Mixed signal simulation in the field of adjustable speed drives

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Abstract

The paper deals with the main problems to solve in order to simulate precisely the behavior of complex power systems with mixed elements (power components and digital regulation devices). The main features of an efficient simulation tool are described. They are focused on modern adjustable speed drives. Finally, the simulation of an industrial application of an induction motor fed by a three-level inverter tuned with a DTC (Direct Torque Control) is presented in details.

1.- Introduction

During the last few years, the efficiency of numerical simulation tools has been considerably improved. It is possible today to simulate in details complex electrical systems comprising several components, like large power systems or modern adjustable speed drives [1]. The electrical, mechanical and electronic power components are represented with sophisticated models also taking into account nonlinear properties. As the regulation part of these complex systems is today more and more based on digital devices, the numerical simulation tools have to offer corresponding models for the different digital regulation devices. Such extended tools are called analog / digital or mixed signal simulation tools. The simultaneous presence in one simulation tool of both analog and digital elements, which interact, must be analyzed very carefully. It is necessary to take into account the interactions and the information exchange between the elements of both types according to their physical behavior. This requirement induces some questions, which must be solved in order to built an efficient mixed signal simulation tool.

2.- Mixed signal simulation tools for complex power systems

This section will present the main characteristics of a mixed signal simulation tool.

2.1.- Analog and digital devices

In addition to the possibilities offered by a conventional numerical simulation program (models for the different electrical and mechanical system components, for the power electronics and for the analog regulation devices), a mixed signal simulation tool must include a model for the most important digital regulation and control devices used today as shown in figure 2.1.1.

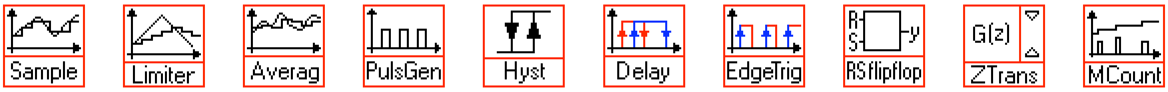

Fig. 2.1.1: *Examples of digital control devices*

An example of a power system including analog and digital elements is represented in figure 2.1.2. To analyze correctly such a system, the simulation tool must be able to simulate analog elements (synchronous machine, transformer, mechanical systems, regulators or other analog control devices), analog nonlinear elements (circuit breaker, semiconductors, saturation) and digital regulation devices (Z-Transformation or other kinds of digital control devices).

