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On Necessity of Taking into Consideration Arc Resistance at Simulation Switching Transients in Electric Power Systems

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ABSTRACT: This paper presents results of research an influence of arc resistance in circuit-breakers on transitional processes have taken place at switching-offs capacitive and small inductive currents by vacuum and SF6 circuit-breakers. Simulation models include the main characteristics of circuit-breakers such as chop current, dielectric strength restoration law and switching duration. Simulations were carried out using methods and simulation parameters provided stable solutions for transitional functions of voltages and currents. Results obtained proved expediency taking into consideration the arc resistance at modeling and computer simulation of processes under consideration at least for switching-off small inductive currents by SF6 circuit-breakers and capacitive currents by vacuum circuit-breakers.

KEYWORDS: Transitional Voltages, Recovery Voltage, Arc Resistance, Dielectric Strength Restoration, Capacitive and Small Inductive Currents, Chop Current.

I.INTRODUCTION

A problem under consideration has had a long and continuous history. As it is known switching transients in electric power systems may cause appearance great voltages and currents can prevail upon their allowable values and worsen functioning of equipment especially its insulation [1, 2]. By this reason studying switching transients and transitional voltages has been always considered as one of important problems of electric power engineering.

Note that the most dangerous kinds of switching transients from the point of view the transitional voltages' magnitudes are switching-offs capacitive currents of capacitor banks, no-load power transmission lines, and small inductive currents of no-load transformers and autotransformers [2, 3]. Just these kinds of transients are considered in this paper.

Taking into consideration arc phenomenon in circuit-breakers especially arc resistance seems to be important enough at studying processes carried near the current zero[4, 5]. For the problems dedicated to determination maximum possible magnitudes of transitional voltages and currents the minded account presents no such evident. Probably by just this reason there are not enough sources concerned to the problem under consideration. Moreover it may seem a priori that taking into account arc resistance must not have a notable influence because it relative minority in comparison with longitudinal impedances of electric networks especially at high free transitional frequencies. Besides in first appearance arc may just decrease magnitudes of transitional voltages but as it will be demonstrated below the matter considered is not as evident as it may seem a priori.

II.THEORETICAL GROUND

In accordance with classical theory overvoltages at switching-off capacitor banks and no-load power transmission lines are conditioned by accumulation of electric charge on capacitors at each series quenching of switching-off arc in circuit-breaker during its contact separation [6]. This explanation does not take into account high-frequency oscillations of recovery voltage across the circuit-breaker's poles and is satisfactory for low-speed circuit-breakers e.g. oil-filled ones. As it had been shown further at switching-off capacitive currents by high-speed circuit-breakers (vacuum and

SF6 ones) the overvoltages' ratios are determined rather by electric charge stayed on capacitance after a break of high-frequency current passed through arc [7].

Overvoltages at switching-off small inductive currents appear due to discharge of magnetic field's energy stored in transformer's (or autotransformer's) core after current chopping through the input capacitance which usually has very little value may cause high frequency free oscillations and high overvoltages [7]. Unlike capacitive currents switching-offs arc's repeating re-ignitions and re-strikes lead to decreasing switching overvoltages and ease switching-off small inductive currents. The greatest ratios of overvoltages and recovery voltages take place at absence of repeated re-ignitions in inter-contact space during the contacts separation time [8].

As it was stated in researches we carried-out earlier overvoltages at switching-offs capacitor banks of rated voltage 110 – 220 kV and reactive power 37.5 – 112 MVAr by vacuum and SF6 circuit-breakers do not exceed allowable values [9]. In the same time overvoltages at switching-offs no-load transformers and autotransformers of the same voltage range also do not exceed allowable values except very seldom cases (see [8]). For both kinds, considered switching recovery voltages across the circuit-breakers' contacts can prevail allowable level [10]. We had also stated that almost in all the cases overvoltages at use vacuum circuit-breakers are greater in comparison with SF6 ones.

