# A PUMPING SYSTEM FED BY HYBRID PHOTOVOLTAIC-WIND SOURCES WITHOUT BATTERY STORAGE
## BOND GRAPH MODELING, CONTROL AND ENERGY MANAGEMENT

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**ABSTRACT**
This paper studies an original energy management system with control strategy dedicated to an autonomous pumping system fed by a hybrid (photovoltaic and wind) generator without battery storage. A systemic approach is developed to reduce complexity and to analyze the system which involves multi-domains with strong couplings. The Bond Graph formalism is then used for the system modeling. In order to validate the simulation model, an experimental system has been set up and tested under various conditions. A power based analysis is developed to understand the system behavior. Finally, control strategies are deduced allowing a "storageless" energy management of the pumping system fed along given sun and wind conditions.

**Keywords**: hybrid source, centrifugal pump, Bond Graph, energy management.

## 1. INTRODUCTION
Hybrid photovoltaic and wind source has become one of several promising alternative to produce electrical energy. The exploitation of this system is relevant and attractive especially for remote area and for small-scale applications such as water pumping and/or desalination [1-3]. Exploitation of drilling water finds a particular interest in arid regions which are neither connected to the hydraulic network nor to the electric grid. In this work, we chose to operate the hybrid source in maximum power point tracking (MPPT) mode. That allows increasing sources efficiency and to extract the maximum of power. The DC bus, on which power sources are coupled is equivalent to a finite and variable "given power source".

Majority of pumping systems operate with the use of batteries which simplify energy management, decoupling, under a certain level, production and consumption but reducing system reliability and increasing its price along the life cycle of the installation. In order to design robust and "low cost" systems for rural applications, we have then removed battery storage, only taking advantage of natural hydraulic storage offered in such devices. In fact, hydraulic tanks play the role of energy buffer between water demand and production. Without battery storage, the DC bus power is imposed directly to the pumping unit through the motor-pump inverter(s). Thus, we may obtain a bad adaptation between the source and the load which would cause efficiency loss.

The main objective of our paper is then firstly to analyze the pumping unit under variable "given DC bus power" without storage. Secondly, original energy management and control strategy are proposed to face particular constraints of this "storageless" structure. We finally proposed a control strategy which allows controlling the DC bus voltage with optimized power transfer towards two motor pumps in parallel. This study requires a convenient modeling of the pumping unit which must reflect main physical and energetic behavior. The experimentation is useful as a reference for the model validation. Bond graphs offer graphical description for dynamic behavior of multi-physical systems. It describes the power flow and models the transformation across domains (electrical, mechanical, and hydraulic). In addition, it provides uniform representation which offers a unified and understandable way to process physical modeling of such system.

## 2. SYSTEM STRUCTURE

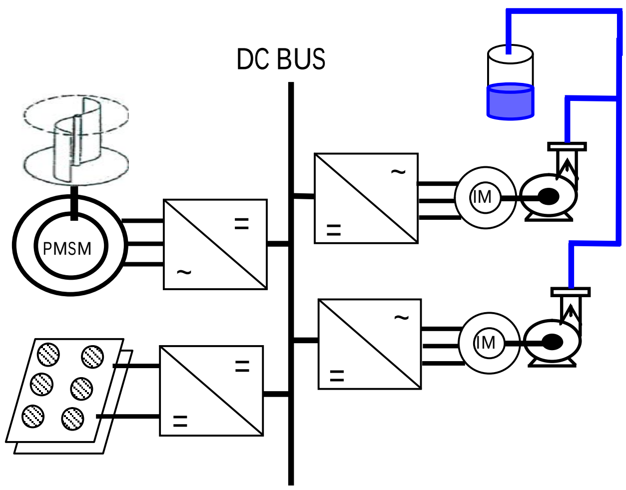


Figure 1: Scheme of the pumping system fed by the hybrid source without battery storage

The pumping system mainly consists on the hybrid source and the pumping unit. The pumping unit can be based on a single motor-pump, [1] or multi-motor pumps. In this paper we have chosen the second configuration with two pumping devices even if development can be generalized. The hybrid source can be composed of wind and photovoltaic generators coupled to the DC bus through static converters ([4-5]) but this part is not focused in this paper in which we have only considered "given power source" for given climatic conditions. The pumping unit is composed of two identical 2HP motor pumps. Each one is driven by a voltage source inverter. Both pumps are associated in parallel with hydraulic pipes (see Figure 1).

