THE NEW EMTP BREAKER ARC MODEL

Jean Mahseredjian and Michel Landry
Institut de Recherche d'Hydro-Québec (IREQ)
1800 boul. Lionel-Boulet
Varennes, Québec, Canada J3X 1S1

Bahram Khodabakhchian
Hydro-Québec/System Planning
855 Ste-Catherine East, 18th floor
Montréal, Québec, Canada H2L 4P5

ABSTRACT:
The most simple breaker model used in transient analysis studies is an ideal switch. Such a model can be acceptably used for transient recovery voltage studies, but fails to recognize the interaction between the breaker arc and the surrounding electrical network. A detailed arc model is required to evaluate the interrupting capacity of a breaker and its influence on the current waveform. This paper presents the implementation of a detailed arc model in the EMTP.
Keywords: Transients, arc model, modeling techniques, nonlinear functions, EMTP

1. INTRODUCTION

The usual breaker model used in transient analysis is an ideal switch which is allowed to open at current crossing zero and may include a current margin parameter used for an approximate representation of possible current chopping. Such a model is applicable in studies where the interaction between the breaker arc and the surrounding network can be neglected. In other studies, where it is needed to evaluate the interrupting capacity of a breaker and its influence on the interrupted current, a detailed arc model must be used. A typical case which illustrates the crucial importance of arc modeling, is shown in Fig. 1. This test case is taken from a Hydro-Québec 735 kV series-compensated network study. The short-circuit current I_{SC} is a line breaker current for a fault applied near a capacitor bank at the remote end of the line. It appears that a sufficiently high arc voltage can force the interrupted current to cross zero earlier than with an ideal switch model. With the ideal switch model the current crosses zero after 113 ms compared to only 63 ms when the air-blast breaker arc model is used. The registered arcing time is of crucial importance for assessing the arc quenching capability of a given breaker type.

A previous paper [1] has presented the practical aspects of experimental and numerical studies undertaken at Hydro-Québec to warrant the breaking ability of in service air-blast breakers and to correctly specify the performance requirements of modern technology SF_6 breakers. The numerical studies in [1] were based on a new arc model available in the next official release of the Electromagnetic Transients Program (EMTP DCG-EPRI version V3). This paper presents the detailed implementation of the new arc model: the numerical method applied in the simultaneous solution of electrical network and arc equations.

The challenge is the solution of the highly nonlinear Avdonin arc equation [2] with experimentally derived air-blast or SF_6 parameters. The solution method must attain convergence within the fixed integration time-step constraint of EMTP and possible numerical overflow conditions of the arc resistance value.

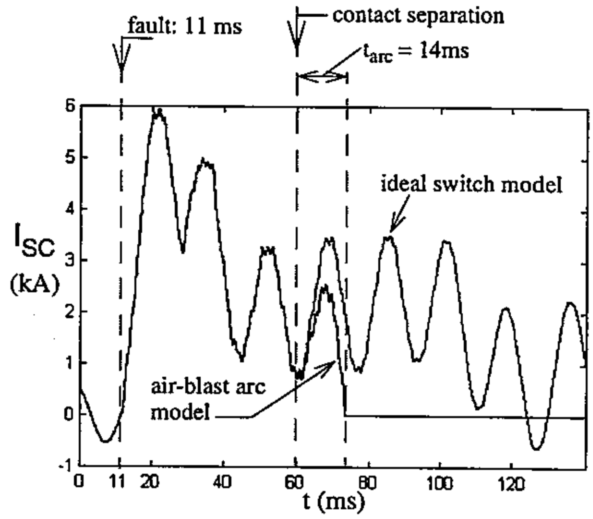

Figure 1: EMTP simulation, breaker current with breaker arc and ideal switch models

A previous solution attempt [3] employed a fixed-point method with predictions on both arc voltage and current. Such a method by nature, has poor convergence properties and requires increased computer time. The approach proposed in this paper is based on a Newton method and uses a polynomial predictor for the arc resistance at each iterative time-loop solution. Practical cases are used to demonstrate convergence properties and the importance of the predictor order. The presented method is applicable to other arc model equations such as Urbanek and Kopplin which have been also implemented using similar solution algorithms in EMTP-V3.

