Overvoltages During Switching of 400 kV, 220 kV and 110 kV Circuit-Breakers in High Voltage Networks

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Abstract: **The paper presents the results of experimental investigations of phase to earth overvoltages on former Yugoslav high voltage networks resulting from switching 400 kV, 220 kV and 110 kV circuit-breakers and discusses the influence of circuit-breakers on overvoltage appearance.**

In investigated topologies of the 400 kV network, the highest overvoltage appeared during the switching in of lines at no load (U_{max}=2.28 p.u.); during the switching out operations high overvoltages didn't apear. In the 220 kV and 110 kV networks, the highest overvoltages were measured during the switching out of lines at no load and the switching out of special loads. The highest measured overvoltages in the 220 kV and 110 kV networks were U_{max}=2.61 p.u. and U_{max}=3.70 p.u., respectively. These high overvoltages during the switching out are caused by the reignition.

Keywords: Overvoltage, Circuit-Breaker, Network, Insulation Coordination.

I. INTRODUCTION

The knowledge of overvoltage magnitudes is indispensable for the correct and rational choice of electrical characteristics of the insulation in high voltage installations. Therefore, in the last thirty years numerous theoretical and experimental investigations of overvoltages were performed in Yugoslav high voltage networks. This paper will present a part of the experimental results of overvoltage investigations for switching operations of 400 kV, 220 kV and 110 kV circuit-breakers.

Switching overvoltages in the networks investigated depend both on network parameters and on the operation and characteristics of the circuit-breaker. From the overvoltage point of view, an ideal circuit-breaker will close all its contacts at the instant each phase-to-ground voltage passes through zero or is around zero (guided switching-in operations) and will interrupt the current when it naturally passes though zero (switching-out). Such a circuit-breaker will not have prestrikes during switching-in nor re-ignitions during switching-out operations and will, therefore, have no overvoltages. Unfortunately, ideal circuit-breakers do not exist, so that the above phenomena regularly occur to some extent. There are no guided switching-in operations in our networks and so the instant of circuit-breaker closure is a random value: the first pole closes independently, while the remaining two poles are in a certain correlation with the first one. These random values, together with other random and deterministic values of the topology in which the circuit-breaker operates, influence the generation of overvoltages which also have a random character.

II. INVESTIGATIONS AND RESULTS OF SWITCHING OPERATIONS OF 400 kV, 220 kV AND 110 kV CIRCUIT-BREAKERS

A large quantity of equipment was used during experimental investigations of switching overvoltages. The basic equipment consisted of: capacitive voltage dividers 400 kV, 220 kV and 110 kV, mixed voltage dividers 400 kV, digital and analogue oscilloscopes, special cameras with moving film, Polaroid cameras, etc.

A. Investigations and results of overvoltages for switching operations of 400 kV circuit-breakers

Extensive investigations of overvoltages for switching operations of 400 kV circuit-breakers have been performed at the following transmission lines: "Djerdap-Beograd", "Nis-Kragujevac", "TPP Nikola Tesla B – Mladost Ernestinovo" and "Konjsko-Obrovac-Melina". The results have been published [1, 2, 3, 4] and are presented here in brief form.

The 400 kV circuit-breakers considered were either oil minimum, air-blast or SF_6 without switching resistance. Investigations of overvoltages during switching operations of 400 kV circuit-breakers were done for different transmission network topologies. Namely:

- for switching in and switching out of 400 kV overhead lines at no load (9 topologies),
- for switching in and switching out of overhead lines loaded with a transformer at no load, i.e. an autotransformer or an autotransformer with a reactor in the tertiary winding (8 topologies),
- for switching in and switching out transformers at no load, i.e. autotransformers and autotransformers with a reactor in the tertiary winding (7 topologies),
- for ground faults and their clearance and single phase fast automatic reclosure (3 topologies)

In all topologies, at least 10 cycles of the switching in and switching out operations on 400 kV circuit-breakers was performed, except in topologies with ground faults. Transient voltages were registered at characteristic topology locations: beginning of line, end of line, transformer and autotransformer terminals. Apart from transient phase-to-ground voltages which were always registered, in many cases we also registered the transient phase-to-phase voltages, circuit-breaker recovery voltages and transient currents.

