

Modeling of A.C Circuit Breakers in the Electromagnetic Transients Program

by

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(ABSTRACT)

The objective of this research project was to develop and implement a model for an A.C circuit breaker in the Electromagnetic Transients Program (EMTP). Various models for the arcing process were evaluated, and the modified Mayr equation was chosen for the model. Other equations were added to demonstrate the generality of the algorithm developed.

Since the Electromagnetic Transients Program was not designed to accommodate directly elements whose resistance varies with time, such as an electric arc, several strategies for interfacing the model with the program were studied. The compensation method was selected, and was used for interfacing the circuit breaker model with the program.

After implementation of the model, it was validated by comparing it's performance with experimentally verified results reported previously. In order to render the model more practical, an auxiliary breaker parameter estimation routine was developed and tested.

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Chapter 1. Introduction

The objective of the research project upon which this thesis is based was to develop and implement an accurate arcing model of a High Voltage A.C Circuit-Breaker, and to install it in the Electromagnetic Transients Program (EMTP).

The EMTP is a large (almost 100,000 FORTRAN statements) computer program for the analysis of transient phenomena in power systems. It contains detailed models for typical power system components such as synchronous machines, transformers, transmission lines and surge arresters. The program allows the user to connect these and other components, along with basic elements such as resistances, inductances, capacitances and switches to represent his system. The models for these and other elements have been enhanced and tested over the last two decades, so that EMTP is now the most widely used tool for analysis of power system transients.

Until now, the program has lacked the capability of simulating the arcing process in a circuit-breaker. This deficiency needed to be remedied since a significant proportion of the transients occurring in a power system originate as the consequence of a circuit-breaker switching operation. Apart from these switching surges, current chopping and restrike phenomena also cause dangerous overvoltages, and the ability to model these is of interest to the EMTP user.

Another area in which the breaker model would be useful is circuit breaker testing. With the increase in short-circuit capacity in modern power systems, the requirements on the interrupting capability of circuit breakers has also risen. Consequently the direct testing of such large breakers, especially multi-break units is prohibitively expensive and difficult. Synthetic testing has been proposed as a cheaper alternative to direct tests, but its validity is still under question. The EMTP breaker model could be used to supplement synthetic test results by simulating an equivalent direct test without the actual expense or risk associated with such a test.

Having established the necessity for a circuit breaker model in EMTP, the question is how best to satisfy that need. Modeling techniques developed during the course of this research are described in the succeeding chapters of this thesis.

In Chapter Two, various models for the arcing process in a circuit breaker are reviewed. The suitability of these models vis-a-vis EMTP implementation is examined, especially with regard to experimental testing and model validation.

Chapter Three consists of an introduction to the EMTP, and a review of its basic solution technique. In particular, the effect of this technique on the modeling of nonlinear and time-varying elements is discussed.

Chapter Four deals with the details of the actual implementation of the equation chosen as a complete model for a circuit breaker. The algorithm for the iterative solution of the nonlinear differential equation is described, along with an explanation of the data requirements of the model.

Chapter Five addresses the subject of model testing. Previously reported results are described and are used as benchmarks to establish the validity of the EMTP model. Good agreement was found between the explicit methods used hitherto and the model described here.

Chapter Six treats the alternate equations for which suitable test results were available. To establish the generality of the solution technique, these equations were also implemented along with the main model, providing the user with a choice of three different models. The differences between the various models are discussed from a theoretical and practical viewpoint. Test results and model validation details are also given.

In order to make the model easily usable, the breaker parameters have to be available. At present these are not standardized, and are not supplied by the manufacturer. In Chapter Seven, the subject of breaker parameter estimation

from experimental data is dealt with. A procedure is described by which a set of breaker parameters can be chosen optimally from oscillograms of the arc voltage and current. The chapter also discusses the validity of the parameters, which were tested by re-using them as input to the breaker model and comparing the interruption performance using the original parameters against that with the estimated ones. In order to obtain more exact parameters, guidelines are given on how to choose the data input to the estimation program.

Chapter Eight presents the conclusions reached, and suggests possibilities for future activity in the area of computer modeling of circuit breakers, with particular reference to EMTP modeling.

Chapter 2. Circuit Breaker Arc Modeling

2.1: Introduction

The subject of high temperature arc modeling has been an active research topic for over six decades. Despite this, complete understanding of the physical processes involved has not been achieved, and to this date, the design of a circuit breaker cannot be done entirely from first principles. Most of the models described in this chapter were derived on a purely empirical basis, and often were designed to describe only one particular aspect of the arc behavior. This makes their use in a general purpose simulation program rather dubious, and therefore a careful review of the equations was necessary before choosing the model for implementation in EMTP.

2.2: Model Selection Criteria

Since the objective of this initial stage of the research was to select a model for use in EMTP, a program designed for the Electric Utility Industry, some constraints on the type of model were imposed. These are summarized here :

1. The model should have been tested extensively, and the results of such tests should be available for comparison. Preferably, the model should have been verified both experimentally and by computer simulation of the experimental set-up.
2. The model should be fairly simple, and numerically robust.
3. The model should be as general as possible without excessive complexity of the equations.
4. The model should not require data regarding the mechanical features of the breaker, such as the number of nozzles, the materials used, etc.

The reasons for the first three constraints are fairly easy to see, since an accurate and useful computer model was to be developed. Numerical stability of the algorithm is essential since the main use of the model would be in simulation of the opening of the breaker, when the resistance changes from zero to infinity in a few milliseconds. The model must be robust enough to handle very large numerical

values without convergence problems. Simplicity is desirable, not just for the sake of modeling ease, but from the standpoint of computation time. The breaker model when complete, will be used as a part of a complex system and should therefore not take an excessive amount of computer time to simulate. This is especially important considering the very small time-step needed to solve accurately the differential equations described later. With a small time-step, a large number of steps would be needed to complete a simulation, and therefore a computationally simple model for the breaker would make the overall simulation considerably faster. The last requirement was necessitated by the nature of current research in arc modeling. Many recently developed models use plasma dynamics and turbulent boundary layer theory to predict the breaker performance, and require knowledge of the mechanical aspects of the arc chamber and nozzles, etc. These models are extremely complex, perhaps theoretically more justifiable than the older, more empirical models, but are not easy to use, and are certainly not suitable for a general program such as EMTP. In addition, the input data needed for such models is not likely to be available to the user of EMTP.

2.3: The Mayr and Cassie Models

These two models are the oldest in the area, and form the basis of many of the newer models developed later. Both were derived from experimental evidence. The equations are :

$$\frac{d(\ln g)}{dt} = \frac{-1}{\theta} + \frac{v^2}{\theta V^2} \quad [2.1]$$

which is the Cassie equation reported first by Cassie [1,2], and :

$$\frac{d(\ln g)}{dt} = \frac{-1}{\theta} + \frac{vi}{\theta P} \quad [2.2]$$

the Mayr equation [3], itself an extension of the Cassie equation. In both the equations, g is the arc conductance, v and i are the instantaneous arc voltage and current respectively, θ is the arc time constant. V is the steady state arc voltage, and P the steady state power dissipation in the arc.

These two models are extremely simple, and continue to be the basis for many practical modeling methods. Due to their simplicity however, they are not uniformly valid throughout the entire arcing process. Experimental evidence of this was presented by Rieder and Urbanek [4,5], and this has caused renewed interest in the development of more detailed realistic models. Basically, it was shown that neither equation is valid in the critical period, the last 20 microseconds before the current zero. The Mayr model is valid before this interval, and the Cassie model from the last 10 microseconds onwards. Due to these shortcomings, there is no published record of experimental verification of these equations in a form suitable for use as a basis for comparison with EMTP. Therefore these two equations were not considered for use in the EMTP implementation.

2.4: The Browne and Frost Models

This equation was developed at Westinghouse by T.E.Browne, one of the pioneers in the area [6,7]. It is based on the assumption that during the critical period, the current can be represented by a linearly decreasing ramp function, until the current zero. This is a valid assumption at power frequencies, and leads to the equation :

$$\frac{d(1/R^2)}{dt} + \frac{2}{\theta R^2} = \frac{2}{\theta} \left(\frac{i}{V}\right)^2 \quad [2.3]$$

where R is the arc resistance, and i, V and θ are as defined previously. This equation can be solved analytically when the current is assumed to have a constant slope. The solution is that the arc resistance at current zero is equal to $\frac{V}{I\theta\omega}$ where I is the r.m.s value of the sinusoidal current being interrupted, and ω the angular frequency of the system.

Another development from the Westinghouse group is the Frost model reported [8] at the same time as the Browne model. It is a switching model based on the sequential use of the Cassie equation, the Mayr equation and then the Cassie equation again. It is defined by :

$$\frac{dg}{dt} = \frac{g}{\theta} \left(\left(\frac{v}{E} \right)^2 - 1 \right) \quad T_0 > t > 0$$

$$\frac{dg}{dt} = \frac{g}{\theta} \left(\frac{vi}{\theta\omega IE} - 1 \right) \quad T > t > T_0 \quad [2.4]$$

$$\frac{dg}{dt} = \frac{g}{\theta} \left(\frac{v^2 g(T)}{\theta\omega IE} - 1 \right) \quad t > T$$

where g is the arc conductance, E the arc extinction voltage, and I the r.m.s current and T_0 is the instant of occurrence of the current zero. T is the instant when the rate of increase of the arc resistance becomes zero. This model neglects the possibility of subsequent dielectric breakdown, as do the other models discussed till now. The model is therefore valid for the thermal interruption failure, which usually occurs just after the current zero. This model has been tested to some extent for the simulation of short-line faults, and the results were in general agreement with experimental data.

2.5: *The Habedank-Kugler Model*

This model was also developed [9] to simulate a short-line fault, and is an extended version of the Mayr equation. The equation is :

$$\frac{dg}{dt} = \frac{1}{\theta} \left(\frac{i^2}{P + |iE_0|} - g \right) \quad [2.5]$$

where P is the steady-state power dissipation, and E_0 a constant fraction of the steady arc voltage. This model was also tested against experimental results, and was found to be in reasonable agreement for short-line faults.

2.6: Unconventional Models

In general, the models described in the next two sections are not very practical. They use methods adopted from conventional modeling techniques for electrical devices, such as the equivalent circuit and the transfer function. Data availability is a problem for most of these models, and only a few will be described here.

