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WATER DELIVERY MAXIMISATION
IN AUTONOMOUS WIND ELECTRIC PUMPING SYSTEMS

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Abstract. *The paper presents the results of an experimental optimisation of the overall performances of an isolated Wind Electric Pumping System.*

In the considered WEPS the wind turbine drives a synchronous generator which is directly connected to the asynchronous motor of a 1 kW multi-stage submersible centrifugal pump. The system has therefore no electric buffer so that both the alternator and the pump run at variable speed and the generated electric energy is characterised by variable voltage and variable frequency.

The analysis of the data shows that the excitation voltage of the synchronous generator can be conveniently used as control variable for both facilitating the start of the electric pump and maximising the water delivery once the pump is running.

A control strategy, based on the measure of the alternator frequency only, has been implemented and tested both in steady-state conditions and with variable wind speed and the results have shown a remarkable increase in the average water delivery of the system.

Keywords: *Wind Energy, Autonomous Pumping System, Synchronous Generator, Field Voltage*

1. INTRODUCTION

The use of low power Wind Electric Pumping Systems (WEPS) is extremely attractive for autonomous applications (without any electric buffer like batteries or grid) in rural areas or isolated sites (Jansen, 1978; Buehring & Freris, 1980). Small size WEPS, in fact, allow flexibility of electric connections and the adoption of widely available components, while offering minimum visual impact and almost zero ground occupancy costs, because their presence is compatible with most agriculture related activities. In addition, these systems are designed for low and medium wind intensity, so they can collect enough energy even in less favourable sites

(Pallabazzer & Sebit, 1998) and the needs of their product – water – is easily defined in terms of average quantity over short-term period, thus storage is easy and inexpensive. Moreover, small size wind turbines are usually equipped with very simple devices for the control of rotational speed and therefore have a low technological content, so that they can be manufactured and maintained by unsophisticated local workshops, thus having a positive impact on developing economies.

However, the components of a WEPS often operate in conditions which are quite far from those designed. This is particularly true in the case of small-size wind turbines (power of a few kW), which are usually equipped with very simple devices for the control of rotational speed. Therefore, a Wind Electric Pumping System needs to be analysed as a whole and great attention is to be paid to the mutual interactions between the various components. The field tests, however, are unsuitable for detailed investigation of the behaviour of all components under variable wind conditions. A test rig has therefore been developed in order to investigate the characteristics of a WEPS components, in the presence of arbitrarily chosen wind intensity, by means of a simulated wind turbine (Amelio & Bova, 1996). The paper presents the results of a performance analysis of WEPS components in the presence of low-intensity winds. In particular the influence of the alternator field voltage on the performance of the overall system has been analysed in detail. On the basis of this study, a control strategy of the field voltage, which facilitates the starting of the pump in the presence of modest wind intensity and maximises average water delivery in any wind condition, has been defined, implemented on an electronic board and tested.

2. EXPERIMENTAL APPARATUS

2.1 Simulated wind turbine and electric generator

The wind turbine and the gear box are simulated by a DC motor connected to a 3-phase AC to DC converter based on a 3-phase fully-controlled rectifier bridge, which independently controls the armature and the field voltage. The converter can control either the motor torque by the armature current or the motor speed by the armature voltage, while the field voltage is usually kept constant. The rated torque is 12.5 Nm and the maximum speed at the rated field voltage is 3750 rpm.

The electric generator is a 3-phase commercial synchronous machine with two pole-pairs (rated power 6.5 kVA at 1500 rpm, 50 Hz). A synchronous generator is well suited to an autonomous WEPS, where the generator and the pump are directly connected by a cable, without interposed electric buffer or rectifier-inverter devices. The synchronous generator can in fact produce electric energy (although with variable frequency and variable voltage) at any rotational speed.

The commercial alternators are usually equipped with a controlling circuit with the aim of keeping the output voltage constant: the field voltage is increased if the output voltage is lower than the rated one. However, such a controlling strategy is self-defeating in the case of a WEPS in which the starting torque of the wind rotor is quite low. In fact, when the alternator starts, the out-put voltage is very low and such a controlling circuit sets the field voltage at its maximum. As a consequence, the resulting breaking torque is so high that the wind turbine runs very slowly.

