PRECISION SIMULATION OF PWM CONTROLLERS

G.D. Irwin D.A. Woodford
Manitoba HVDC Research Centre Inc.
400-1619 Pembina Highway,
Winnipeg, Manitoba, R3T 4Y6
Canada
E-mail: gdi@electranix.com daw@electranix.com

A. Gole
Dept. of Elect. and Computer Eng.
University of Manitoba
Winnipeg, Manitoba, R3T 2N2
Canada
gole@ee.umanitoba.ca

Abstract - **High frequency pulse width modulation (PWM) on large power system voltage sourced converters (VSC) and their controls place high demands on precision in simulation. A method of valve firing using interpolated switching was developed (IPST'99) to avoid very small calculation time steps (in the order of 1µsec). Further improvement to interpolated switching in the form of Instantaneous Solution has been developed to avoid numerical losses in PWM controllers.**

Keywords: VSC Transmission, Simulation, Power Electronics, Voltage Sourced Converters, PSCAD.

I. INTRODUCTION

When voltage or current sourced converters are being designed into a power system, simplified phasor modeling is far from adequate. Harmonic effects, network resonances and controls interact and desirable performance is not always guaranteed without some detailed engineering effort using electromagnetic transients design tools.

The voltage sourced converter is the most important building block of FACTS and for a new generation of dc transmission systems. It is important to ensure they can be simulated with precision and detail.

II. INTERPOLATION METHODS

Switching devices in electromagnetic transient programs are often modeled as resistors that change state (alternative methods use compensation current injections to model the changing resistance, but are limited to only 1 non-linear switching device in the circuit to achieve numerical stability).

Two state devices (thyristors, diodes, GTOs, IGBTs, breakers, faults...) switch from an ON resistance to an OFF resistance, whereas multi-level switching devices (surge arresters) will continuously change the resistance value in a piece-wise linear fashion. Each change of state requires the circuit conductance matrix to be re-triangularized in order to solve for the correct voltages in the next time step. The use of subsystems (sub-circuits separated by traveling wave line models) in the EMTDC program speeds up the switch/solution process since switching operations only force a new solution in its local subsystem, not the entire solution.

In normal fixed time step programs, the switching time resolution is limited by the time step (ie a switching can only occur at time points that are a multiple of the time step). The use of Interpolation as applied to switching devices and control systems removes this limitation by allowing the solution to "back-up" to any instant of time defined by the switching criteria. For example, a diode would cause the solution to back-up in time to when its voltage was exactly 0.0 before it switches, whereas a fixed time step program would switch the diode state in the next time step after the zero crossing.

Interpolation (and variable time step) techniques are described in [1],[2], [3] for both switching devices and control models, both of which are important to achieve best results. The advantages of interpolation are well known, and include:

- Allows simulation to be run with a larger time step without affecting accuracy.
- Results in correct theoretical harmonics generated by switching devices (including HVDC and FACTS controllers) because each switch device fires at the correct time.
- Avoids voltage "spikes" in STATCOM and VSC circuits due to incorrect back-diode turn-on times (unrealistic snubber circuits are required to control these spikes in fixed time step programs).

- Avoids numerical instabilities that can occur due to arrangements of multiple switching devices in close proximity.
- Results in more accurate models of non-linear devices (surge arresters), especially in energy calculations.
- Models correctly the low frequency damping and harmonics of switching devices interacting with SSR effects in machines.

Previous interpolation techniques were used to back-up the solution to a point in time when a switch should occur, after which the switch and time step forward integration were performed in the same step. This is shown in Figure 1 for a thyristor turning off at a current zero.