Now consider circuit-breakers modeling. It is known the main characteristics of circuit-breakers determined their influences on switching process are dielectric strength restoration law, chop current and full operation time [11].It was proposed earlier to use a co-sinusoidal law of circuit-breaker's dielectric strength restoration. This law is formalized as following:

$$V_{str}(t) = 2^{-1}V_m\left\{1 - \cos\left[\frac{\pi(t-t_{off})}{T_{full}}\right]\right\} \tag{1}$$

where $V_{str}(t)$ is the acceptable law of circuit-breaker's dielectric strength restoration;V_m is the maximum value of dielectric strength; t is time; T_{full} is the full switch-off time of circuit-breaker; t_{off} is the initial instant of contact separation [12].

This law:
1. takes into account inertia of contact;
2. is matched good with the movement law of contact;
3. has acceptable coincidence with the real law presented in [13] for auto-compression (SF6) circuit-breakers so it was recommended to be used for their modeling.

For the vacuum circuit-breakers we here use the dielectric strength restoration law we had earlier offered in [14] as:

$$V_{str}(t) = 191.43\log\left\{1 + 5.75x_m\left\{1 - \cos\left[\frac{\pi(t-t_{off})}{T_{full}}\right]\right\}\right\} \tag{2}$$

This law takes into account both inertia of movable contact and inconstancy of vacuum gaps' strength against distance. Computer simulations done at use this law let to explain principal results got in [15].For vacuum circuit-breakers the most of authors use also linear restoration law (e.g. see [16]).

For comparison in the fig 1 the dielectric strength restoration laws by linear, co-sinusoidal and offered ways are presented graphically (the offered law is conventionally named logarithmic law). The corresponding graphs are consistently denoted as 1, 2 and 3. Note that the offered natural law has been distinguished from the corresponding empirical law by some values changing between -7% and +4% and gives satisfactory approximation for all the switching.

III.NETWORKS SIMULATED AND COMPUTATIONAL GROUND

Connection schemes concerned to the problem considered and their equivalent networks are presented in the fig 2 and fig 3.

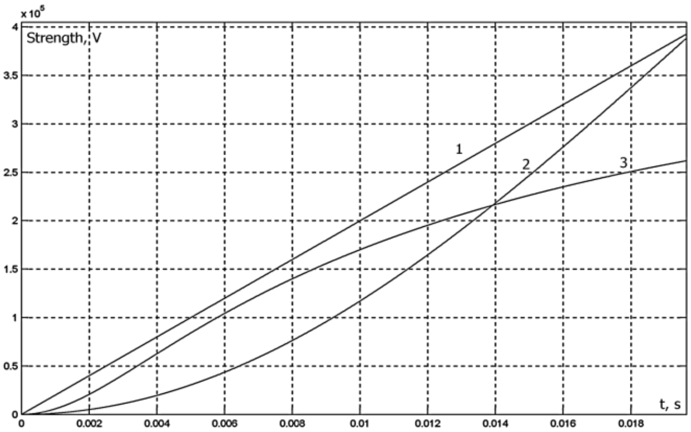
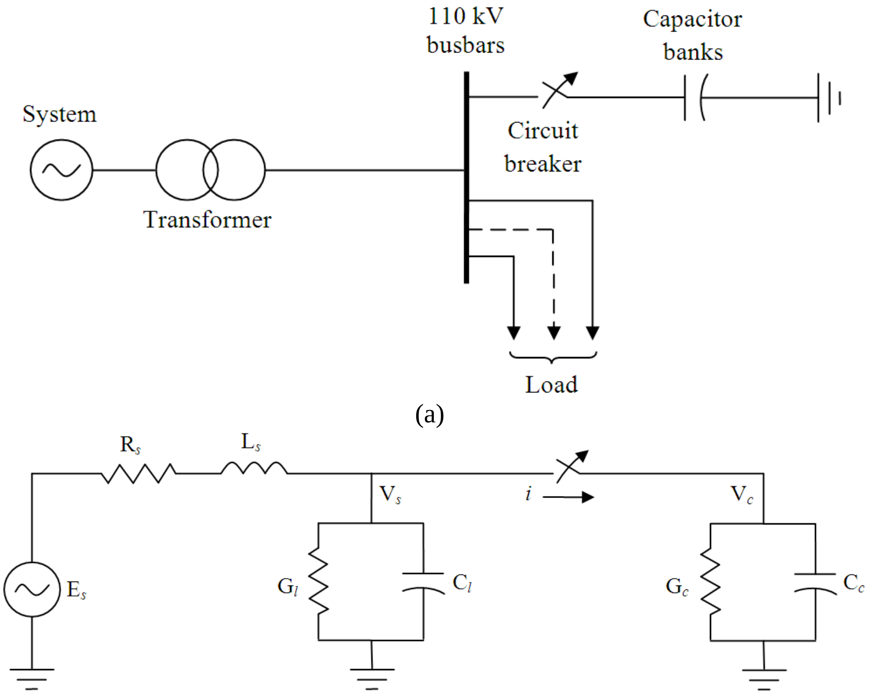


