Switching Surges in Transformer Provoked by Sequential Tripping of Circuit Breakers

I. Uglešić, I. Ivanković, V. Milardić

Abstract: A study of switching surges in a 400/110 kV substation was carried out in order to detect the causes of severe damage to the power transformer, which happened after a busbar fault. The busbar protection generated tripping signals for several circuit breakers and after their sequential tripping, the surge arresters installed on the 10.5 kV stabilizing windings inside the transformer were destroyed. The computer simulations were carried out on an appropriate model, which was developed for the study. The comparison between the recorded and computed fault currents showed good correspondence. Overvoltages of small magnitudes occurred on all three voltage levels: 400 kV, 110 kV and 10.5 kV. The energy generated by overvoltages was below the nominal value of the absorption capacity of the surge arrester installed on the stabilizing windings and the inspection of the arresters showed their defective characteristics.

Keywords: Transformer, Switchyard, Switching, Overvoltage, Computation, Fault, Protection.

I. Introduction

A power transformer represents the most valuable component in the high voltage switchyard and special attention should be paid to its relay and overvoltage protection.

The relay protection of a power transformer (and of a busbar in a switchyard) must comply with the performance requirements of fast operating times for all type of faults, of security for external faults, of security during normal switching conditions, of security with subsidence current present after clearing an external fault, and of minimum delay for identifying faults. All of these requirements must be achieved with minimum current transformer performance requirements [1]. On the other hand, the efficient overvoltage protection of a power transformer requires surge arresters placed as close as possible to the transformer terminals. An integrated arrester system is a very effective protection in which arresters are assembled in oil inside the transformer tank. Such solutions have been employed mainly on medium voltage transformers [2] or on the tertiary windings of power transformers.

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The paper deals with the study of a fault in the switchyard, which was accompanied by the power transformer failure. An effort was undertaken to simulate the development of the fault during its initiation, duration and clearing. Data generated by such simulations of model power systems can be used in the investigations of the influence of power system parameters [3] on the relay protection operation and for check of the relay response to a very complex fault. Additionally the post mortem analyses of the simulation results can help to find out the possible electrical or thermal conditions that could give rise to the transformer failure.

II. Faults in Switchyard and Transformer

A power transformer failure provoked by a busbar fault in the 110 kV switchyard. The fault happened in the switchyard on the 110 kV busbar and it was initiated by a breaker failure in the zone of busbar relay protection. An air-bushing exploded on a 110 kV breaker of the line 7, (Fault 1 in Fig. 1). Operating status at that time was normal; two busbar systems were connected with the bay coupler breaker. Busbar relay protection switched off the faulty busbar system. In such conditions the breakers, on the 110 kV and 400 kV voltage side, switched off the transformer. Altogether, seven circuit breakers on 110 kV voltage level were switched off and one on 400 kV voltage level. After fault clearance the failure of the power transformer 300 MVA with the ratio 400/110/10.5 kV was established (Fault 2 in Fig. 1). The transformer monitoring system indicated a great build-up of gases in the oil and after the factory inspection, severe damage of all active transformer parts was found. The transformer core and coils were deformed at a few points. Nonlinear ZnO-blocks in stabilizing windings were also completely destroyed. Arcing between two phases of 400 kV coils was also identified by inspection.

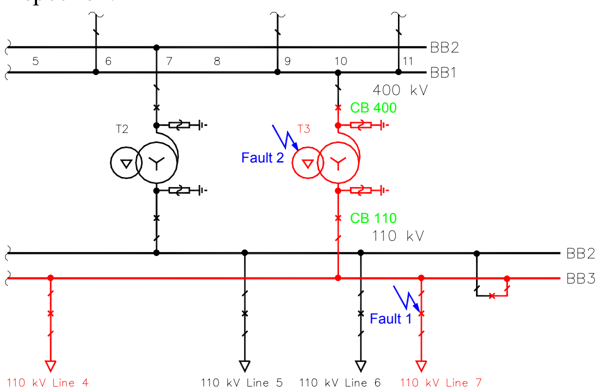

Fig. 1. Part of the 400/110 kV substation

III. Simulation of Switching Operations

The investigation was focused on possible internal overvoltages for the power transformer that could be caused by sequential tripping of circuit breakers. The switching-off operation of several circuit breakers (of different types and voltage levels) was studied in a time interval of some tens of milliseconds.

