# Digital Simulation of Fault Arcs in Power Systems

**M. Kizilcay, T. Pniok**

**Abstract**

*Faults in power transmission systems often take place through long arcs in air. Therefore, the dynamic interaction between a fault arc and the power network is extremely important in relation to the single- or three-pole autoreclosure and to the system protection relaying. Using the theory of constrained switching arc a new dynamic black box model of a long fault arc is developed. Power system transients caused by arcing faults are successfully simulated using the version ATP (Alternative Transients Program) of the universal Electromagnetic Transients Program (EMTP).*

## 1 Introduction

The most frequent faults in power transmission systems are single-phase-to-ground arc faults through air. In HV power systems with earthed neutral point single-pole autoreclosure is an effective means to clear single-phase faults while retaining system stability [1]. When a ground fault is isolated by single-pole switching, the faulty phase remains coupled to the sound phases and a relatively small current compared to the heavy fault current continues to flow through the arc. On the other hand, a single-phase-to-ground fault arc in HV power systems with arc supression coils is cleared after a while automatically. In this case the fault current is forced to be very small due to the parallel resonance circuit consisting of the inductance of the arc supression coil and the line-to-earth capacitances in the zero-sequence mode.

In order to simulate such power system transients caused by arcing faults realistically, the dynamic behaviour of a fault arc should be considered in its modeling. Quite a few authors have studied the digital simulation of arcing phenomena by means of mathematical arc models [2–4]. In their investigations the arc has been represented by semi-static volt-ampere characteristics and the extinction has been decided using an arc recovery characteristics.

In this paper a dynamic fault arc model is developed, which is based on the theory of switching arcs [5, 6]. The theory of the switching arc has been extensively studied by several authors and existing mathematical models based upon the power balance in arc column describe adequately the interaction of an arc and the corresponding electrical circuit during a current interruption process. A unconstrained long fault arc in air is assumed to behave, to some extent, similar to the constrained switching arc. Thereby only the thermal behaviour of the arc column is considered. The dielectric behaviour of the arc and the surrounding media can not be taken into account because of the almost indefinite conditions around the arc column.

## 2 Characteristics of a Long Fault Arc in Air

### 2.1 Basic Arc Behaviour

The dynamic behaviour of an arc can be described by the power balance relation between the electric input power and the heat dissipation. Thereby the arc conductance is expressed as a function of the heat content of the arc column. *Cassie* assumed an arc channel with constant temperature, which is independent of the arc current [7]. An increase of the energie of the arc column results in an increase of the cross-section of the arc. Furthermore the stationary electric field strength is assumed to be constant.

In contrast to the switching arc, the length variation is an important factor in describing the behaviour of a long arc in air. The elongation of the arc is caused by:

- the magnetic force due to the supply current,
- the convection of the plasma and the surrounding air,
- the atmospheric effects (wind).

During the fault duration, when the heavy short-circuit current flows through the primary arc, there is no significant elongation of the arc. This was observed by means of the high-speed film records of long arcs along insulation strings of 110 kV and 380 kV overhead lines [8]. The column of the primary arc has a relatively large cross-section because of the high input electric power supplied by the heavy fault current. A voluminous gas cloud around the arc channel will be formed, which has a low dielectric strength. As the arc tends to bend due to the forces mentioned above, there are more dielectric breakdowns in the surrounding gas cloud, that keeps the length of the arc almost constant.

