TEST OF PWM POWER ELECTRONICS DEVICES FOR ELECTRICITY NETWORK USING DIGITAL REAL-TIME SIMULATOR

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INTRODUCTION

The tests of power system equipments are required either in the design phase, during the qualification and the validation, or in case of malfunctions. These tests are needed to check equipment’s behavior itself as well as its interactions with the power system.

An effective and flexible solution to realize these tests avoiding device destruction and voltage risks for people is to use digital real-time simulation.

Power electronics devices are in sustained development in power systems for power quality (D-FACTS) or power producers interfacing. Generally, control systems of power electronics devices use Pulse Width Modulation (PWM). The main advantages of PWM compared to full wave control are the improvement of controllability, performances and mitigation of harmonic generation.

Real-time simulation of these PWM devices is difficult due to the large needed simulation time-step compared to the high PWM switching frequencies (more than 1kHz).

This paper presents a new solution to obtain real-time simulation of PWM power electronic devices. As a validation, a benchmark was realized for testing a Static Var Generator (SVG, also called D-STATCOM or SVC light) control device for distribution power systems.

DIGITAL REAL-TIME SIMULATION OF CONTROL DEVICES

The digital real-time simulator ARENE URT, used in this work, is developed by the French utility “Electricité De France” (EDF R&D). ARENE URT (figure 1) is composed of a bi-processor calculator, a communication rack and a Graphical User Interface (GUI).

![ARENE URT diagram](image)

**FIGURE 1:** ARENE URT and real-time simulation.

To test power electronics control devices in real-time, the mathematical models of the power system and the power electronics devices are realized in ARENE URT. The tested control device is connected to ARENE URT through the interfaces boards (Analogical and Digital) of the rack.

An interaction is realized between ARENE URT and the control device, signals are exchanged and a closed loop simulation is realized. The real-time constraint means that the simulator has to respect the time of considered phenomena driving physical laws of the tested device.

The applications of real-time simulations for power systems can be:

- the setting and prototyping of an equipment before its connection to the power system [1]. The purpose is to obtain a secured test system for material and personnel. Actually, exchanged signals between the real-time simulator and tested devices have low-voltage levels and small energy;

- the test of a faulty equipment. For example, a scenario can be created on the simulated power system or recorded data of a real power system can be “replayed” by the simulator to check equipments operation. The purpose is to find the problem and to repair or improve the equipment. The security is also guaranteed for the system;

- the test of an industrial equipment [2] by creating faults in the simulated power system. The purpose is to improve the control device behavior in normal but also in critical situations. The main advantage of digital real-time simulation is to obtain reproducible tests.

LIMITATIONS OF REAL-TIME SIMULATORS

Limitation of the simulation size

The real-time simulators need a fixed time-step to synchronize data exchanged with the tested equipment. The length of the time-step is defined by the user before the real-time simulation. But, in order to achieve a real-time simulation, the data computed by the simulator must be restituted to the tested equipment before the end of a time-step (figure 2). Thus, the computation and acquisition time of the simulator must be smaller than a simulation time-step.

![Tasks of the real-time simulator](image)

**FIGURE 2:** Tasks of the real-time simulator.

Moreover, the computation time depends mainly on the...
Fixed time-step and power electronics simulation

The effect of a fixed time-step on power electronics is significant. Commutation time cannot be determined with the great accuracy because firing pulses or current extinctions can occur between two time-steps. Special algorithms have been developed to obtain more accurate representation of the switching events [3], [4]. In the figure 3 example, the CSSC [5] (ARENE URT) is used to correct the wrong negatives values on a diode current. When a negative diode current is detected, the CSSC algorithm performs an interpolation to retrieve the exact current extinction time. From this event, one time-step integration is performed and finally an extrapolation is realized to re-synchronized data with the tested equipment.

The detection algorithms are not able to operate in real-time simulation with higher switching frequencies than the kilohertz [3] because more than one commutation can occur during a time-step. The case of PWM devices is delicate: the switching events can occur aperiodically and asynchronously regarding the three phases. To obtain good simulation accuracy, the minimum impulsion time (Tmin) defined on figure 4 has to be detected. For example, Tmin=10µs for a switching frequency of 10 kHz (i.e. T_PWM=100µs) with a modulation index of 0.8 (= modulation signal amplitude / carrier signal amplitude). Moreover, for real-time simulation of PWM control devices the simulator inputs are the PWM signals. Thus, according to the Shannon’s sampling theorem, the time-step has to be a half of Tmin (5µs) to correctly sample signals. Thus, according to the Shannon's sampling theorem, of PWM control devices the simulator inputs are the PWM carrier signal amplitude). Moreover, for real-time simulation the switching frequency of 10 kHz (i.e. T_PWM=100µs) with a figure 4 has to be detected. For example, T min=10µs for a possible. Reducing the time-step to improve the detection of devices with higher switching frequencies than 1 KHz is not possible because of the limitation of the time-step by the acquisition and computation time.

