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MODELLING OF NONLINEAR CHARACTERISTIC OF SWITCH IN THE ELECTRIC CIRCUIT

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Abstract: *Model of electric arc for numerical calculations has been described. Electric arc between switch contacts has a significant influence on current decay. This phenomenon has been given close attention in the construction of the model. The model has been created in the ATP simulation program. Calculation results for several typical cases of the switch operation has been shown. The results show good compatibility with curves quoted in the literature.*

Key words: *switch model, electric arc*

INTRODUCTION

Numerical calculation of currents in electrical circuit containing switches may be incorrect, if the switches are considered as ideal ones. Electric arc arising between switch contacts at the moment of their separation has a significant influence on current interruption in the circuit branch. It may have an effect both on current limitation and the time of its complete interruption. The necessity of creation of circuital model of switch with electric arc comes from the above. ATP was used as a simulation tool.

1 THE SWITCH MODEL

1.1 Basic structure of the model

Basic structure of the switch model is shown in Fig. 1. It consists of two elements: an ideal switch *Q* and an element R_τ modeling the nonlinear resistance of electric arc.

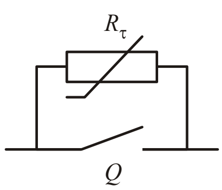

Fig.1: Basic structure of switch model

The switch model was built with the application of components available in ATP with the following assumptions:

- arc is modeled basing on its static voltage-current characteristics,
- arc model includes its simplified dynamic characteristic,
- arc resistance depends not only on the arc current but also on the duration of contacts opening,
- arc suppression takes place when current becomes lower than the fixed threshold.
- no multiple reignitions occur

1.2 Voltage-current characteristic of arc

It can be assumed that field intensity in arc column of the long arc, for stabilized conditions of arc burning is practically constant. [2,3,4]. Hence arc voltage, disregarding anode and cathode drop, can be expressed by a formula [5]:

$$u_\tau = E_\tau l_\tau \tag{1}$$

where: E_τ - electric field intensity in arc column, l_τ - arc column length. Field intensity can by described as follows [4]:

$$E_\tau = C \cdot i_\tau^{-\alpha} \tag{2}$$

where: i_τ - arc current, *C*, α - constants, while α=0,25÷0,5. Considering above relations, it was assumed, that the static characteristic of arc fulfils the following relation:

$$u_\tau = \frac{A}{\left|i_\tau\right|^{\alpha+1} + B} i_\tau \,, \qquad (3)$$

where: A, B – constant coefficients. Fig. 2 provides an example of this function. For comparison reasons Fig. 2 also shows relation (2) for $C=A$. Both curves overlap - the more accurately the higher the value of current is. For small value of currents the curve (2) ascends unlimitedly, while characteristic (3) reaches its maximum and follows towards zero. The differences observed between characteristics (2) i (3) are not substantial, taking into account that coefficient B in the formula (3) was intended to reach maximum below the current of arc suppression. In addition characteristics (3) is continuous and bounded for every current value what helps to eliminate problems with numerical instability.

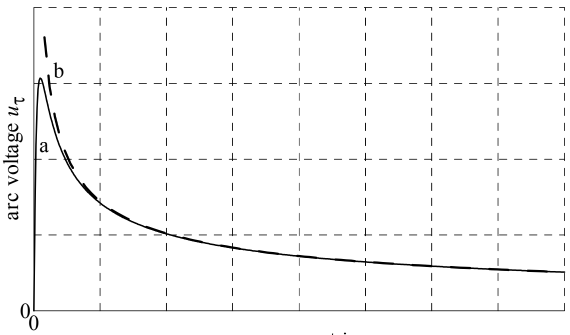

Fig. 2. Comparison of arc functions: a – resulting from formula (3), b – resulting from formula (2)

Nonlinear resistance was used to model the arc in switch, and its value was based on formula (3) in the following way:

$$R_\tau = \frac{u_\tau}{i_\tau} = \frac{A}{\left|i_\tau\right|^{\alpha+1} + B} \qquad (4)$$