In contrast to the primary arc, an obvious elongation of the arc has been observed during the period after the ground fault is isolated. **Fig. 1** shows paths of the secondary arc at different stages in a 2-dimensional

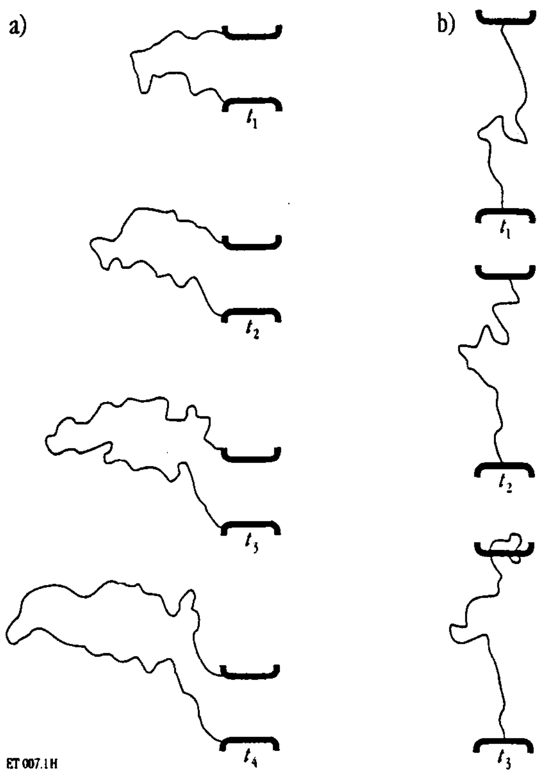


**Fig. 1.** Variation of the secondary arc length as function of time for different insulation strings
a) 110 kV b) 380 kV

plane. The length of the secondary arc reaches up to ten times of its original length before extinction, as it could be noticed by the film records. In this case a relatively very small current flows through the secondary arc, since the faulty phase remains coupled to the sound phases. The elongation of the secondary arc causes a continuous increase of the arc voltage. It is shown in [9] that for long arcs almost all the total arc voltage appears across the arc column. The voltage drops near the arcing horns can be neglected.

## 2.2 Mathematical Model

The arc equation of *Hochrainer* [5] is used to describe the dynamic behaviour of a fault arc. His arc model derived from the viewpoint of the control system theory is based on the energy balance in the arc column. It is written as

$$dg/dt = (1/\tau)(G - g) \tag{1}$$

where

$g$ time-varying arc conductance,
$G$ stationary arc conductance,
$\tau$ time constant.

The stationary arc conductance $G$ can be physically interpreted as the arc conductance value which would set in, if the current were maintained for a sufficiently long time under constant external conditions.

Eq. (2) is proposed as the stationary arc characteristics obtained by the evaluation of the arc measurements in [8]:

$$u_{st} = (u_0 + R\,|\,i\,|)\,l \tag{2}$$

where

$u_{st}$ stationary arc voltage,
$u_0$ constant voltage parameter per arc length,
$R$ resistive component per arc length,
$i$ arc current,
$l$ time-dependent arc length.

The stationary arc conductance follows as

$$G = \frac{|i|}{(u_0 + R|i|)\,l}\,. \tag{3}$$

The length of the primary arc is considered to be constant, whereas a linear time-varying elongation of the secondary arc is taken into account by the model. The time constant $\tau$ is the other unknown parameter of the arc according to eq. (1). It is assumed to be constant during the primary arc. As it will be shown in the next section, the time constant of the secondary arc is time-varying and can be expressed as a function of arc elongation.

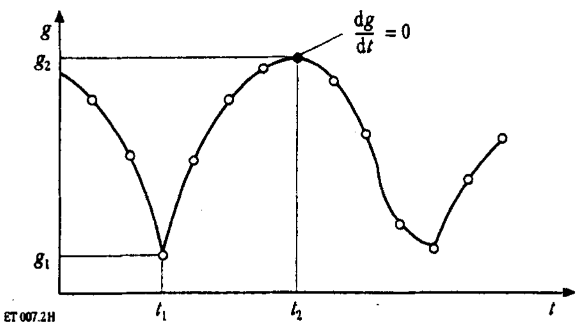


**Fig. 2.** Time-varying arc conductance used to determine the stationary arc characteristics

## 2.3 Determination of the Arc Parameters

The time-varying arc conductance (**Fig. 2**) is computed using the measured arc voltage and current at discrete time points according to the following equation:

$$g = i/u \tag{4}$$

where $u$ is the arc voltage.