The computer simulations were carried out, with the intention of preventing reoccurrence of transformer damage in future. Special attention was dedicated to selection and evaluation of suitable model for elements in the simulation: power transformers, circuit breakers, surge arresters, overhead lines and equivalent high voltage network. Using computer simulations was an attempt to conclude what was the cause of the transformer damage: very high switching overvoltages as a consequence of consecutive switching-off a number of circuit breakers, lack of adequate surge protection or low dielectric strength of transformer insulation. Overvoltages were observed on all three voltage levels of the transformer.

The fault studied was accompanied by a large short circuit current and modeling of the circuit breaker's electrical arc was an important item in all cases. The short circuit current flows through the hot arc until it crosses natural zero. In this way chopping overvoltages are not possible while interrupting short circuit currents. The interaction between the electrical networks on the arc can be significant and in most cases it finishes with a relatively natural current drop to zero. The model of the dynamic behavior of an electric arc is developed in the study according to the Schwarz/Avdonin equation [4].

A general model of the power transformer, when calculating switching overvoltages in the frequency range of 50 Hz – 20 kHz comprises, besides linear R, L, C elements, the nonlinear inductance of the core, whose influence should be taken into consideration when the eddy currents hinder the magnetic flux from passing through the core. This effect can already appear with frequencies of 3-5 kHz.

The transformer model applied in the ATP simulation is depicted in Fig. 2. The supporting program BCTRAN has been used to derive [R], [L] of a three-phase transformer, and impedances are calculated from nominal data of short circuit and open circuit tests.

Equivalent capacitances are added to the transformer terminals in order to take into account the capacitive transfer of surges.

The modeling of the non-linear ferromagnetic inductance, representing the iron core of the transformer, is usually limited by the small number of available points measured in the open circuit test. This is because data given by manufacturers often contain only a few points of the current-voltage nonlinear curve of the transformer. Usually these points are insufficient for modeling the curve in the area of deep saturation. On the other hand a relatively good approximation which is achieved by the use of the inductance L_m which represents the asymptotic slope of the non-linear curve of the transformer magnetizing in the saturation area.

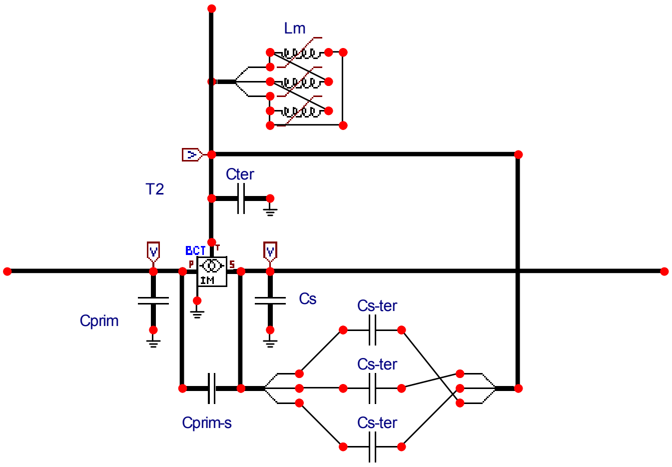

Fig. 2. Transformer model applied in EMTP-ATP

The asymptotic values of this inductance for autotransformer are most often calculated from the relations:

$$L_m = (4\text{-}5)L_K \tag{1}$$

Where L_K is the short circuit inductance obtained from the short-circuit test. Calculations conducted with the piece-wise linearized nonlinear curve showed good correspondence with the measurement [5].

In the EMTP-ATP program the branch with the nonlinear ferromagnetic inductance of the transformer can be modeled by using the nonlinear current-dependent inductor *Type-98*, which is externally connected to the stabilizing windings. This model requires the instantaneous values of the non-linear curve current-flux, Fig. 3. Therefore the starting RMS values of the current-voltage curve should be converted by special mathematical procedure to instantaneous values.

