



CELLULAR WIND-POWER INTEGRATION USING REMOTELY CONTROLLED PUMP HYDRO ENERGY STORAGE

Ion Rares STANCIU¹, Ioan TURCIN², Sebastian MUNTEAN³, Liviu Eugen ANTON¹

¹ “Politehnica” University of Timișoara, Romania

² CAMPUS 02 UAS, Graz, Austria

³ Romanian Academy, Timișoara Branch

E-mail: rares.stanciu@mh.mec.upt.ro

There are three resources currently used to mass-produce electricity: coal, nuclear and hydro. Hydroelectricity is a viable resource for production today. Being renewable, delivering system services and producing the cheapest electricity possible, these are facts that recommend hydroelectricity today. Often power plants work together with storage pumping stations. This ensemble is very important for power system services. Wind energy is another energy resource growing at accelerated pace. However, its intermittent character poses energy integration challenges. This paper considers a cell-type ensemble of a wind turbine and a remotely controlled pumping storage station and explores wind power integration. The hardware used as a pumping station is an experimental facility retrofitted with remote control and video capabilities. Built in the lab, this infrastructure is a valuable platform allowing researchers to target different research directions.

Key words: wind power integration, remote control, pumped hydro energy storage.

1. INTRODUCTION

The demand for electrical energy increases due to the society evolution. The need for electricity is far from constant over the time. During daytime the electricity demand is high while during the night time it decreases considerably. This pattern varies during the day of the week and during the season. Since the electricity cannot be stored there is an obvious need to adjust the production to comply.

The electricity is today mass-produced using: nuclear, thermal, hydro, and recently by wind. The first two work in a similar manner: steam forces the turbine-generator bundles into rotation. On the other hand, the hydro uses water to produce electricity. According to Sternberg [1] 20% of world's electricity is delivered by hydro. Hydro exhibits several advantages worth mentioning. It delivers the cheapest electricity. There is no pollution in the process, which is increasingly important in the actual climate change context. Of growing importance is its “renewable” feature.

Another rapidly growing source of electricity is the wind. Wind plants (typically known as wind farms) are being installed all over the world. They deliver free but intermittent energy. Together with the oscillating demand-pattern, this character raises the problem of so-called wind power integration (from control point of view this can be considered a disturbance which needs compensation to avoid power grid destabilization). So far, the need-pattern is balanced by hydro (for peak demand hydro delivers energy while the excess is used to store the water back into the lakes). In an attempt to protect the power grid stability, a significant number of islands have imposed restrictions on direct penetrations of wind power according to Bueno and Carta [2]. This suggests the kind of effects that wind energy may have on power systems if not properly managed. Several methods for wind power integration have been proposed. Bueno and Carta [2] propose a hydro-storage system to stabilize the wind electricity. Coupled with an economic model, their research targets the optimum sizing of components which form a wind-powered-hydro-pumped system.

Luickx [3] et al., also indicate storage plants for wind integration. From all examined storage types (compressed air, fuel cells, flywheels batteries, heat pumps, and pumped hydro energy storage) they recommend the Heat Pumps (HPs) and the Pumped Hydro Energy Storage (PHES). Both of them are considered in two cases: perfect wind forecast case versus error-affected forecast. PHES offers peak shaving and balancing and suggests that an appropriate balance needs to be found. On the other hand, HPs eliminate

the intermittent behavior of wind power leading to a significant reduction of GreenHouse Gas (GHG) emissions. According to Korpaas et al., [4], properly sized storages allow wind farm operators to take advantage of hourly price variation on energy market.

