DIGITAL SIMULATION OF FAULT ARCS IN MEDIUM-VOLTAGE DISTRIBUTION NETWORKS

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Abstract – This paper deals with the digital simulation of the fault arc in air in a 10-kV medium-voltage distribution network with earth fault compensation via arc suppression coil connected to the neutral point. The arc model enables studies on the interaction of the earth fault arc with the electrical power system. The arc has a damping effect on the earth fault current and on overvoltages caused by the initiation of earth faults. The arc model is validated by a comparison of simulation results with arc tests performed in a high-power test laboratory.

Keywords: fault arc, arc suppression, arc extinction, medium-voltage, distribution network, resonant-earthed system, earth fault, EMTP.

1 INTRODUCTION

Medium-voltage (MV) systems up to voltage level 110 kV in Germany and in some other European countries are equipped with arc suppression coils (Peterson coil) connected between neutral point and local earth. The Peterson coil has the function of compensating capacitive line-to-earth-fault current (single-line-to-earth fault will be called briefly earth fault). If the coil is well tuned, the earth fault current becomes minimal resulting in rush extinction of the fault arc in air. Since the fault current is sufficiently low and the arc in air extinguishes quickly, there is no protective provision against earth faults in resonant-earthed MV systems.

A suitable dynamic arc model is capable of investigating the interaction of the fault arc with the electric circuit during earth faults. The arc model should give an indication whether the arc will sustain or extinguish depending on the network configuration, residual earth fault current and detuning of the Peterson coil.

The arc model developed in [1], [2] was successfully applied to EHV transmission systems to simulate digitally primary and secondary arc of single-line-to-earth faults on overhead lines [3], [4]. The same arc model with parameters adjusted for the resonant-earthed MV systems is used in this paper to compute earth fault transients in a 10-kV resonant-earthed test system. The arc is represented in the simulation language MODELS [5] of the ATP-EMTP (Version Alternative Transients Program of ElectroMagnetic Transients Program) [6].

2 FAULT ARC REPRESENTATION

2.1 Arc Equations

The arc model used in this work is based on the energy balance of the arc column [1], [2]. This model describes the arc in air by a differential equation of the arc conductance g:

$$\frac{dg}{dt} = \frac{1}{\tau}\left(G - g\right) \tag{1}$$

where τ: is the arc time constant,
g: instantaneous arc conductance,
G: stationary arc conductance.

The stationary arc conductance is defined as:

$$G = \frac{\left|i_{arc}\right|}{u_{st}} \tag{2}$$

with

$$u_{st} = u_0 + r_0 \cdot \left|i_{arc}\right| \tag{3}$$

where i_{arc}: instantaneous arc current,
u_{st}: stationary arc voltage.
u_0: characteristic arc voltage,
r_0: characteristic arc resistance.

Parameters u_0 and r_0 are dependent on arc length l_{arc}, and calculated by the following equations obtained from arc measurements [2]:

$$u_0 = 0.9\,\frac{\text{kV}}{\text{m}} \cdot l_{arc} + 0.4\ \text{kV} \tag{4}$$

$$r_0 = 40\,\frac{\text{m}\Omega}{\text{m}} \cdot l_{arc} + 8\ \text{m}\Omega \tag{5}$$

Equation (1) is a generalized arc equation that is suitable to represent an arc between two terminals in an electric circuit. In case of low-current arcs in resonant-earthed systems the parameters vary depending on the arc length l_{arc}, i.e. on arc elongation. The arc length has to be defined as a time-dependent function prior to begin of a simulation. The dependence of the arc time constant τ on l_{arc} can be defined by the relation:

$$\tau = \tau_0 \cdot \left(\frac{l_{arc}}{l_0}\right)^{\alpha} \tag{6}$$

where τ_0: initial time constant,
l_0: initial arc length,
α: coefficient of negative value.

Since the arc length variation is highly dependent on external factors like wind, thermal buoyancy, it is difficult to consider these random effects accurately in the arc model. The phenomenon of the dielectric reignition after arc extinction is not considered in this arc model.