The arc's dynamic characteristic depends on rate of current changes. Therefore the arc model contains an arc resistance scaling factor, proportional to arc current derivative:

$$R_{\tau d} = R_\tau \cdot \left(K_1 \cdot \frac{di_\tau}{dt} + 1 \right) \qquad (5)$$

where: $R_{\tau d}$ – dynamic resistance of arc, K_1 – factor of proportionality. The above relationship was shaped to obtain dynamic resistance $R_{\tau d}$ equal to resistance given by formula (4) for constant value of current (derivative equal to 0).

Dependence between arc resistance and duration of contacts separation was reached by introduction of resistance scaling factor, related to time:

$$R_{\tau t} = R_{\tau d} \cdot K_2(t) \qquad (6)$$

It is assumed that function $K_2(t)$ can be described by:

$$K_2(t) = \begin{cases} 0 & t < t_0 \\ \beta(t - t_0) + 1 & t \ge t_0 \end{cases} \qquad (7)$$

where: β - coefficient describing rate of resistance increase resulting from arc elongation, t_0 – moment when contacts start to separate. Adjusting the value of coefficient β it is possible to regulate the influence of arc resistance on current in the circuit. This enables the study of certain cases when the influence of arc resistance is of minor and of major importance for current value.

1.3 *Structure of the arc model*

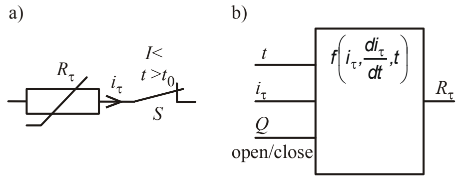

Fig.3: Arc model: a – circuital part, b – analog part

The arc model shown in Fig. 3 consists of two parts: circuital and analog. Circuital part (Fig. 3a) includes a non-linear resistance R_τ and an ideal switch S, with time relation. Resistance R_τ models arc and its present value is computed in the analog part. Switch S breaks the circuit, simulating arc suppression when arc current drops below certain threshold.

The analog part of the model, shown in Fig. 3b in the form of one equivalent block, is used to compute the arc resistance according to relations presented in 1.2. The input data for the analog part are: instantaneous value of the arc current i_τ, time of simulation t and signal defining the state of switch Q (open/close).

2 RESULTS OF EXEMPLARY SIMULATION

2.1 *DC circuit*

The model presented in paragraph 1 was tested in below described computation examples. Results were compared with the curves quoted in the literature. Fig. 4 shows the circuit diagram. It was assumed that supplying voltage ($u_z=U_z$=const.) was switched on at time t=0 and the opening of the switch Q took place at time t_0, after the current has reached the steady state.

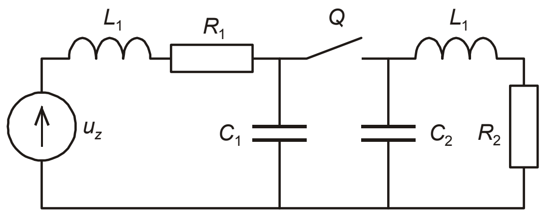

Fig. 4. The circuit used to test the switch model with arc

According to the theory of current breaking, cutting off of the current is possible if arc characteristics is located above the characteristic of the circuit. Both cases possible as per the above were considered: the first one –

when the arc characteristic intersects the characteristics of the circuit and the other one, when both characteristics have no intersections. A change of interruption conditions of the current was achieved by proper modification of coefficients A, B and α which determine the arc characteristics in equation (3).

Arc suppression in the DC switch is a result of considerable arc elongation in the arc chute. Arc elongation results in arc resistance increase and, in consequence, arc voltage increase to a level equal to the supplying voltage or - in inductive circuit - exceeding the supplying voltage. This phenomenon causes the reduction of current to zero. Due to this the coefficient β (equation (7)), describing the rate of arc resistance increase as a result of its elongation should also be adjusted properly in the model.