2.7: The Smith-Colclaser Model

This model, developed by the block diagram method [10], results in a "system" model for the entire system including the arc and the power network. The arc is modeled by the Hochrainer-Grutz model, an elementary equation for thermal decay of the arc plasma. There are 4 assumptions made, namely :

1. The arc is a dipole with conductance $G(t)$.

2. For any current I , there exists a static conductance $SG(I)$ towards which $G(t)$ tends.
3. $G(t)$ and $SG(I)$ are continuous functions of their arguments.
4. $G(t)$ tends to $SG(I)$ according to the relation :

$$\frac{dG(t)}{dt} = \frac{SG(I) - G(t)}{T(I)} \quad [2.6]$$

where $T(I)$ is a current dependent arc time constant. $SG(I)$ and $T(I)$ vary from breaker to breaker, and are to be obtained from oscillograms of interruption tests on the breaker.

Since the model was based on a thermal model of the arc, it has been found to be valid only for thermal breakdown. It is incapable of simulating current chopping, and was found to be more realistic in cases of severe TRV (Transient Recovery Voltage), than in less severe situations. Therefore it could be used for short-line faults, but not for bus faults.

2.8: *The Rizk Model*

This model was developed to simulate the interaction of the arc and the circuit [11], especially the oscillations and overvoltages caused by the interruption of small inductive currents. The model results in an equivalent circuit for the arc.

As the arc resistance increases, a larger proportion of the fault current is diverted into any parallel path across the interrupter, such as the capacitance of the breaker. This decrease in the arc current may cause a premature current zero and interruption, or as has been observed in some cases, oscillation of the current magnitude in the arc due to cyclic charging and discharging of the capacitance. These result in significant over-voltages, and have a definite impact on the interruption. The Rizk model is relevant in the investigation of such phenomena.

The equivalent circuit that results is a R-L circuit, with 2 parallel branches. One branch is purely resistive, with a resistance equal to the static arc resistance. The other branch is a series connection of a resistance R_1 and an inductance L_1 whose values are :

$$R_1 = \frac{R_0 R_d}{R_0 - R_d} \quad [2.7]$$

where R_0 is the arc resistance and R_d is the dynamic or incremental arc resistance, and

$$L_1 = \frac{\theta R_0^2}{R_0 - R_d} \quad [2.8]$$

where θ is the arc time constant.

Data requirements for this model have also proved to be a problem, but it has been used, especially in the simulation of current chopping.

2.9: Practical Models

The main drawback of the models described above is not their lack of validity or their complexity, but the lack of sufficient test results which could be simulated with EMTP for validation of the new model. Three models were found for which this is not a problem, and these are reviewed now. The test results cover a range of breaker types, such as air-blast, oil-filled, sulfur-hexafluoride and generator circuit-breakers.

2.10: The Kopplin Model

This is a simple equation, which has been tested for generator circuit breakers [12]. It is an extension of the Mayr model and consists of the equation :

$$\frac{dg}{dt} = \frac{g}{\tau(g)} \left(\frac{v.i}{P(g)} - 1 \right) \quad [2.9]$$

where $\tau(g) = k_t \times (g + 0.0005)^{0.25}$ and $P(g) = k_p \times (g + 0.0005)^{0.6}$. This model is one of a family of recent models [13], which are derived from the Mayr model by making the arc time constant and the arc power constant functions of the arc resistance.

2.11: The Urbanek Model

This is perhaps the most comprehensive model developed for the arc recently, and is also the most complex. It is capable of simulating both thermal and dielectric breakdown, as well as current chopping and restrike phenomena. It has been tested by various researchers [14,15] and breaker parameters are available for the simulation of test cases. There has also been a computer program developed to evaluate the breaker parameters from test oscillograms [14]. The equation is :

$$\frac{dg}{dt} = \frac{1}{\theta} \left(\frac{vi}{V^2} - g - \frac{P}{V^2} \left(1 - \left(\frac{v}{V} \right)^2 - \frac{20v}{V^2} \times \frac{dv}{dt} \right) \right) \quad [2.10]$$

where the variables have the same meaning as before, and v is the dielectric breakdown voltage for a cold arc channel. The equation was integrated by Blahous [14] to yield a semi-analytic expression for the resistance as a function

of time. The method of estimating parameters is a standard nonlinear estimation problem and is described in more detail in Chapter Seven.

2.12: The Avdonin Model

This is the main equation used in the implementation of a breaker model in EMTP [15]. It is also a modified version of the Mayr equation, with the various constants of the Mayr equation being replaced by arc resistance dependent functions. It is very good for simulation of thermal failure, and has been tested for this, as well as for current chopping. The equation is :

$$\frac{dr}{dt} = \frac{R^{1-\alpha}}{A} - v \times i \times \frac{R^{1-\alpha-\beta}}{A \times B} \quad [2.11]$$

In this expression, the Mayr time constant θ and power P have been replaced by AR^α and BR^β respectively.

This equation has been extensively tested at Hydro-Quebec [15] and therefore test circuit and breaker parameter details are available for use as a benchmark in comparison with EMTP. This is the breaker model that will be referred to as the modified Mayr equation in the rest of this thesis, and is the main model implemented in EMTP. Some more references are provided which give a more detailed explanation of arc modeling, in particular, and circuit interruption in general [16,17,18].

Chapter 3. Introduction to EMTP and Nonlinear Element Modeling

3.1: Introduction

The purpose of this chapter is to provide an overview of the EMTP problem formulation and solution techniques, with special reference to their effect on the modeling of nonlinear devices in the program. Some problems are encountered due to EMTP practices, which are based on considerations which were perhaps more relevant when the program was written (1968) than they are now. These and other issues regarding nonlinear element modeling are discussed in this chapter.

3.2: EMTP - The Electromagnetic Transients Program

The EMTP is a general-purpose program for the simulation of transients in electrical networks, especially power systems [19]. It allows the user to specify his system configuration as an interconnection of typical components, models for which already exist in the program. The type of elements ranges from simple resistances and inductances to complex devices such as synchronous machines and transformers. The program has grown steadily over the last 15 years, due to the addition of models for other devices, thus enhancing its capabilities. However, a transient model of a circuit breaker was not incorporated, for various reasons, chiefly the lack of a validated model with reasonable data requirements and availability. Such models have recently become available, as described in Chapter Two, and the development of a breaker model has become feasible.

The program solves a network by forming its admittance matrix, and solving the resultant voltage-current relationship. To do this, the admittance or [Y] matrix has to be evaluated. Since the use of complex arithmetic was not desired at the time, because of the slowdown in the solution time, the program converts all inductances and capacitances to equivalent resistances with a time-varying current source in parallel. The [Y] matrix thus obtained is real and symmetric, and the system is described by the equation :

$$[Y]e(t) = i(t) - [I] \quad [3.1]$$

where $[I]$ is the vector of the current injections due to the equivalent current sources from inductances and capacitances. Since the program is meant primarily for power system simulation, the $[Y]$ matrix is assumed to be extremely sparse. Therefore in order to solve the above equation most efficiently, optimal ordering techniques are used [20]. In addition to these, for reasons of memory saving, a crucial factor then, the $[Y]$ matrix is not stored directly but is factorized into two parts, one upper triangular and the other lower triangular. These can be stored more efficiently in a list form. The factors remain constant throughout the simulation except in certain special situations. Switching operations affect them, but the effects of these can be pre-calculated and can be made easily. More difficult to handle are elements whose impedance varies with time, since these would cause a change in the $[Y]$ matrix at every time step. Such elements are very common in power systems, for example surge arresters, circuit breakers, and saturation-dependent devices such as synchronous machines and transformers.

There were two possible ways to solve this problem, either to re-factorize the $[Y]$ matrix at every step, or to keep the factors constant and somehow compute the effect of the nonlinear elements on the solution derived with the original factors. Since re-factorization would be extremely time-consuming, the second alternative was chosen. The next issue was then the computation of the effect of nonlinear elements. Several methods for this were reviewed, and the compensation method was selected for use in EMTP.

3.3: The Compensation Method for Nonlinear Element

Modeling

The problem with nonlinear elements was recognized very early, the first paper on the subject [21] appearing about two years after the first paper on EMTP [19]. Reference [21] discusses various means of interfacing the elements with the rest of the program, and indicates that the compensation method [22] would be the best. Since then, the compensation method has been the main one used in EMTP for nonlinear element modeling. Therefore, in implementing the circuit breaker model, the existing routines for the compensation method were used, making the modeling simpler.

The compensation method is based on the application of Thevenin's theorem at the terminals of each nonlinear element. Let nodes k and m be the two nodes between which a nonlinear branch is connected, and let $Z_{k,m}$ be the Thevenin impedance calculated by open-circuiting the nonlinear branch k - m . If an analytical expression for the voltage-current characteristic of the nonlinear branch is known, such as :

$$e_k(t) - e_m(t) = f(i_{k,m}) \quad [3.2]$$

then the net voltage across the branch can be calculated by solving the equation :

$$e_k(t) - e_m(t) = f(i_{k,m}) = e_k^0 - e_m^0 - Z_{k,m} i_{k,m} \quad [3.3]$$

where e_k^0 and e_m^0 are the potentials at nodes k and m when the branch k-m is open-circuited. The solution of the nonlinear equation can be done by any iterative procedure, the Newton-Raphson technique being used very often.

The routines already available in EMTP calculate the Thevenin impedance and voltage, and handle the superposition of the nonlinear element solution on the Thevenin voltages. Therefore the breaker routine was written to take input from the Thevenin calculation routines, and to direct its output, the arc current to the superposition routine. The use of these inbuilt routines simplified the work, and made the breaker model more reliable.

3.4: Limitations of the Compensation Method

The compensation technique is simple and elegant, but naturally has some drawbacks. The most important of these is a constraint on the number of nonlinear elements in a simulation. Suppose there were two nonlinear branches in a circuit, and this was solved by the compensation method. The open circuit solution would be obtained by open-circuiting both the elements, and the branch currents by solving the individual nonlinear equations separately. The superposition would not be valid however, due to the effect of the branch current in one

element on the open-circuit voltage of the other. Therefore only a circuit with just one nonlinear element can be simulated, except in the following situation. If the two elements were separated by a transmission line whose travel time was greater than the time-step used in the simulation, then the effect of one nonlinear element on the other would not be experienced until after the travel time of the line, which is at least one time step later. Therefore the calculation at each element is decoupled from the other, and is valid despite the presence of other nonlinear elements. This artifice makes it possible to simulate several nonlinearities, but would require the addition of many artificial transmission lines, which may not exist in the actual system, to the simulated system. This would slow down the computation, as well as make the system modeling inaccurate.