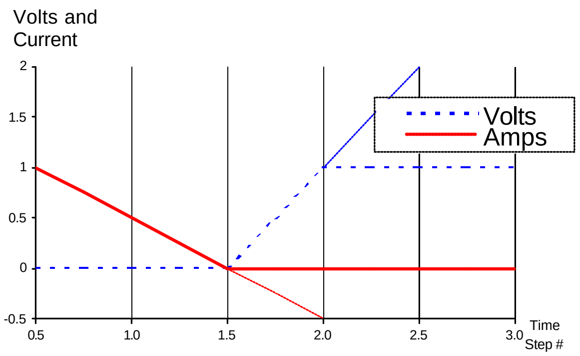

Figure 1: Interpolation (performing switch and integration in one step) for thyristor turn-off

It can be shown, however, that combining the switch and integration steps into one solution can generate higher numerical losses for force commutated switching events (GTO and IGBT). The higher losses result from an interpolated solution point at which both the voltage and current in an ideal GTO are non-zero, as shown for T=2.0 in Figure 2.

To obtain accurate switching losses, it was necessary to decrease the time step, thus resulting in long simulation times.

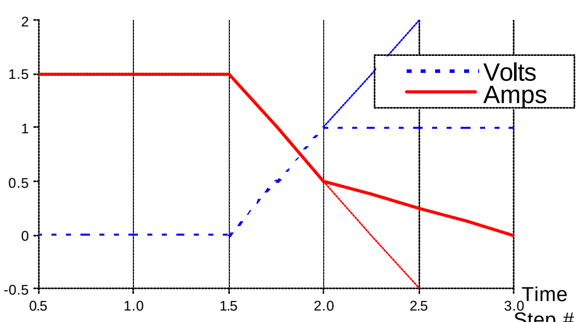

Figure 2: Interpolation (performing switch and integration in one step) for GTO turn-off

III. INSTANTANEOUS SOLUTION INTERPOLATION METHOD

The "Instantaneous Solution" method continues to use the interpolation methods described earlier, however it now separates the solution result due to the switch from the integration process, as shown in Figure 3.

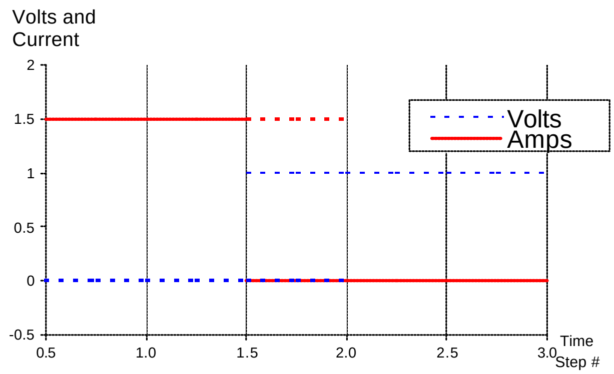

Figure 3: Interpolation (using Instantaneous Solution) for GTO turn-off

Starting from normal operation at Time Step number T=1 (referring to Figure 3), a normal solution is taken to T=2 (the time step is 1 and is constant). The GTO firing controls specify an arbitrary interpolated time (say from the crossing of a PWM level control) at time 1.5, so all node voltages, currents and history terms are linearly interpolated to 1.5 (this is the solution at T-). The GTO changes its branch impedance to its off value, and the GV=I solution is repeated (using the same history terms from I-) to give another solution at T=1.5 (T+), where the branch current is now 0. The integration process is then performed (i.e. the history terms are calculated using voltages and currents from T=1.5+), and a full time step forward is taken to T=2.5 (where GV=I is solved). Finally, a last interpolation is performed to return the solution back to the normal time grid (at T=2), where it can continue normally to 3,4… (until the next switch operation occurs).

Essentially there are 2 solutions (T- and T+) at every point in time that a switch is performed. The T-solution is arrived at using linear interpolation, and the T+ solution is performed using the same current injection input vector (the I in G.V=I), except with the new conductance matrix after the switch. This ensures that any backing-up in time is performed using solutions that are calculated using the same conductance matrix. For the example GTO circuit that exhibited higher losses using classical interpolation methods, now either the voltage or current will be zero, thus giving the correct losses.