The stationary arc characteristics can be determined using eq. (1) from the arc conductance at time points, where

$$dg/dt = 0\,. \tag{5}$$

It follows from eqs. (1) and (5) that

$$g = G = i/u_{st}\,. \tag{6}$$

Only two points, which satisfy eq. (6), are sufficient to determine the unknown parameters $u_0$ and $R$. The first point chosen belongs to the primary arc, whereas the second point is selected at the end of the secondary arc period. The length of the secondary arc at that time point is estimated by observing the film record [8].

The integral form of eq. (1) is used to determine the time constant $\tau$. Inserting eq. (3) and (4) into eq. (1) and rearranging eq. (1) results in

$$\frac{1}{g}\frac{\mathrm{d}g}{\mathrm{d}t} = \frac{1}{\tau}\left[\frac{|u|}{(u_0 + R|i|)\,l} - 1\right]. \tag{7}$$

Eq. (7) is integrated from $t_1$ to $t_2$ with the corresponding arc conductance values $g(t_1) = g_1$ and $g(t_2) = g_2$, respectively (Fig. 2):

$$\int_{t_1}^{t_2}\frac{1}{g}\frac{\mathrm{d}g}{\mathrm{d}t}\,\mathrm{d}t = \frac{1}{\tau}\left[\int_{t_1}^{t_2}\frac{|u|}{(u_0 + R|i|)\,l}\,\mathrm{d}t - \int_{t_1}^{t_2}\mathrm{d}t\right]. \tag{8}$$

The time constant $\tau$ is obtained from eq. (8) as follows:

$$\tau = \frac{\displaystyle\int_{t_1}^{t_2}\frac{|u|}{(u_0 + R|i|)\,l}\,\mathrm{d}t - \int_{t_1}^{t_2}\mathrm{d}t - (t_2 - t_1)}{\ln[g_2/g_1]}. \tag{9}$$

**Tab. 1** shows calculated parameters of the primary and secondary arc along a 380-kV insulation string. There was no significant air motion during the measurement, as it was observed by [8]. **Fig. 3** shows the stationary arc voltage $u_{st}$ of the secondary arc as a function of time along a 380 kV insulation string. The increase of the arc voltage is caused by the elongation of the secondary arc and can be expressed as a function of the time-varying arc length. The elongation of the secondary arc is assumed to be a linear function of time according to the Fig. 3. The time constant of the secondary arc calculated using eq. (9) is also time-varying **(Fig. 4)**. It can also be expressed as a function of the arc length variation.

### 2.4 Arc Simulation in the EMTP

EMTP is an universal simulation program for the analysis of the power system transients [10]. It contains besides lumped RLC-circuit elements various mathematical models of the power system components such as transmission lines, transformers, synchronous machines. The basic computation method of EMTP is the trapezoidal rule of integration. The nonlinear elements are handled by means of the compensation method [11].

The dynamics of the arc will be represented by a block diagram in the program part TACS (Transients Analysis of Control Systems). The arc eq. (1) is solved at each time step using the following equation, with the assumption that the time constant and the stationary arc conductance remain constant during a time step [12]:

$$g(t) = G(t-\Delta t) - [G(t-\Delta t) - g(t-\Delta t)]\mathrm{e}^{-\Delta t/\tau}. \tag{10}$$

The electric network and the control system are solved separately in the EMTP and TACS program at each time step. It was shown in [13] that a switching arc can be modeled using a TACS-controlled time-varying resistance. The principle of TACS-controlled time-varying resistance modelling of the arc is given in **Fig. 5**.

The solution process at each time step of the fault arc simulation is as follows **(Fig. 6)**:

- The arc current $i(t - \Delta t)$ is determined in TACS using node voltages of a small measuring resistance $R_m = 1\ \mathrm{m\Omega}$ as input.
- Stationary arc conductance and time constant are calculated taking into account the length variation of the secondary arc.

