Simulation of a hybrid system Wind Turbine – Battery – Ultracapacitor

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Abstract. In order to improve the predictability of power generation from wind, short term energy storage in batteries combined with ultra capacitors (UCaps) is proposed. The system is simulated with SIMULINK and contains detailed models of a lead acid battery pack and a simple model of the UCap bank. The wind energy conversion system (WECS) is simulated by measured time series with a time resolution of one second.

The objective of the simulation is to determinate the system configuration that is able to guarantee a predictable energy output to the grid during a given time interval. Within this time, the storage system should be able to compensate all type of rapid changes originated by wind speed fluctuations. Another important issue is the integration of an ultra capacitor bank. It is investigated its influence on the charge and discharge stress of the battery.

It is demonstrated that quick changes in wind power generation can be covered by a reasonable size of battery capacity for a prediction time interval of 10 min. Very short transients in energy flow (1-10 s) are absorbed by the UCap bank which minimizes the deterioration of the battery because important current peaks do not reach the battery.

The final system design is based on measurements at a 600 kW constant speed WECS. Its typical, very sharp changes in power output (more than 200 kW/s possible) are smoothed by a 500 Ah lead acid battery with 300 cells in series (voltage range: 480 – 720 V). In parallel to the battery a 10 F UCap bank is connected. To hold 720 V, the bank consists of 240 UCaps connected in series (3 V / 2400 F each).

Key words

Wind/battery/ultra-capacitor system, hybrid system.

1. Introducción

In the last few years, wind energy had extraordinary growth rates in Spain. In some regions it has already reached its penetration limit. This limit is often cited as to be around 20 % but it depends strongly on the topology of the local grid and the mix of conventional power generation [1]. If there is a strong grid with many interconnections, a higher wind penetration level can be permitted. But this level is considerably lower if there is a weak grid and a lack of other energy sources able to compensate the rapid fluctuations of the wind power generation. Because wind power does not correlate with the consumption (load), the penetration level refers to the maximum wind power generation at minimum load conditions (worst case). Therefore it can be expected that the allowable penetration level rises, if the wind power production becomes smoother and more predictable. In the future, energy storage will have to be integrated to permit a higher wind generation penetration, especially in weak grids.

But batteries are not the only way to store electric energy. As one very interesting option for long and mid term storage water pumping is recently investigated to improve the benefits of wind power. Another option is the emerging hydrogen technology. Although the hydrogen option is largely discussed today [2, 3, 4], there is no grid-connected system working yet. The main problem lays in the lack of adequate electrolysers with 1-5 MW of nominal power. In opposition there are a number of large battery systems operating as spinning reserve, voltage control units or peak shaving [5]. Smaller battery systems are widely implemented as UPS (uninterruptible power supplies) [6]. Short term storage systems like batteries and UCaps can cut peaks that are generated by wind gusts or provide energy to start the wind turbine or when the grid fails. In addition they can contribute to an active voltage control because of their very short response time [5, 7]. It can be stated that battery storage is a reliable and proved technology. In addition new developments like Li-Ion batteries and ultra capacitors rapidly get cheaper and open new perspectives to this option.

Both, short and long term storage will be necessary to cope with the challenges of the growing wind energy production. Today the only method to avoid disturbances in the grid is to define limits for wind energy production in seasons of high wind speeds. This can provoke, that whole wind parks cannot produce energy while there are very favourable wind conditions. Reliable prediction and a smooth wind power generation due to short term storage would allow these wind parks to produce more energy and improve its profitability.

2. Description of the system

About the integration of battery energy storage systems (BESS) and WECS there is very little literature although in recent years it gains more and more interest. Existing installations are stand alone solutions at remote sites like islands. About grid-connected solutions only rather generic studies and simulations have been done. The focus is mainly on seasonal energy storage by means of hydrogen production.

