MATHEMATICAL MODEL OF ELECTRIC ARC RESPECTING MAYR THEORY IN EMTP-ATP

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ABSTRACT

The mathematical interpretation of an electric arc is practically very difficult by virtue of its extremely accidental character. But on the other side, the mathematical formulation course of the electric arc is possible with transfer to the area of the mathematical modeling for specific conditions. Limits of influences of the electric arc are possible to determine with using results from mathematical simulations. The mathematical model of the electric arc defined at simulation program EMTP-ATP and respecting Mayr theory is introduced within this paper. Results from simulations defining the influence of the electric arc on the medium voltage system are introduced within paper too.

Keywords: *EMTP-ATP program, arc earth fault, medium-voltage system, Mayr Theory*

1. INTRODUCTION

Faults with time change of resistance, so called electric arc faults, belongs to most frequently incident 1poles fault at medium-voltage systems with cable transmission lines. The interaction between the medium-voltage system and the electric discharge is caused by time change resistance of the electric arc puncture. For safety and reliability running of the each electric medium-voltage system is necessary to know voltage and current conditions also for this mentioned type of faults. For definition voltage and current conditions of electric arc fault is possible to realize experiment with defined parameters of the analyzed system. But on the other side, the realization of this experiment is very difficult and risk of safety system restriction exists. For this case, the possibility of using program EMTP-ATP was verified.

The EMTP-ATP is a universal program system for digital simulation of transient phenomena of electromagnetic as well as electromechanical nature. With this digital program, complex networks and control systems of arbitrary structure can be simulated. ATP has extensive modeling capabilities and additional important features besides the computation of transients.

The mathematical model of medium-voltage system including model of electric arc was completed and voltage and current conditions for electric arc faults were defined with using results from mathematical simulations. Results from mathematical modeling were verified by the real experiment at the medium-voltage system at Czech Republic. The analyzed system was 6 kV with cable transmission lines. The mathematical model of electric arc was created by virtue of results from experiment with using program EMTP-ATP, the programming language MODELS was used at the concrete. The Mayr theory was used for the description of electric arc character [1].

2. MAYR MODEL OF ELECTRIC ARC IN EMTP-ATP

The Mayr model respects conditions for low value of current. This model is applicable for analyze of residual current, which is arisen after current interruption. This stadium is called as a thermal regime and its time interval of persistency is units of $1 \cdot 10^{-6}$ seconds. The breaking capacity can be presented by mathematical formulation of Mayr model, because transient phenomena are defined for concrete time interval. The Mayr model also respects radial diffusion losses to surrounding colder area. Flow losses are neglected by virtue of the small profile electric arc. The radius is presumed as constant as well as size of total losses by radial cooling. The conductivity exponentially increases with the heating accumulated in the plasmatic according to the formula (1):

$$\gamma = \text{konst} \cdot e^{\frac{Q}{Q_0}} \tag{1}$$

The variable Q_0 is defined as a heating necessary for increasing of conductivity about ratio 1/e, where e is Euler's number. The P_P is power supply of plasmatic and γ is coefficient of thermal conductivity. Then, the balance equation according to the Mayr theory is:

$$\frac{1}{\gamma}\frac{\mathrm{d}\gamma}{\mathrm{d}t} = \frac{1}{\vartheta_\mathrm{M}}\left(\frac{P_\mathrm{P}}{\Phi} - 1\right) \tag{2}$$

For the Mayr's time response (Mayr's constant) reads:

$$\vartheta_\mathrm{M} = \frac{Q_0}{\Phi} \tag{3}$$

The resultant formula for arc-drop voltage according to Mayr theory is

$$u_\mathrm{a} = \frac{P_\mathrm{P} \cdot 2\sin(\omega t)}{I_\mathrm{m} S1\left(\cos 2\omega t + 2\omega\vartheta_\mathrm{M}\sin 2\omega t\right) + \left[S2e^{-\frac{t}{\vartheta_\mathrm{M}}}\right]} \tag{4}$$

Where the variable S1 is:

$$\left(1 - \frac{1}{1 + 4\omega^2\vartheta_\mathrm{M}{}^2}\right) \tag{5}$$

And the variable S2:

$$\left(\frac{Rq}{R_{01}}-1+\frac{1}{1+4\omega^2\vartheta_M{}^2}\right)e^{-\frac{t}{\vartheta_M}} \tag{6}$$

The element E_a respects intensity of electric current plasmatic field, R_q/R_{01} is ratio of arc resistances (it can also be 0,1; 1; 10).

