Simulation of the 500 kV SF6 circuit breaker cutoff process during the unsuccessful three-phase autoreclosing

I. Naumkin, M. Balabin, N. Lavrushenko, R. Naumkin

***Abstract*--The paper presents a study on the electromagnetic transients in 500 kV transmission line equipped with shunt reactors. Conditions of unsuccessful three-phase autoreclosing are discussed in the case when the DC component in current flowing through a circuit breaker is significantly greater than the amplitude of the steady-state current which prevents the current from crossing the zero line for a prolonged period of time.**

A model of the electric arc for simulation in a long time spans was developed and employed in this paper. Simulations of an accident in a 500 kV grid are presented.

***Keywords*: electromagnetic transients, three-phase autoreclosing, circuit breaker failure, sulfur hexafluoride circuit breaker, arc model**

I. Introduction

At the present time in Russia overhead transmission lines (TL) of the ultra-high voltage of 1150kV are operated at 500kV. To compensate the high reactive power consumption of the 1150kV-type TLs they are equipped with an increased number of shunt reactors (SR). For example, the transmission line 1150kV connecting substation “Altay” and substation “Itatskaya” is equipped with four SRs, two reactors on each end of the line. If four reactors are turned on, then the line capacitance becomes overcompensated; if three reactors are turned on then the line works in a near-resonance mode. Taking this into account, protective relaying is configured in order to avoid commutations with three shunt reactors enabled.

Nevertheless, not all peculiarities of this type of transmission lines were taken into account completely. As a consequence, on the February 26th 2007 a major accident occurred at the “Altay” substation (SS): phase A of three-phase sulfur hexafluoride circuit breaker (ABB HPL-550B2) was destroyed. The analysis of the accident has revealed that prior to the breaker breakdown a one-phase line-to-ground fault occurred followed by the three-phase line tripping and autoreclosing. The fault still was not cleared successfully at the moment of the autoreclosure and relay protection issued another line tripping command. The breaker at the phase A was not able to extinguish the electric arc because the current did not cross the zero line for more than 130 ms due to a large DC transient presented in the current. The DC transient appeared at the non-faulted phase A as a result of the autoreclosing commutation of the line.

The accident happened during the three-phase tripping of the line at a non-faulted phase. If a one-phase tripping was used, the accident could have been avoided because the circuit breaker performs successfully in faulted conditions. However, such an accident can happen again if appropriate security measures are not taken, even during routine switching operations.

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II. Conditions necessary for the DC component to occur during line autoreclosing

A degree of compensation of capacitive reactance of TL using SR is defined by the formula:

$$K = \frac{X_{TL}}{X_{SRT}} \quad , \tag{1}$$

where $X_{SRT} = X_{SR} / N_r$ is a total inductive reactance of N_r shunt reactors connected to a TL; X_{TL} is a total capacitive reactance of TL, which is determined by the positive sequence capacitive reactance of TL with sufficient accuracy: $X_{TL} = 1/(b_1^0 \cdot l_{TL})$; b_1^0 is a TL positive sequence capacitive reactivity; l_{TL} is a TL length. If compensation degree is close to 1 then TL is in the resonance mode.

An electric scheme of the transmission line connected to a power source on the first end and its equivalent circuit using lumped parameter elements are correspondingly presented on the figures 1a and 1b. The transmission line is represented by a Pi network.

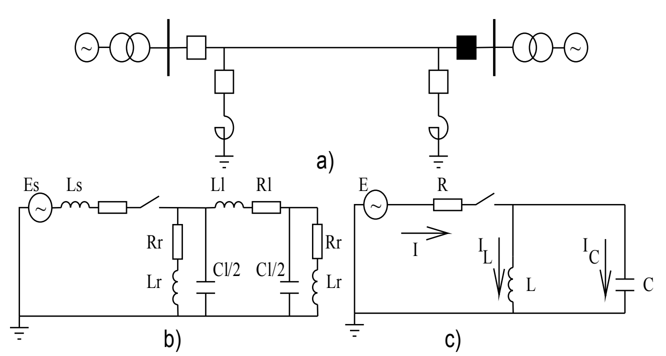


Fig. 1. Scheme of the transmission line under study and its equivalent circuits

To obtain an analytical solution, consider the simplified scheme (Fig. 1c). On the scheme 1c inductance of line L_l is neglected, impedances in the TL branch and SR branch are taken into account by adding them to the resistance R_C. Such simplification of the scheme 1b allows us to study qualitative properties of the circuit based on the simple analytical solution.

