EMTP Simulation of the Secondary Arc Extinction at Overhead Transmission Lines under Single Phase Automatic Reclosing

M. V. Dmitriev, *Student Member, IEEE;* G. A. Evdokunin, *Member, IEEE;* V. A. Gamilko

Abstract - **The paper presents a mathematical model and algorithm of the software for transient phenomena simulation of the burning and extinguishing long secondary arc at high voltage overhead lines. The results of investigations of self extinguishing of secondary arc under automatic single phase reclosing (ASPR) for 500, 750, 1150 kV lines are given as well. Additionally transient recovery voltage after arc extinction and voltage at the neutral terminal of shunt reactor (in a case of four-key reactor) are determined.**

Index Terms – **Air Insulation, Arc Discharges, Circuit Modeling, Circuit Transient Analysis, Failure Analysis, Power Transmission Lines, EMTP.**

I. INTRODUCTION

Single phase short circuit at overhead line is the most frequent failure. In a case if the failure is transistory it is possible to only phase damaged opening and after dead time 1,5...2,0 s reclosing. It allows to restore the transmission normal operation under low disturbance in system. However in order to Automatic Single Phase Reclosing (ASPR) would be successful it is required that the value of secondary arc current at the point of damage would be low enough to extinguish. In Saint-Petersburg State Technical University (Saint-Petersburg, Russia) a mathematical model of dynamic open arc has been developed. This model has been included to Electro-Magnetic Transient Program (EMTP) and enables to determine successful or not arc extinction in the case interested.

The problem of a single-phase reclosing in compact power transmission lines is more complicated than in ordinary-design lines because of higher phase-to-phase capacities resulting in increasing of secondary arc currents for the same degree of compensation for the line charge power. The acquisition of experimental data allowing evaluation of the non-current duration of a single-phase reclosing for non-ordinary-design lines under design seems to be very problematic. So of great importance is the mathematical simulation of transients in a network with account an open AC arc model.

II. THE MATHEMATICAL MODEL OF LONG OPEN ARC

For evaluation of the non-current duration of a single-phase automatic reclosing, a cylindrically-symmetric channel model of a vertical arc with a variable radius may be used [1]. The arc column is assumed to be uniform in height. The model reproduces uniform cooling of the arc channel with no account of transverse air-flow, which corresponds to the most severe conditions of the extinction of an open arc. The outside boundary of an arc channel is a surface with a T_b - temperature that surrounds the area where it is possible to neglect the convective heat transfer because of secondary arc currents comparatively small. A T_b value is determined experimentally [2] ($T_b \approx 5000 \div 6000\,\mathrm{K}$ for currents from 50 A to 300 A).

The electric conductivity of plasma arc below the temperature of 6000 K is close to zero, therefore the surface with a temperature of T_b determines the total arc current in an arc channel.

Under these assumptions the mathematic description of transients in an arc comes to the energy dynamic equation for an arc cylindrical channel:

$$\sigma E^2 + \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda \frac{\partial T}{\partial r} \right) = \rho C_p \frac{\partial T}{\partial t}, \qquad (1)$$

where: E, T - instantaneous values of an electric field strength and temperature of plasma arc; σ, λ, ρ, C_p - conductance, thermal conductivity, density and specific heat capacity with invariable atmospheric pressure, depending on temperature; r - radius coordinate of an arc channel; t - time.

The boundary conditions for the equation (1) follow from a cylindric symmetry of an arc channel

$$\left. \frac{\partial T}{\partial r} \right|_{r=0} = 0$$

and from the thermal flux continuity on the isothermic surface with a temperature T_b:

$$-\lambda(T_b) \left. \frac{\partial T}{\partial r} \right|_{T=T_b} = Q(T_b),$$

Saint-Petersburg State Technical University (Saint-Petersburg, Russia)
M. V. Dmitriev (e-mail: mvdmitriev@mail.ru).
G. A. Evdokunin (e-mail: evdg@etelecom.spb.ru).
V. A. Gamilko.

where: $Q(T_b)$ - thermal flux from an arc channel surface by means of the convective heat transfer and by means of thermal conductivity.

A value $Q(T_b)$ is determined from empiric formula, obtained in [3] ($Q(6000K) \approx 72$ W/cm).

The solution of energy equation (1), jointly with network equations is performed with Ohm's integral law:

$$i_a = 2\pi \frac{u_a}{l_a} \cdot \int_0^{r_b} r\sigma(r)dr , \qquad (2)$$

where: l_a - the length of an arc; i_a, u_a - instantaneous values of an arc current and voltage (here $u_a = E \cdot l_a$); r - instantaneous value of boundary radius ($r_b = r(T_b)$).