To overcome this obstacle, new solutions are developed in this work. Firstly, fast models of power electronics devices are used to reduce the computation time. Secondly, PWM signals are adapted to the real-time simulator with hardware and software interfaces (figure 5).

TEST OF A PWM CONTROL DEVICE OF SVG USING A REAL-TIME SIMULATOR

The Static Var Generator (SVG)

The SVG is used to absorb or provide reactive power to the power system. The core module of the SVG is the three-phase Voltage Source Converter (VSC). Others applications are VSC based as well, like the Dynamic Voltage Restorer (DVR), the Power Quality Conditioner (PQC also called UPFC for grids) or interface devices for power generation like, for example, wind power systems... The SVG is composed of a VSC connected to the power system through a current filter inductor (L) that could be the inductor of a coupling transformer (figure 6). The DC side is composed of a filter capacitor (C) and to represent the inverter active losses: a resistor (R).

The control device maintains the reactive power to its reference Qref and the DC voltage to its reference Voref by generating the PWM signals (U123).
The **average modeling.** An efficient way to obtain fast, simple and accurate models is the average modeling [7] [8]. An average model represents the average behavior of the system between two commutations. The main advantage is to obtain time-invariant models, thus the same state representation is valid for the whole simulation. The main drawback is the frequency range limitation for the studies, because the switching frequency is not modeled.

The first step to realize average model is to build exact mathematical differential equation of the system (classical model). The second step is to apply the average sliding window (width of TPWM) on the states variables (which can be inductors currents and capacitors voltages) and on the input control signals. The average sliding window for a kth harmonic in case of PWM devices is defined as:

\[
\langle f(t) \rangle_k(t) = \frac{1}{\tau_{PWM}} \int_{-\tau/2}^{\tau/2} f(\tau)e^{-jk\omega t} d\tau
\]

**Average model of three-phase VSC.** The classical model of the VSC is defined by a vector representation of differential mathematical equations. The signals can be defined as:

<table>
<thead>
<tr>
<th>PWM signals</th>
<th>( U_{123} = (U_1, U_2, U_3)^T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductors currents</td>
<td>( I_s_{123} = (I_{s1}, I_{s2}, I_{s3})^T )</td>
</tr>
<tr>
<td>Power System voltage</td>
<td>( E_{123} = (E_1, E_2, E_3)^T )</td>
</tr>
<tr>
<td>VSC voltage</td>
<td>( V_{S_{123}} = (V_{s1}, V_{s2}, V_{s3})^T )</td>
</tr>
</tbody>
</table>

A matrix “A” can be defined as:

\[
A = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}
\]

To obtain average model of VSC, the sliding average window (width of TPWM) is applied on the PWM control signal. The average control signal can be expressed as:

\[
\langle U_{123} \rangle_0 = \beta_0 \quad \text{With:} \quad \beta_{123} = (\beta_1, \beta_2, \beta_3)^T
\]

The average control signal can be applied to states variables:

- the average current in the inductor L:

\[
L \frac{d \langle I_{s_{123}} \rangle_0}{dt} = \langle E_{123} \rangle_0 - \frac{1}{6} A \beta_{123} \langle V_c \rangle_0
\]

- the average voltage in the capacitor C:

\[
C \frac{d \langle V_c \rangle_0}{dt} = \sum_{k=1}^{3} \left( \frac{1}{2} + \beta_k \right) \langle I_{s_k} \rangle_0 \frac{\langle V_c \rangle_0}{R}
\]

The inputs and outputs of the average VSC model can be represented as:

![FIGURE 7: Representation of input and outputs of the VSC average model.](image)

**Validation of the average model of VSC.** The validation of the average model of VSC has been realized for the SVG application with the Matlab / Simulink software. To measure accuracy of the average model, two simulations (not in real-time) were realized. In the first simulation, the reference model was established with a classical model (exact mathematical equations) and variable time-step (maximum time-step of 10µs). The second simulation was realized with an average model and a fixed time-step of 20µs. Reference variations of currents and DC bus voltage were realized to compare the models accuracy during transients.

The injected currents of exact and average model of VSC are showed on figure 9.