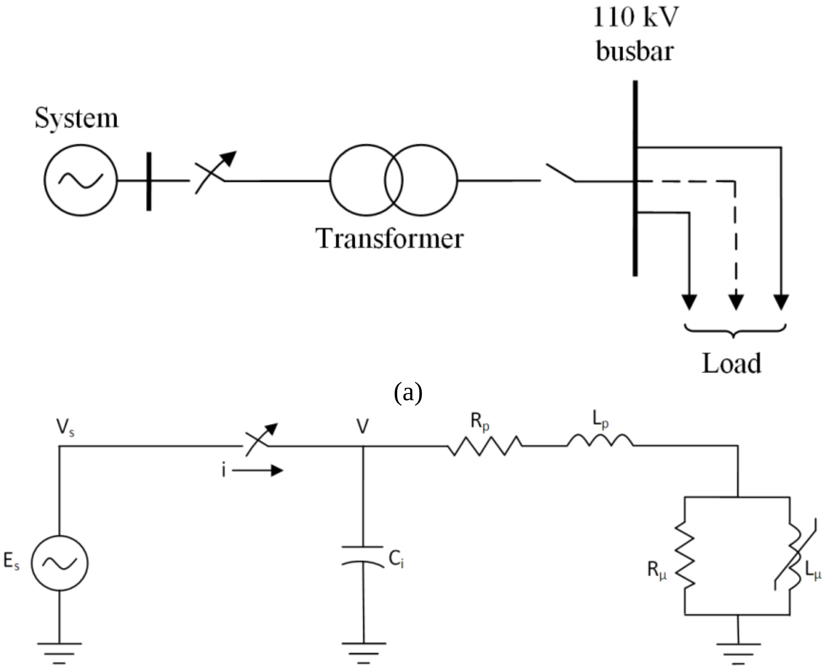
Fig. 1 Dielectric strength restoration laws: 1 and 3 for vacuum circuit-breakers, 2 for SF6 circuit-breaker



(a)

(b)

Fig. 2 Switching-off a capacitor bank: a) connection scheme; b) equivalent network (R, L, C and G are resistance, inductance, capacitance and conductance accordingly. Index “s” concerns to the source parameters, “l”- to the load parameters, “c”- to the capacitor banks parameters, Es is e.m.f. of voltage source)



(a)

(b)

Fig. 3 Switching-off unloaded transformer: a) connection scheme; b) equivalent network (R, L, C and G are resistance, inductance, capacitance and conductance accordingly. Index “s” concerns to the source parameters, “l”- to the load parameters, “c”- to the capacitor banks parameters, Es is e.m.f. of voltage source)

The ode23tb (stiff/TR-BDF2)method from the MATLAB was used for computer simulation. As it had been shown in [17] this method of ordinary differential equations’ solution is the best one from the point of view obtaining stable functions of transitional voltages and currents. The ways to get stable solutions also pointed in [17].