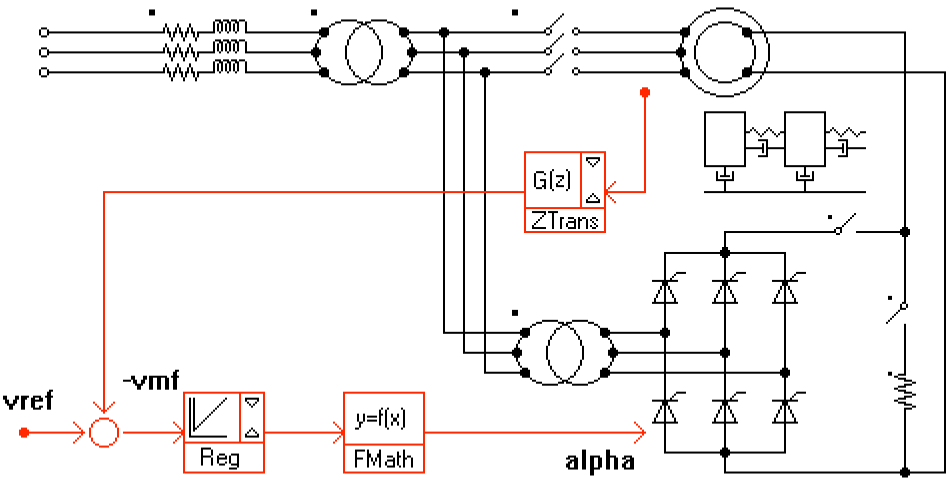

Fig. 2.1.2: Example of power system including analog and digital elements

The nonlinear elements as well as the digital elements generate events during the integration step. To correctly take into account the digital behavior of the regulation, like for example, the different sampling periods or tasks of a DSP (Digital Signal Processor), the simulation tool must be able to calculate each digital value in accordance with its sampling period. The simulation tools have to use back-tracking procedures to restart a new integration with a shorter step in order to reach exactly the detected event. This type of tool is able to simulate correctly analog and digital signals. The solution we developed is the following: After each integration step, the main system is calling all the units involved in the simulation (analog or digital). The system calculates all the new values corresponding to the end of the last integration step. These values are provisional and will be used to detect events during the last integration step. If no event is detected, the system saves the new values and start a new integration step. If one or more events are detected, the system chooses the first one and restarts a new integration with a reduced step in order to reach exactly the detected event.

2.2.- Synchronous and asynchronous behavior

To allow the simulation of asynchronous tasks, it is necessary to implement digital devices with their own clock. This means that each digital component is working independently. The new regulation processes can even use several independent DSP’s having sampling periods without an integer ratio between each other. The synchronization of several digital components belonging to the same task must however be possible. During the simulation, a control task must detect the sampling instant of each digital device. This detection corresponds to an event appearing during the last integration step. In other words, all the values of a digital unit are calculated only at its sampling instant. The main simulation system doesn’t make any difference between an event coming from the change of state of a semi-conductor or from the reached sampling instant of a digital device. If these two conditions are fulfilled, the simulation tool can be called mixed signal simulation system.

2.3.- Measurements and A/D converters

The measurement modelling has to take correctly into account the accuracy of an A/D converter. This means that the sampling unit must not only read the measured value but also convert it in accordance with the range of measurement and the number of bits available for the conversion. The following example can illustrate this feature for a voltage measurement:

4 kV measurement with 10 bits. Removing one bit for the sign, the accuracy is given by:

$$\frac{4kV}{2^9\,levels}=\frac{4000\,V}{512\,levels}=7.81V\,/\,level \qquad (2.1)$$

The same example is illustrated in figure 2.3.1 for a DC-link voltage with the above accuracy and a 100µs sampling period.

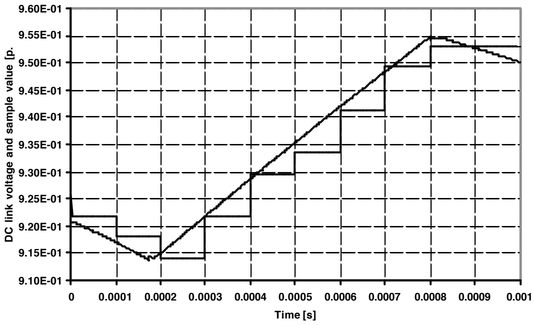

Fig. 2.3.1: *Real and sampled values*

2.4.- Exchange of values

To combine easily digital and analog signals in the regulation part, a possible solution is to develop units that can work independently. Each unit contains input values **x** and output values **y**. A digital unit reads its inputs **x** and calculates its outputs **y** only when the sampling instant is reached. On the other hand, an analog unit does it all the time. In the upper part of figure 2.4.1, the two mathematical functions (FMath) are analog. As their inputs **x** are calculated values coming from a digital unit (Sample), the output values **y** are also digital.