Overvoltages for each of the topologies were statistically analyzed as three-phase events (the overvoltages in all three phases are treated as one sample) for each switching operation (in and out) and for each measurement point.

Highest overvoltages (most critical) appear at the ends of lines switched-in at no load. Somewhat lower overvoltages appear for switching in and out of overhead lines loaded with transformers at no load or autotransformers with and without reactors. Other significant overvoltages appear when switching in transformers at no load and switching out autotransformers with reactors in the tertiary winding. The highest measured phase-to-ground and phase-to-phase overvoltage in the investigated topologies of the 400 kV were U_{ph} = 2,28 p.u. and $U_{ph\text{-}ph}$ = 2,00 p.u..

During ground faults and their clearance there were no significant overvoltages at any of the 400 kV lines. The overvoltages were also low for automatic single phase reclosures (no-voltage pause is approximately 0,9 s) in 400 kV networks. The maximum measured phase-to-ground overvoltage in tested topologies (only 7 single phase automatic reclosures were performed) was U_{max} = 1,62 p.u..

Switching in of circuit-breakers in 400 kV networks proceeded without prestrikes between the contacts. The time lags (dispersion) in 400 kV circuit-breaker pole closure were not significant. The interval between the closing of the first and the last pole of the circuit-breaker was less than 9 ms.

During switching out of 400 kV circuit-breakers, reignition did not occur; this is the principal reason for the absence of high overvoltages on the insulation of overhead lines, transformers and autotransformers.

Experimental investigations of overvoltages for switching operations of 400 kV circuit-breakers resulted in a picture of the critical set of switching overvoltages which can appear in 400 kV networks. One of the more critical sets, namely the single phase automatic reclosure, cannot be considered representative enough due to the small number of samples, i.e. experiments performed. However, it was noticed that, when switching out both sides of the line with passing ground faults, the remaining voltages drop relatively quickly, becoming zero after just a few hundred ms from the moment of disconnection. If there is no remaining voltage, the overvoltages for single phase automatic reclosure of the phase on which the ground fault occurred are less significant than those which appear for normal switching in of the same line at no load. Another critical set of overvoltages is the one that appears for three phase automatic reclosure; that is the reason that three phase automatic reclosure in 400 kV networks is avoided.

Using the data on measured values of phase-to-ground and phase-to-phase overvoltages on overhead lines in given topologies, we calculated the corresponding sparkover risks for switching impulse phase-to-ground withstand voltages of 1050 kV, 950 kV and 850 kV and the corresponding phase-to-phase withstand voltages of 1550 kV, 1425 kV and 1300 kV [2, 4]. It has been determined that the sparkover risks are very low for the set of switching phase-to-phase withstand voltages of 1050 kV and 1550 kV. Mean times between two sparkovers due to commutation significantly exceed the lifetime of the lines except in the case of switching in of HPP "Djerdap", the line "Djerdap - Belgrade" at no load and of the same line loaded with transformer "Belgrade 8" at no load when the power of the network at HPP "Djerdap" was low (only two generators from Djerdap supplied the network). Such topologies do not exist in practice. The set of switching withstand voltages of 1050 kV and 1550 kV is very reliable in operation. For the set of switching withstand voltages of 950 kV and 1450 kV the risks are also low. The mean times between two consecutive sparkovers are long, practically always above 5 years, so that this set offers the necessary reliability in operation of 400 kV overhead lines. The set of phase-to-phase insulation withstand voltages of 850 kV and 1300 kV creates significant risks if we make the same assumption as in the previous two cases that the overvoltages measured at line ends act on the complete line insulation. This assumption can lead to imprecise and even erroneous conclusions on the reliability of line operation. The calculated risks exceed the real ones. This is also true for risks calculated for previous sets of phase-to-phase switching withstand voltages. For them, however, this is acceptable for even with the excessive values obtained in this manner the reliability of operation is very high or acceptable. On the other hand, for the set of withstand voltages 850 kV and 1300 kV, the risks should be calculated on the basis of the overvoltages along the lines.

