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COMPUTING RESPONSES OF SERIES COMPENSATION CAPACITORS WITH MOV PROTECTION IN REAL-TIME

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Abstract. This paper describes a method that was implemented for computing responses of series compensation capacitors with MOV protection in a real-time simulator for relay testing. The salient feature of the method is that the complete circuit is modeled as a single component. Accuracy of the method was verified through extensive comparisons against the full EMTP model. Achievement of the required speed of computation was tested through real-time simulations.

Keywords: Real-Time Simulation, MOV, Series Compensations

INTRODUCTION

The use of Metal Oxide Varistor (MOV) for overvoltage protection of series capacitor on transmission lines is a common practice today. Digital modeling of this nonlinear element became of interest when various simulation studies such as stability [1], short-circuit [1,2], and relay performance [3] were carried out. Each of these studies required a different approach to the modeling since the study requirements were different.

One of the most difficult study requirements is the simulation of MOV responses in real-time. Recently a method based on an approximative solution of algebraic equations has been described [4]. The method is computationally suitable for real-time simulation but depends on a particular assumption about the network impedances. In simulations that involve dynamic changes of the network topology it may not be easy to verify the assumption.

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[1]The work was done while the author was with Texas A&M University

This paper describes the method that was implemented in the real-time simulator for relay testing that was developed at Texas A&M University for Western Area Power Administration [5,6]. The design requirements set a number of very difficult targets for the simulator development. In particular, it was required to achieve the through-put range of around 3 to 4 kHz, which for all practical purposes, was translated to the integration time step of about 50–100μsec. In regard to accuracy, it was required that the results of the computations be compared to the equivalent ones of the Electromagnetic Transients Program (EMTP) [7].

In this connection, one of the most demanding tasks of the simulator development was the requirement to provide for accurate and real-time computation of network responses involving series compensation capacitors. The main difficulty arises in computing response of an MOV which presents a highly nonlinear element. The commonly accepted approach in EMTP studies is to represent the MOV by a 5-piece exponential characteristic and to use Newton-Raphson iterations to solve it [8]. Unfortunately, this method is far from being acceptable regarding the speed of computation. The situation is further aggravated by the fact that the effects of the presence of an MOV will be more pronounced at times right after a fault has been introduced into the network. That is when the amount of required computation will be very high due to the necessity to perform modifications of the network topology [6].

The paper starts with an introduction of an equivalent circuit for the series capacitor with MOV protection. In order to simplify the exposition, the model of the series compensation capacitor with an MOV having only one slope characteristic is presented first. The development for the case of a three slope characteristic is given in a generalized form. An efficient algorithm for performing the change in the network topology due to the MOV operation is presented in the following section. The last section contains computational results based on an actual network section of the Western Area Power Administration system. This new model of the series capacitor with MOV protection is included in the Real-Time System (RTS) software used for simulation of the network responses [6].

AN EQUIVALENT CIRCUIT

A typical single phase circuit of the MOV protected series capacitor is shown in Figure 1.

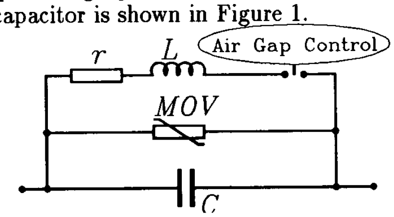


Fig. 1. Series Capacitor with MOV Protection and Triggered Air Gap

The task of the MOV is to ensure that the voltage drop across the series capacitor does not increase to a damaging level and to protect the series capacitor within the MOV's energy capability. This is accomplished by the virtue of a particular MOV characteristic.

The task of the control circuitry is to measure the energy dissipated in the MOV, and to ignite the gap when it exceeds a predefined limit. Additionally, the air gap may be activated using the current magnitude criterion as well. The resistance r and inductance L in the bypass branch represent current limiting reactor and the non-negligible parameters of the connecting leads.

THE ONE-SLOPE MODEL

In the one-slope model, the MOV characteristic is assumed to be as given in Figure 2.

