Comparative Analysis of Shunt Active Filter Models in the EMTP/ATP and SABER Programs

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Abstract – **There are several time domain simulators for electromagnetic circuits and systems involving power electronics devices. An aspect that distinguishes them is the adopted method for the time integration. There are methods with fixed time step or variable time step. The EMTP/ATP simulator is representative for fixed time step and the SABER simulator for variable time step. Problems related to the implementation of power electronics models in both programs are discussed along the paper for each simulator. In addition, convergence problems were identified and discussed. One basic conclusion is that the best simulator is *"that one I have in hand, dominate it, and know its particular solutions to overcome limitations and improve accuracy"*.**

Keywords – Active filter, Time domain digital simulation, Power Electronics.

I. Introduction

There are various digital simulation programs for modeling systems including power electronics devices as well as electromechanical components. Between these simulators, one important difference appears regarding the fixed or variable time step, in the time domain analysis. Representing these two groups, the EMTP/ATP [1, 2] is the one that uses fixed time step for the simulation, which is defined by the user. The other representative, but expensive program is SABER [3], which uses a complex algorithm to evaluate the ideal time step for the simulation, but respecting some minimum and maximum values given by the user.

The objective of the present paper is to evaluate the differences and limitations of these two programs in the case of the study of a shunt active power filter where high frequency switching as well as low frequency phenomena (like in its dc side capacitor) should be accurately represented. For this purpose, a model of a shunt active filter for the elimination of harmonic current generated by a rectifier was implemented in both programs.

II. Power System with a Shunt Active Filter

A simple power system containing a six-pulse thyristor bridge as non-linear load and a shunt active filter, as shown in Fig. 1, was selected to evaluate the EMTP/ATP and SABER simulators. Details for the shunt active filter can be found in [4]. This system allows exploring several issues concerning modeling of power electronics equipment and its influence in the power system. It includes high frequency (about 10 kHz) switching by the PWM control and relatively slow dc voltage oscillation periods of about 50 ms, which should be observed with satisfactory accuracy.

Since both simulators do not work with per unity (pu) quantities, for convenience, 1 V and 1 A were adopted as the basis of the system and the inductances (H) and capacitances (F) in the power system were calculated accordingly.

III. Digital Model in the EMTP/ATP Program

The EMTP/ATP program performs simulations in the time domain, with a fixed time-step integration method. The time step value is passed as a parameter by the user before running the simulation.

At each time step, the system equations that describe the power system and the control system are not solved simultaneously. For a given instant *t* the control system equations are solved sequentially, using the values previously calculated for the control variables and the node voltages and current of the power system determined in the last time step ($t-\Delta t$). Then, the new values of the control system variables are used to update the circuit topology (opening or closing power switches) and the corresponding power system equations are solved again. Therefore, there is a time step delay between sensing voltages and/or currents to the control system and the command to open or close a power switch. This time delay may be particularly

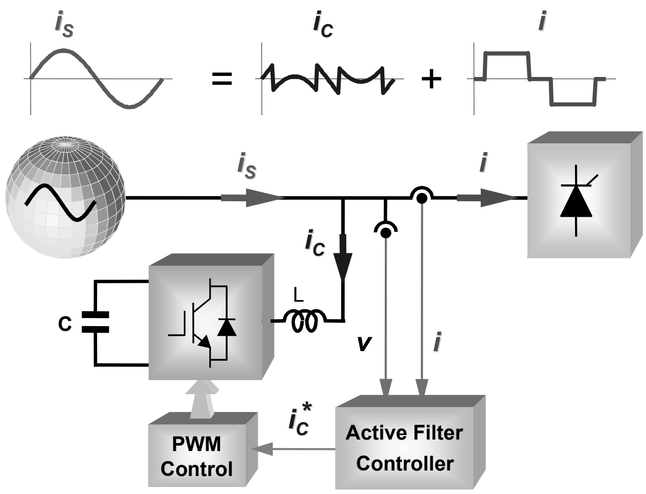

Fig. 1 Power system containing a non-linear load and a shunt active filter.

critical in simulating power electronics converters, since it forces the user to set the time step parameter to values much smaller than the switching frequency of the PWM converter.