2. SOLUTION METHOD

2.a The arc model

The time sequence of events during the opening process in a circuit breaker is shown in Fig. 2. The initial contact parting action is followed by the nonlinear arc equation zone entered near current zero. The T_{part} parameter is based on a signal that can be manually predicted at simulation startup or connected to an EMTP TACS (Transient Analysis of Control Systems) device such as a relay model.

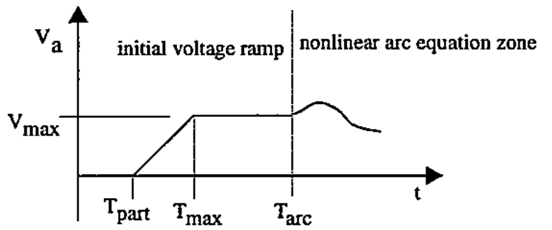

Figure 2: Opening sequence in a circuit breaker

The nonlinear arc equation used for modeling air-blast and SF_6 breakers is the Avdonin arc equation [2]:

$$\frac{dr_a}{dt} = \frac{r_a^{1-\alpha}}{A} - v_a i_a \frac{r_a^{1-\alpha-\beta}}{AB} \quad (1)$$

which is derived from the modified Mayr model:

$$\frac{dr_a}{dt} = \frac{r_a}{\theta}\left(1 - \frac{v_a i_a}{P_0}\right) \quad (2)$$

where:

$$\theta = A r_a^{\alpha} \qquad P_0 = B r_a^{\beta} \quad (3)$$

The variables r_a, v_a and i_a are the arc resistance (ohms), voltage (V) and current (A) respectively. θ is the arc time constant (s) and P_0 is the breaker cooling power. Parameters for this model can be derived from laboratory tests [4]. A typical air-blast breaker has a slower time constant than the single-pressure SF_6 breaker. Equation (1) can be used to represent thermal failure near current interruption and conductivity in the post-arc region.

2.b Inserting the arc model into the network equations

This section presents the programmed solution method and its calibration for solving the most severe convergence problems encountered with nonlinear arc model cases.

A simple and straightforward approach for modeling the arc within an arbitrary EMTP network, is to solve equation (1) using TACS functions. A TACS breaker module can be programmed to measure the arc current in the network and transfer back the arc resistance at each simulation time-point through a controlled current source [5]. This approach usually requires an abnormally small integration time-step Δt and may become numerically unstable due to the one Δt delay between the solutions of network and TACS equations. It is feasible to improve the robustness of the solution method by inserting a TACS controlled arc resistance [4] at the breaker nodes instead of the controlled current source, but the only way to obtain a simultaneous and numerically robust solution between arc and network equations is to resort to hard-coding in the nonlinear branch representation algorithms of the EMTP.

It is feasible to implement a simultaneous solution between an arbitrary network and nonlinear branch equations through the EMTP compensation interface. This interface was previously available only to program developers, but has been made available to program users in the latest program release.

The idea of the compensation method is very simple. It is based on finding the network Thevenin equivalent looking back into given network nodes:

$$\mathbf{V_{th}} - \mathbf{R_{th}} \mathbf{I_{\phi}} = \mathbf{V_{\phi}} \quad (4)$$

Bold characters are used to denote matrices and vectors. $\mathbf{V_{th}}$ is the vector of Thevenin voltages, $\mathbf{R_{th}}$ is the Thevenin resistance matrix, $\mathbf{I_{\phi}}$ is the vector of nonlinear branch currents and $\mathbf{V_{\phi}}$ is the vector of nonlinear branch voltages. $\mathbf{I_{\phi}}$ and $\mathbf{V_{\phi}}$ are related through nonlinear functions. This is a multiphase equation and can account for the simultaneous presence of several nonlinear functions in a subnetwork.

If for demonstration purposes, the only nonlinear element present in a subnetwork is an arc model, then equation (4) can be reduced to its scalar form:

$$V_{th} - R_{th} i_a = \hat{v}_a \quad (5)$$

The number of breaks per breaker pole (n_b) is included assuming that $\hat{v}_a = n_b v_a$.

The trapezoidal method of integration provides the solution of (1) at the simulation time-point t:

$$r_{a_t} = r_{a_{t-\Delta t}} + \frac{\Delta t}{2}\left[\left.\frac{dr_a}{dt}\right|_t + \left.\frac{dr_a}{dt}\right|_{t-\Delta t}\right] \quad (6)$$

Contrary to indications in [3] there is no need to treat r_a, v_a and i_a separately, since $i_a = v_a / r_a$ equation (1) can be rewritten as:

$$\left.\frac{dr_a}{dt}\right|_t = \frac{r_{a_t}^{1-\alpha}}{A} - v_{a_t}^2 \frac{r_{a_t}^{-\alpha-\beta}}{AB} \quad (7)$$

In order to find a simultaneous solution, the combination of equations (5) to (7) must be solved through an iterative process.