The problem can be circumvented by the use of a multi-dimensional Thevenin equivalent, in which Thevenin's theorem would be applied to all nonlinear elements simultaneously, thus forming a vector of open circuit voltages and a matrix of Thevenin impedances. This procedure would require the simultaneous solution of several nonlinear equations, as many as there are nonlinearities. Though this is theoretically feasible, it would not be practical for use in EMTP in all cases. It can be used easily to simulate a multi-phase nonlinearity, in which the governing nonlinear equations in each phase are solved together, but would not be useful for more general situations. This is because it would require interfaces between various models, such as those for the synchronous machine and the breaker, to solve their equations together. This runs counter to the EMTP philosophy of

making each device model totally independent of the others, and would be computationally very complex to handle.

There are other problems with the compensation method, none of which are too serious. It fails when no solution exists for the network with all nonlinear elements open-circuited. Another problem arises in the solution of the nonlinear equation. If the solution is not accurate, there would be a small difference between the device voltage as calculated from the nonlinear characteristic and that from the Thevenin equivalent. Since this cannot exist in practice, leading to violation of Kirchoff's law, some other voltage would change in order to correct this apparent error, creating an actual error. This error would accumulate as the simulation progresses, and cause serious deviations from the true solution. This problem was encountered during the implementation of the breaker model, and is discussed in more detail in Chapter Four.

Chapter 4. The EMTP Circuit Breaker Model - Implementation

4.1: Introduction

This chapter is devoted to the details of the implementation of the Mayr equation as part of a complete model for an a.c circuit breaker in EMTP. The equation itself is described in Chapter Two, and is not the main focus of this chapter. Rather, in this chapter, the question of how to fit this equation into a complete model for a circuit breaker is examined, along with some practical issues that arose during the implementation.

4.2: Circuit Breaker Operation

As explained in Chapter Two, the modified Mayr equation was chosen for the description of the arcing process. However, the period during which the arc behavior can be modeled by the Mayr equation is but a small fraction of the total time-to-open for a breaker. In order to model the device fully, it was necessary to represent the breaker throughout the opening process.

The typical sequence of events during the opening of a circuit breaker is as follows :

1. The relay detects the fault and sends a trip signal to the circuit breaker.
2. After a small delay, the contacts of the circuit breaker start to separate from each other, and a voltage develops across the gap. The arc is now formed between the two contacts.
3. As the current in the arc decreases towards the current zero, the nozzle of the breaker unclogs and from now on the arc behavior can be represented by the Mayr equation. This is the period in which the rate of rise of the arc resistance is very high. Depending on whether or not the interruption is successful, this period ends when the current becomes zero or when a restrike occurs. The current then increases in magnitude and is of the opposite polarity.

From the EMTP user's standpoint, this implies that apart from the breaker parameters themselves, some timing data and the value of the voltage in the pre-Mayr period is necessary to specify the device operation. In the model implemented, three time instants are to be specified by the user; namely the instant of parting of the contacts, the instant of the expected current zero at which interruption is being attempted, and the duration of the Mayr arcing, specified as a period before the current zero.

In EMTP, it is assumed that all nonlinear elements are open-circuits in the initial condition, so as to simplify steady-state calculation. This assumption, though suitable for surge arresters, is not appropriate for circuit breakers, which are closed initially. Therefore, in order to obtain sensible results, the circuit breaker must be short-circuited externally. This can be done by placing a closed switch in parallel with the breaker, and forcing the switch to open as soon as possible after the beginning of the simulation. To force the opening, a large current margin is set for that switch.

Until the time when the contacts part, the breaker is closed so that the voltage across it is zero. Once the contacts part, it is known from field tests that the voltage across the gap rises to a fairly steady value and remains there until the Mayr equation is valid [15]. It has been observed that the value of the steady voltage depends on the type of breaker, ranging from about 10,000 Volts for an oil-filled breaker to about 1000 Volts for a sulfur-hexafluoride breaker.

During the early stages of this work the breaker voltage was set to the constant value immediately after the parting of the breaker contacts. This was found to create an artificial step voltage change in the circuit, leading to undamped oscillations. It was then decided to let the voltage build up in a linear fashion, with the rate of rise determined by the total duration of the steady voltage period. This solved the numerical oscillation problem, and is also more realistic physically. The polarity of the steady voltage is so as to oppose the driving voltage in the circuit, consequently hastening the current zero. Usually in a high-voltage power system, the fault current being interrupted is predominantly inductive. In this case the system voltage is at its peak when the current is near zero, and hence the arc voltage would not have much effect on the instant of the current zero. In the case of load current interruption, or in the case of generator circuit breakers where the system voltage is inherently lower, the current zero may be significantly deformed by the arc voltage. In such cases the arcing interval specified should be large enough so that the current zero does not occur during the constant voltage period.

The actual solution of the nonlinear differential equation is performed in an iterative fashion. The program saves the value of the breaker voltage at the previous time step, and the current is predicted by assuming a constant slope in the period just prior to the current zero. The resistance at the beginning of the interval is known, and this is used to predict the voltage. The slope of the current is tracked throughout the constant voltage period, and is updated at every time step. Using the predicted current and voltage, an approximate value of the resistance can be

found. This is used to determine the rate of change of resistance from the Mayr equation. Using the trapezoidal rule the value of the resistance at the next time step can be evaluated, and hence the breaker current. This is then compared with the initial predicted current; if they agree, the iteration procedure has converged, otherwise the new value of the current is taken as the next prediction for the current and the whole process restarted. A graphical description of the procedure is shown in Figure 1.

4.3: Iterative Algorithm for the Solution of the Nonlinear Equation

A step-by-step description of the iteration procedure is given now.

1. The initial value of the arc resistance is the ratio of the voltage to the current at the previous time step. The initial voltage guess is the previous voltage, since this does not change as rapidly as the resistance in the Mayr regime.
2. The value of current is estimated from the slope and the previous value from the relation :

$$I(T + \Delta t) = I(T) + \Delta t \times \frac{di}{dt} \quad [4.1]$$

3. From the Mayr equation, the rate of change of resistance $\frac{dR}{dt}_1$ is calculated. The values of current and resistance just obtained are used as inputs to the equation.

4. The resistance at the next time step is found by using the trapezoidal rule, as follows :

$$R(T + \Delta t) = R(T) + 0.5\left(\frac{dR}{dt}_1 + \frac{dR}{dt}_0\right)\Delta t \quad [4.2]$$

where $\frac{dR}{dt}_1$ is the rate of change of resistance just calculated, and $\frac{dR}{dt}_0$ the value saved from the previous time step.

5. The new current is obtained from the Thevenin equation :

$$I(T + \Delta t) = \frac{V_{oc}}{Z_{k,m} + R(T + \Delta t)} \quad [4.3]$$

6. This is the end of an iteration cycle. The current and resistance have been evaluated as $I(T + \Delta t)$ and $R(T + \Delta t)$ and the arc voltage is their product. At this stage a convergence check is made, by comparing the last two values for the current. If this is within the specified deviation, the iteration has converged. Otherwise the program returns to step 3 above, calculating the rate of change of resistance again from the Mayr equation, etc.

It was found in practice that the overall success of the scheme was significantly dependent on the tolerance used for the convergence check. By relaxing the criterion from 0.000001 amperes to 0.001 amperes, which does not appear crucial considering the current itself may be of the order of a few hundred to a few thousand amperes, the result of the simulation was found to change in many cases. That is, a case which would be deemed a successful interruption with the tight criterion would be a failure to break with the relaxed one. To make the scheme more general then, the convergence criterion was changed to a voltage related condition, where a tolerance of 0.005 volts was found to be adequate. This procedure is described here next.

1. The initial value of the arc resistance is the ratio of the voltage to the current at the previous time step. The value of current is estimated from the slope and the previous value from the relation :

$$I(T + \Delta t) = I(T) + \Delta t \times \frac{di}{dt} \quad [4.4]$$

2. The voltage is guessed to be the product of the initial resistance and the current $I(T + \Delta t)$.
3. From the Mayr equation, the rate of change of resistance $\frac{dR}{dt}_1$ is calculated. The values of current and resistance just obtained are used as inputs to the Mayr equation.

4. The resistance at the next time step is found by using the trapezoidal rule, as follows :

$$R(T + \Delta t) = R(T) + 0.5\left(\frac{dR}{dt}_1 + \frac{dR}{dt}_0\right)\Delta t \quad [4.5]$$

where $\frac{dR}{dt}_1$ is the rate of change of resistance just calculated, and $\frac{dR}{dt}_0$ the value saved from the previous time step.

5. The new current is obtained from the Thevenin equation :

$$I(T + \Delta t) = \frac{V_{oc}}{Z_{k,m} + R(T + \Delta t)} \quad [4.6]$$

6. This is the end of an iteration cycle. The current and resistance have been evaluated as $I(T + \Delta t)$ and $R(T + \Delta t)$ and the arc voltage is the product of I and R. At this stage a convergence check is made, in this case by comparing the two estimates of the element voltage from the Thevenin equation and the product of arc resistance and current. That is :

$$V_1 = V_{oc} - Z_{k,m} \times I(T + \Delta t) \quad [4.7]$$

$$V_2 = R(T + \Delta t) \times I(T + \Delta t) \quad [4.8]$$

If V_1 and V_2 are close enough, the iteration procedure is complete. Otherwise the program returns to step 2, and continues from there on.

It was also found that the method worked better with a two-step resistance evaluation rather than the single-step method described above. In this scheme the initial resistance is used to calculate the resistance after half a time step, and that value used for the next half time-step. With these modifications, the number of iterations required for convergence was reduced, so that usually 7 or 8 iterations were enough. A further reduction was made by making the slope predictor fairly damped, so that it would not respond to fast changes in the slope near the current zero, which could often be misleading. With this change, convergence was usually attained in 3 or 4 iterations. This is important, since a medium sized case simulation could last for about 1 millisecond, with a time-step of about 0.1 to 1 microsecond. In such a case, the total number of time steps would be about 5000, of which 1000 or more would be in the Mayr regime. Thus a reduction of 1 iteration on the average per time step would result in about 1000 or more iterations saved overall. The saving becomes more significant in the case of a three-phase breaker, when more than one phase current is being interrupted, or in the case of current chopping simulation where the arcing period may be very long, in order to allow interruption at relatively large currents.