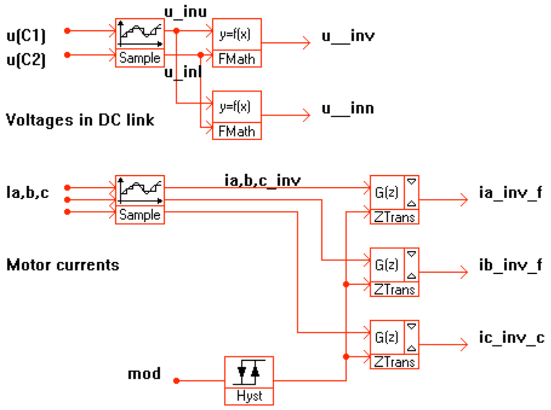

Fig. 2.4.1: *Combination of digital and analog units*

The next code is related to the mathematical function UINV calculating the sum of the two DC-link sampled voltages.

```
- GENERAL DATA :

Name    = UINV
Comment = y1=u__inv
Writing = NO

- REFERENCES X :

USAMPLE y1 1 0 u__inu [p.u]
USAMPLE y2 1 0 u__inl [p.u]

- REFERENCES Y :


- DATA :

SUM
```

To improve the flexibility of the system, each unit is able to modify parameters of other units. In the lower part of figure 2.4.1, the hysteresis control (Hyst) tunes on-line the time constant of three digital low-pass filters (ZTrans).

2.5.- Regulation sequence

To implement the regulation part, a simple solution is to use several predefined units each having a special function. By exchanging values between the different units, it is possible to easily implement the desired regulation algorithm. To respect the regulation sequence, all the regulation units are sorted according to the following rule: each input value **x** of a regulation unit must already be calculated before its use in any other regulation unit. Unfortunately, there are some cases where this rule cannot find a solution, as for example, the case of a Phase Locked Loop (PLL) shown in figure 2.5.1.

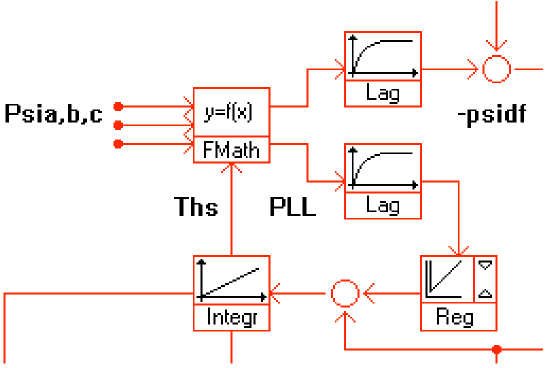

Fig. 2.5.1: *Phase Locked Loop (PLL)*

```
Name     = PSIDQ
Comment  =
Writing = YES

- REFERENCES X :

IM1   Psia 1/PSIREF 0 psia [p.u]
IM1   Psib 1/PSIREF 0 psib [p.u]
IM1   Psic 1/PSIREF 0 psic [p.u]
%THS  y    1        0 Ths  [p.u]

- REFERENCES Y :


- DATA :

PARK1

- GENERAL DATA :
```

The mathematical function FMath is calculating the coordinates transformation from 3 phases to d and q axes. The unit is using 3 phase values Psia,b,c and an angle Ths coming from an other unit Integr. One output **y** of the FMath unit is used in a low-pass filter Lag. The output **y** of that low-pass filter is used in a regulator unit Reg. The output **y** of that regulator unit is used in an integrator unit Integr. One can easily see the problem of the closed loop. The unit FMath is using the output y of the integrator Integr. Applying the rule mentioned in the above section, the check for the regulation sequence will not find a solution. In that case, the simulation tool must give the possibility for the user to either by-pass this check or to impose his own sequence. This possibility has been provided using an additional symbol *%*. If the checking task encounters that symbol, the input signal **x** will not be taken into account for the definition of the regulation sequence. In the end, the user must have the possibility to show the selected sequence in a netlist (list with all the components active in the simulation). In the case of a PLL, it is clear that if the unit FMath is using an angle Ths coming from an integrator, there is only a very small error if the function is using the angle Ths calculated after the last integration step instead of the present angle at the end of the new integration step. Another advantage of this method is the possibility to implement in details the regulation of a complex power system. Simulation tools are generally inefficient when they have to implement a lot of closed loops or when they need to automatically adapt parameters in the regulation part to the operating point of the power system.