## 3. SYSTEM ANALYSIS

### 3.1. The Hybrid system

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): degrees of freedom offered by sources power converters are then used for MPPT control.This principle is presented in preceding works as in [2].

### 3.2. Experimental set up

Figure 2: experimental test bench of the pumping unit

Experiments were conducted to evaluate energy management performance of the pumping system and to validate models. Induction motors driving pumps are connected to Frequency Converter Drive (FCD) devices. We can measure water flow and pressure at the output of the pump. The FCD gives an estimation of the load torque. The hydraulic load variation is possible thanks to a valve setting.

Hydraulic characteristics are given in Figure 3 and 4. These curves are obtained for constant given speeds by setting the valve position VP. Figure 3 shows the centrifugal pump characteristics for various frequencies imposed to the variable speed drive. According to these characteristics we notice that these curves follow the affinity laws.

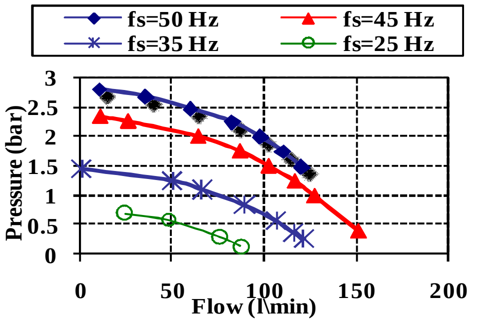


Figure 3: pressure-flow characteristics for several frequencies

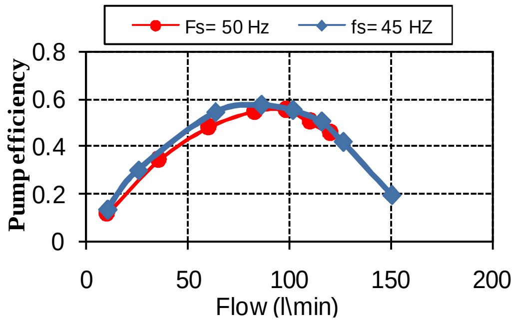


Figure 4: Behavior of the efficiency

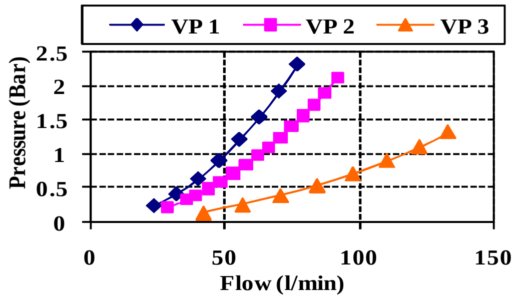


Figure 5: Behavior of the hydraulic load

The hydraulic operating point is fixed by the intersection of the pump (Figure 3) and the hydraulic load curves (Figure 5).

The bell shape characteristic obtained on Figure 4 for motor-pump efficiency shows that an adequate power management is required to avoid energy waste. According to the experimental tests, it exists a tradeoff between efficiency and flow maximization. Indeed, for this application, maximizing the pump flow to obtain a maximum quantity of water is "the" prime objective. This latter factor is linked but not equivalent with efficiency maximization for systems fed by given generated powers.