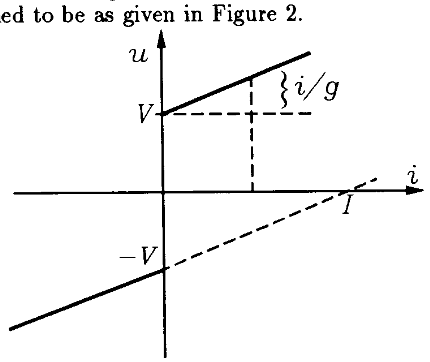


Fig. 2. One-Slope Approximation of the MOV Characteristics

Not withstanding this assumption, the accurate model of the series capacitor with MOV protection is described by the following equation:

$$i = \begin{cases} C\frac{du}{dt} & \text{if } |u| < V \\ C\frac{du}{dt} + g(u - V \cdot sgn(u)) & \text{if } |u| \geq V \end{cases} \quad (1)$$

where:

$$sgn(u) = \begin{cases} 1 & \text{if } u \geq 0 \\ -1 & \text{if } u < 0 \end{cases}$$

The exact solution of the above equation would require an iterative process to determine the fixed point (equilibrium) conditions implied by (1). As this cannot be afforded in real-time, the outcome of testing the voltage u against the clipping level V is applied one time step later. To make this point clear, assume that u denotes the voltage taken at the same time step t, and that u^- denotes the value of one time step ago, i.e., $u^- = u(t - \Delta t)$. Similarly, we use the superscript $^+$ to denote the function value one time step ahead. Then, the equation that is actually being solved can be written as:

$$i = \begin{cases} C\frac{du}{dt} & \text{if } |u^-| < V \\ C\frac{du}{dt} + g(u - V \cdot sgn(u^-)) & \text{if } |u^-| \geq V \end{cases} \quad (2)$$

A similar approach is used in the EMTP to develop the compensation method. The method is applied to network components which represent either nonlinear resistance (given in the EMTP Rule Book as the element Type 99) or inductance (given in the EMTP Rule Book as the element Type 93).

Consistently with the strategy in the RTS development to follow the EMTP techniques as much as possible, the trapezoidal integration method is used to solve the equation (2). This results in the following 4 cases:

1) If $|u^-|$, $|u| < V$, then

$$\begin{aligned} \gamma \cdot u &= i + h \\ h^+ &= 2\gamma \cdot u - h \end{aligned} \quad (3.1)$$

2) If $|u^-| < V$, $|u| \geq V$, then

$$\begin{aligned} \gamma \cdot u &= i + h \\ h^+ &= (2\gamma - g)u + 2I \cdot sgn(u) - h \end{aligned} \quad (3.2)$$

3) If $|u^-|$, $|u| \geq V$, then

$$\begin{aligned} (\gamma + g)u &= i + h \\ h^+ &= 2\gamma \cdot u + 2I \cdot sgn(u) - h \end{aligned} \quad (3.3)$$

4) If $|u^-| \geq V$, $|u| < V$, then

$$\begin{aligned} (\gamma + g)u &= i + h \\ h^+ &= (2\gamma + g)u - h \end{aligned} \quad (3.4)$$

where $\gamma = \frac{2C}{\Delta t}$, $I = Vg$, and where h denotes the current history function. It is important to note that the above equations are different from the one which would result from the EMTP modeling of the series compensation capacitor with the MOV being represented as a Type 99-nonlinear resistance. Namely, doing so would result in only 2 cases depending on whether the MOV is conducting or not, whereas here we have twice as many.

The energy dissipated in the MOV is computed as accurately in as much as the approximation used will permit:

$$E/\Delta t = \sum_{|u|>V} g \cdot |u| \cdot (|u| - V) \tag{4}$$

THE THREE–SLOPE MODEL

The three–slope model is represented by the MOV characteristics shown in Figure 3.

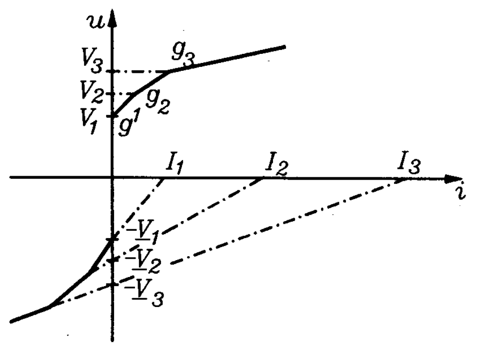


Fig. 3. Three–Slope Approximation of the MOV Characteristics

Note that $\underline{V}_j$ denotes the clipping voltage of the one–slope approximation corresponding to slopes $j = 1, 2, 3$ of the three–slope characteristic. Clearly $V_1 = \underline{V}_1$ while $V_2 > \underline{V}_2$ and $V_3 > \underline{V}_3$.