Simulation results are presented in Fig. 5 and 6. Fig. 5 shows arc voltage and arc current for a case when the current is cut off. Fig. 6 shows switch current in three cases: (a) the switch fails, (b) the switch operates and the current is not broken, (c) the switch operates and the current is cut off.

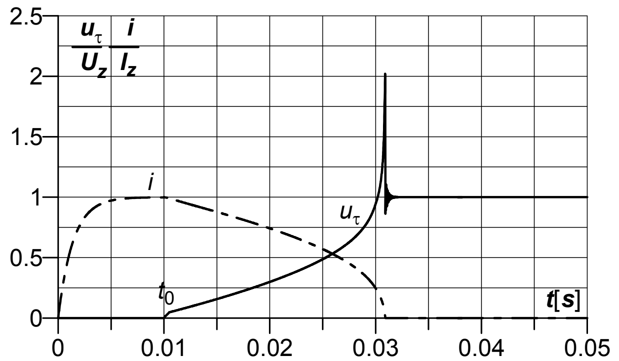

Fig 5. Computed curves in the circuit from Fig. 4 for constant supply, after opening the switch: i – switch current, u_τ - arc voltage

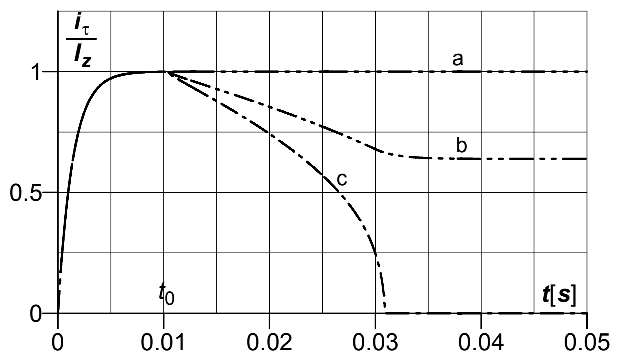

Fig. 6. Switch current in the circuit from Fig. 4 computed for constant supply for three cases: a - the switch fails, b - the switch operates and the current is not broken, c - the switch operates and the current is cut off.

Fig. 7 shows three curves: static arc characteristics chosen in the model (a), characteristics of the circuit in the steady state (b) and dynamic arc characteristics obtained from the simulation – determined on the basis of curves presented in Fig. 5 (c). Static characteristics of arc is mostly located below the circuit characteristics. Still dynamic characteristic of arc appears above circuit characteristics and favourable conditions occur for cutting off the current in the circuit – curve (c) in Fig. 6. If the static characteristic is lowered by 20%, arc is not suppressed and circuit current gets new value in the steady state – curve (b) in Fig. 6.

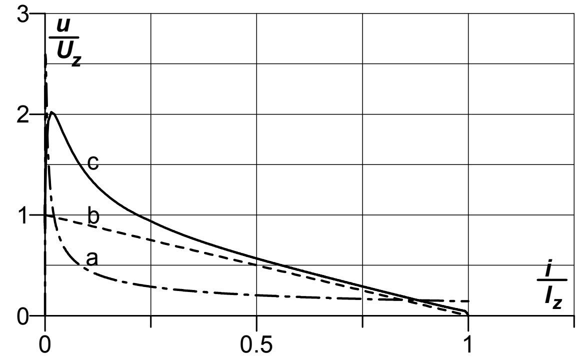

Fig. 7. Arc characteristics in the switch model in the circuit from Fig. 4: a – chosen static characteristics of arc, b - characteristics of the circuit in the steady state, c – computed dynamic characteristics of arc

2.2 AC circuit

Calculations were done for the circuit shown in Fig. 4. It was assumed that:

$$u_z=U_{max}\sin(\omega t+\varphi)$$

The voltage was switched on at time t=0 and the switch Q opened at time t_0. Resistance and inductance values of the circuit were accepted to reach the power factor close to unity. Simulation was carried out for the case when the current in the circuit was not cut off – switch S in Fig. 3a remains closed. This means that the arc periodically gets extinguished when current goes through zero and ignites when voltage between switch contacts reaches proper value. Results are shown in Fig. 8.