Current interruption in circuit-breakers (i.e. arc quenching) has taken place at:

$$|i| \leq I_{ch} \tag{3}$$

where i is decreasing current passing through the switching-off arc; I_{ch} is so called chop currentdepended on the circuit-breaker type and been one of the most parameters of circuit-breakers from the point of view possible magnitudes of transitional voltages at switching-offs [4, 18].

Repeated ignitions of arc has taken place at:

$$|\Delta V| \geq V_{ds}(t) \tag{4}$$

where ΔV is a recovery voltage between poles of the circuit-breaker; $V_{ds}(t)$ is a function of dielectric strength between the contacts of circuit-breaker (in detail see [9]).

Resistance of arc was presened in simulation model in correspondencewith [19, 20] as:

$$R_{arc}(t) = U_0 i_{sc}(t) + r_0 v(t - t_0), \qquad t_0 < t < t_1 \tag{5}$$

Where U_0 is the cathode voltage drop; r_0 is the arc resistance per meter gap length; v is the opening speed may be determined from the movement law of the movable contact; $i_{sc}(t)$ is the instantaneous value of the current passing through the arc; t, t_0 and t_1 are the moments of arcing phase, contacts separation and current zero, respectively.

IV.RESULTS OBTAINED AND THEIR DISCUSSION

The numerous simulation acts implemented for switching-off transitions of no-load transformers and capacitor banks by vacuum and SF6 circuit-breakers taking into consideration arc resistance and without taking into consideration arc resistance showed the following:

1. modeling without taking into consideration arc resistance in circuit-breakers leads to underestimation both overvoltage and recovery voltage at computer simulation switching-offs of small inductive currents by vacuum and SF6 circuit-breakers, in other words arc causes increasing of transitional voltages at switching-offs small inductive currents. The greatest underestimation takes place for recovery voltages' calculated values – about 5-7 % for vacuum circuit-breakers and about 15 % for SF6 circuit-breakers (simulations were implemented for several types of transformers);
2. modeling without taking into consideration arc resistance in circuit-breakers leads to overestimation both overvoltage and recovery voltage at computer simulation switching-offs of capacitive currents by vacuum and SF6 circuit-breakers. The greatest overestimation takes place for recovery voltages' calculated values – about 12 % for vacuum circuit-breakers, for SF6 circuit-breaker it does not exceed 5 % (simulations were implemented for 110 kV capacitor banks of three rated jet powers in the range 37.5 – 75 MVAr).

Some typical curves of transitional voltages are presented in the figures given below. In the fig 4 and fig 5 are presented simulated transitional voltages at switching-off 110 kV no-load transformer (110/35 kV, 40.5 MVA Ukraine-produced) by SF6 circuit-breaker without taking into consideration arc resistance and with taking into account arc resistance respectively.

