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ORIGINAL PAPER

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Overvoltages caused by switching unloaded cable lines by a vacuum switch

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Abstract The paper presents results of the studies on overvoltages generated while switching unloaded medium voltage (MV) power cable lines by a vacuum switch. The studies were carried out while switching real MV cable lines and their physical models. It has been found that overvoltages and overcurrents are generated during switching, and that under certain conditions they may reach significant values. These values depend on the source side circuit parameters, on kinematics vacuum switch parameters as well as on parameters of a switched cable line.

Keywords Cable lines · Vacuum switch · Overvoltages · Overcurrents

Abbreviations

- AR — Arc reignition
- V_p — Test voltages
- t_{bpn} — Time without current between subsequent ARs
- k_{szn} — Coefficient of ground overvoltage in the source side circuit after AR occurrence
- k_{swn} — Coefficient of ground overvoltage in the source side circuit after switching off "*n*" AR
- k_{czn} — Coefficient of overvoltage in the research circuit after AR occurrence
- k_{cwn} — Coefficient of overvoltage in the research circuit after switching off current of *n* AR
- k_{pcn} — Coefficient of overvoltage in the research circuit as an effect of overloading the capacity of the cable line or its physical model as a result of AR

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1 Introduction

Switching processes connected with switching power circuits are accompanied by transient phenomena leading to generation of overvoltages and overcurrents. The analysis of switching phenomena in single-phase and three-phase capacitive low voltage circuits has showed [1, 2, 3] that transient processes while switching a capacitor bank by a vacuum switch may be very complex, particularly in the case of occurring arc reignitions (ARs). Under certain switching conditions, the occurrence of ARs may cause escalation of overvoltages and overcurrents, which are dangerous also to a vacuum switch itself [2].

Our preliminary simulating analysis carried out on medium voltage (MV) networks has proved that similar phenomena occur also while switching off by a vacuum switch of unloaded MV cable lines [4]. Specific vacuum switch properties, such as interruption of alternating current before its natural passing through zero (the so-called choping current), electric strength of the switch electrodes gap and its dependence on the gap length contact as well as the rate of post arc strength increase, which are not fully known and have no complete mathematical description, constituted essential difficulties in that theoretical analysis [4, 5, 6, 7, 8].

In connection with the above it became necessary to verify experimentally the obtained analytical dependences describing recovery voltages, overloads and overcurrents generated while switching by a switch of unloaded MV cable lines (with and without ARs). Such verification was performed when studying transient phenomena while switching unloaded MV cable lines and their physical models.

2 Research system

Studies of switching phenomena were carried out by using a test circuit, and its electric scheme is presented in Fig. 1. That system consisted of the following parts:

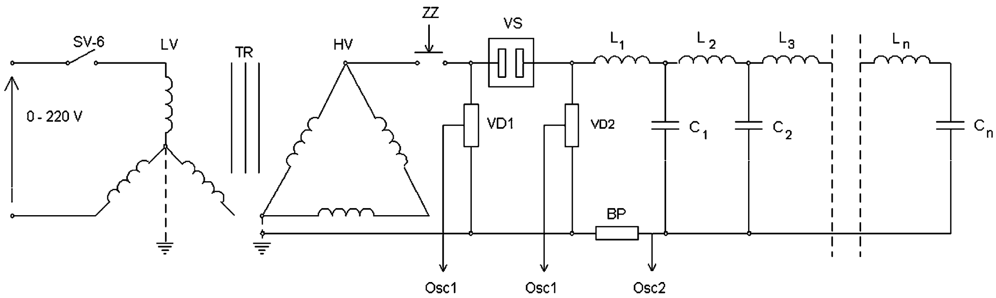

Fig. 1 Test circuit: SV-6—vacuum contactor; TR—supply transformer; ZZ—short circuiting switch; VS—model vacuum switch; C_1, C_2 ... C_n, L_1, L_2, ... L_n—substitute capacities and inductances of a real cable line or its physical model; VD1, VD2—resistance-capacitive voltage dividers; BP—inductanceless current shunt; Osc1, Osc2—digital oscilloscopes

- Source side circuit
- Model vacuum switch
- Research circuit, i.e., unloaded MV power cable line or its physical model
- Control and measuring system

The source side circuit was built using a MV transformer (TR) and a short circuiting switch (ZZ). That was a typical network transformer with the nominal power $S_N = 200$ kV A, voltage $U_N = 6/0.4$ kV operating in the single-phase system. It was supplied on the side of low-voltage windings from an autotransformer with alternating voltage at frequency of 50 Hz regulated within 0÷220 V depending on requirements. By changing the value of that voltage and configuration connections low-voltage and high-voltage windings of the transformer it was possible to change parameters of the source side circuit and the value of test voltage (V_p).

A vacuum contactor of SV-6 type was used to switch on/off the transformer supply. However, for switching off at a strictly definite time the test voltage obtained from the transformer high-voltage windings a short enclosure was used.