In general, beginners in the use of SABER program reach their first simulation results faster than the EMTP/ATP beginners, who spend more time in understanding how to overcome problems with numerical oscillations and other tricks to overcome unwanted phenomena, as well as finding the optimal time step for that simulation case. Once dominated, advanced users can exploit the robustness and high speed of the fixed time-step integration method of the EMTP/ATP.

Fig. 2 and Fig. 3 show the test case built in the EMTP/ATP program. The firing control of the thyristor bridge (Fig. 2) was implemented through the use of several pre-defined control blocks in the program (the TACS routine), whereas the active filter controller in Fig. 3 was mounted with six user defined symbols that contain predefined control blocks forming sub-circuits. Although the control blocks in Fig. 2 appear to be disconnected from each other, they are connected through the use of names of variables properly defined in the FORTRAN expressions entered in each control block.

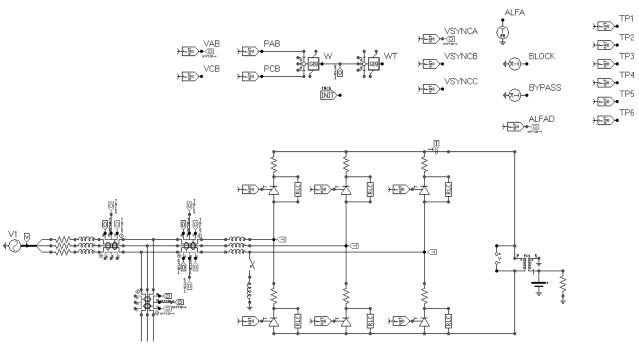

Fig. 2. Power system, the non-linear load and the connection point of the shunt active filter (EMTP/ATP program).

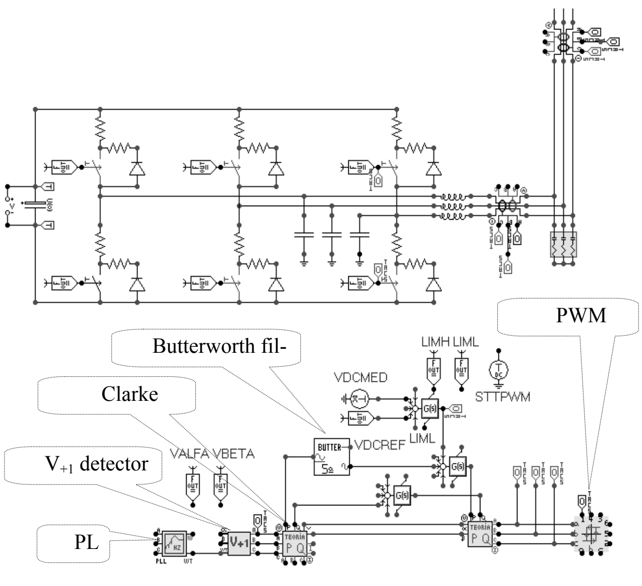

Fig. 3. PWM converter and controller of the shunt active filter.

The thyristors (Fig. 2) are modeled as controlled, ideal switches in parallel with RC branches. The RC branches represent real snubbers. In cases that snubbers are not necessary from the electrical circuit point of view, they are still necessary to provide "numerical snubbers" to avoid numerical oscillations. Another limitation of the EMTP/ATP consists in avoiding the connection of several controlled switches to a same node. This explains the use of six resistors with minimal values in the thyristor bridge. To overcome the absence of ungrounded ideal current source, an ideal, grounded voltage source, and an ideal transformer was used to realize it, as shown in Fig. 2.