An interesting case is the one of Tasmania's described by Potter and Negnevitsky [5] in which power is generated almost solely by renewable sources. They underline the fact that wind-hydro can be a good combination if the environment allows. This also suggests a cell-type wind integration system. Glasnovic and Margeta [6] emphasize the main problems of today's power systems underlining that systems with little or no storage have greater need for peak power. According to them, no storage method (batteries, flywheel, pressure vessels, etc.) can be compared to PHES. Several advantages such as maturity, efficiency, reliability, large volume, etc., coupled with the low price of energy places PHES in front of any other storage method [6]. Indeed, due to the fact that nuclear and coal systems allow small adjustments only, the peak shaving is ensured to this day by PHES. Also known by system services, this means that hydro has to be able to produce the energy (when there is demand – during day time) and to absorb the energy when there is no demand (during night time).

There are two different concepts targeting the wind power integration using PHES. The first one uses a cell-type structure in which the storage absorbs all the energy delivered by a wind farm. The cell is not connected to the power grid. The energy stored by PHES is used by turbines to produce energy when needed. Direct electrical lines connect the two parts. The advantage is that the power grid stability is not affected. Cases in which the wind energy cannot ensure the necessary head must be taken into consideration. The second scenario uses the existing power lines to transfer the wind energy to the storage. Sometime more convenient (when the power lines are available), this setup raises stability challenges.

There are several parts that can significantly contribute to building an intelligent energy management system: weather forecast (for rain, wind and perhaps the sun), electricity-need forecast and energy storage. Weather conditions influence both the electricity production and the need. According to Feinberg and Genethliou [7] the weather condition is one of the most important factors. Equally important is the electricity demand forecast. According to Hobbs et al., [8] a 1% of error reduction in average energy-need forecast helps saving thousands of dollars. Gross and Galiana [9] indicate that electrical-need prediction should be hourly, daily, weekly and monthly. El-Naggar and Al-Rumaih [10] compared the prediction performance of Genetic Algorithms (GA), the Least Error Squares (LES), and the Least Absolute Value filtering (LAVF). The authors compare the percentage errors of the three algorithms, and conclude that GAs approach is closer to the exact value. Short-term energy prediction was also approached by Stanciu and Sorandaru [11]. They have employed a prediction filter to estimate one-step-ahead the electricity demand. This algorithm has delivered estimated values with errors below 4%.

Unlike mid-size power plants, the PHES do not mandatory require personnel to operate. Controlling the plant remotely also reduces the operation cost. The remote control idea is not new. The implementation however, differs from application to application. Bekiroglu and Daldal [12] control remotely an ultrasonic motor. Using a tone decoder and the GSM mobile phone network they are able to control the speed, position and direction of the motor. Abdul Aziz et al., [13] also employed the GPS infrastructure to remotely monitor an agricultural greenhouse using the Short Message Service (SMS). Their remote monitoring temperature system is able to alert the personnel regarding temperature changes. Bashkar and Manohar [14] use GSM to build a remote motor controller. The system they've built can control up to 8 devices by sending SMS from a mobile phone. Tan et al. [15] presents an internet-based which allows process-monitoring from a distributed control system. Chi Chung Ko et al., [16] describes a web-based virtual lab for teaching an undergraduate class. Swamy et al. [17] have developed web-based automation. Al-Ali et al., [18] introduced a Java-based, low-cost remote control for home automation. Unlike the middle-size power plants which usually require personnel to operate, storage pumping stations may function without operators. Their simple task (turn on and off) allow remote control. Indeed, trips to them increase the operation costs. A remote operation eliminates trips to these plants, thus decreasing the costs. Recording operating data allows a more efficient maintenance schedule and the use of a single team to maintain all the plants.

This paper presents a method to integrate the wind power using a cell-type ensemble. The ensemble consists of a wind turbine and a pumping storage and assumes no electrical connection with the power system. The energy produced by wind is transformed into electricity and used by the PHES to store the water into the higher lake. This water is used by hydraulic turbines for electricity production. Section 2 presents

our setup which emulates a pumping station. Section 3 presents the remote control system. Using a client-server backbone an application is being created to completely control the rig in a remote fashion. The performed experiments and the obtained results are described in Section 4. Conclusions and future work are presented in Section 5.

