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doi:10.15199/48.2018.04.23

Modified arc models in a SF_6 power circuit breaker

***Abstract**. Selected operating properties of high voltage power switches that use SF6 as extinguishing medium have been described. Selected physical properties of switching arc that occurs in those devices have been presented, with special focus on results of experimental research conducted in KEMA laboratory in Netherlands. Important flaws of mathematical models of switching arc described in literature have been indicated, despite they include variation of dissipation power, as well as step decrease of voltage during linear decrease of current. Method for obtaining modified Mayr and hybrid models with aforementioned properties have been described. They differ from other known models by consistent introduction of preliminary assumptions and simpler form. Properties of these models have been researched using computer simulations. Their usefulness in engineering work have been demonstrated.*

***Streszczenie.** W artykule opisano wybrane właściwości eksploatacyjne wyłączników wysokonapięciowych mocy, które używają SF6 jako medium gaszeniowego. Zaprezentowano wybrane właściwości fizyczne łuku łączeniowego, który występuje w tych aparatach. Szczególną uwagę zwrócono na wyniki badań eksperymentalnych przeprowadzonych w laboratorium KEMA w Holandii. Wskazano na istotne mankamenty modeli matematycznych łuku łączeniowego opisywanych w literaturze, pomimo że uwzględniają one zmienność mocy rozpraszanej, a także skokowy spadek napięcia podczas liniowego zmniejszania prądu. Opisano metodę otrzymania zmodyfikowanych modeli Mayra i hybrydowego o wspomnianych wcześniej właściwościach. Od innych znanych modeli różnią się one konsekwentnym wprowadzaniem założeń wstępnych i prostszą postacią. Zbadano właściwości tych modeli za pomocą symulacji komputerowych. Wykazano przydatność tych modeli w pracach inżynierskich. **(Zmodyfikowane modele łuku w wyłączniku mocy z SF_6)**.*

Keywords: switching arc, high-voltage power switch, Mayr model.
Słowa kluczowe: łuk łączeniowy, wysokonapięciowy wyłącznik mocy, model Mayra.

Introduction

High-voltage circuit breakers play a very important role in all systems of energy transmission and distribution. The quality of their operation affects the condition of power systems and energy receivers. These devices are used not only for modifying the structure of the power grid, but also for preventing and minimising detrimental effects of emergency conditions in grids and receivers. Among the natural consequences of the presence of both parasitic and beneficial elements in networks are transient states following commutation. Because of that, the challenge for power industry involves not only ensuring continuity and reliability of supply, but also planned and fast interruptions.

High-voltage circuit breakers are classified according to the medium used for extinguishing the electric arc and can be divided into several types [1]. The advantages of using SF_6, as compared to using air, include: 2.5 times greater electric strength, 4 times greater volumetric density of the heat capacity, low intensity of the electric field in the arc column, 5 times higher rated interruption current for a chamber with longitudinal gas flow, being chemically inert with respect to oxygen and hydrogen, low decomposition rate in the presence of an arc and being non-toxic until decomposed. The only disadvantage is a relatively high liquefaction temperature of compressed gas.

An effective operation of a high-voltage circuit breaker requires an ability to interrupt currents in a short time. This ability can be assessed by means of a number of tests carried out in a laboratory. On the basis of such tests, a number of arc models have been proposed [2-5].

The objective of this paper is to present improved mathematical models of an electric arc. The improvement is due to allowing for disturbances in power dissipation, thanks to which the models can adequately represent the behaviour of an electric arc during interruption.

Selected physical properties of electric arcs in circuit breakers

A number of experimental methods have been developed for obtaining selected characteristics of arcs in circuit breakers [1, 3]. Such characteristics include the time constant of thermal processes, restrike voltage between the circuit breaker contacts, static and dynamic voltage-current characteristics, gradient characteristics $\partial U(I,l)/\partial l$ etc.

Challenges connected with designing circuit breakers and ensuring their optimal operating conditions can be addressed by utilising various mathematical models of the electric arc. A point of departure for creating most of them is the equation of the arc energy balance. Adopting certain simplifying assumptions for describing the processes occurring in the plasma makes a model more manageable, and it is possible to determine its parameters both theoretically and experimentally. Such simplified models, however, are of limited applicability, so they are modified in order to better reflect the real characteristics of an arc. Among the mathematical models of the phenomenon, the following major types can be distinguished: constant parameters models, variable parameters models, linear models and nonlinear ones [2-5].