2.6.- Summary of the main features for mixed signal simulation tools

- Linear and nonlinear elements (electrical machines, semiconductors, mechanical systems)
- Analog regulation devices (Regulators, S-Transfer functions)
- Digital regulation devices (Regulators, Z-Transfer functions)
- Synchronous or asynchronous tasks taken into account using a clock for each digital unit
- Accuracy of A/D converters taken into account according to the number of available bits
- Simple exchange of values between analog and/or digital units
- Closed loop regulation sequence may be mastered by the system
- Free definition of the regulation sequence by the user and available check in the defined netlist

If the above mentioned features are present, the simulation tool may be called mixed signal simulation tool and will be able to simulate carefully complex power systems with digital regulation devices.

3.- Example of an industrial drive

The chosen example is related to the new ABB medium voltage drive system called ACS1000 [2].The whole power part as well as the complex digital regulation have been simulated using the ***SIMSEN*** simulation tool developed at the Swiss Federal Institute of Technology [3].

3.1.- Power system part modelling

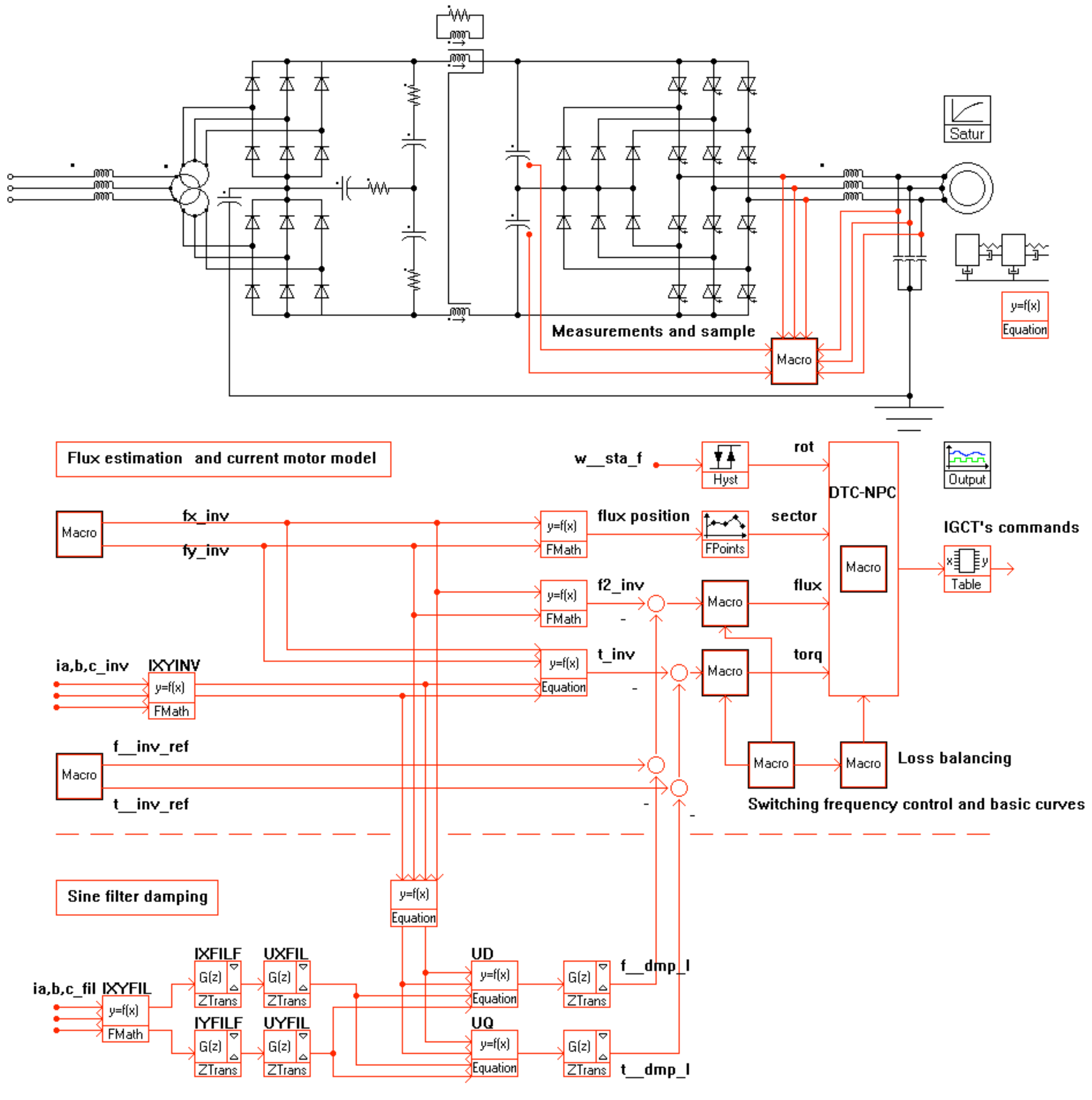

Fig. 3.1.1: Induction motor fed by a three-level inverter with L-C output sine filter

Figure 3.1.1 shows the studied system. The squirrel cage rotor induction motor is supplied through a three-level Voltage Source Inverter (VSI) containing 12 IGCT's (Integrated Gate Control Thyristor [4]) and 6 Neutral Point diodes. An additional L-C output filter is connected between the inverter and the machine. This filter offers three advantages: The motor is supplied with a voltage which closely approximates a sine wave, the starpoint of the filter is grounded to avoid any overvoltage on the insulation of the motor and no zero sequence currents are introduced in the motor. On the other hand, the major inconvenient is an additional control to damp the filter oscillations. The DC-link voltage is stabilized with 2 capacitors. As the starpoint of the filter is grounded, the DC-link contains an additional common mode choke to damp the common mode current. Any homopolar current in the DC-link will induce a current in the third choke. This current is damped by the common mode resistor. The