B. Investigations and results for overvoltages on 220 kV circuit-breakers

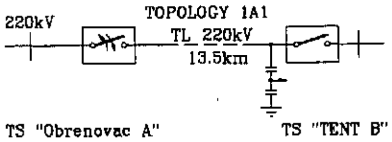
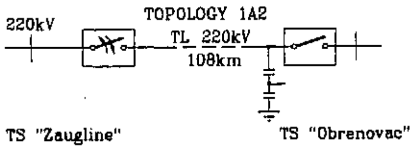
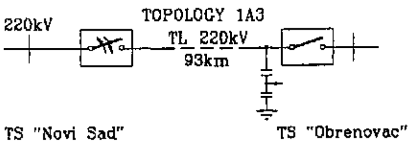
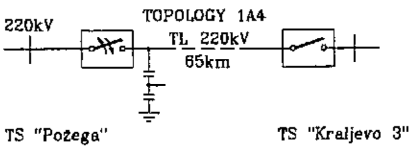
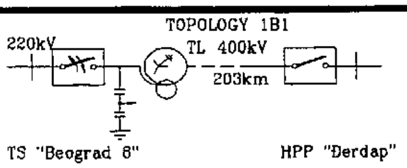
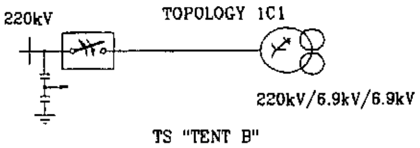
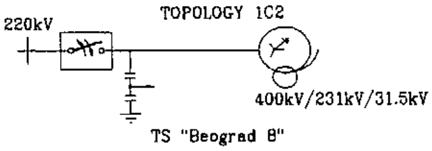
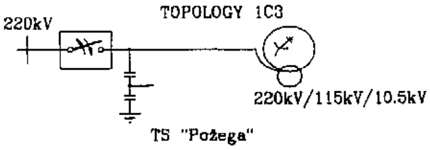
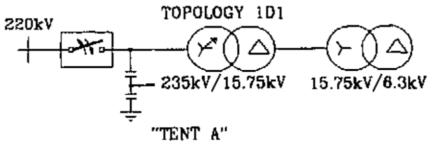
Investigations of overvoltages for switching operations of 220 kV circuit-breakers were made for topologies similar to those of 400 kV.

The following overvoltages were considered:

- for switching in and switching out of overhead lines at no load (topologies 1A),
- for switching in and switching out autotransformers loaded with an overhead line (configuration 1B1),
- for switching in and switching out transformers or autotransformers at no load (topologies 1C),
- for ground faults and their clearing and single phase fast automatic reclosure.

Oil minimum circuit-breakers without the switching resistance were used for the commutations. Phase-to-ground overvoltages in each of the topologies were analyzed as three-phase events, for each switching operation (in and out) and for each measurement point. Table 1 gives the mean (U_m) and maximum (U_{max}) measured values of phase-to-ground overvoltages by topologies and measurement points and the number of three-phase samples (n). Critical sets of overvoltages appear during switching in and, for some topologies, during switching out of overhead lines at no load, then for switching in and switching out of autotransformers loaded with an overhead line and for switching in of transformers and autotransformers at no load. The largest phase-to-ground overvoltage was measured for switching in operations, U_{max} = 2.15 p.u.. During switching in there were no prestrikes between circuit-breaker contacts. The dissipation of the closing times of poles of certain types of circuit-breakers was significant: it sometimes reached values of 16 ms. For switching out of new types of oil minimum circuit-breakers, except in one case (it was later established that the circuit-breaker had incorrect issipation of pole closure times), there were no reignitions nor high

Table 1.* Characteristics of samples of phase-to-ground overvoltages in tested topologies for switching in (C) and switching out (O) of 220 kV circuit-breakers