For calculating the given system of the equations we use implicit difference scheme. As the plasma thermal physical characteristics dependencies on temperature are complicated to be approximated, we use the integral functions

$$S(T) = \int_0^T \lambda(T)dT , \quad F(T) = \int_0^T \rho(T)C_p(T)dT$$

instead of $\lambda(T)$, $\rho(T)$, $C_p(T)$.

After these substitutions we have the following energy equation (1) and boundary conditions:

$$\left.\begin{aligned} &\sigma(S)E^2 + \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial S}{\partial r}\right) = \left(\frac{\partial F(S)}{\partial S}\right)\frac{\partial S}{\partial t}; \\ &\left.\frac{\partial S}{\partial r}\right|_{r=0} = 0; \\ &-\left.\frac{\partial S}{\partial r}\right|_{S=S_b(r=r_b)} = Q(S_b), \end{aligned}\right\} \qquad (3)$$

where: $S_b = S(T_b)$.

According to difference scheme we replace the particular derivatives with their finite differences of the S - functions, and for calculating the integral (2) we use trapezoidal rule and the meanings of S - function along the channel radius. The dependences $\sigma(S)$ and $F(S)$ are performed using piecewise-linear approximation.

In each step in time we solve non-linear system of algebraic equations with the iterative method. After determining the solution, the radius is corrected in such a way equation $S = S_b$ (at the surface of the arc channel) is performed. Criterion of an arc extinction is a decrease of values S in all points of the arc radius until $S < S_b$.

For an arc model, described above provision is made for uniform cooling of the whole arc column. As the channel is assumed to be homogeneous in height, the arc extinction is the full loss of conductivity of the channel.

Thus, the arc model enables us to obtain a non-underestimated value of an arc extinction conditions.

Non-uniform cooling of the arc column may be introduced as a superposition of accidental local cooling of some parts of the column and a uniform cooling of the whole arc column in a quiet atmosphere. As a result of non-uniform cooling the arcing is of an intermittent nature.

The arc extinction assumptions are connected with loss of conductivity of more cooled parts of the arc column. Undoubtedly, an electric break-down of short parts of the column is real, and it depends on a rate of rise and Transient Recovering Voltage Value (TRV). After breaking-down an arc ignites again. It is clear why in an initial investigations many researchers considered that both characteristics were important: steady-state secondary arc current and TRV value [4, 5]. However after summarizing a lot of experimental data it turns out that the maximum time of the last arcing practically doesn't depend on the TRV factor [6, 7]. It may be explained by the fact that a non-underestimated evaluation of the arcing time corresponds uniform cooling of the arc column case, when an intermittent nature of arcing is impossible.

For the arc model [1], described above a reignition will take place if electric break-down of the insulation gap occurs. As a length of line insulator string UHV and EHV lines comes a value of a few meters, electric break-down of the gap is practically impossible regardless of any TRV characteristics.

Thus, the open arc model enables us to obtain non-underestimated evaluation of the non-current duration of the automatic single-phase reclosing in spite of the fact that the model doesn't reproduce a possible intermittent nature of arcing.

III. TESTS OF THE EMTP ARC MODEL

Open air arc equations described above were programmed using EMTP Type-94 Model's Language [9]. The open air secondary arc equations are solved together with the rest part of the circuit.

Using EMTP model the preliminary analyses on determining of secondary arc current values under single phase fault to ground and subsequent single phase opening were carried out for some 500-1150 kV transmission lines (with and without shunt reactors, neutral reactors) in order to compare EMTP results with experimental data presented in [4-8]. Many of EMTP simulations showed good agreement with experimental results.

For arc extinction the length of an arc and it's placement are meaningful. The least favorable conditions of arc extinction are when arc is along supporting isolators string. Along the supporting string also the insulation space of the line is less than in span between towers. So when experimenting with open air arc initiation of the line, short circuit carries out with the help of a thin aluminium or copper wire pulled in parallel with supporting string.

Two various ways of line short circuit creation are possible:

1. Switch on the overhead line with arranged thin wire in parallel with one of the insulator strings.
2. Sudden overlapping of isolators by a thin wire or sudden connection insulator string with parallel thin wire to line, when voltage is applied to the line.

Switching operations when experimenting with line short circuit and open air arc using variants 1 and 2 are illustrated in Fig.1 and Fig.2 respectively.

