Numerical Arc Model Parameter Extraction for SF$_6$ Circuit Breaker Simulations

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Abstract – **In recent years some work has been conducted in the area of circuit breakers modeling in order to improve the capability of high voltage circuit breakers through simulations. Most of the research has been concentrated in describing the circuit breaker behavior by mathematical modeling, as well as numerical modeling of the pre or post current zero periods. The fundamental problem when trying to implement the existing models is to obtain reliable values of the unknown parameters of the mathematical model. Through this work a modified Cassie-Mayr model has been implemented in both EMTP (Electro-Magnetics Transients Program) and MATLAB. The EMTP simulation produces current and voltage oscillograms that are then supplied to the optimization routine in MATLAB for evaluation and validation of the parameter extraction procedure. The modified Cassie-Mayr model has proved to be a reliable tool for the study of arc interruption of high-pressure gas circuit breakers because it takes into account pre and post current-zero conditions. The Cassie-Mayr model has four constant parameters, which changes according to the device (interrupter) and external circuit conditions.**

This work aims to develop a better parameter extraction routine, which is based on the MATLAB optimization function of nonlinear least squares. In this work we present the results of the parameter extraction routine developed to determine the four parameters from voltage and current oscillograms of tested and/or simulated devices.

Keywords – parameter extraction, circuit breakers, arc model, modified Cassie-Mayr equations, nonlinear least squares

I. INTRODUCTION

Reliable accomplishment of circuit breaker duties relies on good electrical as well as mechanical design to ensure that the circuit breaker can satisfy the electrical stresses imposed on it. The electrical stresses are determined by the power network and the arc-quenching medium [1]. For this reason and due to the continue expansion of the power systems capacities, the research and development of circuit breakers during the past decades has led to the better understanding of the basic principles which has allowed circuit breakers to meet systems requirements [2-6].

Most of the research and development efforts have been directed to the use of computer methods for the evaluation and design of circuit breakers, leading to the creation and use of arc models to describe the circuit breaker behavior and interaction with the electrical network [2-6]. The use of computer methods is the most affordable approach to study circuit breakers, reducing the cost and space needed when realizing synthetic test circuits.

Nowadays the fundamental problem when trying to implement the existing mathematical arc models is to obtain reliable values of the unknown parameters from test oscillograms. This is because every researcher creates a parameter extraction routine, which only helps to describe the specific circuit breaker they are studying. There is a need to develop a general tool to solve this problem. Our interest is to develop a general, effective and easy to use tool to extract the parameters needed by most used models for circuit breakers simulation. So, the characterization of the circuit breakers by digital simulation could be done in agreement with the physical behavior of the system.

The main objective of this work is to present a parameter extraction routine based on the MATLAB built-in function of Nonlinear Least Squares, which can be used to extract the parameters from most used arc model in SF$_6$ circuit breaker simulations. The parameter extraction routine objective is to give the researchers, power utilities and circuit breakers manufacturers the opportunity to study the behavior of any SF$_6$ circuit breaker.

This paper is organized as follow: Section II and III introduce the simulation technique and the model used in the simulation of SF$_6$ circuit breakers. Section IV describe the process of obtaining the model parameters and present some results. Finally, Section V provides comments and conclusions of our work.

II. SIMULATION TECHNIQUE

The electric arc has been simulated in ATP version of EMTP as a "black-box" model. The arc was represented as a "black-box" model since it is based on observed data. Model structure and parameters are determine from experimental modeling and little previous knowledge is exploited [7].

The external electrical circuit sees the arc as an equivalent electrical resistance that changes with time and other

physical variables. The process of incorporating electric arc models in circuit breakers simulations involves the following procedure [5,8]:

Choose an arc model: The arc model is described by differential equations, which relate the rate of change of the conductance with the arc current and voltage.

Test Oscillograms: Voltage and current oscillograms must be obtained from field or laboratory tests on circuit breakers. These oscillograms are descriptive of the behavior of the arc during the interruption process.

Arc parameters evaluation: To improve the quality of the arc representation it is common to introduce a number of additional parameters, which has to be determined.