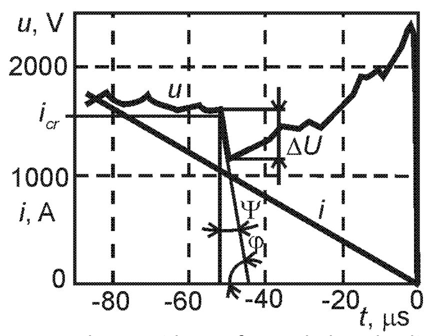

Fig.1. Voltage u and current i waveforms during circuit interruption (Source: own work, based on [3])

Commonly recognised as reliable [3] are the results of investigations of current interruption in a circuit conducted in KEMA Laboratories in the Netherlands, using a SF_6 circuit breaker with the parameters 245kV/50kA/50Hz. Voltages and currents were registered by means of a 10 MHz/12 bits measuring system. Fragments of the waveforms obtained are shown in Fig. 1 [3]. It can be observed that the linear decrease in current from the value of about 1800 A is accompanied by a decrease in voltage from the value of about 1700 V, initially mild, until the current reaches the critical value of i_{cr} = 10^3 A. Then, the voltage drops abruptly from about 1600 V to about 1200 V. Subsequently, despite further decrease in current, the voltage increases steeply up to about 2400 V, and in the current range from about 100 A to zero, it drops abruptly to zero as well. A number of tests indicated that the value of the critical current varies in the narrow range of $i_{cr} \approx$ 1-1.11 kA [4].

Mathematical models of an arc in a circuit breaker

In common use for describing the interaction between an arc and the power grid are black box models. Typically, they are modifications of the simple Mayr and Cassie models [4, 5]. Due to the fact that these simple models are based on simplifying assumptions, they are applicable to low and high current ranges, respectively. For a wide current range the general formula of the arc model obtains, expressed as the following differential equation:

(1) $$\frac{1}{g}\frac{dg}{dt}=\frac{d\ln g}{dt}=\frac{1}{\tau(g(u,i))}\left(\frac{ui}{P_{dis}(g(u,i))}-1\right)$$

where: $g = i/u$ – arc conductance; $\tau(u, i)$ – arc damping function; $P_{dis}(u, i)$ – dissipated power; ui – electrical power supplied.

A more complex and accurate model with a greater set of parameters makes these parameters more difficult to obtain. That is why a model has to be constructed on a rational basis, as is the case with the Schwarz-Avdonin model. Hybrid models are also proposed, as exemplified by the differential equation below [3]

(2) $$\frac{1}{g}\frac{dg}{dt}=\frac{d\ln g}{dt}=\begin{cases}\frac{1}{\tau_M}\left(\frac{ui}{P_0}-1\right) & \text{jesli } |i|\le I_0\\ \frac{1}{\tau_C}\left(\frac{ui}{U_0^2 g}-1\right) & \text{jesli } |i|> I_0\end{cases}$$

where: P_0 – constant value of dissipated power, known as Mayr power; U_0 – constant value of voltage, known as Cassie voltage; I_0 – threshold value of current that can be obtained from the intersection of the Mayr and Cassie static characteristics $I_0 = P_0/U_0$. It was established experimentally [3], that the arc extinguishing function is strongly nonlinear and because of that $\tau_M >> \tau_C > 0$ s. Quite often, however, a simplifying assumption is made that $\tau_M = \tau_C = \tau > 0$ s.

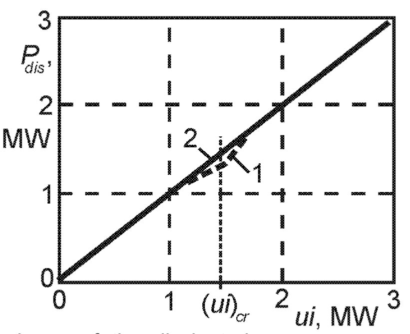

Fig.2. Dependence of the dissipated power P_{dis} on the electric power supplied to the system ui (1 – experiment; 2 – approximation) (Source: own work, based on [3])

In Eq. (2) the dissipated arc power is constant in the low current range, but in the full range of current variation the hybrid model does allow for power dissipation variation. Experimental results [3] indicate, however, that dissipated power depends quasi-linearly on the forcing power (Fig.2). Besides, in the area of the input power ui = 1,2-1,6·10^6 W a small deviation of the characteristics from a fully linear shape can be observed, which corresponds to a sudden drop in arc voltage (Fig.1). The authors of [5] assume a constant value of the threshold power 1,5·10^6 W.