The equations describing the series capacitor with the MOV protection are:

$$i = \begin{cases} C\frac{du}{dt}, & |u^-| < V_1 \\ C\frac{du}{dt} + \\ g_j(u - \underline{V}_j \cdot sgn(u^-)), & V_j \leq |u^-| < V_{j+1} \end{cases} \tag{5}$$

Computation of the three–slope model is carried out using equations that are essentially the same as equations (3.1–3.4). Of course, $g = g_1$, g_2 or g_3 and $I = I_1$, I_2 or I_3 depending on the actual operating slope. The only difference is that here we have to account for a possible change in the operating slope. More specifically, we have to consider the fifth case when $|u^-|$, $|u| > V_1$ and there is a change of the operating slope (six possible transitions). Then:

$$\begin{aligned} (\gamma + g^-)u &= i + h \\ h^+ &= (2\gamma + g^- - g)u + 2I \cdot sgn(u) - h \end{aligned} \tag{6}$$

where g^- denotes admittance of the operating slope of one time step ago, and $I = \underline{V}_j g_j$.

NETWORK TOPOLOGY CHANGE

At each time step, the RTS solves the network voltage equations:

$$v_A = G_{AA}^{-1}(h_A - G_{AB}v_B) \tag{7}$$

where A and B denote the sets of the network nodes whose voltages are known and unknown, respectively. The RTS keeps the inverse G^{-1} (We have dropped the subscripts in order to simplify the notation) in an explicit form. Hence, the voltage equations are solved by simple matrix multiplications. In doing that, the RTS takes advantage of the fact that the matrix can be permuted into a block diagonal form by maintaining the inverses of the individual diagonal blocks $G_1, \ldots, G_k$. The block diagonal form is shown in Figure 4.

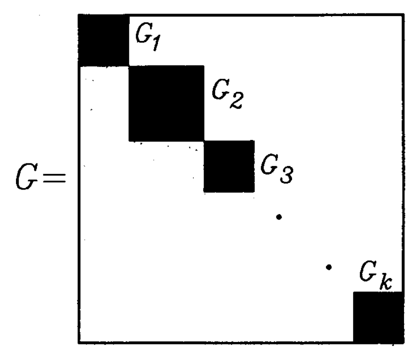


Fig. 4. Block Diagonal Structure of the Admittance Matrix

Let i and j be the indices of the end nodes of the series capacitor, and let e be a vector of the appropriate size such that:

$$e_l = \begin{cases} 1 & \text{if} \quad l = i \\ -1 & \text{if} \quad l = j \\ 0 & \text{otherwise} \end{cases}$$

Note that i and j will always belong to one of the blocks of G. Then the modification of the admittance matrix as a result of an MOV operation is equivalent to inserting or removing a resistance in the network.

This simple type of network topology change amounts to a (symmetric) rank–one matrix update given by the following equation:

$$\underline{G} = G + g \cdot e \cdot e^T \quad (8)$$

By the inverse matrix modification lemma of Sherman, Morrison and Woodbury [9] we have:

$$\underline{G}^{-1} = G^{-1} - \frac{g}{1 + g \cdot e^T G^{-1} e}(G^{-1}e) \cdot (G^{-1}e)^T \quad (9)$$

The equation (9) needs to be applied each time when an MOV either starts or stops to conduct. (In the latter case, g in (9) has to be replaced by $-g$).

It is important to note that (9) can be employed on a block–by–block basis. Since the number of arithmetic operations is proportional to the square of the matrix size, the computational savings are indeed significant.

This method of network topology changes is extensively used in the RTS for computing time–controlled switches and circuit breaker operations (See [6]) – that is for the operations which are comparatively infrequent.

As in a typical simulation run one can expect to see many changes in the state of MOVs, an alternative approach had to be developed for handling the network topology changes as the result of MOV operations.