DC-link is supplied through a 12 pulse diode rectifier supplied itself by the AC network through a three-winding transformer. Additional snubber circuits in the DC-link are also taken into account. The mechanical shaft, rotor and pump have been modeled with 2 rotating masses. The mechanical load is a square function of the speed to respect the pump behavior. All the semi-conductors are modeled with lumped R-L elements and voltage supply. This kind of modelling is good enough to analyze complex power systems as long as the physical behavior is correctly taken into account [5]. It presents two other advantages: speed of computation and numerical stability.

3.2.- Regulation part modelling

3.2.1.- Measurements and sample

Even if it is possible to measure the motor voltages, this solution is actually too complicated and too expensive. For that reason, the control is only measuring the two DC-link voltages in the upper and lower parts of the inverter. These two voltages are sampled with 100µs. The inverter and filter phase currents are measured. These currents are sampled with 25µs.

3.2.2.- Flux estimation and current motor model

All the regulation is defined in a fixed referential using two axes x and y 90° phase shifted. The principle of the stator flux estimation is based on a voltage integration acting every 25µs. Depending on the switching state of the inverter, the voltages in the x and y axes are deduced from the two DC-link voltages. Such an estimation is naturally not good enough at low frequency (< 10%) even if the stator winding resistance is taken into account. An additional and complex current motor model has been implemented in details to correct the output of the voltage integration every 200µs. The obtained results are very good, even at standstill. The frequency is also deduced from the motor model.

3.2.3.- Direct Torque Control (DTC)

The DTC is explained in [6]. The main advantage of this regulation is the fast response of the electromagnetic torque (some milliseconds). Figure 3.2.1 shows the voltage vectors numbering, the allowed transitions and the x, y axes defined for the regulation. The principle of the DTC regulation is to select an optimal vector in order to correct the stator flux magnitude and position. The x, y area is split in 12 sectors of 30°. The sector 1 is defined between the x axis and the vector number 1.