2.2 Arc Model in ATP-EMTP

The arc as a nonlinear dynamic element is represented alternatively by two different components

- Thevenin-type
- Iterated-type

in the ElectroMagnetic Transients Program ATP-EMTP [6]. The arc is described in MODELS language. In the Thevenin-type component the electric arc is a two-pole element, whereas the rest of the electric circuit is represented by a Thevenin equivalent (see Figure 1). Inputs to arc model are Thevenin voltage v_{th} and resistance r_{th} at the terminals for the current time step. The arc model calculates the value of the resulting arc current i_{arc}.

At each time step first the stationary arc voltage u_{st} and time constant τ are updated using (3), (4), (5) and (6), which depend on instantaneous arc length l_{arc}. The arc current i_{arc} can be expressed referring to Figure 1 as follows

$$i_{arc} = \frac{g \cdot v_{th}}{1 + g \cdot r_{th}} \quad (7)$$

The arc equation (1) is solved using MODELS' LAPLACE function to obtain g:

$$g(s) = \frac{1}{1 + \tau \cdot s} \cdot G(s) \quad (8)$$

Equations (2), (7) and (8) are solved simultaneously using an iterative method available in MODELS as "COMBINE ITERATE … ENDCOMBINE" [7].

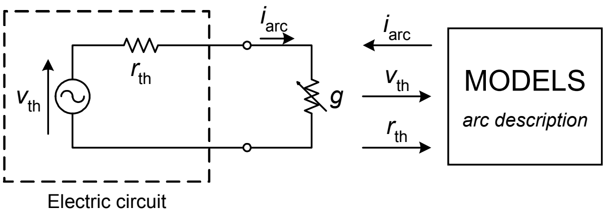


Figure 1: Interaction between the electric circuit and the arc represented by Thevenin-type component

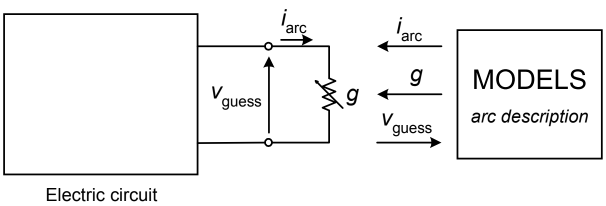


Figure 2: Interaction between the electric circuit and the arc represented by Iterated-type component

The use of *type-94 component* [7] in ATP-EMTP enables simultaneous solution of the arc equations together with the equivalent system of the electric network. The Thevenin-type component allows the existence of only one component in a sub-network. Use of more than one component is allowed, if each sub-network with one component inside is separated from the other sub-networks by transmission lines, i.e. if they are decoupled in time. To represent two arc faults in a network, an artificial stub line with travel time equal to simulation time step Δt has to be placed in front of one arc component.

Another solution is to use *Iterated-type* component in ATP-EMTP to represent more than one electric arc in a network. The interface of the Iterated-type component with the remaining electric circuit is given in Figure 2.

The voltage across the arc v_{guess} is estimated and passed to the MODELS part. Using this value an estimated arc current is calculated:

$$i_{arc} = g \cdot v_{guess} \quad (9)$$

Practically, equation (9) replaces equation (7). The above explained procedure of solving equations (2), (8) and (9) remains the same. The exact solution for arc voltage and current is found by an iterative method in ATP-EMTP by solving the differential equations of the electric circuit and of the electric arc at each time step simultaneously. Consequently, the computation speed of the Iterated-type component may be slower than the Thevenin-type component.

3 VALIDATION OF THE ARC MODEL

3.1 Arc Tests

In [9] it was reported on arc tests that were performed in a high-power test laboratory using a three-phase test circuit. The test circuit shown in Figure 3 was built using lumped elements to represent a resonant-earthed 20-kV system in a simplified way. The source impedance $\underline{Z}_s = R_s + jX_s$ corresponds to a three-phase short-circuit power $S_k^{''} = 250\ \text{MVA}$. The reactance X_L shown represents the faulty phase of a 25-km long overhead line with earth-return path. The sound part of the 20-kV system is modelled by a T-circuit with series reactances X_{ser} and line-to-earth capacitances C_e.