On the basis of the foregoing considerations, the above-mentioned standard output voltage regulator has been disconnected in the alternator used during the reported tests, and the field voltage has been supplied from outside, initially as a constant voltage, selected by the operator, and subsequently by a new regulator, whose logic will be described later.

A torque transducer with an angle marker, for the measure of the torque and of the rotational speed, is placed between the DC motor and the alternator.

A computer equipped with A/D input and D/A output converter manages the test rig and allows one to operate the DC motor either at constant velocity or at constant torque or along the torque- speed characteristic of a given wind rotor. Figure 1 gives the scheme of the rig: the computer reads the rotational speed of the DC motor and sets the required torque according to the selected torque-speed characteristic. The calculated torque as well as the measured actual torque are sent to the AC to DC converter which feeds the motor.

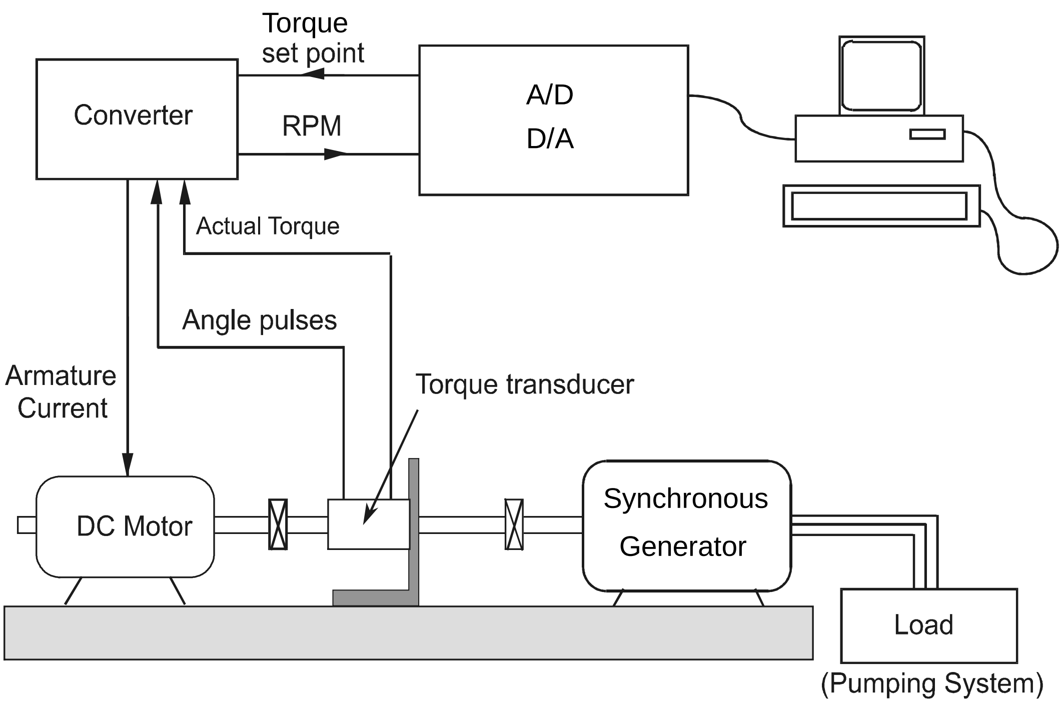

Figure 1. - Schematic diagram of the test-rig for components of a WECS

The effect of the difference between the moments of inertia of the real rotor and of the DC motor has been taken into account (Amelio *et al.,* 1999), while the inertia of the horizontal axis wind turbine, which derives from the yaw rotation, has been neglected.

2.2 Electric pump and hydraulic circuit

The electric pump is inserted in an hydraulic loop which simulates the hydraulic load of the WEPS (Fig. 2).

