THEORETICAL AND EXPERIMENTAL INVESTIGATION FOR "STORAGE LESS" CONTROL OF A WATER PUMPING SYSTEM FED BY INTERMITTENT RENEWABLE SOURCES

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ABSTRACT

This paper focuses on an original control experimentally implemented for water pumping system fed by hybrid (PV-Wind) generator without battery storage. The water pumping system uses centrifugal pumps driven by variable speed three phase Induction Motors (IM) controlled by a new Power Field Oriented Control (PFOC). As we have eliminated the battery storage, the system operating point is imposed by the intermittent renewable source, given the hydraulic load characteristic; the basic idea is to use both degrees of freedom offered by the inverter in order to control the DC bus voltage and the rotor flux of the induction machine. Experimental investigations show the satisfying performance of the system even with variable power source.

Keywords: Intermittent source, water pumping, Power Field Oriented Control, hydraulic storage, experimental setup.

1. INTRODUCTION

Water and electricity are vital for human beings especially for their socio-economic development. However, given the increasing demographic situation, demand significantly increases, varying from one region to another depending on the migration of people. These two shortcomings are more evident in remote areas, often deprived of electricity and water. Thus, water pumping systems fed by intermittent hybrid (wind and/or photovoltaic) generators are relevant especially for remote areas where wind and sun resources are widely existent (Brian 2012; David 2011; Elgendy 2010; Dali 2007; Vongmanee 2005). One major and basic idea of our proposal is to prefer hydraulic storage to replace or at least to minimize electrochemical batteries in order to decrease system owning costs especially by increasing life cycle. In order to operate renewable sources at their maximum power, these latter have to be coupled to a voltage controlled DC link (Dali 2007). One issue is then related to the bus control: in classical approaches with grid connection or including storage device, the DC bus voltage is set from the grid or from the storage sub system. In standalone mode, without storage device, the issue is: "how to control the DC bus, knowing that renewable sources are power (MPPT) controlled"?

The aim of this paper is to present a new Power field Oriented Control for a pumping system fed by intermittent renewable source without battery storage. A steady state analysis will present the energy behavior and the available degrees of freedom to be exploited for the pumping system. A control strategy is conducted to manage the pumping system fed by intermittent power sources. An experimental setup is carried out to validate and test performance of the developed control.

2. THE "STORAGE LESS" PUMPING SYSTEM STRUCTURE

2.1. The hybrid pumping system

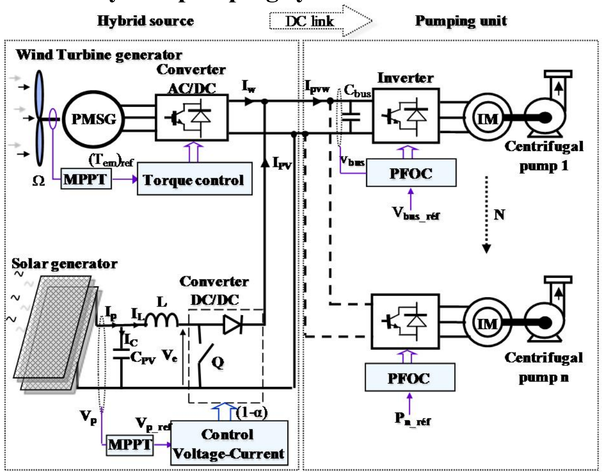

Figure 1: The proposed pumping system

The pumping system mainly consists of the hybrid source and the pumping unit. The pumping unit can be based on a single motor-pump or (N) multi motor-pumps. In this paper we present the first configuration. The hybrid source can be powered by wind and photovoltaic generators coupled to the DC bus through static converters. The wind generator is a direct drive technology based on a multi-poles permanent magnet synchronous generator associated with a PWM rectifier, the photovoltaic panel is connected to the DC link via a boost chopper. To increase the energy availability, MPPT techniques are used to maximize the power transfer (these sources are power controlled if the maximum power of the pumping system is reached): all degrees of freedom offered by power converters connected to renewable sources are then used for MPPT control. This principle is presented in preceding works as in Ben Rhouma (2008). In this paper, we have only considered "given power source" given climatic conditions. The pumping unit is composed of 1 HP motor pumps driven by a voltage source inverter. The pump is associated to hydraulic pipes (see Figure 1).

2.2. Steady state system analysis

A preliminary static study of the operation for the overall system (the hybrid sources and the pumping unit) is needed to analyze the energy behavior and to determine all Degrees Of Freedom (DOF). This study is useful for the development of power management strategies.