Protection of the test system from results of short circuits was a suitably selected power fuse (type WBWMI) installed on the high-voltage side of the transformer.

A model vacuum switch (VS) was used to switch off unloaded MV cable line or its physical model [4]. The vacuum switch had cooper electrodes and cover plate contacts in the forms of disk made with Cu75Cr25. For separation of these contacts, electromagnetic drive was used.

The research system was controlled by a rotary programming device, which was connected to a five-channel electronic generator of voltage and current impulses. These impulses controlled a synchronous work of the research system by switching on/off its devices in a definite order, i.e., a short enclosure drive, model vacuum switch drive, a time-base generator of measuring oscilloscopes. For registration of transient overcurrents and overvoltages in the source side and the research circuits, wide-band digital oscilloscopes, type HM 1507 by Hameg and type OS 3060 by GoldStar, were used. It should be mentioned that for registration of transient overcurrents, the oscilloscope was switched into the research circuit with the help of a pipe inductanceless current shunt (BP). However, for registration of transient overvoltages, the oscilloscopes were switched into a circuit by means of resistance-capacitive voltage dividers VD1, VD2.

The research circuit was presented by unloaded MV cable line made of power cable of YHKXS type, with cross section of core conductor $s_k = 120$ mm^2 or by physical models of MV cable lines. The MV cable lines in these models were modelled by a catenary electrical line formed of passive four-terminal networks of Γ type. The values of elements of each passive four-terminal network, such as inductance L and capacitance C, were changed to adjust them to parameters of a modelled cable line. For instance, unit parameters (unit inductance and unit capacitance) of the modelled power cable of YHKXS type, with cross section of core conductor $s_k = 120$ mm^2, amounted to 0.65 mH/km and 0.34 μF/km. The modelled cable lines had the length $l_k = 10$; 17; 20; 29; 46; 50; 100; 1,000; 2,000 and 5,000 m.

3 Conditions and the scope of studies

The studies of switching transient overvoltages and overcurrents were carried out while switching off the following circuits:

- Unloaded MV cable lines made of power cable of YHKXS type, with cross section of core conductor $s_k = 120$ mm^2 and having the length $l_k = 17$; 29 and 46 m
- Physical models of unloaded MV power cable lines, made of YHKXS cable, with cross section of core conductors $s_k = 70$; 120 and 150 mm^2 and having the length l_{mk} changed from 10 to 10,000 m

Values of test voltages V_p during the studies were equal to 1.7; 3.5; 5.8; 8.7 kV rms and conformed to the following values of the power line interphase voltages: 3; 6; 10 and 15 kV rms.

Kinematics parameters of the model vacuum switch were following: the gap length contact (d_c) in the state of a full opening of contacts was $d_c = 1$; 2; 3 mm; the acceleration "a" of the movable contact was changed within 2 to 6 m/s^2.

