Transitional Recovery Voltages at Capacitive Currents Switching-offs by Vacuum And SF6 Circuit-Breakers

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***Abstract*—The paper presents results of computer simulation the recovery voltages conditioned by capacitive currents switching-offs by high voltage vacuum and auto-compression (SF6) circuit-breakers. Dependence of recovery voltages on some influencing factors, especially on type of circuit-breaker was researched.**

Keywords: recovery voltages, capacitive currents, switching overvoltages, capacitor banks, dielectric strength restoration law

I. Introduction

In studying transitional processes a great importance has mainly been given to evaluation the maximum values of voltages (overvoltages) on switched elements of power system or currents (overcurrents) through these elements. As a rule recovery voltages (inter-contact voltages) are studied in the view of their influence on the minded transitional voltages and currents. It is known that repeating re-ignitions of arc in inter-contact spaces of circuit-breakers take place in a case of predomination the recovery voltage upon the dielectric strength of inter-contact space [1, 2]. In the same time recovery voltage itself has an important interest conditioned by it influence on the voltage divisors (capacitive and resistive ones) connected between poles of circuit-breakers. It must be noted that especially capacitive elements are sensitive enough to overvoltages influence.

It is widely known that magnitudes of all the transitional voltages (including overvoltages on switched installation and on busbars of feeding transformer and also transient recovery voltage) depend on numerous factors. According to [3] there are:

- temporal derivatives of switched-off current just before current zero and inter-contact voltage just after current zero;
- maximum value of switched-off current;
- contact distance at current zero;
- arcing time;
- contact materials and their shape (note that last two factors determine value of so called chopping current);

Although these influencing factors were pointed for vacuum circuit-breakers they may be spread also to SF6 circuit-breakers.

Note that at computer simulation of switching processes accepted law of circuit-breakers dielectric strength's restoration may have great influence on calculated overvoltages and their probabilistic characteristics [4, 5]. Because of this reason one of the main problems for researchers is to determine an adequate law of circuit-breaker dielectric strength's restoration (see the third chapter of the present paper).

It must be mentioned that resistance of switching-off arc in pole-to pole space may also influence on switching process [6].

The dependence of transitional voltages' magnitudes on distance between contacts mentioned in [3] expresses in general influences of other factors such as dielectric strength restoration law and so called time-off, i.e. the instant when the contacts of circuit-breaker begin to separate. This time has quite random value. It is one of the main factors influencing on number of repeating re-ignitions during the contacts separation.

II. Theoretical Ground of Switching-off Process Simulation

The equivalent networks of schemes under consideration are shown in the figure 1. Corresponded electrical schemes and numerical values of parameters used for computer simulation were given in [8] for the cases of unloaded power transmission lines and in [9] for capacitor banks switching-offs.

While carrying out the present research we have applied a mathematical model described in [5, 10]. The known phenomenon of current chopping was modeled in accordance with [5, 11]. Electrical strength of vacuum and auto-compression circuit-breakers had been given in the numerical models in accordance with restoration laws presented in [4, 5].

It is known that there are numerous methods for numerical solution of differential equations and their systems and simulation the processes they have described [12, 13]. Effective application of each method depends on some factors, especially on stability of solutions which is determined mainly by so called stiffness of equations [12]. In one's turn the stiffness depends on coefficients of differential equations solved. As we stated earlier in [14] the best method (i.e. the most optimal method) for the problem under consideration (generally speaking, for a class of problems) and ranges of parameters from the point of view the stability is ode23tb (stiff/TR-BDF2) method. For this reason we used just this model which has shown satisfactory adequacy in our previous and present researches.

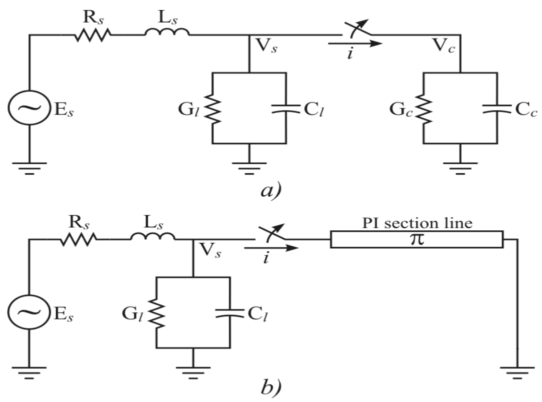

Figure 1. The equivalent networks of connection schemes for the cases of switching-off the capacitor banks (a) and unloaded power transmission line (b). R, L, C and G are resistance, inductance, conductance and capacitance accordingly. Index "s" concerns to the source parameters, "l"- to the load parameters, "c"- to the capacitor banks parameters, Es is e.m.f. of voltage source (rms value).