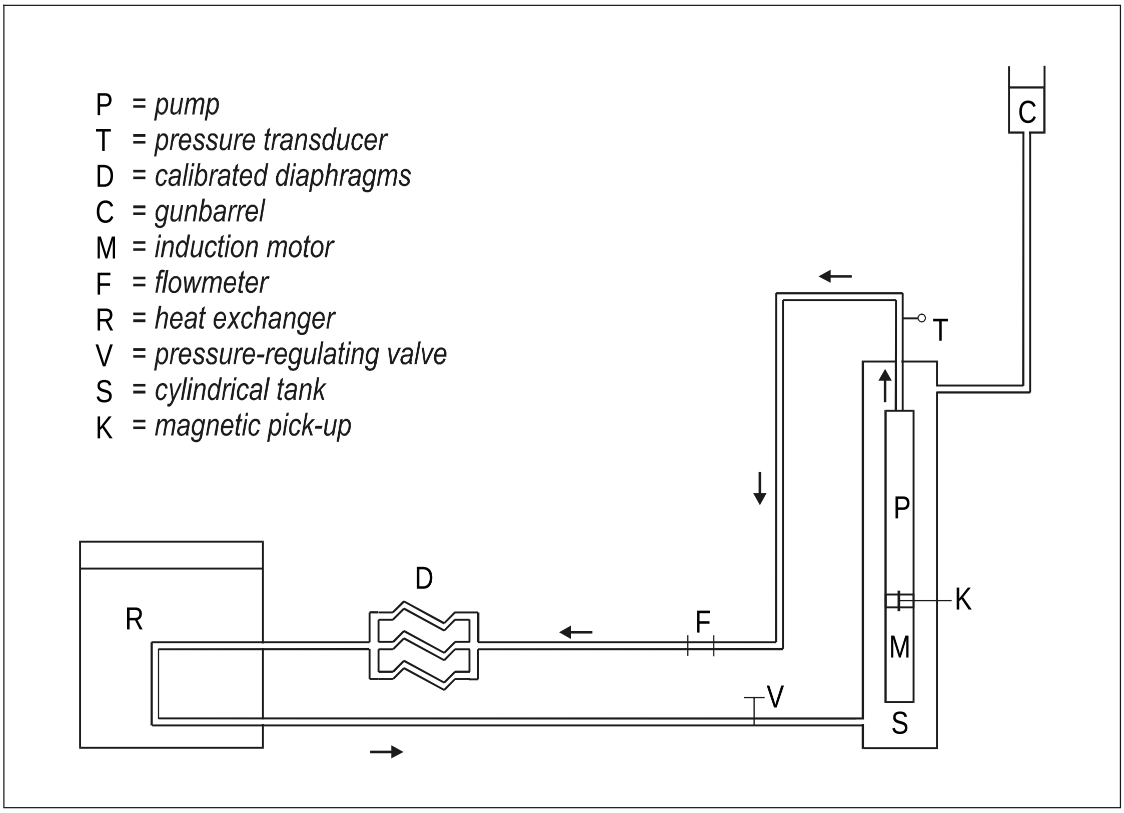

Figure 2. - Hydraulic loop

The 20-stage submersible centrifugal pump has the following b.e.p characteristics: water flow rate Q = 65 l/min; head H = 94 m; hydraulic efficiency 0.7. The pump is driven by a 2 pole asynchronous motor, which provides 1.5 kW at 2900 rpm. The electric pump is located in a cylindrical tank S, which is kept under a fixed head by a gunbarrel C.

The required hydraulic power can be adjusted by a pressure regulating valve V, which causes a constant pressure drop (independent of the flow rate) in the range 0 - 40 m, and by three diaphragms which yield a pressure drop dependent on the water delivery. The pressure regulating valve therefore simulates the geodetic head and the diaphragms fix three working points on the characteristic curves. The hydraulic circuit incorporates a heat exchanger in order to avoid significant increases in the water temperature.

The discharge head of the pump is determined as difference between the reading of a pressure transducer T and the head given by the gunbarrel C while the water flow rate is gauged by a turbine flow meter F. Finally, a magnetic pick-up installed on the pump shaft enables one to measure the pump rotational speed.