Solution for the steady-state current through the circuit breaker on a simplified scheme using the complex representation can be written as

$$\dot{I}_{ss}=\frac{\dot{E}}{\dot{Z}} \quad , \tag{2}$$

where the impedance of the circuit $\dot{Z}$ is

$$\dot{Z}=R-j\frac{\omega L}{\omega^2 LC-1}=R-j\frac{X_L X_C}{X_L-X_C} \quad , \tag{3}$$

assuming that $X_L=\omega L$, $X_C=1/(\omega C)$.

As it follows from (2) and (3), steady state current $\dot{I}_{ss}=0$ when $X_L=X_C$, e.g. in the resonance mode. Condition for the resonance is

$$\omega LC=1 \ . \tag{4}$$

Since natural frequency of the circuit is $f_{nat}=1/\left(2\pi\sqrt{LC}\right)$ and driving frequency is $f_{dr}=\omega/\left(2\pi\right)$ then (4) means that the natural frequency of the circuit is equal to the driving frequency of the circuit: $f_{nat}=f_{dr}$.

When $X_L=X_{SR}/N_r$, (3) can be transformed to

$$\dot{Z}=R-j\frac{X_{SR} X_C}{X_{SR}-N_r\cdot X_C} \quad ,$$

which means that if no reactors are connected ($N_r=0$) then $\mathrm{Im}(Z)=-X_C<0$ and the current has a capacitive nature. If we start adding reactors to line, then eventually $N_p\cdot X_c>X_{SR}$ will become true and the current will become inductive by nature (e.g. $\mathrm{Im}(Z)>0$).

In the considered case sinusoidal driving voltage $e=E_m\sin(\omega T+\psi)$ is applied to the resonant circuit under study. According to (2) and (3) we can write as follows:

$$i_{ss}=\left(\frac{X_L}{X_C}-1\right)\frac{E_M}{Z}\sin(\omega t+\psi+\phi) \quad , \tag{5}$$

where $\phi=\arctan\frac{X_L}{R(X_L/X_C-1)}$, $Z=\sqrt{R^2\left(\frac{X_L}{X_C}-1\right)^2+X_L^2}$.

Total current i through the circuit breaker is a sum of the steady-state current i_{ss} and the transient current i_{tr}: $i=i_{ss}+i_{tr}$. Transient current is found as a solution to the following system of equations:

$$\tau_L\tau_C\frac{d^2 i_{L,tr}}{dt^2}+\tau_L\frac{d\, i_{L,tr}}{dt}+i_{L,tr}=0; \tag{6}$$

$$u_{tr}=L\frac{d\, i_{L,tr}}{dt}; \tag{7}$$

$$i_{C,tr}=C\frac{du_{tr}}{dt}; \tag{8}$$

$$i_{tr}=i_{L,tr}+i_{C,tr}, \tag{9}$$

where $\tau_L=L/R$ and $\tau_C=RC$ are characteristic time constants of the circuit; $i_{L,tr}$ and $i_{C,tr}$ are transient currents flowing through inductance and capacitance, accordingly.