Since we are really interested in computing the voltage values, let us multiply (9) from the right by the vector of the history currents h. This gives us

$$\underline{G}^{-1}h = G^{-1}h - \frac{g}{1 + g \cdot e^T G^{-1} e}(G^{-1}e) \cdot e^T G^{-1} h \quad (10)$$

Let $v = G^{-1}h$ and $\underline{v} = \underline{G}^{-1}h$ be the vectors of the node voltages before and after the network topology change. Note that $e^T G^{-1} h = v_i - v_j$ is the voltage drop across the capacitor which would have been observed had it not been for the topology change, and that $G^{-1}e = G_i^{-1} - G_j^{-1}$ is just the difference between the $i-th$ and $j-th$ column of the inverse matrix. Hence,

$$\underline{v} = v - \frac{g \cdot (v_i - v_j)}{1 + g \cdot e^T G^{-1} e}(G_i^{-1} - G_j^{-1}) \quad (11)$$

If n is the size of the diagonal block of G that is affected by the topology change then, from (11) it follows that the correct nodal voltages can be computed in just about n additional multiplications and $2n$ additions. This compares quite favorably with the outright modifications of the matrix which would require about $2n^2$ additions and n^2 multiplications for each cycle of the MOV operation (insertion and removal of the resistance). Doing the modification that way would appear to be beneficial only if the continuous MOV operations would, on an average, last longer than $2n$ time steps. As the diagonal blocks to which series capacitors belong tend to be comparatively large, it can be expected that the method of the voltage corrections will be superior to the matrix modifications.

COMPUTATIONAL RESULTS

A number of computational experiments have been carried out involving different fault conditions and relay operation scenarios. The test cases were based on a network section of Western Area Power Administration shown in Figure 5.

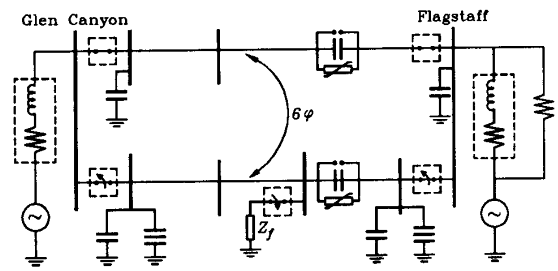


Fig. 5. WAPA Test System

The MOV characteristic used for the EMTP modeling, and the RTS one–slope and three–slope modeling are given in Figure 6.

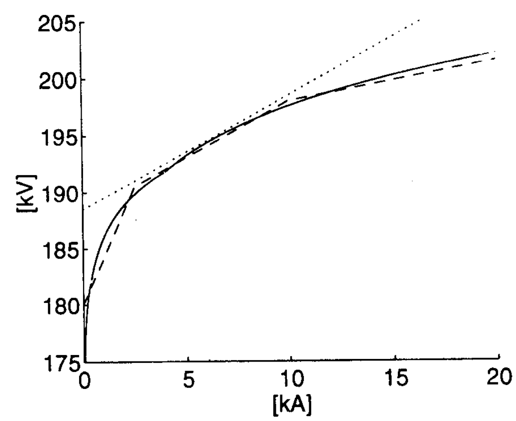


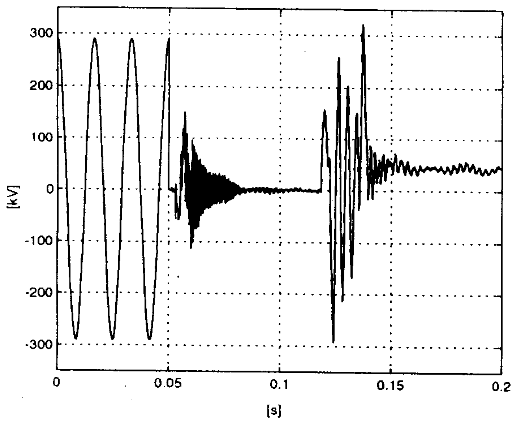
Fig. 6. MOV Characteristics: — EMTP, ... RTS (One–Slope), - - - RTS (Three–Slope)

Results of two cases involving single and three phase, zero impedance, ground faults at the line side of the capacitor bank are presented here. These kinds of faults and their location were chosen because they inevitably result in prolonged MOV operations. Since the RTS keeps the number of nodes constant throughout simulation, the faults are modeled by inserting a small resistance ($Z_f = 10^{-3}\Omega$) between the fault locations and the ground.