Numerical Simulations: After all the above steps are completed we can proceed to reproduce the entire process of arc interruption in the circuit breaker and study its behavior under different circuit conditions.

III. SF$_6$ Arc Model

SF$_6$ is commonly used as an extinction medium in circuit breakers for high, extra and ultrahigh voltage. SF$_6$ has great insulating and extinction characteristics. Its characteristics are quite unusual compared with the arc plasma of other gases. Its extinction ability is significant and its speed to change from conductive arc into an insulating material is very high. The arc model used to represent the SF$_6$ arc in this research is the modified Cassie-Mayr equation, which is a combination of the principles stated by Cassie's and Mayr's on their respective models. The modified Cassie-Mayr model represents the conductance nonlinear behavior of the arc and states the following,

$$\frac{1}{g}\frac{dg}{dt}=\frac{1}{t}\left(\frac{ui}{P}-1\right)=\frac{1}{t_0 g^b}\left(\frac{ui}{P_0 g^a}-1\right) \qquad (1)$$

where,
g is the conductance of the arc, in Siemens.
u is the voltage drop across the arc, in Volts.
i is the current through the arc, in Amperes.
t is the time constant of the arc, in seconds.
P is the power dissipated from the arc to the surrounding gas, in Watts.
a is the parameter that influences the conductance dependency of P.
β is the parameter that influences the conductance dependency of t.
Both a and β are experimental constant parameters.

IV. Parameter Fitting

The four parameters of the Modified Cassie-Mayr model presented in Table 1 change according to the device and the circuit conditions. The parameters must be determined

for validation of the arc model. A program based on the MATLAB optimization function of nonlinear least squares was designed to extract the parameters from voltage and current test oscillograms. The procedure followed was similar to the one presented by Glinkowski et al. in [5] and Orama in [6], the main difference is that they used the MATLAB *fmins* function. A general diagram describing the optimization routine is shown in Figure 1.

Table 1 – Arc model parameters of the SF$_6$ circuit breaker [5]

Parameter	Value
P_0	2.0 MW
t_0	11.2μs
α	0.59
β	0.523

A. Parameter Extraction Routine

A brief description of the program logic written in MATLAB follows.

1. The initial guess is provided for the four parameters. It is not obligatory for the user to input the initial guess, the program has a default initial guess for all the parameters (lower value encounter by the authors in the literature and experience).

2. The oscillograms are imported from the test data. In the case of the oscillograms having to much noise they are filtered assuming the noise is a white noise.

3. Conductance and its rate of change are calculated. The program calculate the conductance and its derivative from the tests oscillograms.

4. The modified Cassie-Mayr equation is rearrange to make it analogous to a system identification problem of linear and nonlinear parameter estimation.

5. Linear/Nonlinear Optimization is performed using MATLAB and its Nonlinear Least Squares built-in function. The process iterates trying to find a global minimum.

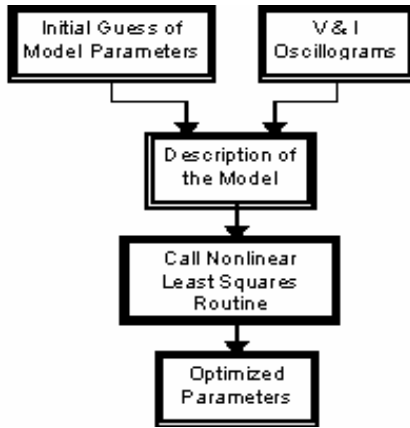6. The optimized parameters of the modified Cassie-Mayr equation are extracted.

Figure 1 – General Diagram of the Optimization Routine

B. Parameter Fitting Results

Simulated oscillograms of voltage and current across the circuit breaker were used to evaluate the performance of our parameter fitting routine; since we know these exact parameters used to simulate the circuit breaker behavior and a comparison can be performed. The test circuit simulated to extract the oscillograms was the one presented in figure 2. The circuit parameters were,

$Esys$ =245 kV
Rs = 0.105 Ohms
Ls =13.0 mH
Cb =6.0 nF
Rd =450 Ohms
$$\frac{di}{dt} = 18.85 \text{ A/µs}$$