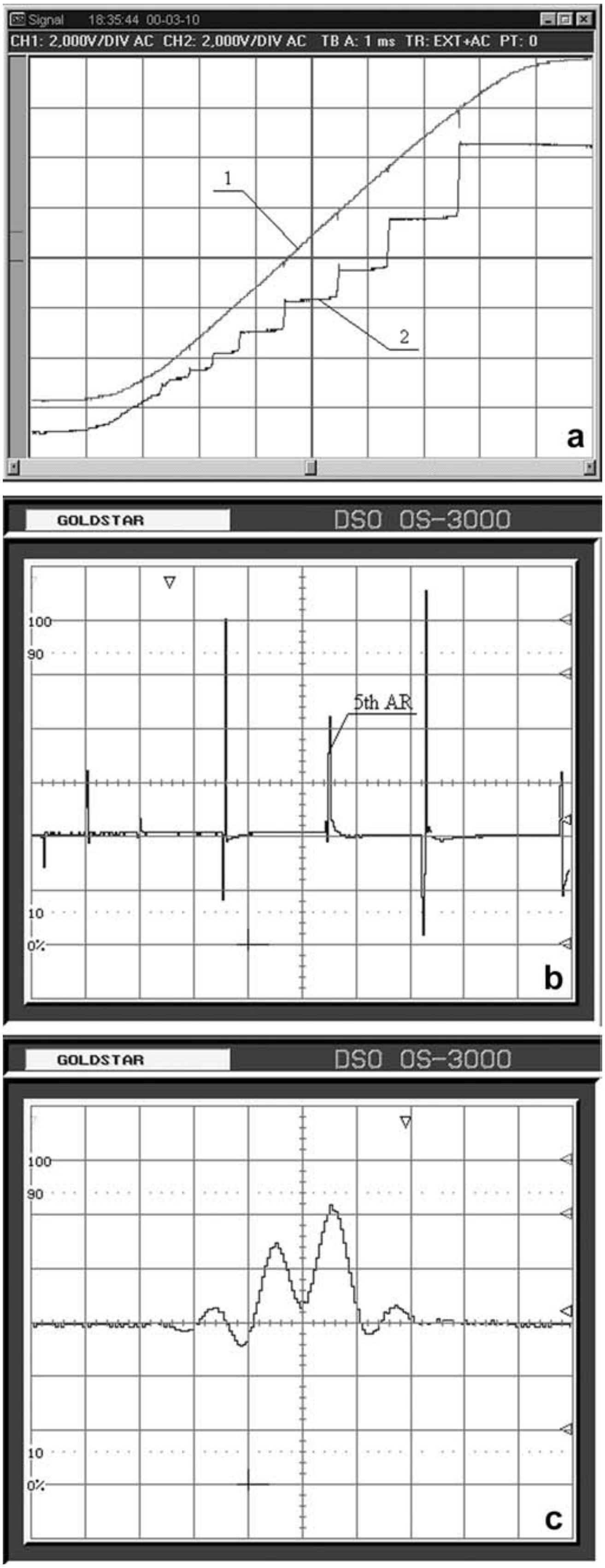

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Fig. 2 a Transient overvoltages in the source side circuit (1) and in switched circuit (2). **b** and **c** Transient overcurrents while switching unloaded MV cable line made of power cable of YHKXS type having the length $l_k = 17$ m. **c** Transient overcurrent of the 5th AR; test voltage $V_p = 5.8$ kV rms; voltage constant—2.31 kV/div; current constant—20 A/div. Time constants: **a** 1 ms/div, **b** 0.5 ms/div and **c** 0.2 ms/div

In the period under study, transient overvoltages in the source side circuit and transient overvoltages and overcurrents in the research circuit were measured while switching off. In addition the following were recorded: the gap length contact (d_c) of a vacuum switch; the velocity (v_s) and motion of its movable contact. That made it possible to calculate the acceleration a of a movable contact and the real gap length contacts at the moment of AR occurrence.

4 Results of studies and discussion

Figures 2, 3, 4 and 5 present examples of transient overvoltages and overcurrent in the source side and research circuits, i.e., of unloaded MV cable line or its physical model, measured while switching off by a vacuum switch. Transient overvoltages generated in the source side circuit were designated as 1 in the oscillograms; whereas, temporal runs of the analogical quantities in unloaded cable line or its physical model were designated in the oscillograms as 2. Figures 2 and 3 show transient overvoltages and overcurrents obtained, when switching unloaded cable line made of a cable of YHKXS type, with cross section of core conductor $s_k = 120$ mm^2 and having the length $l_k = 17$ m (Fig. 2) and 46 m (Fig. 3). Figure 2c presents a time-extended transient overcurrent run for the 5th AR.

Figures 4 and 5 present transient overvoltages obtained while switching physical models of MV cable lines modelling unloaded cable lines made of YHKXS cable, having the lengths $l_{mk} = 50$; 150; 500; 1,300; 5,000; 7,800 and 9,300 m and cross section of core conductor $s_k = 120$ mm^2.

Results of measurements were used to determine coefficient values of overvoltages "k" (in the source side circuit and research circuit) defined as a ratio of the instantaneous value transient overvoltage to the test voltage amplitude.

Coefficient values of ground overvoltages in the supply system and in the research circuit at n AR occurring after the time t_c from the moment of contact opening are presented in Fig. 6. It should be mentioned that the values of overvoltages coefficients given in Fig. 6a were determined from the measurements made when switching a cable line having the length $l_k = 17$ m; whereas, overvoltage coefficients in Fig. 6b and c were determined from the measurements obtained when switching physical cable line models having the length $l_{mk} = 150$ and 1,300 m. In Fig. 6 the coefficient value of ground overvoltage generated in the source side circuit

