FAULT ARC MODELING IN EMTP

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Abstract: The dynamic interaction between a fault arc and the power network is extremely important to determine the instant of successful reclosure of a faulted system. It is also relevant in the development of new very-high-speed protection relaying. In the present work an improved fault arc model [1] for both primary and secondary arc is implemented using the MODELS simulation language available in the ATP version of the EMTP. An illustrative example is also presented in order to study the influence of the arc behavior in the distortion of the arc voltage as well as the evaluation of the self-extinction time of the secondary arc current.

1 Introduction

The most frequent faults in power transmission systems are temporary in nature, involve just one phase and occur through long arcs in air. For these reasons, single-phase switching (SPS) has been successfully used over the years to overcome the problem of transient stability and to reduce the torsional impact on generator rotors when reclosure occurs. Moreover, allowing some electric energy to flow through the faulted line, the SPS technique prevent other lines to become overloaded. On the other hand, when a ground fault is isolated by SPS, the faulty phase remains coupled to the other phases, mainly by capacitive coupling. In result, a small current will still flow through the arc. It is not until this current is extinguished that successful reclosure of the faulty phase can take place.

In order to improve power systems performance, both from protection and insulation point of view, the evaluation of the transients produced by faults is to be made with a high degree of accuracy. For this purpose it is commonly accepted that digital simulation provides an efficient and appropriate method, where the Electromagnetic Transient Program (EMTP) is the best known in this field.

If realistic results are to be obtained, the dynamic interaction between a fault arc and the power network is of extreme importance. In the present work, this interaction is implemented using the simulation language MODELS [2,3] in the ATP version of the EMTP.

As far as the arc model is concerned, it can be divided into the primary arc, when the fault occurs and the secondary arc, after the breakers trip. To some extent, the primary arc characteristics can be assumed similar to the constrained switching arc, with no significant elongation. The secondary arc is a highly complex phenomena which involves successive arc extinctions and restrikes until the final extinction is reached. Its length cannot be considered constant so the elongation of the secondary arc must be evaluated as well as the recovery characteristics of the arc path.

This paper addresses the problem of accurate modeling of the fault arc and its interaction with the power network using the MODELS simulation language in the EMTP. An illustrative example is also presented in order to determine the instant of successful reclosure.

2 Fault Arc Modeling

For digital simulation studies of electromagnetic transients, fault arcs have been traditionally represented by a constant linear resistance [4] connecting the two extremes of the fault, for instance between a phase and the ground in case of a single-line to ground fault.

However, with the ever increasing demand for more accurate evaluation of power systems transient response, the fault arc model has become a matter of further investigation. In result, models for the fault arc have been developed by several authors in order to achieve results in accordance to those measured in practice [5-8].

2.1 Model by Cornick, Ko and Pek [9]

In 1981, Cornick [9] proposed a model based on experimental data made available by Strom [5], who investigated long power arcs in free air.

Although there were variations from test to test and from cycle to cycle within the same test, Strom concluded, from the large number of results obtained, that the arc-voltage gradient lies between 12 and 15V/cm for currents in the range of 100A to 20kA. The variations observed were explained by the movement of the arc due to magnetic forces, which tend to shift the arc into new paths that are less ionized.

According to the results of Strom, Cornick obtained a normalized arcing-fault characteristic (Fig. 1) which represents a piecewise simplification of the arc-voltage and arc-current relationship, after the arc is established.