User defined symbols were also implemented, for convenience, in the power system. For instance, three blocks for three-phase voltages and currents measurements were used in Fig. 2. Moreover, those three commutation inductances of the thyristor bridge are part of a single user-defined symbol that contains resistors in parallel with each inductor. The use of high resistances (R_L) in parallel with inductors, as well as low resistances (R_C) in series with capacitances consists in a well-known technique to damp numerical oscillations in the implicit trapezoidal integration method of the EMTP/ATP. To realize critical damping (suppress numerical oscillations in two time steps), for a given simulation time step, Δt, inductance, L, and capacitance, C, the values of R_L and R_C are given by

$$\begin{aligned} R_L &= \frac{2L}{\Delta t} \\ R_C &\approx 0.15\frac{\Delta t}{2C} \end{aligned} \quad . \tag{1}$$

Resistors employed to all inductances that appear in Fig. 2 and Fig. 3. Note that this technique cannot be strictly applied in the SABER program, since it uses variable time step. Although this is not a common practice in modeling power circuits in the SABER program, the same values of R_L were also connected in parallel to inductors, to allow better comparison between results.

Due to the same reasons above, additional resistors with minimal values were employed in the PWM converter of the shunt active filter (Fig. 3). There are anti-parallel diodes, instead of RC branches, connected to the ideal switches. In fact, the ideal switches used in Fig. 3 that model GTOs (or generic self-commutated power semiconductor devices) differ from those used in Fig. 2, with models thyristors. The switches in Fig. 3 are fully controlled. They receive firing pulses and blocking pulses as well.

The shunt active controller was compacted by defining six user-defined symbols: *i)* the synchronizing circuit (PLL circuit), *ii)* the positive-sequence voltage detector, *iii)* the Clarke Transformation and real and imaginary power calculation, *iv)* the 5th order Butterworth filter, *v)* the compensating currents reference equations and the inverse Clarke Transformation, and *vi)* the PWM current control (hysteresis band control).

IV. Digital Model in the SABER Program

The SABER program performs simulations in the time domain, with variable time-step integration method. The time step value is continuously evaluated during the simulation and is increased as much as possible to accelerate simulation, but maintaining the required accuracy. An elaborated predictor/corrector algorithm controls time progress and can go back in time to recalculate new values, in case of loss of accuracy or sudden changes in topology of the circuitry. For each time step, the SABER calculates the whole system of non-linear and linear equations simultaneously, disregarding if they are from the power system or from the control system. Thus, there is no inherent time delay between sensing voltages or currents and resulting commands to the power switches.

The values of the voltage source, current source, and inductances in both models are identical. As mentioned, here, parallel resistors with the same values as those used in the EMTP/ATP model are used. Thus, to keep similarity between models, all principal parameters are the same in both models. However, the models differ where special procedures must be adopted in a different way due to particularities of each simulator. For instance, the RC branches in parallel to the switches in the thyristor bridge, which serve as "numerical snubbers" in the EMTP/ATP, are no longer needed in SABER. In fact, there is no ideal switch template in SABER. In other words, the time integration method of SABER does not tolerate discontinuities in time domain, that is, instantaneous changes from open state ($R_{OFF} \approx \infty$) to closed state ($R_{ON} \approx 0$), and vice-versa. Hence, the rise and fall time of the switches in the thyristor bridge as well as in the PWM converter were set equal to 10 ns.

Fig. 4 shows the model of power system implemented in the SABER simulator. Fig. 5 shows details from the non-linear load and the shunt active filter and Fig. 6 shows the active filter controller. If compared with the figures of the EMTP/ATP model, the SABER model seems more compact. This is explained due to the easier way that one can define symbols containing sub-circuits in the SABER simulator. Another facility of SABER is the MAST programming language, combined with a vast list of pre-defined templates. These features were well exploited. An example is the power-meter symbol in Fig. 4 that contain voltage and current sensors, analog adders and multipliers to realize the Clarke Transformation and the instantaneous real and imaginary powers calculation.

