A Circuit Breaker Model for Small Inductive Current Interruption

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Abstract

In this paper, the behaviour of a circuit breaker during the interruption of small inductive currents is modelled. The importance of representing non-ideal switching in the interruption of small inductive currents is also investigated. A multi-parameter mathematical model is used exploiting MODELS utility of EMTP/ATP.

Key-words: circuit-breaker model, arc, small inductive current interruption, EMTP

I. INTRODUCTION

Modelling of power switch behaviour during current interruption has been the subject of extensive research [1-16], due to the harmful consequences provoked to the electric energy system equipment. In particular, interruption of small inductive currents is characterised by the development of considerably high overvoltages [4-7].

More specifically, when the steady-state current is highly inductive, interruption does not take place at normal current zero but few instants earlier, due to current chopping [5-7]. This occurs when the instantaneous current value tends to zero and switch contacts start separating from each other, initiating the formation of an arc process (thermal period). This is represented by a high-frequency oscillation with negative damping (**arc instability**). If the arc quenches, then current conductance is terminated and only an extremely small current flows (**post-arc current**). If the arc does not extinguish, current continues flowing (**thermal reignition**), thus leading to interruption failure.

In the case of successful arc extinction, the thermal period is terminated and the dielectric period starts. Thus, the voltage between switch contacts (transient recovery voltage) starts to increase rapidly, and similarly dielectric strength in the switch interior can not be automatically restored. If the rate of rise of recovery voltage (***RRRV***) exceeds the rate of recovery of dielectric strength dielectric reignition occurs, otherwise interruption is successful. In case of dielectric reignition, a high-frequency current starts flowing again through the switch. This current can be further interrupted by the switch, provided that this is within its switching capabilities, i.e. the rate of change of current is of fairly small value. Furthermore, the aforementioned procedure can be repeated several times (multiple reignitions) leading to **voltage escalation**[4-7].

Interruption at non-zero current [1-11], i.e. chopping current i_{ch}, means that there is some energy stored in the inductive elements which is transferred to the nearby capacitances, C, according to the energy preservation principle:

$$\frac{1}{2}Li_{ch}^2 = \frac{1}{2}Cv^2 \tag{1}$$

As the capacitance values are extremely small, the corresponding voltage value is very high. This high voltage is superimposed to the, due to the inductive character of the network, close-to-peak steady-state value. Thus, considerable overvoltages can be developed which stress the switching equipment [4-7].

The purpose of this paper is twofold: first to present a switch model that can represent phenomena occurring during small inductive current interruption; second, to investigate the importance of representing these phenomena in terms of the developed overvoltages which stress the switch equipment. The developed black-box model, is flexible allowing investigation of the possible evolution of the switching process. All the simulations are performed using the widely known computer program EMTP/ATP [12-13] and in particular exploiting its incorporated MODELS utility.

II. SWITCH MODELLING

A. *Thermal period*

Thermal period begins when the instantaneous current value drops below chopping level, i_{ch} . The circuit model of a switch arc conductance during this period is a variable resistor the value of which is obtained from the solution of a non-linear differential equation.

In the case of small inductive current interruption, the arc equation providing the most accurate results is the modified Mayr-Avdonin arc equation [4]:

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\tau_0 g^{\alpha}}\left(\frac{u.i}{P_0 g^{\beta}} - 1\right) \tag{2}$$

where

u,i,g: arc voltage, current and conductance respectively

$\tau_o, P_o, \alpha, \beta$: arc model parameters.

Arc model parameters $\tau_o, P_o, \alpha, \beta$ have no physical meaning and they are obtained by interpolation in curves obtained from experiments, as thoroughly described in [4,8-11]. It is worth noting that their values, which depend on the circuit breaker type and the interrupted network have been reported to be within certain limits [4]. Therefore an investigation of their influence in the evolution of interruption is feasible.

The initial conditions of the differential equation (2), i.e. the initial value of arc conductance is the steady-state conductance, g_{ss} ,which is obtained from equation (2) if the left hand side is set equal to zero:

$$g_{ss} = \sqrt[(\beta+1)]{i / P_0} \qquad (3)$$

B. Dielectric period

The switch state in this period is specified by the comparison of the calculated RRRV with the critical rate of recovery of dielectric strength (**dv_{cr}/dt**) regarding reignition, as well as the comparison of the voltage developed with the critical value **v_{cr}** for reignition. Moreover, it is also specified by the comparison of the current derivative di/dt with the corresponding critical value (**di_{cr}/dt**) regarding interruption of a dielectric reignition, as described in section I.