2.3 Unconventional field voltage controller

Results of a previous work (Amelio & Bova, 1996) have shown that the starting up of the electric pump in a WEPS is facilitated by the weakening of the alternator excitation and that the maxima of the water flow rate exhibit a linear trend both versus the alternator rotational speed and versus the field voltage (Fig. 3) . A linear relation therefore exists also between the field voltage and the rotational speed of the alternator, which, for the reported tests can be written as:

$$V_{field} = 2.0 + 0.075 \cdot f \qquad (1)$$

where V_{field} [V] is the alternator field voltage and f [Hz] is the output frequency, which for a 2 pole-pair machine is linked to the rotational speed N [rpm] by $f = 2 \cdot N/60$.

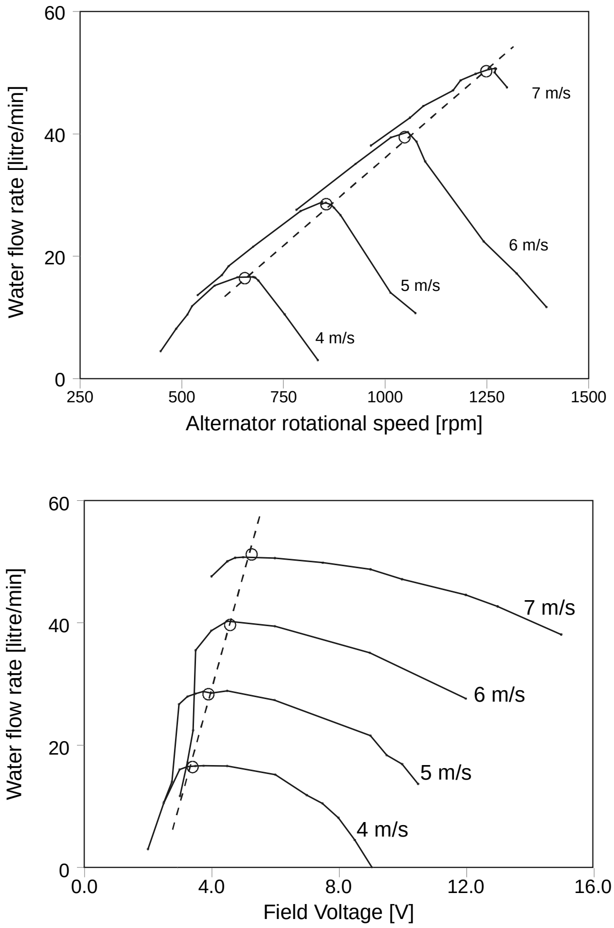

Figure. 3.- Water flow rate versus alternator speed and versus field voltage. The flow rate peaks have a linear variation with both variables.

Because the torque, that the alternator requires at constant speed and constant electric load, increases as the field voltage increases, a dependence of the field voltage on the output frequency, such as the one proposed, reduces, for any fixed electric load, the required torque at low rotational speed (which is the result of modest wind intensity) and increases the resistant torque at higher rotational speed (which is obtained under stronger wind conditions). Obviously, such a control strategy does not keep either the output voltage or the output frequency constant, but this is acceptable, if the goal is water delivery maximisation rather than the quality of electric energy.

An electric circuit, that implements the control rule (1) and that is as simple as the standard output regulator and can be easily installed within the alternator, has been developed and tested (Amelio *et al.,* 1999).

The new controller performance has been verified by imposing constant torque values to the alternator shaft and by recording the rotational speed and the field voltage, which resulted very close to the desired one.

3. RESULTS

The Wind Electric Pumping System has been tested preliminary by supplying the field voltage from outside, as a constant voltage, selected by the operator. For any fixed field voltage the torque and the rotational speed at the alternator axis, the water flow rate, the discharge head and the rotational speed of the pump have been measured, while the characteristics of the hydrau-