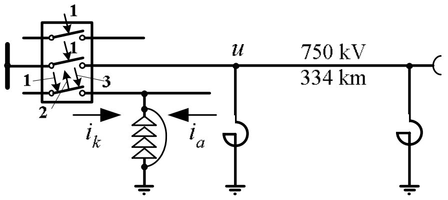

Fig. 1. Circuit 1 when experimenting with open air arc on overhead line.

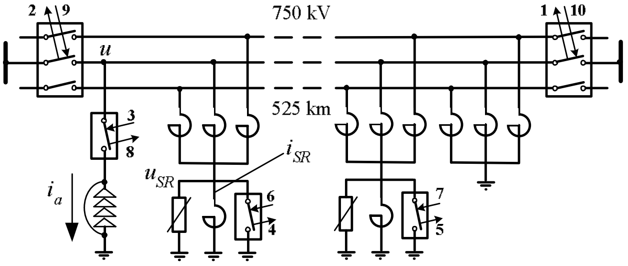

Fig. 2. Circuit 2 when experimenting with open air arc on overhead line.

Experimental data, obtained in circuits Fig.1-2 and described in [8], are shown on Fig.3-4.

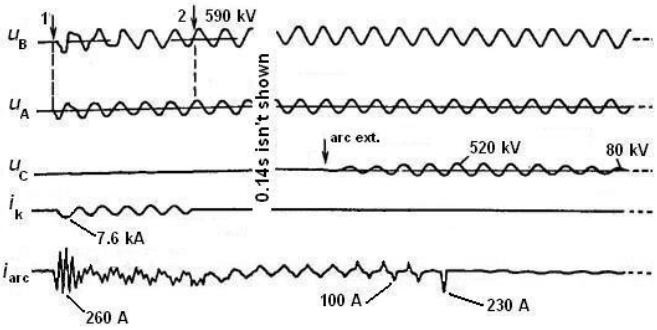

Fig. 3. The experimental data [8], obtained in circuit 1.

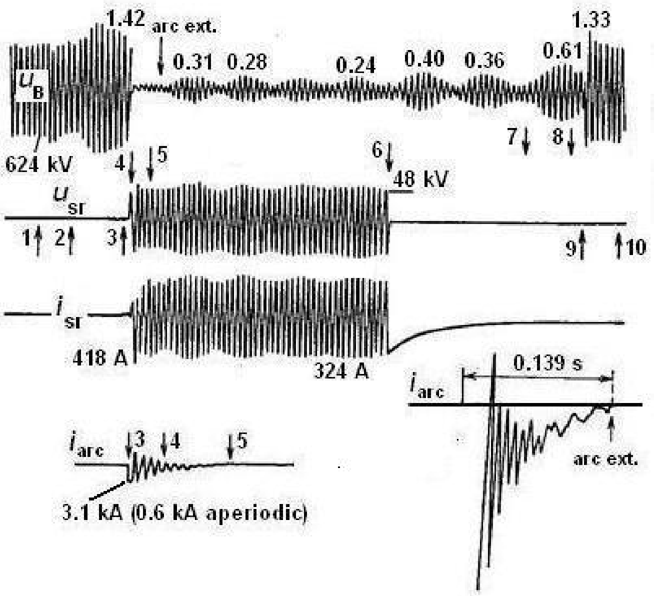

Fig. 4. The experimental data [8], obtained in circuit 2.

Using EMTP open air arc simulations were made for circuits Fig.1 and Fig.2. Results presented in Fig.5-6.

One can see that arc current has components: high frequency (Fig.3-6), aperiodic (Fig.4,6), periodic (Fig.3-6). High frequency components are traveling wave reflections of the line ends and short circuit place. Aperiodic components are due to shunt reactors and damping approximately 0.17 s after arc occurrence (Fig.4,6). Periodic components are from energized phases influencing.

After arc extinction transient restoring voltage at damaged phase has two components: power frequency component and component of free oscillations with frequency close to 50 Hz.