C. Circuit Breaker model

The solution algorithm described above has been applied in EMTP/ATP [12-13], the switch component is modelled exploiting the MODELS utility and, in particular, the general-purpose multi-port component (type 94-component driven by MODELS [13]).

The Circuit Breaker is modelled as a non-linear resistance the value of which is calculated by (2). The latter is integrated using the trapezoidal rule [12-16].

It is worth noting, that the mathematical solution of the network becomes more complicated in case of three-phase switch units, due to the mutual couplings amongst phases of the interrupted network.

The parameters of the switch model are the following:

- concerning thermal period: $\alpha, \beta, P_o, \tau_o, i_{ch}$
- concerning dielectric period: dv_{cr}/dt, di_{cr}/dt

III. STUDY CASES

The switch model described above has been used in the simulation of the following cases:

- **single-phase reactor interruption**, where the influence of the model parameters on the interruption process is investigated.
- **three-phase reactor interruption**, where the influence of representing is investigated in two methods of reactor earthing.
- **three-phase reactor loaded transformer interruption**, where the influence of representing non-ideal switching is also investigated.

IV. SIMULATION RESULTS- DISCUSSION

A. Single-phase reactor coil interruption

The network with the circuit breaker considered is shown in Figure 1, while the characteristic values of the circuit components are tabulated in Table I.

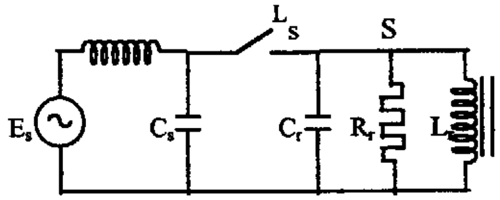

Figure 1 Single phase reactor coil interruption

Table I. Data of the network considered in Figure 1.

E_s=30 kV (rms)	C_r= 1.0 nF
L_s= 10 mH	R_r=4.5 kΩ
C_s= 0.5 nF	L_r= 57 mH

Regarding switch model parameters, the tabulated values on Table II, correspond mostly to SF6 and air-blast type circuit breakers [4,8-11]

Table II. Switch model parameters of the network shown in Figure 1

<table>
<tr><td>α=0.9</td><td>β=0.2</td><td>Po=2000</td><td>τ_0=10 E-6</td><td>i_{ch}=10 A</td></tr>
<tr><td colspan="5">dv_{cr}/dt= 9 kV/μs v_{cr}=80 kV di_{cr}/dt= 1 A/μs</td></tr>
</table>

Using this setup, waveforms like the one shown in Figure 2, are obtained. These results are comparable with those reported in the literature [5-7].

More specifically, in Figure 2, where the current waveform is presented, at 9.962 ms the thermal period begins and a remarkable current chopping is recorded, leading, however, to arc extinction. The frequency of the corresponding oscillation is in the order of 250 kHz. Approximately at 9.974 ms when arc has quenched, the dielectric period begins. Thus, when the calculated rrrv value exceeds the preset threshold of 9 kV/μs, dielectric reignition takes place. This reignition can not be interrupted at the subsequent current zero as the corresponding current derivative exceeds the marginal value of 1 A/μs.

In the following, the effect of the switch model parameters that are critical in the thermal period is investigated. The same network is used. Each time one parameter varies its value within the range presented in Table III, while the rest of the parameters is set according to Table II.

