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EXPERIMENTAL RESULTS OF A WIND POWERED PUMPING PLANT WITH ELECTRICAL TRANSMISSION.

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Summary

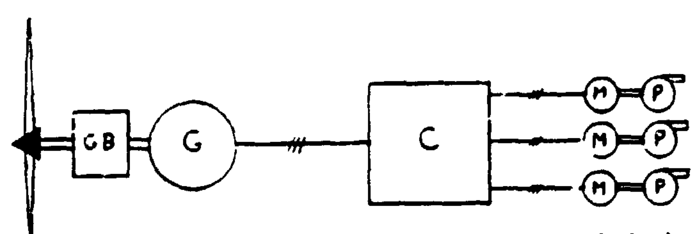
A demonstrative application of deep well pumping employing a wind powered pumping plant with electric transmission has been set-up and tested for two years at the test field of the Casaccia center of ENEA, near Roma.
The tests permitted to evaluate the practical performances, advantages and drawbacks of a wind pumping plant of this type, in order to permit a design optimization and a proper choice of components and of control strategies for future commercial applications.
The main point of investigation has been the evaluation of the effectiveness of a control scheme based on a "permanent link" between electric generator and electric motor, avoiding any electronics and switching components, and leading to a very robust and reliable mean of transferring energy to the pump at variable speed, at low cost.

Keywords

Autonomous energy systems; Water pumping; Wind energy conversion.

1. Introduction

In remote areas and in windy sites not connected to a national or local grid, electric transmission provides an effective mean for transmitting energy from a Wind Energy Converter to a pumping plant located within some hundreds of meters from the Wind Turbine.
A stand-alone plant of this type, called WEPS (Wind Electric Pumping System), is composed by a Wind turbine, an electric cable, a control system and one or more electric pumps (fig. 1).



GB Gearbox G: Generator C: Control device
M: Electric motor P: Pump

Fig. 1 Stand alone WEPS

The adoption of electric transmission gives the chance of employing commercial and widely available components (Wind Turbine, electric pump and control equipment). Applications can be to deep well pumping, drainage, desalination, irrigation; all of these can be of particular interest in the case of island communities.

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In most of the cases, typically in the deep well pumping, the storage of energy for compensating diurnal or weekly mismatch between available wind power and water consumption can be easily accomplished by storing water in a proper tank or in a little basin, thus avoiding expensive battery and AC-DC/DC-AC conversion typical of other stand alone applications.

2. Market issues.

The market of WEPS can be of some importance for windy sites in isl and coastal zones in the Mediterranean area. W come competitive with respect to mechanical transmission Wi. ers as the size of the plant and the average mean windspeed of the increase [1]; a quantitative trade-off should probably give a res like that presented in fig. 2.

the Mediterranean area WEPS could in effect be in competition with conventional pumping systems supplied by diesel engines or by diesel generating sets; in this respect, a rough comparison can be performed confronting the cost of electric energy produced by a Wind Turbine of small-medium size, taking into account the need to have a water storage able to face periods of lulls (ideally some days-one week or even more), with the cost producing electric energy by means of Diesel generator sets.

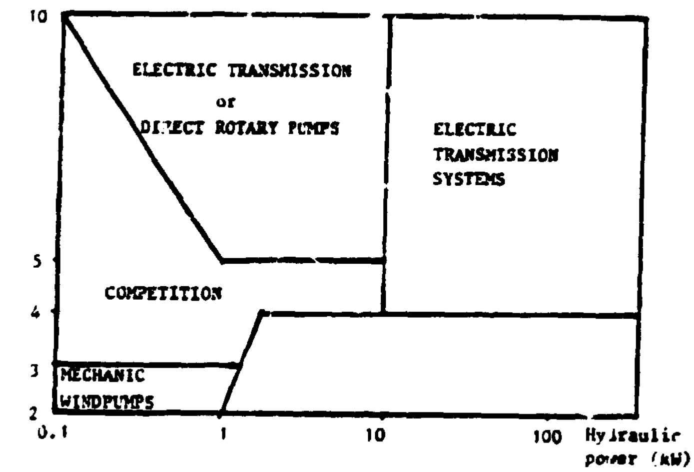

Fig. 2

More likely, in many cases a WEPS will comprise a diesel set as backup source of energy, thus dramatically reducing the size of the water storage required. In this case the comparison of cost should take into account primarily the savings in fuel costs; in terms of energy flows a stand-alone WEPS with backup Diesel can be analysed as a Wind-Diesel plant with an intermediate storage of water.