In their further analyses the authors of [3] included in the ultimate formula the phenomenon of linear increase in dissipated power along the increase in the power supplied in the low current range. Then, Eq. (2) becomes

(3) $$\frac{1}{g}\frac{dg}{dt}=\frac{d\ln g}{dt}=\begin{cases}\frac{1}{\tau}\left(\frac{ui}{P_0+p_1 ui}-1\right) & \text{if } |i|\le I_0\\ \frac{1}{\tau}\left(\frac{ui}{U_0^2 g}-1\right) & \text{if } |i|> I_0\end{cases}$$

where p_1 – coefficient of the variable (linear) component of the dissipated power. The constant cooling power P_0 depends on the parameters of the circuit breaker, i.e. the system od nozzles, type of gas, its pressure, and so on). The cooling power coefficient p_1 represents the influence of the input power on the dissipated power, which causes the heating of the extinguishing agent due to arc resistance and increase in pressure [3].

To obtain the input form of the hybrid model equation for a low current range, a reverse action can be performed on the first term of Eq. (3). It becomes evident that it does not meet the power balance conditions. Under such circumstances it is necessary to define detailed initial assumptions of this mathematical model, as is done with Nowikow-Schellhase model. Despite this shortcoming, model (3) was elaborated in a number of works [4, 5].

Assuming the condition $U_0^2 g \cong U_a|i|$, valid in the high current range, Eq. (3) becomes

(4) $$\frac{1}{g}\frac{dg}{dt}=\frac{d\ln g}{dt}=\frac{1}{\tau}\left(\frac{ui}{\max\left(U_a\cdot|i|, P_0+p_1 ui\right)}-1\right)$$

where U_a – constant arc voltage in the high current range, V. This model is not capable of accounting for the abrupt voltage change and because of that it was further modified in [5].

In the low current range an additional slight disturbance $\delta p_1 ui$ of the dissipated power $P_0 + (p_1 + \delta p_1)ui$ was introduced, which led to

(5) $$\frac{1}{g}\frac{dg}{dt}=\frac{d\ln g}{dt}=\frac{1}{\tau}\left(\frac{ui}{P_0+(p_1+\delta p_1)ui}-1\right)$$

Subsequently, it was assumed that current decreases linearly so that the change in arc voltage near the critical current can be described as

(6) $$\left.\frac{du}{dt}\right|_{cr}=\left.\frac{di}{dt}\frac{du}{di}\right|_{cr}=-\alpha\left.\frac{du}{di}\right|_{cr}$$

where: $\alpha = -di/dt =$ const. The derivative $(du/di)|_{cr}$ in the neighbourhood of the critical current i_{cr}, where a sudden voltage drop occurs, behaves similarly to Dirac's delta function. To simplify the simulation, the derivative $(du/di)|i_{cr}$ was approximated as Gaussian

(7) $$\left.\frac{du}{dt}\right|_{cr}=\left.\frac{di}{dt}\frac{du}{di}\right|_{cr}=-\alpha\left.\frac{du}{di}\right|_{cr}$$

where: Δu – voltage drop value that can be obtained directly from experimental data (cf. Fig.1). With this, a formula for disturbance can be obtained:

(8) $$\delta p_1(u,i)=\frac{\tau p_1^2\alpha\Delta u}{u\sqrt{\frac{\pi}{\beta}}\exp\left(\beta(i-i_{cr})^2\right)+\tau p_1\alpha\Delta u}$$

By applying the substitution $(du/dt)|_{cr}$ = -cotψ in Eq. (7) the parameter β can be obtained (cf. Fig.1)

(9) $$\beta=\frac{\pi}{(\alpha\Delta u)^2}\cot^2\psi$$

The arc model equation for a SF_6 circuit breaker thus becomes [5]

(10) $$\frac{d\ln g}{dt}=\frac{1}{\tau}\left(\frac{iu}{P_0+\frac{p_1iu^2}{u+\gamma\exp\left(-\beta(i-i_{cr})^2\right)}}-1\right)$$

where $\gamma=\tau p_1\cot\psi$. The arc model so obtained is quite complex.