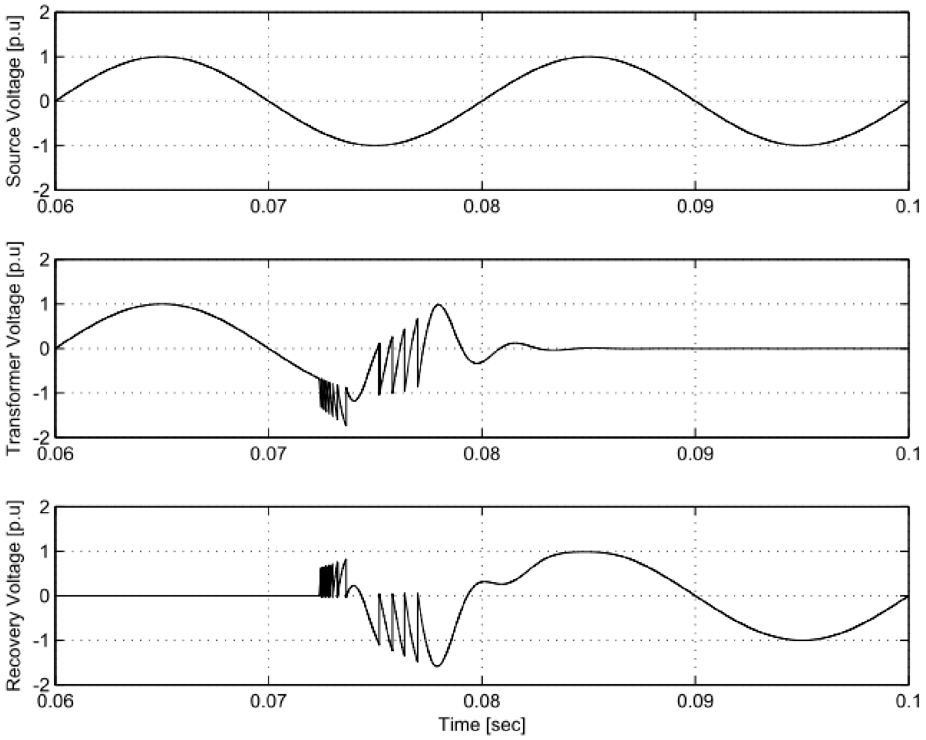


Fig. 4 Simulated transitional voltages at 110 kV no-load transformer switching-off by SF6 circuit-breaker without taking into consideration arc resistance

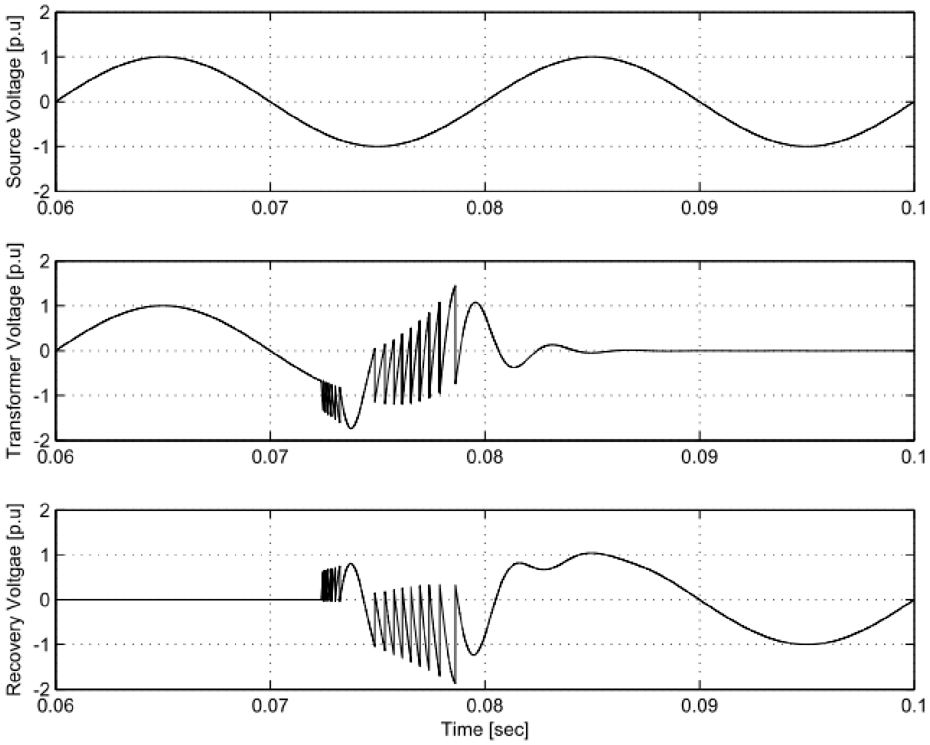


Fig. 5 Simulated transitional voltages at 110 kV no-load transformer switching-off by SF6 circuit-breaker taking into consideration arc resistance

As it is seen from the curves obtained taking into consideration arc resistance has serious influence on the simulation results. Taking arc into consideration provokes more computational re-ignitions due to additional attenuation of transitional voltages' free oscillations.