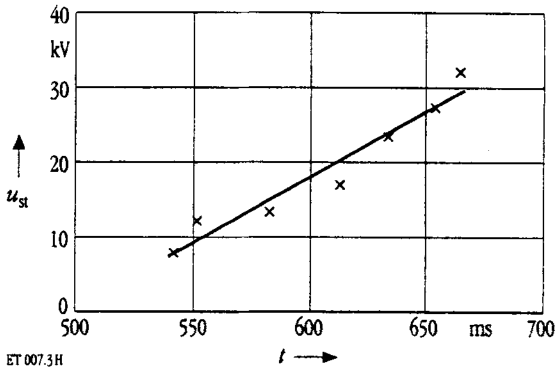


**Fig. 3.** Calculated stationary voltage of the secondary arc as function of time along 380 kV insulation string [8]

| Parameter | | Primary Arc | Secondary Arc |
|---|---|---|---|
| $u_0$ | in V/cm | 9,6 ... 13,5 | 9,6 ... 13,5 |
| $R$ | in mΩ/cm | 1,6 ...1,0 | 1,6 ... 1,0 |
| $\tau$ | in ms | 0,8 ... 1,1 | 1,3 ... 0,3 continuously decreasing |
| $l$ | in cm | ≈ 350 | 350 ... 2800 continuously increasing |
| $\Delta l/\Delta t$ in cm/ms speed of arc elongation | | ≈ 0 | 9 ... 12 |

**Tab. 1.** Model parameters of the arc over a 380 kV insulation string

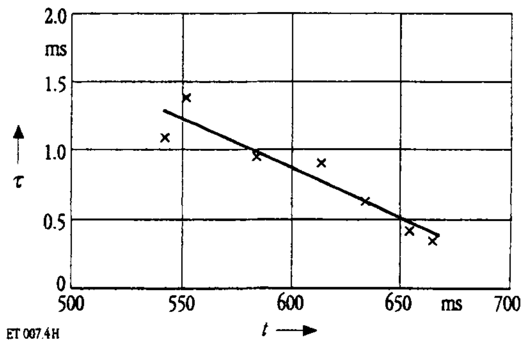


**Fig. 4.** Calculated time constant of the secondary arc as function of time along 380 kV insulation string [8]

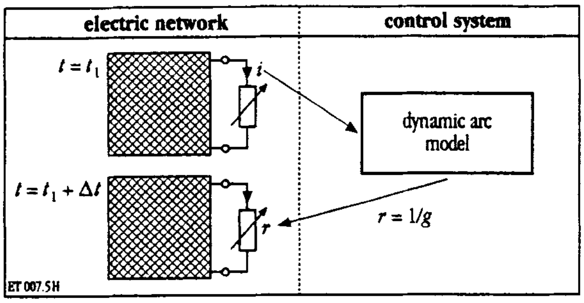


**Fig. 5.** Dynamic interaction between electric network and the control system to simulate an electric arc

- The arc eq. (1) is solved for the arc conductance using eq. (10).
- When the present and previous value of the arc conductance is less than a predefined limit, then it is held constant at this limit till the end of simulation.
- The value of the instantaneous arc resistance is passed to the time-varying element (type-91) of the ATP/EMTP.
- The node equations of the electric network are solved, whereas the arc is simulated by means of this ATP/EMTP component according to the compensation method.

The simulation is always started from the steady-state fault conditions. Thereby the fault is represented by an ideal switch from line to ground. After one or two periods the switch is opened, when the current passes through zero. From this moment the dynamic arc will be active. The transient caused by this sudden change decays very rapidly.

In case of arc extinction the value of the arc resistance increases towards infinity. Therefore it should be limited to a certain value in order to avoid numerical overflow. A proper limit is about 500 kΩ.