The capacitive line-to-earth current amounts to

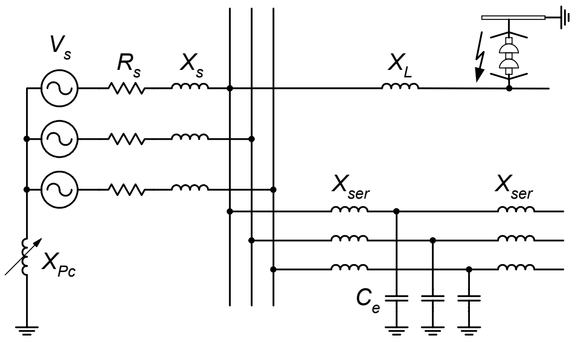
$$I_{Ce} = 3 \cdot \omega \cdot C_e \cdot V_s = 263\ \text{A}$$

where V_s is the line-to-neutral source voltage.

The reactance of the Peterson coil X_{Pc} was selected in order to achieve earth fault compensation degree of $v = -20\ \%$. Thus, the prospective earth fault current amounts to $I_e = 52.5\ \text{A}$. The reactor used in the tests was a real plunger-core Peterson coil. The arc was initiated by means of a fuse wire across a 20-kV line insulator as indicated in Figure 3.

Recorded earth fault transients of two tests were shown in [9]. Figure 4 shows waveforms of arc voltage, arc current and Peterson coil current, when the earth fault arc was initiated at voltage maximum.

The arc extinguishes after 96 ms for the fault inception at voltage maximum. The waveforms of the same measured quantities are given in Figure 6 for the case of arc initiation at voltage zero-crossing. Fault inception at voltage zero-crossing causes due to Peterson coil a DC component with large time constant in the earth fault current. Consequently, the arc was sustained for a long period.



$V_s = 21\,\text{kV}/\sqrt{3}$; $R_s = 0.096\,\Omega$; $X_s = 1.76\,\Omega$

$X_{ser} = 5\,\text{m}\Omega$; $C_e = 23\,\mu\text{F}$; $X_L = 17.5\,\Omega$ $(f = 50\,\text{Hz})$

Figure 3: Test circuit representing a resonant-earthed system with a earth fault arc (system nominal voltage: 20 kV)

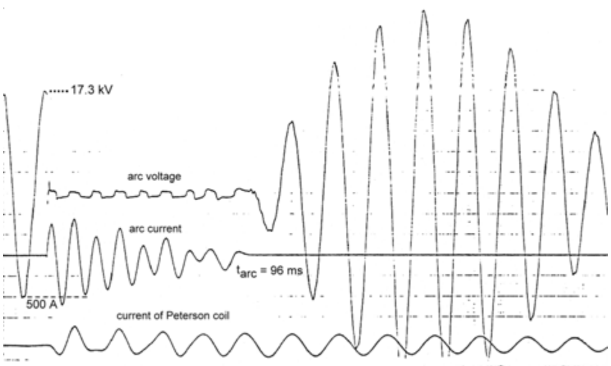


Figure 4: Recorded waveforms of arc voltage, arc current and current of Peterson coil for the inception of the earth fault at voltage maximum [9]

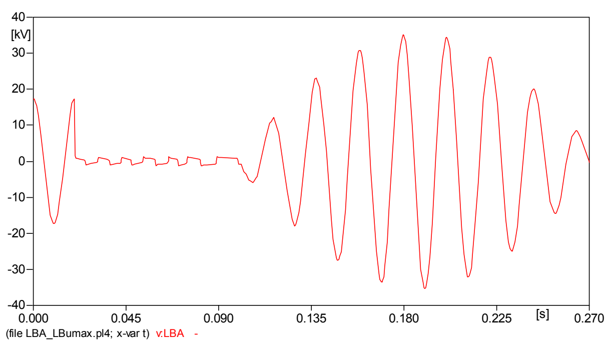


Figure 5: Computed voltage at earth fault location to compare with the waveform in Fig. 4

3.2 *Arc Simulation*

Those two tests reported in [9] have been represented in ATP/EMTP in order to validate the arc model. Following parameters for the earth fault arc across 20-kV line insulator are used:

$$\tau_0 = 0.25\ \text{ms},\quad \alpha = -0.4,\quad l_0 = 0.20\ \text{m}.$$

The elongation speed of the arc is assumed as follows for the two test cases to replicate the measurements:

– fault inception at voltage maximum:

$$\frac{\Delta l}{\Delta t} = \frac{8l_0 - l_0}{200\ \text{ms}}$$

– fault inception at voltage zero-crossing:

$$\frac{\Delta l}{\Delta t} = \frac{8l_0 - l_0}{400\ \text{ms}}$$

According to the time function defined for the arc length, u_0, r_0 and τ_0 are updated as the simulation evolves using (4), (5) and (6), respectively.