2. THE EXPERIMENTAL SETUP

This infrastructure was developed in the Pumps Laboratory at “Politehnica” University of Timisoara to target several domains: hydraulics testing, control and remote control, variable speed pumping, etc. a team-effort result, it can be seen in Fig. 1. It is composed of a closed hydraulic circuit, two reservoirs of 1m^3 each, vanes, a PCN 80-200 pump, sensors (for pressure, temperature, discharge and electrical power), and data acquisition system to acquire sensors data.

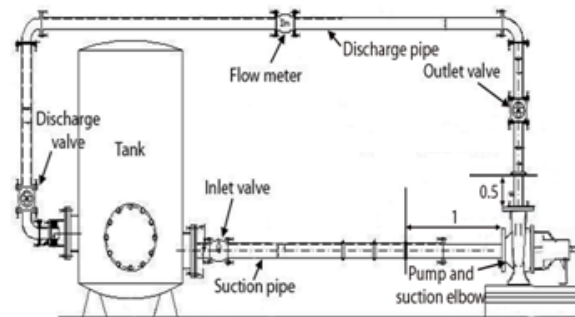


Fig. 1 – The experimental setup: left – the hardware, right – the schematic.

To be able to perform measurements and acquire operating data, an acquisition system was built. The variables of interest are the inlet and outlet pressures (in order to assess the pumping head), the speed, the discharge, and the electrical power. Called “SES-A1” and built as a distinct module, it has 32 channels (with voltage/current differential inputs), 12 bits resolution, 100kb/sec acquisition frequency, 512k sample memory and allows computer connection. An interface module provides the compatibility needed for computer interfacing using the RS232 standard. This board is able to accommodate the voltage-output or the current-output sensors.

A 37kW asynchronous motor is used to actuate the entire ensemble. This actuator is the industry’s workhorse today due to its constructive simplicity, the absence of brushes and the low-cost maintenance, features that make it the preferred actuator. Its single drawback is related to the speed adjustment. Fortunately, an inverter sidesteps this problem. To be able to efficiently adapt to the requirements (adjust the hydraulic parameters), a Direct Torque Control (DTC) inverter was installed. The DTC technology allows large speed adjustments and thus, many different values of flow rate. On the other hand, the variable speed actuation allows the motor to absorb the amount of energy produced by a wind turbine (wind farm). Wind integration can be achieved using such an infrastructure by periodic adjustment of absorbed electrical power.

A software platform completely controls this infrastructure. Developed inside the lab, it acquires the needed variables (the motor’s speed, the temperature, the inlet and outlet pressures, and the discharge) and stores them into a log file.

3. THE REMOTE CONTROLLER

The so-called remote control is an increasing important direction in automation. First implemented during the space exploration era, it becomes more and more important today. Its application sphere has also grown: from space shuttles to autonomous robots (drones, Unmanned Aerial and Ground Devices), home automation and plant control. Many of the remote-control implementations use the GSM infrastructure. An important advantage of such an implementation is the wide GSM availability. However, PHES may not be covered by the GSM networks mainly because of their remote locations.

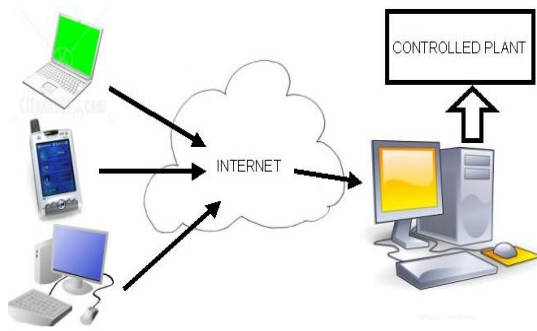


Fig. 2 – The remote control.