If one is interested on macroscopic view of the phenomena, which could be, for instance, the influence of power

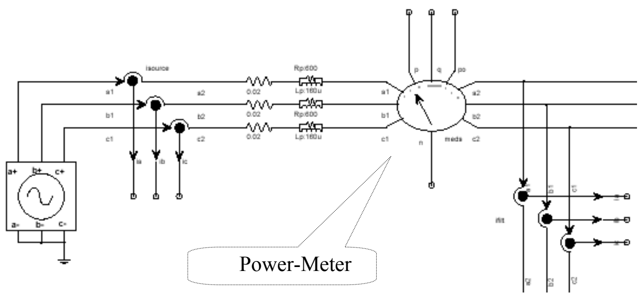

Fig. 4 Power system model implemented in SABER simulator.

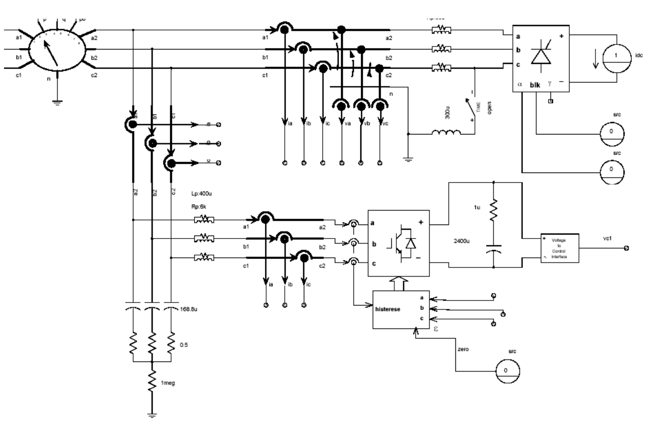

Fig. 5 Six-Pulse Thyristor Bridge and the PWM converter of the shunt active filter implemented in the SABER simulator.

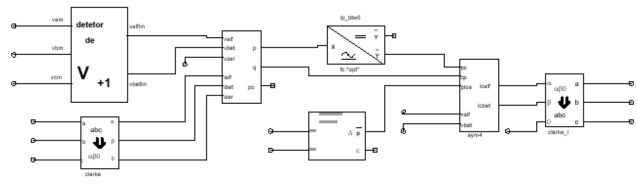

Fig. 6 Shunt active filter controller implemented in the SABER simulator.

electronics devices in the power system, it does not matter if the transition of a diode, which occurs within few tens of nanoseconds, is perfectly well represented or shown in a simpler way. However, since the SABER does not tolerate discontinuities, all transition phenomena must be represented, with more accuracy, but with very complex models and time consuming, or faster and with greater tolerances, but numerically more unstable. The numerical instability of piecewise-linear power diodes – the generic "ideal" diodes used in the SABER model of Fig. 5 – is evidenced in next section.

V. Simulation Results: Comparisons and Discussions

For the following discussions, two cases were performed in the EMTP/ATP and SABER containing the same chronological sequence of events, that is,

- start of thyristor bridge at t = 200 ms
- start of PWM converter of the shunt active filter at t = 250 ms
- ramp in firing angle of thyristor bridge from 0º to 180º in 200 ms < t < 500 ms, then instantaneous reset at t = 500 ms
- blocking of firing of thyristors during 550 ms < t < 608 ms
- short-circuit in c-phase close to the thyristor branch, during 650 ms < t < 700 ms
- total simulation time = 0.8 s

All transients caused by the above-listed events were verified with great similarity in both simulators, as shown in the following figures.

The currents of the non-linear load (thyristor bridge) presented almost the same shape in SABER and EMTP/ATP programs, and Fig. 7 shows the results only from the EMTP/ATP model, for the whole simulation time. The start of the bridge, firing blocking and short-circuit at *c*-phase is easily identified in this figure.

