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STUDY OF A CENTRIFUGAL PUMP, ASYNCHRONOUS MOTOR AND INVERTER, USING HARDWARE IN THE LOOP SIMULATION CONCEPT.

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RESUME

Ce travail traite d'une forme à faible coût de l'application du concept de la simulation Hardware in the Loop (SHIL) à l'étude d'un onduleur triphasé, un moteur asynchrone et une pompe centrifuge. Il présente la réalisation d'une commande rectangulaire grâce à un micro contrôleur (ATMEGA 168). Les signaux générés par le micro contrôleur ont été utilisé pour programmer le port parallèle d'un ordinateur. En lisant l'état des bits programmés sur le port parallèle, dans l'environnement de programmation LabVIEW, les signaux provenant du micro contrôleur ont été restaurés et mis à disposition du modèle de simulation du groupe formé par l'onduleur triphasé, le moteur asynchrone et la pompe centrifuge. Ce modèle avait déjà été réalisé dans le logiciel de simulation LabVIEW. Ce modèle qui lui est dans l'ordinateur est alors contrôlé par des signaux externes provenant du micro contrôleur. La difficulté était de pouvoir transférer les signaux externes du microcontrôleur vers le modèle logé dans l'ordinateur et réaliser une simulation comme dans le cas classique où tout le système étudié est simulé entièrement dans l'ordinateur. Nous avons comparé les résultats de notre simulation et ceux d'une simulation classique et avons constaté qu'ils correspondaient l'un à l'autre.

Key words: ATMEGA168, Hardware In the Loop, Onduleur de tension, Moteur asynchrone, Pompe centrifuge.

ABSTRACT

This work is about a low coast application of Hardware In the Loop simulation (HILS) concept to the study of a three-phase inverter, asynchronous motor and centrifugal pump. It presents the realization of the rectangular control using a micro controller (ATMEGA 168). The signals generated by the micro controller have been used to program the parallel port of a computer. By reading the recorded bits of the parallel port in LabVIEW software, the signals from the micro controller have been restored and made available to the simulation model of the three-phase inverter, asynchronous motor and centrifugal pump, made in advance in LabVIEW. These models realized in the computer are then controlled by external signals coming from the micro controller. The challenge was to be able to transfer signals from the micro controller to the model lodged on the computer and perform a simulation like in classical case, where all the system under study is simulated. We compare the results of our simulation with those of classical simulation. We notice that both results match.

Keywords: ATMEGA168, Hardware In the Loop Simulation, voltage inverter, asynchronous motor, centrifugal pump.

I. INTRODUCTION

In sub-Saharan countries like Benin, the use of photovoltaic power for pumping water is interesting, due to the non sufficient of power supply combined to the good sunstroke we have. To study photovoltaic pumping in laboratory, we generally simulate all the system. But simulation reproduces almost never so true behaviors of the actual process because several behaviors of the system are approximated. In the early 90s, it was introduced Hardware In the Loop Simulation (HILS). It is a type of simulation linking classical simulation and real test on physical process. It consists in linking of a physical part and a simulated part trough an interface, in a closed loop and in real time (Schaffnit et al., 1999). That simulation technique is now well established and become inescapable in test and control of systems or processes. But, application of HILS concept requires means such as costly software (Lu et al., 2007) and drivers that we lack in developing countries. In This work, we simulate a pumping system (inverter + motor + centrifugal pump) using HILS concept. But we use the parallel port for the communication between physical part and simulated part. That avoid us the realization of driver. By reading the parallel port state in the computer with LabVIEW software, we reconstruct the command sent by the physical part.