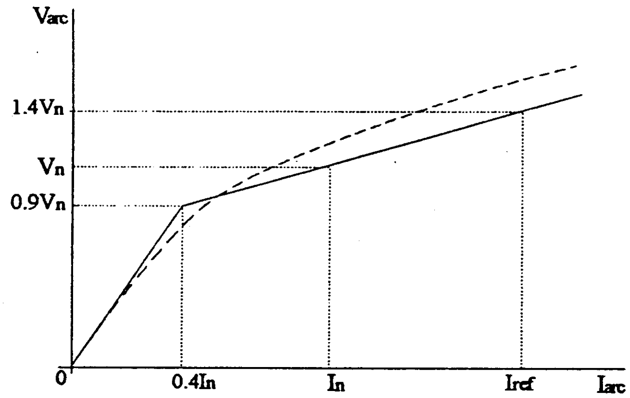

Fig. 1 *Normalized arcing-fault characteristic*
—— Piecewise
- - - Modified 7th order

To overcome the discontinuities of the piecewise characteristic at ± 0.4 I_n, which could cause numerical difficulties, a seventh-order power function was proposed to redefine the volt-ampere characteristic of the arc:

$$I_{arc} = K_1 (V_{arc}) + K_2 (V_{arc})^7 \qquad (1)$$

In this equation the constants K_1 and K_2 are evaluated in terms of the short-circuit current (I_n) and the voltage drop across the arc path (V_n=grad V.l_{arc}):

$$K_1 = \frac{0.9V_n}{0.4I_n} \qquad K_2 = \frac{3.4I_n}{(1.4V_n)^7} \qquad (2)$$

With this formulation the arc resistance is given by:

$$R_{arc} = \frac{V_{arc}}{I_{arc}} = \frac{1}{K_1 + K_2 \cdot V_{arc}^6} \qquad (3)$$

2.2 Model by Kizilcay and Pniok [10]

Another work of great importance in the field of fault arc modeling was done by Kizilcay [10]. In there, it was simulated the dynamic interaction between a fault arc and the power network, using an arc model based on the energy balance in the arc column.

According to this model, the arc conductance is ruled by the differential equation:

$$\frac{dg}{dt} = \frac{1}{\tau}(G - g) \qquad (4)$$

where

- g time-varying arc conductance
- G stationary arc conductance
- τ time constant

Both primary and secondary arc conductance are represented by the same equation. Nevertheless, non-varying time constant and stationary conductance are considered for the primary arc, while the secondary arc time constant and stationary conductance are time-varying and can be expressed as a function of the arc elongation.

2.3 Model by Johns, Aggarwal and Song [1]

The work presented by Johns [1] comprises a mathematical arc model which determines the arc behavior and also the arc parameters derived from experimental tests [5]. This way, more precisely prediction of transient waveforms were achieved when considering a realistic arc description.

From a modeling point of view, the arc can be classified into the primary arc, after fault inception and the secondary arc, after the faulted phase is isolated, which is sustained by mutual coupling between the healthy and faulted phases.

2.3.1 Primary Arc Model

The primary arc is characterized by the heavy short circuit current, for the large cross section of the arc path and for the relative constant length.

The dynamic arc conductance is obtained by the solution of the equation presented by Kizilcay [10]:

$$\frac{dg_p}{dt} = \frac{1}{T_p}\left(G_p - g_p\right) \qquad (5)$$

where g_p is the primary arc conductance and G_p is the stationary primary arc conductance which value is determined by:

$$G_p = \frac{|i|}{V_p \cdot L_p} \qquad (6)$$

In this relation i is the fault current that flows through the arc, V_p is the arc voltage gradient and L_p the arc length, considered to be constant.

Over the range of current 1.4kA to 24kA, the average arc voltage gradient is:

$$V_p = 15\ V/cm \tag{7}$$

The time constant in eq. 5 is inversely proportional to the rate of rise of the voltage, empirically obtained by fitting with the experimental volt-ampere cyclograms. Thus, we get:

$$T_p = \frac{\alpha I_p}{L_p} \tag{8}$$

with $\alpha = 2.85x10^{-5}$ from the fitting and I_p is considered to be the arc peak current under the conditions of a bolted fault.