Let's consider characteristic equation of the differential equation (6):

$$\tau_L\tau_C p^2+\tau_L p+1=0 \quad .$$

Its roots are:

$$p_1=-\frac{1}{2\tau_C}\left(1-\sqrt{1-4\frac{\tau_C}{\tau_L}}\right);$$
$$p_2=-\frac{1}{2\tau_C}\left(1+\sqrt{1-4\frac{\tau_C}{\tau_L}}\right). \tag{10}$$

According to the (6)-(9) solution for the transient component of the current through the circuit breaker assuming zero initial conditions $i_L\big|_{t=0}=0$, $i_C\big|_{t=0}=0$ is expressed as:

$$i_{tr}=-\frac{E_m}{Z}\sin(\psi+\phi)\frac{1}{p_1^2-p_2^2}\Big[\left(1+\tau_L\tau_C p_1^2\right)\left(p_2^2+\omega^2\right)\cdot e^{p_1 t}-\left(1+\tau_L\tau_C p_2^2\right)\left(p_1^2+\omega^2\right)\cdot e^{p_2 t}\Big]. \tag{11}$$

Values of p_1 and p_2 are real if $\tau_C/\tau_L<1/4$. For a typical set of parameters of 500 – 1150 kV transmission line equipped with reactors the stronger assumption is valid:

$$\tau_C\ll\tau_L \quad . \tag{12}$$

Under the assumption (12) we can apply the series expansion $\sqrt{1-x}\approx 1-x/2$ to the expression (10):

$$p_1\approx-\frac{1}{\tau_L}\ ;\ p_2\approx-\frac{1}{\tau_C}\,. \tag{13}$$

If we simplify the formula (11), the result will be as follows:

$$i_{tr}=-\frac{E_m}{Z}\sin(\psi+\phi)\left[\frac{X_L}{X_C}\cdot e^{-\frac{t}{\tau_C}}-\left(1+\frac{X_L}{X_C}\frac{\tau_C}{\tau_L}\right)\cdot e^{-\frac{t}{\tau_L}}\right]. \tag{14}$$

Let's study two cases of the circuit breaker reclosing: the first case with $\psi=0$, the second case with $\psi=\pi/2$.

In the first case $\psi=0$, the total current trough the circuit breaker is equal to

$$i=\left(\frac{X_L}{X_C}-1\right)\frac{E_m}{Z}\sin(\omega t+\phi)-$$
$$-\frac{E_m}{Z}\sin\phi\left[\frac{X_L}{X_C}\cdot e^{-\frac{t}{\tau_C}}-\left(1+\frac{X_L}{X_C}\frac{\tau_C}{\tau_L}\right)\cdot e^{-\frac{t}{\tau_L}}\right]. \tag{15}$$

Taking the assumption (12) into account, the circuit breaker current for $t>3\tau_C$ will be determined mostly by the steady-state current

$$i_{ss}=\left(\frac{X_L}{X_C}-1\right)\frac{E_m}{Z}\sin(\omega t+\phi) \tag{16}$$

and the transient current corresponding to the time constant τ_L :

$$i_{tr}=\frac{E_m}{Z}\sin\phi\left(1+\frac{X_L}{X_C}\frac{\tau_C}{\tau_L}\right)\cdot e^{-\frac{t}{\tau_L}}\approx\frac{E_m}{Z}\cdot\frac{X_L}{Z}\cdot e^{-\frac{t}{\tau_L}} \quad . \tag{17}$$

The value of X_L/Z may exceed X_L/X_C-1 significantly because $X_L/Z\approx 1$ and X_L/X_C-1 approaches the zero line when $X_L\rightarrow X_C$. Therefore, the DC component in current flowing a circuit breaker may exceed the steady-state component and the current would not cross the zero line for a long time. As follows from (16) and (17), time needed for the transient component to decay to the amplitude of steady-state component is approximated by the following formula:

$$t_1\approx\tau_L\cdot\ln\frac{X_L/Z}{X_L/X_C-1} \tag{18}$$

and the value of t_1 can be quite significant. Thereby, we have shown that the DC component is present in the current flowing through the circuit breaker if reclosing is done with $\psi=0$. The magnitude of a DC component may exceed the amplitude of the steady-state sinusoidal current and delay the zero-crossing event.