An advantage with respect to a "true" Wind-Diesel system should be, in this particular case, the decoupling between operation of Wind Turbine and Diesel set, thus avoiding the complexities due to electromechanic interaction and to battery or flywheel managment, simplifying the design methodology, and leading to a very simple and straightforward control strategy.

Actual prices show that, depending on the plant size and on local availability and price of fuel, at least for average windspeed values higher than 5 m/s, stand-alone WEPS can be economically attractive in the Mediterranean area.

3. Experimental-demonstrative WEPS's.

At the moment several experimental-demonstrative plants with sizes ranging from few KW to tens of KW have been built and tested around the world with quite good results. Apart from particular applications where the windturbine is specifically designed in order to permit the maximum amount of "appropriate technology" for technological transfer purposes [2], [3], a WEPS is generally made up adopting a commercial windturbine available on the market ([4] through [8]). All these plants employ one windturbine and one or several electric pumps, adopting a variety of control schemes.
Plants in the size of hundreds of Kw with sophisticated control hardware are currently under development [9].

4. The demonstrative program of ENEA.

The ENEA development effort has been mainly aimed at providing an insight on performances and technical issues related to the operation of small size WEPS.

The WEPS operated for two years at the test field of the Casaccia center of ENEA, near Roma [11], [12]; now it has been transferred at the Rotondella Center, in the South Italy

The design of the plant has been performed by ENEA in conjunction with the Wind Energy sector of Riva Calzoni (manufacturer of the wind Turbine) and with Caprari s.p.a. (manufacturer of the electric pump).

The WEPS is made up of a 3.5 single blade MP5 windturbine connected to a 1.5 Kw submersible pump operated at variable speed. The tests lasted almost two years, and were performed employing a closed loop test well of 100 mts. of depth, especially developed and built for the purpose by ENEA.

The closed loop test well permitted to fix the static head on the pump without being limited by the real depth of the aquifer; the value was chosen at 60 mts., corresponding to typical deep well pumping application.

The choice of a closed loop well instead of an artificial pressure tank (more effective from some experimental points of view) was adopted in order to be more effective from the "demonstrative" point of view. The scheme of the plant and of the data acquisition system is shown in fig. 3.

5. Design of the ENEA WEPS.

A very straightforward design procedure, described in [10] and [11], was adopted for the sizing of the pump; no sophisticated optimization calculations were performed, given the limited amount of data available; simply, among the limited set of electrical pumps available from the chosen manufacturer, two pumps were selected assuming as data the Head vs. Flow diagrams of the pumps at 50 Hz published in the data sheets, and assuming that similarity laws could apply for variable speed operation; two pumps (1.5 and 2.2 Kw of nominal power) were selected in order to "match" as far as possible the power vs. windspeed diagram of the windturbine, and to permit a reasonable cut-in windspeed of the WEPS.

The two pumps were subsequently tested at the Riva Calzoni laboratory; in order to have a more precise idea of the relationship between power absorption of the electric motor and water output, the two pumps were tested connecting them to the electric generator of the MP5 Wind turbine, and driving it at variable speed in the operating range of the turbine (30 to 60 Hz. for the battery charging version).

The lab. tests, described in [10] and [11], showed that starting problems could occur when trying to start the 2.2 Kw pump, and also when connecting permanently to the electric generator the 1.5 Kw pump, in the so called "permanent link" control scheme.

Practically, the inrush current of the electric motor caused a so high voltage drop that the self excited synchronous generator was not able to cope with, and the voltage dropped to zero.