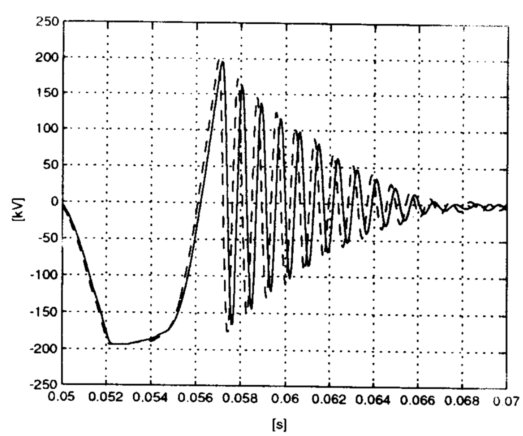
Computations were carried out in two steps. The first step was completed in an off-line (non real-time) setup with a $50\mu s$ time step. The objective was to compare the RTS results against the same ones of the EMTP.

The first case involves a three phase fault at the time $t = 0.05s$ and zero incidence angle. The Flagstaff and Glen Canyon circuit breakers trip commands were initiated 4 ($t = 0.11666s$) and 5 ($t = 0.1333s$) cycles later.

From Figures 7b and 8b, it can be observed that Phase A MOV started to conduct closely after $t = 0.052s$ and that the air gap closed at $t = 0.057s$. It can be seen from Figure 7a and 8a that the effects of circuit breaker operations are delayed due to the modeling of the zero crossing current interruptions. Also, the difference between the RTS and the EMTP simulations is so small that it is not noticeable for the time scale given.

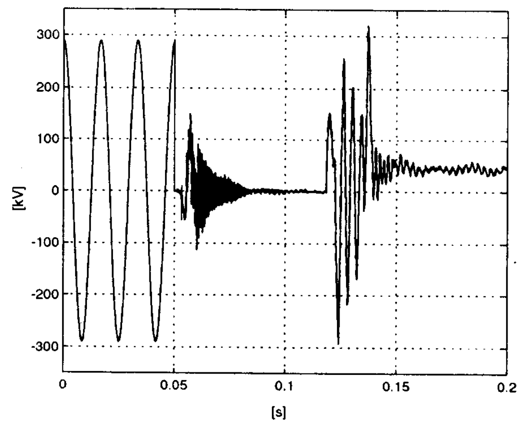


a) Flagstaff Voltage–Phase A

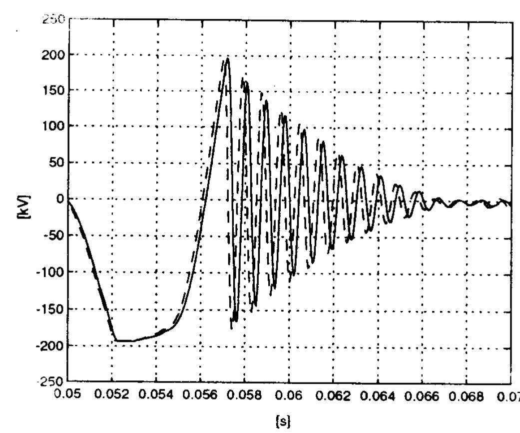


b) Voltage Across Capacitor
Phase A: - - - RTS, — EMTP

Fig. 7. Case 1: Comparison of the One–Slope RTS Model vs the EMTP Model Simulations