The Mayr model of electric arc was selected for mathematical modeling in EMTP-ATP, because its mathematical formulation relatively exactly respects the course of voltage at area ignition and the arc suppression peak.

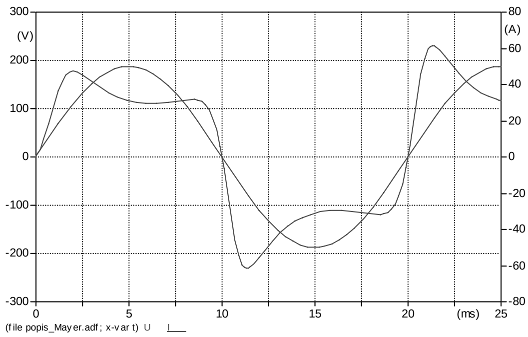

Fig. 1 The course of arc-drop voltage (V) and current by electric arc (A) determined by EMTP-ATP.

The course of arc-drop voltage and current by electric arc determined by simulation program EMTP-ATP is shown in Fig. 1. The electric arc as a nonlinear dynamic element is represented by the nonlinear time-dependent resistor TYPE 97 in EMTP-ATP. The mathematical model in EMTP-ATP was completed with the respecting equation for arc-drop voltage (4). Thus, from equation (4) is defined current by electric arc and identified value of electric arc resistance. This characteristic is inserted to the time definition of function time-dependent resistor TYPE 97 in EMTP-ATP. It comes to this, that resistance of electric arc is changed by virtue of current conditions in the analyzed medium-voltage system. This fact is respected in the dynamic characteristic of electric arc and displayed in the Fig. 2. However, the phenomenon of the dielectric re-ignition after arc extinction is not considered in this arc model, because, the arc length variation is highly dependent on external factors like wind or thermal buoyancy.

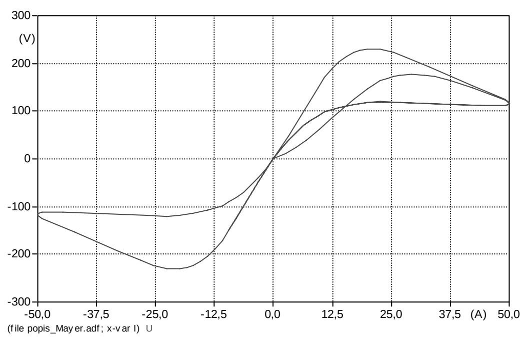

Fig. 2 The dynamic characteristic of electric arc generated by EMTP-ATP.

3. SIMULATION OF 1POLES ARC-EARTH FAULT IN THE MEDIUM-VOLTAGE SYSTEM

The verified mathematical model of electric arc respecting Mayr theory was used for definition current and voltage conditions at 1poles arc-fault. This type of fault is typical for medium-voltage systems with cable transmission lines. The analysis is specified on the self-consumption systems at Power Stations [2]. These medium-voltage systems are operated as an insulated or indirectly grounded by resistor or inductor; results from simulation at insulated medium-voltage systems are described in this paper at the concrete.

The effect of arc earth-fault was determined at the medium voltage insulated self-consumption system; the block scheme of mentioned system is in Fig. 3. The test configuration of the medium-voltage system was selected for verification utility of the arc model in EMTP-ATP. The source of system voltages is respected by the transformer 15,75/6,3 kV and modeled by procedure BCTRAN in EMTP-ATP ("TrDd0" in Fig. 5). The parameters of transformer are introduced in the table 1.