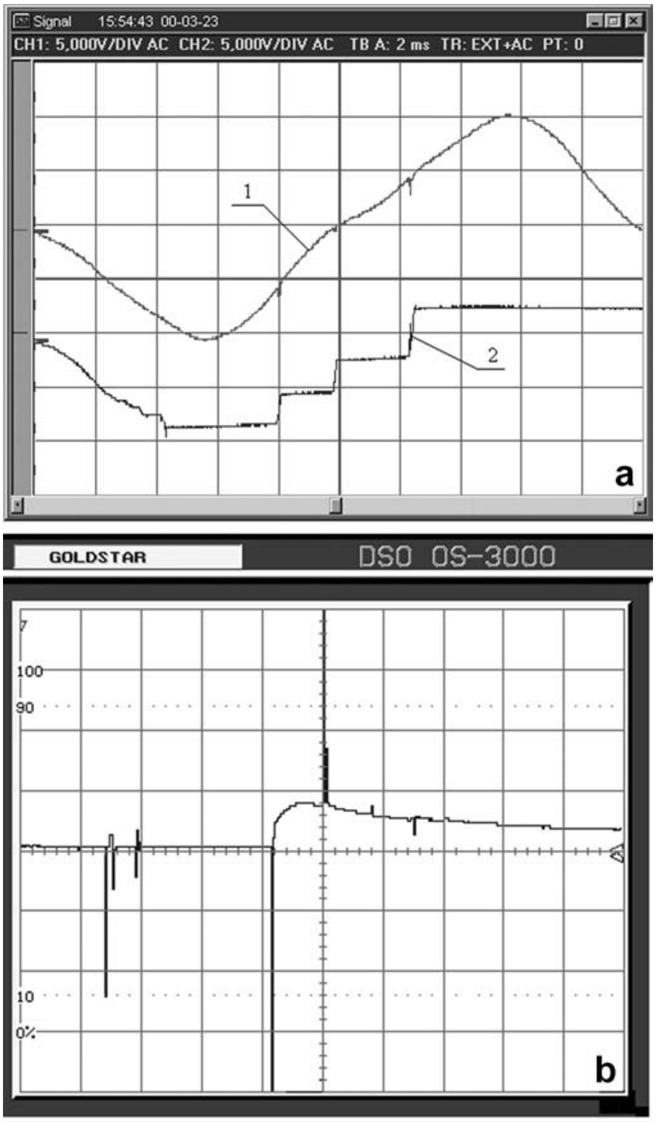

Fig. 3 a Transient overvoltages in the source side circuit (1) and in switched circuit (2). **b** Transient overcurrent while switching off unloaded MV cable line made of power cable of YHKXS type having the length $l_k = 46$ m; test voltage $V_p = 8.7$ kV rms; voltage constant—5.77 kV/div; current constant—100 A/div; time constants—2 ms/div

after AR occurrence was designated as k_{szn}, while that of the overvoltage coefficient after switching off current of n AR as k_{swn}. Analogous to the coefficients values of overvoltages in the research circuit were designated as k_{czn} and k_{cwn}. On the y axis, the value of overvoltage coefficient k_{pcn} is also given in the research circuit as an effect of overloading the capacity of the cable line or its physical model as a result of AR.

When analysing the measured temporal runs, the number of n ARs, the time t_c of AR occurrence and the values of occurring overvoltages, it may be inferred that together with growth of the length of a switched cable line the number of ARs is decreasing while the time of their occurrence is growing. According to our analysis it is caused by the following phenomena: namely, growth

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Fig. 5a–f Transient overvoltages in the source side circuit (1) and in switched circuit (2) obtained while switching off physical models of unloaded MV cable lines having the length l_{mk}: **a** 150 m, **b** 500 m, **c** 1300 m, **d** 5000 m, **e** 7800 m, **f** 9300 m; test voltage for **a**, **b**, **c**—$V_p = 8.7$ kV rms and for **d**, **e**, **f**—$V_p = 5.8$ kV rms/div; voltage constant for **b**, **c**, **d** runs—11.55 kV/div, voltage constant for **a**, **e**, **f** runs—5.77 kV/div

of the length of a switched cable line brings about decrease of the steepness of overvoltage wave head. Moreover it causes the increase of time needed to propagate this wave through the line and the decrease of the steepness of transient component of returning voltage occurring between switch contacts. These phenomena are the cause that, the increase of line length reduces the probability of another AR.