2.3.2 Secondary Arc Model

The dynamic behavior of the secondary arc conductance is ruled by a differential equation in the same way as it is for the primary arc model:

$$\frac{dg_s}{dt} = \frac{1}{T_s}\left(G_s - g_s\right) \tag{9}$$

where G_s is obtained by:

$$G_s = \frac{|i|}{V_s \cdot l_s(t_r)} \tag{10}$$

In the range of currents of 1A to 55A, the constant voltage gradient can be approximated by the following expression:

$$V_s = 75\, I_s^{-0.4} \quad V/cm \tag{11}$$

Contrasting with the primary arc, the secondary arc elongation has to be taken into account. In this respect the arc length is expressed as a function of the time spent from the initiation of the secondary arc (t_r).

For low wind velocities the arc length is considered to increase according an empirical expression:

$$l_s(t_r)/L_{s0} = \begin{cases} 10 \cdot t_r & , t_r > 0.1s \\ 1 & , t_r <= 0.1s \end{cases} \tag{12}$$

where L_{s0} is the initial arc length, therefore equal to the primary arc.

The time constant in eq. 9 is empirically determined according to the rate of rise of the secondary arc voltage and is given by:

$$T_s = \frac{\beta I_s^{1.4}}{l_s(t_r)} \tag{13}$$

where β=2.51x10^{-3} obtained by fitting to the test results.

It is known that after the primary arc clearing the air gap contains a great volume of ionized gas that is at a high temperature.

However, as the secondary arc persists in time the arc path lengthens, cools and the ionized particles progressively disperse. Therefore the withstand voltage of the air gap after the arc extinction will increase. This way, as well as being a function of the time interval from secondary arc clearing to the peak recovery voltage, the air gap withstand voltage is also a function of the total time elapsed since extinction of primary fault current[6].

Based on the available experimental results, an empirical expression was used by Johns to represent the arc reignition voltage:

$$V_r(t_r) = \left[5 + \frac{1620 \cdot T_e}{2.15 + I_s}\right] \cdot (t_r - T_e) \cdot h(t_r - T_e) \cdot l_s(t_r) \quad [kV] \tag{14}$$

The arc current is held at zero as long as the magnitude of the voltage impressed across the arc path remains bellow the value given by eq. 14.

3 Implementation in the EMTP

The characteristics of the fault arc are represented by a time-varying resistance RSARC1 (type 91 element) and a controlled switch (type 13 element). The value of the non-linear resistance of the arc and the command SIGNAL are computed inside MODELS and introduced at each timestep in the EMTP.

When the simulation of a fault is required the switch is closed and the arc resistance is ruled by the primary arc conductance (eq. 5). After a certain time, corresponding to the detection of the fault and operation of the protection system, the breakers at each end of the line trip and the secondary arc is established.

From this instant the dynamic resistance RSARC1 is evaluated according to the secondary arc formulation given by eq. 9 and use is made of the status of the controlled switch to simulate the extinctions and restrikes of the secondary arc current.

In this respect, every time the fault current magnitude is less than a minimum established, the air begins to regain its dielectric properties and the reignition voltage starts to increase according to eq. 14.

While the voltage impressed across the arc path is less than the reignition voltage, the controlled switch is opened in order to simulate the extinction of the arc. Once the recovery voltage exceeds the reignition voltage the switch is closed to simulate a restrike.

This procedure is taken until the rate of rise of the reignition voltage is such that its value is always greater than the recovery voltage imposed across the air gap. Under these circumstances the final extinction is reached and the reclosure of the faulty phase can take place without causing any damage to the system.

The interaction between the fault arc and the power network is achieved using the communication between the EMTP and its subroutine MODELS. The fault arc voltage and current as well as the status of the controlled switch are the input variables of the MODELS. These inputs are used to produce the MODELS outputs: the variable SIGNAL that controls the arc extinctions and restrikes and the arc resistance that is introduced into the simulation as a time-varying resistance.

4 Simulation results

In the present study a 400kV transmission line, 128km length is chosen with source capacities at both ends taken to be 5GVA and modeled by a Thévenin equivalent circuit.

Frequency dependent parameters of the line are calculated via the EMTP line constant program where the earth conductivity is considered to be 0.01 S.m^{-1}.