The arc model parameters used for the simulation are presented in Table 1, this parameters are adopted from [5].
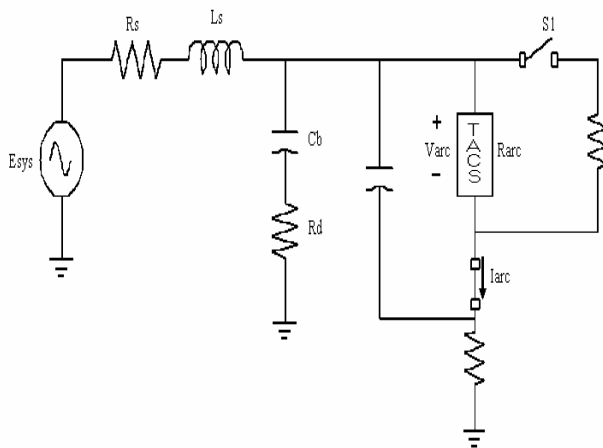

Figure 2 – Test circuit diagram for the simulation of a breaker terminal fault in EMTP.

The best fit parameters at this moment are presented in Table 2. The simulations results with these fitted parameters are compare with the test oscillograms (simulated) in figures 4 and 5. From those figures we can observe how the current and voltage curves of the simulation with the fitted parameters are well approximated to the oscillograms of the test circuit. The results are interesting since the resulting parameters were not exact to the value used to generate the oscillograms. Figure 6 presents the error percentage varying with time, where we can observe how well the optimization routine performed. The performance of this routine seems as a good start in our search for a general parameter optimization tool for arc modeling in circuit breakers simulations.

Table 2 – Estimated parameters from test oscillograms in Figure2 using a modified version of the MATLAB built-in function *lsqnonlin*.

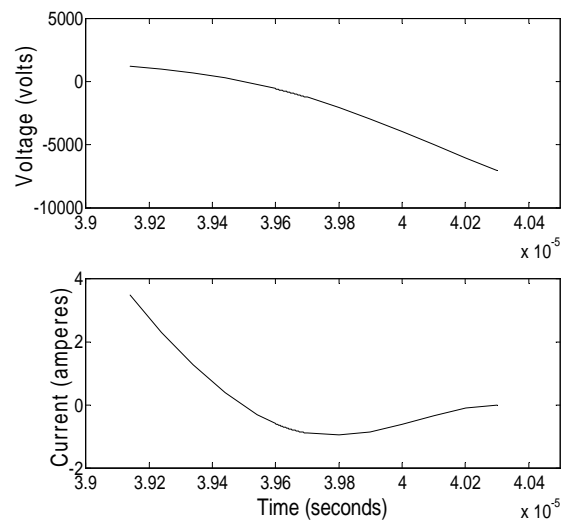| Parameter	Value
P_0	1.8803 MW
t_0	10.933µs
α	0.5713
β	0.51955

Figure 3 – Oscillograms obtained from the circuit in fig.2. Oscillograms represent the post-arc period of current interruption (post-arc current and transient recovery voltage).
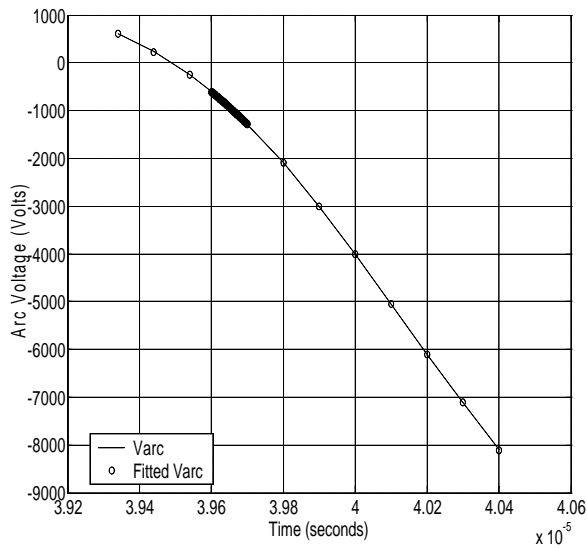
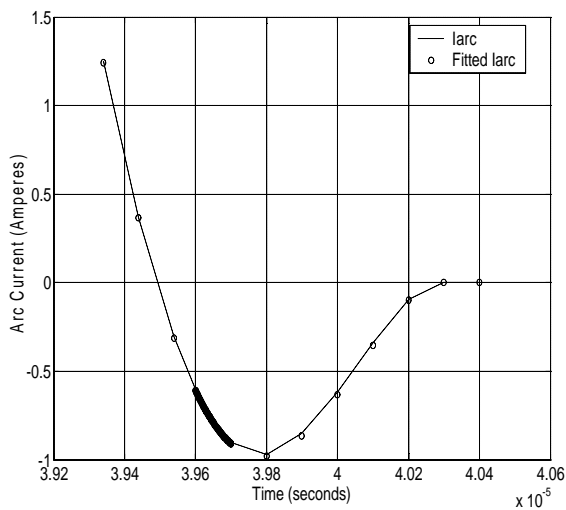Figure 4 – Arc voltage of the simulated circuit with the actual and fitted parameters.