The two-step algorithm is as follows :

$$R(T + \frac{\Delta t}{2}) = R(T) + 0.25(\frac{dR}{dt}_1 + \frac{dR}{dt}_0)\Delta t \quad [4.9]$$

The rate of change from this resistance is now evaluated from the Mayr equation.

Let this be $\frac{dR}{dt}_{0.5}$. Then the final resistance is calculated as :

$$R(T + \Delta t) = R(T) + 0.5\left(\frac{dR}{dt}\right)_{0.5} + \frac{dR}{dt}\bigg|_0 \Delta t \quad [4.10]$$

This algorithm uses an approximation to the average resistance over the interval to calculate the average rate of change of resistance and hence the next resistance by the trapezoidal rule.

Although a single-phase breaker model would have been adequate to satisfy the requirements of the research project, for the sake of generality, a three-phase breaker model was implemented. It should be noted that in a three-phase balanced power system, the three poles would open over a period of one third of a cycle, or about 5 milliseconds. This would require immense computer time, since the EMTP time step is fixed, and cannot be increased in the period between the actual Mayr regimes for each pole. The three-phase breaker model should therefore be used with caution.

Once the arc resistance, and hence the arc current and voltage, have been calculated, the breaker routine is ready to return these values to the main program for processing, as explained in Chapter Three. Before this however, the routine is in a position to calculate the status of the breaker for the next time-step. This is in fact essential. If the breaker is still in the constant voltage period, there are no further calculations needed. Once the breaker is in the Mayr period, there are three possibilities, namely :

1. **The interruption has failed.**

$$\frac{d^2r}{dt^2} \leq 0 \quad [4.11]$$

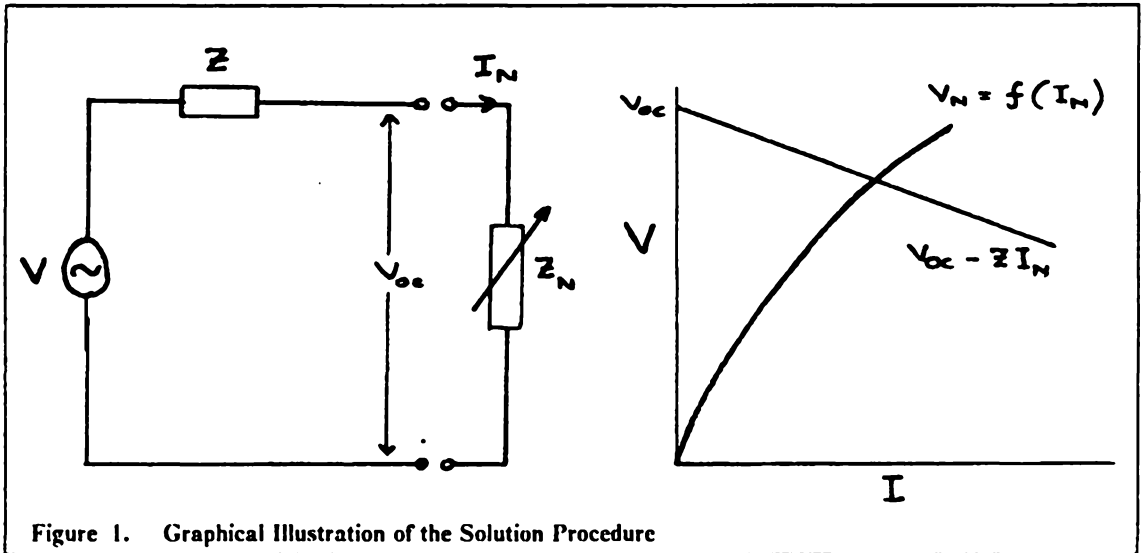
This is signalled by a decrease in the rate of change of the resistance. If allowed to continue, the Mayr equation would then lead to negative resistances very quickly, and hence the rate of change is monitored in order to avoid negative arc resistance. Once failure has occurred, the breaker is assumed to have a constant voltage across it, due to the re-established arc across the contacts. The polarity of this constant voltage is opposite to that in the pre-Mayr constant voltage period. The decrease of the rate of change of the arc resistance can be seen in Figure 10 in the case of unsuccessful interruption.

2. The interruption has been successful.

This is indicated by one of two conditions, namely either the arc resistance or its rate of change exceeding a preset value. This value, theoretically infinite, has to be set at a large finite value to prevent numerical overflow in the computer. Once the breaker is deemed to have interrupted the current, the current is set to zero from the next time step onwards, and the normal recovery voltage builds up across the contacts.

3. No change in breaker status.

In this case no decision can be made, based on the criteria described in the paragraphs above, on the outcome of the interruption effort. The program then uses the Mayr equation in the next time step to determine the voltage and current.



Chapter 5. The EMTP Circuit Breaker Model - Validation

5.1: Introduction

Having discussed the practical issues that arose during the implementation of the Mayr model in EMTP, the next logical topic of interest is the validation of the new model. This chapter describes the test circuits used, their simulation and the testing criteria used, and compares the results obtained with EMTP simulation of these circuits to the results presented in the reference [15]. The chapter also contains plots of the variation of arc parameters such as voltage and resistance with time during the simulation.

5.2: Test Circuits and Parameters

Three test circuits were used, all taken from the paper by St-Jean and Wang [15]. These circuits are all "direct" test circuits, in that if the test were to be actually conducted, there would be a large power capacity requirement on the source. The other type of test circuit is the "synthetic" one, where the voltage is applied by one source and the fault current injected by another. This technique demands considerably less power than an equivalent full-power interruption test. The EMTP simulations were conducted for three different direct test circuits. All three test circuits have the same topology, differing only in the values of the circuit elements. Figure 2 shows the basic test circuit configuration, while Figure 3 gives the component values for each circuit.

Each circuit was used to test three different types of breaker, namely air-blast, oil-filled and sulfur-hexafluoride. Parameters for a typical breaker in each class were also taken from [15], and are presented in Figure 4. In all, nine different configurations were tested, resulting from the combination of three circuits and three types of breakers.

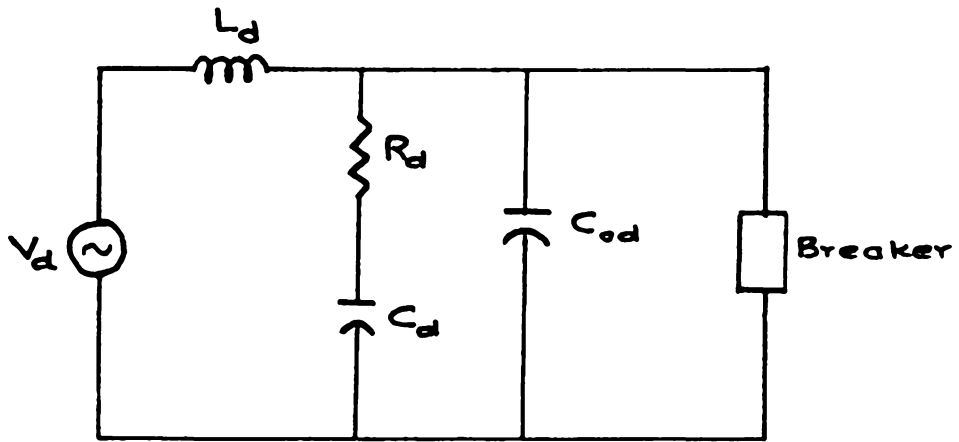


Figure 2. Basic Test Circuit Topology

Circuit Number	R_d (ohms)	L_d (mH)	C_d (nanoFarads)	C_{od}
1	57.38	6.90	1.055	0.0
2	60.34	6.90	1.037	22.56
3	62.77	6.90	1.029	44.26

Figure 3. Test Circuit Component Values

Parameter	Air	Oil	SF_6
A	6×10^{-6}	6×10^{-6}	13×10^{-7}
B	16×10^6	10×10^7	1×10^6
α	- 0.2	- 0.15	- 0.15
β	- 0.5	- 0.60	- 0.28

Figure 4. Breaker Parameters for the Mayr Equation

5.3: Test Criteria

The type of simulation carried out was interruption testing at high fault currents, in order to establish a limit on each breaker. The test was conducted by gradually raising the source voltage V_d in the circuit until at some value $V_d = V_1$, the interruption is a success while at a value $V_d = 1.01 \times V_1$ the interruption fails. The results are presented as the value of V_1 for each breaker-test circuit combination.

Physically, the arc resistance would have to become infinite for the interruption to be a success, and become zero for a failure. Since infinite values would not be feasible in a computer simulation, a different criterion for success was used. It was taken from [15], so that those results and those from EMTP could be compared directly. The criterion is that the interruption succeeds if the arc resistance R exceeds $10^{10} \Omega$ or if $\frac{dR}{dt}$ exceeds $10^{18} \Omega / \text{second}$. In the case of a failure, the $\frac{dR}{dt}$ would become negative and the resistance would decrease. Due to the discrete nature of the simulation and the large numerical values for R and $\frac{dR}{dt}$, it was found that the resistance would become negative very soon after $\frac{dR}{dt}$ became negative. This, apart from being physically absurd, would also cause numerical problems in the program. Therefore failure detection before the occurrence of a negative resistance was necessary. This was done by monitoring $\frac{dR}{dt}$ and deeming the interruption a failure when this starts to decrease. To test this condition, many simulations were carried out, and in no case did the interruption proceed to be successful after a decrease in $\frac{dR}{dt}$.

5.4: Numerical and Graphical Results

In this section the numerical results of the simulations described in the previous sections are listed. They are given in Figures 5, 6 and 7 as the peak value of the a.c voltage V_d in Figure 2, and expressed in a per unit system taken from [15], in which 1 p.u is equal to 106.1445 kV.

As can be observed from these figures, there was excellent agreement between the EMTP simulations and those in [15]. In 8 out of 9 cases, the difference is less than 1.5 %, with the deviation being 2.6 % for the ninth case. This is in spite of the fact that the results in [15] were derived using a variable step-size routine for solving the differential equation more accurately, and that the arc resistance could be directly incorporated into the circuit, eliminating the interfacing problems encountered with EMTP that were described in Chapter Three.