Faults can be applied by closing the switch that connects the auxiliary busbar FAULT1 to earth through the dynamic arc resistance RSARC1. The circuit diagram corresponding to phase 1, which is considered to be the faulty phase, is shown in Fig. 2.

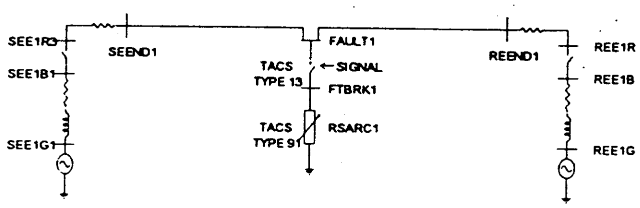

Fig. 2 *Data-case circuit model*

Computed results obtained from the system described are shown in Fig. 3 to 8.

One of the most relevant features of the fault arc, observed in experimental studies [8] is the hysteresis loop. This can be confirmed to be adequately simulated by the analysis of the cyclogram in Fig. 3.

It is also observed that the voltage approach higher values for increasing currents while it is nearly linear when the current is decreasing. This is so because the more the current increases, the higher the temperature becomes and the arc resistance becomes smaller.

The volt-ampere characteristic of the arc is placed in the first and third quadrants of the plane, which indicates the resistive nature of the arc phenomena.

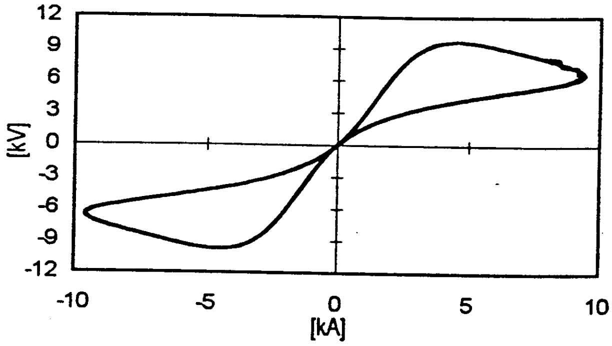

Fig. 3 *Volt-ampere characteristic*

The arc has a highly nonlinear behavior as seen in Fig. 4 producing high order harmonics in the fault arc voltage, which in turn distort it into a near square wave (Fig. 5).

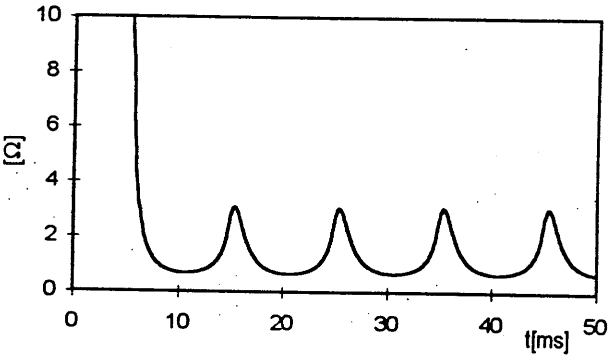

Fig. 4 *Primary arc resistance*

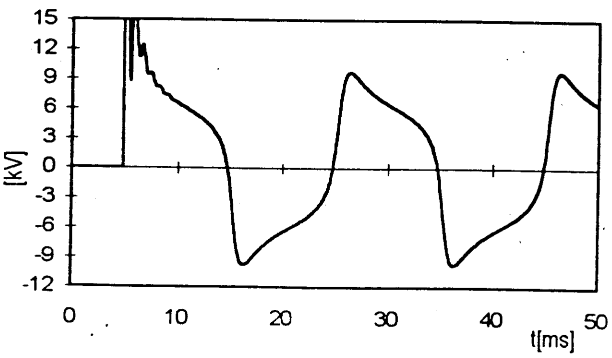

Fig. 5 *Primary arc voltage*

In Fig. 6 and 7 it is shown the voltage and current at the sending end busbar. The instant T1 corresponds to the fault inception, T2 is the opening of the breakers and T3 the extinction of the secondary arc current.