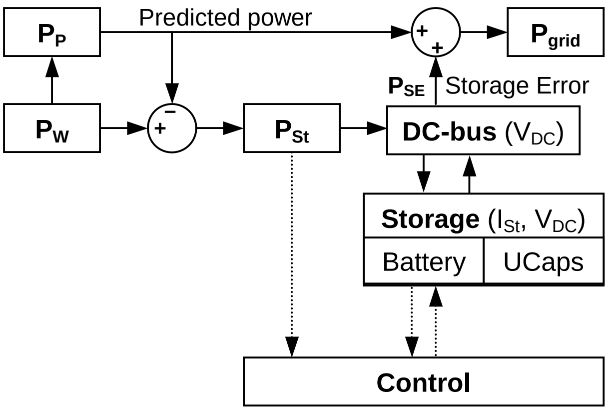

Fig. 1. Structure of the SIMULINK model for simulation of a short term storage system for WECS.

A simplified representation of the simulation model can be seen in Fig. 1. The first step is the generation of a time series of wind power generation $P_W(t)$. In order to permit a detailed simulation of the storage system, the overall complexity of the model has to be reduced. Therefore it was decided to represent the WECS by time series of measurements with a resolution of 1 s.

The second step is the calculation of the power which has to be exchanged with the storage system. It can be defined as the difference between the actual wind power output and the predicted output to the grid. This definition is given by equation (1):

$$P_{St}(t) = P_W(t) - P_P(t) \tag{1}$$

P_{St} is the power input to the storage system (or prediction error), P_W is the measured wind power output, P_P is the predicted power output to the grid and t represents the present time. As a first approach, for the predicted power output P_P a very simple prediction method was chosen. This method represents a worst case scenario for the prediction error when no information of the future development of the wind speed is available. More sophisticated prediction models can reduce substantially the prediction error and therefore the storage capacity needed. Given the prediction time interval I, it is assumed, that the power output in a future time $t + I$ will be the same as the average power output of the past time interval from $t – I$ to t. So it is defined as the running average of P_W with an average window width equal to the forecast interval I. To calculate the actual power exchange with the storage system, the average window has to be placed from $t – 2I$ to $t – I$. So the predicted power output to the grid can be written as

$$P_P(t) = \frac{1}{I}\int_{\tau=t-2I}^{t-I} P_W(\tau)\,d\tau \tag{2}$$

which results in the final equation for the storage power:

$$P_{St}(t) = \frac{1}{I}\int_{\tau=t-2I}^{t-I} P_W(\tau)\,d\tau - P_W(t) \tag{3}$$

The storage power P_{St} can be positive (discharge) or negative (charge).

The next step is the DC-bus. It is assumed, that the energy exchange between WECS, the DC-bus and the grid takes place with constant losses because no detailed model of power electronic devices has been included. Again this is due to computational limits. It was simulated a simple configuration where the battery and the UCap bank are connected directly in parallel to the DC-bus.

The battery is modelled as a system of differential equations as described in [9, 10].Its input is the battery current I_{Bat} and its outputs are the battery voltage V_{bat} (equal to the DC-bus voltage V_{DC}), temperature and the state of charge (SOC). It is introduced to the electric circuit of the DC-bus as a current controlled voltage source. The battery current I_{Bat} is defined by the storage current I_{St} and the capacitor current I_C as follows:

$$I_{Bat}(t) = I_{St}(t) - I_C(t) \tag{4}$$

with $I_C(t)$ depending on the derivate of V_{DC}:

$$I_C(t) = C\frac{dV_{DC}(t)}{dt} \tag{5}$$

Equation (5) means that if the capacity C is very large, relatively slow changes in voltage lead to considerable currents into or from the capacitor. For C = 10 F, a voltage change of dV_{DC} = 10 V/s results in a current in the capacitor of I_C = 100 A. In the reverse case, a sudden current peak produces only a slight voltage change. The effect is very important when the battery calendar life is taken into account. Especially lead acid and Li-Ion batteries will have a considerably longer life, when sharp current peaks are avoided.