### 3.3. The pumping unit modeling

The centrifugal pump is directly coupled to a three phase squirrel cage induction motor (IM) which pumps water from a storage tank. The mechanical power is transformed into hydraulic power through the impeller. This power transformation can be expressed as [7]:

$$T_l = a.\Omega.Q + b.Q^2 \qquad (1)$$

$$P = a.\Omega^2 + b.\Omega.Q \qquad (2)$$

Where:

- $T_l$ is the load torque of the pump.
- *P* is the fluid pressure
- *Ω* is the rotation speed of the induction machine.
- *(a,b)* are the parameters of the pump.
- Q is the water flow

Hydraulic losses occur throughout the hydraulic network and depend on the static head, on the nature of the flow due to the Reynolds number as well as the characteristics of pipelines (relative roughness and restrictions).

The expression of losses is given by :

$$P_l = \rho.g.Hs + k.Q^2 \quad (3)$$

where :

- *k* is a parameter due to the losses in the pipeline.
- ρ is the water density.
- g is the gravity.
- Hs is the static head.

The knowledge of pressure losses in the hydraulic pipeline is very important in order to choose a pump well adapted to its hydraulic load then ensuring good efficiency. Practically, efficiency of such system can be strongly degraded if the pump "is not conveniently adapted" to its hydraulic load: this efficiency should be identified and taken into account for the energy management of the system. Indeed, by considering the whole system, it is useless to optimize the power sources (MPPT) if the consumed power is wasted by a bad adaptation with the hydraulic load which would cause a very weak efficiency of the global system. Figure 6 presents the Bond graph model of the centrifugal pump associated with the hydraulic pipe.

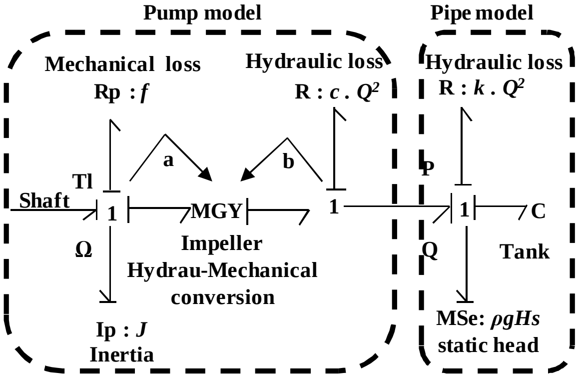


Figure 6: Bond graph model of the centrifugal pump

In this model the hydraulic power is transferred to the pipe of which a part is lost ($c \times Q^2$) by the shocks and frictions of the water between the volute and the pump's impeller. From the experimental study we have the possibility to aggregate the modeling. Indeed, we have identified three parameters (a, b, c) of the pump model starting from experimental curves.

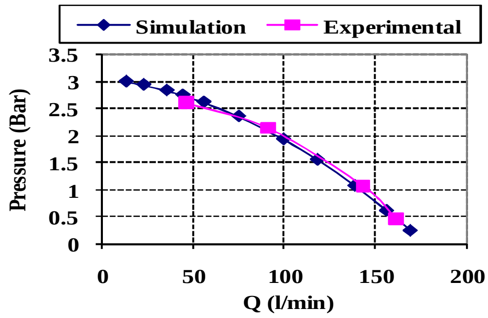


Figure 7: Performance curve of the pump

## 4. SYSTEM ENERGY MANAGEMENT STUDY

Due to the absence of power storage, this class of system deals with a non classical issue in terms of control and energy management strategy. In fact, without battery storage and with a given generated power, the full generated power is transmitted to the load via the DC link, as shown on figure 8.