Figures 5, 8, 9 show the simulation results corresponding to recordings of the arc test in Figure 4, whereas Figures 7, 10, 11 show the computed waveforms corresponding to recordings of the arc test in Figure 6. In the case of fault inception at voltage maximum the arc sustains only for a duration of 80 ms compared to 96 ms in the arc test. In the second simulation case with fault inception at voltage zero-crossing no arc extinction was observed within simulation period of 0.4 s.

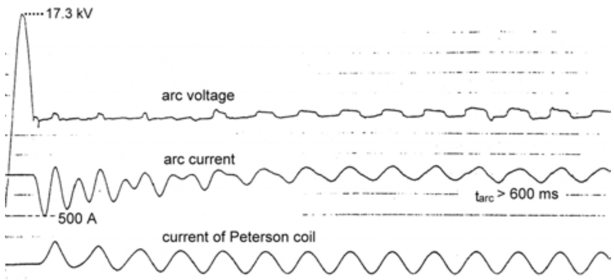


Figure 6: Recorded waveforms of arc voltage, arc current and current of Peterson coil for the inception of the earth fault at zero-crossing of the phase voltage [9]

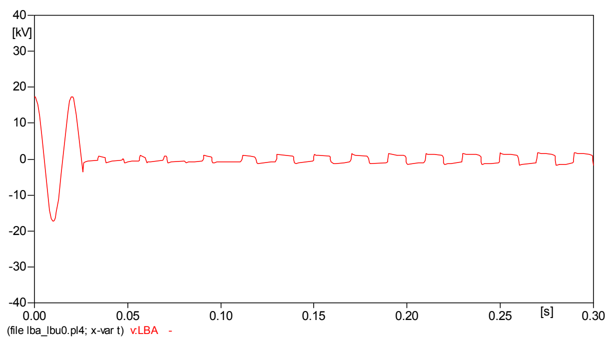


Figure 7: Computed voltage at earth fault location to compare with the waveform in Fig. 6