Table 1

The remote control commands

Commands	Action
"startmotor"	Turns on the pump motor
"stopmotor"	Turns off the pump motor
"increasespeed"	Increase the motor speed
"decreasespeed"	Decrease the motor speed
"startautoacq"	Starts the data acquisition
"stopautoacq"	Stops the data acquisition
"getdata"	Retrieves the acquired data
"setacqinterval"	Modifies the acquisition interval
setelpower	Sets the absorbed electrical power

Internet support was preferred when developing this automation structure. The fact that no interfacing modules are required is an important advantage of this solution. Indeed, interfacing modules (not available at the moment) are needed to implement the remote control using the cellular network. Another advantage of using the Internet is represented by the implementation of the vision system (which is this work uses IP-cameras).

The remote control structure described here is built using a client-server backbone. In this approach, two modules are required to function: a client and a server. In such an application, the server listens while the client attempts a connection. The server was implemented in the software platform that controls the rig. The structure of a remotely controlled application can be seen in Fig. 2. As it can be seen, the physical support for the remote controller can be a laptop/PC, or a Pocket PC (PPC). The remote controller sends commands to the PC in control of the plant. After identifying them (parsing them) this local computer issues commands accordingly. Several commands were designed in order to achieve client-server communication. Together with their action, they are presented in Table 1.

The remote control mechanism is composed of two parsers (on each side), the client-server mechanism, and a set of commands. Shown in Table 1, the commands were designed to prove the concept of pump station remote operation. To distinguish between them, a parser is being integrated in the software platform's code along with the webserver. The "startmotor" command forces the software platform to instruct the inverter to start the motor (basically starting the pump).

The "stopmotor" command works in similar manner and stops the pump. The "increasespeed" and the "decreasespeed" instruct the software platform to add or subtract a constant value to the reference speed and submit the result to the inverter to modify this value. The commands "startautoacq" and "stopautoacq" instructs the software platform to start and stop data acquisition. The "getdata" command instructs the software platform to submit the acquisition data to the controller. When a "getdata" command is received the software platform constructs a string with the values for the motor speed (reference and actual values), the electrical and mechanical power, the hydraulic parameters (the input and output pressure, the flow-rate in order to compute the head), the efficiency, and the acquisition interval. To make the parsing easier, each parameter is preceded by its name and followed by its measuring unit. The so-built string gets sent to the remote controller. After parsing, the controller displays the data in the screen and logs it into a file for later analysis. The "setacqinterval" command is the only one taking a parameter: the sampling time (in seconds). Upon request, new commands can be added to the modules involved.

4. EXPERIMENTAL RESULTS

This research presents a wind power integration method using a cell-type (wind turbine and PHES) ensemble. The cell has no electrical contact with the power grid. The experiments intended to study the behaviour of this ensemble uses our remotely-controllable experimental setup as a PHES. The target was to prove that it can absorb a certain amount of electrical energy in order to ensure wind power integration. A new command called "setelpower" was coded in the software platform. This new command sets the

electrical power absorbed by the pump. As such, the platform modifies the PHES speed to adjust the power accordingly. The data representing the electrical power is sent by the remote controller after detecting it at the wind farm. Power data to be fed to the PHES was calculated from data taken from a variable-speed wind turbine installed for investigations purpose.

Due to the fact that the wind power varies frequently (every second) and the PHES cannot keep up due to the mechanical and fluid inertia, a mechanism to deliver electrical power data at lower pace to the PHES is needed. It is important to underline the fact that the problem is not just a needed filter. A Kalman filter would definitely eliminate the spikes but this is simply not the issue. The problem is slightly different: to average and/or estimate the data such that it follows the spikes as close as possible the wind power and the frequency of data allows PHES to keep up.

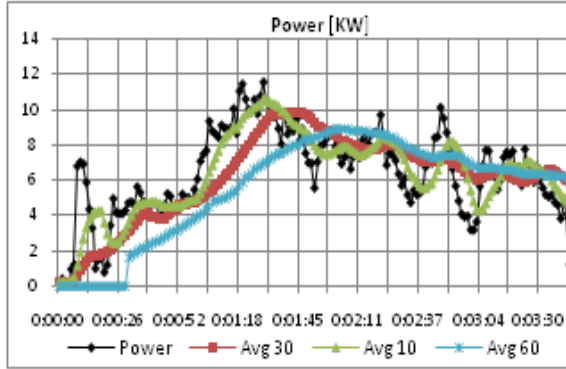


Fig. 3 – The wind power and averages for 10s, 30s, 60s.