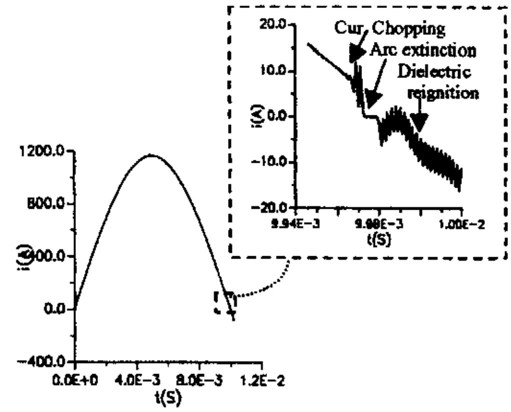

Figure2 Switch current (arc is quenched, however dielectric regnition occurs)

Table III. Range of values of switch model parameters

$\alpha = -2 \ldots +2$
$\beta = -2 \ldots +2$
$P_0 = 200 \ldots 20000$
$\tau_0 = 1E\text{-}6..10E\text{-}6$
$I_{ch} = 6..14$ A

The effect of each parameter on the value of the arc conductance is presented in Figures 3-7 and the following conclusions are drawn:

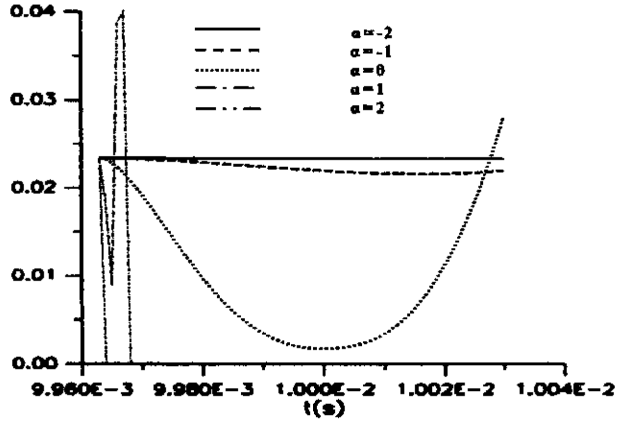

Figure 3 Influence of parameter α on arc conductance

- small values of parameter α lead to thermal reignition, Fig. 3, while as α tends to increase then arc extinction occurs without any noticeable current chopping oscillation. Therefore, it can be argued that arc conductance sensitivity with respect to α is of negative value.

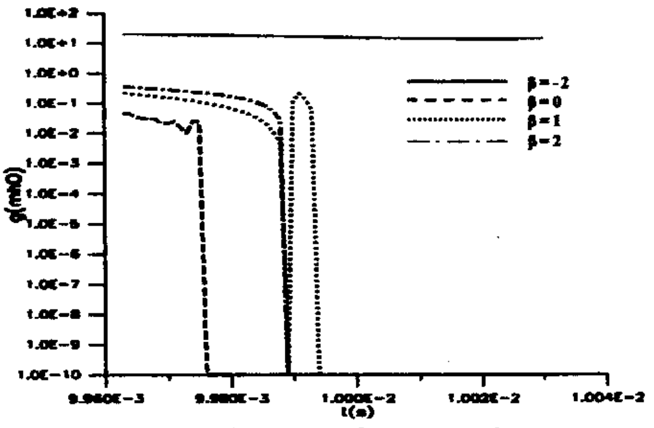

Figure 4 Influence of parameter β on arc conductance

- regarding the influence of parameter β, in case of small values in the vicinity of 0, arc extinction occurs, whereas if the absolute value of β exceeds 1, thermal reignition takes place, Fig 4. It is worth noting, that this parameter does not influence only the evolution of arc conductance like the other parameters, but the initial value of this conductance, too (see equation 3).
- concerning parameters P_0 and τ_0, it can be observed that the more their values increase the more significant current instability becomes, Figs 5-6.