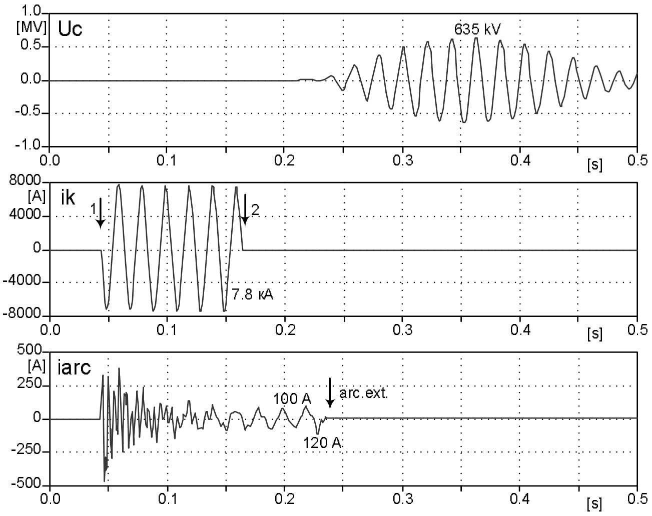

Fig. 5. EMTP calculations, obtained in circuit 1.

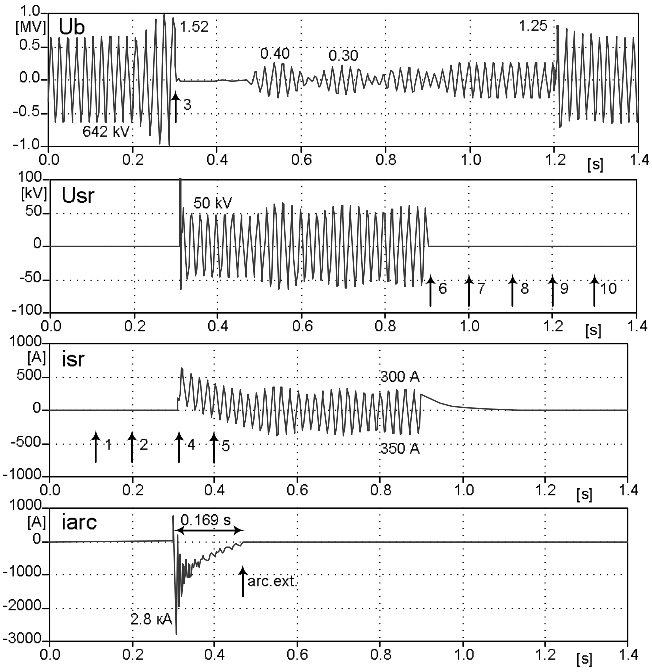

Fig. 6. EMTP calculations, obtained in circuit 2.

The experimental data for 500, 750 and 1150 kV lines [8] have shown that the arc length during arcing is lengthened very little, therefore an arc length is adopted to be constant.

It is seen from Fig.5-6 that the nonlinear arc equations make a shape of the arc current not sinusoidal.

Time interval for self extinction of the arc for Fig.5-6 is about 0.2 s. Such a way determined the time interval is the minimum dead time to reclose. To ensure more reliable deionization of arc channel after sharp limitation of its conductivity it is necessary to add the time interval approximately $0.3 \div 0.5$ s based on experimental data. In a result the sum of these two time intervals gives the dead time required for the conditions adopted and accounts from the opening the last circuit breaker. However if it will be foreseen of the neutral reactor switching during transient then it may result of increasing of extinguishing time due to appearance of additional components in a secondary arc current.

IV. EMTP SIMULATIONS USING ARC MODEL

Based on preliminary calculations it has been determined that the short circuit point along the line, faulted phase name (a,b,c), transmitted power value influence very low on secondary arc current value. However the current value itself equals $I_{arc} = 90...100\,\text{A}$ (peak value) turns out to be great enough in order to self-extinguishing would become to be low probability event. Besides an inadmissible resonant increasing of voltage at opened phase presents an additional obstacle in a case of arc extinction and non switching of line shunt reactors.

For decreasing of secondary arc currents values while opening a damaged phase use neutral reactors is very effective.

One can see it on Fig.7, where without neutral shunt reactors periodic component of the secondary arc current is to high for arc self extinguishing.

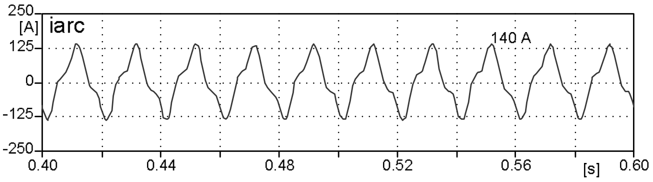

Fig. 7. EMTP simulations in the case of transmission line (Fig.2) without neutral reactors. No self extinguishing of the secondary arc current.

Some ASPR simulations using EMTP open air arc model were made for 750 kV 272 km long overhead line “Kolskaya Nuclear Power Plant - Cherepovec”. Both ends of the line are equipped with 3x110 MVAr line shunt reactors (Fig.8.). The issue to discuss for this line was the necessity of arrangement of neutral reactor.