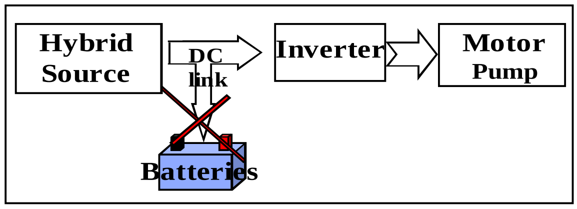


Figure 8: Principle of power/energy transfer into the conversion chain without storage

Before establishing the energy management and the control of the pumping system, a preliminary static study is necessary. The sources operating in MPPT modes are coupled through the DC bus which must be previously regulated to ensure a convenient MPPT control. The DC bus control cannot be achieved thanks to power converters on generators sides which are dedicated to MPPT control. Given climatic conditions, powers are imposed on the DC bus; which then behave as a power sources. A static study of this particular system shows that for a given generated power and for a particular hydraulic load, the hydraulic characteristic of the pump is really different from the one obtained in the case of a traditional grid connected source with "infinite" power [2]. In our case, the operating point of the system is fixed by the source power and the hydraulic load. So, changing the operation in the hydraulic plan leads to change the input power or to modify the hydraulic load. Then, it is not possible to regulate the pump flow by using a conventional control strategy. In this device, the system efficiency will depend on the power of the DC bus.

Figures 9 and 10 respectively show the evolution of the flow and the global (motor + pump) efficiency according to the DC bus power. These curves are obtained from different static heads (ie different hydraulic network characteristics). Note that the efficiency is affected by the static head: then the energy management strategy has to take into account the hydraulic load characteristic. For a given power, the optimal efficiency is obtained for a high head, not for a maximum flow which emphasizes the tradeoff efficiency-flow.

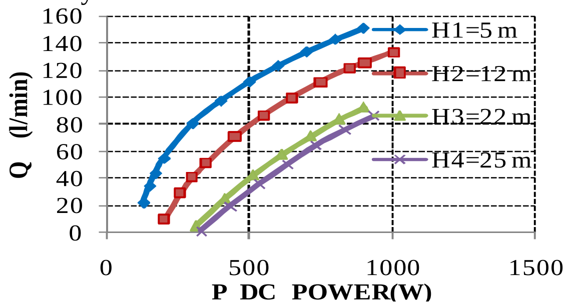


Figure 9: Water flow rate for different static heads

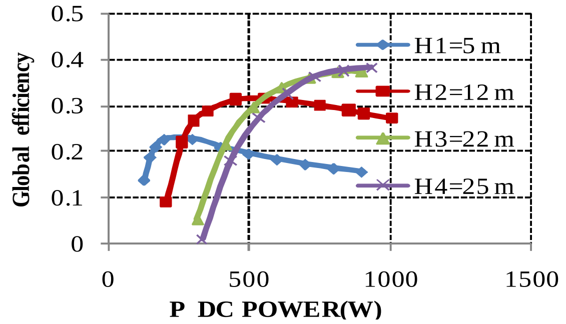


Figure 10: Global efficiency for different static head

Basic conclusions can be put forward:

- Efficiency evolution strongly depends on the hydraulic load characteristics.
- With very low or, at the opposite, with very high powers, efficiency can be so degraded that it becomes inadequate to exploit the motor- pump inside this zone: in this case, *we may prefer to store power in a battery (if any) or to exploit system "modularity"* by using several pumps which would operate sequentially with better efficiencies.

In our case study, without any storage device (except of hydraulic tanks), exploiting modularity of a "multi motor-pump system" is our goal which also constitutes an original way in terms of energy management [6].

## 5. CONTROL STRATEGIES

Following the previous analysis, we have developed a management strategy in the simplified case of a parallel association of two motor pumps. Both motor pumps are fed by voltage source inverters that offer two degrees of freedom for each: the first one is used to control the magnetic state of the induction machine, and the second one is useful for the management strategy according to the control mode:

- DC bus voltage control: the motor current is set at the output of a voltage bus regulator. This loop allows stabilizing the DC bus voltage to permit the correct operation of all sources especially in MPPT mode.
- Power transfer control: the DC bus being previously controlled (from another motor pump), a power variable operation control can be achieved on the considered motor pump. In particular, it is possible to optimize the power transfer (then the flow) through the motor pump by taking into account efficiencies. Controlling power means that an optimal control of the water flow may be achieved in the considered pump.

This original system management is illustrated by the Figure 11.