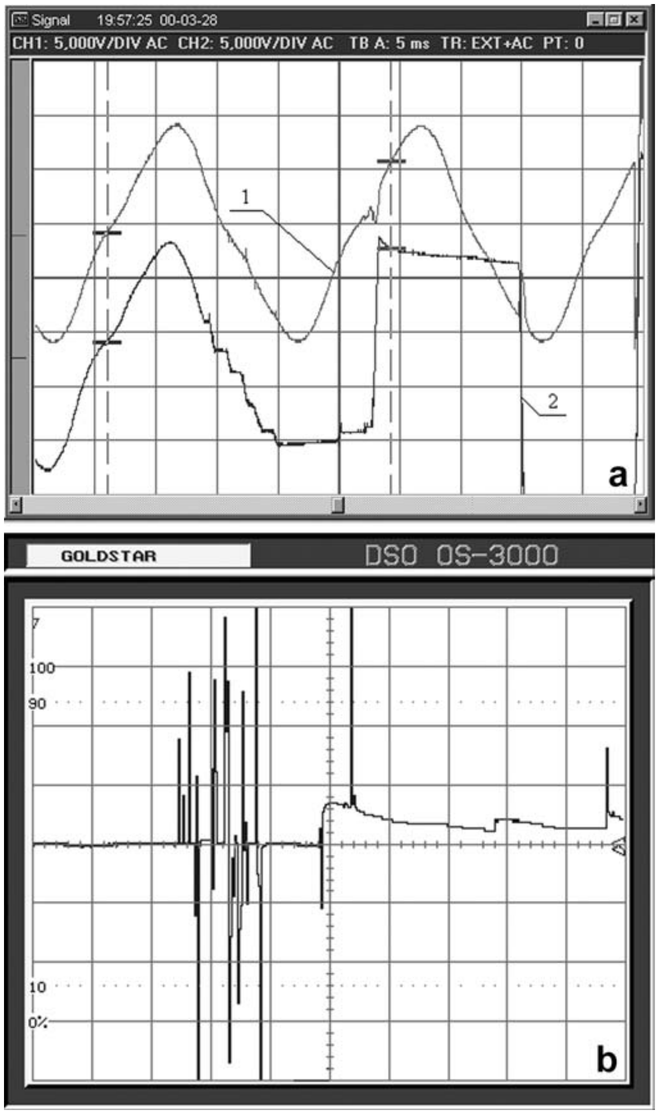
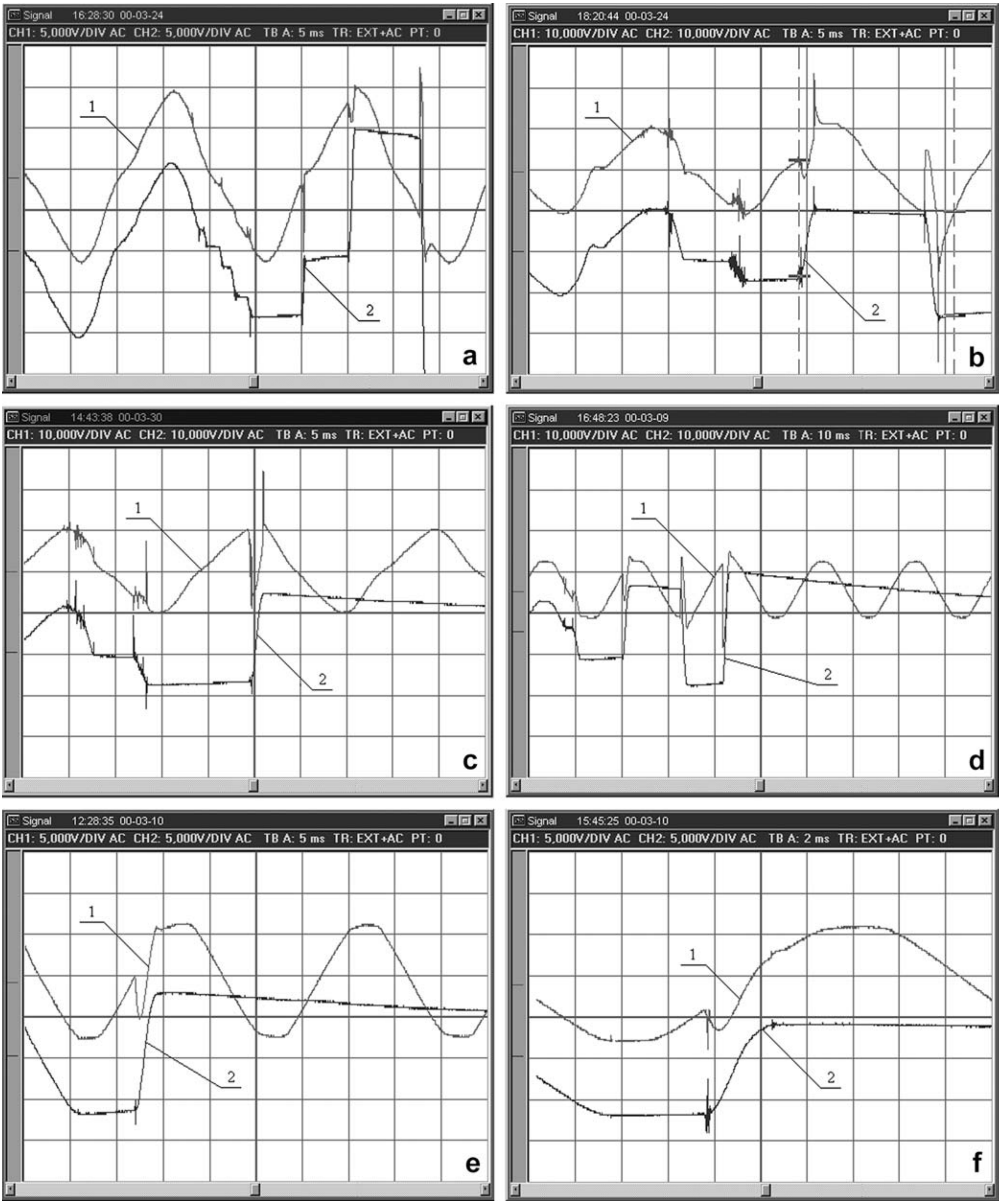