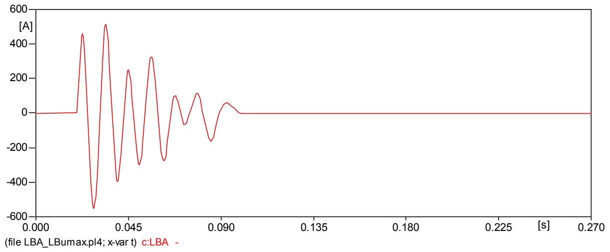


Figure 8: Computed earth fault current to compare with the waveform in Fig. 4

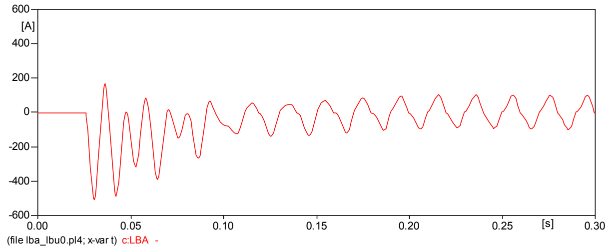


Figure 10: Computed earth fault current to compare with the waveform in Fig. 6

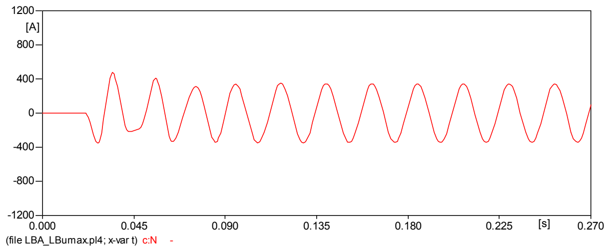


Figure 9: Computed Peterson coil current to compare with the waveform in Fig. 4

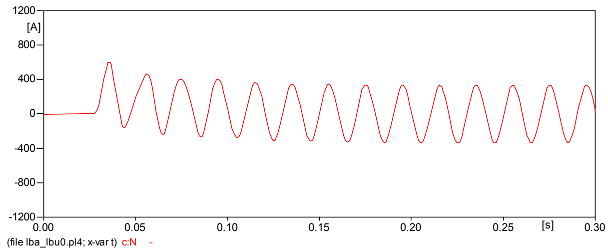


Figure 11: Computed Peterson coil current to compare with the waveform in Fig. 6

4 SINGLE-LINE-TO-EARTH FAULT ARC IN A 10-KV RESONANT-EARTHED SYSTEM

4.1 Test Power System

The 10-kV distribution system is supplied with power by a 110-kV grid via 30-MVA transformer as shown in Figure 12. The 110-kV system is represented in a simplified manner by a Thevenin equivalent consisting of voltage source in series with the short-circuit impedance. The resonant-earthed 10-kV system consists of several overhead lines and cables as radial feeders. To reproduce fault current waveforms and overvoltages caused by travelling waves on lines realistically, the lines are represented by *Constant-Parameter Distributed Line Model* (CPDL) of the ATP-EMTP [6].

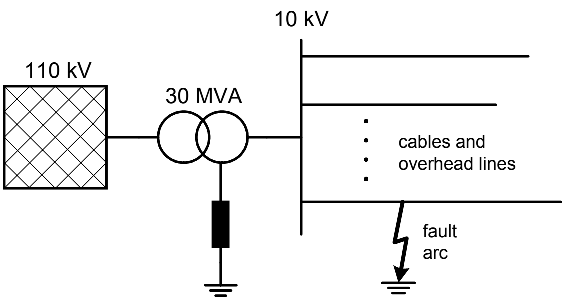


Figure 12: Configuration of the studied power system

No load is connected to the feeders of the 10-kV system in order to distinguish the damping effect caused by the fault arc from the damping resulting from the loads. Important system data are summarized in Table 1.

110-kV grid: $V_n = 110\text{ kV}$; $\underline{Z}_{sc-pos} = (0.668 + j6.684)\ \Omega$
110/10.5-kV transformer: $S_{rT} = 30\text{ MVA}$; $u_k = 11.8\ \%$; Yy0
10-kV feeders: F: overhead line, Al/St 70/12, $l_{total} = 20\text{ km}$ K1: cable, NA2XS2Y 3x1x185, $l_{total} = 25\text{ km}$ K2: cable, NKBA 3x70, $l_{total} = 20\text{ km}$ Total capacitive line-to-earth current, $I_{Ce} = 78.6\text{ A}$ ($I_{Ce} = \sqrt{3} \cdot \omega \cdot C_e \cdot V_{line}$; $V_{line} = 10.5\text{ kV}$)
10-kV Peterson coil: steplessly adjustable; $L_{P0} = 242\text{ mH}$ for $v = 0$ (detuning degree, $v = \dfrac{1}{3\omega^2 L_P C_e} - 1$)

Table 1: Data of the test system

The arc parameters τ_0 and l_0 are obtained from measurements [2] as average values:

$$\tau_0 = 0.25\text{ ms}, \quad l_0 = 0.15\text{ m}$$

The initial arc length l_0 is taken as an average value of minimum air clearance specified for 10-kV systems [8].

For arc extinction the following limiting values per arc length were used:

$$g'_{\min} = 50\,\mu\text{S}\cdot\text{m}; \quad \frac{dr'}{dt} = 20\,\text{M}\Omega/(\text{s}\cdot\text{m})$$

where r' is the arc resistance per length.

At first stage elongation of the arc is omitted to determine the worst-case earth fault current limit for the arc extinction. It is known that smaller arc time constant τ speeds up the arc extinction. The earth fault is assumed to occur across the insulator of an overhead line on a steel-tower. Therefore an extra $1\,\Omega$ grounding resistance is included in the simulations.