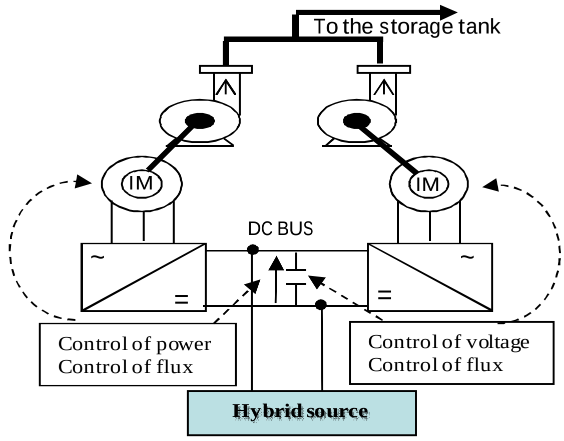


Figure 11: Principle of the energy management of the system with two parallel pumps

The induction motor can be represented using the (d,q) Park's reference frame. In order to generate references for DC bus voltage, power and magnetic flux, a Field Oriented Control (F.O.C) is used to decouple flux and torque. The rotor flux is regulated along the "*d*" axis. The torque is then controlled through the "*q*" axis current. The torque current reference ($I_{sq}^{ref}$) is set following the control mode (power, or DC bus voltage). Finally, three control loops are proposed for flux, power and DC voltage [1,3].

### 5.1. DC voltage control

In the case of Figure 14, the voltage control loop is inserted along the "q" axis of the left induction motor (index '*1*') to maintain the voltage constant whatever the power transfer between the hybrid source and the motor- pumps. To keep the power balance, we must fulfill:

$$V_{bus}.I_{e1} = E_{d1}.I_{sd1} + E_{q1}.I_{sq1} \qquad (5)$$

($E_{d1}, E_{q1}$) are the "*d*" and "*q*" axis back emf.

($I_{sd1}, I_{sq1}$) are the "*d*" and "*q*" axis stator current for the induction machine in the left part of figure 14.

From the previous equation and by considering that the motor current loop is fast with respect to the bus voltage dynamic, the cascaded structure of figure 12 is proposed. Finally with the inverter '*1*', we can control the rotor flux of the induction machine and the voltage of the DC bus.

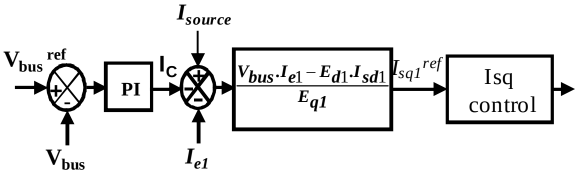


Figure 12: DC voltage control loop

### 5.2. Power control

The DC voltage being established by the inverter '*1*', a power optimized control is possible by controlling the torque current ($I_{sq2}$) at the input of the second inverter. The reference current ($I_{sq2}^{ref}$) is set to maintain the power balance (see Figure 13):

$$I_{sq2}^{ref} = \frac{V_{bus}.I_{e2} - E_{d2}.I_{sd2}}{E_{q2}} \quad (6)$$

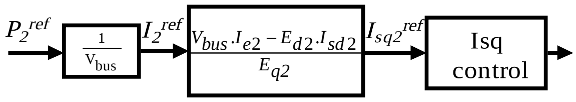


Figure 13: Diagram block of the current regulation.

The general control scheme of the two induction motors is presented on the Figure 14.

Note that the control mode (bus voltage or power control) may by inversed following operating conditions of the whole device. The PI parameters are adjusted using the pole placement method to eliminate all overshoot.