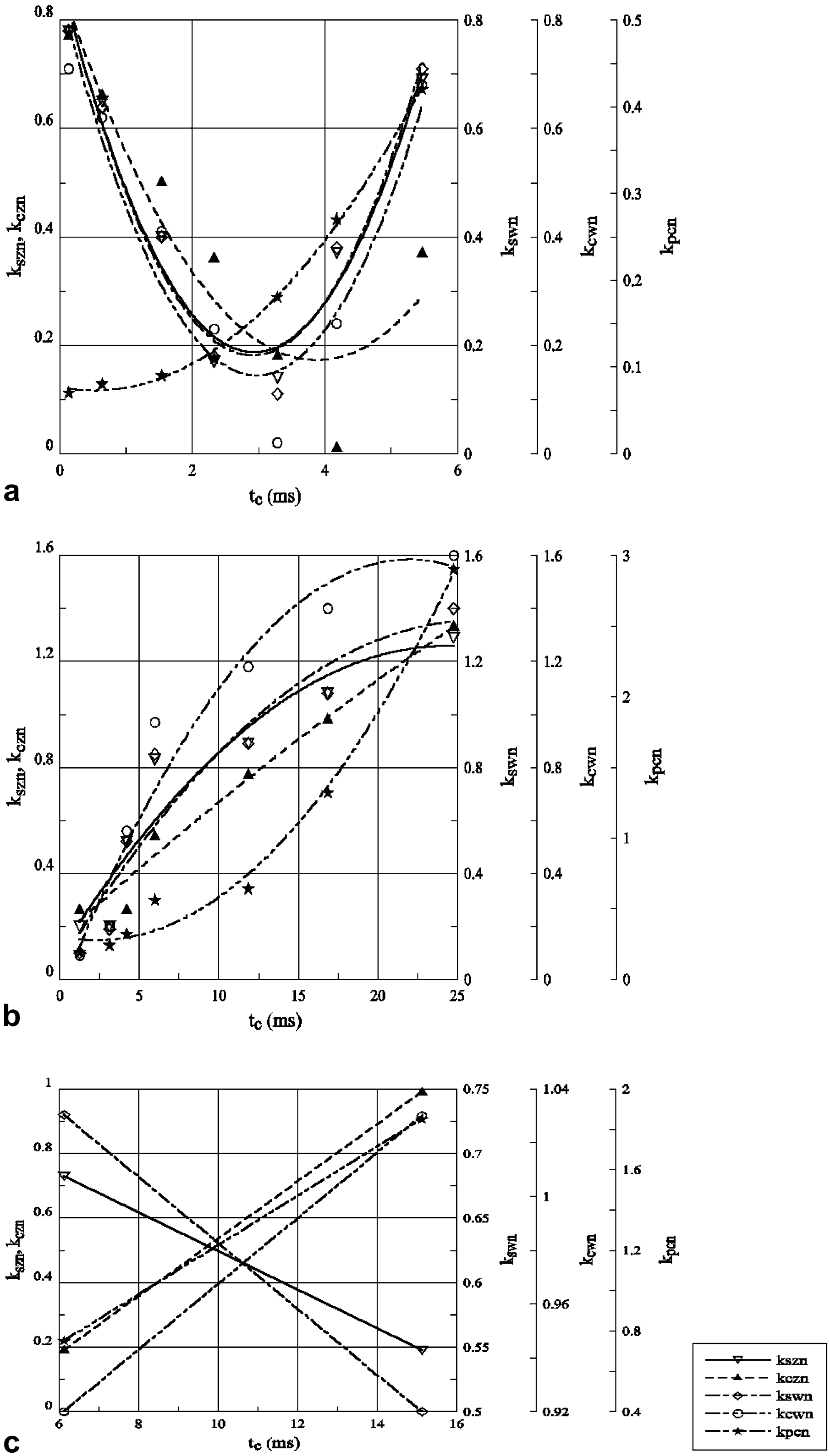