Example of secondary arc current and phase voltage versus the time is shown on Fig.9. This figure is a result of EMTP simulations for ASPR of 750 kV line “Kolskaya Power Plant - Cherepovec”. Corona on phase wires is not taking into account, so high temporary overvoltages are possible.

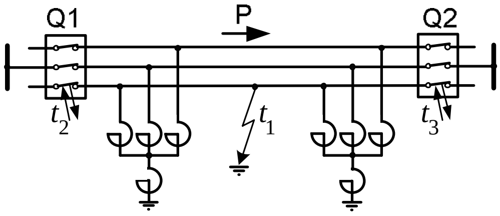

Fig. 8. Transmission line with neutral shunt reactors under ASPR.

On Fig.9 one can see the self extinction of open air arc (time moment 4). Neutral reactors isn’t necessary for lowering arc current. The time of arc self extinction is about 0.1 s.

All calculations for 750 kV “Kolskaya Nuclear Power Plant - Cherepovec” line not using neutral reactors gave that amplitude of periodic component of secondary arc current is less than $I_{arc}{}^{ampl} = 70$ A. In [8] authors give an approximation of ASPR dead time versus amplitude of secondary arc current

$$t_{dead} = 0.2 + 2.86 \cdot 10^{-4} \left(I_{arc}{}^{ampl} \right)^2 ,$$

so for analyzed 750 kV line $t_{dead} = 1.6$ s.

If neutral shunt reactors are installed at this line (like it’s shown on Fig.8), then amplitude of periodic component of secondary arc current would be less and necessary dead time would be less as well.

When applied ASPR there is another important thing except secondary arc current – TRV. In case of Fig.9 TRV is too high for station equipment (e.g., shunt reactor surge arresters). The way to reduce TRV at opened phase is switch off one of two shunt reactors, connected to the phase being under ASPR (phase “B” for Fig.9).

Fig.10 represents TRV when during ASPR one shunt reactor of damaged phase “B” disconnected from the line. One can see that TRV is lowered enough.

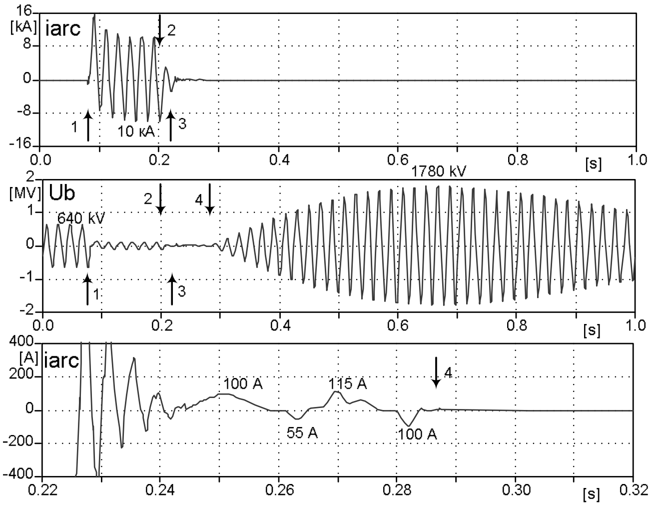

Fig. 9. ASPR of phase “B” for “Kolskaya Nuclear Power Plant - Cherepovec” line obtained in circuit Fig.8 where neutral reactors are not used.

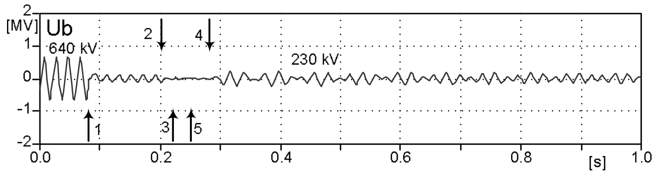

Fig. 10. ASPR of phase “B” for “Kolskaya Power Plant - Cherepovec”. Obtained in circuit Fig.8 where neutral reactors are not used. At moment 5 one of two shunt reactors of the damaged phase “B” switched off.

V. ASPR USING HIGH SPEED GROUNDING SWITCHES

Fig.11 shows an operating sequence of High Speed Grounding Switch (HSGS).

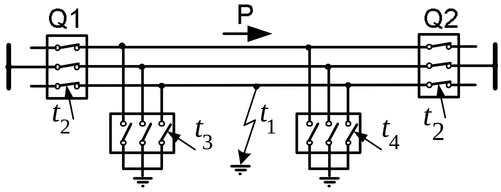

Fig. 11. Transmission line with high speed grounding switches.