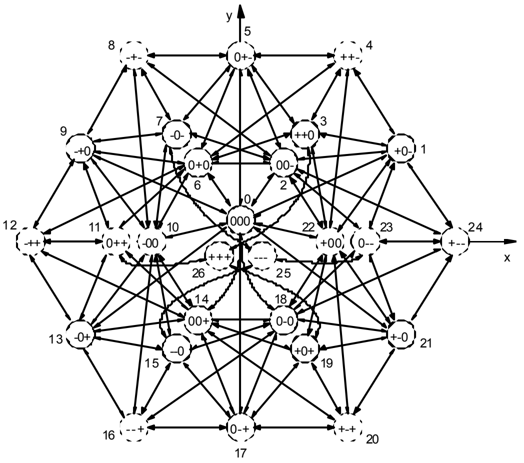

Fig. 3.2.1: *Vector numbering and allowed transitions*

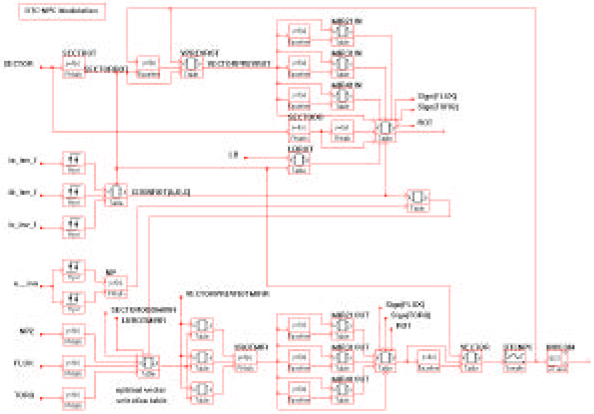

Fig. 3.2.2: *DTC and NPC implementation*

At each regulation step (25µs), the control calculates in which sector the stator flux is located. The flux magnitude and the estimated torque are compared to their reference values through hysteresis controls. Depending on the flux sector and the output signals of the hysteresis controls, an optimal vector is selected among the set of available vectors shown in figure 3.2.1. For example, if the stator flux is in the sector No 1 (0-30°) and the flux and the torque magnitudes are too small, the DTC will choose the voltage vector No 5 (0+-) to increase the flux magnitude and the flux angle (this will increase the torque). As the inverter is built using only one snubber circuit for the three phases, one can only have one transition in each half of the inverter at one time. This is the reason why the allowed transitions are also taken into account. The whole DTC control has been implemented with logical tables as shown in figure 3.2.2.

3.2.4.- Neutral Point Control (NPC)

It is interesting to observe that some vectors with different numbers provide the same output voltage but are acting either on the upper DC voltage U_{DC1} or the lower DC voltage U_{DC2}. The Neutral Point Control (NPC) is responsible for the deviation between the 2 DC-link voltages keeping it as small as possible [7]. The NPC is also working with hysteresis control. Having a look at figure 3.2.1, one can easily see that for vectors 2-3, 6-7, 10-11, 14-15, 18-19, 22-23, one phase is connected to the middle point of the inverter. This means that a current will charge or discharge the related capacitor. Without any regulation, the deviation can increase. To avoid this problem, the NPC will choose between the different possible vectors of the above set according to the sign of the phase currents.

3.2.5.- Sine filter damping

The resonance frequency of the L-C filter has been chosen in the range of 350-400 Hz. Thus both main frequency (up to 75 Hz) and switching frequency of the valves (500 Hz) don't match the L-C filter resonance frequency. Nevertheless, an additional regulation is needed to damp the oscillations of the filter [8]. This regulation is based on uncoupled d and q components calculated with the flux and the voltage of the motor every 25µs. Both components are added to the torque and flux set values. In comparison with the control without L-C filter, this is only a small adaptation and doesn't have a big influence on the regulation algorithm.