II. HARDWARE IN THE LOOP SIMULATION

Hardware In the Loop Simulation (HILS) is a technique linking classical simulation and test on a physical device. It is strictly linked to real time simulation (Schaffnit et al., 1999), (Lu et al., 2007), (Hanselmann, 1993), (Kiffmeier, 1996). The HILS includes a mathematical model of the process and a hardware device such as electronic control unit (ECU) we want to test, e.g. an industrial PID controller. The hardware device is normally an embedded system. To perform (HILS) of a process P, we divide it into two parts. One will be simulated; we will note it (S) (This is often the operative part of the process under study) and the other is kept physical; it will be noted (R) (It may be the control/command system of the process). Then the model of (S) is carried out in a computer for simulation. (R) is kept as such. It is made a communication interface between (R) and (S). Thus, the physical part (R) and the simulated part (S) communicate in a closed loop in real time through the interface (Lu et al., 2007), (Munteanu et al., 2010). The advantage of HIL simulation is that we are much closer to the actual behavior of the process because all the process is not simulated. This increases the realism of the simulation (Lu et al., 2007). Moreover, that type of simulation allows the easy use and reuse of the model lodged on the computer, it also avoid carrying a loss of material and life in some cases. For us, using the parallel port for performing that simulation has the following advantages: reduce the simulation cost, be closer of the true behaviors of the process under study, valorize the old hardware we have in our laboratory and which still have that kind of port.

III. SPECIFICATIONS

The objective of this work is to reproduce the behavior of a pumping system, using HILS concept instead of conventional or classical simulation. The components of the system under study are the following: a three-phase voltage inverter, an asynchronous motor and a centrifugal pump. The pumping system is furnished by a continue voltage (coming from a photovoltaic system which is not under consideration in this study). The continue voltage produced by photovoltaic system is 750V. The three-phase inverter is controlled in rectangular. The frequency of the signals generated by the inverter is 50Hz. Figure 1 shows the form of the system and its separation into two parts: the operative part and the control part.

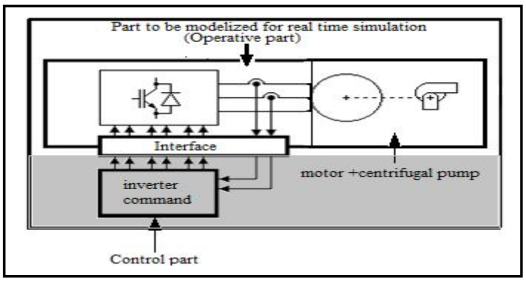

Figure 1: Illustration of the process under study
Illustration du processus étudié

We choose to simulate the inverter without its command, the asynchronous motor and the pump. The command part of the inverter is realized using a micro controller (ATMEGA 168) and represents the physical part.
For reaching our objective,
Primary, we generate the command signals using the micro controller and realize the inverter model without command in LabVIEW.
Secondary, we implement a mean of acquisition of signals generated by the micro controller. We observed the generated signals using a physical oscilloscope to be sure of their conformity with the desired signals. We command the inverter model which is lodged in the computer with the command signals coming from the micro controller. We observe the inverter output in LabVIEW.
Thirdly, we realize the model of the asynchronous motor with its charge and link this model with that of the inverter. At each level, we compare the results with those of a classical simulation to proof that with these simple means, it is possible to reproduce the behaviors of our process.
Now we will present the generation of the rectangular control signals, the inverter model, the motor-pump model and finally the simulations results.

IV. GENERATIONOF THE RECTANGULAR CONTROL SIGNALS

There is many type of control of inverter such as rectangular, PWM (Pulse Width Modulation) and full-wave. In the present study, we use a rectangular control. The needed control signals are six (each control signal will activate or deactivate one of the six switches of the inverter).

But to produce these signals will mainly be a question of generating three square waves. This is more explained in the coming section (section 5. Modelization of the inverter). The former wave has a phase lead of 160° with respect to the following, which has also a phase lead of 160° in relation to the third. These three signals correspond to control voltages v_{ao}, v_{bo} and v_{co} of the inverter's leg. As we have six signals which present two levels on a period, we divide the period in six and observe the level of each signal on each interval. By proceeding like that, we obtain the logical levels to be programmed. The various logical levels obtained by division on one period of the three signals are on Figure 2.

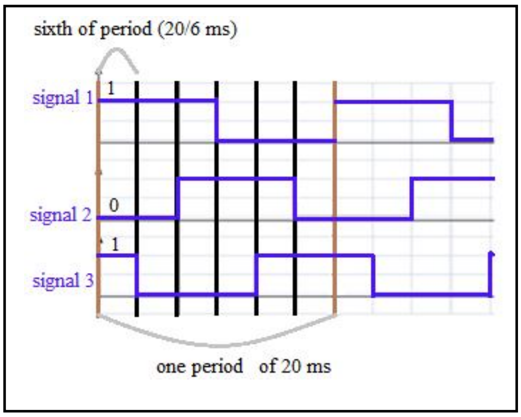

Figure 2: Division of the control signals with the corresponding logic states. For example, the logics states of the three signals in the first interval are respectively 1, 0 and 1.