4.2 Line-to-Earth Fault Transients

When an earth fault occurs in a resonant-earthed system, three types of transients are initiated:

– travelling waves on lines,
– re-charging of line-to-earth capacitances of sound phases over supplying transformer,
– transients of the Peterson coil with power frequency and transition to a new steady-state.

The drawing of the test system for ATP-EMTP computation created using *ATPDraw* is shown in Figure 13.

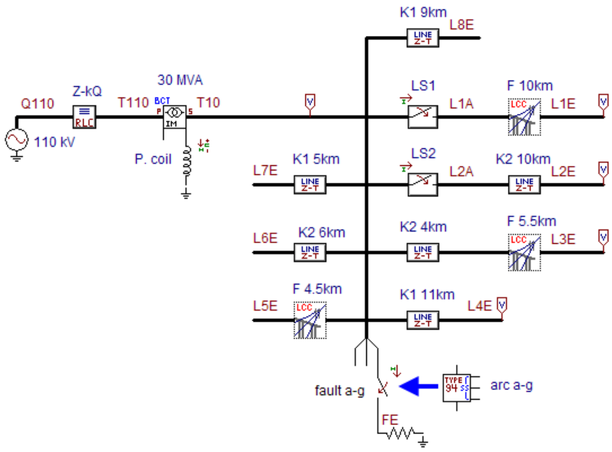


Figure 13: ATPDraw representation of the 10-kV test system

The line-to-earth fault *a-g* occurs at the 10-kV busbar. First, a time-controlled switch will be used to initiate the fault. Later, the fault will be launched by the arc model as indicated in Figure 13.

The computed waveforms of line-to-earth voltages at the 10-kV busbar due to metallic earth fault by a switch are shown in Figure 14. The detuning degree $v = +5\,\%$ is adjusted at the Peterson coil. Figure 15 shows the resulting voltage waveforms, when the arc model is applied. Fault currents for both cases are compared in Figure 16.

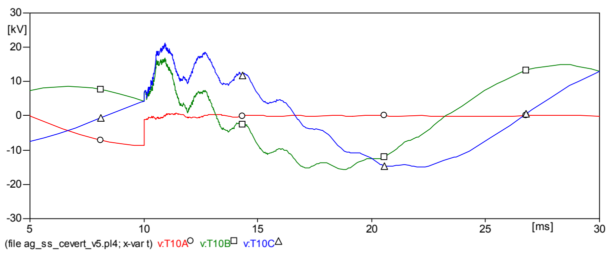


Figure 14: Line-to-earth voltages at the 10-kV busbar (metallic fault by a switch)

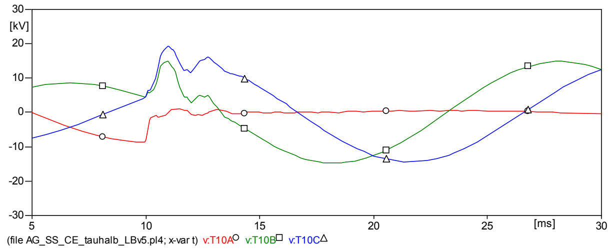


Figure 15: Line-to-earth voltages at the 10-kV busbar (arc)

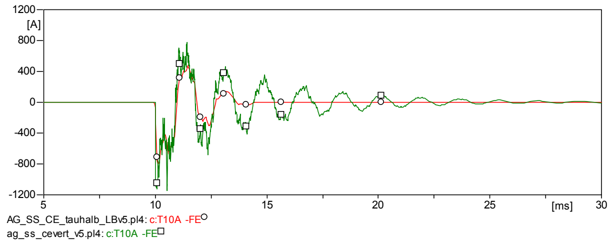


Figure 16: Comparison of the earth fault current
□ metallic fault by a switch (Fig. 5), ○ arc fault (Fig.6)

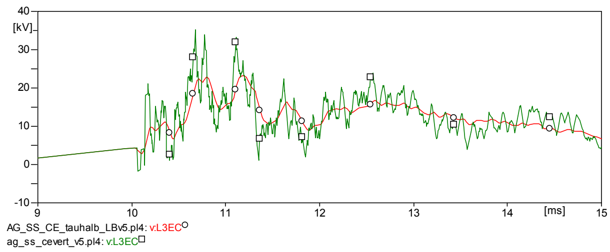


Figure 17: Comparison of voltage waveforms at node "L3E"
□ metallic fault by a switch, ○ arc fault

The arc extinguishes referring to Figure 16 at $t = 16$ ms. The highest overvoltage of 35 kV occurs at node "L3E", phase *c*, (see Figure 13) due to travelling waves, if the fault is launched by a switch. The fault arc damps those travelling waves as shown in Figure 17. The peak value of the voltage at node "L3E" reaches only 19.2 kV in this case. It can be concluded that the arc significantly damps transients caused by travelling waves on lines and re-charging transients in the system.