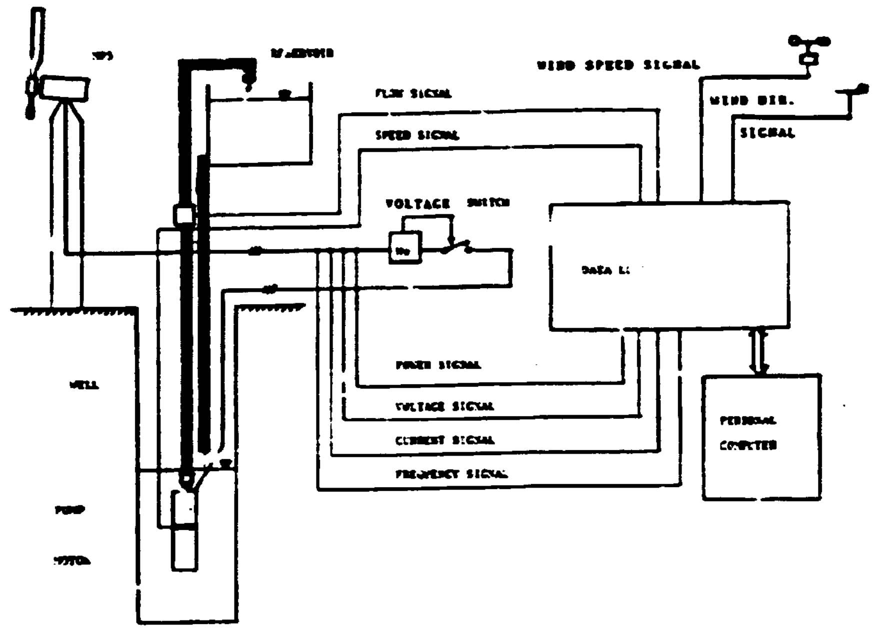

Fig. 3 MP5 WEPS with scheme of D.A S.

No problems were instead observed regarding the possible overheating of the generator, due to the limited inertia of the pump.

The adoption of a "compound exciter" solved the problem of voltage drop; unfortunately the limited time and limited knowledge at that stage of the project did not permit an optimization of this new excitation circuit of the synchronous generator; in particular, no electronic current limiter was introduced in the field circuit, and this caused severe power losses in high winds.

6. Results of the field tests

Investigations on the "permanent link" concept.

One of the main issues of the field tests was the investigation of the behavior of the so called "permanent link" control mode, as opposed to the classical "controlled link".

Here "controlled link" means that the pump is switched on and off as the Voltage crosses the minimum voltage in order to have a net water output from the plant; that's quite a straightforward way to control the pump. The plant was originally conceived as controlled in this way, by means of a voltage sensor actuated switch.

The "Permanent link", utilized at first by Twente University [5] for their Wind electrical transmission project, instead means that the electric motor and the generator are permanently connected through the electric cable. Advantage of "permanent link" is its simplicity and reliability for a small size stand alone pumping plant, given that there is not any possibility of faults due to the control system and any electronics is avoided.

The "permanent link" operation was considered an interesting field of investigation anyway, given that faults to the voltage sensor can eventually cause an unexpected operation in "permanent link"; such event occurred two times during the first tests in controlled link configuration, and after that it was decided to exercise the plant continuously in this way.

Also unexpected and strong variations in water depth can definitely produce regimes typical of the permanent link configuration, if no protection against this situation is provided.

To understand what happens in a variable speed plant operated in permanent link, if ideally we imagine to increase windspeed from the cut-in to the cut-out value (and therefore the speed of the turbine rotor) we will have at first a dissipative regime in which the electric energy produced by the generator is dissipated in the generator's and motor's windings and in the cable, while the pump remains standstill: when the electric motor torque overcomes the standstill torque in the pump a second dissipative regime will occur in which energy will be dissipated in the electric windings and in hydraulic friction and mechanical losses; when the pressure produced by the pump overcomes the static head of the plant, the pump will enter in the "operative regime", producing an increasing water output as windspeed increases up to the nominal windspeed.