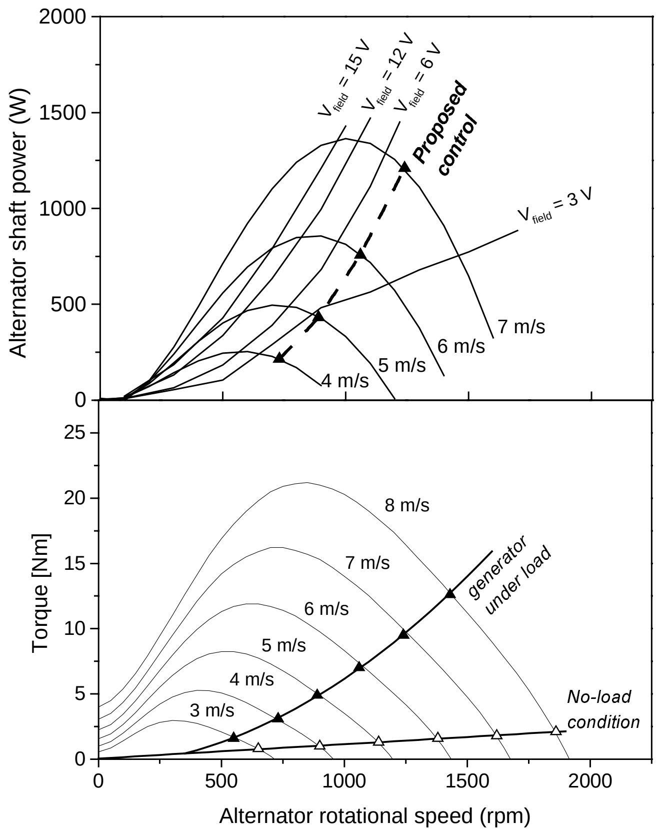

Figure 4 - Top: Mechanical power required to drive the alternator for different field voltages and power generated by the wind turbine at different wind speeds, vs. alternator rotational speed. Dashed line shows the power required with the proposed control.
Bottom: Steady-state working points of the alternator in the presence of different wind speeds. Filled symbols: alternator feeding the pump; Empty symbols: alternator under no load condition.

lic circuit have been kept unchanged (Amelio & Bova, 1996). Figure 4 (top) shows the mechanical power required to drive the alternator vs. the rotational speed for different values of excitation voltage. The figure also shows the power generated by the wind turbine for different wind speeds (Boccazzi & Pallabazzer, 1991).

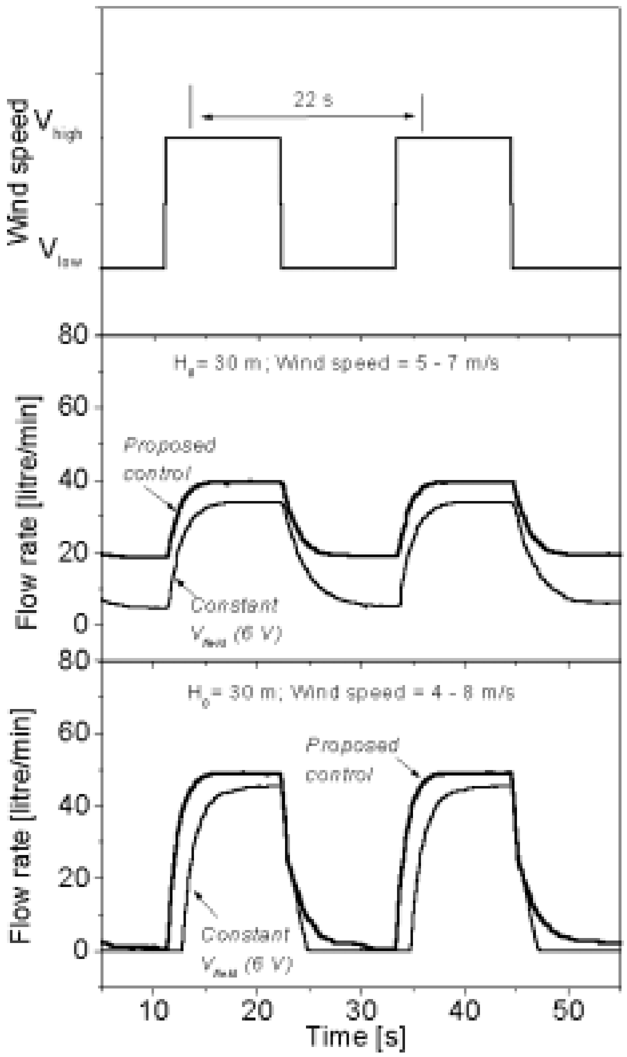

Figure 5- Top: Simulated wind condition. The wind speed varies between the values V_{high} and V_{low} with period = 22 s and duty cycle 50%.
Middle and bottom: Instantaneous flow rate obtained with the proposed control and with a constant field voltage, under 5-7 (middle) and 4-8 m/s (bottom) wind speed in the case of a 30 m geodetic head.