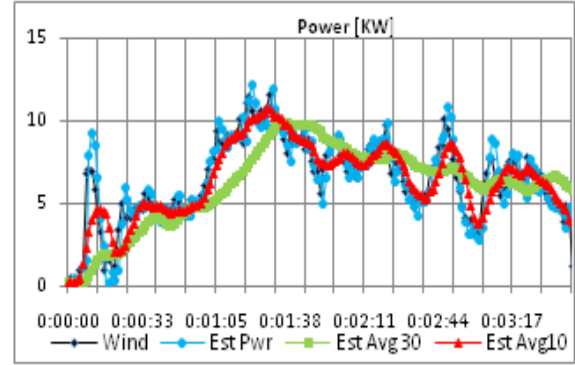


Fig. 4 – Estimating the power and averaging it after.

Since wind power value changes very often (even a small PHES can hardly keep up, and if it does it will work in a continuously transient regime), three scenarios were considered here: averaging the power values for different time intervals (10, 30 and 60 seconds – Fig. 3), estimating the wind power for one-step-ahead, and averaging the estimated values. As it can be seen, averaging power values generates a lag between the averaged curve and the original one. This way not only wrong information gets sent to the PHES, but the system fails to take full advantage of the power spikes. The shorter the averaging time is, the better it follows the power curve (the worst is the 60 sec averaging curve and the best is the 10 seconds one). Estimation was employed for the second scenario. Consequently, the “ $\alpha - \beta - \gamma$ ” tracking filter was implemented.

Initially intended for radar tracking, this family of filters was developed in the cold-war era by Sklansky [19]. Since then, they have been used for both predictions and tracking. Kalata and Murphy [20] have tried to use them for tracking with rate variations. Tenne and Singh [21] have studied ways to design them for optimal performance. In their work they also indicate how to select the parameters to obtain a stable filter. Corke and Good [22] have compared their performance with Kalman filters in the computer vision domain. They have underlined that in case of using Kalman filters the coefficients will converge to constant values. The filter works in two steps: prediction and correction. In the first step, the position and velocity is being estimated based on the observed position (equations 1 and 2).

$$x_p(k+1) = x_s(k) + T \cdot v_s(k) + \frac{T^2}{2} \cdot a_s(k), \quad (1)$$

$$v_p(k+1) = v_s(k) + T \cdot a_s(k). \quad (1)$$

Here T is the sampling time, and $x_p(k+1)$ and $v_p(k+1)$ are the predicted values for power and its gradient. In the second step, these are being corrected (equations 3, 4, and 5).

$$x_s(k) = x_p(k) + \alpha \cdot [x_o(k) - x_p(k)], \quad (3)$$

$$v_s(k) = v_p(k) + \frac{\beta}{T} \cdot [x_o(k) - x_p(k)], \quad (4)$$

$$a_s(k) = a_s(k-1) + \left(\frac{\gamma}{2 \cdot T^2} \right) \cdot [x_o(k) - x_p(k)]. \quad (5)$$

The α , β , and γ are the filter parameters and $x_o(k)$ is the current observed value of power. The filter's stability is examined using the Jury's test. To obtain the transfer function (which relates the predicted and the observed positions) one has to apply the Z-transform to the prediction and the correction equations. By applying it to the prediction equations one ends up with:

$$zX_p(z) - zx_p(0) = X_s(z) + TV_s(z) + \frac{1}{2}T^2 A_s(z) \quad (5)$$

$$zV_p(z) - zv_p(0) = V_s(z) + TA_s(z). \quad (6)$$

By applying the Z-transform to the correction:

$$X_s(z) = X_p(z) + \alpha \cdot [X_o(s) - X_p(z)], \quad (7)$$

$$V_s(z) = V_p(z) + \frac{\beta}{T} \cdot [X_o(s) - X_p(z)], \quad (8)$$

$$A_s(z) = \frac{1}{z} \cdot A_s(z) + \left(\frac{\gamma}{2 \cdot T^2} \right) \cdot [X_o(s) - X_p(z)]. \quad (9)$$