Division des signaux de commande avec les états logiques correspondants. Par exemple, les états logiques des trois signaux dans le 1^er^ intervalle sont respectivement : 1, 0 et 1

Thus into the micro controller was programmed different logic levels corres-

ponding to the state of each signal. Observed with a digital physic oscilloscope, we find that the three control signals are generated with the corresponding period and phase shifts, as shown on Figure 3. The vertical blue lines delimit one period.

Yellow signals (which is high) is the control signals S_1, and produce the voltage v_{ao} ; the green (which is in the middle) is control signals S_2, which produce v_{bo} voltage and the one purple (which is low) is control signals S_3, producing v_{co} voltage.

V. MODELIZATION OF THE INVERTER (CHOUDER ET AL., 1999)

In that model, the electronic switches of the inverter are considered as perfect

The control signals S_1, S_2, S_3 of the inverter switches are voltages v_{ao} , v_{bo} and v_{co} . "o" is an imaginary point which allows us to represent the voltage v_{cc} (continuous voltage which furnish the inverter) in two levels. Each level is a voltage of $\frac{v_{cc}}{2}$; *n* is the neutral point at the three-phase load side. The phase voltages may be written as a function of control signals S_i ; then:

$$v_{ao}, v_{bo}, v_{co} = \begin{cases} \frac{v_{cc}}{2}, \text{ when } S_i \text{ is closed} \\ -\frac{v_{cc}}{2}, \text{ when } S_i \text{ is open} \end{cases} \quad (S_i = S_1, S_2, S_3) \tag{1}$$

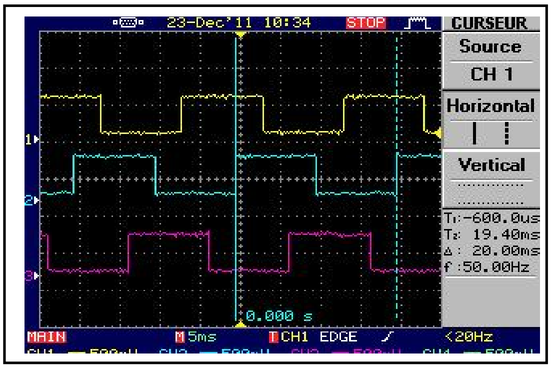

Figure 3: The three rectangular control signals observed on a digital physical oscilloscope /

Les trois signaux rectangulaires de commande observés avec un oscilloscope physique

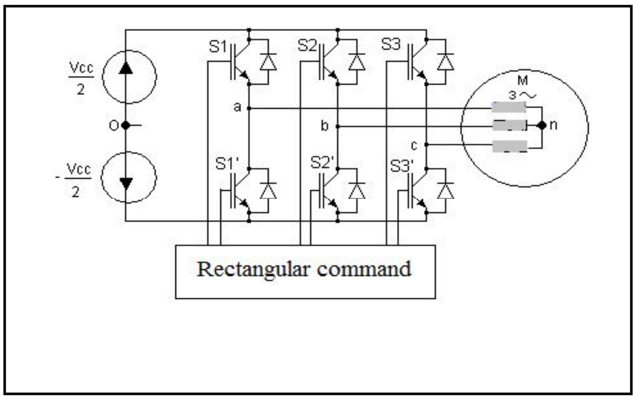

Figure 4: Three-phase inverter + charge / Onduleur triphasé + charge

v_{on} voltage is linked to the phase voltages by the following relationships:

$$\begin{cases} v_{ao} + v_{on} = v_{an} \\ v_{bo} + v_{on} = v_{bn} \\ v_{co} + v_{on} = v_{cn} \end{cases} \quad (2)$$