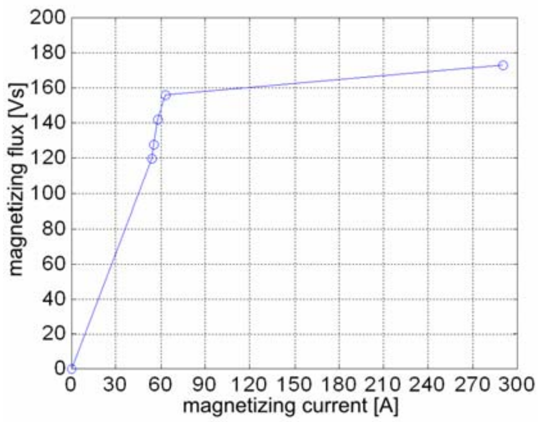

Fig. 3. Nonlinear magnetizing curve of transformer

A. *Short circuit currents in the switchyard*

Transformer differential relay protection was activated by a fault that happened in the substation and the currents taken by the disturbance recorder are shown in Fig. 4. and Fig. 5. The fault clearance times were short; the fault lasted less than 85 ms in the 110 kV switchyard (Fig. 4) and it was cleared after

120 ms by the 400 kV circuit breaker (Fig. 5).

This dynamic sequence of events was simulated on the computational model with the aim of reconstructing the transients provoked by the fault and to calculate voltages and currents during transient processes in the switchyard and inside the power transformer. The main goal of the investigation was to find out possible overvoltages that can initiate a fault of transformer insulation.

Fig. 4 and Fig. 5 present currents captured by the disturbance recorder and computed on the model.

The tripping took place first on the 110 kV side of the power transformer, as it can be seen in Fig. 4. Transformer 110 kV circuit-breaker was opened after 4.5 periods of 50 Hz (Fig. 4), and the same time was chosen in the computation. The circuit-breaker on the 400 kV side was slower and it switched-off afterwards. The current I_{L3} in Fig.4 does not fall to zero immediately, but in reality the circuit breaker had successfully opened the contact and it was estimated that this part of the current recording is false due to the saturations in the current transformer.

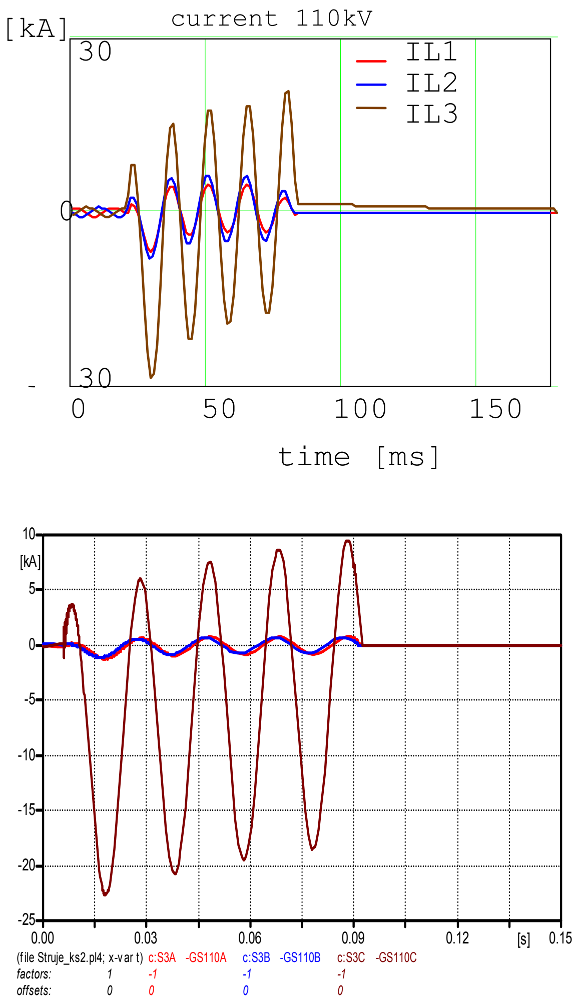

Fig. 4. Recorded and computed currents on 110 kV side of transformer

The internal transformer fault happened in the last stage of opening both 110 kV and 400 kV transformer breakers (yellow box in Fig. 5.). Transformer 400 kV circuit breaker was opened after 6 periods of 50 Hz (Fig. 5.). The fault on the stabilizing winding of the transformer caused a sudden rise of the currents (yellow boxes in Fig. 5.). Then the currents exceeded the nominal value on the 400 kV side of the power transformer. The internal fault started at the stabilizing winding and it was a fast evolving fault, which finished like a three phase fault. The recorded currents in Fig. 5 did not fall to zero, but in reality the circuit breaker had successfully opened the contact and it was estimated that this part of the current recording is false due to recorder inaccuracy.