In the second case $\psi=\pi/2$ the current through the circuit breaker may be expressed as:

$$i=\left(\frac{X_L}{X_C}-1\right)\frac{E_m}{Z}\cos(\omega t+\phi)-$$
$$-\frac{E_m}{Z}\cos\phi\left[\frac{X_L}{X_C}\cdot e^{-\frac{t}{\tau_C}}-\left(1+\frac{X_L}{X_C}\frac{\tau_C}{\tau_L}\right)\cdot e^{-\frac{t}{\tau_L}}\right]. \tag{19}$$

Similar to the first case, for $t>3\tau_C$ the circuit breaker current will be determined mostly by steady-state current

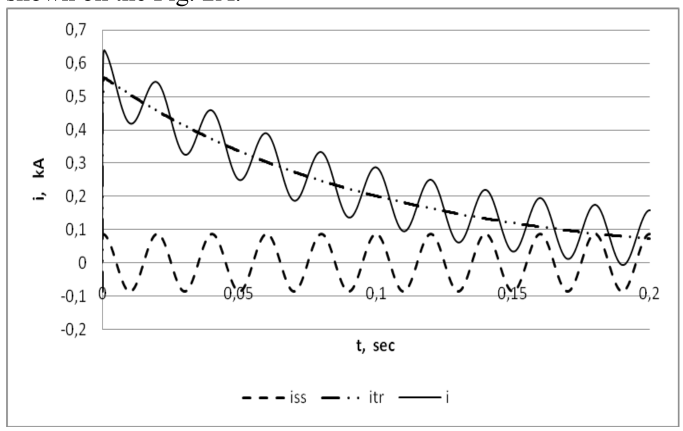
$$i_{ss}=\left(\frac{X_L}{X_C}-1\right)\frac{E_m}{Z}\cos(\omega t+\phi) \tag{20}$$

and transient current corresponding to the time constant τ_L :

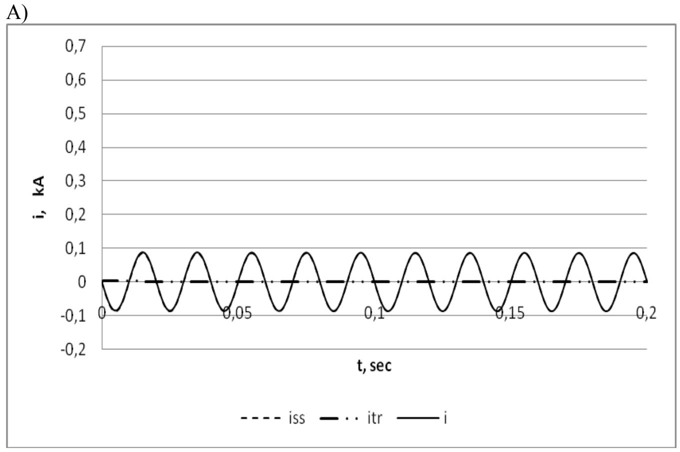
$$i_{tr}=\frac{E_m}{Z}\cos\phi\left(1+\frac{X_L}{X_C}\frac{\tau_C}{\tau_L}\right)\cdot e^{-\frac{t}{\tau_L}}\approx\left(\frac{X_L}{X_C}-1\right)\frac{E_m}{Z}\cdot\frac{R}{Z}\cdot e^{-\frac{t}{\tau_L}}. \tag{21}$$

Since $R\ll Z$, it is apparent from (20) and (21) that DC component is much less then steady-state current amplitude in any case. Problem with delayed zero-crossing does not arise in this case.

Plots shown on the Fig. 2 illustrate analysis made in this section. Model parameters typical for 500 kV transmission line were used. Transmission line is 400 km long with two shunt reactors connected. E_m=428.7 kV, R=25 Ω; X_L=765 Ω, X_C=663 Ω, τ_L=97.5 ms, τ_C=0.12 ms. The formula (18) yields an estimate $t_1\approx0.182$ s which is consistent with the results shown on the Fig. 2A.



A)



B)

Fig. 2. Current through the circuit breaker A) if ψ=0 B) if ψ=π/2.