With increasing firing angle and before the reset to zero, at t = 500 ms, the α firing angle is very large and close to 180º. Between $0.49 < t < 0.50$ s, it is large enough to cause commutation failure in the thyristor bridges. Fig. 8 shows that both simulators reproduce this phenomenon with great similarity. Moreover, during thyristor valves commutations, both simulators have represented well the dependence of *di/dt* with firing angle α. As expected, the commutation angle μ is greater after t = 0.5 s, where the firing angle α is zero.

Problems related to numerical instability were verified, particularly with templates of ideal power diodes, as well as in the ideal thyristors of SABER. Somehow, those templates do not work properly for short periods and introduces unreal sudden changes in conducting current that induce very high voltage spikes in the circuit. They are small in amplitude and almost not visible in the curves of current. However, they have very short durations, which represent a very high *di/dt* for the commutation inductances in series with those thyristors. This results in short spikes of voltages across the inductances, but with very high magnitudes. Fig. 9 shows two occurrences of such spikes, in the *a*-phase voltage at the node where the power system is connected with the thyristor bridge and the active filter (point of common coupling, PCC).

With help of Fig. 8, it is possible to see that the first spike of voltage occurs where both thyristors of the branch of phase "a" should remain blocked and was caused by sudden changes of *di/dt* in the thyristors of phase *b* and *c*. The second spike occurs at the beginning of closing the thyristor #1 of phase *a*.

Loss of controllability in the PWM converter of the shunt active filter was also verified, as can be seen in Fig. 10, for the EMTP/ATP, and Fig. 11 for the SABER. During low dc voltage, the PWM converter cannot respond with fast *di/dt* and the synthesized currents do not track their references within the specified tolerance band. Although this phenomenon is verified in both simulators in the same period, here, slightly different behaviors were observed. Although the causes and effects are not easily identified, some aspects that contribute to this divergence of behavior can be addressed, regarding particularities of each implemented model and characteristics from the

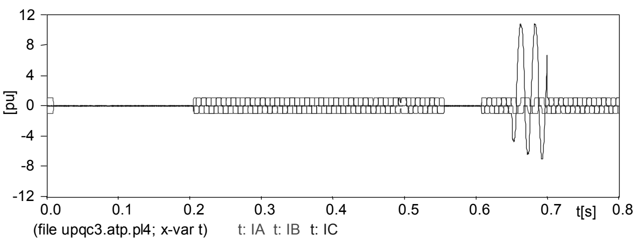

Fig. 7 Currents of the non-linear load (EMTP/ATP simulator).

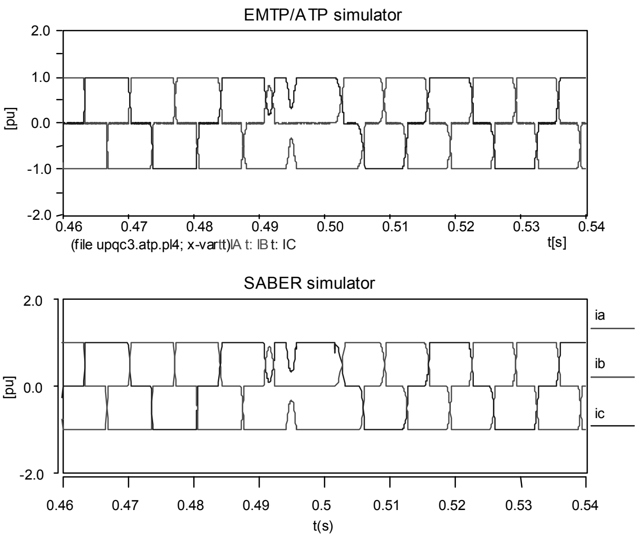

Fig. 8 Thyristor commutation failure in EMTP/ATP (upper) and SABER (bottom) simulators.