If a fixed-point method is used, then the iterative procedure at time t, starts with a prediction $\hat{r}_{a_t}$ of r_{a_t} followed by an iterative loop where equations (5), (7) and (6) are called in succession until convergence. A first order predictor such as:

$$\hat{r}_{a_t} = r_{a_{t-\Delta t}} + \Delta t \left.\frac{dr_a}{dt}\right|_{t-\Delta t} \quad (8)$$

can be implemented. But a fixed-point method has inherent limitations: slow convergence and no guarantee of convergence even with the best initial guess. Due to the extremely nonlinear nature of (7), the usage of such a method will also require an unnecessary small Δt.

A better approach is to use a Newton method for solving the nonlinear system of equations (5)-(7). In addition to quadratic convergence speed, there is a guarantee of convergence when the initial guess is sufficiently close to the solution.

The Newton formulation for solving (5) is given by:

$$r_{a_t}{}^{(j+1)} = r_{a_t}{}^{(j)} - \left[\left. \frac{df}{dr_{a_t}} \right|_{r_{a_t}{}^{(j)}} \right]^{-1} f(r_{a_t}{}^{(j)}) \quad (9)$$

with:

$$f(r_{a_t}) = \quad (10)$$

$$-r_{a_t} + r_{a_{t-\Delta t}} + \frac{\Delta t}{2}\left[\frac{r_{a_t}{}^{1-\alpha}}{A} - v_{a_t}^2 \frac{r_{a_t}{}^{-\alpha-\beta}}{AB} + \left. \frac{dr_a}{dt} \right|_{t-\Delta t} \right]$$

found from the combination of (6) and (7). The arc voltage at each iteration is found from (5):

$$v_{a_t}{}^{(j)} = V_{th} r_{a_t}{}^{(j)} \left[n_b r_{a_t}{}^{(j)} + R_{th} \right]^{-1} \quad (11)$$

The predictor of (8) is acceptable for most simulation cases, but experimenting with practical cases suggests the usage of a higher order predictor more appropriate for the highly nonlinear nature of (7). It is chosen to apply a fourth order Adams Bashforth predictor given by:

$$\hat{r}_{a_t} =$$

$$r_{a_{t-\Delta t}} + \frac{\Delta t}{24}\left[55\dot{r}_{a_{t-\Delta t}} - 59\dot{r}_{a_{t-2\Delta t}} + 37\dot{r}_{a_{t-3\Delta t}} - 9\dot{r}_{a_{t-4\Delta t}} \right] \quad (12)$$

It is selected for its simplicity and requires the recursive updating of only 3 more terms. This predictor achieves faster convergence specially for large arc resistance excursions, and the largest possible time-step usage for a large set of test cases. Moreover, poor prediction may cancel the finding of an existing solution.

The fast increase of arc resistance near arc extinction, requires the implementation of numerical overflow tests. The preset bounds will affect convergence properties and partly defeat the purpose of computing derivatives. This is why the first detection of nonconverging or oscillatory Newton solution is followed by the implementation of the previously discussed fixed-point method. It is possible that a fast arc resistance rise does not end up in arc extinction and restrike conditions may also exist.

The final implementation is a combination of Newton and fixed-point methods where the fixed-point method is switched on only when the Newton method encounters convergence problems.

The proposed solution method remains compatible with the solution of other nonlinear functions in the EMTP and mixing of nonlinearities is feasible through the general equation (4). A simple algorithm is achieved by replacing V_{th} by V'_{th} in equation (11). If there is a total of n nonlinear functions then for a given ith arc model V'_{th} is found from:

$$V'_{th_i}{}^{(j)} = \sum_{\substack{k=1 \\ k \neq i}}^{n} \left[V_{th_i} - R_{th_{ik}} I_{\phi k}{}^{(j)} \right] \quad (13)$$

Equation (4) can be viewed as a linearized circuit where the arc model contributes a resistance value at each iteration. According to (13) and (9) the iteration numbers are not synchronized when there is more than one nonlinear branch in a subnetwork, this now constitutes a quasi-Newton solution for multiple nonlinearities.