III. Hypotheses explaining the causes of SF6 circuit breaker failures.

The considered situation happens in non-faulted phases of a breaker during the three-phase autoreclosing in the cycle O-t-CO, when an unsuccessful reclosing of an overhead transmission line is taking place. In this case, next to reclosing the idle non-faulted phases after the dead time, a line tripping signal is issued immediately. If there is a large DC component flowing through the breaker, cutting off the breaker becomes a considerable problem.

Until recently air circuit breakers have been used to cut off the 500-750 kV lines. They handle the considered line reclosing well. However, usage of the new SF6 circuit breakers led to new unexpected problems. Analysis of the accidents has shown that the cause of the failures of arc extinguishing was the presence of the large DC component in the cutoff current which delayed the moment of zero crossing. We have shown conditions for the occurrence of such DC component on a simple scheme.

We would propose the following hypothesis in order to explain the reasons for the success of air circuit breakers, as well as the reasons for failures of SF6 circuit breakers.

Firstly, during the reclosing of air circuit breakers, the closure of an intercontact gap of the breaker is most likely to occur at times close to reaching the voltage maximum, that is when $\psi=\pi/2$. It may be explained from a physical point of view – when the contacts are moving to meet each other the contact closure is being carried out due to the breakdown of the air intercontact gap, which occurs close to the voltage maximum. As we already know, in these circumstances the DC component flowing through the breaker is negligible, and there are no problems during the subsequent cutoff.

Analysis of the oscillograms obtained during the operation of SF6 circuit breakers has showed that in contrast to the air circuit breakers the intercontact gap may also close when the voltage is near zero, that is when $\psi=0$. The insulating properties of sulfur hexafluoride compared to the air may be the reason for that. When contacts are moving sulfur hexafluoride does not break until the contacts are approached to very short distances, which may be got over in time less than a quarter-period of power frequency (5 ms), that is the time during which the voltage does not reach its peak value. Contact closure occurs with an equal probability for all values of voltage, including values close to zero. Under these conditions a large DC component in the cutoff current appears to be leading to an accident.

Another reason for the difference in the behavior of an air and gas-insulated circuit breaker may be the following. Modern SF6 circuit breakers have a closed volume of arc chute, in which the intensity of the arc extinguishing is largely dependent on the energy of the arc defined by the cutoff current. During the concerned reclosing of currents in non-faulted phases their value is negligible, especially near the resonance modes. Therefore, SF6 circuit breakers cannot cut off these currents until they cross the zero line. Such behavior of the breaker is considered as advantageous when handling small inductive currents, because the overvoltages are minimal in this case. However, in this particular case, these qualities are represented as disadvantageous, as they may lead to accidents. Air circuit breaker, having a supply of air under constant pressure, extinguishes the arc off at a rate almost independent of the current. A more rapid decay of the DC component may also contribute to more rapid arc extinguishing in the air circuit breakers, because the significant resistance of the extinguishing arc, with its intensification during extinguishing, is added to the active resistance of the circuit.

Taken together, this leads to the fact that there is no problem of cutoff currents for air circuit breakers in the non-faulted phases during three-phase autoreclosing cycle. To test the proposed hypotheses, the simulation of arc extinguishing processes in the above scenarios of accidents was made. For this purpose, a model of an extinguishing arc adequately reflecting the process of arc burning over the entire range of currents from peak values to zero-crossing was developed.

IV. The electric arc model

Based on the integral description of the arc as a cylindrical nonlinear resistor $u=R\cdot i$ with with varying length l and cross-sectional area S, it is possible under the assumption of constant pressure to write the following relations:

$$R=\rho(h)\frac{l}{S};\quad H=hlS;\quad P=p(h)lS, \tag{22}$$

where R is the arc resistance; ρ is the resisitivity; h is the volumetric enthalpy; p is the heat loss per unit of the arc column volume.