First, let remind that electric power delivered by hybrid sources (in MPPT mode) will be transmitted via the DC bus to the pump unit through the inverter. The operation of the pumping system over wind and sun differs from a conventional system that works with batteries. Indeed, for systems that include batteries, the power required by the load is the sum of the power generated by hybrid sources (PV-Wind energy) and power stored in the batteries. In this case, the power consumption being imposed by the load, the power management generally optimizes energy efficiency, at least when the battery is properly charged (SOC inside correct range): this mode is quite similar to the one obtained with a traditional grid connected source with "infinite" power.

On the opposite, for systems which depend on wind and sun intermittent conditions and without electrochemical storage, electric power transmitted to the load will be imposed ("given") by the hybrid source. Furthermore, given an "hydraulic" load characteristic, the operating point (*H,Q* plan: *H* being the manometric height and *Q* the volumic flow) is locked at a single operating point imposed at the crossing of given source powers and hydraulic characteristic.

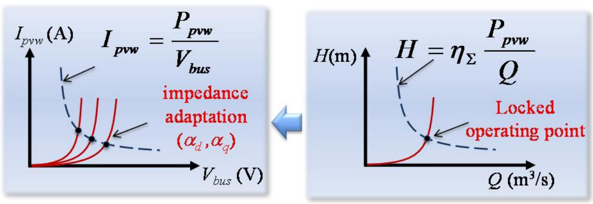

Figure 2: Locked operating point for given input power sources and given load

Figure 3 shows that the operating point is locked to the intersection of the hyperbola of the hybrid power P_{PVW} and the load characteristic (right curve) while the inverter duty cycles may be used to vary the bus voltage in the electric plan, adapting the system impedance (left curve).

So, changing the operation in the hydraulic plan leads to change the input power or to change the hydraulic load. Then, the original idea is to exploit the two degrees of freedom offered by the voltage source inverter (as example varying duty cycles: α_d, α_q) supplying the induction motor: the first DOF α_d is used to set the magnetizing flux in the machine and the second one α_q is "free to be exploited" in order to control the DC bus voltage.

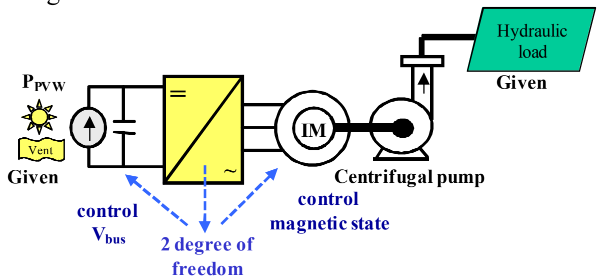

Figure 3: Cooperative energy management inter domain: control of the DC bus voltage by the inverter

3. CONTROL STRATEGY DESIGN

3.1. The Power Field Oriented Control

The induction motor dynamic model can be represented according to the usual (*d,q*) Park's reference frame. To decouple flux and torque a Field Oriented Control (F.O.C) is classically used. The torque is then controlled through the "*q*" axis current. In our case, the torque current reference ($I_{sq\ ref}$) is set following an external loop for the DC bus voltage control. The rotor flux is regulated along the "*d*" axis. Finally, two control loops are proposed for flux and DC voltage.

3.1.1. DC voltage control

As the hybrid system is a power source, it is required to include a link capacitor (C_{bus}) between the source and the inverter. The DC bus voltage (V_{bus}) has to be maintained constant whatever the power transfer in the DC bus.

The current balance in the DC bus is given by the following equation.

$$I_{bus} = I_e + I_c . \qquad (1)$$

The basic idea to control the DC bus voltage is to keep the power balance at the input/output of the inverter:

$$V_{bus} . I_e = E_d . I_{sd} + E_q . I_{sq} . \qquad (2)$$

(E_d, E_q) are the "*d*" and "*q*" axis motor voltages, which can be estimated from rotation speed knowing machine resistance and flux.

(I_{sd}, I_{sq}) are the "*d*" and "*q*" axis stator current.

The characteristic equation of the DC bus capacitor and the induction machine is represented by the following diagram.

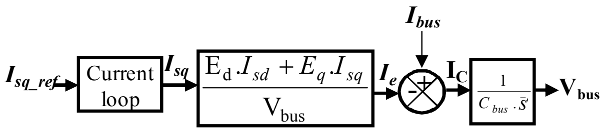

Figure 4: block diagram of the DC bus vs torque current transfer function

From previous equations and by considering that the motor current loop dynamic is faster than the bus voltage dynamic, the cascaded control structure of figure 5 is proposed.