The real behavior is highly influenced by the relationship between voltage produced by the electric generator and speed.

No further information was available on the concept from the work of Twente University, but it was clear that the adoption of a self-excited generator had been particularly advantageous in order to run the plant in this way; ideally the self-excited generator produces a very low voltage at low frequencies, and this voltage increases quite abruptly as the self excitation process begins; that is quite favorable in order to keep the losses in the dissipative regime at an acceptable level.

The optimized design of such a system (self-excited compound synchronous generator-electric motor-pump connected permanently) is quite complex, given that also saturation and hysteresis have a definite influence.

A very simplified treatment of the problem adopted in the design phase and detailed results on the transitory behavior of the real plant are in [10] and [1 .

Here some experimental results of the transitory behavior are presented; in fig. 4 the voltage is shown.

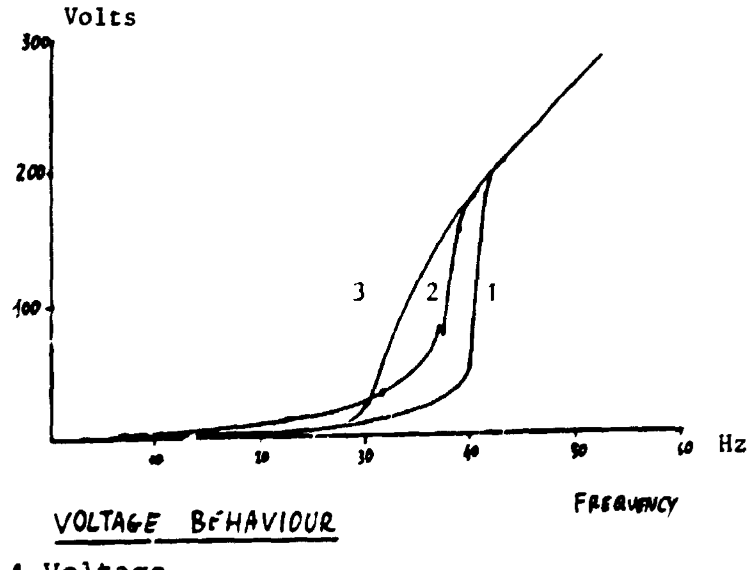

Fig. 4 Voltage

1: speeding-up, switch-on at 2000 r.p.m.
2: speeding-up, permanent link
3: speeding-down, permanent link

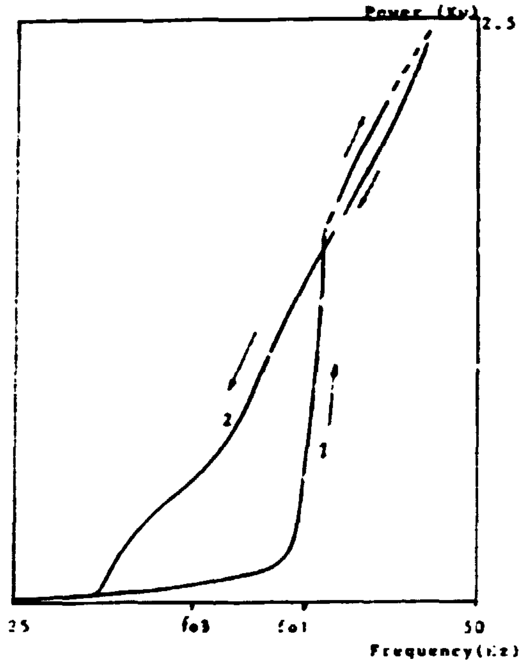

Fig. 5 Electric Power

In fig. 5 the electric power absorbed by the pump is shown; the water output is greater than zero for frequencies higher than fo1 (40.6 Hz) in the acceleration phase, and for frequencies higher than fo3 (33.9 Hz) in the deceleration phase.

It is clear that the magnetic hysteresis and the mechanical and water column inertias have a strong influence on such behavior.
An overheating test was performed operating the plant artificially out of wind in order to drive the pump near the fo1 frequency for half an hour, no overheating of the pump was observed in the dissipative regime. It should be noticed that the test well has a diameter of 0.5 meters, therefore the dissipation of heat is quite easy; that could not be the case of a real borehole. The maximum total power dissipation was anyway below 500 watts.