In the above simulations the fault is initiated at maximum value of the line-to-earth voltage (see Figure 14). If the earth fault starts at zero-crossing of the line-to-earth voltage, then a DC component in the fault current is expected at fault location. As confirmed by field measurements and arc tests [9], the fault arc substantially damps the DC component. Figure 18 shows a comparison of earth fault current waveforms for a metallic line-to-earth fault and for an arcing earth fault. The arc extinguishes after approximately 55 ms.

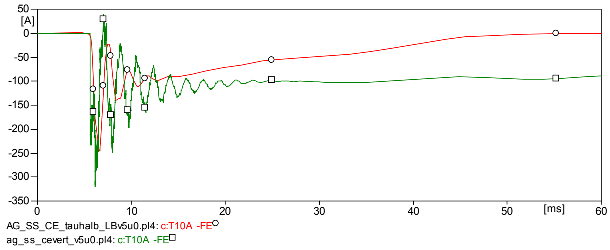


Figure 18: Comparison of earth fault current waveforms for a line-to-earth fault started at voltage zero-crossing
□ metallic fault by a switch, ○ arc fault

4.3 Extinction of Earth fault Arcs

Field tests about earth fault arc extinction were performed in Germany only in 20-kV systems relatively long time ago [9], [10]. Records of earth fault (arc) transients were shown for certain cases in [9], where the main goal of the tests was to determine the influence of harmonic contents in the line-to-earth fault current on arcing time. A summary on quenching of earth fault arc in resonant-earthed systems can be found in [11]. In [12] the self-extinguishing current limit is defined depending on the nominal voltage of the system and the line-to-earth fault current amplitude. For 10-kV systems with Peterson coil this limit is at 60 A (effective value).

Various factors influence the quenching of the arc. The slowly-rising recovery voltage after arc extinction in resonant-earthed systems is favourable for shorter arcing time. The arc length and, depending on it, the arc time constant are important factors for self-extinction of the arc. Physically, the arc time constant defines the speed of arc conductance change depending on the energy content of the arc and thermal power dissipation.

Using the arc model described in section 2 the self-extinguishing current limit is determined by means of series of simulations. For this purpose the inductance of the Peterson coil has been changed in both directions, i.e. operation in the over- and under-compensation region is realized. To be on the safe side following assumptions for the modelling are made:

– arc length is selected as minimum (0.15 m)
– no arc elongation during the fault duration
– non-varying arc time constant with $\tau = 0.25$ ms (average value) and $\tau = 0.5$ ms (high value, worst-case regarding arc extinction).

The present arc model developed is not capable of simulating re-ignitions after arc extinction. For the above 10-kV test system the self-extinguishing current limits are summarized in Table 2 depending on arc time constant. The current limits are effective values of the line-to-earth fault currents determined by an additional steady-state calculation at 50 Hz without fault arc modelling.

Certainly, the arc may extinguish in the case of larger line-to-earth fault currents, if the arc is elongated by wind and thermal buoyancy.

arc time constant τ (ms)	detuning degree v	earth fault current (A)
0.25	+60 %	46.2
0.25	–60 %	47.6
0.5	+35 %	25.9
0.5	–20 %	16.4

Table 2: Self-extinguishing current limits for a line-to-earth fault arc in the 10-kV test system

Figures 19 and 20 show arc voltage and current waveforms respectively for a case, where the arc reaches five times of its initial length, $l_0 = 0.15$ m, within 0.2 s. The coefficient α of time constant is selected as zero. The Peterson coil is adjusted to $v = -65$ % (under-compensation of the earth fault current). The fault location is the same as shown in Figure 13. The arcing time is obtained as 182 ms. Note that arc voltage waveform deviates significantly from rectangular shape which is known from protection practice. The reason of this deviation is the relatively small current flowing through the arc, which causes that the instantaneous arc resistance becomes significantly large compared to the reactances of the line-to-earth capacitances and of the inductance of the Peterson coil.