The three-phase system is assumed balanced and then:

$$v_{an} + v_{bn} + v_{cn} = 0 \quad (3)$$

Summing member wise equations (2), and considering (3), we obtain:

$$v_{on} = -\frac{v_{ao} + v_{bo} + v_{co}}{3} \quad (4)$$

Replacing (4) in (2) we obtain finally:

$$\begin{cases} v_{an} = \frac{2}{3}v_{ao} - \frac{1}{3}v_{bo} - \frac{1}{3}v_{co} \\ v_{bn} = -\frac{1}{3}v_{ao} + \frac{2}{3}v_{bo} - \frac{1}{3}v_{co} \\ v_{cn} = -\frac{1}{3}v_{ao} - \frac{1}{3}v_{bo} + \frac{2}{3}v_{co} \end{cases} \quad (5)$$

v_{an}, v_{bn}, v_{cn}

For obtaining voltages, we need to generate signals which order the switches S_1, S_2, S_3 and S'_1, S'_2, S'_3 represented on figure 2. But it is sufficient to generate signals to order S_1, S_2, S_3 because S'_1, S'_2, S'_3 are respectively the complementary of S_1, S_2, S_3 (when $S_i = 1, S'_i = 0$; and when $S_i = 0, S'_i = 1$; with $i = 1,2,3$). That model is implemented in LabVIEW.

VI. Interfacing signals from the microcontroller with LabVIEW

Now we need to send the control signals generated by the microcontroller to the inverter model realized with LabVIEW

To send signals to the computer, we have chosen the parallel port as we need to transmit three signals simultaneously, and also that port has 8 pins for data transmission (Anderson, 1996). A DB 25 printer cable was then used to prick the signals generated by the microcontroller and send them to the parallel port.

To reconstruct the signal, we read the different states of the parallel port in real time. For this, we used LabVIEW software as it has modules exclusively dedicated to reading and writing on the parallel port. In fact, it is the modules Inport and Outport (National Instruments., 2013).The model implemented for signal acquisition in LabVIEW is shown in Figure 5

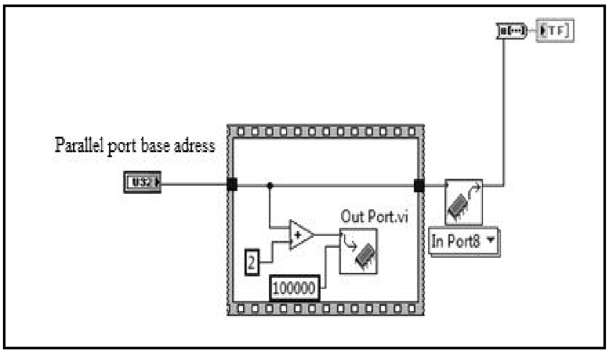

Figure 5: Acquisition block of signals sent to the parallel port /
Block d'acquisition des signaux envoyés par le microcontrôleur.

To be able to send data through the parallel port, we need to set data lines as input (we previously verified that our parallel port is bidirectional). In fact they are used to output datas from computer to printer in case of printing. But in our case, we want to send data to the computer through data lines. For this purpose, the direction bit must be set for input. This is the bit 5 of the control register (base address + 2). For setting that bit, we need to write to the port. For this, we use the Outport module in LabVIEW. The parallel port bits status are provided by the Inport module. But they are received in LabVIEW as a binary number. We then mask the bits we do not need the status and read only the needed bit, for having the corresponding control signal. At that step, we notice that some conditions must be respected. The model lodged on the computer must be sufficiently reduced; or the computer characteristics as processor speed and the computer RAM (Random Access memory) must be large to permit a rapid treatment of the model put up in the computer and which will be commanded by the microcontroller signals. Otherwise, the command signals come with delay and distort the inverter output.

VII. RESULTS OF SIMULATION BY (HILS) CONCEPT

The controls signals produced by the micro controller and receive in the computer with LabVIEW software are shown on Figure 6.