Modified Mayr and hybrid models for a circuit breaker arc

One of the fundamental assumptions of Mayr model is the condition tying conductance g and enthalpy Q:

(11) $$\frac{g}{g_0}=\exp\left(\frac{Q}{Q_0}\right)$$

The derivation of the linear dependence of the dissipated power P_{dis} on the input power $p = ui$ in the power balance equation

(12) $$\frac{dQ}{dt}=\frac{Q_0}{g}\frac{dg}{dt}=p-P_{dis}=ui-\left(P_0^{'}+p_1^{'}ui\right)$$

also leads to Mayr model

(13) $$\tau\frac{dg}{dt}+g=\frac{i^2}{P_M}$$

or to

(14) $$\tau\frac{d\ln g}{dt}=\frac{ui}{P_M}-1$$

where: $\tau=Q_0/P_0^{'}$; $P_M=P_0^{'}/\left(1-p_1^{'}\right)$ i $0\le p_1^{'}<1$. Then, Eq. (3) can be transformed into

(15) $$\frac{1}{g}\frac{dg}{dt}=\frac{d\ln g}{dt}=\begin{cases}\frac{1}{\tau}\left(\frac{ui}{P_0^{'}/\left(1-p_1^{'}\right)}-1\right) & \text{if } |i|\le I_0\\ \frac{1}{\tau}\left(\frac{ui}{U_0^2g}-1\right) & \text{if } |i|>I_0\end{cases}$$

and (4) into

(16) $$\frac{1}{g}\frac{dg}{dt}=\frac{d\ln g}{dt}=\frac{1}{\tau}\left(\frac{ui}{\max\left(U_a\cdot|i|,P_0^{'}/\left(1-p_1^{'}\right)\right)}-1\right)$$

If at the initial stage of deriving the formulas for the arc in circuit breakers the disturbance in the dissipated power is introduced into Eq. (12)

(17) $$\frac{dQ}{dt}=Q_0\frac{d\ln g}{dt}=p-P_{dys}= =ui-\left(P_0^{'}+p_1^{'}ui\right)+\Delta P\cdot\delta\left(i-i_{cr}\right)$$

then, a modified Mayr equation is obtained for an arc fed with a linearly decreasing current

(18) $$\tau\frac{d\ln g}{dt}=\frac{ui}{P_M}-1+\frac{\alpha\tau}{U_{cr}}\Delta U\cdot\delta\left(i-i_{cr}\right)$$

a different form of which is

(19) $$\tau\frac{dg}{dt}+\left[1-\alpha\tau\frac{\Delta U}{U_{cr}}\delta\left(i-i_{cr}\right)\right]g=\frac{i^2}{P_M}$$

where U_{cr} = $u(i_{cr})$. When Eq. (18) is transformed, Bernoulli equation is obtained with respect to the voltage u

(20) $$\alpha\tau\frac{du}{di}+\left[1-\alpha\tau\left(\frac{1}{i}+\frac{\Delta U}{U_{cr}}\delta\left(i-i_{cr}\right)\right)\right]u=\frac{i}{P_M}u^2$$

Approximating disturbance (7) leads to

(21) $$\alpha\tau\frac{du}{di}+\left[1-\alpha\tau\left(\frac{1}{i}+\frac{\Delta U}{U_{cr}}\sqrt{\frac{\beta}{\pi}}\exp\left(-\beta\left(i-i_{cr}\right)^2\right)\right)\right]u= =\frac{i}{P_M}u^2$$

If β is large, then in a small neighbourhood of i_{cr} free variable terms can be disregarded and Eq. (9) will be obtained, in which case (21) ultimately becomes [6].

(22) $$\alpha\tau\frac{du}{di}+\left[1-\alpha\tau\left(\frac{1}{i}+\frac{\Delta U}{U_{cr}}\sqrt{\frac{\beta}{\pi}}\exp\left(-\beta\left(i-i_{cr}\right)^2\right)\right)\right]u= =\frac{i}{P_M}u^2$$

Simulations of connecting processes in a circuit with modified models of an arc supplied by linearly decreasing current

Simulation methods are often employed in electrical engineering for designing power devices and networks. Thanks to them it is possible to analyse many constructional variants of devices and structures of networks in a fast and cost-effective way, and to select optimal solutions [1, 7]. The data necessary for the calculations and for assessing the ultimate effectiveness of a device come from experiments. Due to incidental operation of circuit breakers, the tests are performed in laboratories with the use of appropriately suited current sources.