Fig. 4 a Transient overvoltages in the source side circuit (1) and in switched circuit (2). **b** Transient overcurrent while switching off physical model of a MV cable line having the length $l_{mk} = 50$ m; test voltage $V_p = 8.7$ kV rms; time constants—5 ms/div; voltage constant—5.77 kV/div; current constant—100 A/div



Further analysis of measured temporal runs showed that the values of overvoltages in the supply and the switched circuit depend on the time without current (t_{bpn}) between subsequent ARs. Namely, when ARs occur early, just after opening vacuum switch contacts and times without current $t_{bpn} < 5$ ms, the values of

Fig. 6a–c The values of ground overvoltages coefficients in the source side circuit (k_{szn}, k_{swn}) and in the research circuit (k_{czn}, k_{cwn}, k_{pcn}) as a function of the time t_c measured from opening switch contacts while switching off by a model vacuum switch of: **a** a cable line having the length $l_k = 17$ m, **b** a model of a cable line having the length $l_{mk} = 150$ m and **c** a model of a cable line having the length $l_{mk} = 1{,}300$ m



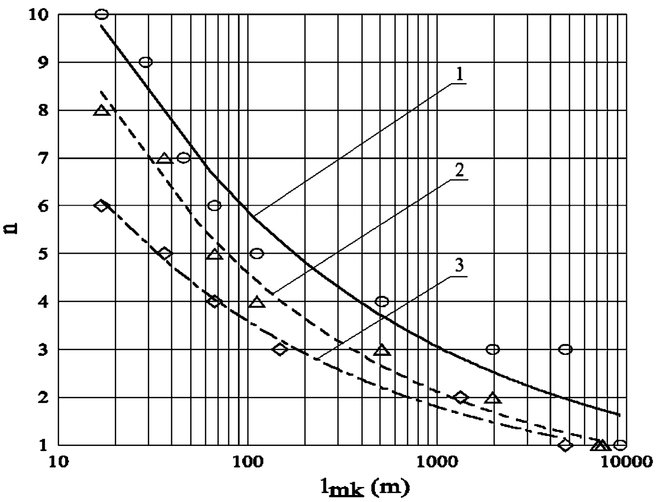


Fig. 7 The n number of ARs as a function of the length of unloaded cable line for different acceleration values a of a movable vacuum switch contact: 1—$a = 2.5$ m/s^2, 2—$a = 3.6$ m/s^2, 3—$a = 5.1$ m/s^2; test voltage $V_p = 8.7$ kV rms

generated overvoltages are small. However, ARs occurring after the time without current $t_{bpn} > 5$ ms lead to generation of significant overvoltages, both in the supply and the research circuits. It is caused by the fact that, due to the short time without current (t_{bpn}) the value of original voltage, i.e., the voltage difference between supply and circuit capacity, is small. That is why AR does not generate overvoltage of significant value. Moreover short arc ignitions, occurring between switch contacts, cause conditioning of this switch, leading to the increase of electric strength of switch gap. Thus, occurrence of subsequent AR demands the higher value of original voltage, and consequently longer time without current. Then, the occurring subsequent arc ignition leads to generation of the overvoltage having high value.

The dependence of n number of ARs on the length of a switched unloaded cable line is shown in Fig. 7. Characteristics presented in Fig. 7 were drawn up for three accelerations a of the vacuum switch movable contact and test voltage value $V_p = 8.7$ kV rms. Similar dependences were obtained also for the remained values of test voltages and movable contact accelerations of a vacuum switch used in the studies.

When parameters of a switched circuit were constant, it has been found that an increase in a movable contact acceleration a of a vacuum switch caused:

- A decrease in the n number of (mainly early) ARs
- An increase of the currentless time t_{bpn}

Dependence of the overvoltage coefficient k_{pcn} in the studied circuits on the currentless time t_{bpn} until subsequent AR is presented in Fig. 8. Measurement points presented in Fig. 8 are arithmetic means of 10 independent measurements. However, dependences in Fig. 8a were determined for 4 subsequently occurring ARs obtained on the basis of measurements made when