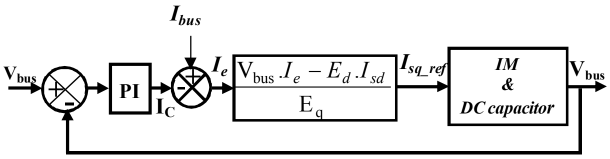

Figure 5: DC voltage control loop

3.2. The experimental setup

The proposed system shown in figures 6 and 7 is composed of a programmable power source (DLM 4kW from Sorensen), a voltage source inverter (Semikron 20kVA), a three phase centrifugal motor-pump (DAB 750W), a Dspic microcontroller and a card generating the DC current reference.

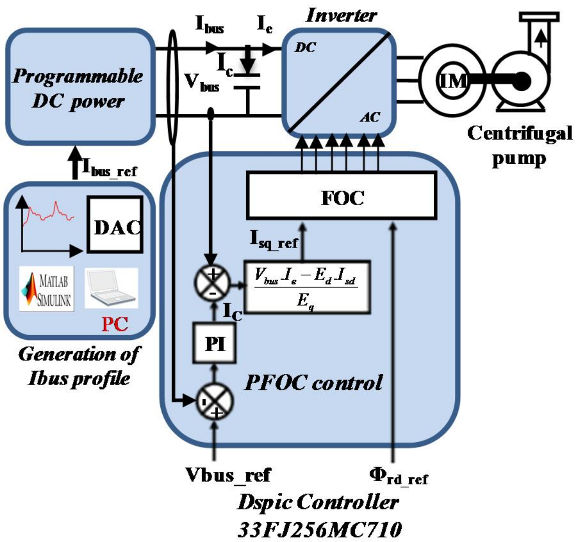

Figure 6: The experimental water pumping system without battery storage

The target for the digital implementation of the PFOC is an “explorer 16” board from microchip.

Three Hall Effect current sensors (LEM LTS-25nP) are used to measure two stator currents of the induction motor and DC bus current produced by the programmable power supply.

One Hall Effect voltage sensors (LEM LV-25P) is used to measure the DC bus voltage.

An acquisition card NI-DAQ 6008 from national instruments is used to measure and save four data: DC bus current, DC bus voltage, hydraulic pressure and water flow.

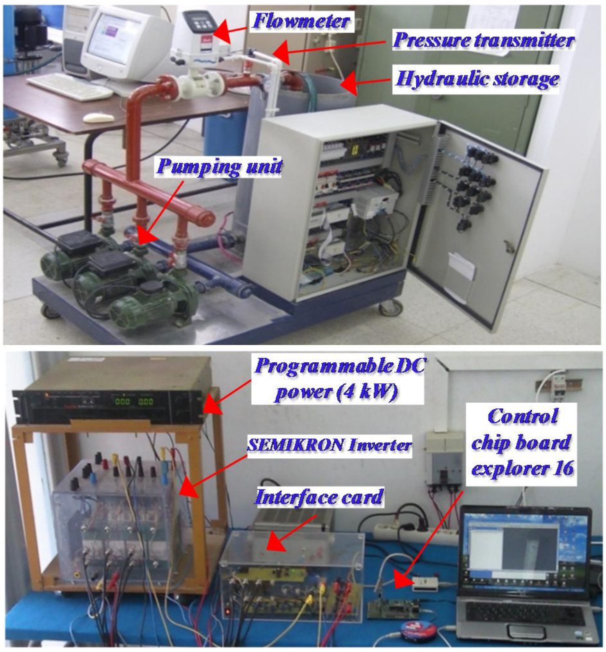

Figure 7: The experimental test bench for water pumping system

The proposed control strategy was implemented using a digital control system based on DSPic 33FJ256MC710 microcontroller. This microcontroller has a high-performance 16-bit central processing unit (40 MIPS) and peripherals that are particularly suitable for motor control applications.

Four analog quantities acquisition has been implemented by using the internal analog–digital (A/D) converter: two stator currents of the induction machine, DC bus current (I_{bus}) and DC bus voltage (V_{bus}).

The interruption of the A/D converter is executed every 62.5µs being triggered every PWM period (the switching frequency of the PWM is set at 16 kHz). The conversion result is transferred and stored in DMA buffer (direct memory access).