For any given field voltage, the slope of the required power curve is slightly lower than the optimum cubic power speed of the wind turbine. In the tested system the overall efficiency therefore increases as the generator rotational speed increases. In addition, the measured mechanical power diminishes as the excitation voltage is reduced. Moreover, a quite different behaviour can be observed for a very low field voltage (3.0 V): in this case the power has in fact a nearly linear instead of cubic trend. This fact indicates an almost constant transmitted torque and therefore the presence of a considerable slip.

The above reported results show clearly that the field voltage of the alternator has a strong influence on the performances of the overall system and can therefore play an important role in its optimisation (Amelio & Bova, 1996).

The performance of the WEPS with the field voltage control defined by the equation (1) has then been tested both in steady-state conditions and with variable wind speed.

Figure 4 (bottom) shows the steady-state working point obtained at different wind speeds as torque-speed pairs. Filled symbols refer to the normal working condition, when the pump is fed by the alternator, while empty symbols show the system behaviour when no electric load is applied to the generator. It is evident, that the load-curve (filled symbols) intersects the wind turbine power always at the right of the maximum. Nevertheless, these are the conditions for the maximum water delivery. In fact, for any given wind speed, the field voltage determined by the new controller determines the highest possible pump speed and therefore the maximum flow rate. Higher fields would determine lower generator speed and lower pump speed, while lower field voltages would determine higher generator speed but lower pump speed, due to high slip of its motor (Amelio & Bova, 1996).

The tests with variable wind speed further point out the advantage of the proposed field voltage control. In a period of 22 s the characteristic of the rotor corresponding to a wind intensity V_{high} has been imposed for 50% of the time and the one corresponding to a wind intensity V_{low} has been imposed for the remaining part of the cycle (Fig. 5 – top). The pairs of wind speed V_{high} - V_{low} (7-5 m/s and 8-4 m/s) have been selected in order to have the same average wind speed (6 m/s). The test have been repeated for different geodetic heads H_0 (H_0 = 20, 30, 40 m) and in any situation the alternator field voltage was provided either by the proposed controller or as a constant voltage (6 or 9 V). Constant field voltages lower than 6 V could not be used, because these would cause excessive system speed in conjunction with wind speed higher than 7 m/s.

Figure 5 (middle and bottom) also shows the instantaneous flow rates resulting from two different pairs of wind speed (5-7 and 4-8 m/s) for a head H_0 = 30 m both with the proposed control and with the constant 6V field voltage. The case of 9 V constant field voltage has given the worst results in any situation and is therefore not shown. In the case of 7-5 m/s (Fig. 5 middle) the proposed control gives a higher water delivery during the entire cycle. On the other hand, in the case of the 8-4 m/s (Fig. 6 – bottom) the steady-state flow rate tends to be similar both in the low-part of the cycle (where the flow rate becomes zero) and in the high-part of the cycle (where the flow rate approaches 50 litre/min). The better transient behaviour of the WEPS with the proposed control determines anyway a considerable gain in average water discharge.