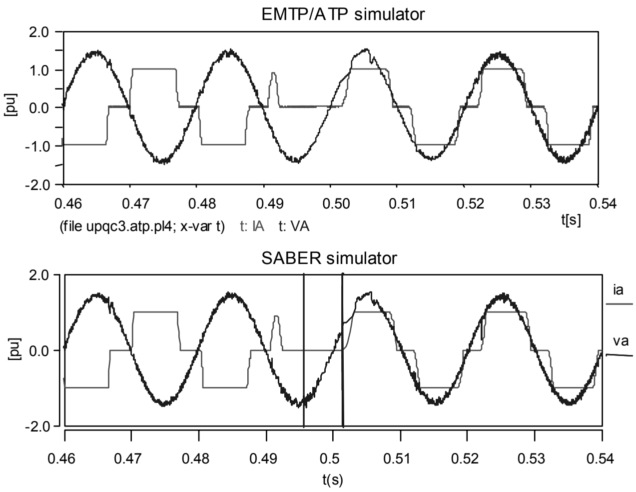

Fig. 9 Numerical instabilities in SABER, which does not occur in EMTP/ATP simulator.

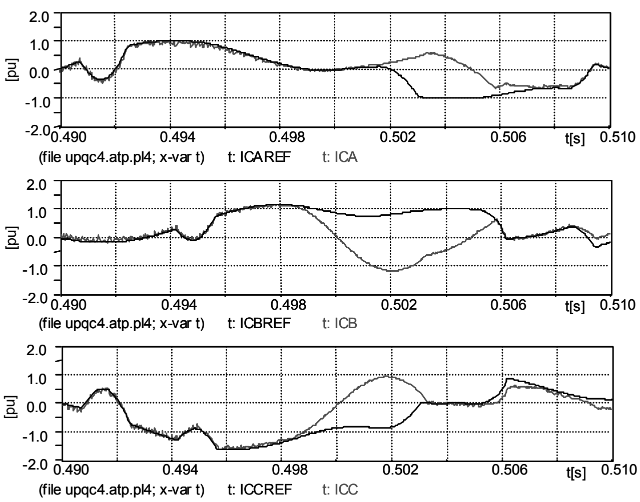

Fig. 10 Loss of controllability in the shunt active filter. Results from the EMTP/ATP simulator.

EMTP/ATP and SABER programs.

The active filter controller works in a closed loop manner to regulate its dc voltage. The reference values for the compensating currents that are determined by the active filter controller contain a portion related to a real power that should be drained by the network in order to keep the dc capacitor charged at its nominal value [4]. In the control system, there are fifth order, low-pass, Butterworth Filters to separate oscillating and average portions of a composed control signals. Such high order transfer functions may be a source of imprecision or divergence between results. Additionally, the hysteresis-band current control of the PWM converter of the shunt active filter comprises an auxiliary control circuit to limit the maximum switching frequency, as well as to limit the minimum pulse width for the power semiconductors, i.e., minimum time that they must remain in ON-state. These features are implemented by relatively complex control subsystems, which were realized with existing predefined templates together with commands in the MAST programming language of SABER. Such powerful commands and built-in templates of the SABER do not meet similar in the TACS (control language/blocks of the EMTP/ATP) and the inherent differences in the implementations may also cause divergences in the simulation results. On the other hand, during loss of controllability, the actual currents of the shunt active filter generate improper real power, causing uncontrollable dc voltage oscillations. Certainly all above issues can contribute, in cascade and in closed loop form, to the observed differences.

The shunt active filter tries also to compensate the fault current, as can be verified by comparing the faulty load currents of Fig. 7 with the compensated currents of Fig. 12, for the EMTP/ATP, and Fig. 13 for SABER program. Again, slightly different behaviors during short periods can be identified, and their causes and effects are very difficult to be pointed out, but the above comments can be addressed here. The fault current contain high amount of zero-sequence components, since c-phase to ground fault is applied. Thus, a three-phase three-wire shunt active filter cannot maintain sinusoidal and balanced the compensated currents. It is supposed that shunt active filters are not adequate for the use in fault current compensations. The short-circuit case shown above has only the purpose of reporting loss of controllability during requests to synthesizing of very high compensating currents and its consequences in the simulation results.