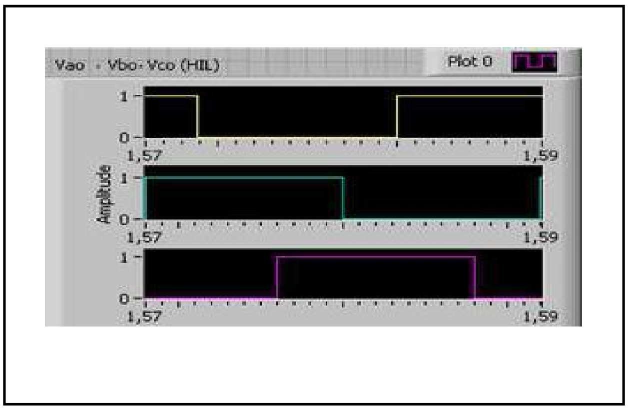

Figure 6: The three control signals v_{ao} , v_{bo} and v_{co} obtained by the HIL'S method/
Les trois signaux de commande obtenus par la méthode HIL

These three signals are observed each one over a 0.02s period.

Yellow signals (which is high) is the control signals S_1, producing the voltage v_{ao} ; the one in green (which is in the middle) is control signals S_2, producing v_{bo} voltage and the one purple (which is low) is control signals S_3, producing v_{co} voltage.

A. ***Analysis of the control signals acquired with LabVIEW***

It is necessary that the acquired signals in labVIEW correspond to those we observed with the physical oscilloscope. Comparing the signals acquired with LabVIEW, and those we observed on the physical scope on Figure. 4, we note that they are the same. Now we will control the inverter model with these signals. The inverter model bound to the acquisition model of Figure. 5. is shown on Figure. 7.

We compare the outputs of the inverter controlled by the physical control board with the outputs of a fully simulated three-phase inverter, (is to say which rectangular control is performed in LabVIEW).

The outputs of the inverter fully performed in LabVIEW are white while those produced by the inverter controlled by the micro controller are blue (Figure 8).

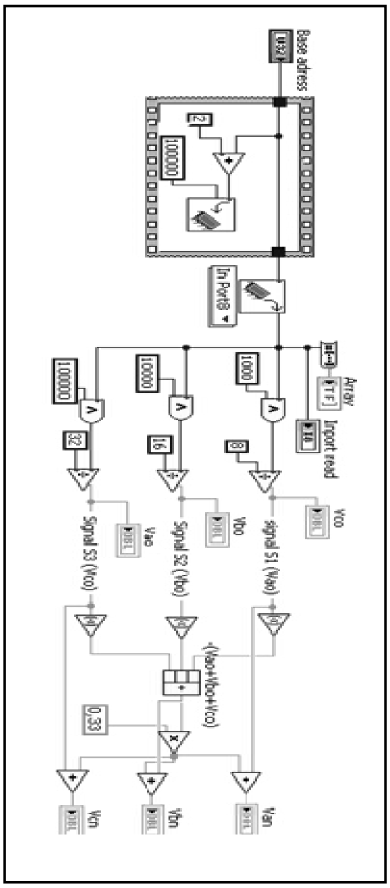

Figure 7 : Signal acquisition model bound to the Inverter model in LabVIEW / Modèle d'acquisition des siganux relié au modèle de l'onduleur dans LabVIEW

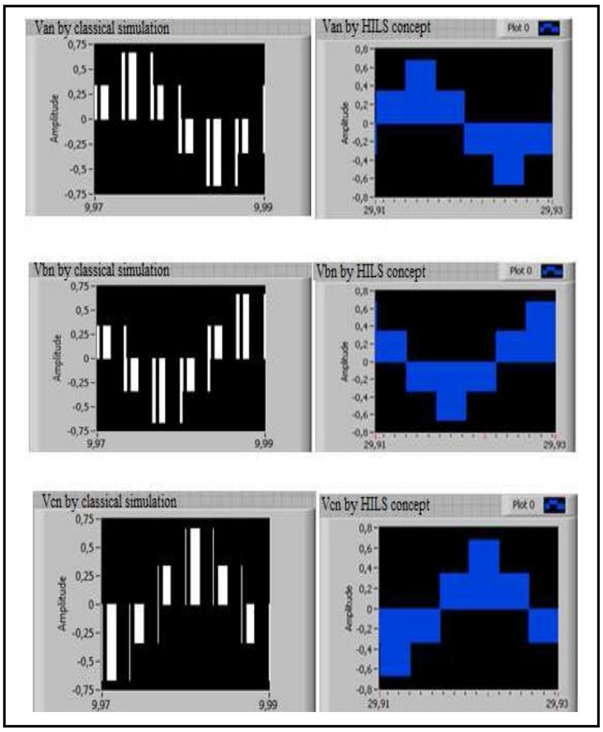

Figure 8 : Comparative Outputs of v_{an}, v_{bn}, v_{cn} for simulation by HILS concept and classical simulation / Sortie comparée de pour les simulations par le concept HIL et classique