The energy conservation law with integral description of the arc is represented as:

$$\frac{dH}{dt}=i\cdot u-P. \tag{23}$$

A.M. Cassie's assumptions [1] are valid in the area of current amplitude values:

$$S=var\,;\, h=h_C=const\,;\, p=p_C=const.$$

As a result

$$R=\rho_C\frac{l}{S}\text{ , whence }S=\frac{\rho_C l}{R}\;; \tag{24}$$

$$H(R,l)=h_C\frac{\rho_C l^2}{R}\;; \tag{25}$$

$$P(R,l)=\frac{p_C\rho_C l^2}{R}\;. \tag{26}$$

O. Mayr's assumptions [1] are valid near the zero-crossing of current:

$$\begin{gathered} S=S_M=const\,; \\ h=var;\quad \rho=\rho_M e^{-h/h_M}; \\ p(h)=p_M=const. \end{gathered} \tag{27}$$

As a result we get

$$R=\rho_M e^{-h/h_M}\frac{l}{S_M}\text{ , whence }h=h_M\cdot\ln\left(\frac{\rho_M l}{RS_M}\right)\;; \tag{28}$$

$$\begin{aligned} H(R,l)&=h_M\cdot\ln\left(\frac{\rho_M l}{RS_M}\right)\cdot l\cdot S_M= \\ &=h_M S_M l\left(\ln\frac{\rho_M}{S_M}+\ln l-\ln R\right); \end{aligned} \tag{29}$$

$$P(l)=p_M S_M l\;. \tag{30}$$

As it may be seen from given computations, enthalpy of electric arc in asymptotic cases of high and low currents depends only on the arc resistance and its length: $H=H(R,l)$ In accordance with the assumptions of A.M. Cassie and O. Mayr we get from (23):

$$\begin{gathered} \frac{dH(R,l)}{dt}=i\cdot u-P\,; \\ \frac{\partial H}{\partial R}\frac{dR}{dt}=R\cdot i^2-P-\frac{\partial H}{\partial l}\frac{dl}{dt}. \end{gathered} \tag{31}$$

Introducing the notation:

$$H_M = h_M S_M l \;;\; R_{CM} = \frac{\rho_C l}{S_M} \;;\; R_M = \frac{\rho_M l}{S_M} \;;$$
$$P_M = p_M S_M l \;; \tag{32}$$
$$R_1 = \frac{h_C}{h_M} R_{CM} \;;\; R_2 = \frac{p_C}{p_M} R_{CM} \;;\; R_3 = \frac{\rho_M}{\rho_C} R_{CM} \;.$$

According to (24)-(30) we can form the following Table I:

TABLE I

Model type	$\frac{\partial H}{\partial R}$	$\frac{\partial H}{\partial l}$	P
A.M. Cassie's model	$-H_M \cdot \left(\frac{R_1}{R}\right)\frac{1}{R}$	$H_M \cdot \frac{1}{l} \cdot \left(\frac{R_1}{R} + \frac{R_1}{R}\right)$	$P_M \cdot \left(\frac{R_2}{R}\right)$
O. Mayr's model	$-H_M \cdot (1) \frac{1}{R}$	$H_M \cdot \frac{1}{l} \cdot \left(\ln \frac{R_3}{R} + 1\right)$	$P_M \cdot (1)$

Both models may be combined to the one generalized model by introduction of the functions:

$$\alpha_m(i) = \begin{cases} \alpha_{m0} + (1 - \alpha_{m0})\left(2 - \frac{i^2}{I_C^2}\right)\frac{i^2}{I_C^2}, & if\ |i| < I_C; \\ 1, & if\ |i| \geq I_C, \end{cases} \tag{33}$$

where m=1,2,3; I_C is transition current from low currents to high currents (transition current from O. Mayr's model to A.M. Cassie's model). The expression (33) is obtained if functions $\alpha_m(i)$ are in the following form:

$$\alpha_m(i) = \begin{cases} \sum_{n=0}^{N} \alpha_{mn} i^{2n}, & if\ |i| < I_C; \\ 1, & if\ |i| \geq I_C, \end{cases}$$

providing continuity of function values and their derivatives at I_C point.