The next set of figures show the variation of arc current, voltage and resistance with time. They are from the EMTP simulations for the air-blast circuit-breaker in test circuit 1. The current and voltage graphs, Figures 8 and 9 are for a case of successful interruption, while the resistance graph, Figure 10 shows two cases, a success and a failure to interrupt.

One variable that is of interest is the duration of the Mayr period, as specified by the user. It must have a certain minimum value in order that the arc resistance have a chance to increase. On the other hand, the longer this period more is the

computation required. The Mayr period must therefore be kept as short as possible. The value finally reached for this interval was 40 microseconds. It was observed that there was practically no influence of variation of this duration on the interruption limit. This is in agreement with the conclusions reached in [15].

Circuit	Reference [15]	EMTP
1	3.55	3.542
2	3.82	3.825
3	4.13	4.145

Figure 5. Results of the Interruption Tests on an Air-Blast Breaker

Circuit	Reference [15]	EMTP
1	5.04	5.040
2	5.27	5.294
3	5.59	5.615

Figure 6. Results of the Interruption Tests on an Oil-Filled Breaker

Circuit	Reference [15]	EMTP
1	5.52	5.445
2	7.35	7.160
3	8.70	8.573

Figure 7. Results of the Tests on a Sulfur Hexafluoride Breaker

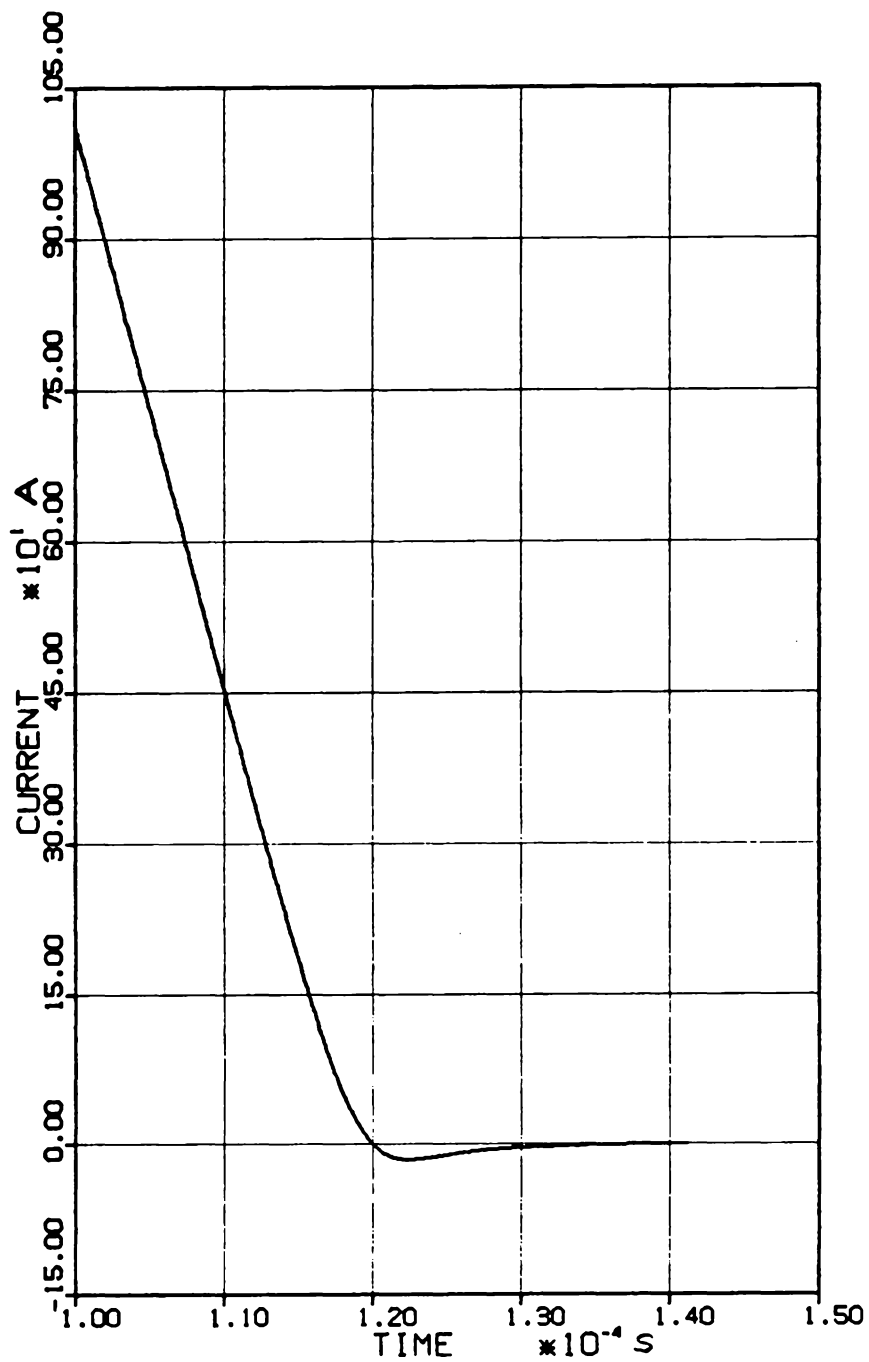


Figure 8. Arc Current Variation with Time

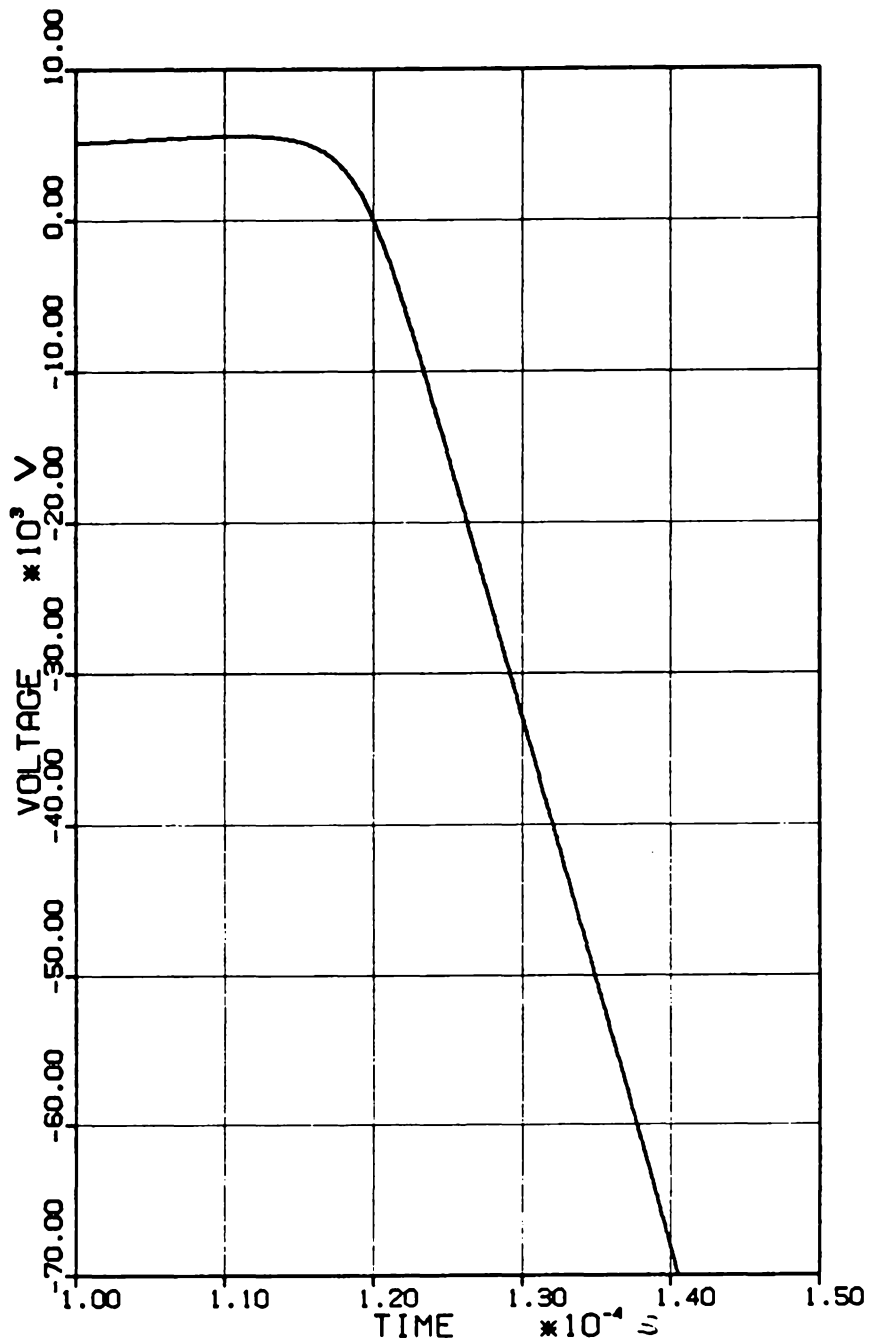


Figure 9. Arc Voltage Variation with Time

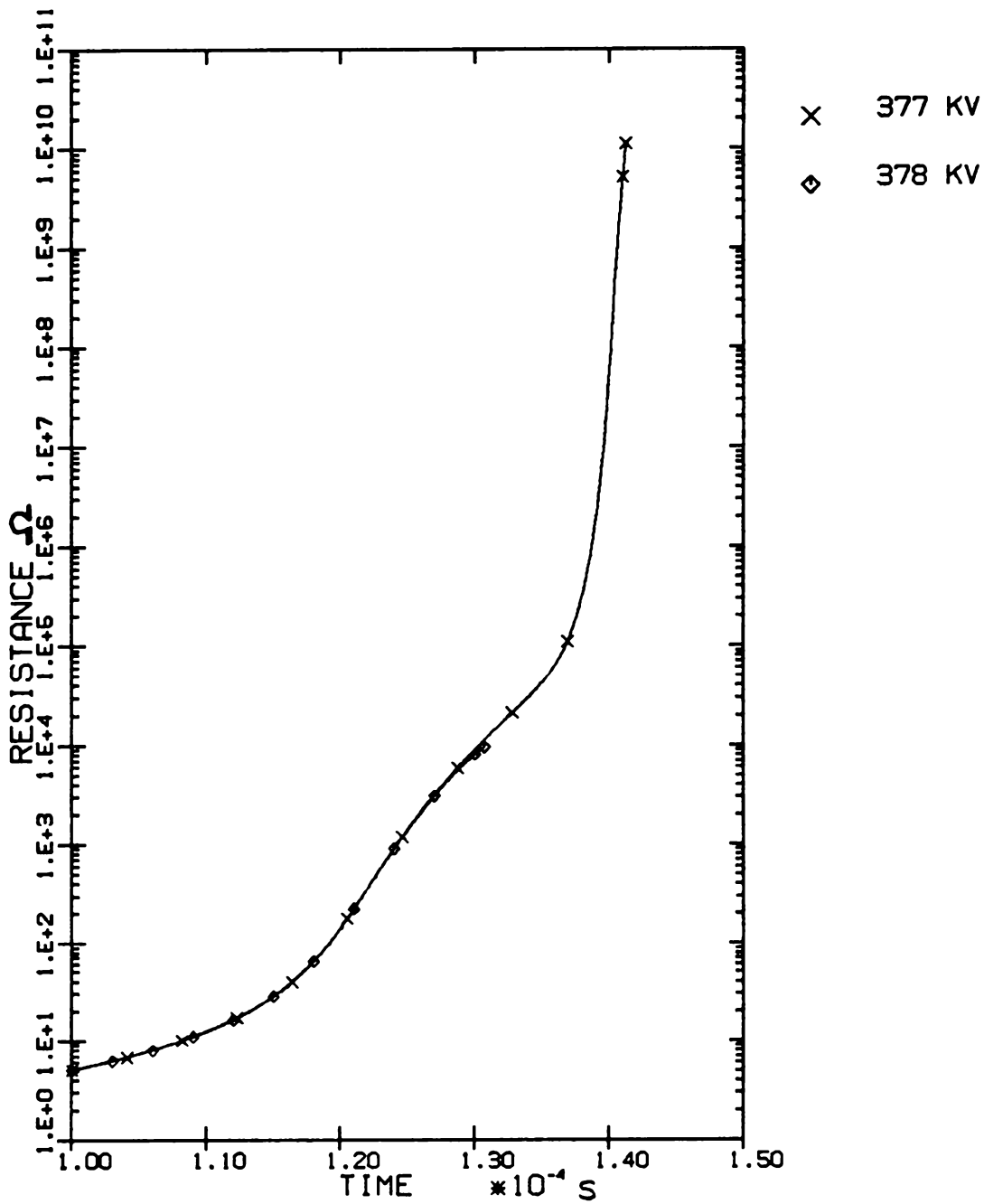


Figure 10. Arc Resistance Variation with Time

Chapter 6. Alternate Breaker Models

6.1: Introduction

Although the modified Mayr equation is a valid and useful model for a circuit breaker, some of the other models reviewed in Chapter Two are also useful in particular contexts. In this chapter, the implementation and testing of two other models is described, and an explanation of their advantages vis-a-vis the Mayr model is given.

6.2: The Urbanek Model

This model has advantages over the Mayr model in two respects, namely, it is capable of representing both thermal and dielectric failures, as well as current

chopping and restriking phenomena, and that it can be expressed in an integral form, thus reducing the possibility of numerical instability. This model also needs 4 parameters to describe the breaker, and these parameters can be obtained by estimation methods from test data [14]. The equation itself is more complex than the Mayr equation, and would therefore use more computer time.

6.3: The Kopplin Model

This model was developed at Siemens, and is popular among European authors. As implemented in EMTP, it is used to represent generator circuit breakers. These are breakers located between the machine and the step-up transformer, and therefore operate at a relatively low voltage, ranging from 11 to 30 kV. They have an extremely high current breaking capacity, in the range of a hundred kilo-amperes. A peculiar problem has been found to occur in practice with these breakers, the "missing" current zeroes. Since the breaker is electrically adjacent to the generator, it interrupts the fault current at the terminals of the machine. This is offset by a d.c component, whose value is dependent on the instant of occurrence of the fault. The nature of the fluxes in a synchronous machine may cause the current zero to be delayed, often by a significant period. The breaker operation must not be affected by this delay, and the simulation of missing zeroes is thus a practical problem. Another complicating factor is the effect of the arc voltage near the current zero. In E.H.V systems, the magnitude of the arc voltage

is not important in comparison to the system voltage, and hence has little influence on the current zero. This is not the case for generator circuit breakers, where the operating voltage is much smaller.

6.4: Implementation and Testing

One of the reasons for implementing the new models, apart from the technical factors described above was to test the generality of the algorithm used to implement the Mayr equation. In particular, the convergence of the iterative procedure used to solve the nonlinear differential equation and the accuracy of the two-step resistance evaluation method was of interest. It was found that the implementation of the two models could be carried out in exactly the same manner as the Mayr equation. The same techniques were used, along with the same convergence criteria, etc and performed well.