The improved solution algorithm also now allows any branch (or any combination of branches) to be ideal (0 resistance) and allows true infinite bus voltage sources (either to ground or from node to node). All additional features of the original interpolation algorithm [1] are maintained:

- Large portions of a network separated by traveling wave transmission lines or cables are separated into subsystems (so interpolations and switchings are isolated to only the required sub-network without having to manipulate the entire network).
- Control of chatter at inductive nodes and in capacitor loop currents is still controlled using the proven ½ step chatter removal process.
- The solution can be interpolated numerous times to accommodate multiple switches that occur in the same time step.

The Instantaneous Solution has all the advantages of the original Interpolation algorithm, plus it will now correctly represent the switching losses for forced commutated devices.

IV. SIMPLE TEST CIRCUIT

A simple circuit to illustrate the excellent performance of the Instantaneous Solution is shown in Figure 4.

The IGBT is first turned on and current IL ramps up through the inductor. Then the IGBT is turned off, and at the same instance, the diode must turn on as the inductor current commutates to it. The commutation process is as shown in Figure 5. The turn-on and turn-off of the IGBT is determined by the instant of transition of the switch (ramp) signal against the level signal.

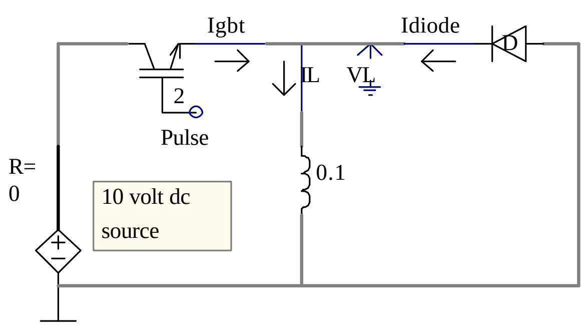

Figure 4: Simulation graphic of simple test circuit with no snubbers.

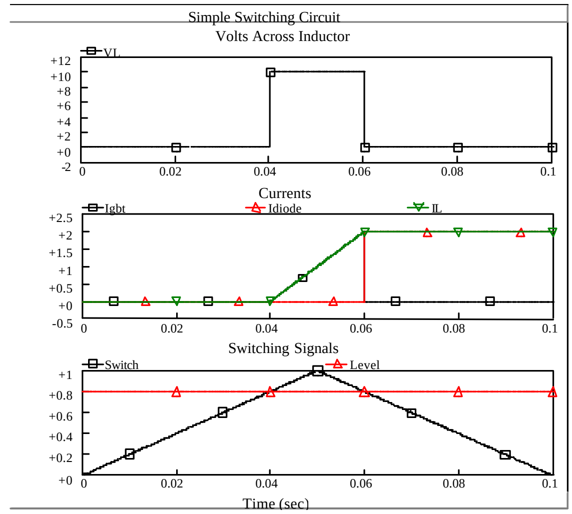

Figure 5: Correct solution to IGBT turning on and off for the simple test circuit.

To observe the turn-off operation, the plots of Figure 5 are zoomed at the point of switch off at around 0.06 seconds in Figure 6. The time and plot step are both 50 µsec.

The results of Figures 5 and 6 are plotted at each discrete time step. Interpolated time steps are not plotted hence the apparent ramp of currents and voltages across the time step that interpolated switching is occurring. The success of the Instantaneous Solution is evident in Figures 5 and 6 as no spikes in voltage and current occur. The simple test circuit of Figure 4 without snubbers on the IGBT or diode is an excellent test for any simulation algorithm.