3. SIMULATION EXAMPLES

The following test cases are selected to demonstrate the advantages and capabilities of the previously presented solution method.

3.a Test Case 1

The first test case is taken from a 735 kV reactor isolation study. The diagram of the studied circuit is shown in Fig. 3. The network equivalent is for the 735 kV network connected to the substation where the reactor is being switched off. It is composed of a short-circuit inductance and an RC branch for TRV representation. The breaker is connected between two very short line sections simply modeled with pi sections. The reactor is modeled to match its natural frequency with a parasitic capacitor and a large damping resistor.

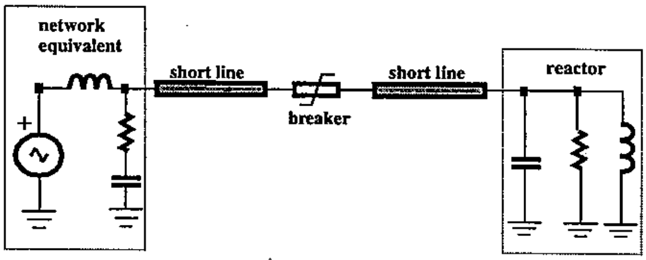

Figure 3: 735 kV reactor isolation study with a detailed arc model

The breaker model parameters are chosen for the SF_6 case. The integration time-step is 1 μs. Contact parting time is manually set to occur at t=0 and the complete network is initialized with a 60 Hz solution with the breaker in its closed position. The arc current and resistance are presented in Fig. 4 and Fig. 5 respectively. These simulation results have been checked against measurements [7]. Resistance instability occurs around the current chopping. Such an instability justifies the search for the exact solution, even if preset bounds may be called in at a given iteration, the final solution can be a resistance lower than the computer representation of infinity. At ≈ 0.17 ms the arc resistance jumps from 1000 Ω to infinity and the proposed method automatically switches from Newton to fixed-point to unable convergence. The mean number of iterations is 2.3 when the high order predictor of equation (12) is used.

If the same arc model is programmed using TACS with a TACS controlled arc resistance, then it requires 200 times the computer time of the proposed solution method. This large ratio is partly due to the requirement of a 100 times smaller time-step in TACS to remain stable.

If the fixed-point method is set to remain on throughout the entire simulation, then the mean number of iterations jumps to 30 and the computer time doubles. The programming of the Newton method is more complex and cancels some of its convergence speed advantages.

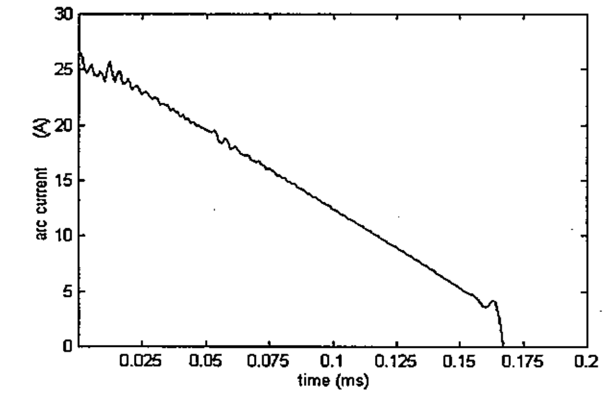

Figure 4: Simulation of breaker current with the new arc model, test case of Fig. 3

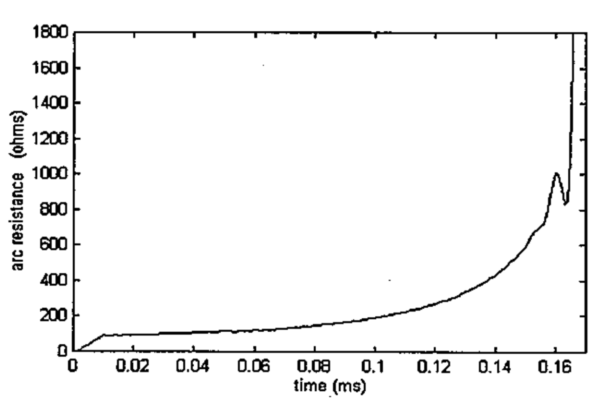

Figure 5: Simulation of breaker resistance with the new arc model, test case of Fig. 3

3.b Test case 2

This test case uses the test circuit of Fig. 6. It is a direct test circuit [1] Fig. 6for generating delayed current zero conditions in the short-circuit current. Circuit parameters are set to reproduce in-network conditions for the Hydro-Québec series compensated network. The tested breaker is TB and auxiliary breakers AB_1 and AB_2 are closed in an appropriate sequence for reducing the ac component of the short-circuit current while maintaining its dc component.