The power variation gradient is then obtained from equation 9.

$$A_s(z) = \left(\frac{z}{z-1} \right) \cdot \left(\frac{\gamma}{2 \cdot T^2} \right) \cdot [X_o(s) - X_p(z)]. \quad (10)$$

By combining the above equations, the position transfer function becomes:

$$G_{P\alpha\beta\gamma}(z) = \frac{X_p(z)}{X_o(z)} = \frac{\left(\alpha + \beta + \frac{\gamma}{4} \right) \cdot z^2 + \left(-2 \cdot \alpha - \beta + \frac{\gamma}{4} \right) \cdot z + \alpha}{z^3 + \left(\alpha + \beta + \frac{\gamma}{4} - 3 \right) \cdot z^2 + \left(-2 \cdot \alpha - \beta + \frac{\gamma}{4} + 3 \right) \cdot z + \alpha - 1}. \quad (11)$$

A stability criterion is needed to examine the filter stability. Since the z-plane's boundary is different from that of the s-plane, the Routh-Hurwitz stability criterion cannot be applied directly. However, a similar method but for discrete systems is represented by the Jury's stability test. This is used in the following to study the filter's stability. A table is constructed based on the coefficients of the characteristic polynomials. The Jury's table was used to determine the proper parameter values which ensure a stable operation. For a sampling time of 1s, the parameter values are $\alpha = 0.75$, $\beta = 0.8$, and $\gamma = 0.25$. The filter was implemented using these values. The estimated wind power values can be seen in Fig. 4 (the blue curve). Two averaging curves were also computed for 30 s (the green curve in Fig. 4) and 10 sec (the red curve in Fig. 4).

In an effort to determine which scenario is the best, the errors were plotted in case of using the estimation. The estimation and estimation averaging errors (for 10 s and 30 s) can be seen in Fig. 5. If an averaging interval of 10 seconds is used the error is around 1kW (5% if the considered power is the 20kW).

The 10s averaged power data (computed after estimation) was remotely sent to our experimental setup every 10 s. A mechanism to increase/decrease the speed was introduced in the software platform. In its simplest form, this logic increases the speed and reads the electrical power. Because the pump's curve is not linear, the increase/decrease amount varies with speed from 100rpm (below 10kW) to 75 rpm (between 10kW and 15kW) and to 50 rpm (above 15KW electrical power value). The PHES transient regimes (hydraulic and electrical) were not taken into consideration at this moment. Figure 6 shows its response to this command.

A minimum power threshold has to be established corresponding to the pumping head associated to the PHES site conditions. In these experiments this hydraulic limitation was set to 3kW. One option is to stop the PHES when there is no sufficient wind power in order to cover the energy associated to the minimum

pumping head. The alternative is to continue to operate without pumping water in the upper reservoir in order to avoid another starting transient regime and to ensure fast response. The first option was selected in our experiments.

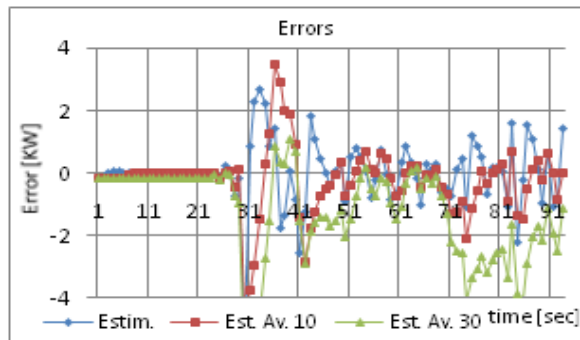


Fig. 5 – The averaging errors in case of estimation.