Until the instant T1 the system is operating under steady-state conditions. When a phase to earth fault occurs a heavy short-circuit current flows through the faulty phase until the breakers trip at T2. The time interval between T1 and T2 corresponds to the what is called the primary arc.

When the breakers trip (at instant T2) the electric power supplied to the arc is just derived from the coupling with the other two phases therefore becomes much smaller. As a result, the condition to the self-extinction of the arc is established because the energy supplied to the arc is now lower than the energy dissipated to its surroundings. Therefore the arc will persist as long as the the energy stored from the primary arc conditions is enough to counterbalance the difference between the input and output energy in the arc column.

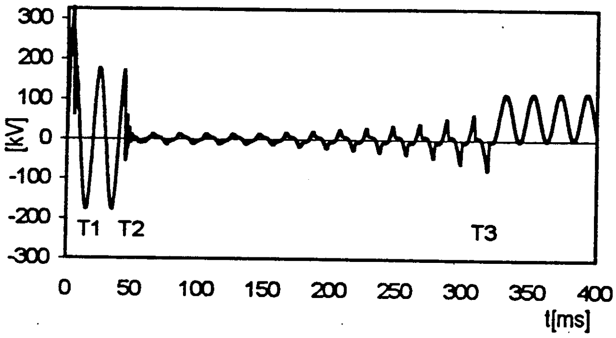

Fig. 6 *Sending end voltage*

The analysis of the sending end voltage is very important to prevent a reclosure from happening in the case of a permanent fault when the secondary arc current self-extinction will never occur and serious damage would be caused to the system.

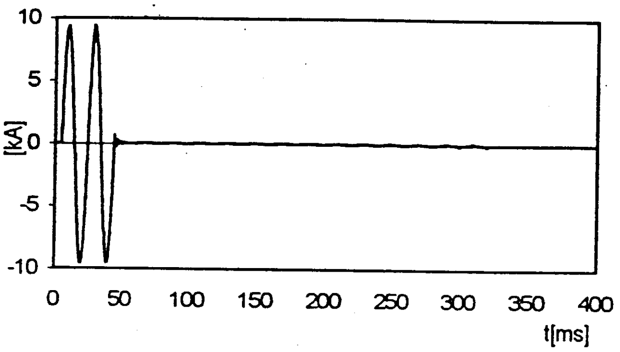

Fig. 7 *Sending end current*

In Fig. 8 the secondary arc current at the sending end busbar is shown. It takes place between T2 and T3 when several partial extinctions and restrikes are observed until the final extinction occurs at T3.

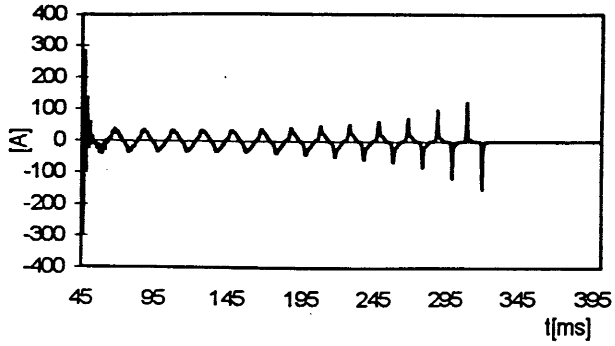

Fig. 8 *Secondary arc current*

5 Conclusions

The arc behavior was implemented in the EMTP as a time-varying resistance (type-91 element) and its value computed inside the MODELS by a first order differential equation. For the representation of the secondary arc, an additional controlled switch (type-13 element) was included to simulate de arc extinctions and restrikes. This switch operates according to the comparison between the reignition voltage and the transient recovery voltage applied across the arc path.

An illustrative example was also presented where the secondary arc self-extinction time can be analyzed and, therefore, the instant of successful reclosure evaluated.

6 Acknowledgment

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7 References

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