B. Analysis of the output voltages of the inverter

These signals are observed here over a period of 20ms. To obtain these results, we use directly the logical states (0, 1) for furnishing the inverter. This is the reason why the amplitudes of the outputs are under 1. For having the real voltage at the output of the inverter, we just need to multiply the command signals by the desire amplitude. As the command signals that we receive in LabVIEW have the amplitude 1, the inverter signals amplitudes are 2/3. We can note that the classical simulation output matches our HILS result.

We can now use the signals from this inverter to feed the model of any other three-phase load like a motor-driven pump in order to study it.

VIII. MOTOR-PUMP MODEL **(HOUNGAN K. T., 1996, CARON J. P, HAUTIER J. P., 1995).**

This model is based on the original park transformation in the system of reference which turns with a speed corresponding to the pulsation of synchronism ω_s .

The outputs of the inverter which are v_{an}, v_{bn}, v_{cn} are considered like v_{sa} , v_{sb} , v_{sc} in the induction motor model. They represent the supplies of the motor. This model begin with transforming voltages v_{sa} , v_{sb} , and v_{sc} to voltages $v_{s\alpha}$ and $v_{s\beta}$ using matrix of Clark.

Thus $V_{s\alpha} = V_{sa}$ and $V_{s\beta} = 1/\sqrt{3}\,(V_{sb} - V_{sc})$

Then we determine $i_{s\alpha}$ and, $i_{s\beta}$ which respectively verify the following equations:

$$V_{s\alpha} - V_{m\alpha} = R_s.i_{s\alpha} + \sigma L_s \frac{di_{s\alpha}}{dt} \quad (6)$$

$$V_{s\beta} - V_{m\beta} = R_s.i_{s\beta} + \sigma L_s \frac{di_{s\beta}}{dt} \quad (7)$$

With $\begin{bmatrix} v_{m\alpha} \\ v_{m\beta} \end{bmatrix} = \begin{bmatrix} \cos(\theta_s) & -\sin(\theta_s) \\ \sin(\theta_s) & \cos(\theta_s) \end{bmatrix} \begin{bmatrix} v_{md} \\ v_{mq} \end{bmatrix}$ (8) where $v_{md} = (1-\sigma) l_s \frac{di_{mr}}{dt}$

(9)

and $v_{mq} = \omega_s (1-\sigma) l_s i_{mr}$. (10)

θ_s is the angle of rotation between the d, q axis and α, β axis and $\theta_s = \int \omega_s dt$ (11),

with $\omega_s = p\Omega_m + \frac{1}{\tau_r}\frac{i_{sq}}{i_{mr}}$ (12)

which is the angular speed of the rotating magnetic

i_{mr} which is the current of magnetization relative to the rotor, verify the following equation:

$$\frac{di_{mr}}{dt} + \frac{1}{\tau_r} i_{mr} = \frac{1}{\tau_r} i_{sd} . \quad (13).$$

Then we can calculate the electromagnetic torque which is given by the following expression;

$$T_{em} = \frac{3}{2} p \frac{L_m}{L_r} (\phi_{rd} i_{sq} - \phi_{rq} i_{sd}) \quad (14)$$

By directing the rotor flux on axis d, what make ϕ_{rq} =0, the electromagnetic torque becomes:

$$T_{em} = \frac{3}{2} p \frac{L_m^2}{L_r} i_{mr}.i_{sq} . \quad (15)$$

As we know currents $i_{s\alpha}$ and $i_{s\beta}$, we can obtain currents i_{sd} and i_{sq} .

The pump is considered as a classical charge and is modeled in the equation (16) using his factor k.