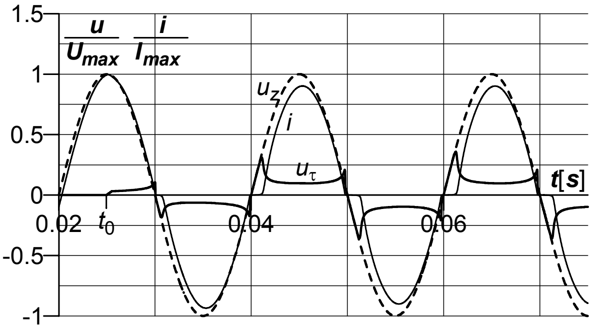

Fig.8. Curves computed in the circuit in Fig. 4 for sinusoidal voltage supply and power factor close to unity: u_z – supplying voltage, i – switch current, u_τ - arc voltage

The current curve contains sections when value of current is practically equal to zero. The current falls down to zero earlier then sinusoidal function and subsequently starts growing only when the voltage reaches the value of striking voltage. High spikes of striking voltage and lower spikes of arc suppression voltage can be visibly noticed in the voltage curve. Using computed curves of arc voltage and switch current, which is also arc current, dynamic characteristic of AC arc was plotted – Fig. 9. The characteristics contains distinct loops named arc hysteresis loops.

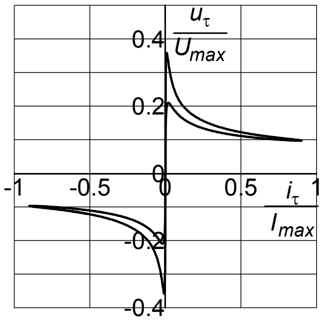

Fig. 9. Dynamic characteristic of arc in the switch model in the circuit in Fig. 4 computed for alternating current

Calculations in the simulated circuit were repeated for the case when the inductive reactance dominates the resistance. Two variants were considered: with low resistance of the arc and with high resistance of the arc. Results for the first case are shown in Fig. 10 and for the other one in Fig. 11.

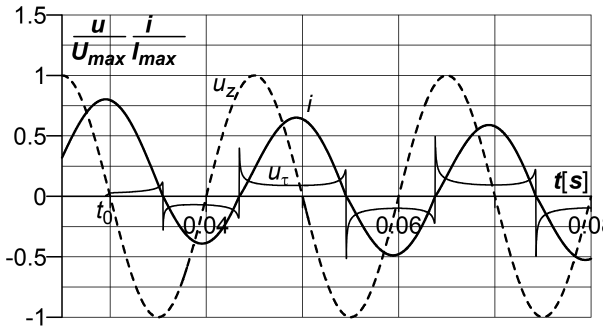

Fig 10. Curves computed in the circuit from Fig. 4 for sinusoidal supply, for inductive circuit and for low arc resistance: u_z – supplying voltage, i – switch current, u_τ - arc voltage

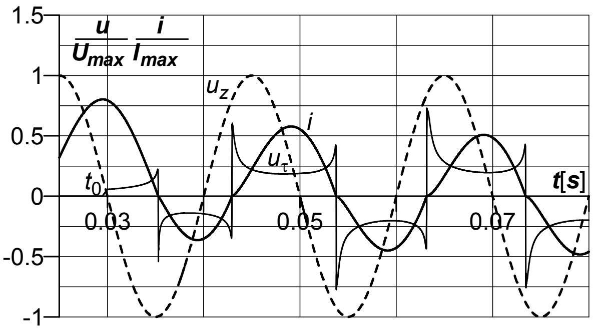

Fig 11. Curves computed in the circuit from Fig. 4 for sinusoidal supply, for inductive circuit and for high arc resistance: u_z – supplying voltage, i – switch current, u_τ - arc voltage