As a result the last peak of recovery voltage (see interval 0.075 – 0.08 s in the Fig.4 and Fig.5) determined its maximum magnitude takes place at the greater time and subsequently at the greater value of dielectric strength. In other words due to taking into consideration arc resistance intersection between recovery voltage and dielectric strength curves occurs at greater times i.e. at their greater magnitude. Note that at the case of SF6 circuit-breaker this effect is more evident because of its dielectric strength restoration law's softness in comparison with one for vacuum circuit-breaker.

In the fig 6 and fig 7 are presented simulated transitional voltages at switching-off 110 kV capacitor bank of rated reactive power 75 MVAr by vacuum circuit-breaker without taking into consideration arc resistance and with taking into consideration arc resistance respectively. Note that modeling without taking into consideration arc resistance at switching-off capacitor banks leads to the notable overestimation transitional voltages may exceed 10 %. For the considered case the minded overestimation is about 12 % (see Fig.6 and Fig.7). Arc increases attenuation of voltages' free oscillations that leads to decreasing both overvoltages across the capacitor banks terminals and recovery voltage on circuit-breaker. This effect is more notable for vacuum circuit-breakers because that maximum recovery voltage at the case of vacuum circuit-breaker begins to decay from the higher magnitude than at the case of SF6 circuit-breaker. Remind that in general transients conditioned by vacuum circuit-breakers switching-offs have been accompanied with greater transitional voltages because of higher steepness of their dielectric strength restoration law [21].

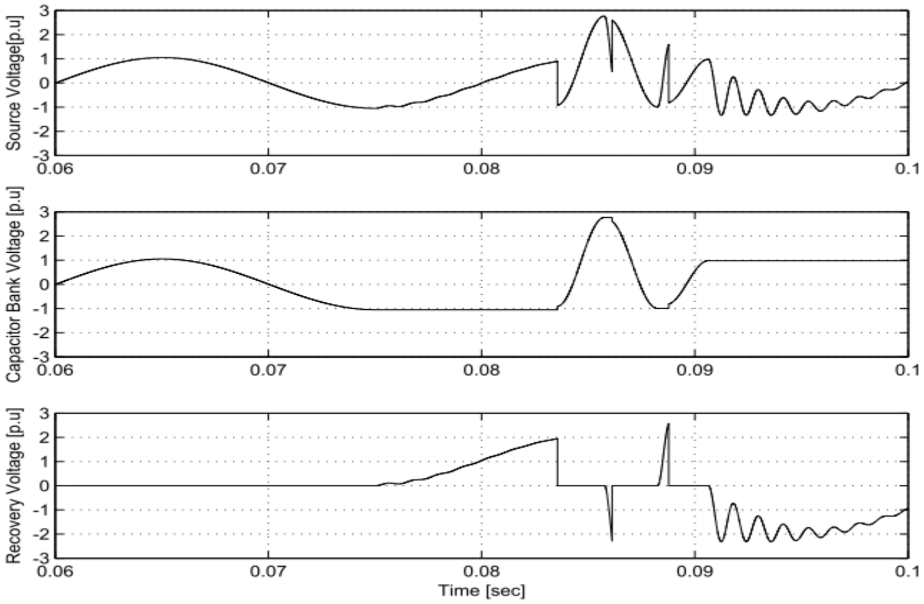


Fig. 6 Simulated transitional voltages at 110 kV, 75 MVAr capacitor bank switching-off by vacuum circuit-breaker without taking into consideration arc resistance