N°	Topology	Breaker operation C-sw. in O-sw. out	Mean value (U_m), max. measured value ($U_{max.}$) of overvoltages in the sample and number (n) of elements in the sample		
			U_m (p.u.)	$U_{max.}$ (p.u.)	n
1		C	1.47	2.15	36
		O	1.04	2.00	33
2		C	1.63	2.15	14
		O	2.15	2.61	9
3		C	1.47	1.73	12
		O	1.02	1.08	12
4		C	1.24	1.60	27
		O	1.01	1.10	27
5		C	1.20	1.50	30
		O	1.40	1.68	33
6		C	1.02	1.10	24
		O	1.00	1.00	24
7		C	1.16	1.58	36
		O	1.01	1.07	33
8		C	1.11	1.35	14
		O	1.01	1.15	14
9		C	1.17	1.60	24
		O	1.03	1.20	15

*Data on sample characteristics of phase-to-ground and phase-to-phase overvoltages of 400 kV networks for switching in and switching out of 400 kV circuit-breakers are given in references [5] and [7].

overvoltages. Older types of oil minimum circuit-breakers have reignitions and, therefore, relatively high overvoltages. Reignitions appear also when switching out overhead lines at no load. i.e. for interrupting small capacitive currents; they are usually multiple and occur on all phases. The maximum measured phase-to-ground overvoltage was $U_{max} = 2.61$ p.u..

For ground faults and their clearing (two ground faults were tested in one topology) and for single phase fast automatic reclosure the overvoltages were not high.

C. Investigations and results of overvoltages for switching operations with 110 kV circuit-breakers

Investigations of overvoltages for switching operations with 110 kV circuit-breakers encompassed:

- switching in and switching out of overhead and cable lines at no load (topologies 2A),
- switching in and switching out cables loaded with transformers at no load (topology 2B),
- switching in and switching out of transformers at no load (topologies 2C),
- switching in and switching out of autotransformers with a reactor in the tertiary winding (topologies 2D1),
- switching in and switching out of transformers loaded with special loads (topologies 2E),
- ground faults and their clearance and single phase fast automatic reclosure.

The following circuit-breakers were used for commutations: oil minimum (topologies 2A3, 2A4, 2B1, 2B2, 2C2, 2C3, 2D1, 2E1, 2E2, 2E3), SF_6 (topologies: 2A1, 2A2, 2C1, 2C4, 2C5, 2E4) and air-blast (topologies: 2E5, 2E6), without the switching resistance.

Table 2 gives the mean (U_m) and the maximum (U_{max}) measured values of phase-to-ground overvoltages by topologies and measurement points and the number of three-phase event samples (n). Significant overvoltages appear during switching in of most of the considered topologies. However, they are not so high as to threaten the insulation of the 110 kV network. The largest measured phase-to-ground overvoltage for switching in operations was $U_{max} = 2.15$ p.u.. Opening of circuit-breakers in some cases resulted in very high overvoltages. One such case is the disconnection of a transformer loaded with special loads, such as loads in aluminum works and steel works and for switching out of lines at no load. These cases usually result in current cutting before it naturally passes through zero and multiple reignitions in the circuit-breaker. The largest measured phase-to-ground voltage for switching out operations was $U_{max} = 3.70$ p.u..

For ground faults and their clearance (two ground faults were tested in a single topology) and for single phase fast automatic reclosure, the overvoltages were not significant.

III. CONCLUSIONS

The analysis of overvoltages in 400kV, 220 kV and 110 kV networks for switching operations with HV circuit-breakers has shown the following:

- The tested HV 400 kV circuit-breakers do not cause high overvoltages in tested topologies of the 400 kV network; this means that if circuit-breakers with good characteristics are used, it is possible to install overhead lines with phase-to-ground and phase-to-phase insulations with impulse withstand voltages lower than the existing 1050 kV, i.e. 1550 kV. A satisfactory reliability is achieved with the set of withstand voltages of 950 kV (phase-to-ground insulation) and 1450 kV (phase-to-phase insulation). The use of insulation with impulse withstand voltages of 850 kV and 1300 kV requires a more precise risk calculation for each network topology and the possible use of devices for limiting overvoltages.
- The existing new types of oil minimum 220 kV circuit-breakers (without reignitions) do not cause high overvoltages in operation and do not threaten the insulation of 220 kV networks. Old oil minimum circuit-breakers should be replaced. Their use in certain topologies (when disconnecting lines at no load, multiple reignitions occur) should be reduced to a minimum.
- 110 kV circuit-breakers depending on the type and construction might lead to high overvoltages in operation. The existing new types of oil minimum circuit-breakers (without reignitions) do not cause high overvoltages and do not endanger the insulation of 110 kV networks. Circuit-breakers with reignitions and circuit-breakers with possibilities of current cutting should be avoided, especially in topologies with special loads (induction and electric arc furnaces, capacitor batteries, etc.).

IV REFERENCES

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[2] Z. Zdravković, "Switching phase-to-ground and phase-to-phase overvoltages on 400 kV lines and sparkover risks", *Elektroprivreda*, N° 3-4, 1989, pp. 108-122.

[3] Z. Zdravković, P. Vukelja, "Investigation of switching overvoltages on 400 kV transmission lines, CIGRE, SC 22, *Transmission lines open conference, Sarajevo, october 11, 1989, pp. 49-61.*

[4] Z. Zdravković, P. Vukelja, "Switching overvoltages and risk of flashover on Yugoslav 400 kV transmission lines", *IEE Proceedings-C*, vol.139, N° 2, March 1992, pp. 141-151.

Table 2. Characteristics of samples of phase-to-ground overvoltages in tested topologies for switching in (C) and switching out (O) of 110 kV circuit-breakers