Fig. 14 evidences the numerical oscillation that appears in the voltage at PCC when the short-circuit switch is opened at $t = 0.7$ s, for the EMTP/ATP (upper graphic). Certainly, such oscillations with very high magnitude have no relation to a real physical phenomenon. On the other hand, more frequent short-time spikes appears during "arbitrary instants" in the SABER simulation (lower graphic). Of course, these phenomena are from different nature and particular for each simulator. They are put together as example of possible unwanted inaccuracies that appears in the use of digital simulators. Unfortunately, these undesired aspects are inherent from the integration method adopted in each simulator and the user must be prepared to deal with their possible negative consequences on the obtained results. Certainly, other simulators in the market

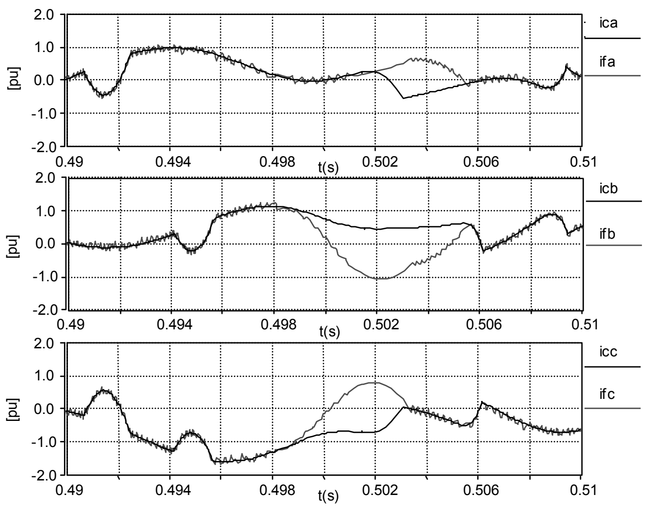

Fig. 11 Loss of controllability in the shunt active filter. Results from the SABER simulator.

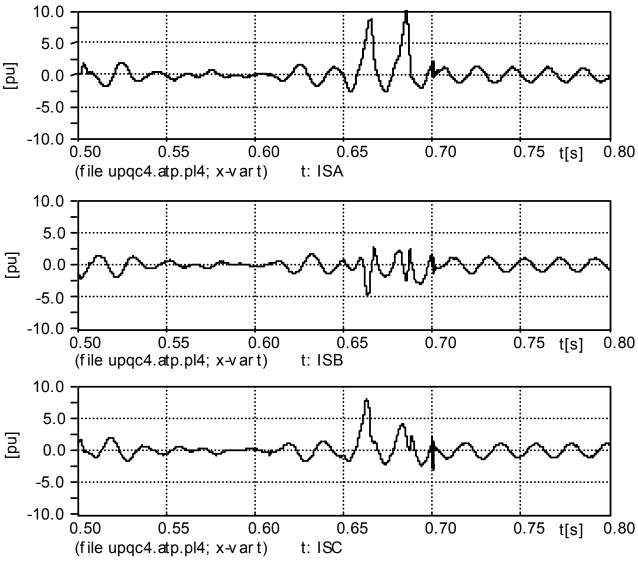

Fig. 12 The compensated currents from EMTP/ATP simulator.

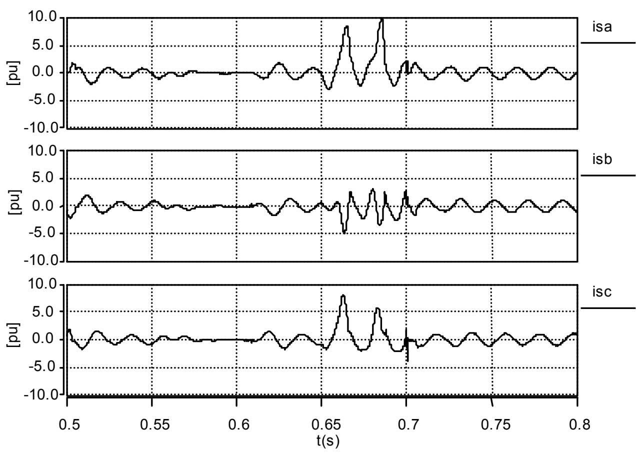

Fig. 13 The compensated currents from SABER simulator.