The total storage current I_{St} is defined by the DC-bus voltage V_{DC} and the storage power P_{St} :

$$I_{St}(t) = \frac{P_{St}(t)}{V_{DC}(t)} \tag{6}$$

Given the storage power P_{St}, the storage current I_{St} can be introduced to the storage circuit as a voltage controlled current source.

Control

A control unit prevents the battery from hazards due to high currents or voltages, over charge and deep discharge. If the permitted current, voltage or SOC limits are reached a storage error P_{SE} is generated. This error means a deviation from the predicted wind power because it is assumed, that energy which cannot be stored in the storage system is injected to the grid. From the storage error, a prediction error PE is defined:

$$PE = \int_t^{t+I} \frac{P_{SE}(t)}{P_P(t)}\,dt \tag{7}$$

The design aim is a prediction error PE of less than one percent (?) within the prediction interval I.

In a real system the control unit has several functions. At one hand it controls the conversion of the AC power of the wind generator in DC power. At the same time it controls the amount of energy that is stored or delivered to the grid. This in turn is governed by the state of charge and the temperature of the battery and by the difference between the predicted and the actual wind power generation. Due to the number of simplifications in the model, the control unit is simplified too and only assure that the battery limits are not exceeded.

The grid itself is not integrated in the simulation because the focus had been in the design of a storage system that can deal with the given wind generation data. In this case it is crucial to be able to simulate a larger time interval which calls for a less complex model to limit the computational effort. A next step will be to investigate the influence of the integration of short term storage on the stability of the grid. Then, only a few seconds have to be simulated and the model can be more complex.

Time resolution:

Most of the simulation models are limited in time steps of one hour. To include effects like gusty winds it is necessary to study the system behaviour with a much higher time resolution. This is important especially for battery simulation as noted by Ruddell [11]. It is emphasized that microcycles of charge and discharge can influence the calendar life of the battery. Very little literature can be found about grid connected WECS-battery systems. In [12] a neuronal network is applied to simulate the effects of gusty winds and the possibility to compensate the energy fluctuations by means of a battery bank.

The present work models a hybrid system dynamic behaviour in one second time steps although an interpolated variable time step method is adopted. A time interval of one second ignores the more rapid changes of the inverters. Wind power generation in general does not change so rapidly. In [1] it is stated that for calculations of the stability of energy systems a frequency band between 0,1 and 10 Hz is sufficient. In the model presented, the focus is on energy prediction and sizing of the storage system. Therefore it seems that the available wind data with one second time resolution is sufficient. The time constants of the components are between some tenth of a second (WECS, UCaps) up to more than one hour (charge/discharge and temperature of the battery). Because it is necessary to simulate time intervals of several months to evaluate the size of battery capacity, simulation results are compared with wind speed inputs with even lower time resolution.

Objectives:

The simulation demonstrates several aspects of the integration of short term storage in a WECS.

First it shows the viability and advantages of the proposed system. The incorporation of UCaps reduces the number of charge/discharge cycles and the maximum currents in the battery.

Secondly, it is a very good tool to optimize the system elements to obtain a predictable and smooth wind energy generation. At the same time it can be quantified the requirements and limits of such a system in function of the prediction interval.

Finally it will help in future to develop an intelligent control strategy for energy management and voltage control in weak grids with high penetration of renewable energies.

3. Results

In order to find the limits of this approach, a number of different system configurations and time intervals were simulated. First only the battery was investigated. In order to estimate the battery size preliminarily, the input data was analysed. The results are shown in Table I. From the input data the cumulated energy and the maximum power peaks can be calculated which leads to the restrictions for the battery sizing: maximal power and energy capacity.

TABLE I. - Estimation of needed battery size to cover the calculated time series P_{St} , extracted from [13]

Time interval	Estimated number of cells		
	Power Restriction	Energy Restriction	Final election
10 s	**188**	105	**188**
30 s	**236**	169	**236**
1 min	**244**	210	**244**
5 min	**264**	**264**	**264**
10 min	264	**330**	**330**
30 min	276	**575**	**575**
1 h	404	**1010**	**1010**

In Table II an economical evaluation of the battery systems for the different time intervals is shown.