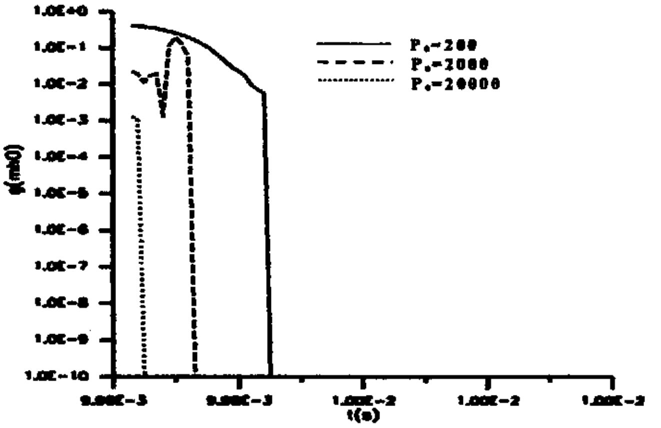

Figure 5 Influence of parameter P_0 on arc conductance

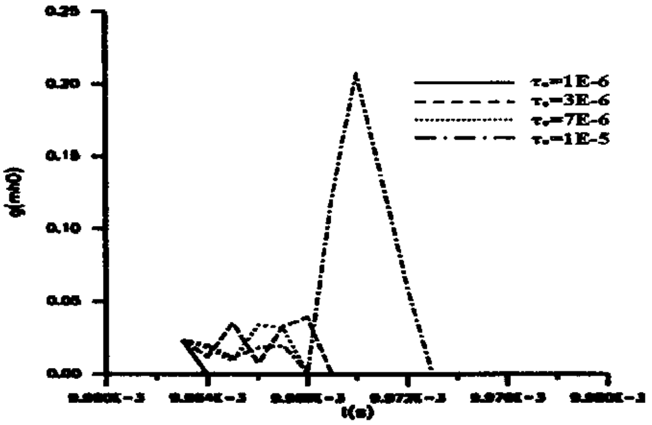

Figure 6 Influence of parameter τ_0 on arc conductance

- regarding parameter i_{ch}, in the region 6 A-10 A, current chopping oscillation becomes increasingly significant as current grows, while the opposite is valid in the region 10 A-14 A, Fig 7.

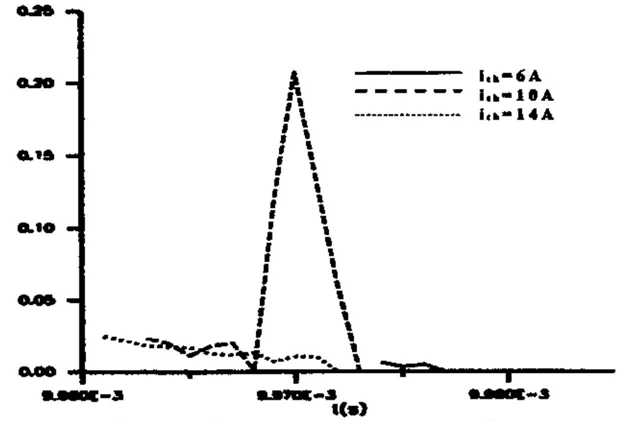

Figure 7 Influence of parameter i_{ch} on arc conductance

- in most cases, arc extinction leads to dielectric reignition. As mentioned above, the latter occurs when the developed rrrv exceeds a preset critical value; in a more exact representation however this critical value would be time-dependent.
- a general remark is that the interruption process simulation is very sensitive to all the model parameter values.

B. Three-phase reactor coil interruption

The main characteristics of the network considered, are presented in Table IV, while the circuit breaker data are the same with those of the single-phase case, see Table II. Two different ways of reactor winding connection have been examined, namely non-grounded star connection and grounded star connection.

Table IV. Data of the 3-phase reactor network

System voltage	25 kV	
System Impedance	*Inductance*	10 mH/phase
	Capacitance	0.5 nF/phase
compensation reactor coil	*self inductance*	44.88 mH/phase
	Mutual inductance	-12.42 mH/phase
	Capacitance	1 nF/phase
	Resistance	4.5 kΩ/phase

In Figures 8-9, switch currents for the cases of grounded and ungrounded star connection are shown. It can be seen that:

- in all cases, current interruption is successful. At the interruption instant, the current chopping effect and the arc instability can be observed.
- in grounded star connection, all three phases clear independently from each other. Furthermore, arc instability differs from phase to phase, being more remarkable in the first-pole-to-clear case.
- on the contrary, in the ungrounded star connection, when the first-phase clears the system turns into single-phase mode and the remaining two phases clear simultaneously. However, current chopping is almost identical in all the three phases. On the other hand, in both star grounded and ungrounded cases, current chopping observed in the first-phase-to-clear is identical, since at this clearance the network is symmetrical.

The influence of non-ideal switching can be observed if the overvoltages obtained in this case are compared with those obtained in the case of ideal switching (interruption exactly at current zero).