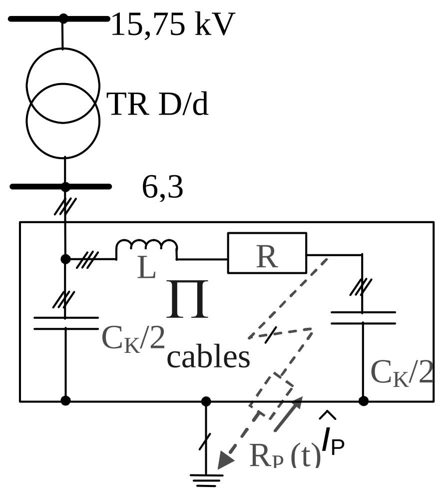

Fig. 3 The block scheme of tested system.

Table 1 Transformer parameters.

Nominal voltage primary(L-L)	15,75	(kV)
Nominal voltage secondary(L-L)	6,3	(kV)
Nominal power	25	(MV·A)
Short-circuit voltage	8,6	(%)
Short-circuit losses	131	(kW)
No-load current	0,3	(%)
No-load losses	30	(kW)
Connection	Dd0	

The total capacity current of simulated system for tested configuration was 7,5 A according to equation (7), which is capacitive line-to-earth current of cable lines 2000 meters 6-kV type AYKCY 185 mm^2.

$$\hat{I}_{\mathrm{P(kap)}} = j3\omega C\hat{U}\,, \tag{7}$$

Where C (F) is equivalent total line-to-earth capacity of system and U (V) is line-to-neutral voltage of system. The cable 6-AYKCY was modeled by procedure Line Cable Constants (LCC) in EMTP-ATP ("AYKCY" in Fig. 5). The model of used cable line is created by LCC by virtue of geometrical parameters and parameters of dielectrics or conductive part of the cable. The cable cut is shown in Fig. 4; the description of individual cable parts is introduced in the table 2.

Table 2 6-AYKCY cable description (according to Fig. 4).

1	Aluminum core
2	PVC isolation
3	cushioning cover
4	inner sheath
5	tape
6	Cooper concentric conductor
7	Tape
8	PVC outer sheath

According to block scheme of tested medium-voltage system, the mathematical model was created in EMTP-ATP (see Fig. 5).

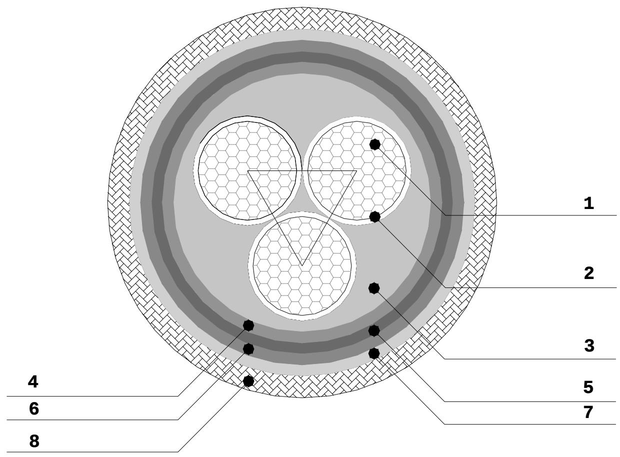

Fig. 4 The block scheme of tested system.

The block denoted as a „Zs" respects the source impedance $\hat{Z}_s = R_s + jX_s$ and corresponds to a 3phase short-circuit power S''_k = 200 MV·A. The arc-earth fault is respected by model of electric-arc; this model is inserted into total scheme of analyzed medium-voltage system ("R(t)" in Fig. 5).

Courses of systems voltages in the fault point and current by electric arc-fault generated by EMTP-ATP are shown in the Fig. 6. The courses were obtained with using mathematical modeling in EMTP-ATP for case inception of fault.