3.2.6.- Switching Frequency Control (SFC) and loss-balancing

As the switching instants are not provided by a carrier signal like in a Pulse Width Modulation (PWM), the hysteresis widths have to be well selected. Constrained by the power electronic part of the drive, the switching frequency of each IGCT cannot go over 500 Hz. The SFC is acting on the hysteresis width of both flux and torque controls to increase or decrease the switching frequency (average value). The goal of that regulation is to keep the switching losses in an acceptable range. An additional loss-balancing control equalizes the losses in the upper and lower part of the inverter at low speed (n < 30%). The SFC is working every ms.

3.2.7.- Reference set values

The flux and torque set values are calculated in the flux reference chain and torque reference chain. The flux reference chain is taking into account the rotor time constant of the motor in order to avoid over current during changes of set value and the field weakening point of the motor, based on the operating point, the DC-link voltage, the frequency and the desired set value of the flux. The torque reference chain contains a PI control for the speed, taking into account the slip of the motor. Additional features compensate the hysteresis of the DTC. The set values are updated every 2ms.

3.3.- Simulation results and measurements

All the simulations have been applied to a real industrial drive with the rated values 1.4 MVA, 4 kV, 60 Hz, 2p=6. Measurements have been recorded in steady-state and in transient operating modes. The simulation is providing one results file per element. The user can see more than 1000 signals coming from both the power and the regulation parts. The main problems that have been successfully solved are the multiple interactions defined in the regulation. For example, the SFC (Switching Frequency Control) is adapting the width of the hysteresis control used in the DTC (Direct Torque Control). The calculation of the new selected vector is based on the previous value of the vector. The 25µs calculation time of the DSP is also taken into account.