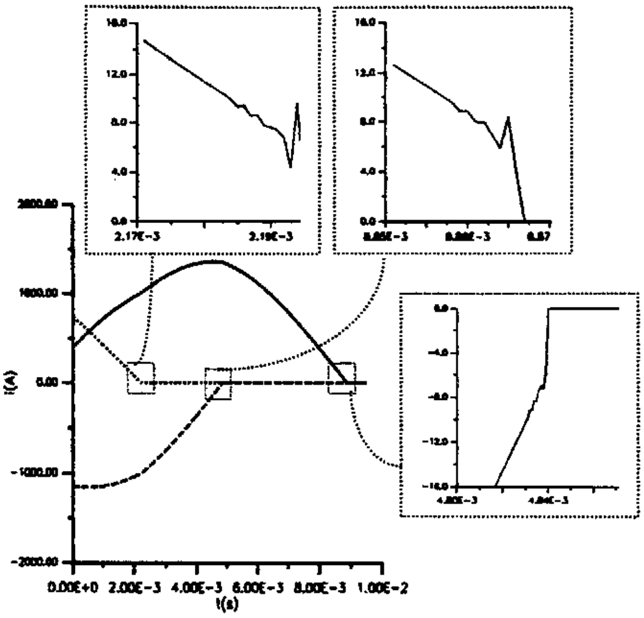

Figure 8 Three-phase currents in the interruption of a reactor with grounded star connection

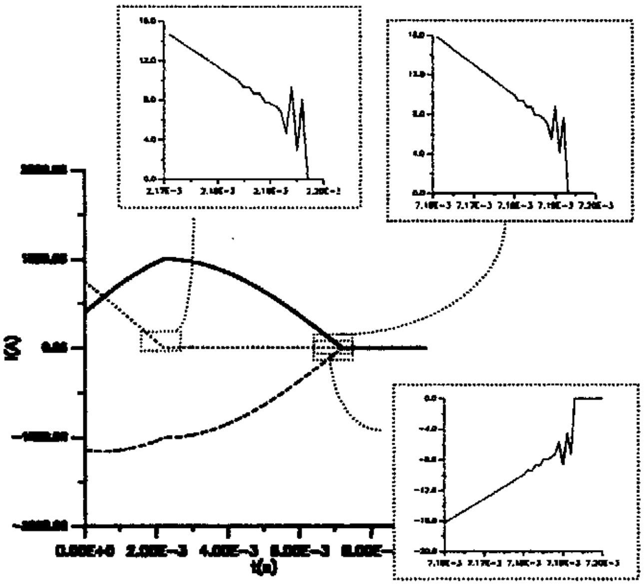

Figure 9 Three-phase currents in the interruption of a reactor with ungrounded star connection

In Tables V-VII, the maximum overvoltage values are compared. As it can be seen:

- non-ideal switching leads to considerably higher overvoltages than those of the ideal case. The differences noticed vary from 24% up to 68%.
- greater differences are observed in the second- and third-phase-to-clear.
- in the ungrounded star case, the highest peak overvoltage is noticed in the first-phase-to-clear, whereas, in the grounded star case, the second- and third-phase-to-clear overvoltages are the highest.

Table V. Maximum overvoltages in the case of ideal switching

winding connection	*1st phase to clear ("c")*	*2nd phase to clear ("b")*	*3rd phase to clear ("a")*
ungrounded star	50.16 kV (2.05 pu)	29.70 kV (1.21 pu)	32.38 kV (1.32 pu)
grounded star	27.11 kV (1.11 pu)	30.81 kV (1.26 pu)	29.32 kV (1.20 pu)

Table VI. Maximum overvoltages in the case of non-ideal switching

winding connection	*1st phase to clear ("c")*	*2nd phase to clear ("b")*	*3rd phase to clear ("a")*
ungrounded star	62.14 kV (2.54 pu)	45.99 kV (1.88 pu)	49.36 kV (2.02 pu)
grounded star	40.27 kV (1.64 pu)	48.81 kV (1.99 pu)	49.25 kV (2.01 pu)

Table VII. Comparison of maximum overvoltage values in the cases of ideal and non-ideal switching

winding connection	*1st phase to clear("c")*			*2nd phase to clear ("b")*			*3rd phase to clear ("a")*		
	ideal	non-ideal	%difference	ideal	non-ideal	%difference	ideal	non-ideal	%difference
ungrounded star	2.05pu	2.54pu	23.9	1.21pu	1.88pu	55.4	1.32pu	2.02pu	53.0
grounded star	1.11pu	1.64pu	47.7	1.26pu	1.99pu	57.9	1.20pu	2.01pu	67.5

C. Interruption of three-phase reactor loaded transformer

The main characteristics of the network considered are presented in Table VIII. The transformer model is as described in [19-20].