The Urbanek model was tested using the three circuits that were used to validate the Mayr model, as described in Figure 3. The source voltage in each circuit is raised gradually, until a value is reached where the interruption is successful and it fails at a voltage 1 % higher. This is the interruption limit shown in Figure 12, and is expressed in a per unit system, with 1 p.u = 106.14 kV peak. The results obtained with EMTP are compared with those in the paper by St-Jean and Wang [15] from which the breaker parameters are taken.

The Kopplin model was tested in a somewhat different manner, with the model parameters being varied and the test circuit voltage kept constant. This is the procedure used in [12], from which the model data and the test circuit configuration are taken. The tests were carried out by keeping the value of K_p at 4 MW and varying the value of K_r to find its critical value. The results are expressed in terms of the value of K_r for which the breaker is able to interrupt the fault current with a source voltage of 29.4 kV. The circuit was similar to the test circuit used in the previous tests, with the source voltage value as above. The constant arc voltage was chosen to be 100 Volts, a low value being used due to the decreased system voltage. There was an external resistance in parallel with the main arcing chamber; this serves to reduce the recovery voltage across the breaker contacts after interruption. The circuit is shown in Figure 11.

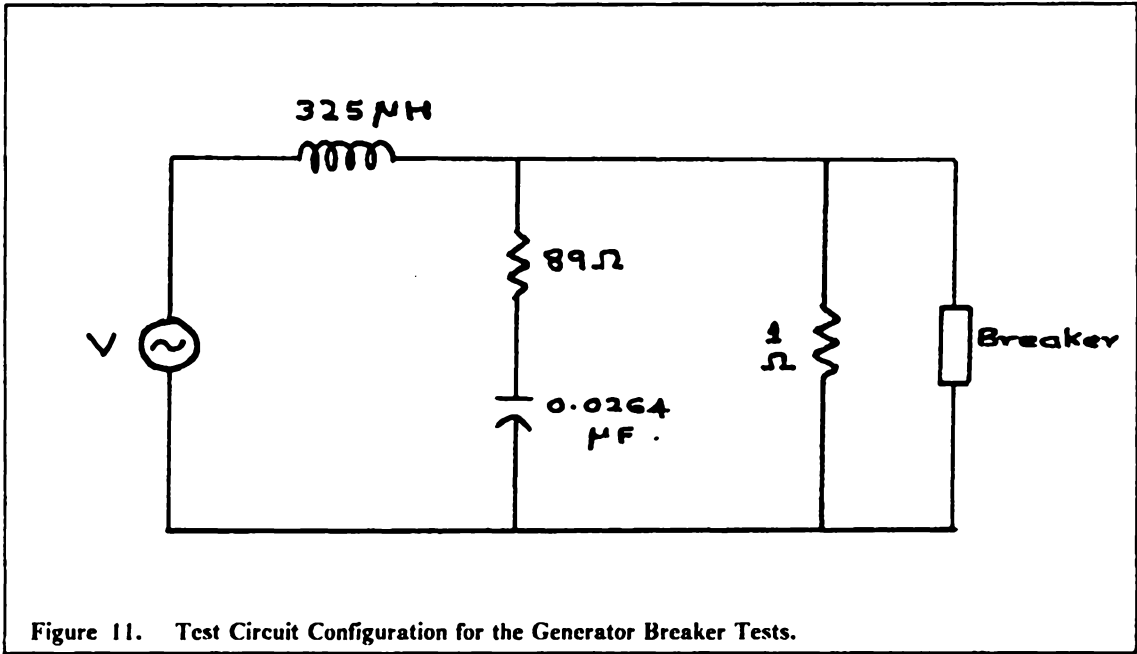


Figure 11. Test Circuit Configuration for the Generator Breaker Tests.

Circuit	Reference [15]	EMTP
1	2.79	2.779
2	3.24	3.101
3	3.61	3.495

Figure 12. Results of the Interruption Tests with the Urbanek Equation

K_t (microseconds)	Reference [15]	EMTP
13	Success	Success
15	Success	Success
17	Success	Success
18	Failure	Failure

Figure 13. Results of the Interruption Tests with the Kopplin Equation

Chapter 7. Circuit Breaker Parameter Estimation

7.1: Introduction

Having implemented a model for the circuit breaker in EMTP, it must now be ensured that the model can be used with as much ease as possible. The main problem likely to be faced by potential users is the lack of data on the circuit breaker itself. Breaker design has always been an empirical process, and in the absence of a definitive equation for the electrical performance of a breaker, there are no standard parameters specified by the manufacturers to predict the electrical performance analytically.

It was felt therefore that in order to make the model more useful, an auxiliary program should be provided to evaluate the parameters required by the EMTP model from breaker test data. This chapter describes the method used for this

purpose, the type of experimental data required and the testing that was performed to verify the validity of the estimated parameters.

7.2: Problem Formulation and Solution Methodology

Since the main breaker model implemented in EMTP is based on the modified Mayr equation, the estimation program was designed to evaluate the parameters required for this model. From the description in Chapter Four, it can be seen that five parameters are needed, namely the constant voltage before the unclogging of the nozzle and the values of the four parameters A, B, α and β in the Mayr equation.

$$\frac{dr}{dt} = \frac{r^{1-\alpha}}{A} - v \times i \times \frac{r^{1-\alpha-\beta}}{A \times B} \quad [7.1]$$

The constant voltage can be chosen directly from the oscillogram of the arc voltage, and hence the program objective is to evaluate the parameters A, B, α and β from the data supplied. The first step was a least-squares polynomial fitting algorithm to obtain an analytical expression for $r(t)$, the arc resistance. This polynomial is then differentiated, and the derivative evaluated at all the sample points. The next stage is to choose the parameters of the Mayr equation optimally, so that the values of the derivative from the polynomial and the Mayr

equation agree as closely as possible. This is done using a nonlinear least-squares estimation technique.