3.3.1.- Steady-state operating point at rated flux, speed and current

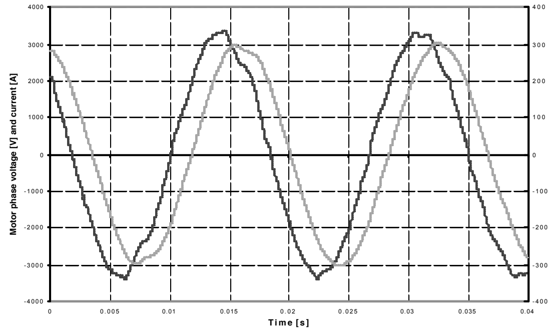

Fig. 3.3.1: Simulation: Motor phase voltage and current

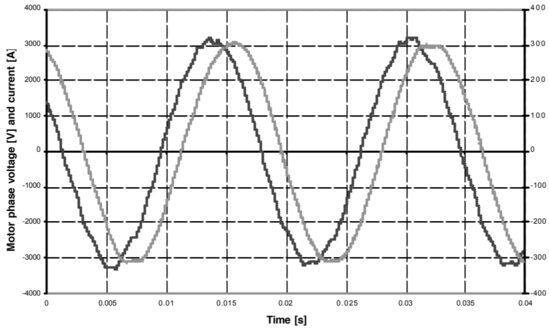

Fig. 3.3.2: Measurements: Motor phase voltage and current

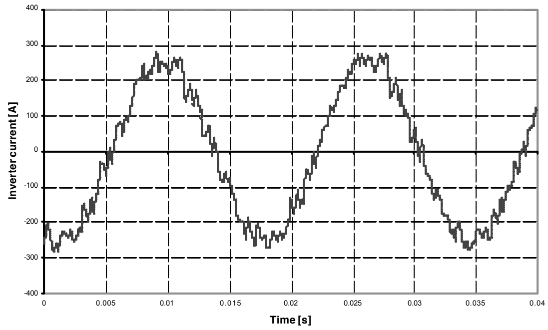

Fig. 3.3.3: Simulation: Inverter current

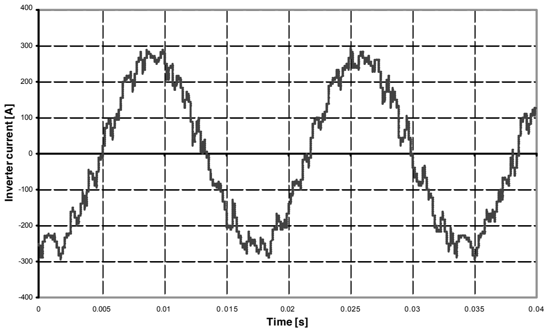

Fig. 3.3.4: Measurements: Inverter current

3.3.2.- Torque step at 20% speed, 100% flux

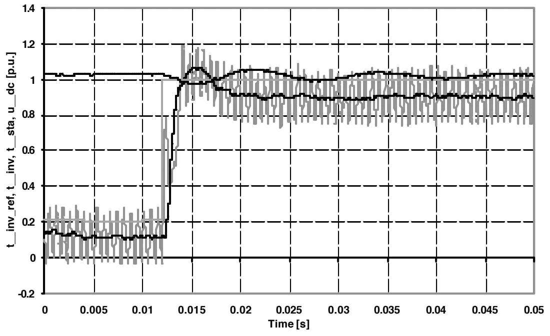

Fig. 3.3.5: Simulation: torque set value, inverter torque, motor torque, DC-link voltage

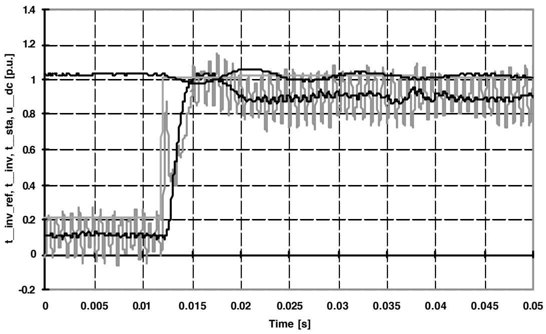

Fig. 3.3.6: Measurements: torque set value, inverter torque, motor torque, DC-link voltage

3.3.3.- Additional simulation outputs

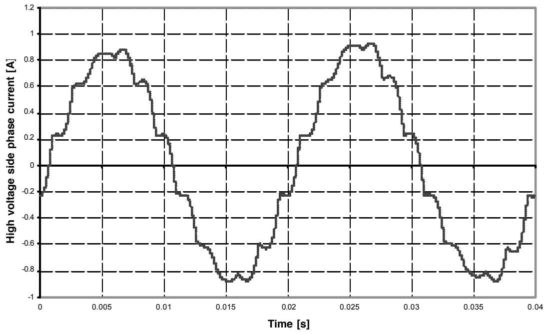

Fig. 3.3.7: Main transformer phase current

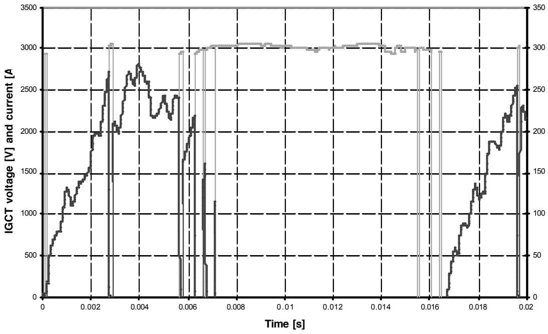

Fig. 3.3.8: Voltage and current of a IGCT

3.3.4.- Results discussion

A very good agreement between measured and computed values can be observed. This is due to the very well detailed implementation of all the system including the regulation part. The remaining small difference between measured and computed values comes from the random behavior of the DTC-NPC with the sine filter. Even at steady-state operating point, it is very difficult to obtain two identical periods.

4.- Conclusion

The paper presents the main problems that have to be solved in order to simulate precisely drives including power electronics, machines, analog and digital regulation devices. The requirements an efficient mixed signal simulation tool has to fulfill have been explained. Finally, an example of a real industrial drive for medium voltage applications has been described. The simulation results have been compared to measurements, even in transient operating mode.

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