At the first stage of testing, the system operation was verified by means of an arc macromodel obtained according to Eq. (10). Current was forced decreasing linearly from the value 1800 at the rate of $20\cdot10^6$ A/s. Curves were obtained as shown in Fig. 3. As can be seen, they coincide with the curves obtained in [5] and approximate experimental data fairly well. The result was obtained by means of the asymptotic method of obtaining arc model parameters.

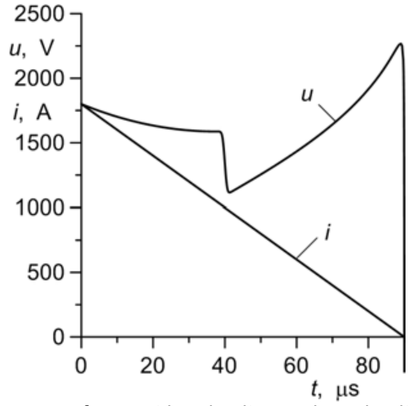

Fig.3. Time curves of current i and voltage u in a circuit with the arc model (10) during current interruption (P_0 = 3413,5 W; p_1 = 0,999275; β = 4,6923·10-3 A-2; ψ = 0,00259 rad; i_{cr} = $1 \cdot 10^3$ A; τ = 0,069365 μs; G_0 = 1 S)

The same current was forced in a circuit with an arc described by Eq. (16). The results of the simulation are presented in Fig. 4. It can be seen that this hybrid Cassie-Mayr model does not allow for the sudden drop of voltage in the neighbourhood of the critical current. It can thus be used for simulating processes in circuit breakers of a different construction.

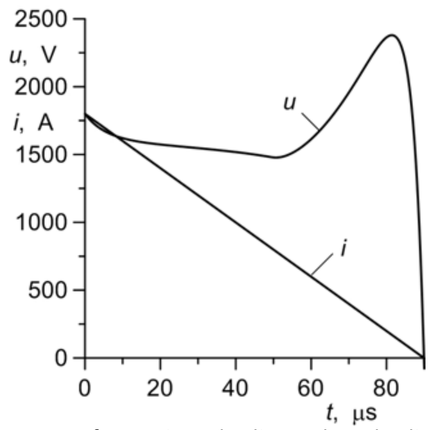

Fig.4. Time curves of current i and voltage u in a circuit with the arc model (16) during current interruption ($P_0^{'}$ =960000 W; $p_1^{'}$ = 0,3; U_a = 1700 V; τ = 6 μs; G_0 = 1 S)

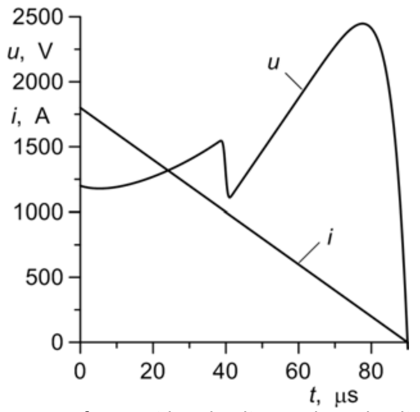

Fig.5. Time curves of current i and voltage u in a circuit with the arc model (22) during current interruption (P_M = 2233964,8 W; τ =9 μs; *cot*ψ = 386,1; U_{cr} = 1250 V; i_{cr} = 1000 A; β = 4,683·10-3 A-2; G_0 = 1.5 S)

The possibility of allowing for a sudden voltage drop is offered by the arc model (22), which is connected into the circuit with the same forced current as previously. The simulations gave rise to curves as presented in Fig. 5. The differences in the shapes of the voltage curves presented in Figs 3 and 4 are due to applying the initial stage of investigations of Mayr arc model with a sudden voltage change. In this case no analytic method was employed for obtaining arc model parameters and because of that, the approximation is less accurate. It should be noted that both models include the same number of parameters, i.e. 5.

Conclusions:

1. The arc model presented in publications [4, 5] applied in SF_6 circuit breakers was obtained by modifying and combining the extant simple models. Due to this, it is more complex and more difficult to interpret in physical terms.
2. Introducing modifications to the ultimately derived equations representing the arc model carries a serious risk of a violating the initial assumptions and makes it necessary to develop new simplifying initial assumptions.
3. The arc model presented in the paper was obtained on the basis of rational initial assumptions and because of that it is characterised by a simple form and is relatively easy to interpret in physical terms.
4. Simulation experiments of processes in a circuit with the proposed macromodel of the connecting arc indicate that its ability to represent the voltage waveform during interruption by means of a SF_6 circuit breaker is satisfactory.

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