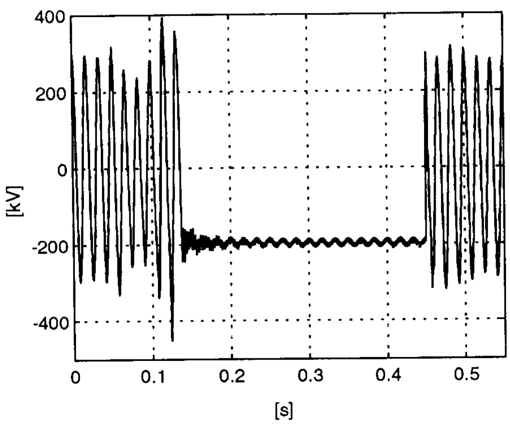


a) Flagstaff Voltage–Phase A

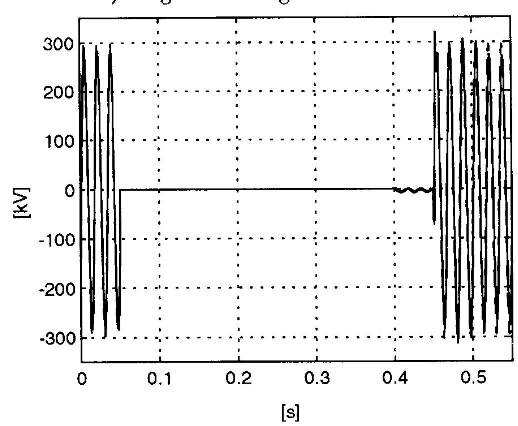


b) Voltage Across Capacitor
Phase A: - - - RTS, — EMTP

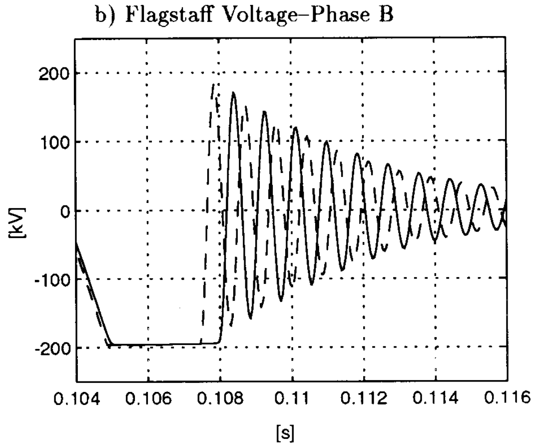
Fig. 8. Case 1: Comparison of the Three–Slope RTS Model vs the EMTP Model Simulations



a) Flagstaff Voltage–Phase A

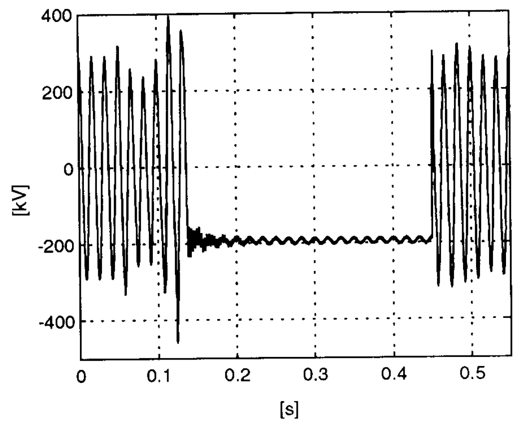


b) Flagstaff Voltage–Phase B

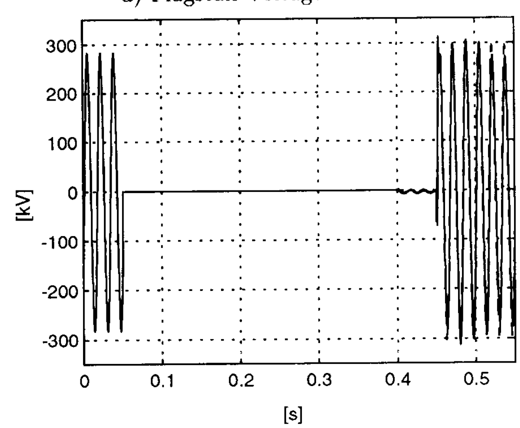


c) Voltage Across Capacitor
Phase B: - - - RTS, — EMTP

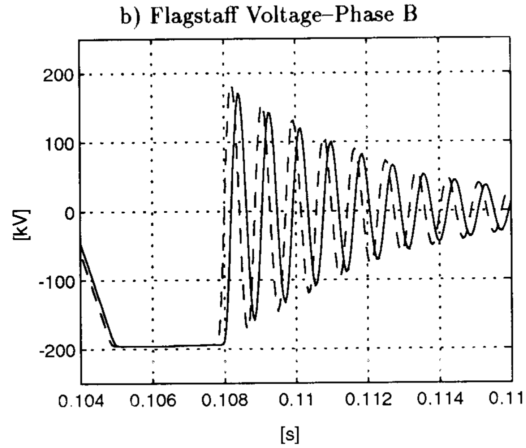
Fig. 9. Case 2: Comparison of the One–Slope RTS Model vs the EMTP Model Simulations



a) Flagstaff Voltage–Phase A



b) Flagstaff Voltage–Phase B



c) Voltage Across Capacitor
Phase B: - - - RTS, — EMTP

Fig. 10. Case 2: Comparison of the Three–Slope RTS Model vs the EMTP Model Simulations