Generalized model of the arc for the entire range of currents from peak values to zero-crossing is obtained as follows:

$$-H(i,R)\frac{d \ln R}{dt} = R \cdot i^2 - P(i,R) - H_l(i,R)\frac{d \ln l}{dt} \;, \tag{34}$$

where

$$H(i,R) = H_M \left(\frac{R_1}{R}\right)^{\alpha_1(i)} ; \quad P(i,R) = P_M \left(\frac{R_2}{R}\right)^{\alpha_2(i)} ; \tag{35}$$

$$H_l(i,R) = H_M \left\{ \alpha_3(i)\frac{R_1}{R} + \left[1 - \alpha_3(i)\right] \ln \frac{R_3}{R} + \left(\frac{R_1}{R}\right)^{\alpha_1(i)} \right\}. \tag{36}$$

When $\alpha_{m0} = 0$ (m=1,2,3) the equation (34) with current value $i=0$ becomes O. Mayr's equation, and with $i \geq I_C$ becomes A.M. Cassie's equation. In general case the assumption $\alpha_{m0} \neq 0$ may be made, then with $\alpha_m(i) = \alpha_{m0} = const$, Schwarz model [3] is obtained.

V. The arc extinguishing model for gas circuit breakers

In modeling of arc extinguishing process for gas circuit breakers, the convention $l=const$ is made. When using equation (34), model of arc in the breaker is described by the equations:

$$\begin{aligned} & u_1 - u_2, \quad if\ t < t_I; \\ & \frac{u_1 - u_2}{k_{ag}} - R_I i = 0, \quad if\ t = t_I; \\ & \left.\begin{aligned} & -\tau_M \left[\left(\frac{R_1}{R}\right)^{\alpha_1(i)}\right]\frac{d \ln R}{dt} = \frac{R i^2}{P_M} - \left[\left(\frac{R_2}{R}\right)^{\alpha_2(i)}\right]; \\ & \frac{u_1 - u_2}{k_{ag}} - R i = 0, \end{aligned}\right\} \; if \quad t > t_I \\ & i = 0, \;\; if\ R \geq R_m, \end{aligned} \tag{37}$$

where k_{ag} is the number of arc gaps in the breaker;

R_I is the initial resistance of arc burning;

$\tau_M = h_M / p_M = H_M / P_M$ is Mayr's time constant;

R_m is the resistance of arc extinguishing.

To determine the parameters of equation (37) experimental results are used. We introduce the Cassie's time constant: $\tau_C = h_C / p_C$. From (32)-(35) we get a number of relations:

$$R_1 = \frac{\tau_C}{\tau_M} R_2 ; \tag{38}$$

the arc voltage is constant at high currents $(u_{eff} = u_0 \approx const)$, then:

$$P_M = \frac{u_0^2}{R_2} \;, \tag{39}$$

when $R = R_{\max}$ (in case of failure of arc extinguishing during a thermal breakdown):

$$\frac{u_{R\max}^2}{P_M} = R_{\max}\left(\frac{R_2}{R_{\max}}\right)^{\alpha_{20}} ; \tag{40}$$

if $i=0$:

$$\tau_M \left(\frac{R_1}{R_{i=0}}\right)^{\alpha_{10}} \frac{d \ln R}{dt}\bigg|_{i=0} = \left(\frac{R_2}{R_{i=0}}\right)^{\alpha_{20}} . \tag{41}$$

If the time constant of the arc near zero current τ_M (Mayr's time constant) and time constant of the arc at high currents τ_C (Cassie's time constant) are obtained from the experiment, then having the experimental oscillograms $u_e(t)$, $i_e(t)$ for the arc model we may consistently determine all the other parameters of the model (37). The minimum of residual function should be obtained:

$$F(\alpha_{20}) = \int_{t_0}^{t_k} \left[R(t) - R_e(t)\right]^2 \mu(t)\, dt \;, \tag{42}$$

where $\mu(t)$ is the weighting function.

Sequence of calculations is as follows:

1) α_{20} value is set;
2) $P_M, R_1, R_2, \alpha_{10}$ are obtained from (38)-(41) and experimental oscillograms;
3) solution of the equation (37) is obtained;
4) residual function is obtained according to (42);
5) parameters are determined when a minimum value of residual function is obtained.