<u>Long term performance evaluation</u>

The measured Water output vs. Windspeed curve is shown in fig. 6. The two curves have been measured by a bin method with 30 seconds averages; such non-standard averaging time has been chosen in order to get a reasonable amount of data in the "high windspeeds range", due to the very low average wind speed of the test site (about 2.7 m/sec.).

Two different data sets are graphed: PI is relative to first long term test campaign (february 1988), PII is relative to the fifth test campaign (july-october 1988); the difference in output for windspeeds of value less than 11 m/sec. is due to the pump performance degradation that occurred after some time, due to mud accretion in the suction bell. The difference in outputs for windspeeds higher than 11 m/sec. is due to the enhancements on performances after a better setting of the cut-out sensor of the Wind Turbine was introduced; such sensor initially provoked a large amount of cut-out manouvers for windspeed values largely lower than the nominal cut-out windspeed.

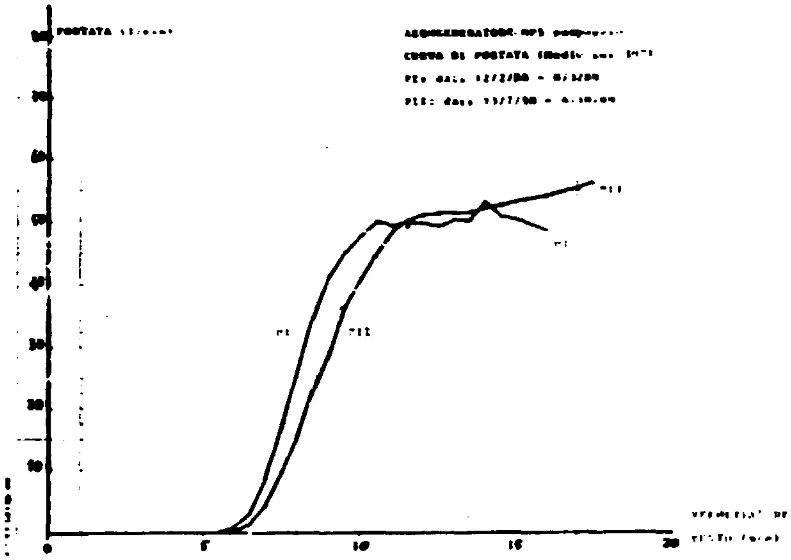

Fig. 6 Water output with 30" averages

In fig. 7 the Water output curve of the 5th campaign with 10' averages is shown.