7.3: Detailed Description of the Algorithm

Assuming that the input consists of N simultaneous samples of the arc voltage and current, we can directly calculate N values of the arc resistance. This set of points is used as input to a variable-order least-squares polynomial fitting program. The fitting algorithm tries various degrees for the polynomial depending on the value of N and the accuracy of the fit, before choosing the final degree. The initial guess for the degree of the polynomial is taken as $\frac{N}{2}$ approximately. Having evaluated the optimal polynomial, its derivative can also be calculated directly.

The problem then reduces to that of finding values of the set X consisting of A , B , α and β such that the function $D(t,X)$, the time derivative of resistance obtained from the Mayr equation evaluated at the sample points and the derivatives $d(t)$ derived from the polynomial fitted to the test data agree as closely as possible. This is a standard nonlinear estimation problem, which can be solved by an iterative procedure.

Let the initial guess for the parameters be denoted by the set X_0 and let ΔY be the vector of the difference between $d(t)$ and $D(t,X)$ at each of the sample points. Then, the correction to the guess for X , ΔX is :

$$\Delta X = (H^t H)^{-1} H^t \Delta Y \quad [7.2]$$

where H is the Jacobian matrix, consisting of the partial derivatives of $D(t,X)$ with respect to each member of the set X at each of the sample points. Since there are four parameters that make up X , the matrix H will have four rows and N columns, where N is the number of samples. The new estimate for X is then $X_0 + \Delta X$. At this stage the estimate just obtained is checked to see if it is an adequate fit, by calculating the new residual vector ΔY and evaluating its norm. If this is less than a pre-specified tolerance, the estimation is deemed to be over. Otherwise the new Jacobian is formed, and a correction to the most recent estimate calculated. The entire process continues until convergence is reached.

The procedure just outlined appears to be a straight-forward one, where a reasonable answer can always be expected. In practice however, quite a few problems and issues exist, and these are described in the next few sections.

7.4: Voltage and Current Sampling

The whole process is based on the samples from the breaker test, and hence these are crucial to the success of the estimator. Since the arc is to be fitted approximately by the Mayr equation, the samples must be chosen from an interval in which the Mayr equation is valid. It is known from experimental evidence that the Mayr equation can only be used from about 50-100 microseconds before the current zero. Therefore the samples should be chosen fairly close to the current zero, in order to be certain of their validity. If the samples are taken too far before the current zero, the rate of change of resistance in the sampled period will be relatively small, and therefore the order of the polynomial used to fit the curve will also be low. In such a case there is a danger of a loss of accuracy due to the lack of a sufficient number of terms in the derivative calculation. If a higher order fit is forced through these points, in order to retain accuracy, the derivative will be inherently flawed, and the estimation will most probably converge to erroneous values, or will fail to converge at all.

On the other hand, if the samples are taken well after the current zero, that is, in the period of maximum rate of change of the arc resistance, other problems are likely to be encountered. Due to the large values that will occur in the Jacobian and in the polynomial evaluation, numerical problems are quite probable. Numerical overflow is likely during the fitting process, and there may be difficulty in inversion of the matrix term in the iteration procedure.

Based on the two factors discussed above, a general rule has been formulated, that is, the samples should be taken so that about 70 % of them are from the pre-current zero period, and the rest from after the current zero. The samples must be spaced at a regular interval, which should be fairly small, in the order of a half of a microsecond.

7.5: Number of Samples

This is another crucial choice which has a bearing on the accuracy of the estimated parameters. From an instrumentation viewpoint, one would desire that there be as few samples as possible, while retaining a valid estimate. The same objective is desirable from a computational standpoint, since a larger number of samples implies a higher degree polynomial fit, and also greater dimensions of the matrices in the estimation algorithm. However a sufficiently large number should be taken so that the samples represent adequately the actual behavior of the arc.

Trials were carried out with various values for N , the number of samples. It was found that at least 10 samples, spaced at intervals of a microsecond would be needed to provide a reasonably usable estimate. This was increased to 30 points at a spacing of half a microsecond, yielding much better estimates; at this stage, it was felt that a reasonable balance had been achieved between the two con-

flicting priorities of accuracy (demanding more data) and speed (demanding less data).

7.6 Implementation

At present, since there are no readily available records of circuit breaker tests, some improvisation was done to obtain input data for the estimation program. The breaker simulation program was run with the parameters specified in the testing and validation procedures of the model, as given in Chapters Five and Six. The outputs from these simulations were used as input to the estimator, as "pseudo- measurements". This, though a very convenient alternative in the absence of actual experimental data, is not totally realistic, for the reasons explained next.

Effectively, since computed results are being used, the assumption is being made that there is no measurement error at all. This is not true, especially since the measurements will be taken in the electrically harsh environment of a high power switchyard. To test the algorithm for its sensitivity to noise distortion of the data, a random number generation program was used to add noise to the samples. Tests were conducted with different levels of maximum distortion, but it was found that the estimator is sensitive to the noise, and the estimates would be very poor for noise amplitudes of more than 1 % of the data sample. Hence filtering

of the input data would be necessary if it were suspected that the measurements are noisy. A more detailed description of the filtering technique is given in the next section.

Another characteristic of the computed results is their smooth nature. The current decreases monotonically in both experimental and computed cases, but the arc voltage measured often contains a lot of spikes and irregularities which are not present in the case of the computed results. If the samples also contained these spikes, the effect on the polynomial fitting algorithm could be very severe. This would be especially true if the algorithm kept trying to increase the order of the polynomial, in a futile attempt to follow the input. To prevent this from happening, an upper limit on the order of the polynomial has been built into the program; the value of the limit being related to the number of samples in the input. In order to completely alleviate this problem, the samples would have to be filtered before being input to the fitting routine. The current could be filtered by a predictor based on the average slope of the current, which would correct any deviations. This would be a valid process only in the pre-current zero period, since the slope of the current changes dramatically after the zero. The voltage data presents more problems, since there is no simple predictor available. Work on both these issues is going on, but at this stage, without access to actual data, the filtering algorithms have not been tested fully.

7.7 Validation of the Parameters Estimated

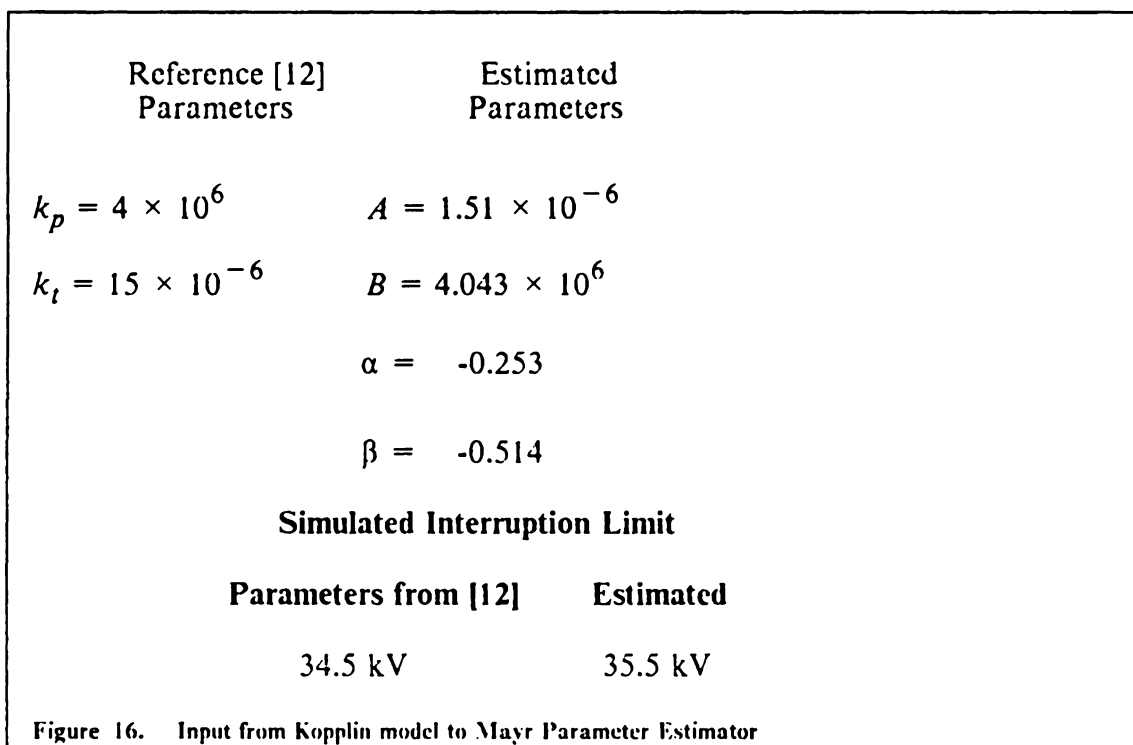
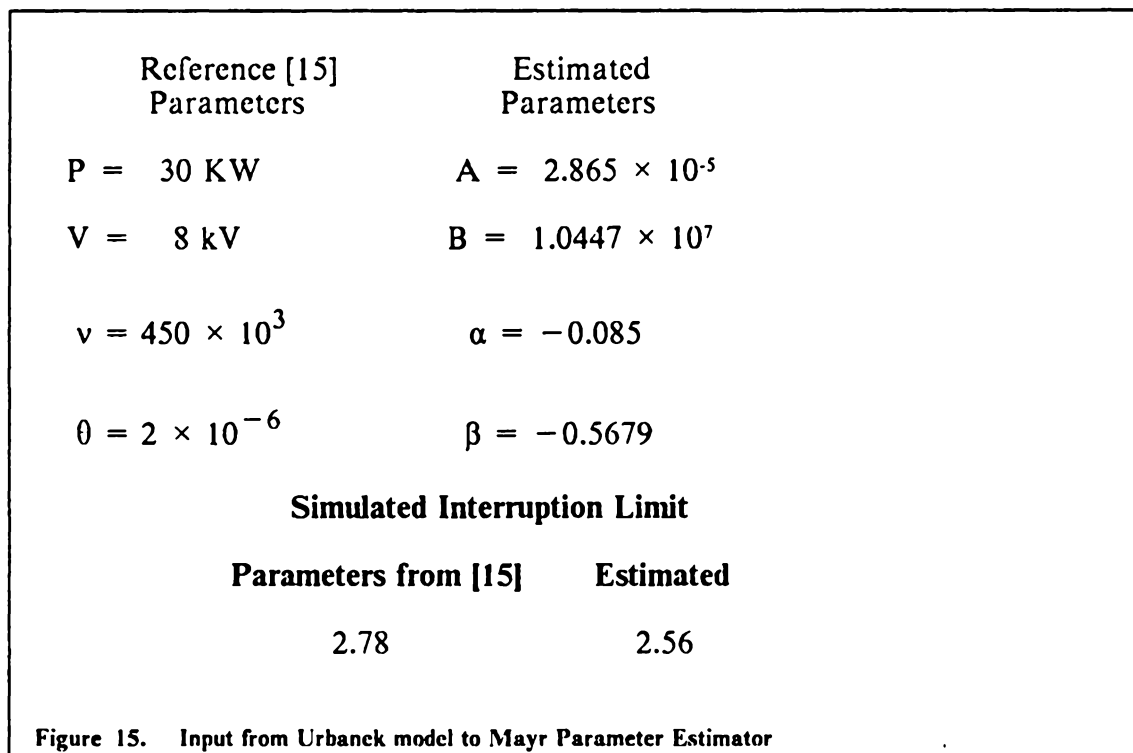
Two different techniques were used to evaluate the performance of the estimation algorithm. Both methods rely on a comparison between the interruption limits obtained with the actual parameters and those obtained with the estimated parameters. The difference between the methods lies in the data input to each of them. In one case the input to the estimator is the output of a simulation carried out with the Mayr equation used as the governing equation for the arc. Since the estimator produces parameters for this model, its output can be used directly in the simulation to calculate the interruption limit.