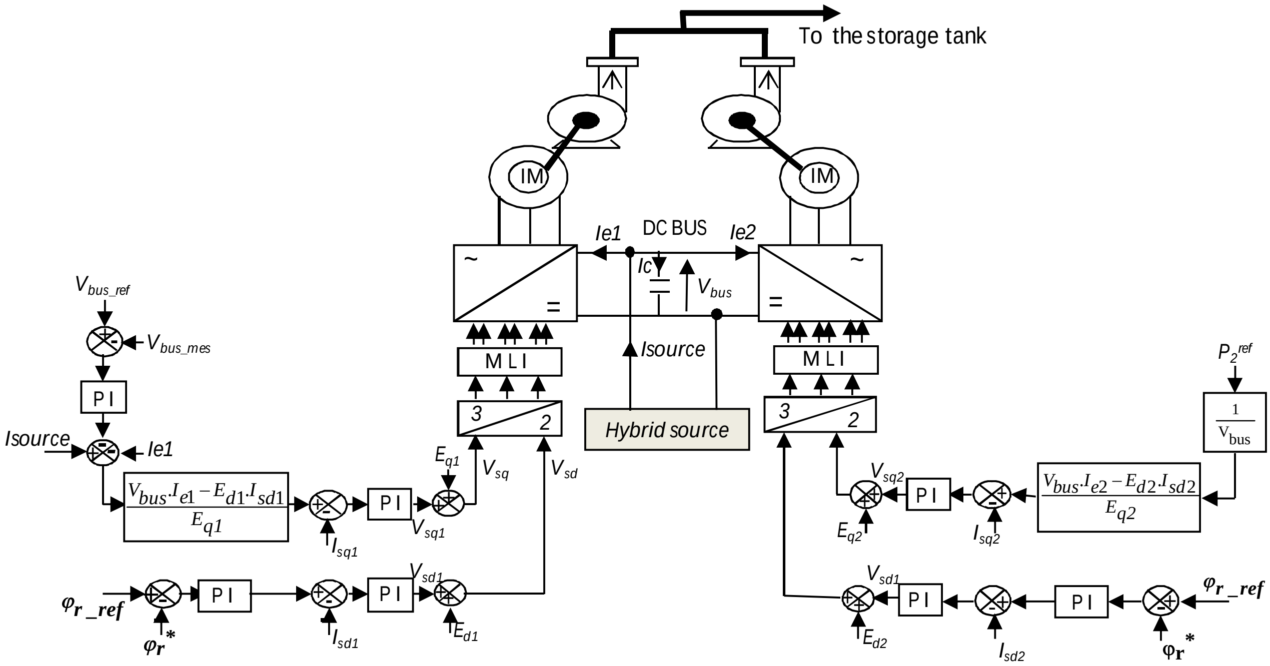


Figure 14: block diagram of the system with two parallel motor pumps

### 5.3. Simulation results and analysis

Different scenarios allow testing performance of both control and system management. The actual hybrid source is emulated by a "given" power source. The DC voltage is regulated through the motor '*1*'.

The input power imposed on the DC bus is limited between a minimum power (which makes it possible to turn one of the two pumps) and a maximum power (that doesn't exceed rated powers of both pumps)In the first case, from 0 to 10 seconds, a constant input power of 1500W has been applied before increasing to 1800W after 10s.

A constant 600W power reference is applied to the inverter of the pump '*2*' from 0 to 5 seconds then it is increased to 900W. One can see that the system follows the references, the power in inverter '*1*' being set consequently to the bus voltage regulation.

Note that after 10 seconds, the power surplus is imposed to the first inverter.

It is emphasized that, for a given power of the DC bus, the energy management of the second motor pump automatically leads us to set the power in the motor pump '*1*'.

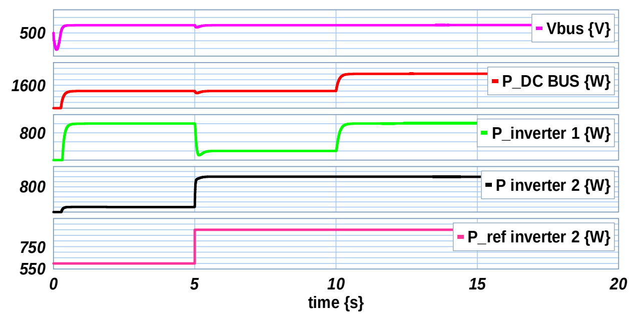


Figure 15: performance of the system control.