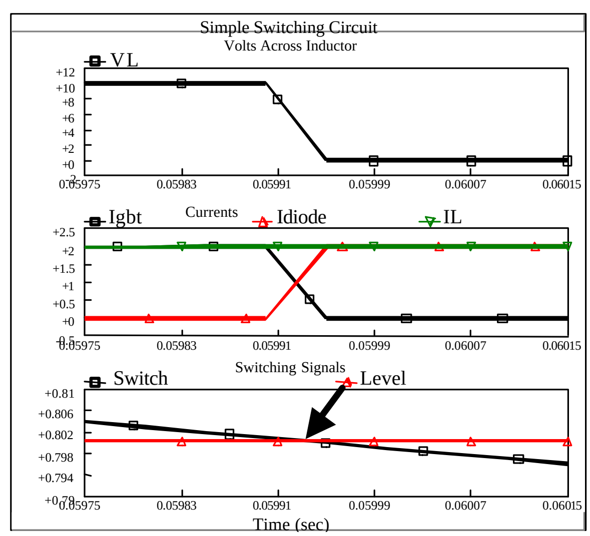

Figure 6: The instant of turn off. The point of transition is between time steps (shown by arrow).

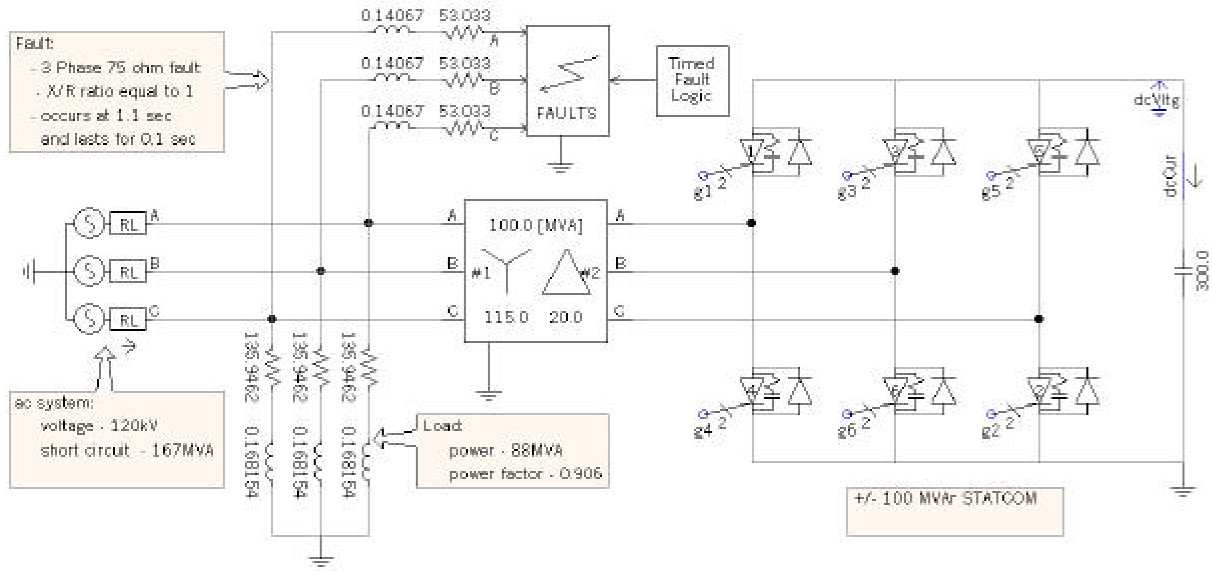

Figure 7: Simulation Graphic of simple 100 MVAr STATCOM

V. LOSS PERFORMANCE

The simple STATCOM of Figure 7 was modeled on PSCAD Version 3. The objective was to examine the impact instantaneous switching has on the observed losses of the STATCOM when high frequency PWM is applied. From the discussion above, interpolated switching allows for the exact instant of valve firing and turn-off in PSCAD and is possible both with and without instantaneous switching.

When applying an interpolated solution without instantaneous switching, a significant portion of the observed losses is numerical and not real. This serves as a caution to any attempting an interpolated switching algorithm.

Varying the solution time step between 1 µsec to 20 µsec both with and without instantaneous switching was applied in the solution method. The apparent losses for the 100 MVAr STATCOM operating at a PWM switching frequency of 1980 Hz is plotted in Figure 8. Losses with the Instantaneous Solution are relatively constant at approximately 0.6 MW.