TABLE II. - Economical evaluation of the battery system (assumed battery system cost: 200 €/kWh), extracted from [13]

Time interval	number of cells	Energy capacity [kWh]	Battery system cost [€]	Cost relative to WECS [%]
10 s	188	94	18800	3.1
30 s	236	118	23600	3.9
1 min	244	122	24400	4.1
5 min	264	132	26400	4.4
10 min	330	165	33000	5.5
30 min	575	288	57500	9.6
1 h	1010	505	101000	16.8

In [13] it is concluded that a 10 min time interval is economically viable because it only costs about 5 % of the overall installation.

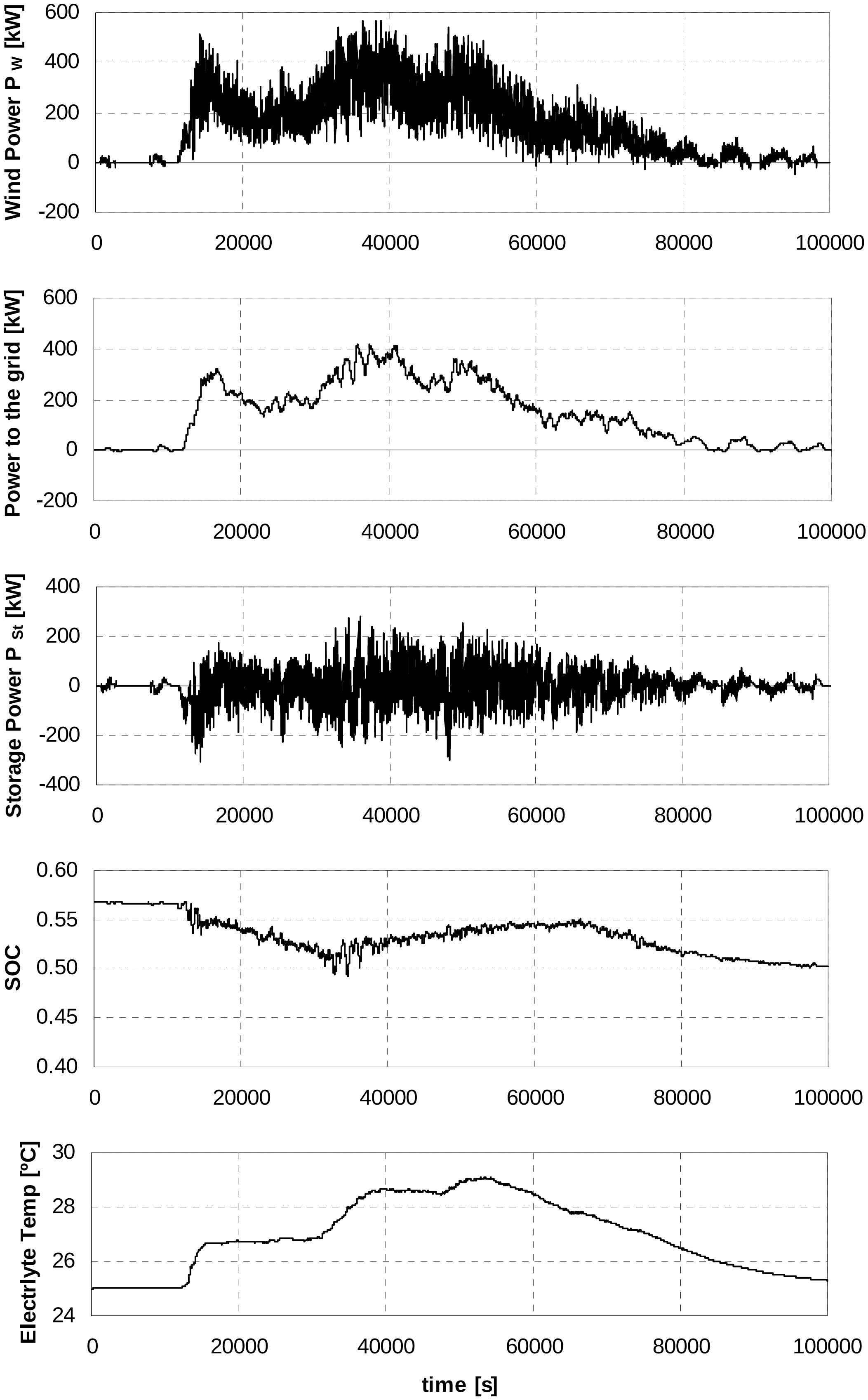

Fig. 2. Simulation results for the battery system designed for a 10 min time interval.