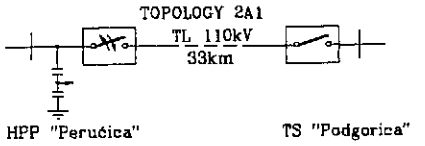
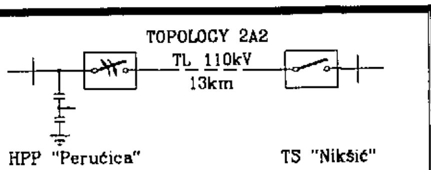
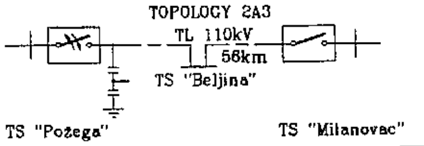
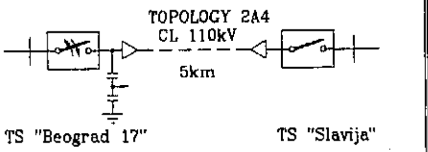
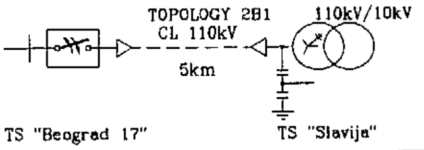
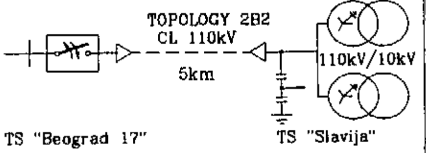
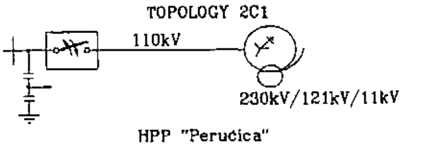
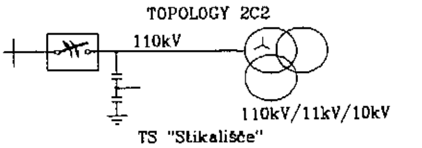
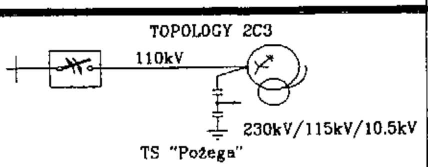
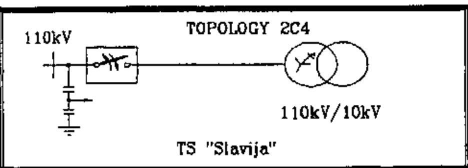
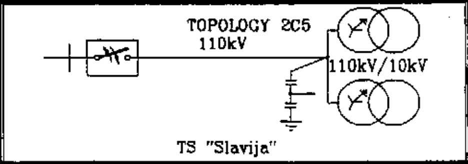
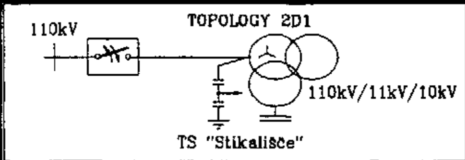
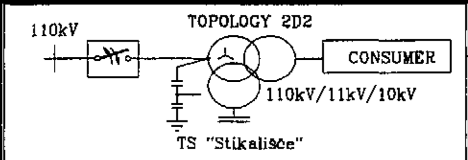
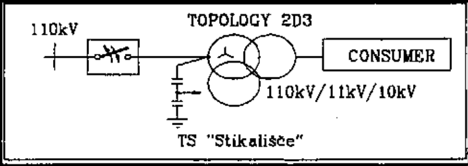
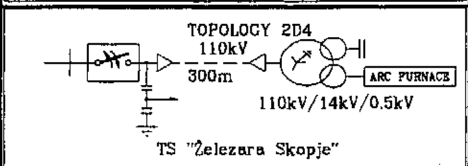
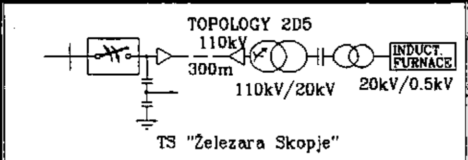
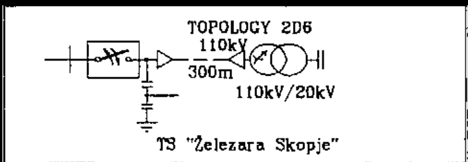
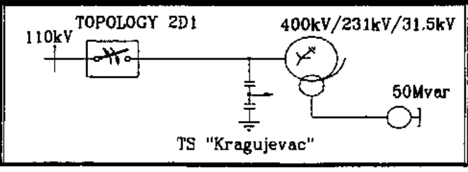
N°	Topology	Breaker operation C-sw. in O-sw. out	Mean value (U_m), max. measured value ($U_{max.}$) of overvoltages in the sample and number (n) of elements in the sample: U_m (p.u.)	$U_{max.}$ (p.u.)	n
1		C	1.14	1.45	45
		O	1.00	1.00	45
2		C	1.08	1.25	30
		O	1.00	1.00	30
3		C	1.06	1.30	36
		O	1.50	2.50	33
4		C	1.20	1.75	45
		O	1.00	1.00	45
5		C	1.39	2.15	36
		O	1.30	1.50	36
6		C	1.31	1.80	40
		O	1.18	1.42	39
7		C	1.00	1.00	15
		O	1.00	1.00	15
8		C	1.04	1.35	54
		O	1.00	1.00	9
9		C	1.13	1.60	15
		O	1.06	1.40	15

Table 2. (cont.) Characteristics of samples of phase-to-ground overvoltages in tested topologies for switching in (C) and switching out (O) of 110 kV circuit-breakers

N°	Topology	Breaker operation C-sw. in O-sw. out	Mean value (U_m), max. measured value ($U_{max.}$) of overvoltages in the sample and number (n) of elements in the sample		
			U_m (p.u.)	$U_{max.}$ (p.u.)	n
10		C	1.12	1.60	39
		O	1.00	1.00	36
11		C	1.14	1.65	40
		O	1.01	1.40	42
12		C			
		O	1.20	1.35	12
13		C			
		O	1.06	1.55	12
14		C			
		O	1.40	2.80	21
15		C	1.05	1.45	33
		O	1.14	1.55	30
16		C	1.08	1.55	21
		O	2.24	3.70	27
17		C	1.03	1.05	12
		O	1.10	1.30	15
18		C	1.15	1.55	28
		O	1.24	1.55	25