III. Dielectric Strength Restoration Laws Used

As it is known the main characteristics of circuit-breakers determined their influence on switching process are dielectric strength restoration, chopping current and full operation time [15].

It was proposed earlier to use a co-sinusoidal law of circuit-breaker's dielectric strength restoration. This law is formalized as following:

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

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 [4].

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 [16] for auto-compression (SF6) circuit-breakers.

It was shown that the co-sinusoidal law may be used both for auto-compression and vacuum circuit-breakers. This law gives the most successful approximation for real $V_{str}(t)$ curves of auto-compression circuit-breakers. For vacuum circuit-breakers the most of authors use linear restoration law [17, 18].

Concerning to influence of restoration law (linear or co-sinusoidal) we have earlier stated the following:

- using the linear law of circuit-breaker's dielectric strength restoration leads to overestimation of over-voltages calculated ratios both for auto-compression and vacuum circuit-breakers;
- using the linear law of circuit-breaker's dielectric strength restoration leads to underestimation of arc repeated re-ignitions' probability both for auto-compression and vacuum circuit-breakers;
- circuit-breakers presented with linear restoration law have greater "stiffness" from the point of view switching-off processes in comparison with ones presented with co-sinusoidal law [4].

These results are in accordance with general representations of switching over-voltages' theory and also with the main strength characteristics of circuit-breakers.

We have found an approximation for dielectric strength of vacuum circuit-breaker [19] on the base of empirical curve given in [20] as following

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

For comparison in the figure 2 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 period.

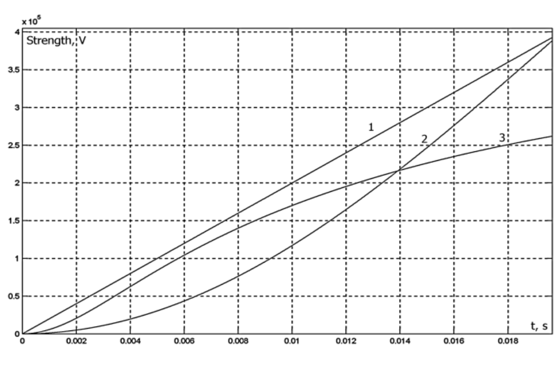

Figure 2. Linear (1), co-sinusoidal (2) and logarithmic (3) laws of circuit-breaker's dielectric strength restoration.

IV. DISCUSSION

We had stated earlier that maximal ratios of overvoltages conditioned by capacitive currents switching-offs by vacuum and auto-compression circuit-breakers do not exceed the rated amplitude's triple value [5]. Our results are corresponded with the results obtained for unloaded transmission lines' switching-offs [21]. We had also determined that magnitudes of recovery voltages may in some cases reach more than triple value.

The results of capacitor banks with rated jet powers of 37-112 MVAr switching-offs' computer simulation are presented below. The results were obtained for the three different laws of circuit-breaker's dielectric strength restoration. In accordance with [20] the value of chopping current accepted was 5 A.

TABLE I. CALCULATED RATIOS OF OVERVOLTAGES ON CAPASITOR BANKS TERMINALS (V_C) AND INTERCONTACT VOLTAGES OF CIRCUIT-BREAKER (ΔV) FOR RANGE OF JET POWERS AND DIFFERENT LAWS OF DIELECTRIC SRENGTH RESTORATION, $V_C/\Delta V$

Accepted Restoration Law \ Jet Power of Capacitor Banks	37 MVAr	56 MVAr	75 MVAr	112 MVAr
Linear, $\frac{dV}{dt} = const = 20\frac{kV}{ms}$	$\frac{2.24}{2.12}$	$\frac{2.53}{2.28}$	$\frac{2.56}{2.30}$	$\frac{2.74}{2.49}$
Co-sine, $\left(\frac{dV}{dt}\right)_{aver} = 20\frac{kV}{ms}$	$\frac{1.91}{2.91}$	$\frac{2.21}{2.20}$	$\frac{2.32}{2.31}$	$\frac{2.46}{2.49}$
Logarithmic	$\frac{2.44}{2.13}$	$\frac{2.69}{2.43}$	$\frac{2.77}{2.58}$	$\frac{2.84}{2.67}$

Consider now some obtained results. For all the compared and presented simulation acts we accepted a convention of maximum possible similarity of conditions.