In the simulation test of Figure 16, the system is fed with a variable power profile which reflects the response to wind variations.

For a constant reference imposed on the motor-pump '2', the fluctuation of the power will be completely transmitted to the motor-pump '1', consequently to the bus control which balances powers.

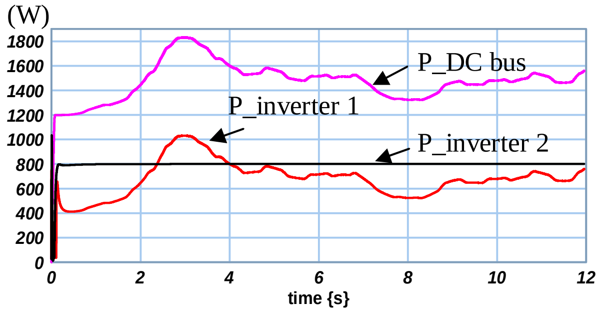


Figure 16: performance of the power control with fluctuating input power conditions

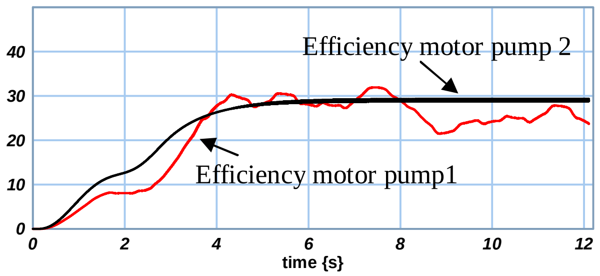


Figure 17: efficiencies of both motor pumps.

Figure 17 shows that efficiency of the voltage controlled motor pump ('*1*') is imposed by the power conditions ($P_{DCbus}$-$P_{inv2}^{ref}$) given the hydraulic load characteristics while the power controlled motor pump '2' efficiency depends on the imposed power reference and may be optimized by a system management strategy: it emphasizes the need of a system management for two or, more generally, for 'n' pump devices that will be the aim of future development.

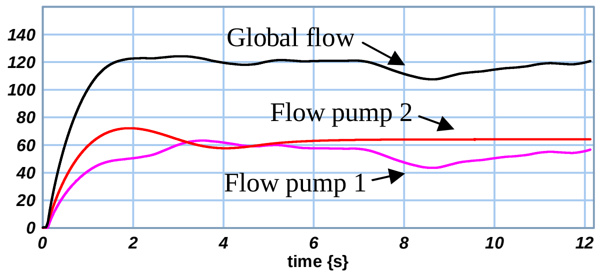


Figure 18: Evolution of the water flow.

By coupling the two pumps in parallel with the hydraulic pipe, the total flow will be the sum of both flows from the two pumps (Figure 18). The system management can be set by solving a real time optimization problem. Indeed, the issue is to optimize water quantity along sun and wind conditions by fulfilling system (technological, rating) constraints.

## 6. CONCLUSION

A pumping system fed by hybrid source without battery storage was presented in this paper. A special attention was focused on the centrifugal pump's model. Regarding this multi field (electrical, hydraulic, mechanical) device, the Bond graph formalism was proposed to model power exchanges. Experimental tests were carried out for the characterization of the pumping unit and the identification of the bond graph model parameters. Power/energy based analysis has been proposed to evaluate performance of the pumping unit for different 'given' input powers and hydraulic heads. This analysis shows that the input power level and the hydraulic network (here the water head) play an important role in terms of system efficiency. For given water head, we can manage the power to ensure a good efficiency and then to maximize water production. For that purpose, we have developed a control strategy allowing the power management through the two pumps. This study makes it possible in the future to develop a system supervisor which would allow managing the optimal level of pumped water whatever the input power provided to the DC bus along wind and sun conditions at the environment of this "sensorless" hybrid renewable energy generator.

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