The cumulative effect of the above considered differences is shown in Fig. 6 as average flow rate vs. geodetic head for the three different wind conditions (6, 5-7, 4-8 m/s) and two control strategies (6V constant field, proposed control). The advantage of the field voltage variable with the proposed criterion is evident and becomes proportionally more important as the geodetic head

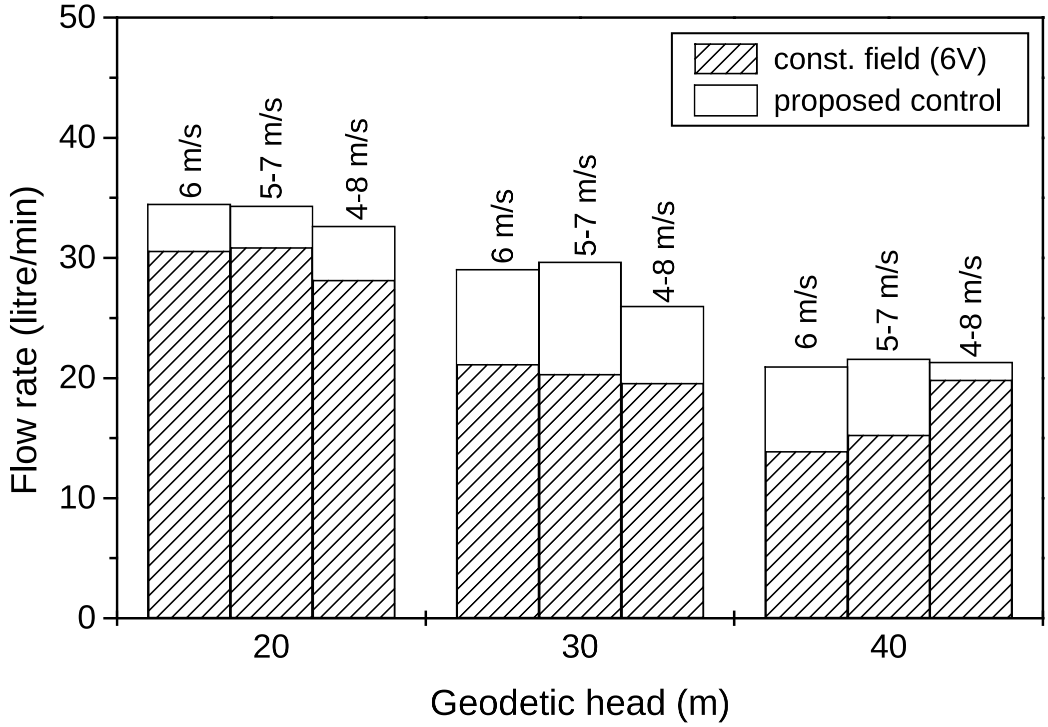

Figure 6 - Average water flow rate under the variable wind condition of Fig 5, obtained with constant field voltage (slashed bars) and with the proposed field voltage controller (white bars) for different geodetic heads.

increases. The reason is that with the proposed controller the pumps runs faster than with the constant field voltage for any wind speed lower than 8 m/s. On the other hand, a fixed fraction of the pump rotational speed is used to overcome the geodetic head, while only the remaining part – if any - is useful for water delivery. As a consequence, for higher wind intensity and lower geodetic head the difference in the water delivery obtained with the two field voltage management is negligible, while for low wind intensity and high geodetic head this difference can be very significant. Moreover, it can be noted, that in the case of the proposed control the 4-8 m/s wind condition yields the lower average flow rate for any geodetic head, even though the wind energy content is higher and the flow rate is non-zero also in the low-wind part of the cycle. This is due to the lower efficiency of the system components in the first half-period and to higher pressure losses during the high flow rate part of the cycle. Finally, it is worth pointing out, that the difference in the average water delivery between the two field voltage control strategies would be even greater if a period longer than 22 s with the same 50% duty cycle were considered.

4. CONCLUSIONS

A laboratory test rig, which enables the simulation of variable wind conditions, has been used for analysing the mutual interaction of the components of a WEPS. The tests have shown that submersible pump performances are strongly influenced by the control strategy of the alternator field voltage. In particular:

a) the standard field voltage regulator of a commercial alternator is not suited for a WEPS;
b) a non-conventional control, which increases the field voltage proportionally to alternator rotational speed, improves WEPS performance;
c) in the presence of low wind intensity and/or high geodetic heads the proposed control strategy determines a considerable increase in water discharge of the WEPS in comparison with constant field voltage or standard output voltage control.

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