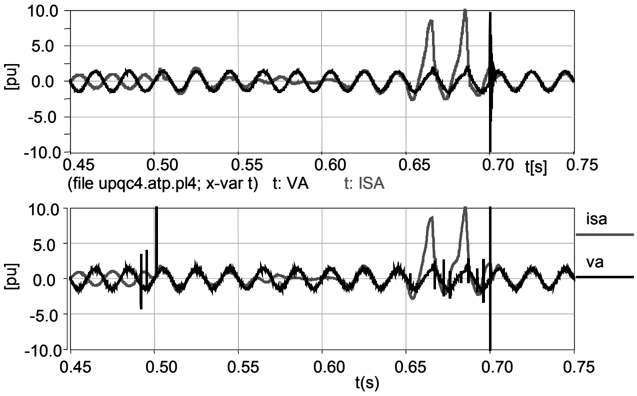

Fig. 14 Compensated current and voltage at the PCC from EMTP/ATP (upper) and SABER (bottom) simulators.

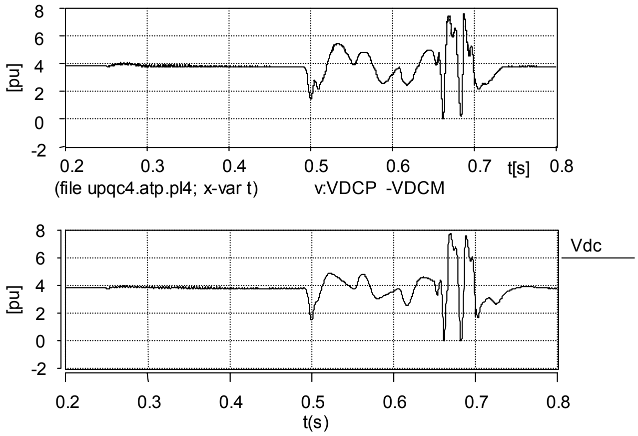

Fig. 15 DC voltage of the shunt active filter from EMTP/ATP (upper) and SABER (bottom) simulators.

have also similar problems.

The dc voltage of the shunt active filter integrates the different behaviors during the simulation, as can be seen in Fig. 15. Although the EMTP/ATP and SABER presented different results, the resulting curves present equal tendencies and periods of oscillations, as well as similar local maximum and minimum values. Therefore, with some restrictions and known limits of operation, one can say that the active filter models are equivalent and both simulators are capable of modeling power systems involving power electronics devices.

VI. CONCLUSIONS

Problems related to the implementation of active filter and thyristor bridge models in both programs, the EMTP/ATP and SABER simulators, are addressed. In addition, convergence problems, numerical instability and oscillations were identified and investigated. One basic conclusion is that *"the best simulator is that one I have in hand"*, dominate it, and know its particular solutions to overcome its limitations and improve accuracy.

Finally, it was possible to conclude that both simulators can be used to study the active filter with satisfactory and coherent results when “macro phenomena” are in the focus of study. In this case, the details related to the semiconductors switches cannot be analyzed. However, accurate models of power semiconductor devices have to be used, if the objective is to analyze details inside the high frequency switching PWM converters. In this case, the program SABER is the best option. On the other hand, when the interest is focused in the investigation of the power system involving fast transient phenomena, refined transmission line models has to be used in place of lumped components as resistors, capacitors and inductors. The EMTP-ATP presents a good model for transmission lines, if the user decides to use its own model. To define a specific model is a difficult task. The SABER simulator does not have a good transmission line model, so far, in its library.

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