The second case is a ground fault at the Phase B. The simulation scenario calls for 3 pole operatons of the circuit breakers 4 and 5 cycles after the fault, and their reclosing 20 and 21 cycles after the fault. The fault itself is removed at $t = 0.4s$.

The waveforms for the second case are shown in Figures 9 and 10 for the one-slope RTS and the three-slope RTS models respectively. Again, the results shown in Figure 9 (a and b) and 10 (a and b) indicate that the difference between the RTS and the EMTP simulations is so small that it is not noticeable for the time scale given.

However, the most noticeable difference between the RTS and the EMTP can be observed on the last two plots of Figures 9 and 10. These plots show that the air gaps in the RTS closed earlier than in the EMTP. Expectedly, the errors in computing the energy dissipated on the MOV for the one-slope RTS characteristic are larger than for the three-slope one. This can be seen from Figure 11 (a and b). This comes from the fact that the three-slope approximation used in the RTS is closer to the EMTP characteristics. The one-slope RTS characteristic was selected to provide a good approximation around the operating point of the MOV. As a result, the RTS waveforms closely follow the ones of the EMTP until the air gap closure.

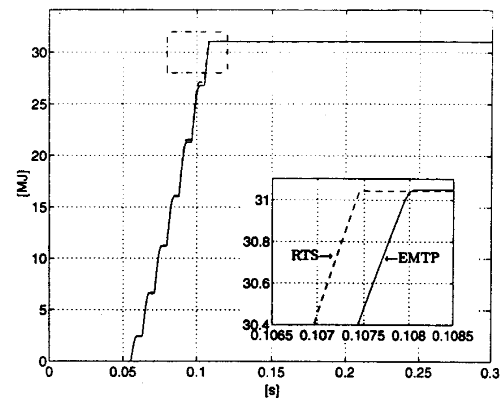
This problem did not show up in the first case since the air gaps were triggered by the additional criterion for the MOV maximum current (8000 A) rather than by the energy criterion.

In the second step, the computations were carried out on the real-time simulator to determine the minimal attainable real-time simulation time steps (maximum throughput rates). The results are summarized in Table I.

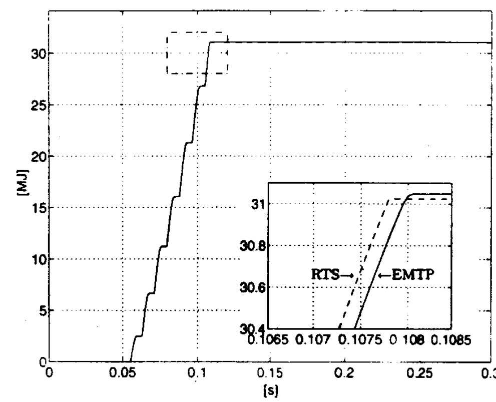
Table I. Minimal Real-Time Simulation Time Steps

Run	Case 1 [μs]	Case 2 [μs]
No MOV	69.93	73.10
One-Slope Model	76.28	78.86
3-Slope Model	77.39	79.48

The minimal time steps given indicate that the proposed models are quite efficient when compared to the cases with no MOVs and that the time steps are well within the range of the real-time simulation requirements.



a) One-Slope RTS Model vs EMTP Model



b) Three-Slope RTS Model vs EMTP Model

Fig. 11. Case 2-MOV Energy Calculations

CONCLUSIONS

Based on the results presented in the paper, the following conclusions are drawn:

- The proposed method for the component representation is computationally very efficient and satisfies the simulator real-time requirements.
- The one-slope and the three-slope MOV characteristics proposed give comparable results for the given studies and they are very close to the ones obtained with EMTP.
- The three-slope MOV characteristic is easier to use since the fitting process is more straightforward than in the one-slope case.

ACKNOWLEDGEMENTS

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