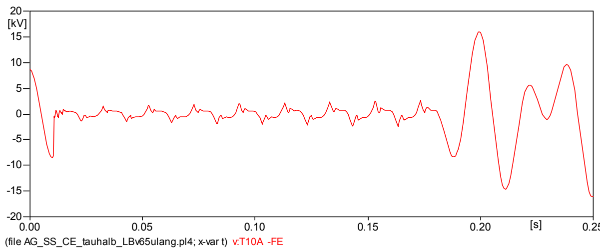


Figure 19: Voltage at fault location (phase a) in the case of arc elongation and of largely detuned Peterson coil

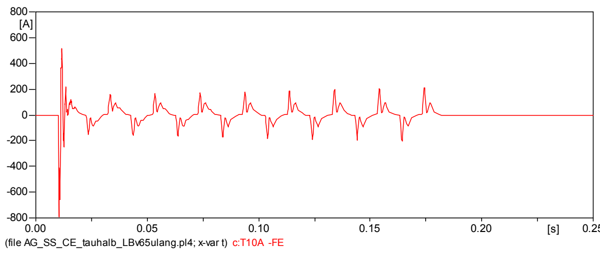


Figure 20: Fault arc current with reference to Figure 19

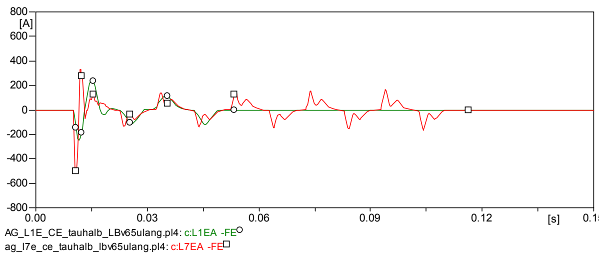


Figure 21: Fault arc current for the fault locations; (○) open end "L1E" of an overhead line, (□) open end "L7E" of a cable

The fault location in the 10-kV system influences also the arc quenching as reported in [9] based on field tests in a 20-kV system. In the above simulation case with arc elongation and $v = -65\,\%$ the arc location is moved to the open end of 10-km long overhead line ("L1E" in Figure 13) and alternatively to the open end of 5-km long underground cable of type K1 ("L7E" in Figure 13). In both cases (overhead line vs. cable) the arc extinguishes earlier with arc duration of 50 ms for the overhead line and 112 ms for the cable compared to the fault location at the 10-kV busbar (Figure 20). This observation is not in line with the field measurements reported in [9], where longer arcing time was observed at the open end of a 17.3-km long 20-kV overhead line. The transient re-charging current in the simulations has smaller amplitude, if the earth fault is at the end of a line, compared to the fault location at the 10-kV busbar (compare Figures 20 and 21). This is due to relatively larger impedance of the earth-return path of the lines.

5 CONCLUSION

A digital arc model has been presented that is capable of representing fault arcs in air in resonant-earthed medium-voltage systems. The arc model takes into consideration the dynamic interaction of the arc with the remaining electric circuit. However, re-ignitions of dielectric type after arc extinction are not considered by the model. Due to highly random behaviour of the arc it is difficult to reproduce the real arc quenching phenomenon by digital simulations. In spite of this difficulty the arc model can be successfully utilized to find main factors of interaction of the arc with the power system and to define conditions of arc extinction in resonant-earthed systems.

As application two test systems of voltage level 10 kV and 20 kV with earth fault compensation have been modelled using simulation program ATP-EMTP, where a line-to-earth fault is represented by the arc model. It can be concluded that the arc significantly damps transients caused by travelling waves on lines and re-charging transients in the system, as this phenomenon was observed in field measurements and laboratory arc tests.

The simulation results of earth fault transients are in good agreement with the recordings of arc tests performed in a high-power laboratory using a real arrangement of 20-kV overhead line insulators.

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