Note that there are certain correspondence between laws accepted and circuit-breaker type (e.g. see [9, 15]): thus for modeling of dielectric strength of auto-compression (SF6) circuit-breakers the co-sinusoidal law is more preferable [4, 15] whereas for the vacuum circuit-breakers most of authors use the linear restoration law [17, 18]. Other differences between circuit-breakers types in simulation models are: different values of dielectric strength in inter-contact spaces; different full times of contact separation which is usually greater for auto-compression circuit-breakers; different chopping currents (the last parameter is important especially for cases of unloaded power transmission lines switching-offs [8]).

As it was shown in [19] dielectric strength restoration of vacuum circuit-breakers may have been also expressed by logarithmic law which allows take into account inconstancy of the strength in vacuum gaps (see also chapter III of the present paper).

Some calculated transitional voltages taken place at switching-off capacitor banks of high jet power are presented in the figure 3, 4 and 5. There are voltages on source busbars V_S, voltage on capacitor banks terminals V_C and intercontact voltages of circuit-breaker ΔV. The calculated cases shown are switching-offs the capacitor bank of rated jet power 75 MVAr at use linear, co-sinusoidal and logarithmic restoration laws. As it was noted above the linear and logarithmic laws are more preferable for vacuum circuit-breakers unlike co-sinusoidal one which is suitable for SF6 circuit-breakers.

In correspondence with results obtained and presented in the table 1, figure 3, 4 and 5 we can state the following:

- the greatest switching overvoltage ratios take place at use the logarithmic law (see chapter III). There is 8-12 % difference between ratios of terminal voltages and intercontact voltages conditioned by the restoration law used. Note that according to our evaluations the average velocity of dielectric strength restoration at use the logarithmic law in the 0 – 7 ms time range is very close to the constant velocity of the linear law used;
- the logarithmic restoration law is characterized by decreasing of strength at increasing intercontact distances. This is quite suitable to the physical nature of vacuum intercontact gaps. As it was described in [22] there are some probabilities of arc's repeated re-ignition during the decades of milliseconds conditioned by strength velocity decreasing. In our case the minded fact reveals itself due to the third repeated re-ignition of vacuum arc (see figure 5). In our opinion it confirms expediency of use the logarithmic restoration law for vacuum circuit-breakers. So, results obtained at use the logarithmic law (see table 1 and also [10]) are more adequate for vacuum circuit-breakers than ones obtained at use other known laws.

In the table 2 the results of computer simulation of 110 kV power transmission lines are presented. As it is seen from this table there is the some tendency on overvoltage ratios as it has taken place for capacitor banks: the greatest transitional overvoltages corresponds to the case of use the logarithmic law. Note that unlike capacitor banks almost all the simulation acts for power transmission lines was accompanied just a single repeated re-ignition. Besides, unloaded lines have relatively less current. For these reasons switching-offs of power transmission lines cause less transitional voltages than capacitor banks (see also [8]).

TABLE II. CALCULATED RATIOS OF OVERVOLTAGES ON 110 KV UNLOADED POWER TRANSMISSION LINES' BUSBARS (V_S) AND INTERCONTACT VOLTAGES OF CIRCUIT-BREAKER (ΔV) AT USE DIFFERENT LAWS OF DIELECTRIC SRENGTH RESTORATION, $V_S/\Delta V$

Accepted Restoration Law \ Length of Line, km	50	100
Linear, $\frac{dV}{dt} = const = 20\frac{kV}{ms}$	$\frac{1.40}{2.03}$	$\frac{2.06}{2.40}$
Co-sine, $\left(\frac{dV}{dt}\right)_{aver} = 20\frac{kV}{ms}$	$\frac{1.35}{1.97}$	$\frac{1.98}{2.33}$
Logarithmic	$\frac{1.52}{2.05}$	$\frac{2.17}{2.59}$