Now, we calculate the rotation speed of the motor Ω_m which verify the relation

$$T_{em} - T_{rs} = J \frac{d\Omega_m}{dt} + F_V \Omega_m + k\Omega_m^2 \quad (16)$$

Where T_{rs} is the Static resistant torque, F_v the coefficient of viscous friction.

d, *q* : axes corresponding to the asynchronous reference axes in Park model *Ls* , *Lr* , *Rs* ,*Rr* and *M* are: stator and rotor main

inductances, resistances and mutual inductance respectively. J is the rotor inertia moment, σdispersion factor of Blondel. i_{sd}, i_{sq} ,are d-axis stator current and q -axis stator current and p is the number of pole pairs, ωs is the angular speed of the rotating magnetic, k is the pump torque factor.

IX. SIMULATION RESULTS

Now we show some outputs of the global simulation. (The micro controller sends signals which command the inverter for making the 750V continuous voltage, an alternative voltage; afterwards, the inverter furnishes an asynchronous motor which entails the pump). We show: current $i_{s\alpha}$, Torque Tem, and Speed Ω_m. The outputs which are blues are obtained by HIL concept simulation and the blacks are those obtained by classical simulation. Those results are resumed on Figure 9, Fig 10 and Figure 11.

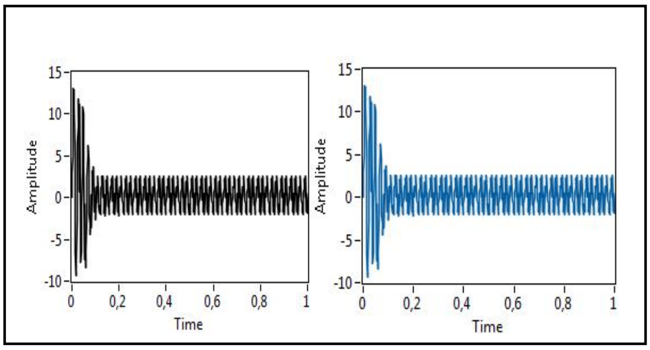

Figure 9: Comparison of currents $i_{s\alpha}$ / Comparaison des courants $i_{s\alpha}$

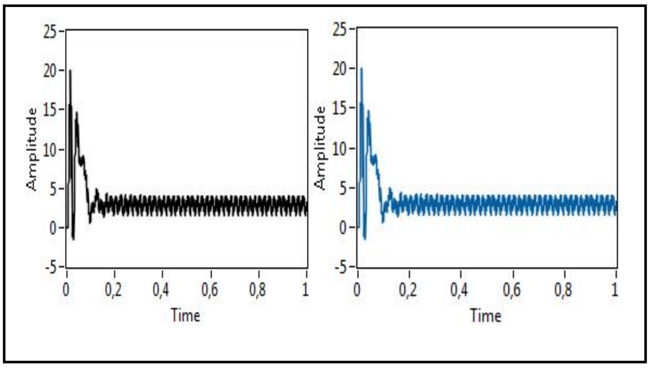

Figure 10: Comparison of torques Tem / Comparaison des couples Tem

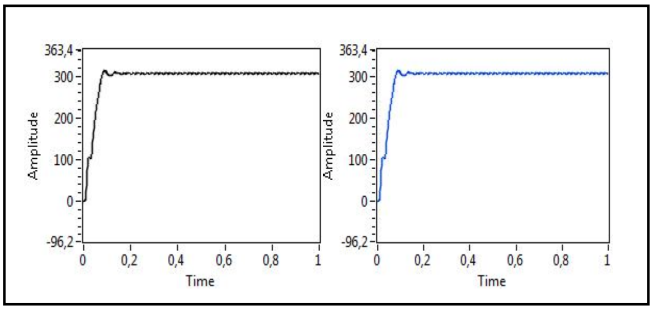

Figure 11: Comparison of Speeds/ Comparaison des vitesses

The currents, the torques and the speeds in both cases match and show a good acquisition in LabVIEW of the command signals send from the micro controller through the parallel port. As Hardware in the Loop simulation increases the reality of a study, these results shows it is more interesting as much as possible to perform this kind of simulation instead of classical simulation. Moreover we can note that using a rectangular command for the inverter not permit to obtain signals correctly filtered. What we could expect.