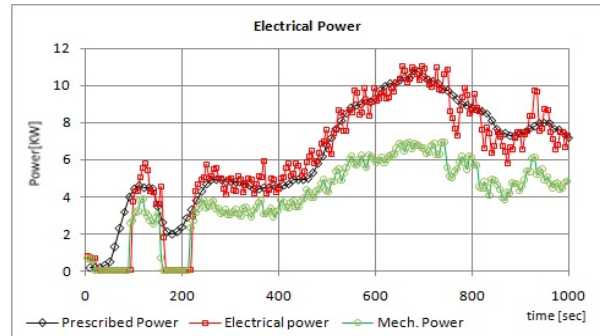


Fig. 6 – The electrical power prescription, the actual values and the mechanical power delivered to the fluid.

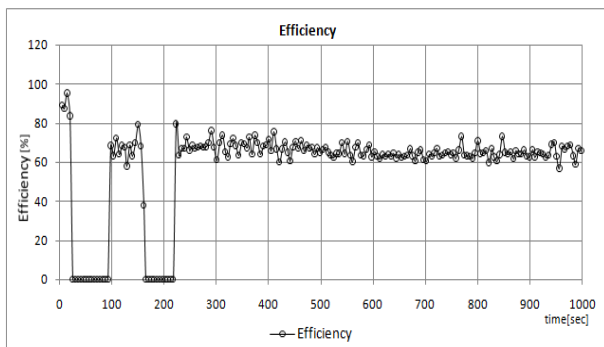


Fig. 7 – The PHES efficiency.

At this moment, it was important to determine the mechanical power at the PHES output in order to assess its efficiency. The mechanical power transferred to the fluid is plotted in Fig. 6. The PHES efficiency can be seen in Fig. 7. The values are placed in the interval 60-70% (appropriate values for a small pump) for our test rig (experimental measurements performed on the pump storage PRO10-195, actuated by a 10MW motor, revealed an efficiency of 85%). The efficiency variation during the experiment is perhaps due to the modification of the operating point on the pump's

hill chart and the operation in a continuous transient regime. The latter raises an important question regarding the unit lifetime (estimation and design constraints).

5. CONCLUSION AND FUTURE WORK

This paper presents a way of integrating the power wind using a cell-type structure composed of the wind turbine(s) and a pumping storage facility. A multi-purpose testing platform built in the Pumps lab at “Politehnica” University of Timișoara was used as a remotely controlled pumping station. This hardware was instructed to absorb a variable electrical power which was produced by a wind turbine. A filter able to estimate one-step-ahead the available electrical power was implemented. The obtained values are averaged for 10 s and 30 s. The 10 s averaging of estimated values revealed the smaller errors so far while increasing the time interval from 1 sec to 10 s. Future work is needed to increase this interval into the minute range.

The performed experiments proved a viable, easy controllable concept but also revealed some challenges. Due to the intermittent nature of the wind, sudden power variations are likely to occur. The first challenge is to integrate them while minimizing the errors. A researching direction here is the wind prediction (a better prediction can work hand in hand with the power management for the power system's benefit). Developing and investigating long-term estimation algorithms is one way to increase the efficiency of wind integration methods (small pumping station may be able to respond in a short time interval but a large one is likely not to).

Another challenge is of mechanical nature and concerns the pumps and the motors which in this context are likely to operate in a continuous transient regime for which they were most likely not designed. Therefore, future work is needed to estimate the mechanical parts lifetime in these new conditions.

ACKNOWLEDGEMENTS

This paper was supported by the project “Development and support for multidisciplinary postdoctoral programs in major technical areas of national strategy for Research – Development – Innovation” 4D-POSTDOC, contract nr. POSDRU/89/1.5/S/52603, project co-funded by the European Social Fund through Sectorial Operational Program Human Resources Development 2007-2013. Dr. Sebastian Muntean was supported by the Romanian Academy program.

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Received December 6, 2012