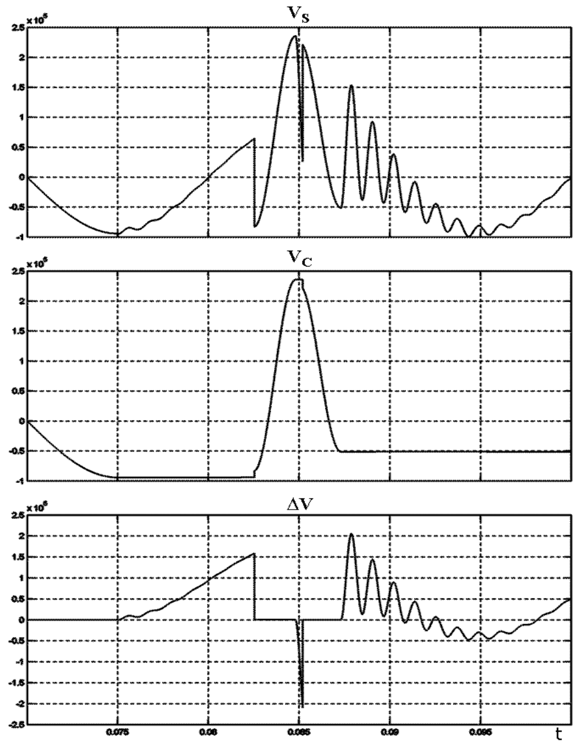

Figure 3. Transitional voltages conditioned by capacitor banks switching-off at use the linear restoration law

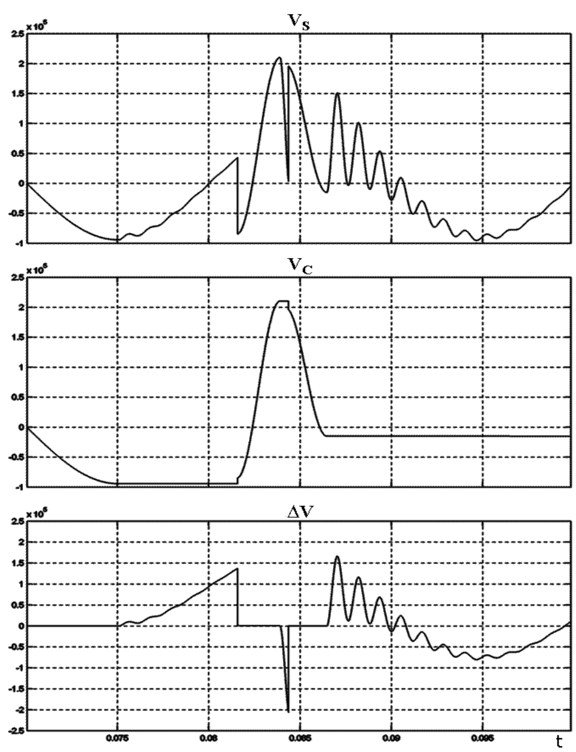

Figure 4. Transitional voltages conditioned by capacitor banks switching-off at use the co-sinusoidal

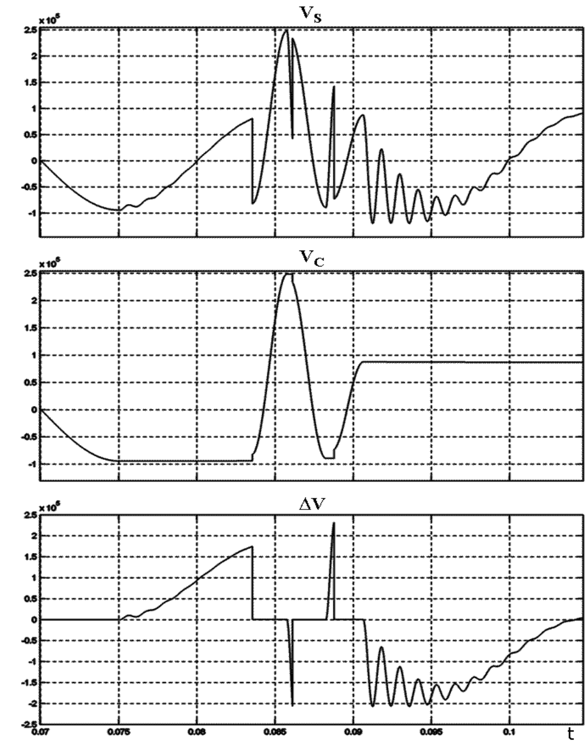

Figure 5. Transitional voltages conditioned by capacitor banks switching-off at use the logarithmic restoration law

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