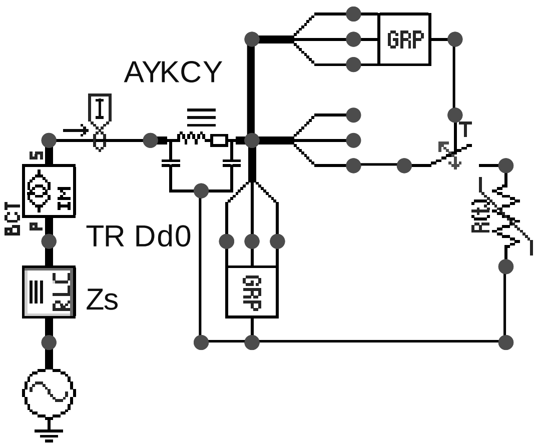

Fig. 5 The simplified block scheme of tested system in EMTP-ATP.

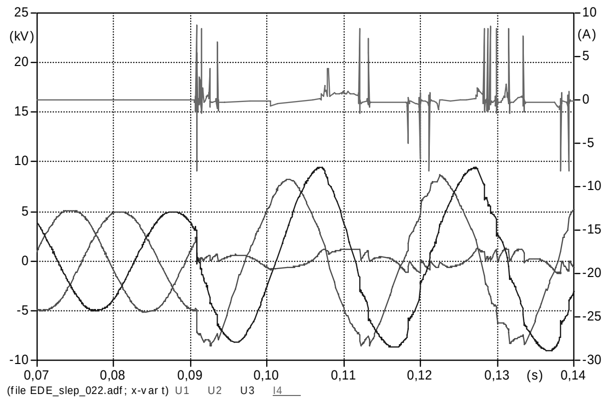

Fig. 6 Courses of systems voltages in the fault point (U_1, U_2, U_3 (kV)) and current by electric arc-earth fault (A) generated by EMTP-ATP.

The voltage drop phase with fault is followed by discharging shunt capacities of circuit; it is evidently from the Fig. 6. Courses of voltages individual phases are determined by sum of voltage before fault and by voltage of transient phenomenon; see equations 7, 8.

$$\hat{U}_2 = \left(a^2 - \frac{\hat{Z}_{(0)} - \hat{Z}_{(1)}}{3R_\mathrm{p} + 2\left(\frac{1}{C_0 + 3\cdot C_{12}} \cdot \frac{j\omega}{\omega_1^2 - \omega} \right) + \frac{1}{\mathrm{C}_0} \cdot \frac{j\omega}{\omega_0^2 - \omega^2}} \right) \hat{U} \tag{7}$$

$$\hat{U}_3 = \left(a - \frac{\hat{Z}_{(0)} - \hat{Z}_{(1)}}{3R_\mathrm{p} + 2\left(\frac{1}{C_0 + 3\cdot C_{12}} \cdot \frac{j\omega}{\omega_1^2 - \omega} \right) + \frac{1}{\mathrm{C}_0} \cdot \frac{j\omega}{\omega_0^2 - \omega^2}} \right) \hat{U} \tag{8}$$

Where $\hat{Z}_{(0)}$ and $\hat{Z}_{(1)}$ are impedances of zero and positive-sequence components, C_0 and C_{12} are shunt and inter-phases capacities. The inductivity of circuit with self-frequency oscillation (ω_0 a ω_1 for zero and positive-sequence) is dominant after transient phenomenon response.

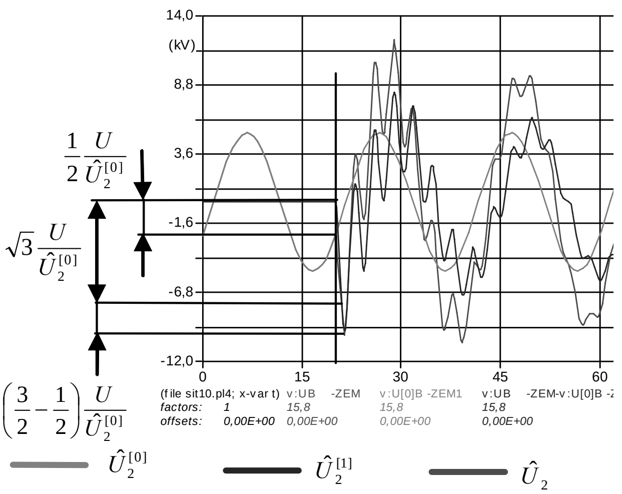

Fig. 7 Detailed courses of individual component voltage at phase 2 in the fault point (kV) generated by EMTP-ATP.