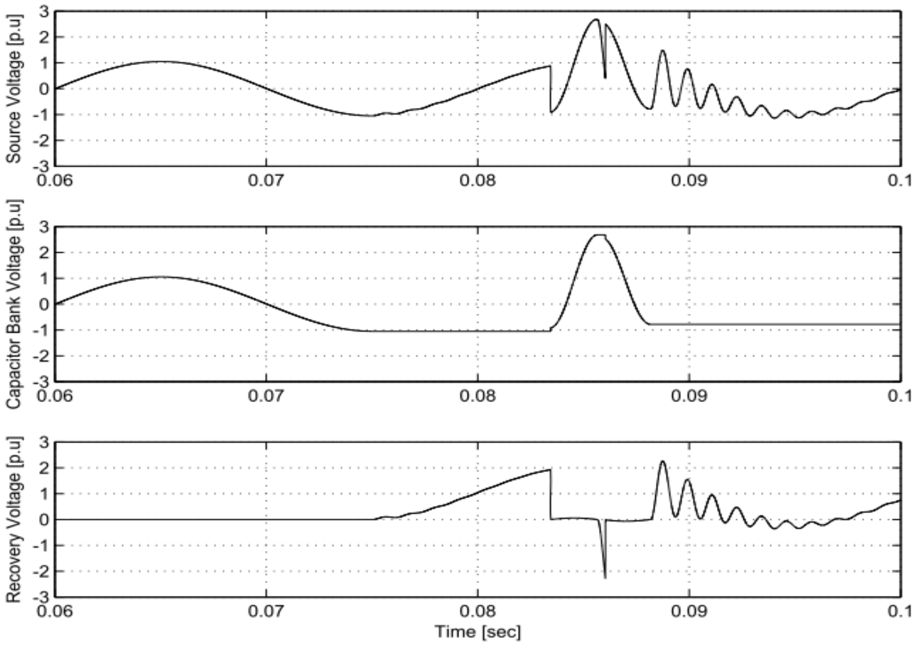


Fig. 7 Simulated transitional voltages at 110 kV, 75 MVAr capacitor bank switching-off by vacuum circuit-breaker taking into consideration arc resistance

V.CONCLUSION

Modeling without taking into consideration resistance of arc in circuit-breakers on transitional processes may have notable influence on transitional voltages have taken place at switching-offs in electric power systems. Modeling without taking into consideration resistance of arc in circuit-breakers can both underestimate and overestimate magnitudes of transitional voltages dependently on type of switched-off installation. It is expedient to take arc resistance into consideration at least for switching-off small inductive currents by SF6 circuit-breakers and capacitive currents by vacuum circuit-breakers.

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BIOGRAPHY

Tahir Lazimov was born in Baku, Azerbaijan in 1955. He received the engineer qualification in electrical engineering from the Azerbaijan State Oil Academy, Baku, in 1977, Ph.D. degree in high voltage engineering from the Tomsk Polytechnic Institute, Tomsk, Russia Federation, in 1989. From 1977 to 2004 he worked in the Power Engineering Research Institute, Baku, Azerbaijan. Since 2004 he has been a head of the Electric Supply and Insulation Department in the Azerbaijan Technical University, Baku. He is the author of about 170 scientific works including three books, dozens of articles and papers. His research areas include transitional processes in power electric systems and their computer simulation, power systems electromagnetic compatibility. Professor T. Lazimov is IEEE Senior member, the member of the Scientific Board on Electrical Power Engineering at the Azerbaijan National Academy of Science and also some other scientific councils and editorial boards in Azerbaijan and abroad.

Esam Saafan was born in El-Mansoura, Egypt in 1977. He received the B.Sc. and M.Sc. degrees in Electrical Engineering from Faulty of Engineering, University of El-Mansoura, Egypt in 2001 and 2007 respectively. He obtained the Ph.D. degree in High Voltage Engineering in 2012 from Azerbaijan Technical University, Baku. From 2001 to 2012 he worked in the Electrical Engineering Department, University of El-Mansoura, Egypt as a Lecturer Assistant. Since 2012, he has been a Lecturer in the same university.
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