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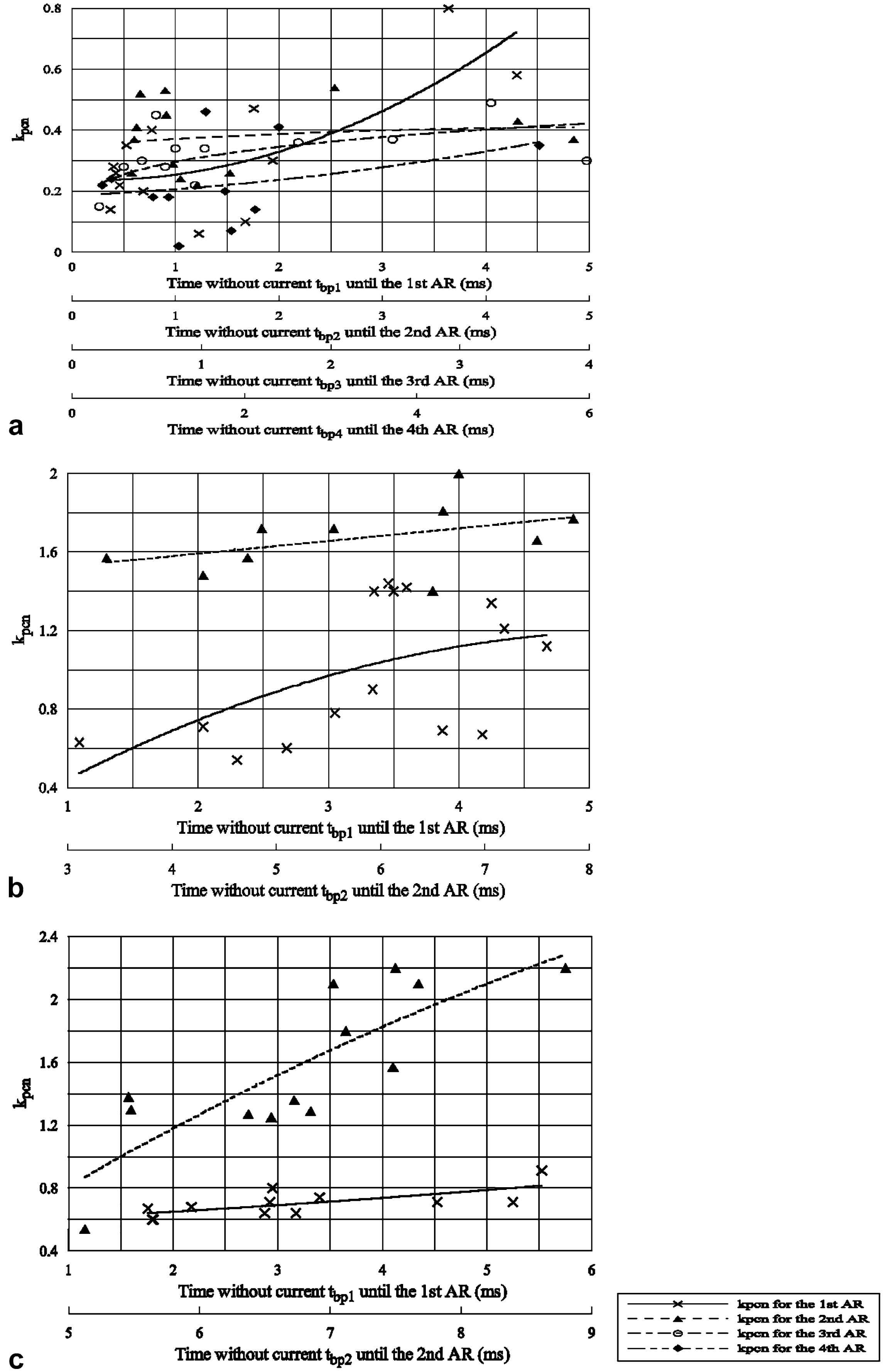
Fig. 8a–c The value of overvoltage coefficient k_{pcn} of the research circuit as the function of currentless time t_{bpn} to subsequent AR while switching off physical models of a cable line having the length of: **a** 150 m, **b** 500 m, **c** 1,300 m; test voltage $V_p = 8.7$ kV rms; acceleration of a vacuum switch movable contact $a = 6$ m/s^2

switching off a physical model of a cable line 150 m long. However, dependences presented in Fig. 8b and c were performed for two currentless times—t_{bpn}, t_{bp2} until subsequent ARs when switching the cable line model having the length of 500 and 1,300 m. Since for the times $t_{bpn} < 5$ ms the value of the overvoltage coefficient k_{pcn} is substantially influenced by voltage polarity in the supply system at the moment of AR occurrence, the figures also present calculated curves k_{pcn} of change tendencies for the analysed times without current.

5 Conclusions

The performed studies have resulted in the following conclusions:

1. From a comparative analysis it follows that there is no difference between transient overcurrents and overvoltages when switching unloaded real MV cable line by a vacuum switch and between analogous transient overcurrents and overvoltages occurring while switching its physical model consisting of a catenary electrical line of passive four-terminal networks of Γ type containing L and C elements.
2. While switching unloaded MV cable lines by a vacuum switch, depending on parameters of the source side and research circuits and on switch parameters, there may occur exclusively early or late ARs, or these two forms may occur simultaneously.
3. Early, multiple ARs occurring in short time intervals are induced by a voltage wave reflected from the end of a cable line. They mainly occur while switching short cable line sections and do not generate significant overvoltages and overcurrents both in the source side and research circuits.
4. Late, multiple ARs occurring under the influence of recovery voltage, which appears on the switch contacts after switching off current, generate already significant overvoltages and overcurrents in the both source side and research circuits.
5. The numbers of early and late ARs decrease with an increase in the length of a switched cable line and acceleration of the vacuum switch movable contact.
6. For a vacuum switch characterized by definite kinematic parameters (the gap length contact in the state of a full opening of contacts, and the acceleration of the movable contact), switching off unloaded cable line, there is a certain limiting length of the research line, below which exclusively early ARs generating no overvoltages of significant values occur during switching.


a
kpcn
Time without current t_{bp1} until the 1st AR (ms)
Time without current t_{bp2} until the 2nd AR (ms)
Time without current t_{bp3} until the 3rd AR (ms)
Time without current t_{bp4} until the 4th AR (ms)
b
kpcn
Time without current t_{bp1} until the 1st AR (ms)
Time without current t_{bp2} until the 2nd AR (ms)
c
kpcn
Time without current t_{bp1} until the 1st AR (ms)
Time without current t_{bp2} until the 2nd AR (ms)
kpcn for the 1st AR
kpcn for the 2nd AR
kpcn for the 3rd AR
kpcn for the 4th AR

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