VI. Simulation of electric arc in air and sulfur hexafluoride circuit breakers

On Fig. 3 results of simulation of air circuit breaker cutoff process are presented for the case when the current does not cross zero. As can be seen on the figure, arc resistance makes the current decrease. When the current approaches the zero level, voltage of electric arc increases and, eventually, current chopping occurs.

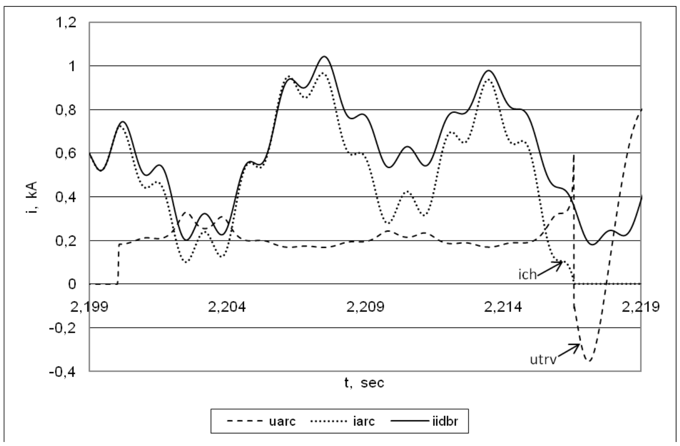


Fig. 3. Arc extinguishing process during air circuit breaker cutoff
iidbr – current through a circuit breaker without arc simulation (ideal breaker);
iarc – current through an air circuit breaker with electric arc taken into account;
ich – current chopping;
uarc – voltage of electric arc;
utrv – voltage on the circuit breaker contacts after extinguishing the electric arc

On Fig. 4 results of simulation of a SF6 circuit breaker cutoff process are shown. The same current as in the previous case flows through the breaker. As indicated on the picture, the arc in the breaker is not extinguished for a prolonged period of time. During that period of time arc extinguishing conditions are changing significantly due to considerable heating of breaker contacts and arc chute walls. Conditions of fanning of the arc by sulfur hexafluoride become significantly worse. Changed conditions lead to a situation when the arc is not extinguished even when the current crosses the zero line. To model the breakdown process completely, the time-variability of parameters must be taken into account in the arc equations.

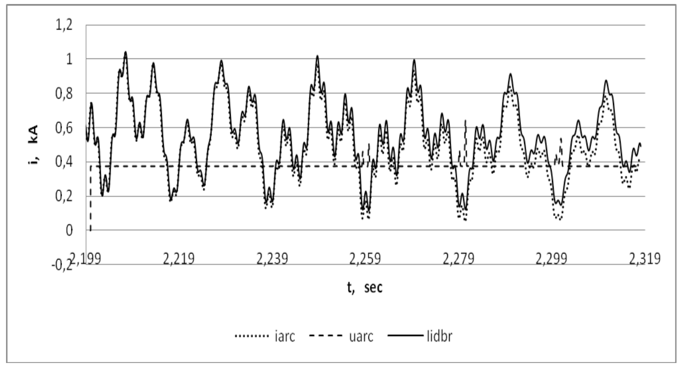


Fig. 4. Arc extinguishing process during SF6 circuit breaker cutoff

VII. Conclusions

1. In case of an unsuccessful three-phase autoreclosing during a one-phase transmission line fault it is possible that a circuit breaker has to cut off the current that does not cross zero for a long time. This situation occurs on 500 kV and higher voltage lines with shunt reactors in a near-resonance mode on a first harmonic. Reclosing of non-faulted phases of a transmission line when voltage of the power source is close to zero leads to a DC component of considerable magnitude occurrence in the current through a circuit breaker. At the same time, sinusoidal steady-state component is quite small in the magnitude. As a result, the current does not cross zero for a long period of time.

2. It was shown that air circuit breaker can cut the current which does not cross zero. Current chopping occurs in this case. Sulfur hexafluoride breaker can not cut off such current, leading to the circuit breaker damage. Additional measures should be taken to prevent such accidents when SF6 circuit breakers are used.

VIII. References

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