![FIGURE 8: Injected current by classical and average model of VSC.](image)

The classical and average models of VSC simulated respectively with a variable time-step and a fixed time-step of 20µs are similar. During the transient a small gap is visible, but in steady state the accuracy of the average model is quite good. We can see on figure 8 that harmonics on currents are not modeled by the average model, but these harmonics are weak due to the filter inductor and the higher cutting frequency (10 kHz).

If the accuracy determined by a criterion of root mean square deviation is fixed at 10%, the average model can be simulated with a fixed step of 55µs. For the classical model simulated with the same conditions, the fixed time-step needed to obtain the same accuracy is dramatically reduced to 2µs. Thus, regarding their accuracy, average models of PWM power electronics devices are very well adapted to fixed time-step simulations and particularly for real-time simulations (50µs typical fixed time-step).

**Realization of the hardware interface**

The aim of the hardware interface is to extract the average value of the PWM signals. The hardware interface is located inside the closed loop performed by the real-time simulation (figure 5).
It is the reason why the delay of the interface must be minimized to avoid closed loop instability in the real-time simulation.

A very good solution to reduce this delay is on use of Digital Signal Processor (DSP) to compute the average value of the three-phase PWM signals during $T_{PWM}$. Special tools of the DSP called “Timers”, are dedicated to time intervals measurement and can be synchronized with rising or falling edge of the PWM signal. Thus, the computation of average value can be performed simply.

The original signal (modulation signal) is used by the control device to generate the PWM. The PWM is input of the hardware interface and as it can be seen in figure 9 the extracted signal is very similar to the original signal. Compared with the simulator time-step of 50µs the measured extraction delay of the interface is very tiny (2µs).

REALIZATION OF THE BENCHMARK

The objective of the benchmark (figure 10) is to test the PWM control device of SVG with the real-time simulator ARENE URT. The tested control device is realized with DSPACE (real-time system dedicated to control device prototyping). The DSPACE is DSP based which can be easily programmed with compiled source generated by Matlab / Simulink.

Because of the use of a VSC average model and a small size power system, the simulation time-step of ARENE URT can be reduced to 30µs. Each simulation time-step, measurements from the simulated power system and the average model of VSC are generated by ARENE URT. The control device of SVG (DSP) takes these measurements, realizes the computations to control injected reactive power to the power system and the DC bus voltage of the VSC and generates PWM (10 kHz cutting frequency). The hardware interface (DSP) extracts modulation signals from PWM for ARENE URT and thus, a real-time closed loop simulation is realized.

Results of the test of the PWM control device of SVG

To validate the test of the PWM control device, the results of the real-time simulation perform with ARENE URT were compared with a “classical” simulation (not in real-time version of ARENE) taken as reference. It must be noticed that to perform the classical simulation, the control device of SVG had to be also simulated: the same parameters as the real-time simulation were used and a fixed time-step of 30µs was chosen. Moreover, delays were included to model the acquisition and computation time of ARENE URT: two simulations time-steps (60µs) and for DSPACE one fixed simulation time-step (120µs).

The real-time working of the system was verified for steady state operation but also for transients. Step variations are performed for the reactive power reference ($Q_{ref}$) of +100% and in the DC bus voltage reference ($V_{ref}$) of +5%.
The figure 12 shows the three phase injected currents to the power system by the SVG, the figure 13 shows its DC bus voltage. The figure 14 shows the modulation signals used by the average model of VSC. In red dash line, the real-time simulation results and in blue straight line the classical simulation results. In steady state the simulations are very similar, but little gaps in transients are visible. These gaps are mainly due to the delays not compensated in the classical simulation. Delays cause instability is the closed loop simulation; it is the reason why little oscillations are visible on the curves figures 12 and 14. Delays were mainly caused by:
- the physical restitution of simulation signals by the digital to analog converters of ARENE URT;
- the generation of the PWM by DSPACE;
- the hardware interface.

But these effects are weak and the results obtained with the real-time simulation are very similar to the classical simulation. These good results validate the benchmark.

CONCLUSION

The test of a PWM control device of SVG with a real-time simulator was successful. The use of an average model of VSC combined with a hardware interface made it possible and seems to be a very good solution to test others power electronics devices controlled with high switching frequencies.

The results show that average models are very well adapted to fixed time-step simulations of power electronics devices because of their accuracy and their low computation time. For the future prospects, other applications will be realized like for example hybrid simulation to test power equipments. The hybrid simulation can be realized with the real-time simulator and a power amplifier. In that case, signals generated by the simulation are amplified by the power amplifier to drive the tested power equipment. The aim is to study the interaction of the physical equipment in a simulated power system, in normal and disturbed working cases by realizing faults in the power system.

REFERENCES