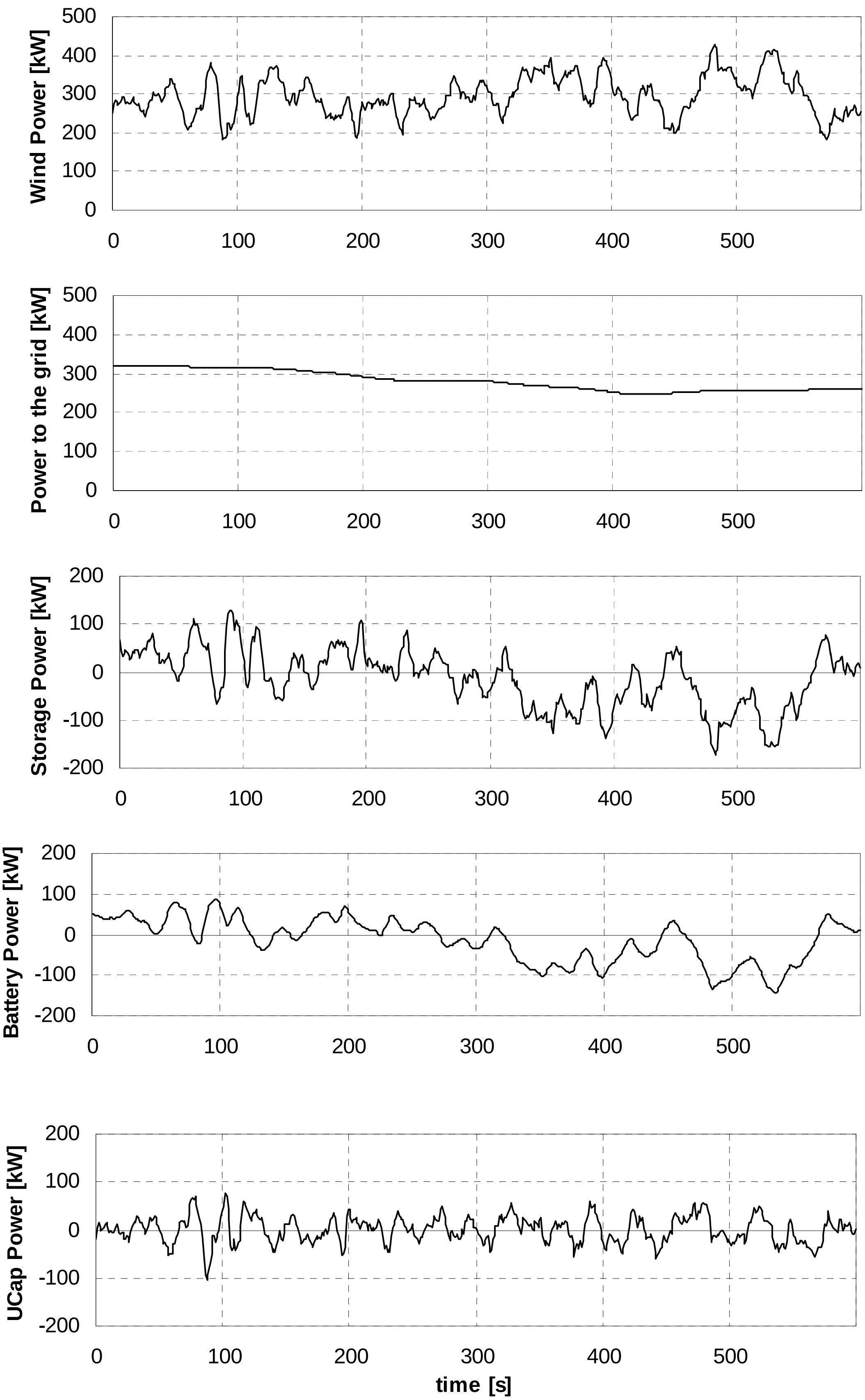

Fig. 3. Simulation results for the battery system with a 10 F ultra capacitor bank designed for a 10min time interval.
From above: total input power to the storage system, input power to the battery, input power to the ultra capacitor bank.

The simulation of all time intervals named in Table I showed good behaviour of the storage system. A typical time series for a 10min prediction time interval is shown in Fig. 2. The battery temperature always remained below 30 ºC and the SOC remained within the defined interval of 20 – 80 %. The power injected to the grid is considerably smoother than the generated wind power P_W. In Fig. 2 it can be seen very well that the power input to the storage system shows heavy fluctuations. In order to obtain a longer calendar life of the battery, it is desirable to smooth the battery input power. Simulation results show that an ultra capacitor bank in parallel to the battery can reduce the stress to the battery. The final system design consists of a 500 Ah lead acid battery with 300 cells in series (voltage range: 480 – 720 V). In parallel to the battery a 10 F ultra capacitor bank is connected. To hold the maximum voltage of 720 V, the bank consists of 240 UCaps connected in series (3 V / 2400 F each). The battery has a nominal Energy capacity of 315 kWh at a nominal power of 31.5 kW (maximum power 150 kW). The nominal values of the UCap bank are 0.72 kWh and 1872 kW of maximum power. In Table III the data of the storage components are given.

In Fig. 3 the simulation results of the system described above are depicted. The five diagrams from top to bottom: First the generated wind power P_W is depicted and then the predicted power injection to the grid. Because only a 10min time interval is shown, the predicted power remains almost constant. Below the total input power to the storage system in given. It shows the typical sharp fluctuations of the constant speed wind generator. In the middle, the battery power appears much smoother. At the bottom the power absorbed by the UCap can be seen.