HSGS operate as follows [11,12]:

1. A fault current is generated at the fault point when fault occurs;
2. The fault current is interrupted by circuit breakers. A secondary arc current flows at the fault point which is caused energized phases;
3. The grounding switch №1 is closed;
4. The grounding switch №2 is closed and the secondary arc is extinguished (Fig.13) or not (Fig.12);
5. The grounding switch are opened;
6. The circuit breakers on the line are closed.

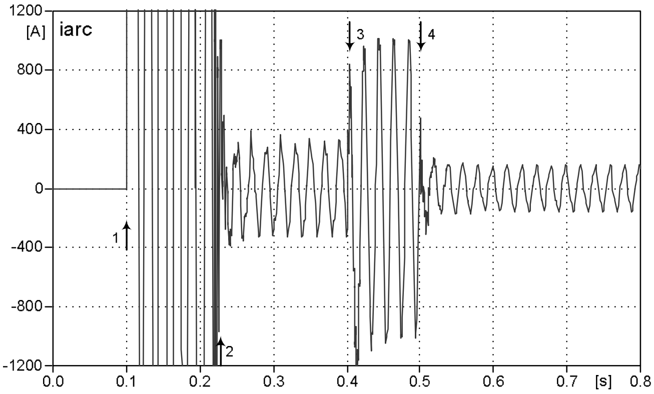

Fig. 12. ASPR of 1150 kV 500 km transmission line. Transmitted power is 5000 MW; fault point is 250 km from line end. Arc is not extinguished.

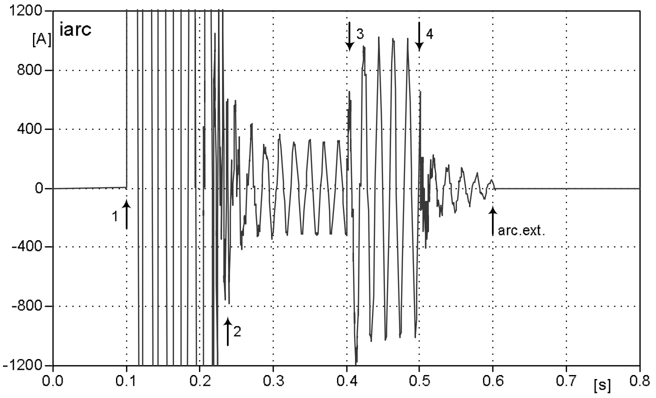

Fig. 13. ASPR of 1150 kV 500 km transmission line. Transmitted power is 5000 MW; fault point is 170 km from line end. Arc is extinguished.

VI. CONCLUSIONS

The basic results determining the possibility of existing of secondary arc current, obtained with developed arc model give results close to experimental data on 500, 750 and 1150 kV lines.

The EMTP model of open air AC secondary arc enables to determine the possibility of arc extinction in a transmission line, elaborate measures to be taken to effect a single phase reclosing as early as the stage research and developmental works.

Developed arc model could also be used for arc extinction calculation on line with short-circuiting switches at the ends of a line (instead of neutral reactor).

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VIII. BIOGRAPHIES

M. V. Dmitriev was born in Saint-Petersburg, Russia, on July 29, 1980. He graduated from the Saint-Petersburg State Technical University in 2003. His special fields of interest included electromagnetic transient processes. He began to study post-graduate course in 2003, from 2004 he is an IEEE Student Member.

G. A. Evdokunin was born in Slavjansk (USSR), on March 22, 1944. He graduated from the Saint-Petersburg State Polytechnic Institute in 1968. His special fields of interest included: Electromagnetic Transients in Power Systems, Electromagnetic Compatibility, Electrical Power Transmission. He received his Candidate and Doctor of Science degrees from the Saint-Petersburg State Polytechnic Institute in 1974 and in 1989 accordingly. From 1991 he is a Professor at Electrical Power System and Network Department, Polytechnic Institute (now State Technical University), Saint Petersburg. He is an IEEE Member from 1997 to Present.

V. A. Gamilko was born in Saint-Petersburg, Russia, on January 27, 1952. She graduated from the Saint-Petersburg State Technical University in 1975. Her special field of interest is electromagnetic transient processes. She received her Candidate of Science degree from the Saint-Petersburg State Polytechnic Institute in 1986. Now she is working at a Dispatcher Center.