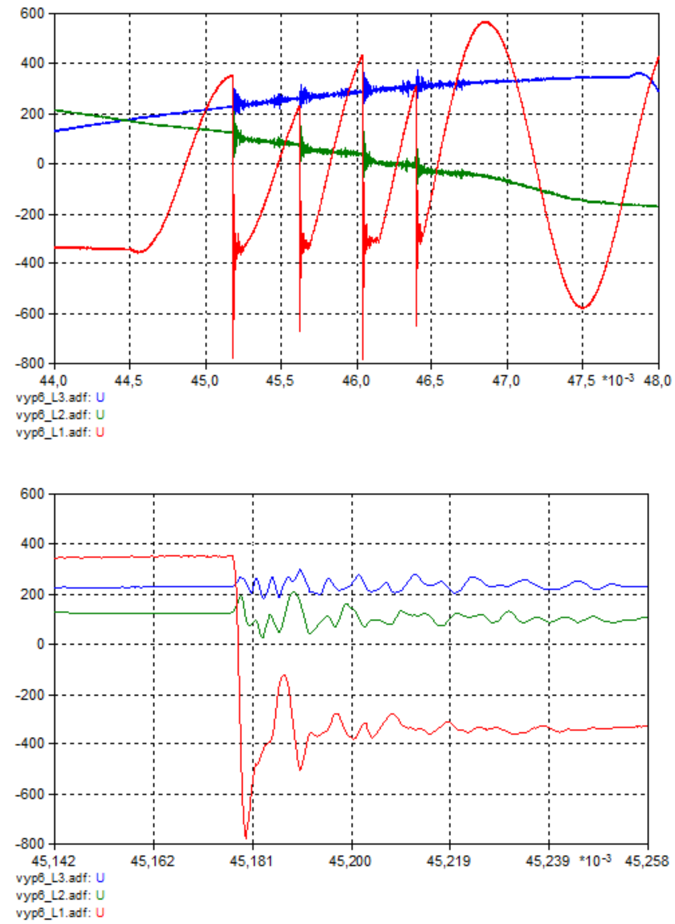


Fig. 9 Reactor de-energizing with C.B. multiply re-ignitions

The detailed view of the re-ignition waveform indicates clearly the voltage stress of the reactor insulation (sensor was installed closer to the reactor bushing-Figure 3). This type of the stress can be dangerous for reactor winding for its very fast steepness and voltage high value. The surge arrester performance depends on the distance from reactor bushing.

V. Results of the Measurement of Reactor Switching Transients with Using Controlled Switching

Controlled switching of the reactor supports de-energizing to ensure re-ignition free behavior. In addition, controlled closing also serves as a useful method for minimizing inrush currents. The main task of the control is the optimal tuning of the control automatic.

Reactor-energizing: From the pre-ignition occurrence point of view it is important to minimize the voltage when switching-on. From another point of view the minimizing of inrush currents needs energizing at voltage maximum. The measurement should investigate overvoltage and reactor insulation stress in case of minimizing inrush current.

Reactor de-energizing: Controllers for shunt reactor circuit breakers are set in such a manner that contact separation is made in sufficient timing advance before current crossing zero while final interruption is performed. The contact gap is too wide at that moment so the re-ignition development isn`t possible. The measurement should confirm the proper tuning of the control automatic.

There were performed 8 switching on/off manipulations during the test (October 2014). Between 4th and 5th test series the synchronizing automatic was deactivated with purpose to check C.B. performance.