Table VIII. Data of 3-phase reactor loaded transformer case

System voltage	400 kV
Transformer	400 kV/150 kV/30 kV, 280/280/60 MVA, Ye/Ye/Δ, 5-leg core
Reactor coil	60 MVA, Y connection, losses 132 kW
Circuit breaker	α= 0.25 β=0.9 P_0=2.5x10^5 τ_0=1E-5 i_{ch}= 8A dv_{cr}/dt=9 kV/μs v_{cr}=800 kV di_{cr}/dt= 1A/μs

Current waveforms of the three phases are presented in Figure 10, while the maximum overvoltage values and their comparison with the values provided in the case of ideal switching are tabulated in Table IX. It can be seen that:

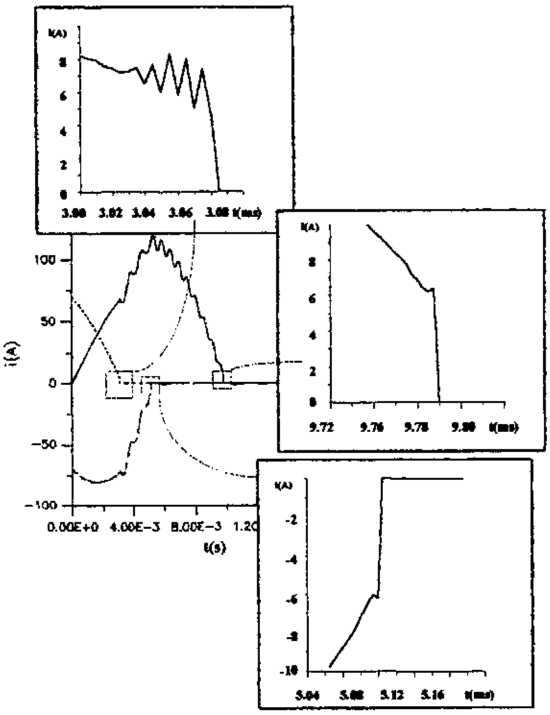

Figure 10 Three-phase currents in the interruption of reactor loaded transformer

- The greatest overvoltage value is that of the first-phase-to-clear, phase "c", followed by the second-phase-to-clear, phase "b" and finally the third phase "a". However the developed overvoltage does not exceed 2.0 p.u. in any case.
- the most intensive current chopping is observed in the first-phase-to-clear, phase "c"; as soon as this phase clears, at 3.0 ms, high frequency oscillations are developed in the other two phases which keep supplying the system in two-phase mode. Further change is noticed when phase "b" clears at 5.5 ms and the system is supplied only by the circuit formed by phase "a" and the earth return. Finally, phase "a" interrupts at 9.8 ms.
- the values of the developed overvoltages are considerably lower than those developed in the case of direct reactor switching, see Tables VII and IX, which is in accordance with the conclusions of [5-7].
- Non-ideal switching leads in higher overvoltages due to current chopping, as expected.

Table IX. Comparison of maximum overvoltage values in the cases of ideal and non-ideal switching

	1st phase to clear "c"			2nd phase to clear "b"			3rd phase to clear "a"		
	non-ideal	ideal	%difference	non-ideal	ideal	%difference	non-ideal	ideal	%difference
Maximum Over-voltage	-1.97 pu	-1.80 pu	9.5%	1.75 pu	1.65 pu	6%	1.56 pu	1.39 pu	12%

V. CONCLUSIONS

In this paper, a multi-parameter mathematical model representing the behaviour of a circuit breaker in the interruption of small inductive currents is presented. The model is used to investigate the evolution of the switching process, as well as the significance of modelling non-ideal switching emerged in characteristic practical cases. It is shown that, the parameter values of the mathematical model used, play a significant role to the simulated interruption process. In addition, from the simulations performed it is observed that ideal switch models can result to misleading conclusions especially in three-phase circuit interruption cases.

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