The analysis of individual components voltage without fault generated by EMTP-ATP is shown in Fig. 7. The course denoted as a $\hat{U}_2^{[0]}$ presents voltage at steady state before inception of the earth-fault, $\hat{U}_2$ presents voltage at steady state for permanent earth-fault. And last but not least, the course $\hat{U}_2^{[1]}$ presents course of transient component with the oscillation frequency according to the equation (7). It comes to this, that final course of voltage without fault is defined by the vector sum $\hat{U}_2^{[0]} + \hat{U}_2^{[1]}$ for the inception of the earth-fault.

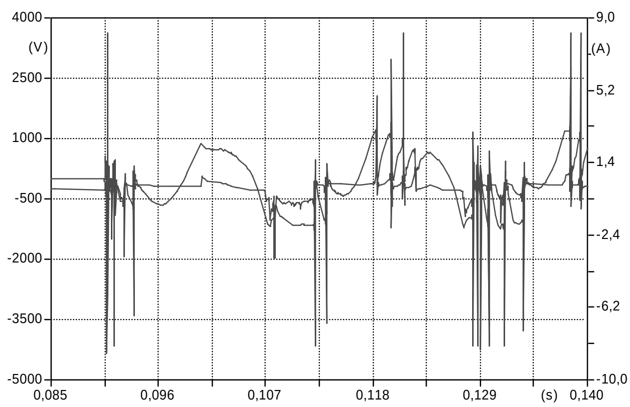

Fig. 8 The detail record courses of arc-drop voltage (V) and current by electric arc (A) at inception of electric arc.

The maximum value of over-voltage was defined by EMTP-ATP 1,9 at phase 3. The amplitude of fault current is changed to ten times the amount of capacity current after fire penetration of electric arc puncture. The ignition peak with amplitude 18% of nominal phase voltage is evidently from detail at Fig. 8. When the initialize energy is sufficient, the electric arc is re-ignited (see Fig. 8). The electric arc extinctions after deficit of initialize energy at course of current by zero. However, initialize energy is sufficient for re-ignition of electric arc all of time for cables transmission lines. Therefore, the electric-arc at cables lines not burns in principle.

4. CONCLUSION

Most of 1poles earth fault at medium-voltage systems are by arc character. The over-voltage is not only one problem at arcing. The main problem is percent occurrence of an electric arc, which is defined by parameters of a medium-voltage system. The mathematical program EMTP-ATP was used for definition of percent occurrence of an electric arc at medium-voltage system for 1poles earth fault. The verification possibility of using EMTP-ATP was executed for simulation 1poles arc-earth fault within this paper. The time change of fault resistance was respected by mathematical model of electric arc. The Mayr mathematical interpretation of electric arc was used for the mathematical model. Although the mathematical model is not universal for all kinds of faults, the possibility of using mathematical modeling at power systems was verified and results from simulations are applicable and veracity. This proposition was verified by the real experiment at the medium-voltage system at Czech Republic.

Results from mathematical modeling are applicable for optimizing of medium-voltage system, where the method of earth connection is considered with respect to voltage and current conditions for inception of earth fault. The concept of system protection is possible to optimize by virtue of results from simulation too.

This paper was created within the research project MSM 6198910007.

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Received January 25, 2008, accepted June 30, 2008

BIOGRAPHY

Stanislav Mišák was born on 15.9.1978. In 2003 he graduated (Ing.) with distinction at the Department of Electric Power Engineering of the Faculty of Electrical Engineering and Computer Science at Technical University in Ostrava. He defended his PhD. in the field of electric power engineering in 2007; his thesis title was "Analysis of 1polar Faults at Self-Consumption of Medium-Voltage Systems ". Since 2002 he is working as a research worker at the Department of Electric Machines and Apparatus.