As the solution time step reduces, the overall calculation time increases. For the computer used (500 Mhz Pentium III), the solution time was observed for one second of simulation and recorded in Figure 9.

There is some overhead in computing time for the instantaneous solution but it is compensated for the fact that together with interpolation, significantly larger time steps are possible with retained precision as shown in Figure 10. Here a 0.1 second three phase remote fault is applied causing the STATCOM to respond in an attempt to control ac volts. A 10 µsec calculation time step exhibits negligible deviation from simulations compared with 1 and 5 µsecs calculation time steps. The 20 µsec calculation time step shows some deviation. Consequently, for this case with 1980 Hz PWM, 10 µsec is a reasonable calculation time step to use.

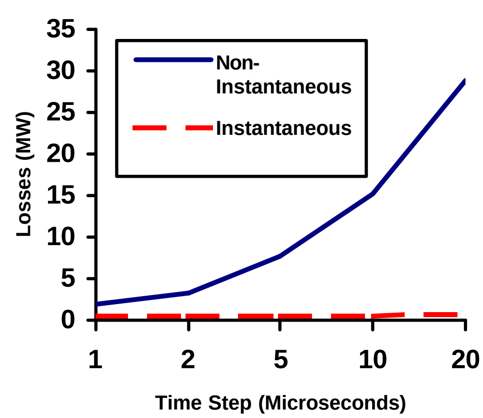

Figure 8: Apparent losses for 100 MVAr STATCOM operating at a switching frequency of 1980 Hz for non-instantaneous and instantaneous network solution methods.

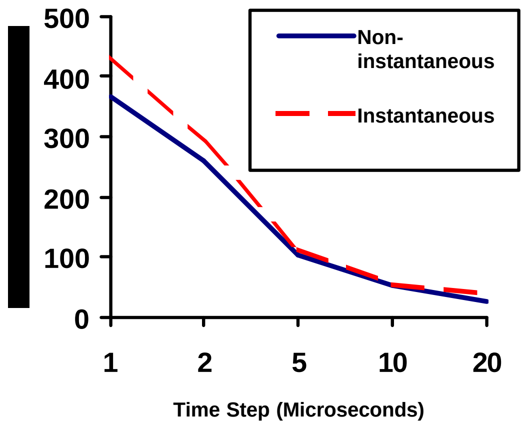

Figure 9: Overall computation time for non-instantaneous and instantaneous solution methods for STATCOM example with PWM switching frequency of 1980 Hz.

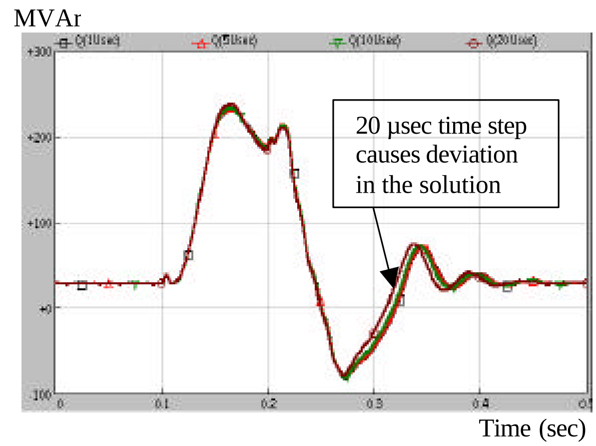

Figure 10: Response of measured reactive power of STATCOM simulation for calculation time steps of 1, 5, 10 and 20 µsec.

VII. CONCLUSIONS

The need for good performance when modeling voltage sourced converters places increased demands on simulators. High frequency PWM is a particular challenge that required the solution method of PSCAD to be improved by incorporating instantaneous switching into the interpolated switching algorithm.

The results of this successful development allow larger calculation time steps and hence faster solution times without compromising on precision in the simulation.

Although very simple examples have been presented, the Instantaneous Interpreted Solution is being successfully applied to large power electronic simulations without known limitations.

VIII. REFERENCES

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