The other case is a much more interesting one, in which the concept of an equivalent model is used. Assuming that the simulation is carried out using either the Urbanek or the Kopplin equation, an equivalent set of parameters for the Mayr model can be obtained by using the output of the simulations as input to the estimator. In this case, to verify the validity of the estimate, the interruption limit from the original simulations with the Urbanek or Kopplin model is compared to that obtained from simulations using the Mayr equation. The parameters for the Mayr model are the output of the estimator when its input was the results from the original model. In this way, an equivalent Mayr model can be fitted to the Urbanek and Kopplin models. In the following section results are presented for three types of estimation results, namely input from the Mayr model, the Urbanek model and the Kopplin model.

7.8 Numerical Results

	Reference [15] Parameters	Estimated Parameters
A =	6×10^{-6}	6.046×10^{-6}
B =	1.6×10^7	2.098×10^7
α =	-0.2	-0.19527
β =	-0.5	-0.5255
Simulated Interruption Limit		
	Parameters from [15]	Estimated
	3.55	3.69

Figure 14. Input from Mayr model to Mayr Parameter Estimator



As can be seen from the above figures, the estimation program produces parameters that cause interruption limits to vary by less than 8 %, even in the case of the equivalent model fitting simulations.

Chapter 8. Conclusions

8.1: Introduction

This chapter concludes the thesis, and consists of a brief review of the work described more fully in the thesis, and a survey of possible future applications of the work and the modifications that will be required for such usage.

8.2: Review of the Thesis

Three different validated models for the circuit breaker arc were implemented in the Electromagnetic Transients Program (EMTP). These models were chosen after a review of available models, and allow the user to simulate interruption failure in both the thermal and dielectric regimes. The default options provided

with the program give the user data for air-blast, oil-filled, sulfur-hexafluoride and generator circuit breakers. Computer simulation of test cases from published literature was performed, and the results compared with the original ones. There was excellent agreement between the EMTP simulations and the benchmark cases. A routine was written to estimate the breaker parameters needed for EMTP usage of the Mayr model from experimental circuit breaker interruption test oscillograms. The algorithm was tested using the output of EMTP simulations, and performed very well. Guidelines are provided in the thesis for the best choice of input data to the estimation program.

8.3: Future Applications and Research

As this was the first research project aimed at implementing a circuit breaker model in EMTP, a variety of improvements and features are yet to be added. For example, the capability of simulating current chopping and dielectric restriking is yet to be tested due to a lack of test cases. There is a possibility of numerical instability in such situations, and modifications to the algorithm may be necessary to surmount this difficulty. The estimation routine has to be interfaced with EMTP, and its operation fully automated. More extensive testing of the estimation algorithm is needed, especially with actual test data. The filtering techniques in the program at present will have to be enhanced to handle the spiky nature of measured samples with noise.

Simulation of multi-step resistance and capacitance switching in parallel with the breaker may be useful for users to improve the interruption performance of their breakers by damping the Transient Recovery Voltage (TRV). Such a simulation would not be possible with existing EMTP components, and the switching devices would have to be incorporated into the breaker model. With the implementation of the Kopplin model for generator circuit breakers, investigations into the possibility of " missing " current zeroes due to the effect of the synchronous machine fluxes and the transient fault current offset are of interest, especially considering the effect of the arc voltage in the pre-Mayr period. The program will have to be changed to accommodate the delayed current zeroes, and this may require changes in the basic modeling of the breaker for better utilization of computer time.

Another likely extension of the algorithm would be directed towards the modeling of a H.V.D.C circuit breaker. Preliminary designs for such a device have appeared, and they are expected to be used in multi-terminal networks. These pose a special modeling problem, since there is no inherent instant of expected current zero, nor is there the linear decay of the current towards the zero, which enabled the implementation of a relatively simple iterative algorithm for the solution of the nonlinear equation in the work reported here.

Finally, enhancement of the existing algorithm is always possible. Areas in which this is likely are the convergence properties of the iteration scheme, and increasing the minimum time-step size needed for adequate modeling of the arc. At present

this is about 0.1 microsecond, and an increase in this would save considerable computer time and make the routine more efficient.

References.

1. Cassie, A.M.,“Arc Rupture and Circuit Severity” ; *CIGRE Report 102*, Paris, 1939.
2. Cassie, A.M.,“Post-Arc Conductivity in Gas-Blast Circuit Breakers” ; *CIGRE Report 103*, Paris, 1956.
3. Mayr, O.,“Beitrage sur Theorie des Statischen und des Dynamischen Lichtbogens” ; *Archiv fur Electrotechnik,Berlin*, Vol.37, 1943, pp.588-608.
4. Rieder, W. and Urbanek, J.,“New Aspects of Current-zero Research on Circuit-Breaker Re-ignition” ; *CIGRE Report 107*, Paris, 1966.
5. Urbanek, J.,“The Time Constants of High Voltage Circuit Breakers before Current Zero” ; *Proceedings of the IEEE*, Volume 59, April 1971, pp. 502-508.
6. Browne, T.E.,“Practical Modeling of the Circuit Breaker Arc as a Short-Line Fault Interrupter” ; *IEEE Transactions on Power Apparatus and Systems*, March/April 1978, pp. 838-847.
7. Browne,T.E,(editor).*Circuit Interruption - Theory and Techniques* , Marcel Dekker, 1984.
8. Frost, L.S.,“Dynamic Analysis of Short-Line Fault Tests for Accurate Circuit Breaker Performance Specification” ; *IEEE Transactions on Power Apparatus and Systems*, March/April 1978, pp. 478-484.

9. Habedank, U. and Kugler, R., "Theoretical and Experimental Studies of the Critical Line Length for the Interruption of Short-Line Faults" ; *IEEE Transactions on Power Apparatus and Systems*, July 1981, pp. 3545-3552.
10. Smith, R.K. and Colclaser, R.G., "A Modified Cybernetic Arc Model Capable of Describing the Energy Balance in a Power Circuit Breaker" ; *IEEE Power Engineering Society Summer Power Meeting, 1976*, Paper No. 76 SPM A76 308-7.
11. Gardner, G.E and Urwin, R.J., "Arc Instability and Current Chopping in an Air-Blast Interrupter" ; *Proceedings of the IEE*, July 1977, pp. 619-627.
12. Thuries, E., Van Doan, P., Dayet, J. and Joyeux-Bouillon, B., "Synthetic Testing Method for Generator Circuit Breakers" ; *IEEE Transactions on Power Delivery*, January 1986, pp. 179-184.
13. Kopplin, W., "Mathematische Modelle des Schaltlichtbogens" ; *ETZ-A.2* 1980, pp. 209-213.
14. Blahous, L., "Derivation of Circuit Breaker Parameters by Means of Gaussian Approximation" ; *IEEE Transactions on Power Apparatus and Systems*, December 1982, pp. 4611-4616.
15. St-Jean, G. and Wang, R.F., "Equivalence between Direct and Synthetic Interruption Tests on High Voltage Circuit Breakers" ; *IEEE Transactions on Power Apparatus and Systems*, July/August 1983, pp. 2216-2223.
16. Lee, T.H., *Physics and Engineering of High Power Switching Devices*, MIT Press, 1975.
17. Flurscheim, C.H. (editor), *Power Circuit Breaker Theory and Design*, Peter Peregrinus, 2nd edition, 1982.
18. Ragaller, K. (editor), *Current Interruption in High Voltage Networks*, Plenum Press for Brown Boveri and Co., 1978.
19. Dommel, H.W., "Digital Computer Solution of Electromagnetic Transients in Single- and Multiphase Networks" ; *IEEE Transactions on Power Apparatus and Systems*, April 1969, pp. 388-399.
20. Tinney, W.F. and Walker, J.W., "Direct Solution of Sparse Network Equations by Optimally Ordered Triangular Factorization" ; *Proceedings of the IEEE*, November 1967, pp. 1801-1809.

21. Dommel, H.W., "Nonlinear and Time-Varying Elements in Digital Simulation of Electromagnetic Transients" ; *IEEE Transactions on Power Apparatus and Systems*, November/December 1971, pp. 2561-2567.
22. Tinney, W.F., "Compensation Methods for Network Solutions by Optimally Ordered Triangular Factorization" ; *Proceedings of the Power Industry Computer Applications Conference (PICA)*, 1971, pp. 377-382.

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