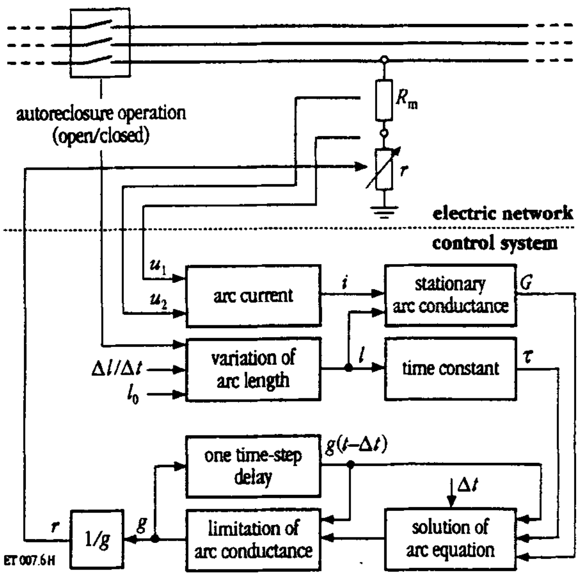


**Fig. 6.** Block diagram representation of an arc for EMTP simulation

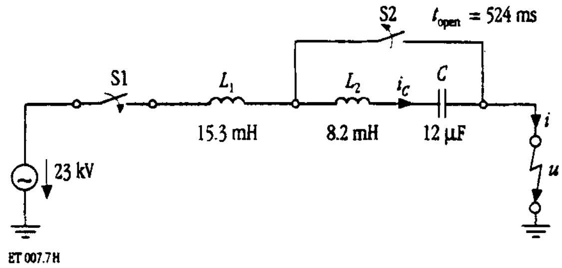


**Fig. 7.** Synthetic test circuit [8]

## 3 Sample Study

The synthetic test circuit shown in **Fig. 7** was used for field measurements [8]. The arc along a 380-kV insulation string is initiated by means of a fuse wire, when switch S1 in Fig. 7 is closed. Initially, switch S2 is closed. In this state a high sinusoidal current of 4,3 kA (rms) flows through the primary arc, until switch S2 is opened at $t_{open}$ = 524 ms. After opening of switch S2, the current is limited to a very low value. If the resistance of the secondary arc is assumed to be zero, a current of 90 A (rms) would flow.

The measured voltages and currents are given in **Fig. 8**, whereas the voltages and currents computed using ATP/EMTP are shown in **Fig. 9**. The time step of the simulation is chosen to be $\Delta t$ = 50 μs.