X. CONCLUSION AND PERSPECTIVES

This work based on the HIL S technique and its application to the study of a three-phase inverter, an asynchronous motor and a centrifugal pump uses a simple approach but nevertheless allows the realization of a real-time simulation. Moreover, it shows that it is possible to realize simulations more realist than the case of a classical simulation. It shows too that the parallel portal though increasingly abandoned remains interesting for its main quality is to allow simultaneous transmission of multiple data at once. Then by changing the program which makes run the micro controller, we can change the control signals of the inverter and realize for example an inverter based on a PWM command. That is the prochain work we will do.

APPENDIX

Table 1: Motor and his charge characteristics

Machine Characteristics	Parameters and values and units		
	Parameters Symbols	***Values***	***Units***
Stator resistance	R_s	10.621	Ohms
Rotor resistance	R_r	7.001	Ohms
Mutual Inductance	L_m	1.0154	Henry
Stator leakage inductance	L_s	0.0278	Henry
Rotor leakage inductance	L_r	0.0549	Henry
Load constant	K	$2.7729.10^{-5}$	$Nm/(rad/s)^2$
coefficient of viscous friction	F_v	$3.499.10^{-5}$	Nm/(rad/s)

Motor-pump model realized with LabVIEW

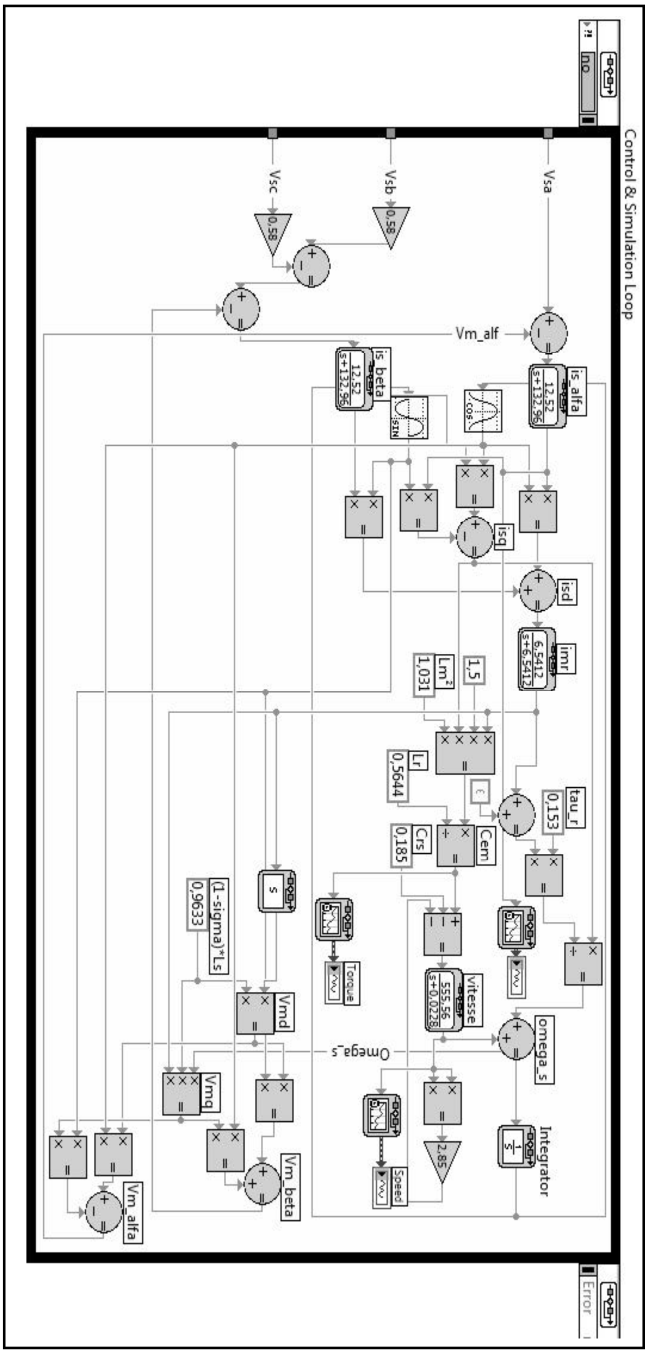

Figure 12: Detailed model of the motor-pump realize with LabVIEW / Modèle détaillé du groupe motopompe réalisé avec LabVIEW

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