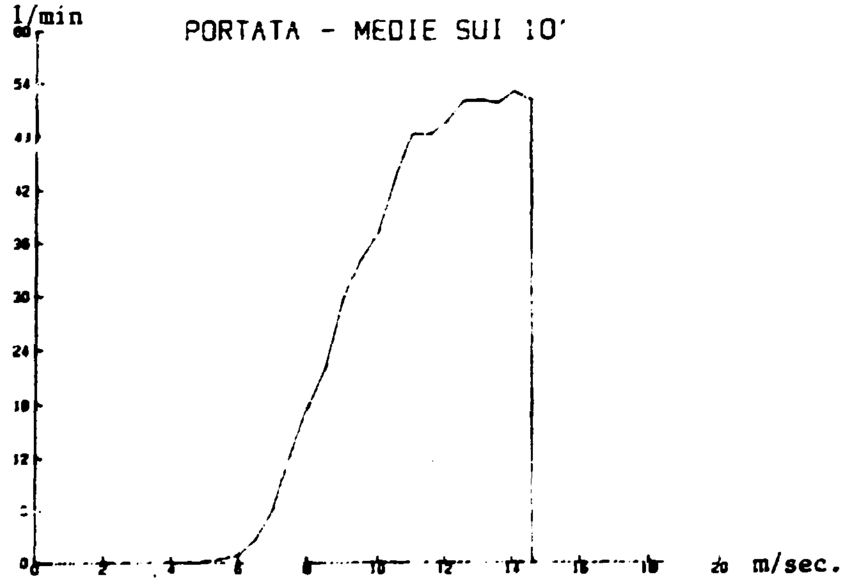

Fig. 7 Water output, with 10' averages

The overall performance of the plant, in terms of water output and efficiency, was poorer than it had been expected at the beginning of the project.
In the figure 8 the measured and projected water outputs are confronted, the first having been evaluated from the laboratory tests on components and from the results of former data acquisition activities on the battery charging version of the MP5 machine.
It can be noticed that the ratio between measured and expected

performance is of the order of 60% ; this means that a better design procedure could give better results; moreover, it was understood that different brand of turbines could give better results. In fact, after a detailed analysis the causes of performance reduction have been classified as follows:

- causes related to the peculiar electric system that has been adopted, namely the reduction of electromechanical efficiency of the electric motor when driven by the 16 poles generator of the MP5 wind turbine; the output of such generator was characterized by a high harmonic distortion of the waveform, and also the reduction in nominal voltage of the pump from 380 to 220 volts in order to match the generator, originally designed for battery charging, had some influence. The two factors accounted for a 10% overall reduction with respect a standard 380 Volts 4 poles generator.

- causes related to the specific installation, namely the reduced performance due to wear and impurities accretion in the pump impeller; among the others, this have been the major effect on the reduction of performances, accounting for roughly a 20% in overall terms.
After the two years operation the pump was taken out from the well. The overhaul indicated also some wear in the impellers (made of NORYL, a plastic resin). Indeed the main reason for the reduction of water output was, as indicated by the maintenance service, the mud accretion in the suction bell.
With respect to the content of impurity in the water, this had definitely an influence; the water of the closed loop well contained a large amount of sand and concrete particles, and also algae accretion was observed.

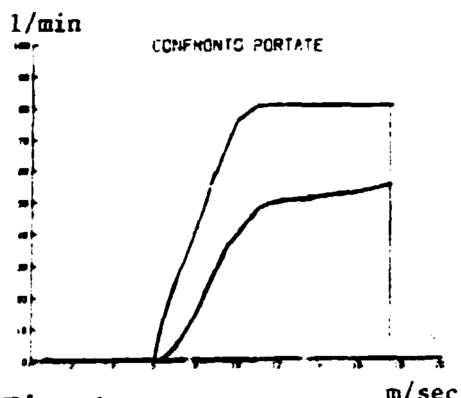

Fig. 8

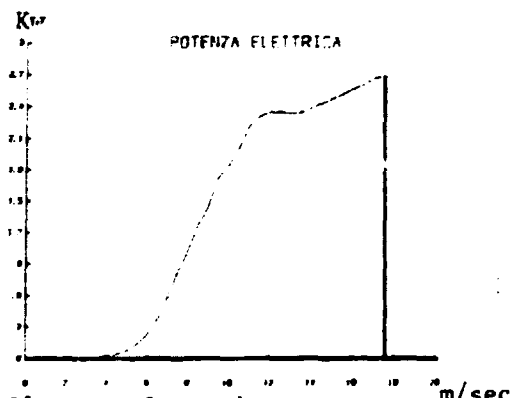

Fig. 9 Electric output

It was not possible to quantify the influence on wear and on mud accretion of the operation regimes really peculiar to the application to wind pumping, namely the operation at very low speeds, the operation in the dissipative regime at low speed connected to periods of standstill due to lulls; it seems clear that for that only laboratory tests or a combined test (operating two pumps, one at fixed speed and nominal voltage and one driven by a variable speed Wind Turbine, in the same environmental conditions) could give more informations.
It is anyway to be considered that pump brand (type and materials) and countermeasures (special filters) can have a definite influence on pump performance along time.
- not optimal load matching of wind turbine and pump: this is clearly visible examining the fig. 9; it can be observed that the maximum electric power produced has been of the order of 2.7 Kw, while the rated power of the wind turbine was of 3.6 Kw.