A big impact on the initial value of the short circuit current is caused by a DC component, which strongly depends on the time instant of the fault's initiation. The correspondence between the recorded and computed currents is satisfactory.

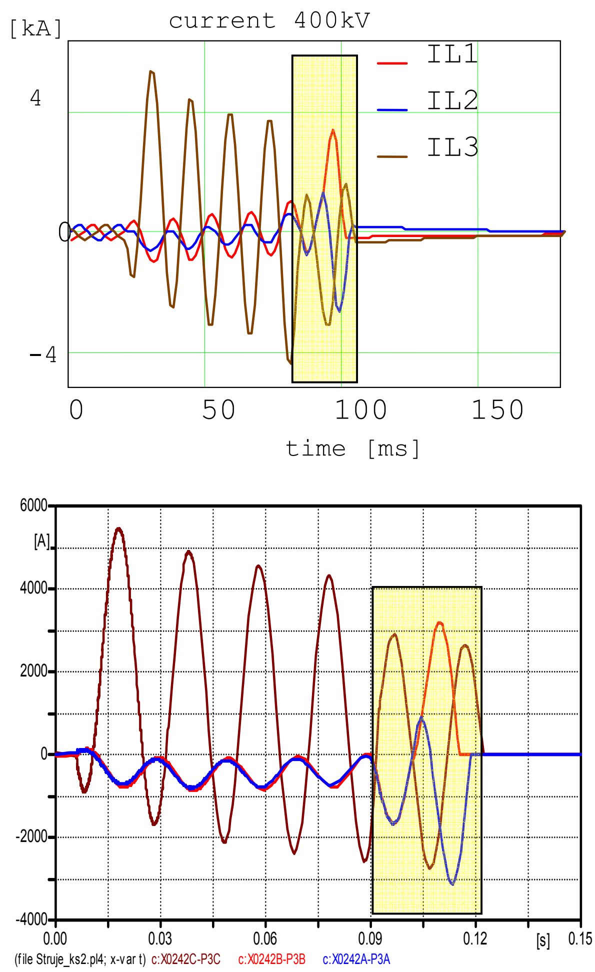

Fig. 5. Recorded and computed currents on 400 kV side of transformer

B. Overvoltages provoked by fault

The main focus and effort was put on the sequential tripping of circuit breakers. In those circumstances the occurrences accompanying the fault in the switchyard were examined, simulated and analysed in order to calculate the maximum overvoltages that can appear on the power transformer. Severe internal overvoltages may arise between adjacent coils of high voltage windings in switching condition involving current chopping and multiple reignition phenomena [6].

The overvoltages are calculated on all three voltage sides of the transformer for the sequential tripping of six 110 kV line circuit breakers and one 400 kV transformer breaker.

Fig. 6. depicts voltages on 110 kV side of transformer during the fault at 110 kV switchyard. The maximal computed overvoltage at 110 kV side reached a very moderate value of 148 kV (Fig. 6.), which was caused by opening of the 110 kV circuit breaker during the one phase fault in 110 kV switchyard (blue line).

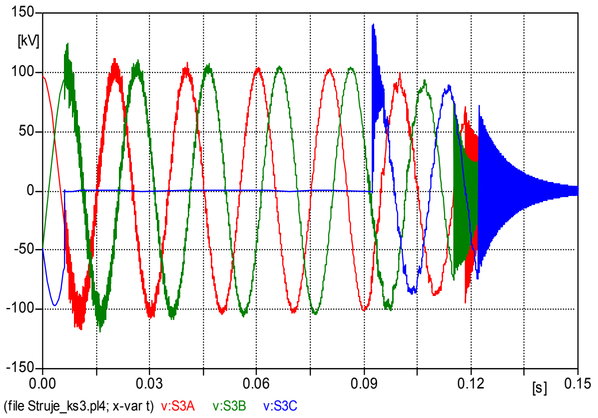

Fig. 6. Voltages on 110 kV side of transformer

Fig. 7. depicts transient voltages on the 400 kV side for the same case, and no overvoltages could be noticed. The computation result shows how the 400 kV voltage (blue line) decreased during the initial one-phase fault at 110 kV switchyard. After the relay had tripped on the 400 kV transformer side, all voltages were oscillatory falling to zero.