The variations of the arc resistance are shown in Fig. 7 for a contact parting time of 43 ms till interruption at 80 ms. In this test case the fixed-point method cannot find a solution with the integration time-step used for the Newton method. The high-order predictor of equation (12) is able to maintain the mean number of iterations close to 1 throughout the variations in arc resistance shown in Fig. 7 and the fixed-point method is never needed. It is again noticed that the fast variations in the arc resistance do not always end up in arc extinction and the solution search must stay on even if preset bounds are hit. Experimental validation for this case can be found in [1].

The computer time gain compared to the predictor of equation (8) is 1.5 times. This is not a major gain, but the importance of the predictor becomes dramatic when it can achieve convergence in cases where a lower order predictor fails. Such cases are found when simulating the detailed network with transmission lines as in the introductory case of Fig. 1.

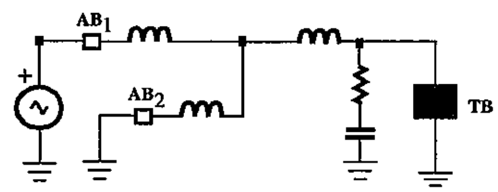

Figure 6: Test circuit used for creating delayed short-circuit current zero conditions

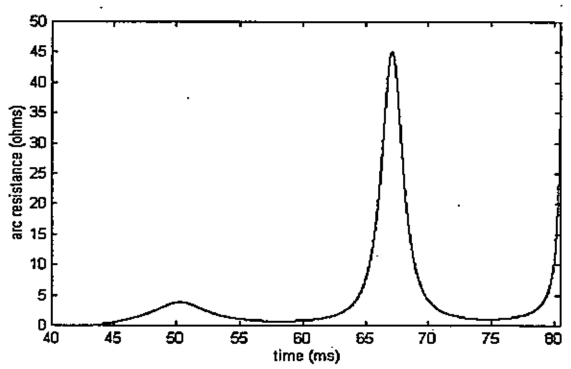

Figure 7: Arc resistance in a successful current interruption case with an air-blast breaker

4. CONCLUSIONS

This paper has presented the numerical implementation of the new EMTP arc model. The solution method is a simultaneous solution of linear network equations with the nonlinear arc model. The Newton method is started with a high-order predictor and allowed to switch to a fixed-point solution near arc extinction or when the Newton iterations cannot converge. Practical simulation cases impose the above adjustments to unable convergence in worst conditions with a maximized integration time-step.

The presented approach was used for solving the particular case of the arc equation, but shown new ideas can be also exploited in other nonlinear model solution problems in the EMTP.

REFERENCES

[1] Q. Bui-Van, B. Khodabakhchian, M. Landry, J. Mahseredjian and J. Mainville: Performance of series-compensated line circuit breakers under delayed current-zero conditions. Paper 96 SM 405-1 PWRD, IEEE PES Summer Meeting, July 28 - August 1, 1996, Denver, Colorado.

[2] A. V. Avdonin et al.: Some problems of EHV and UHV air-blast circuit breakers. CIGRE paper 13-04, 1980 session

[3] V. Phaniraj and A. G. Phadke: Modelling of circuit breakers in the Electromagnetic Transients Program. IEEE Trans. on Power Systems, Vol. 3, May 1988, pp. 799-805

[4] G. St-Jean, M. Landry, M. Leclerc and A. Chenier: A new concept in Post-arc analysis to power circuit breakers, IEEE Transactions on Power Delivery, Vol. 3, No. 3, July 1988.

[5] M. Kizilcay: Dynamic arc modeling in the EMTP. EMTP Newsletter, July 1985

[6] H. W. Dommel: Nonlinear and time-varying elements in digital simulation of electromagnetic transients. IEEE Trans. PAS, Vol. 90, 1971, pp. 2561-2567

[7] M. Landry and G. Ouellet: Caractéristiques de la transitoire de tension aux bornes de la réactance lors de réallumage de son disjoncteur. Rapport IREQ-4559, 25 janvier, 1990.