The synchronization of the different control blocks is made through the interrupt mechanism. It generates the instants and the order execution of the various modules. This order must take into account the speed of the internal and external loops of the FOC.

The current (I_{sd}, I_{sq}) loop bandwidth is chosen at 5 kHz. The DC voltage loop bandwidth is chosen as 500 Hz.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

To test the performance of the designed control, we have programmed a variable power profile from a cycle test under variable wind generation. The test is validated by simulation. We have chosen a model of wind with rapid fluctuations; its speed is modeled as a function of time as determined by the sum of several harmonics (equation 3):

$$V_{wind} = A_0 + \sum_{i=1}^{n} \left(a_i . \sin(b_i . \omega_v . t) \right) \quad (3)$$

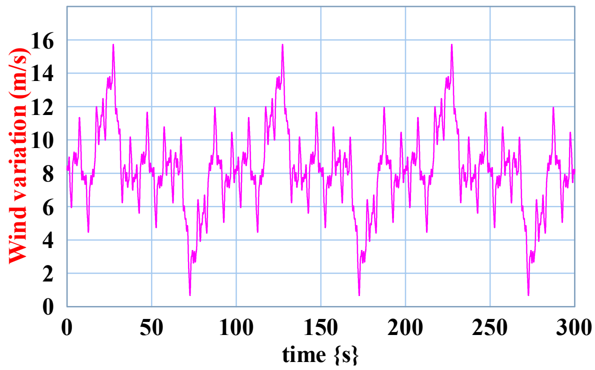

Figure 8: Model of wind variation

The wind model (figure 8) is tested, by software simulation, on a 1kW wind turbine generator with the architecture presented in figure 1. From the simulation, we have taken the variable DC current I_{bus} in digital data format to put it as an input to the control card. By this way, we can generate the adequate analog reference I_{bus} to the programmable power supply.

The current profile will be active only if the power supply operates as current source.

From this device, we can emulate the operation of a wind turbine submitted to variable wind coupled to the DC bus. The emulation process from experimental device is presented in figure 9.

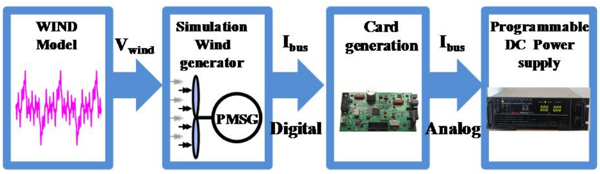

Figure 9: Experimental emulation of the wind power source

Initially, before starting the PFOC control, the programmable power supply works as a voltage source. The source voltage and current limits are also initialized.

The voltage provided by the programmable source is set to an initial value of 320V.

At the initial instant t=0s, we start the Field oriented Control: in this case, only the rotor flux and the current torque "I_{sq}" are controlled.

At the instant t_1= 52s, the DC voltage external loop regulation is started and set to a reference of 300V (PFOC mode). The power supply is then switched to constant current mode. The voltage and the current converge to their references. So, the motor-pump is power controlled. The generated current profile is constant and equal to 1.5A.

From the card of profile generation, we start in t_2=135s the profile with variable powers which emulates the wind turbine operation.

The electrical and hydraulic variables are stored for 600 seconds to fully assess the test cycle.

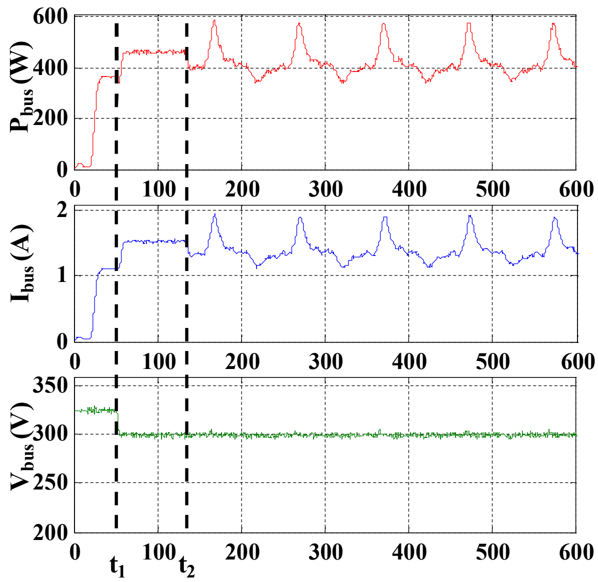

Figure 10: Input power, current and voltage in the DC bus

Figure 10 shows the good performance of the DC bus voltage control V_{bus} for variable DC power. Note that from t1 to 600 seconds the DC power P_{bus} varies according to the reference generated by the card generation. From t2, the programmable power supply operates as wind turbine emulator. The power produced is then variable. This variation is smoother than the wind variation (Figure 8) due to the large inertia of the turbine.