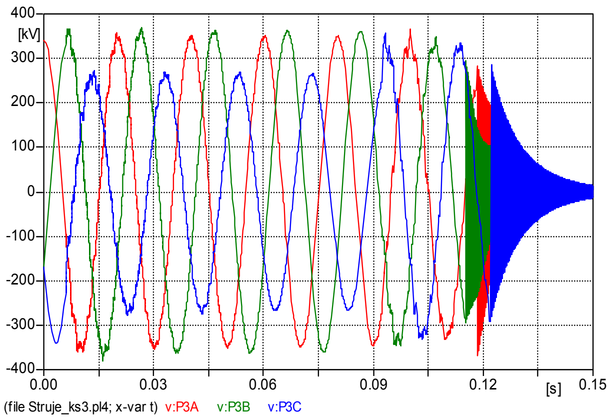

Fig. 7. Voltages on 400 kV side of transformer

The results of computation did not give significant values of phase-to-phase (Fig. 8.) and phase-to-ground (Fig. 9.) overvoltages at stabilizing winding. Small voltage peak can be noticed only at the moment of the internal fault ignition (Fig. 10).

Phenomena of resonance or ferroresonance can appear in some critical configurations in the network that could be excited by 50 Hz voltage. Resonance can occur in an oscillatory circuit, which has coupling to source of electric energy with frequency equal or near to frequency of free oscillation of the circuit. On the basis of recorded current oscillograms on 110 kV and 400 kV side of the transformer it was concluded that all circuit-breakers in all three phases have successfully switched-off and that the transformer was completely separated from the source of electric energy some hundred milliseconds after the fault initiation. Recorded currents in the switchyard have typical shapes of short circuit currents and they do no reveal possible resonance phenomena.

Therefore it is supposed that the resonance did not appear in the studied case.

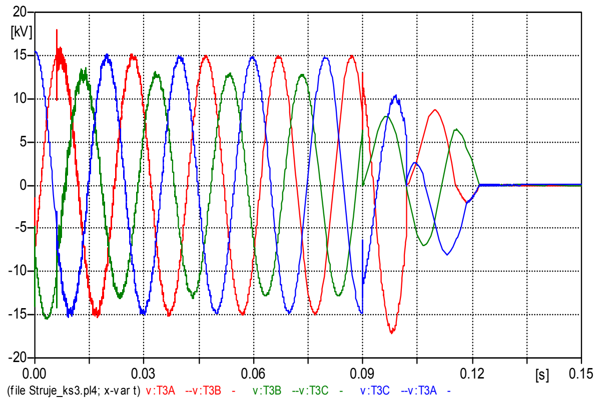

Fig. 8. Phase-to-phase voltages on 10.5 kV side of transformer

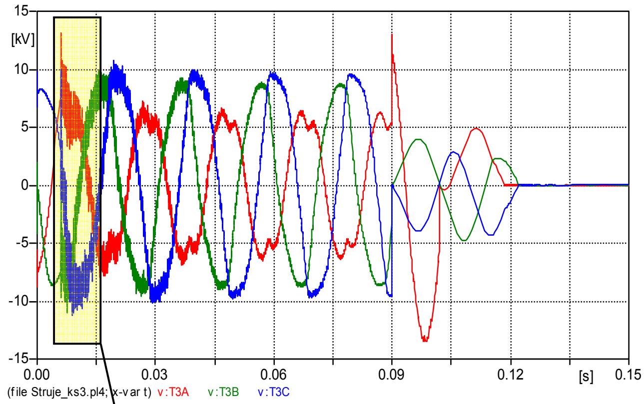

Fig. 9. Phase-to-ground voltages on 10.5 kV side of transformer,

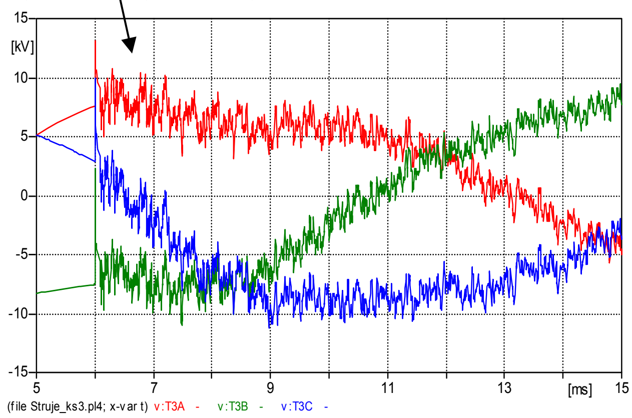

Fig. 10. Detail, phase-to-ground voltages on 10.5 kV side of transformer

IV. SURGE ARRESTER FAULT INSIDE TRANSFORMER

The purpose of the integrated arrester system on the stabilizing windings of the power transformers is the optimal overvoltage protection of the transformer insulation. The principal benefits demonstrated are that arresters in oil are protected from external environmental conditions. Additionally, the overvoltage control, in particular for steep transients, is improved due to the intimate proximity between the arrester and the coils.