Figure 5 – Arc current of the simulated circuit with the actual and fitted parameters.
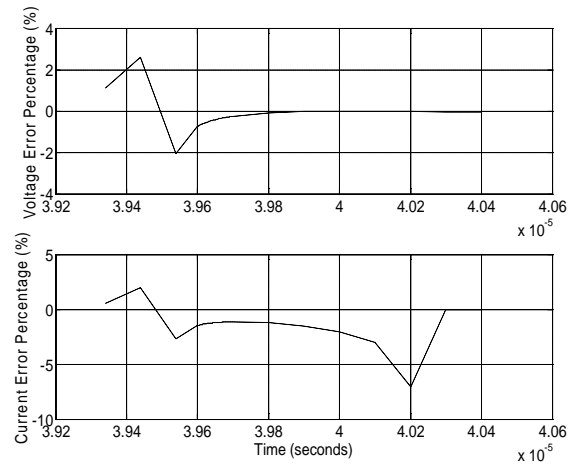

Figure 6 – Voltage and current error percentage between the simulation (fitted parameters) and the oscillograms with actual parameters.

The selection of a correct time window is important when using our fitting routine, in the case presented above and most of the cases a suitable time window for the analysis is just before current zero to a few microseconds after. This can be explain since for an SF_6 circuit breaker the TRV starts to develop when the current reach zero and the Modified Cassie-Mayr model intend to describe this post-arc region. Our parameters initial guess were based on values encounter by the authors in the literature and experience.

A sensitivity analysis should be perform to investigate how sensitive is the implemented model to changes in the parameters. This would influence the time spent obtaining good parameters estimates. Also, this would also help us in the search of general parameter extraction tool and consequently improve circuit breaker simulations prediction capabilities.

From the general parameter extraction tool point of view, the nonlinear least squares routine will not accomplish the work by it self. An intelligent optimization technique should be implemented to serve as a starting point for the parameters optimization routine eliminating the need of good initial parameters guess. Then when the optimization process reach some desired level, the routine may change to the nonlinear least square technique to conclude the parameters optimization.

The methodology developed by the current research and the expected future work will then be applied to the Continuous Transition Model of the post arc plasma in Vacuum interrupters.

V. CONCLUSIONS

Through this work a modified Cassie-Mayr model was been implemented as a "black-box" model in EMTP. The EMTP simulation produced current and voltage oscillograms that were then supplied to a nonlinear least squares optimization routine in MATLAB for evaluation and validation of the parameter extraction procedure.

The nonlinear least square optimization routine resulted in a good curve fitting routine. The parameter extracted didn't match perfectly the values used to generate the oscillograms, however the algorithm still found values close enough to describe the simulated oscillograms almost perfectly.

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Bienvenido Rodríguez Medina received his B.Sc. degree from the University of Puerto Rico-Mayagüez in 2001. He is currently working towards his M.Sc. in Electrical Engineering. His current research is in vacuum and high-pressure gasses arc models parameters extraction and sensitivity analysis. His others interests include electrical discharges and plasma, vacuum and SF_6 switchgear, electric transients in power systems, power quality and alternate energy sources.