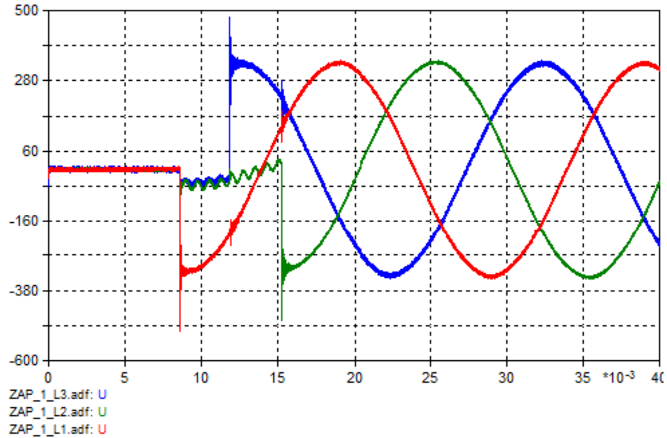


Fig. 10 Reactor energizing with C.B. control of synchronizing

The waveforms of voltages from shunt reactor switching-on with Switchsync activated are in Figure 10. It can be observed that the junction was at the amplitude of the voltage during energizing contact. Inrush current value doesn't exceed 300 A (measured with fault recorders). Re-ignitions were not detected in all testing cases (No.1-No.4). The maximum overvoltage coefficient was 1,6 but the sensor layout was not so optimal, interphase interference can be marked and the value of the overvoltage coefficient is a bit approximated. The rate of the interphase interference can be simply found out in the measured waveforms in case of step changes of the measured voltage. The interfaced voltage steps can be observed similarly like it is explained in Figure 5.

There are recorded waveforms of voltages from shunt reactor de-energizing with switchsync activated in Figures 10. In all of the testing cases (No.1-No.4) re-ignitions were not detected. The repeated correct performance of synchronizing de-energizing was confirmed.

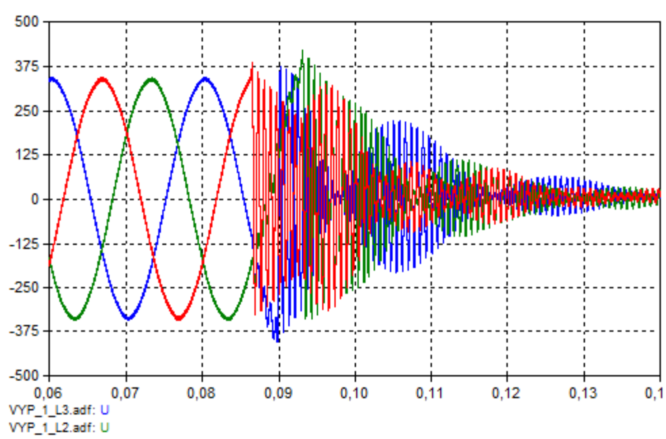


Fig. 11 Reactor de-energizing with C.B. control of synchronizing

For test cases No5-No8 were synchronizing automatic deactivated. The inrush current of the reactor so increased up to 1200 A (Figure 12) but no re-ignition was observed. One case of re-ignition was noticed in case of the reactor de-energizing (Figure 11).

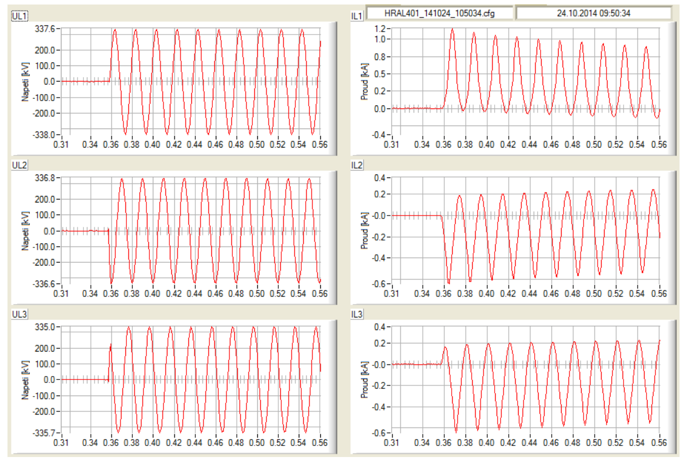


Fig. 12 Reactor energizing without C.B. control of synchronizing recorded with fault recorder. Inrush current are in the right column

VI. Conclusion

The paper presented the very effective method for on-site overvoltage measurement on substation high voltage equipment using e-field sensors. The main advantage of the method is a minimal impact into continuous operation of transmission system and easy way of the measurement system installation.

The accuracy and measurement uncertainty in practical way is covered by simple calibration process with two steps. The first step is the response checking of the sensor to impulse voltage (150 ns steepness) before measurement. The second step is calibration of the measurement signal via known system steady state 50 Hz voltage.

The measurement of two 420 kV reactors switching was performed using e-field sensors. In the first case the results of the measurement made a diagnostic of the reactor C.B. and there was detected a serious C.B. failure. The reactor insulation voltage stress was evaluated.

In the second case the performance of the synchronizing switching of the reactor C.B. was checked. No serious problems were observed and availability of such way of switching was confirmed.

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