The typical ZnO block can withstand a discharge current of a few tens kA if the duration of the impulse is less than 1 millisecond and the energy of longer impulse (e.g. 4 ms) can be absorbed by the ZnO-block if its current amplitude is lower (e.g. 250 A). Otherwise, the ZnO-block warms up and breaks downs. The ZnO-block absorbs energy according to the following equation:

$$E(J) = \int_0^T u(V) \cdot i(A) \cdot dt \qquad (2)$$

Although a ZnO-block should be homogeneous, discharge current passes through paths of a lower resistance. That is the reason for local overheating of ZnO-block and cracking, Fig. 11.

Fig. 11. ZnO-block damaged by very high impulse current

The pictures of ZnO-blocks from the transformer, which was damaged during the short-circuit fault in the substation, show typical crackings provoked by overheating of the ZnO-blocks due to high currents, Fig. 12.

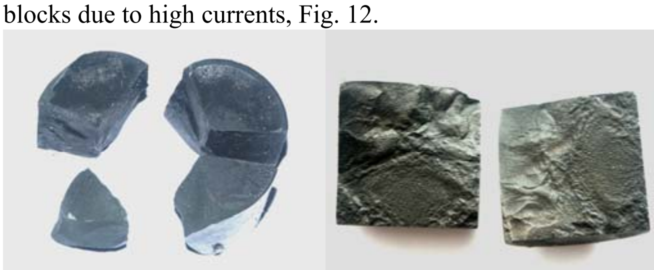

Fig. 12. The ZnO-block remains from transformer

The ZnO-block remains indicate that the surge arresters connected between stabilization winding and earth were damaged due to thermal instability. Furthermore, the arresters were immersed in transformer oil with higher temperature than the surroundings, which might have had an influence on lowering the energy absorption capability of arresters. It is also possible that their protection characteristics were degraded.

Therefore particular attention should be paid to maintaining thermal stability under all expected performance conditions, and nominal parameter control of surge arresters is recommended for integrated arrester systems.

V. CONCLUSIONS

An attempt was undertaken to reconstruct the fault in the switchyard during which the busbar protection tripped seven 110 kV circuit breakers and one 400 kV transformer breaker. The analysis was conducted on the basis of the computer simulations for which purpose detailed models of all switchyard components were built and very special attention was devoted to forming the model of the circuit breaker and power transformer.

The comparison between the recorded and computed fault currents showed good correspondence. It implies that the developed model could be used to investigate the influence of power system parameters on the operation of relay protection and to check the relay response to a very complex fault.

The main goal of the investigation was to find out possible overvoltages that could initiate a fault of transformer insulation. Recorded current do no reveal possible resonance phenomena.

Overvoltages of small magnitudes which should have only negligible influence on transformer insulation occurred on all three voltage levels: 400 kV, 110 kV and 10.5 kV. The energy generated by overvoltages was below the nominal value of the absorption capacity of the surge arrester installed on the stabilizing windings. Inspection of the arresters showed that they were damaged due to the thermal runaway. Their characteristics could have degraded with time, since the arresters were placed in mineral oil of relatively high temperature.

Therefore, the special attention should be paid when selecting nominal parameters of the integrated surge arresters and a long-term stability of the ZnO blocks must be guaranteed in such cases.

VI. REFERENCES

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VII. Biographies

Ivo Uglešić was born in Croatia in 1952. He received Ph.D. degree from the University of Zagreb, Croatia in 1988. Presently, he is a Professor of the Department of High Voltage and Power Systems at the Faculty of Electrical Engineering and Computing Zagreb. He is a head of the High Voltage Laboratory of the Faculty of Electrical Engineering and Computing in Zagreb His areas of interest include high voltage engineering and power transmission. He is a member of Cigré WG C4 301.

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