TABLE III. - Battery and Ultra Capacitor data for the storage system that corresponds to Fig. 3

	Battery	Ultra capacitor
Number of single cells	300	240
Rated capacitance	500 Ah	10 F
Rated voltaje	630 V	672 V
Maximum voltaje	720 V	720 V
Rated Power	31,5 kW	
Maximum Power	150 kW	1872 kW
Energy capacity	315 kWh	0.63
Lifetime (cycles)	1500	500000

4. Conclusions

It was shown that the integration of a battery system into a wind generator improves the predictability and assures a very smooth power output to the grid. In combination with meteorological long term prediction methods a very high degree of reliability in wind energy could be achieved. A prediction interval of 10 min seams reasonable based on present costs for lead acid batteries. To smooth the wind power output for 10 min intervals energy storage of 315 kWh is needed with a cost of 5 % of the WECS.

Due to very sharp power changes, the effect of the integration of a 10 F ultra capacitor bank in parallel to the battery was examined. The results are very encouraging and a longer battery life can be expected. An economical analysis shows that the UCap bank today would mean an investment as high as for the battery which would mean a 10 % investment compared to the costs of the WECS. If the calendar life of the battery can be improved by more than a factor 2, the investment would pay itself even based on current prices. But it has to be noted, that both, ultracapacitor and battery technology is very fast developing at the moment. That means it can be expected an important price reduction for these storage systems. So in the very near future it will be an interesting and reasonable option.

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