It was then evaluated that the adoption of a different transmission ratio between generator and rotor (namely increasing it of 20%), quite easy in the case of a machine with a gearbox, but impossible in the case of the MP5 turbine, would have improved the power matching.

- intrinsic limits of the impellers : not only the wind turbine but also the electric motor have been not fully exploited, as it can be seen examining the average power factor. The value of this parameter has been higher of the nominal value (0.75) in all the operating range, varying from .95 near the cut-in to .78 at high windspeeds, therefore denoting a partial loading of the electric motor.

In order to increase the power absorption of the pump, mainly at the lower windspeeds, it should be necessary to adopt impellers with steeper characteristics in the Head-Flow plane.

- design of the field circuit. a more accurate design of the field circuit should be developed in order to reduce the electrical losses; the optimal Voltage to Frequency ratio should have been 4 (200V/50 Hz) from 36 to 60 Hz, instead it was variable from 4 to 5. Moreover, the field current was not limited, and this caused high losses in the field circuit at high speeds.

- not optimal setting of the speed limiter and of the maximum windspeed sensor of the wind turbine: the speed limiter of the wind turbine, acting on the blade pitch, and the cut-out sensor were set at too low values, due to the initial worry for the possibility of damages caused by strong wind gusts. Definitely it resulted evident that such setting was too conservative, at least from the point of view of power output, resulting in frequent cut-out manouvers and operation below frequency limit, thus reducing energy output in high winds.

6. Cut-in windspeed

The only real drawback of electric transmission over mechanic transmission applied to displacement pumps, for low power applications and apart from technological considerations, is the higher cut-in windspeed that can be attained; this is due to the more complex conversion of power (from mechanical to electrical, again from electrical to mechanical and, at the end, from mechanical to hydraulic power) instead of the simple conversion mechanical-hydraulic of a directly coupled displacement pump and to the intrinsic limits of low solidity rotors in low windspeed regimes.

The 5 m/s cut-in windspeed (with 10' averages) obtained in the MP5 WEPS cannot be regarded as a lower limit given that, for example, CWD reported less than 4 m/s in the case of their 10.6 meters plant at Kootwijkerbroek.

The size of the plant will play strong role; moreover, if the total head is mainly due to pipe losses (this can be the case of low head-high flow plants with long pipes) the required pumping power at low speed will be reduced, and the minimum windspeed will be correspondently lower than in the case of a deep well.

For a given plant, the reduction of the cut-in windspeed is related to the choice of a wind turbine with a good performance at low windspeeds, the choice of the pump, the choice of the control scheme: the adoption of 2 or more pumps with a controlled link scheme (for example, with a little size pump operating at low speeds and one or more larger units operating at higher windspeeds) can give better results.

7. Conclusions

The experimental activity confirmed most of the expected features of the electrical transmission concept applied to wind water pumping; in general terms this type of plant is now mature for a commercial phase in the mediterranean area; provided that a reliable control hardware is provided, its reliability will be of the same order of the wind turbine generator itself.

Of course, if an "optimized" plant is to be developed, more sophisticated design tools of the turbine-pump matching and of the electromechanical behavior are needed.

For low power applications, the permanent link scheme proved to be interesting, from the side of simplicity and robustness.

For the commercialization of this particular concept a deeper insight should be needed in order to quantify the possible pump degradation effects connected with the operation at low speeds and in the dissipative regime of operation, in relation with water quality, pump brand and materials, and to evaluate the effect of possible countermeasures.

A deeper insight should also be needed in order to be able to quantify the total heat production and dissipation in more general terms, and to design a field circuit that more accurately fits the needs of a "permanent link" scheme.

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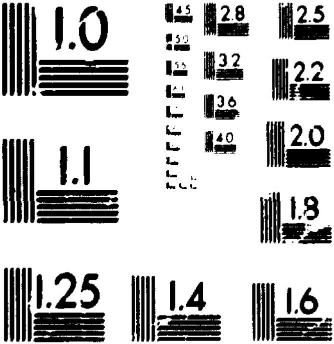

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