For low arc resistance the current curve forms an almost undistorted sine curve. It results from the fact that arc voltage is very flat between arc ignition and arc suppression spikes. It changes the amplitude but not the shape of the curve. When the arc resistance is higher the arc voltage is also higher in the whole half-period (Fig. 11) and becomes a significant component of voltage balance in the circuit.

Another simulation was carried out for the case when after switch contacts separation conditions preventing re-ignition of arc occurred and the current was cut off. It was achieved by inserting additional condition into the switch model, which enabled the switch *S* to open when the following inequalities were fulfilled:

$$t > t_0 + \Delta t, \quad |i| < I_0 \qquad (8)$$

where: t_0 – instant of contacts separation in switch *Q*, Δt – delay time of switch *S* operation, I_0 – the current of arc suppression. Introduction of delay time Δt enabled us to consider a case when conditions for cutting off of the current didn't occur at the time of zero crossing closest to time t_0 but at one of the subsequent zero crossings. It was assumed that opening of the switch in the circuit in Fig. 4 took place in the steady state of short circuit, for the maximal value of current. Results are presented in Fig. 12.

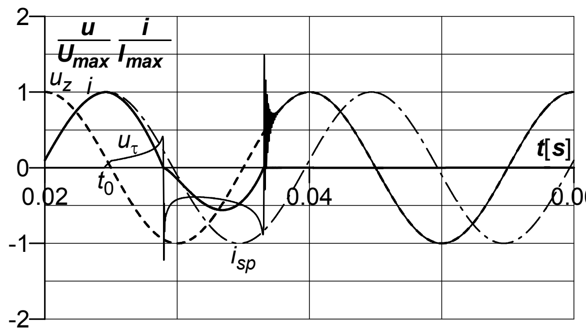

Fig 12. Curves computed in the circuit from Fig. 4 for sinusoidal supply, for inductive circuit and for a case when the current is cut off: u_z – supplying voltage, i – switch current, u_τ - voltage between contacts, i_{sp} – current expected if switch failed

From the moment of switch contacts separation the impact of arc voltage on the current becomes more and more strong. The current increasingly differs from a curve expected for a case with closed switch. (Fig. 12). At the moment of current cutting off, between switch contacts there occurs strongly damped oscillatory voltage, overlapping sinusoidal supplying voltage. This voltage is known as re-striking voltage. Fig. 13 shows calculated curves in extended range.

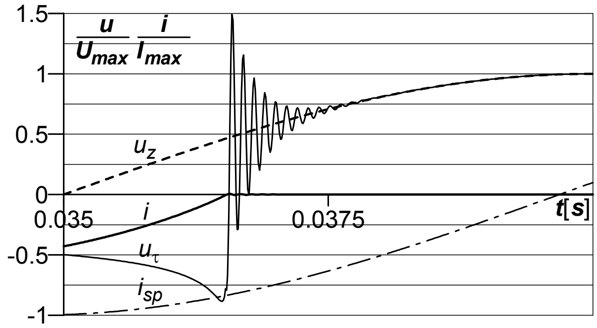

Fig. 13. Extended piece of plot in Fig. 12

3 SUMMARY

Simulation results are in good compatibility with curves quoted in the literature [2,3,4,5]. Implementation of the switch model as shown here satisfactorily simulates electric arc between switch contacts for cases considered. Increase of simulations' accuracy can be reached by extending the model by arc re-ignition when the recovery voltage exceeds electric strength of the post-arc column. It can be reached by introduction of the relationship between state of the switch *S* (Fig. 3a) and voltage between switch contacts. Also function of break-down strength of the post-arc column should be defined.

4 REFERENCES

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