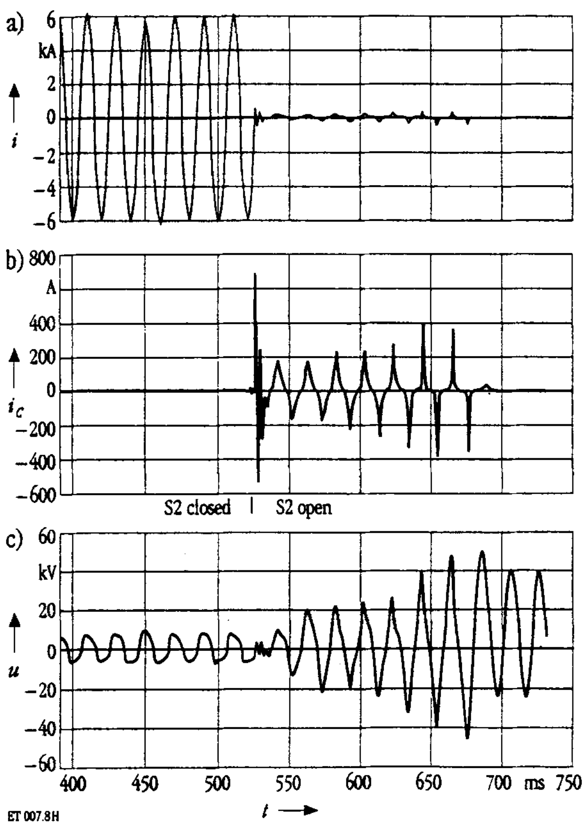


**Fig. 8.** Measured voltages and currents [8]
a) arc current $i$
b) secondary arc current $i_C$
c) arc voltage $u$

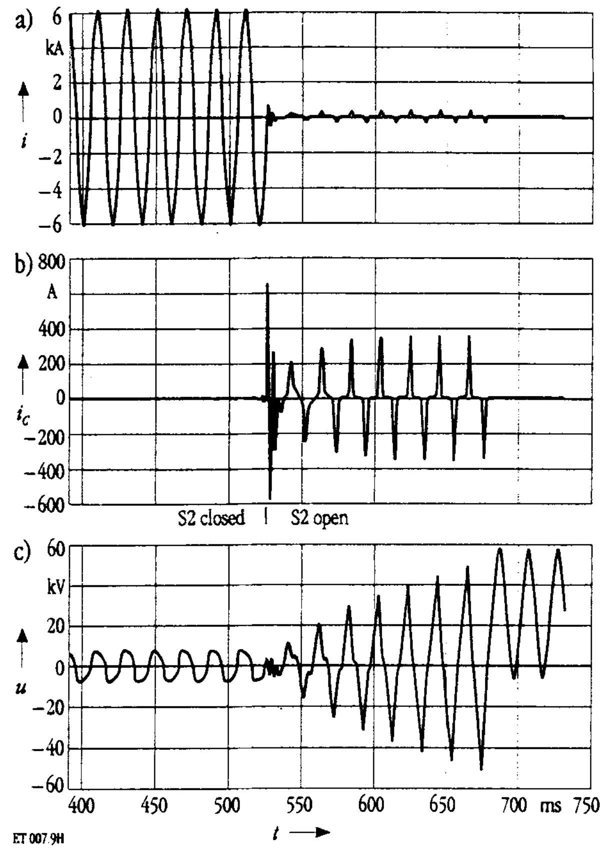


**Fig. 9.** Computed voltages and currents using EMTP
a) arc current $i$
b) secondary arc current $i_C$
c) arc voltage $u$

## 4 Conclusions

A deterministic arc model, that takes the thermal dynamic behaviour of a fault arc in air into account, is presented. The model is based on the extended theory of the switching arcs in circuit breakers.

The dielectric behaviour of the arc is not considered in the model because of uncontrolled and almost indefinite conditions in and around the arc column. The field measurements [8] show, however, astonishing stable and deterministic behaviour of arcs in air.

The primary arc can be represented by means of a non-varying time constant and a stationary characteristics using arc eq. (1). No significant elongation of the primary arc has been observed [8]. The time constant and stationary characteristics of the secondary arc is time-varying and can be expressed as a function of arc elongation. The arc extinction is mainly affected by the arc length variation as a function of time.

The constant voltage parameter $u_0$ of the stationary arc characteristics could not be determined precisely from the measurements, because the elongation of the secondary arc can not be measured directly. As an approximation for $u_0$, the equation given by *Maikopar* [14] and applied in [3] can be used

$$\frac{u_0}{\mathrm{V/cm}} = 75\, I_p^{-0.4} \qquad (11)$$

where $I_p$ is the peak value of the secondary arc current, which is estimated by calculating the stationary arc current assuming zero arc resistance.

The proposed model can be used successfully in auto-reclosure studies to determine the current interruption duration for a successful extinction of fault arc. In the same manner, the suppression of a single-phase-to-ground fault arc can be simulated in HV-power systems with Peterson coils connected to the neutral point.

## 5 List of Principal Symbols

| | |
|---|---|
| $g$ | arc conductance |
| $G$ | stationary arc conductance |
| $i$ | arc current |
| $l$ | arc length |
| $l_0$ | initial length of the arc column |
| $r$ | arc resistance |
| $R$ | resistive component of the stationary arc characteristics per arc length |
| $t$ | time |
| $\Delta t$ | time step of digital simulation |
| $u$ | arc voltage |
| $u_{st}$ | stationary arc voltage |
| $u_0$ | constant voltage parameter of the stationary arc characteristics per arc length |
| $\tau$ | arc time constant |

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