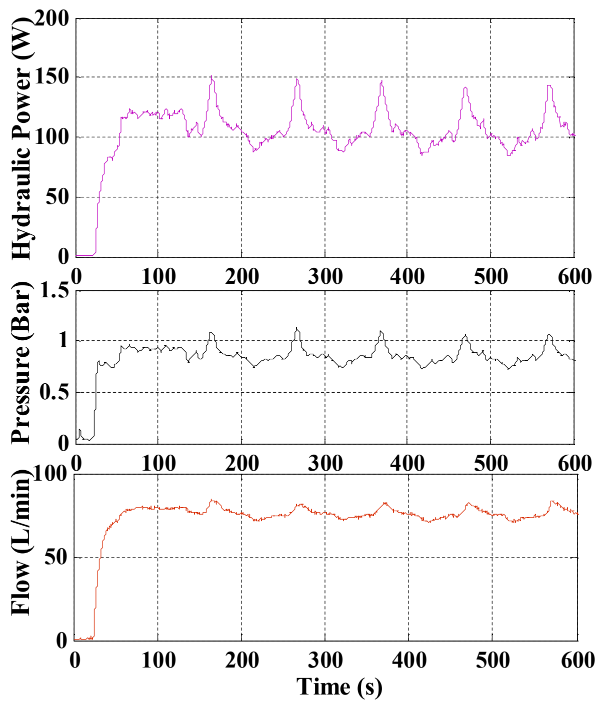

Figure 11: Hydraulic power, pressure and water flow according to DC power variations

Figure 11 shows that, given the hydraulic load, pressure and flow variables follow the variations of the DC bus power P_{bus}.

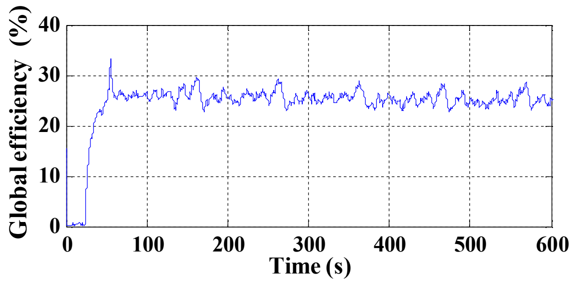

Figure 12: Global efficiency variation

The global system efficiency, shown in figure 12, is the ratio of the hydraulic power and DC bus electrical power. This efficiency is nearly constant for varying power DC bus P_{bus} but it should be noted that this performance can be increasingly fluctuating and even degraded following the hydraulic load.
Indeed, we have shown in previous works Ben Rhouma (2010) that the global efficiency strongly depends on the hydraulic load characteristics and the level of the DC power. As a solution, we have shown the relevance to exploit system modularity by using several pumps which would operate sequentially with better efficiencies. Consequently, for the pumping system as presented in figure 1, using N motor-pumps (N inverter) will increase the number of DOF, 1 DOF would be dedicated to the DC bus voltage regulation of the first motor-pump, while the (N-1) remaining DOF may be exploited to optimize the power management of the overall system.

5. CONCLUSION

An original Power Field Oriented Control PFOC is proposed, based on the two degrees of freedom offered by the voltage source inverter supplying the motorpump. The PFOC is mainly based on FOC principles: motor currents are controlled in Park's reference frame (d,q) oriented along the rotor flux as for the classical rotor field oriented control; an external loop is added for the regulation of the DC bus voltage along the 'q' axis, with an inner loop for the q axis torque current control. The second degree of freedom is used for the regulation of the rotor flux according to the 'd' axis. The PFOC is implemented on a DSPic microcontroller. We have realized experimental device based on a programmable DC power source to emulate the hybrid (solar PV & wind turbine) generator function. Experimental results demonstrate the validity and the performance of the developed control.
For this case study without or with minimum electrochemical storage, the hydraulic operating point is locked so that a bad adaptation between the source and the load may cause weak efficiency. To face such issue, the system modularity principle (using several motorpump devices) offers a convenient solution to optimize the power management for this type of system.

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